HIGH SPEED CHEMICAL ROTORS

by

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SYNOPSIS

This report is an account of the work carried out, mainly by the author, on the development of high speed rotors for the production of hypersonic colliding beams of molecules.

Initially a brief comparison is made between various standard techniques used for the production of molecular beams with translational energies in the range 1 to 20eV. Then consideration is given to the part that rotors, producing tip speeds of 2km/s, can play in producing colliding molecular beams with available reaction energies from 1 to 10eV.

Following this, the theoretical and practical considerations used to produce a successful high speed rotor, using carbon fibre composite arms, are discussed. A full description of the single rotor unit is given and also of the double rotor unit, which is designed to produce colliding beams. Full circuit details of the rotor suspension system, the drive unit and a semi-digital and a fully-digital unit for phase-locking two rotors for use when producing colliding beams are given.

Results of an experiment are described, using one rotor, to measure the energy-intensity characteristics of a rotor-produced beam of mercury atoms. Finally, a description of a proposed experiment to optically excite mercury atoms by collision of two rotor-produced beams is given, this to be conducted in the double unit.
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* This Chapter does not constitute a part of the thesis but is a supplement to conclude the work presented within it. The work was accomplished by the author in the period between the submission of the thesis and the oral examination.
CHAPTER I

INTRODUCTION TO MOLECULAR BEAM PRODUCTION USING ROTORS

Molecular beams are required by chemists and physicists to study the laws that govern the properties of molecules and atoms, just as the cyclotron is needed to study the physical realities of sub-atomic particles. In particular, molecular beams have been used to study intermolecular forces, bimolecular reactions and, now, internal energy transfer accompanying bimolecular collisions. Various techniques are used for beam production to give a fairly continuous range of energies. However, the range of energies between 1eV and 20eV is an interval which is comparatively difficult to produce, but is of great interest to chemists. It covers the energy range for the dissociation of chemical bonds and also the activation energies for most chemical reactions.

Nozzle-produced beams can cover part of this range by running them at elevated temperatures using a plasma jet technique (R. W. Kesslen and B. Koglin, 1966). In this technique an arc is struck within the nozzle raising the effective temperature to several thousand degrees Kelvin. This method produces energies of about 3eV with beam intensities of $10^{19}$ atoms/sr/s. General requirements for the nozzle technique are large differential pumping speeds of typically $10^4$ litres/s.

Another method which is being investigated is called Sputtering. This method uses a solid target made of the material which is required for the beam and bombards this with high energy ions. The sputtered atoms are then collimated and velocity selected to form a beam. This method
appears only to produce low intensities of the order of $10^{13}$ atoms/sr/s. (10) (J. Politiek et al, 1968) and hence is not greatly favoured. (11) The seeded beam technique is useful for producing beams where the carrier gas does not affect the reaction. Heavy molecules, which are required for the beam, are added to a light inert carrier gas, usually helium, in proportions ranging from 1 to 5% and then the mixture is expanded through a nozzle. The speed of the mixture is mainly determined by the carrier gas. By multiple collisions, the heavy gas molecules are accelerated to nearly the speed of the carrier gas and the emerging beam is skimmed and collimated to produce a beam of heavy molecules with kinetic energies per molecule much greater than that of the carrier gas. This method has advantages over the plasma technique in that the molecules are accelerated comparatively gently and hence molecules, which would dissociate when violently heated, can be successfully formed into beams. This technique produces typical intensities of $10^{16}$ molecules/sr/s with a typical spread in beam velocity of 10%. (10) Charge exchange beam methods are usually used to produce higher energy beams than 20eV but can be used to produce energies between 5eV and 10eV, but with very low intensities, typically $10^{12}$ atoms/sr/s. The reason why only low intensities are possible at low energies is due to mutual repulsion of ions within the ion beam, limiting the density and hence making focussing very difficult. The method relies on the fact that the cross-section for the resonant charge transfer process is very much larger than the momentum transfer cross-section. The low beam intensities make this method less attractive than the seeded nozzle method.
Now, considering the use of rotors in the production of molecular beams, D.G. Marshall and P.B. Moon demonstrated that rotors could be used to produce fast molecular beams. In 1954 T.H. Bull and P.B. Moon showed that a beam of carbon tetrachloride produced using a rotor had sufficient translational energy to react chemically with caesium atoms. At this time the maximum tip speed obtainable using high tensile steel was of the order of 1 km/s, which meant that an atom of mercury, of atomic weight 200, would possess a kinetic energy of 1 eV when travelling at this speed. This energy, however, is comparatively small and can satisfactorily be produced by many other methods. With the advent of new materials, discussed in Chapter II, a tip speed of 2 km/s is now possible and this leads to a four-fold increase in obtainable energy.

Further to this point, if two rotors are used to produce beams of atoms with the same molecular weight, e.g. 200, and these beams are allowed to collide head-on, then the available energy for chemical reactions is doubled and hence energies of 8 eV are possible.

Considering one rotor and the beam produced by it, there are various methods of transporting the beam material to the tip of the rotor, prior to the production of the beam. The method mainly considered for the rotor arm design presently used is the simple sweeping up of the molecules. The vessel can be filled with vapour of the required material and then the rotor arm collides with the molecules, which then condense and, after a time sufficient for them to come into thermal equilibrium with the rotor arm, re-evaporate with thermal velocities. Another similar method is to use a locally produced beam of slowing moving atoms travelling perpendicular to the plane of the rotor arms. This method is more
economical on gas and it reduces the frictional couple on the rotor. If a molecule collides with the rotor arm and is elastically scattered, then the translational velocity imparted to the molecule is twice the velocity of the rotor tip. These two methods have dealt with collisions between the rotor and the molecule prior to beam production. This causes heating of the rotor, which is undesirable as will be explained later. It is possible, though difficult, to feed molecules via a small tube set within the rotor arm and allow them to emerge on the leading blade of the rotor arm. The source of molecules could either be a solid material set into the body of the rotor prior to the rotor being run, or molecules could be fed, via a small tube approximately on the rotational axis of the rotor body, into the body and then, by centrifugal pumping, to the tip.

The resultant velocity of a molecule observed in the laboratory frame of reference, is the vector sum of the rotor tip velocity at the moment the molecule leaves the surface, added to its thermal velocity. If the molecules are considered to come from a single point on the rotor arm with thermal velocities equivalent to energies of the order of kT, then the beam produced will have an angular spread of approximately $V_t/V_r$ radians (half angle) where $V_t$ is the thermal velocity and $V_r$ is the velocity of the tip of the rotor. For rotor temperatures of 370°K and molecules of molecular weight 200, the angular spread of a 2km/s beam is of the order of 0.1 of a radian. The velocity spread of the beam is about 10%. This means that the beam will be more mono-energetic if the rotor body is as cool as possible and heavy molecules are accelerated.

Considering this rather simple view of the beam produced by the tip of the rotor, it will be apparent that molecules leaving the rotor arm
perpendicularly will have a velocity given by the algebraic sum of the rotor velocity plus the thermal velocity. However, molecules leaving the rotor arm at other angles will have an increasingly smaller speed as the angle from the normal increases. Assuming that all the molecules have a thermal velocity $V_t$, the lowest speed would result when a molecule had all its thermal velocity parallel to the plane of the blade. Although this would, in principle, make it impossible for the molecule to escape from the blade, a small component perpendicular to the plane would enable it to do so. This would mean that molecules leaving perpendicular to the arm would have a speed of $V_r + V_t$ and the others could have a speed as low as $(V_r^2 + V_t^2)^{\frac{1}{2}}$. If all the velocity components of the molecules leaving the rotor arm are resolved along a line perpendicular to the blade of the rotor arm, the velocity components would range from $V_r$ to $(V_r + V_t)$.

If two collimation slits are set up in a line which forms a tangent to the locus of the rotor arm tip, the speeds of the molecules exiting from the furthest slit will show a peak when the rotor arm is perpendicular to the axis of the slits and will fall off either side of this point. This assumes the slits to be narrow and fairly close to the rotor arm, such that the differences in speed have not significantly changed the time-energy distribution of the beam. As can be seen from the previous discussion, the beam does have a velocity spread but the effectiveness of this can be reduced due to the pulsed nature of the beam. Conventional beam methods are usually continuous and this produces problems in accurate measurement of the energy of the beam. However, the energy of these beams can be measured by using choppers to make the
continuous beam pulsed, allowing time-of-flight measurements to be made. The rotor produces pulses of molecules of the order of $10^4$/s at tip speeds of 2km/s and it is therefore possible to measure directly the energy spread of the beam. If the beam is allowed to travel some distance before detection, the square of the time of flight of the molecules will be inversely proportional to the translational energy of the molecules. However, the path length must not be allowed to become too long as fast molecules from the next pulse will catch up with the slow molecules from the previous pulse. If the path length is too short, the molecules with different velocities will not have time to re-position themselves in order of energy and will still possess the velocity/time function produced by the molecular emissions from the rotor arm scanning the collimation slits.

The pressure within the apparatus must be kept low, such that the mean free path of molecules within the vessel and associated areas is longer than the beam path. If this is not the case, collisions between the beam and slow background molecules will result in the broadening of the velocity spread within the beam and a reduction in the intensity.

The considerations of a beam produced by a single rotor are of interest if molecule-surface phenomena are to be considered, but the main work in the following chapters will concern the apparatus required for colliding beams produced by two rotors.

The following derivation for available reaction energy, resulting from the collision of two beams of molecules with the same mass $m$, is a very much simplified case, but serves to highlight a useful principle connected with this type of beam production. Consider the situation
where two rotors which are counter rotating at an angular speed $\omega$ are locked in phase such that, at some point in time, both rotor blades are parallel and also perpendicular to a line joining their centres of rotation, (see Figure 1.1). If, at this time, a molecule leaves point A with a velocity $V_1$, making an angle $\theta$ with the common tangent, and a molecule leaves point B with a velocity $V_2$, making an angle $\phi$, then a time $T_c$ will elapse, before the molecules could collide at point C. The time $T_c$ is given by:

$$T_c = \frac{d_1}{V_1 \cos \theta} = \frac{d_2}{V_2 \cos \phi}$$ (1.1)

Now, to find the available reaction energy it is necessary to resolve components of momentum and two suitable axes are parallel and perpendicular to the common tangent. For simplicity, there are no components of velocity parallel to the axis of rotation of the rotors. The available reaction energy $E_r$ is given by, assuming that the molecules bond after collision:

$$E_r = \frac{1}{2}mV_1^2 + \frac{1}{2}mV_2^2 - mV_3^2$$ (1.2)

where

$$V_3^2 = \frac{1}{4}[(V_1 \cos \theta - V_2 \cos \phi)^2 + (V_1 \sin \theta + V_2 \sin \phi)^2]$$ (1.3)

and also:

$$d_1 \tan \theta = d_2 \tan \phi = p$$

Substituting equation 1.3 in 1.2 and substituting $V_1$ and $V_2$ from relationships given in equation 1.1, the available reaction energy is given by:

$$E_r = \frac{m}{2T_c^2} \left[ \frac{d_1^2}{\cos^2 \theta} + \frac{d_2^2}{\cos^2 \phi} - \frac{1}{2}(d_1 - d_2)^2 - 2p^2 \right]$$ (1.4)

This can be further simplified as:
\[
\cos^2 \theta = \frac{d_1^2}{(p^2 + d_1^2)} \quad \text{and} \quad \cos^2 \phi = \frac{d_2^2}{(p^2 + d_2^2)}
\]

to give a fairly simple equation:

\[
E_r = \frac{mD^2}{4T_c^2}
\]

(1.5)

\(T_c\) is the time measured from the shooting position to an observed collision. Thus, the available reaction energy is inversely proportional to the square of the time between the in-phase position of the rotors and the collision. If one of the molecules were to leave the rotor blade just prior to the in-phase position, this would not significantly change the result as the distance travelled by such a molecule would not be significantly different from the distance it would have travelled in the same time had it stayed on the blade. This assumes the thermal velocity component is much less than the tip velocity. If an imaginary plane is set up perpendicular to the common tangent, the time of arrival of molecules from either tip is mainly governed by the velocity of the molecules and not be the time at which any given molecule leaves the rotor tip. This is true for quite appreciable angles of the rotor arm from the perpendicular position of the order of \(\pm 5^\circ\) and path lengths of 300mm.

In practice, the molecules do not come from a single point on the arm but from an area. This will complicate the situation but not severely change the general results.

Thus this technique lends itself to time-of-flight measurements and, with the use of laser-assisted detection, it should be possible to study molecule-molecule collisions. It is a simple unit which is cheaper
than conventional methods and can be run by a small team of one or two people. Measurements of beam intensity for mercury show intensities of the order of $5 \times 10^{15}$ atoms/sr/s. However, this can probably be increased by using differently shaped blades, discussed in Chapter II.
CHAPTER II

THEORETICAL AND PRACTICAL PROBLEMS OF PRODUCING A HIGH SPEED ROTOR

2.1 Introduction

The following discussion will concern rod-type rotors as they are one of the most useful shapes to be considered for molecular acceleration. Disc shaped rotors do have their applications, but as they can only be thinned in one dimension they have a lower peripheral speed limit than a rod spun about its short axis.

Steel rod-type rotors have been used in Birmingham previously to produce beams of molecules. These rotors were made of high tensile strength steel and reached speed just in excess of 1 km/s. The rotors were of the form of a ball-and-double-cone, which had tip-to-tip lengths of typically 5.25 ins.

2.2 Shape Considerations.

It will be clear that the limiting peripheral velocity of a rotor will depend on its shape and the material from which it is made. Considering the criterion of equal longitudinal stress, the ideal profile shape for a rotor arm follows the form of a Gaussian function.

\[
A_r = A_0 e^{-Kr^2}
\]

Thus, the cross-sectional area of the arm \(A_r\) varies as \(A_0 e^{-Kr^2}\) assuming all the forces contributing to the failure of the arms to be longitudinal. This leads to infinite tip speeds as \(r\) tends to infinity, but, as the diameter of such an arm tends to zero, a truncated Gaussian is the most practical form. Unfortunately, a truncated Gaussian is also difficult to machine and hence an approximation to this shape is produced by a ball and cones, as used above. If a rotor arm has a truncated
Figure 2.1A

Figure 2.1B

Figure 2.1C
Gaussian profile and the arm is circular in section (Figure 2.1A) then the stress $S$ on the central area is given by:

$$S = \frac{\omega^2 \rho R^2}{4 \ln \left( \frac{a}{b} \right)} \left[ 1 - e^{-2 \ln \left( \frac{a}{b} \right)} \right]$$

(2.1)

where $\omega$ is the angular velocity, $\rho$ is the density of the rotor material and $R$ is the distance between the central area, of radius $a$, and the tip area, of radius $b$. As the tip velocity is given by $\omega R$ then the stress at the central point of the rotor is only dependent on the square of the tip speed and the ratio of $a/b$. If the ratio of $a/b$ is $4$, the maximum tip speed $V_m$ of such a shaped rotor is given by:

$$V_m = 2.432 \sqrt{\frac{S_o}{\rho}}$$

(2.2)

where $S_o$ is the tensile breaking stress of the material. The limiting speed is only dependent on the shape of the rotor and the material from which it is made and is independent of the absolute size of the rotor.

2.3 Composite Rotors.

It can generally be shown that for any shape of rotor the limiting tip speed will always be proportional to $\sqrt{S_o/\rho}$ and hence it is this which mainly limits the maximum attainable speed. The speeds obtained using all steel rotors could only be improved slightly by making the rotor arm profile a Gaussian. The type of steel used had a tensile breaking stress of $1.16 \times 10^9$ N/m$^2$ and, although substantially stronger steel was available, there were problems in machining such steel as it is usually extremely hard. If the steel were softened and then machined, the final rotor would have to be heat treated to increase its tensile strength and this could cause deformation of the body. This means that the most
attractive way of increasing the peripheral speed of the rotor is to use material which has a considerably lower density, while still possessing a high tensile strength. This can be realised when some non-metallic substances and, in particular, carbon fibres are considered.

Carbon fibres have a typical tensile strength of 2.7 GN/m² and a density of 2 x 10³ kg/m³. However, the single fibres are very thin and impractical to use for the arms of a rotor, but if the fibres are combined with epoxy resin to produce a matrix of fibres and resin, the resultant carbon fibre composite substantially retains the advantageous characteristics of the fibres. The tensile strength of the composite is dependent on the volume fraction k of the fibres to resin. The tensile strength $S_c$ of the composite is given by:

$$ S_c = S_r + k (S_f - S_r) \quad (2.3) $$

where $S_f$ is the tensile breaking stress of the carbon fibres and $S_r$ the tensile breaking stress of the resin. For a 60% volume fraction and $S_r$ of the order of 6 x 10⁷ N/m², the tensile strength of the composite is 1.6 x 10⁹ N/m². This is slightly larger than for the machinable steel used previously. The density of the composite $\rho_c$ is given by:

$$ \rho_c = \rho_r + k (\rho_f - \rho_r) \quad (2.4) $$

where $\rho_r$ is the density of the resin and $\rho_f$ is the density of the fibres. This gives a density of the order of 1.54 x 10³ kg/m³ for a 60% volume fraction. The results of the above indicate that, if carbon fibre composite is used, an increase in tip velocity of $\sqrt{\rho_s / \rho_c}$ times the maximum achieved using the steel of earlier rotors can be expected, assuming the
PLATE 2.1 Photograph of high speed rotor which reached tip velocity of 2km/s.
tensile breaking stresses to be comparable. Considering the density and the tensile strength of carbon fibre composite, the maximum obtainable tip velocity is given by:

$$V_m = F \sqrt{\frac{S_f + k (S_f - S_r)}{\rho_f + k (\rho_f - \rho_r)}}$$  \hspace{1cm} (2.5)$$

where $F$ is a coefficient which is a function of the profile used. As $S_f$ is approximately a factor of 30 times greater than $S_r$ but $\rho_f$ is only a factor of two greater than $\rho_r$, the limiting tip velocity will be improved by increasing the volume fraction $k$ until just prior to the point when the fibres are no longer bonded together with the resin to form a composite.

As carbon fibre composite is not isotropic, it has to be carefully used so that forces perpendicular to the axis of the fibres are not allowed to pull the composite apart. The tensile strength of the material in this direction is only about a tenth of the longitudinal strength as the former is mainly due to the binding resin. As the material is not metallic, a centre boss, made of nickel chromium molybdenum steel EN24, having a tensile strength of $1.16 \times 10^9 \text{ N/m}^2$, supplied by Thos. Firth and John Brown Ltd., Sheffield, was used to enable magnetic suspension and electromagnetic drive to be applied. A $\frac{3}{4}$" diameter steel sphere was used in conjunction with a composite, tapered arm, hand finished by J. H B. to produce a rotor which ran up to 1.75km/s before breaking. This was a promising start as the design had not been particularly optimised for high speed running.

The design adopted for high speed running was produced by Professor Moon and is shown in Plate 2.1. The steel boss is machined with slowly varying curves to minimise stress concentration and with a 4mm diameter
hole drilled through the centre to hold the carbon fibre composite shaft.

For the stable running of the rotor, it is necessary for the rotor body to spin on an axis, about which the moment of inertia of the rotor is a maximum. The moment of inertia of the rotor is approximately 4.4 x 10^{-6} Kg/m^2.

The composite shaft has a profile shown in Figure 2.1B. The width of the rotor shaft was kept as thin as possible to reduce lateral stresses within it to a minimum. These stresses are proportional to the cross-sectional area for this arm, and are at a maximum where this is largest. Calculation of the lateral stress for this shape of arm shows the lateral stress to be less than one hundredth of the longitudinal stress.

The composite shaft has a cylindrical section to allow gluing within the steel boss and two cones, which are truncated at ±7.5 x 10^{-2} m, as measured from the centre. Stress calculations show three points of high stress concentration. The first and maximum point of stress is at the mid-point of the arm and given by the equation:

\[
S_{\text{max}} = \frac{\rho \omega^2}{a} \left[ \frac{a^2 z^2}{2} + \frac{m}{4} \left( R^4 - z^4 \right) + \frac{2cm}{3} \left( R^2 - z^2 \right) \right] + \frac{c^2}{z} \left[ R^2 - z^2 \right] \]  

(2.6)

where \( m = \frac{b-a}{R-z} \) and \( c = \frac{Ra- zb}{R-z} \)

The second and third points at which large stresses occur are at ±2.87 x 10^{-2} m from the centre. This corresponds to the point of maximum stress for a cone, which is a third of the height from the base. However, as the arm is a truncated cone, this moves the point of maximum
Figure 2.2

Rotor arm stress as a function of distance from centre of rotation.

Rotational frequency = 5kHz.

Circular section and truncated cone profile

Gaussian profile

Distance along rotor arm $\times 10^{-2}$ m

Stress $\times 10^9$ N/m$^2$
stress from $3.19 \times 10^{-2}$ m to the points nearer the centre. The ratio of the stress levels gives 1.0124, thus making the centre point the most likely point for a fracture to occur. Figure 2.2 shows the curve of stress as a function of the radius from the centre of the arm. The other curve show a Gaussian profiled arm of the same centre and tip radius. The maximum tip velocity is given by:

$$V_{\text{max}} = 2.4019 \sqrt{\frac{S_0}{C}}$$

(2.7)

By comparison of equations 2.7 and 2.2 it will be seen that this profile produces a very close approximation to the truncated Gaussian. The percentage maximum speed obtainable, as compared with the truncated Gaussian, is 98.7%. With a tensile strength for the carbon fibre composite of $1.64 \times 10^9$ N/m$^2$ and a density of $1.54 \times 10^3$ kg/m$^3$, a maximum theoretical speed of 2.47 km/s could be reached.

This type of arm has been used for the rotors which have already been run. However, as the tip surface area is small, it is not ideally suited for accelerating molecules. Another shape of rotor arm, which has been under consideration is one which has a bladed end similar to a screw driver tip, as shown in Figure 2.1C. This also has a cylindrical section but is then tapered to a fine blade with a width of 4mm. This would increase the surface area used for accelerating molecules approximately by a factor of four. However, computer analysis shows that the optimum profile for an arm of this form is when $z$ is equal to zero and therefore allows no cylindrical section for cementing into the steel body of the rotor. For this reason a length of untapered composite must be left for this purpose. One method of producing such an arm is
Figure 2.3  Rotor arm stress as a function of distance from centre of rotation.

Rotational frequency = 5kHz.

Circular section and wedge bladed profile.

Gaussian profile.
to take a length of 4mm diameter composite rod and grind a blade onto both ends. This would result in a profile which, if spun about the short axis, would produce a force $F_x$ at some point $x$ along the bladed section of the arm, given by:

$$
F_x = \omega^2 \rho a^2 (R - z) \left[\left(\frac{R - z}{4}\right) \cos 2\theta - R \cos \theta \right] \left(\pi - 2\theta + \sin 2\theta\right) + \frac{(R - z) \sin \theta}{4} + \frac{R \sin 3\theta}{3} - R \sin \theta - \frac{(R - z) \theta}{4} - \frac{(R - z) \sin 4\theta}{16} \right]_0^{\pi/2}
$$

(2.8) 

where $\theta = \cos^{-1} \left[\frac{R - x}{R - z}\right]$ 

The point of maximum stress of the whole arm, including the circular rod section, is at the centre and a maximum velocity limit is given by:

$$
V_{\text{max}} = 2.070 \sqrt{\frac{S_o}{\rho}}
$$

(2.9) 

Comparison of this with equation 2.2 yields a percentage maximum speed compared with the truncated Gaussian profile of 85%. The stress as a function of the radius, from the centre of the arm, is shown in Figure 2.3. 

The carbon fibre composite has been made and tested by Dr. Barker of the Chemical Engineering Department in the University of Birmingham. 

Carbon fibre composite is a difficult material to produce, with reproducible characteristics when the material is fabricated by forcing resin into a mould containing basic carbon fibres. This process was used to produce composite with a fibre fraction of 50%, which resulted in the construction of a rotor which was accelerated to 4,250 revolutions/s.
PLATE 2.2 Section of carbon fibre composite showing a void and resin-rich areas.

Courtesy of Chemical Engineering Department, University of Birmingham.
and produced a tip velocity of 2km/s. However, attempts to increase the volume fraction failed by this method, as shown in Plate 2.2. The upper plate shows a section of carbon fibre composite which has bad fibre packing and also large resin-rich areas, which would substantially reduce the strength. The lower plate shows a void in the material where there is an absence of fibre and resin. These flaws in the composite are quite typical of this type of process. Plate 2.3 shows the results of tensile fracturing of the material.

New material, called Fibredux 914C prepreg., is now being used for the manufacture of the composite. This material is in the form of sheets of carbon fibres surrounded by resin, which has not been cured. The sheets are laid one on top of the other such that all the fibres have the same orientation. An autoclave applies heat and pressure to laminate the sheets. The results have been very successful so far with fibre fractions of 60% and tensile strength of 1.5 GN/m².

2.4 Securing the Rotor Arms to the Body.

The rotor arms are held in the body of the rotor with epoxy resin glue, which is recommended for gluing metal to carbon. This joint between the rotor body and the rotor arms has produced the most problems in the production of a high speed rotor. Initially, the rotor arms were glued into the rotor body such that the geometric centre of the rotor body approximately coincided with the physical centre of the arms. However, as the composite is not isotropic, due to different fibre packing, the centre of mass of the arm is difficult to locate and place in such a way that it coincides with the axis of rotation of the boss. As the mass of the boss is much larger than that of the arms, the rotor boss can be assumed to
PLATE 2.3 Photographs of rotor arm fracture and general view of carbon fibre composite fracture under tensile loading.

Courtesy of Chemical Engineering Department, University of Birmingham.
spin on an axis passing through its centre of mass. If the rotor arm has a mass of $M_a$ and has a centre of mass separated by $\Delta R$ from the axis of rotation, then the force $F_a$ required to hold the rotor arm within the rotor boss is given by:

$$F_a = \omega^2 \Delta R \cdot M_a \quad (2.10)$$

Now, if the glued area of the arm to the boss is equal to $A_g$ and the shear breaking stress of the glue is $S_g$, then the limiting linear speed of the tip of the rotor is given by:

$$V_{\text{max}} = R \sqrt{\frac{S_g \cdot A_g}{\Delta R \cdot M_a}} \quad (2.11)$$

As the speed of the rotor arm is limited to $2.47 \text{km/s}$, due to longitudinal stress, this is the limit which can be used to define the maximum value of $\Delta R$. Measurement of shear glue strength for various samples gave a value for $S_g$ of $1.16 \times 10^7 \text{N/m}^2$ compared with the manufacturer's value of $1.38 \times 10^7 \text{N/m}^2$ for aluminium to carbon. The rotor arms had a mass of $1.54 \text{g}$ with a glued area of $3.142 \times 10^{-4} \text{m}^2$ giving a maximum value for $\Delta R$ of 2mm. However, while measurements of the strength of the joint for a specimen at $20^\circ \text{C}$ and $100^\circ \text{C}$ showed little or no change in shear breaking stress. The effect, however, of cycling a joint under tension between these two temperature limits for six cycles showed a reduction of the breaking stress to a quarter of the un-cycled strength, this being probably due to differential thermal expansion. As this temperature cycling can take place when the rotor is in use, the balance factor of 2mm should be reduced to 0.5mm. Also the failure of the joint was not always a complete breakdown in strength, but the joint
had a tendency to slip and then lock again, this partial failure sometimes taking place at relatively low stress levels. As the increased displacement of the arm would increase the force exerted on the glued joint, the initial weakness of the joint would result in its complete failure, therefore making a good balance essential.

To achieve this degree of balance a method had to be found of dynamically balancing the rotor. One attempted method was to observe the motion of the slowly spinning rotor boss and then, by observation of the wobble when the rotor arm was in place, it could be moved until the wobble was minimised. This was detected by using the wobble to modulate the intensity of a laser beam grazing the edge of the body, but this method proved to be too insensitive. A method devised by Professor Moon and refined by the author proved most satisfactory and produced a degree of balance to less than 0.1 mm. The method employed two nylon collars fitted around the rotor arms in such a way as to prevent the un-glued arms from slipping out of the rotor body. The collars were set such that the rotor arms had a small amount of play within the boss and were positioned so that the physical centre of the arms roughly corresponded to the centre of the rotor boss. With one of the collars touching the rotor body, the rotor was spun to 100 Hz and then brought back to rest. The collar was then observed to see if it still touched the rotor body; if it did, the shaft was pushed to put the other collar against the body and the procedure repeated. If both collars did not move from the position to which they had been set, prior to spinning the rotor, the space between the collars was reduced. If the shaft moved with one collar against the body, but not when the other collar was placed against the body, both
Figure 2.4 Heating and cooling curves of rotor.

- Polished body
- Coated with carbon-pigment paint
- Coated with Ebonide

Heating and cooling period in minutes.
collars were moved along the shaft slightly such that the centre of mass of the arm was more centrally placed with respect to the collars and the tests were repeated. By this iterative procedure the balance could be achieved.

2.5 Cooling the Rotor

Due to the detrimental effect of heat on the carbon fibre composite and the resin used to hold the arms in the rotor boss, a good estimate was needed of the equilibrium temperature of the rotor body when heated by the eddy currents produced by the electronic drive. Also, measurements were required to ascertain the effect of coating the rotor body with a substance such that the most effectively 'black' material could be used to maximise the radiative heat loss. A calibrated thermistor was recalibrated to check its accuracy and then glued into the centre hole of a rotor boss. The rotor boss was then highly polished to produce a very poor emitting surface. Two fine wires, of 36 gauge copper, were connected to the rotor to carry the resistance information for measurement of temperature and these were fed through a seal in the rotor vacuum vessel. The rotor body was suspended in mid-vacuum with the only contact to the walls of the vessel via the two thin wires, which also served to prevent the rotor from rotating. The vessel was then evacuated to a pressure of $10^{-6}$ Torr and the electronic drive turned on. The heat input under these conditions would be almost a maximum, only surpassed by the heating effect produced when the rotor is decelerated from high speed rotation and the frequency difference between the rotor body and the driving field would be approximately double.

The temperature as a function of time is shown in Figure 2.4; also
the temperature/time function when the rotor body was covered with a black matt lacquer (Ebonide) and a carbon-pigmented, water-based, paint. From the curves the rotor can be seen to lose most heat by radiation when the surface is coated with Ebonide and, hence, the final rotors have the steel section coated with this lacquer.
CHAPTER III

THE PHYSICAL ARRANGEMENT OF THE SINGLE
AND DOUBLE ROTOR UNITS

3.1 The Single Rotor Unit

The single rotor unit is shown in Plates 3.1 and 3.2. This unit is much simpler than the double unit as it is used for balancing and testing rotors to high speed before possible transfer into the double unit.

It consists of a glass rotor vessel which stands on top of a 2-inch diffusion pump, the vacuum seal between the two being achieved using an O-ring. The rotor vessel (Figure 3.1) is made from a two litre spherical glass flask, which has a 120mm flange moulded into the top and a 150mm flange at the bottom, on which it stands. The upper flange is used to support the lifting solenoid which is housed in a glass well filled with oil. The removal of the lifting magnet allows free access to the interior of the vessel. It is through this hole that the rotor is put into the vessel and also entry and adjustment is made of the rotor damping table. This table is supported by a T-piece, glass arrangement, which is moulded into the cylindrical sides of the port leading to the lower flange. The rotor is positioned such that the plane of rotation is approximately half way up the spherical section of the vessel, hence producing maximum clearance, this being approximately 5mm.

The description of the rotor suspension and optical arrangement is given in Chapter IV. The optical arrangement mainly comprises the prisms, lamp and detectors, which are housed inside brass shields to reduce r-f pick-up from the drive coils and also to add protection in the event of a rotor smash.
Figure 3.1  Rotor vessel assembly.

Water cooling

Cooling oil

Lift coil

Pole piece

To servo electronics

Laser

12V DC lamp

Magnet E

Damping oil

Height sensor

Pin diode

Phasc-lock electronics

Diffusion pump
PLATE 3.3  Single rotor unit without rotor vessel.

- Drive coil
- Prism and lamp housing
- Part of wooden barricade
- Diffusion pump
A periscope and telescope system was used to observe the rotor during high-speed running. This allowed safe observation of any low frequency oscillation of the rotor or orbital motion.

In the side of the vessel was placed a small cone joint which was used to attach an ionisation gauge to measure the vessel pressure. The typical pressure obtainable in the vessel is $5 \times 10^{-7}$ Torr. The cone joint port also serves to allow positioning of the rotor arms when balancing, prior to final rotor assembly.

Surrounding the upper section of the rotor unit are 4-inch wooden blocks to provide a protective barricade in the event of a high-speed rotor smash. The barricade is necessary not only to prevent the escape of the steel rotor boss but also to stop particles of glass and carbon fibres. Wood was used as this would dissipate the energy of the particles by allowing them to penetrate or bounce inelastically. The rotor possesses approximately 3kJ of kinetic energy when running at full speed. A wooden top covers the unit and protects the laser, which is mounted above this and used for rotational speed measurement.

The backing pump is connected to the diffusion pump by means of a 1-inch copper pipe with a flexible coupling to minimise the transmission of vibration caused by the rotary pump. The ionisation gauge control unit is connected to the gauge head via a relay, which is held 'on' when there is current flowing in the heater circuit of the gauge. This relay allows power to flow into the backing pump and the diffusion pump. In the event of a rise in pressure within the vacuum chamber, the current to the gauge heater is turned off by the control unit and this releases the relay, which in turn closes the magnetic isolation valve on the backing
PLATE 3.2  Single rotor unit.
pump. A very rapid increase in pressure occurs when the rotor has crashed and so the shutting of the valve reduces the amount of damage to the backing pump. Under certain conditions it is possible for the heater in the gauge head to burn out before the control unit has turned off the current, but as this also releases the relay, it ensures that the pumps are turned off as soon as possible after the smash. A switch is used to override this arrangement when protection is not required. Unfortunately this does not protect the diffusion pump, nor the pumping line, and these are contaminated with powdered glass and carbon fibre fragments.

3.2 The Double Rotor Unit.

The double rotor unit is shown in Plate 3.3. This unit was designed to run two rotors in a vessel arrangement such that molecules, accelerated by each rotor, could be made to collide. As chemical reactions produced, using the rotors, would require much larger pumping speeds than the simple pumping system used, it was proposed to attempt an optical excitation experiment. As a photo-multiplier could be used for observing the resonance, this was much simpler than the detection of chemical reaction products, which would involve a mass spectrometer and hence an added complication to the vacuum system. A convenient resonance line exists in mercury and so it was decided to produce two colliding beams of mercury and detect the photons produced. As the resonance is in the ultra-violet part of the spectrum, the photo-multiplier, P.M., used had to have a quartz window, so it was decided to use an EMI 9558QA, specially selected for optimum quantum efficiency at 250 nm. The P.M. is optically coupled to the collision volume, using a spectrosil light pipe, 150mm long and 40mm diameter. This is
joined to the collision volume by means of an O-ring which allows a small
degree of flexibility. The upper half of the light pipe and the P.M. are
housed in a brass and steel unit, shown in Plate 3.3. This provides
cooling for the cathode of the P.M. to reduce noise levels, and also
electrostatic and magnetic screening. The cathode is also screened
with mu-metal. A PTFE sleeve is used to provide protection for the
light pipe within the P.M. housing and also to prevent excess water
vapour from condensing inside it near the cooled cathode.

The double rotor unit is built on a steel frame, which has two two-
inch oil diffusion pumps, type EO2, mounted beneath the rotor vessels
and capable of providing pumping speeds of 200 litres/s. These are
pumped by the rotary piston backing pump used for the single apparatus,
producing a pumping speed of 170 litres/min., the combination of which
produces vessel pressures of typically 10^-6 Torr.

The two rotor vessels are basically the same as the one used in the
single apparatus with the exception that there are more ports. The
positioning of the ports is shown in Figure 3.2 and these are used to
allow insertion of various components necessary for colliding beams
experiments.

The glass tube, which constitutes the collision volume, is connected
to each vessel by means of ball and socket joints, these providing some
degree of flexibility. The collision volume can be seen in Plate 3.3
and is composed of a double-walled tube with a port and flange set per-
pendicular to the tube, on to which the light pipe connects, and opposite
this a Wood's horn to give a nearly black background to reduce the
ambient noise level detected by the P.M. to a minimum. The cavity
Figure 3.2 Port arrangement of double rotor unit.

- Light pipe
- Photo-multiplier
- Cold finger
- Collision volume
- Wood's horn
- Primary beam unit
between the two walls is filled with cooled liquid and this holds the walls of the collision volume at \(-30^\circ C\). Lower temperatures are, of course, possible, but due to this particular arrangement, it was felt that the stress resulting from the use of much lower temperatures could cause failure of the glassware. This cooling provides a small degree of cryogenic pumping to prevent an increase in pressure at this point.

The mercury beams are derived from the rotor tips, which, in turn, collect their molecules from two primary beam units mounted in each vessel. The molecules are fed through a small tube of 2mm diameter, which originates in each beam unit. The tube leads to a small boiler, situated well below the plane of the rotor arms and outside the vacuum. These are shown in Plate 3.3 and a diagram (Figure 3.3) and are reasonably simple and made of Pyrex glass. They consist of a bulb which is partially filled with the liquid - in this case with mercury - and this is heated by a heater coil wound around the outside of the bulb. Also connected to the outside of the bulb is a thermistor which measures the temperature of the boiler and may be used as the sensing element of a temperature controller. The heater wire and the thermistor are fixed to the glass with epoxy resin, which completely surrounds the base of the boiler and provides some thermal insulation from the air, further insulation being provided by a PTFE jacket. The epoxy resin can stand \(200^\circ C\) in this application because there is no need for great strength. The glass tube is connected to a constriction above the liquid level and this is joined to a point on the wall of the bulb, where the heating coil directly heats, and hence the tube's only contact with the vessel is at a point which should be as hot as the liquid. This should mean that the tube remains
Figure 3.3
Primary beam unit.
fairly warm. The temperature at the top of the tube will, however, be lower than at the bottom due to radiation losses, and it is possible for condensation of the vapour to take place. However, experiments with mercury indicate that the rate of condensation is extremely slow, as a beam unit run for many hours produces no apparent deposit of mercury onto the tube. Yet it was noticeable that the mercury vapour was reaching the vessel as the pressure in it rose from $10^{-6}$ torr to $10^{-5}$ torr with the beam unit running. A cone joint is used to connect the beam unit to the rotor vessel and this is water-cooled to ensure that heat from the boiler does not soften the vacuum grease on the joint.

Above the beam unit and above the plane of the rotor arms is positioned a cold finger which traps some fraction of the molecules that are not swept up by the rotor arm. The cold finger is made of glass and cooled to $-30^\circ C$. In the case of mercury, this cold finger would not be effective in collecting atoms until a layer of the mercury atoms had built up on the surface, which could take a long time. However, it was found that mercury would condense on a glass surface if the surface was at $-30^\circ C$, as will be described in Chapter VIII.

The ionisation gauges placed in a line with the collision volume (Figure 3.2) may be used as beam detectors. The fraction of the beam that passes through the collision volume, through the opposite rotor vessel and into the detectors would enable crude measurements to be made of beam intensity and energy spread. The energy spread would be assessed using time-of-flight measurements. Surrounding these detectors are copper cylinders which are cooled at $-30^\circ C$ to provide some degree of cryogenic pumping, the effectiveness of which was measured by using
the ionisation vacuum gauge unit to measure the vacuum in the detector with and without cooling. The results showed a factor of four increase in pressure when the gauge was not cooled. This metal cylinder also provides electrostatic screening, significantly reducing the noise level from the unit, when it is used with a current amplifier. The circuit used for the operation of the gauge as a beam monitor is described in Chapter VIII.

The laser beam is used, as in the single apparatus, for angular speed measurement, but the position of the beam is important in this case because the rotor's interception of the beam is used to give the in-line position of the rotor arm. In other words, the point in time when the long axis of the rotor arm is perpendicular to the axis of the collision volume. Adjustment of the position of the laser beam is achieved using a beam splitter and prisms.

The cooling liquid used in the collision volume, etc., is produced by a small mobile refrigerator unit consisting of a Primary and Secondary cooling circuit. The primary cooling circuit utilises a standard compressor refrigeration unit using freon. This cools a copper coil fitted inside a 5 litre brass container used as a heat exchanger and well insulated from its surroundings by styrofoam. The secondary circuit uses ARCTON 113 as the coolant and this is pumped by a small chemical pump to the areas requiring cooling.

The temperature of the Arcton is held at \(-30^\circ C\) by a thermostat fitted in the secondary circuit which controls the freon cooling circuit. The reason for using a heat exchanger instead of directly using the freon is that cooling is required within the glassware and, if a rotor smash were to break it, the freon would have to be replaced. The unit can
extract approximately 3kJ per second from the rotor vessel. The connections to the unit are made with normal rubber tubing with 'Armorflex' insulation to increase its efficiency. The drive coils are tied to the outside of the rotor vessels with nylon thread. This means that the coils are as close to the rotor body as possible and therefore the magnitude of the driving magnetic field at the centre is as large as possible. The coil separation is critical because the magnitude of the magnetic field at the centre of the vessel varies as the cube of the spacing and the drive torque is proportional to the square of the magnetic field.

The whole unit can be enclosed in a two-piece barricade, visible in the upper frame of Plate 3.3. This forms a large box in which the double rotor unit can be operated safely. The bottom of the box has a skirt, which may be lowered to form an almost light-tight box.
CHAPTER IV

ASSOCIATED CONTROL AND MONITORING ELECTRONICS.

4.1 The Rotor Suspension System.

The rotors are suspended in mid-vacuum using an electro-magnetic servo system. Complete magnetic suspension is an attractive method of producing an axis about which the rotor can rotate and has been used very successfully in the past. Magnetic support offers a simple method of producing a 'soft' bearing, enabling the rotor to spin about its centre of mass and alleviate the need for accurate balancing of the rotor body.

The acceleration and deceleration of the rotor is accomplished using electro-magnetic induction, which produces only a small torque, but as the friction of the magnetic bearing is almost non-existent, this is acceptable.

4.1A The physical arrangement of the suspension system.

The physical arrangement of the suspension system is shown in Figure 4.1. The rotor is suspended beneath an electro-magnet, the current feeding the coil being supplied by the servo electronics. The coil consists of 600 turns of 18 gauge, enamel-covered, copper wire wound on a plastic former, which is hollow and into which a soft iron core is placed. The end of the core is cone-shaped, so the magnetic field is concentrated to enable the rotor body to have point suspension.

This produces the required divergent magnetic field, which provides the restoring force to centre the rotor, but in the absence of any damping, the rotor could swing or produce orbital motion. Damping for these is provided by the 'cornstalk' arrangement, comprising the fixed magnet E,
Figure 4.1  Rotor vessel assembly.

Water cooling

Cooling oil

Lift coil

Pole piece

12V DC lamp

Magnet E

Damping oil

Diffusion pump

To servo electronics

Laser

Height sensor

Pin diode

Phase-lock electronics

Phase-lock electronics

Height sensor

Pin diode

Phase-lock electronics

Diffusion pump

Height sensor

Pin diode

Phase-lock electronics

Diffusion pump
the support wire and the damping coil. The glass housing for this provides a table on which the rotor rests when not suspended. The current in the lifting-magnet is arranged so that the permanent magnet is attracted to the induced magnetic dipole within the steel rotor body.

The iron core of the electro-magnet serves as a cold finger, removing heat from the inner turns of the solenoid. Cooling of the outer turns is achieved by thin transformer oil, which surrounds the coil and core. Water is fed to a copper coil attached to the core, which removes the heat from the coil unit. The weight of the coil and core is taken by the thick glass walls at the top of the lift coil unit, so that the hemisphere near the pole piece does not have any extra load placed on it.

The height of the rotor is sensed by the partial obscuration of the light beam passing over the top of the rotor and beneath the glass hemisphere. A single filament 24V linear-coiled bulb is used to produce the light beam, this being run from a 12V supply to increase the lifetime of the bulb and hence increase the reliability. This is important as the failure of the light beam would result in the complete collapse of the magnetic support system and in the destruction of the glass vessel if the rotor were spinning at a high angular velocity. The power supply for the lift-servo electronics and the lamp is derived from a mains fail-safe power supply, which will be described later in this chapter.

The light from the lamp passes through a 43mm focal length convex lens and then through a prism to bring the image of the filament to a focus at P (Figure 4.1). The image is orientated so that the long dimension of the filament is vertical. As the filament is narrow compared with the effective width of the top of the rotor, the variation in
transmitted light is approximately proportional to the change in height of the rotor. The transmitted light is fed to another prism and a 25mm focal length convex lens, to enable light to fall on the photo-voltaic cell (MS2BE, Ferranti Ltd.). The photo-voltaic cell has a sensitive area of 0.34in\(^2\), so that accurate focussing is not necessary.

For the stable suspension of the rotor in mid-vacuum, the servo unit must apply a current to the lifting magnet such that, if \( z_0 \) is the desired height to suspend the rotor, measured from the pole piece, the direction of the resultant force on the rotor is always forcing it back to this height. However, for stable suspension, not only must the height of the rotor equal \( z_0 \) but the velocity of the rotor must also be zero. This means that a net force on the rotor must also be produced proportional to the velocity of the rotor in such a way as to oppose motion, i.e. a damping term. Unfortunately, the simple solution of the transfer function of this arrangement is not possible as the very non-linear attractive force between the rotor and the lifting solenoid would produce a complex, non-linear differential equation which would be almost impossible to set up. However, the variables previously mentioned will still produce a potential well with damping of motion within it, independent of the power law, which relates the current in the lifting solenoid to the force on the rotor body and also the force on the rotor as a function of height, provided the coefficients of the height and velocity information are large enough. Therefore, if the height of the rotor is \( z \), as measured from the pole piece, then the current \( I \) into the lift coil is given by:
Figure 4.2  Rotor suspension circuit.
\[ I = A (z_o - z) + B \frac{dz}{dt} + C \]  

where \( A \) and \( B \) are coefficients of the height and velocity information respectively. The constant \( C \) is the value of the current that is required to produce a force on the rotor at the height \( z_o \), which is equal and opposite to the gravitational force on the rotor.

For convenience, all distances measured below the axis have a negative sign and all forces acting down are also negative. If the function that relates the current, \( I \), in the lift coil and the height of the rotor, \( z \), to the force on the rotor body, is given by \( F(z, I) \), then the net force on rotor \( F_r \) is given by:

\[ F_r = F(z, I) - mg \]  

(4.2)

The value of \( I \) in equation 4.1 cannot become less than zero and hence the maximum possible downward force is equal to \( mg \). When the servo unit was constructed it was found possible to produce an approximation to the function \( F(z, I) \) by direct measurement.

4.1. B The Servo electronics.

The circuit of the servo was designed to reproduce equation 4.1. The co-efficients \( A \) and \( B \) were made to be independently adjustable and the constant, \( C \), was also variable. Figure 4.2 shows the complete circuit diagram and Plate 4.1 shows the lift magnet and the optical arrangement for the suspension of a rotor. The height of the rotor is sensed, as previously stated, by a photo-voltaic cell which produces a current proportional to the displacement of the rotor from the glass hemisphere. This current is fed, via \( R_3 \), to the inverting input of amplifier \( A_1 \). This means that, as the rotor falls from the hemisphere,
PLATE 4.1 Components of rotor suspension system.
the current through $R_3$ increases. The typical input current-to-displacement ratio is approximately $30 \mu A/mm$ and this is converted to a voltage of $30 \times R_7, V/mm$ on the output of $A_2$. As the inverting input of $A_1$ has negligible impedance to ground, because the amplifier is used in virtual earth mode, the photo-voltaic cell is loaded only by the resistor $R_3$, $68 \Omega$, which was included to prevent the cell driving a short circuit. It is, however, necessary to load the cell because under no-load conditions it produces a near constant voltage of about $500mV$ independent of the light input. Now, to reproduce equation 4.1 it is necessary to subtract the required suspension height from the actual height and, as the parameters have been converted to current, then a current equivalent to $z_0$ must be subtracted from the input current. As $A_1$ has a virtual earth input, it is simple to use this as a subtracting stage. The current equivalent to $z_0$ is produced by the variable resistor $VR_1$ stabilised by the zener diodes $D_1$ and $D_2$. The feedback loop of $A_1$ also contains a capacitor, $C_4$, which integrates the input current above $1kHz$ given by $1/(2\pi R_7 C_4)$. The integration serves to limit the unwanted band width and hence reduce the noise which would be fed into the differentiator.

The necessary response time of the system was estimated by using the time which the rotor would take to free fall $2mm$, this being about $20\mu s$ resulting in an approximate band width of $100Hz$. This stage, therefore, produces the height error signal and feeds to the differentiator.

The next stage produces the time derivative of the input up to a frequency of $1.6kHz$ given by $1/(2\pi C_8 R_{14})$ with a gain of $-10^{-3} \frac{dV_{max}}{dt}$. Above $1.6kHz$ the stage integrates and hence reduces the noise band
Variable resistor VR₅ is used to set the output to zero volts for zero input. This is necessary as a constant D.C. output would cause the control of the coefficient B, VR₄, to produce not only a voltage dependent on the velocity of the rotor but also a constant term which would be dependent on the setting of VR₄.

A₃ is a summing amplifier which produces an output voltage proportional to the height error, plus a constant and minus the time derivative of the height. The coefficient of the height error is taken from VR₃ and is variable. Stage A₃ has a voltage gain of $\frac{R_{28}}{R_{13}}$ for the coefficient A. The constant is produced by VR₂, producing a variable voltage which is also stabilised by the Zener diodes D₁ and D₂. It is necessary to subtract the $\frac{dz}{dt}$ information as this has been negated by the action of A₂.

The output from A₃ is now fed through R₂₀ into the output stage. This is simply a voltage-to-current converter with current feedback, as the current in the coil produces the force on the rotor and not the voltage across it. The output current feeds through R₂₂ which produces a voltage and so feeds current through R₂₁ to the base of TR₁. The voltage-to-current conversion factor is equal to $\frac{R_{21}}{(R_{20} \cdot R_{22})} = 0.5A/V$. The output current has a range of 0 to 6.25A with the supply voltage and electro-magnet used. L₁ is the lift coil and has a resistance of $3\Omega$, the output transistors being protected from over-voltage due to L₁ $\frac{di}{dt}$ by the parallel diode D₄.

Diode D₃ in the emitter of TR₁ was included to raise the voltage on the base of TR₁ relative to the -12V rail, to enable the slightly limited output swing of A₃ to completely turn off TR₁ and thereby enable all the
current flowing through $R_{18}$ to produce maximum output current when necessary.

Outputs are available for monitoring the height error voltage and the control voltage, these being used during setting up of the servo and also during a rotor 'run' to monitor the stability of the rotor. Two servo units were constructed to support two rotors and were both supplied by a ±12V DC supply, derived from the mains fail-safe power supply.

4.1.C Adjustment of the suspension unit.

For adjustment of the suspension unit, a rotor is placed on table F (Figure 4.1) in the vacuum vessel with a clearance of 3mm between the top of the rotor and the bottom of the glass hemisphere. The light beam is positioned such that it passes between the lowest point of the hemisphere and the highest point of the rotor. The detector is then adjusted so that the current from the photo-voltaic cell is a maximum, measured using a sensitive ammeter. The detector is then connected to the servo electronics and an oscilloscope is connected to the height error output. With $VR_3$ and $VR_4$ set on zero, the circuit is turned on and the voltage noted on the oscilloscope for the rotor in the un-lifted state. The constant control, $VR_2$, is then used to lift the rotor completely up to the hemisphere and the new setting on the oscilloscope noted. By adjustment of $VR_1$ it is possible to set the output $E$ so that the voltage for the lifted rotor is equal to minus the voltage for the un-lifted rotor. When this has been achieved, the servo height ($z_o$) of the rotor is approximately 1.5mm, therefore giving equal clearance above and below, when suspended. The control of $Bdz/dt$ is then increased to a maximum and $VR_3$ is increased to about half the available range. At this point the rotor is
PLATE 4.2 Various responses of lift servo.

Rotor height

Time

Rotor height

Time

Rotor height

Time
freely suspended but at the wrong height. By varying the constant, \( VR_2 \), and observing the output \( E \), the constant should be adjusted until \( E \) equals \( OV \). This is now the correct value of the constant for this specific suspension height.

If the light beam is obstructed and the voltage \( E \) is observed using the oscilloscope with a slow timebase, the stability of the rotor can be observed. When the obstruction is removed rapidly from the light beam, the rotor will rise to the reference height. The setting of \( VR_4 \) and \( VR_3 \) will affect the amount of 'ringing' due to insufficient damping and, with adjustment of \( VR_3 \) and \( VR_4 \) a satisfactory step-function can be produced. Plate 4.2 shows three possible responses of the rotor height to a slow step-function. The lowest trace shows the correct adjustment of the controls \( VR_4 \) and \( VR_3 \).

4.1. D Simple analysis of the lift servo.

If the suspension coil has a constant current flowing through it and the magnetic field density \( B \) varies as some function \( B_z \) on the axis of the coil, then the force on a single induced magnetic dipole \( M \) is generally:

\[
F = (\mathbf{M} \cdot \nabla) B
\]

and if \( M \) only has a component in the \( z \) direction, then the force in this direction is given by:

\[
F_z = m \frac{\partial B_z}{\partial z}
\]

where \( m \) is the magnitude of the induced magnetic dipole.

If \( m = \chi H_z \), where \( \chi \) is the magnetic susceptibility and also \((1 + \chi) = \mu \), then
\[ m = (u_r - 1) H_z \]

also
\[ B_z = \mu_0 \mu_r H_z \]

therefore
\[ m = (u_r - 1) \frac{B_z}{\mu_0 \mu_r} \] (4.5)

Therefore the force in the z direction of a magnetic dipole is given by:
\[ F_z = \frac{(\mu_r - 1)}{\mu_0 \mu_r} B_z \cdot \frac{\partial B_z}{\partial z} \] (4.6)

Now, if the rotor is considered to have a large number of differently orientated induced magnetic dipoles, but the resultant dipole lies on the z-axis and if the non-linear magnetization effects are small, then the attractive force on the rotor body may be approximated by:
\[ F_{\text{ROTOR}} = KB_z \cdot \frac{\partial B_z}{\partial z} \] (4.7)

where K is a constant.

If the lifting solenoid is considered to comprise a long coil with a core, which is thin, then a possible relationship for the variation of B in the z-direction can be formulated. If a current loop of radius a is considered to have a current I flowing in the loop, then the component of B on the axis of the loop at point P, a distance z from the coil, is given by:
\[ B_z = \frac{\mu_r \mu_0 I a^2}{2(z^2 + a^2)^{3/2}} \] (4.8)

and if \( a \ll z \), then:
\[ B_z \approx \frac{\mu_0 I a^2}{2 z^3} \cdot \mu_r \] (4.9)

If a large number of these loops are used to make a solenoid of
length \( L \), then the field at the point \( P \) on the axis is approximately equal to:

\[
B_z = \frac{\mu_o \mu_r I a^2 n}{4z^2}
\]  

(4.10)

where \( L \gg z \) and \( n \) is the number of turns per unit length.

Therefore, using equation 4.7, the force on the rotor may be approximated by:

\[
F_z = \frac{K I^2}{z^5}
\]  

(4.11)

where \( K \) is a constant. As the exact measurement of the distance \( z \) is not possible, it was made equal to \((R + z)\), where \( z \) is now the distance from the pole tip to the top of the rotor. Therefore, the force equation becomes:

\[
F_z = \frac{K I^2}{(R+z)^5}
\]  

(4.12)

where \( K \) and \( R \) are constants.

The rotor was stably suspended during the following measurements and these are independent of the lift servo electronics being used to stabilise the rotor. The variation of force was achieved using a weight pan attached to the rotor, such that the lift magnet only applied the force of attraction to the rotor body, but the apparent weight of the rotor could be increased and so an increase in the lift coil current required to suspend the rotor at the same height was produced. The height was measured using a travelling microscope.

The servo-controlled rotor was used to measure the variation of the attractive magnetic force on the rotor body as a function of the lift current with a constant height of \( 0.938 \pm 0.006 \text{mm} \), i.e. the spacing
Figure 4.3  Graph of the force on the rotor body as a function of the lift coil current with a constant height of 0.938 mm.
Figure 4.4  Graph of the force on the rotor body as a function of the height of the rotor, with constant lift current of 5A.
Figure 4.5  Graph of $F^{-2}$ as a function of the height of the rotor, with a constant lift current.
between the hemisphere and the top of the rotor. This was achieved by changing the weight of the rotor and observing the current produced by the servo to maintain a constant height. The constancy of the height was checked using the travelling microscope and the results are shown in Figure 4.3. These results show the force to be more closely proportional to the current \( I \) than \( I^2 \). This is probably due to saturation effects within the body of the rotor and in the pole-tip.

The next measurement was made to determine the relationship between the height of the rotor and the attractive force on it. This was achieved using a constant lift current of 5A. The results are shown in Figure 4.4 and using equation 4.12, a straight line plot was produced to verify the relationship; this is shown in Figure 4.5.

Finally, a measurement was made of the variation of the height of the rotor as a function of the lift current with a constant force of 0.537N producing a relationship given in Figure 4.6. Again using equation 4.12, a straight line plot was made (Figure 4.7) and this also gave fairly close agreement to equation 4.12.

The results of these measurements enabled an approximate relationship to be produced for the force \( F_z \) on the rotor, given by:

\[
F_z \propto \frac{K_1 I}{(K_2 - z)^5} \tag{4.13}
\]

when \( K_1 = 4.78 \times 10^{10} \text{ Nm}^5 / \text{A} \) and \( K_2 = 15.05 \times 10^{-3} \text{ m} \).

The minus sign in front of the \( z \) is to allow for the fact that earlier distances below the hemisphere were regarded as negative.

Equation 4.13 can now be combined with equation 4.1 and substituted in equation 4.2 to give:
Figure 4.6 Graph of the lift coil current as a function of the height of the rotor body with constant force of 0.537N.
Figure 4.7  Graph of $I^2$ as a function of the height of the rotor in mm.
$I$ is current in lift coil.
Figure 4.8  Force on rotor as a function of height.

Value of coefficients of $A$

$A_1 = 34 \times 10^3 \, A/m$

$A_2 = 8.5 \times 10^3 \, A/m$

$A_3 = 2.125 \times 10^3 \, A/m$

$A_4 = 0.53 \times 10^3 \, A/m$
\[ F_r = \frac{K_1}{(K_2 - z)^5} \left( A [z_o - z] + B \frac{dz}{dt} + c \right) - mg \]  
\[ (4.14) \]

This equation should give a reasonable indication of the response of the whole servo loop, between the limits:

\[ 0 \leq (A [z_o - z] + B \frac{dz}{dt} + c) \leq 6.5A \]

Below 0.0A, \( F_r = -mg \)

Above 6.5A, \( F_r = \frac{K_1 6.5}{(K_2 - z)^5} - mg \)

The full range of the force function \( F_r \) is shown in Figure 4.8 for \( z_o = -2 \times 10^{-3} \) m.

Also, disregarding the time derivative term, the potential energy well to which the rotor is confined is given by:

\[ P.E. = mg \left[ (z - z_o) + \frac{(K_2 - z_o)}{4} - \frac{(K_2 - z_o)^5}{4(K_2 - z)^4} \right] \]

\[ + AK_1 \left[ \frac{(K_2 - z_o)}{4(K_2 - z)^4} - \frac{1}{3(K_2 - z)^3} + \frac{1}{12(K_2 - z_o)^3} \right] \]

This equation is only valid for:

\[ 0 \leq (A (z_o - z) + c) \leq 6.5A \]

The full range of the potential energy function is shown in Figure 4.9 for \( z_o = -2 \times 10^{-3} \) m with the zero point of potential energy defined at \( z = z_o \). The zero metre point of the height axis corresponds to the rotor touching the lift-magnet pole-piece.

4.2. A The mains fail-safe power supply

The mains fail-safe power supply is essential for the efficient
Figure 4.9  Rotor suspension, potential energy as a function of height.
Fan for cooling
heat sinks

Power supply
10A, 4-16

Power supply
10A, 4-16

240V RMS
Inverter
50Hz

Auto transformer

Figure 4.10 Mains fail-safe power supply.
Figure 4.10 Mains fall-safe power supply.

Fan for cooling heat sinks

Power supply
10A, 4-16V

Power supply
10A, 4-16V

240V RMS Inverter 50Hz

Auto transformer

-12V +12V
0V +12V -12V
0V +12V -12V
0V +12V -12V
0V +12V -12V
0V +12V -12V

0-10A
running of the rotors. As previously described, the rotors are suspended by a magnetic field servo, which must not fail during rotor runs. If the unit should fail for even a short time, sufficient for the spinning body to touch any part of the vessel, the rotor would be likely to go irrevocably out of control, destroying the vessel (Plate 4.3) and the rotor. Therefore, a power unit has to be used for the servo circuit which will not produce any interruption of the supply in the event of a mains failure.

To do this reliably the author decided that the minimum of active components should be used, even to the detriment of the stability of the supplied voltage. The circuit used is shown in Figure 4.10. As will be seen from the circuit diagram, no output fuses are used and no transistors for stabilisation. The lack of output fuses minimises the number of series components which might fail as a result of thermal and vibrational stresses. Therefore the diodes act as fuses if required.

The mains section of the unit consists of two Advance power supplies producing \( \pm 15\text{V D.C.} \) at a maximum current of 10A each. The batteries, \( B_1 \) and \( B_2 \) are 12V heavy duty car batteries with a capacity of 55 A-hours each. This is equivalent to stored energy of 4,752 M joules and, as the general consumption of two rotors under suspension is 160W, then these can provide suspension power for approximately eight hours.

4.2B Circuit Operation

Under no-load conditions, current flows through diodes \( D_1 \) and \( D_2 \) and hence charges batteries \( B_1 \) and \( B_2 \) respectively. This current flows through \( R_1 \) and \( R_2 \) both of 2.3 \( \Omega \), which limit the charging rate to 2A with a flat battery. When they are fully charged, the voltage
across the terminals is approximately 13.6V, which means that the charging current is less than half an amp. This enables the supply to be left on, charging continuously and so maintaining the batteries at full charge.

During normal operation, current flows to the lift circuit through diodes D₁ to D₅ for the positive supply rail, and D₆ to D₉ for the negative rail. As a result of the voltage drops across D₃ to D₅, the voltage at A is less positive than the voltage at B and hence the diode D₉ does not conduct. Therefore current is not drawn from the battery and the same process applies to the other battery. Also, point C is more positive than B; therefore a charging current is still provided for the batteries. If the mains fails, the voltage across D₁₁ collapses and the voltage at C falls to that of B. Also, D₁ and D₂ prevent both batteries discharging through their respective power supplies. As there is no longer any voltage supplied from the mains to hold the potential at A above that of B, the voltage at A falls until it is held stationary by the potential of the battery. The voltage $V₁$ was adjusted with a load on the output of the positive supply such that a current of 10A was passed to ground. The current in the ammeter M₁ was observed and the voltage $V₁$ was adjusted until the meter M₁ just gave a reading of 10A. If the reading was less than 10A, the difference in the current was being met by the battery. The maximum current which can be sourced by the mains power packs is 10A and thereafter the internal current limiter comes into operation and reduces $V₁$ until a current of 10A is passed. This means that, if a current of greater than 10A is required, it can be provided by the battery and the mains power pack. This can be seen from the fact that, as the
current limiter reduces the voltage at C and therefore at A, a voltage will be reached which will turn on $D_9$. This will reduce the current from the mains supply and therefore the current limiter will raise the voltage $V_1$ until it just produces a current of 10A. Diodes $D_{11}$ and $D_{12}$ are included to protect the mains power supplies during turn-on, when a supply could be damaged by the other supply driving it. All diodes are mounted on heat-sinks and the charge-limiting resistors $R_1$ and $R_2$ are of 150W power dissipation type.

Supplied from D and F is an inverter which produces 250V R.M.S. A.C. at 50Hz with a maximum power available of 150W. This inverter is used to power a small laser, used for rotational speed sensing. It was found that while the R.M.S. voltage supplied by the unit was equivalent to the requirements of the laser, the laser's performance was impaired when using this supply. However, a study of the laser revealed that its power supply was produced by a form of voltage multiplier and therefore required a greater peak-to-peak voltage, provided by the mains but not by the square wave voltage output waveform of the inverter. This was corrected by feeding the inverter supply into an auto-transformer with a voltage step-up ratio of 1.5, which produced sufficient peak-to-peak voltage to drive the laser.

The reason for powering the laser and also other speed monitoring equipment from the mains fail-safe power supply was that, in the event of a mains failure occurring when rotors were spinning at very high speeds, there would still be power available for audible speed measurement. The diffusion pumps would slowly cease to operate and therefore the frictional torque on the rotors due to the gas load would slow down.
the rotors. However, from a safety point of view it would be useful to know the approximate speed of the rotors and so the laser, PIN diode amplifier and an audio speed unit are all run from the fail-safe supply.

The supply voltage at D and F falls by 0.5V when the mains fails, but as the height servo circuit is protected against changes in the supply voltage, the height of the suspended rotors only changes by 0.025mm, which does not produce any instability. The main reason for the change in height is that the filament bulbs, used for height sensing, dim and hence this lowers the rotors fractionally.

4.3. A The P.I.N. diode amplifier.

The detection of the angular frequency of the rotor was achieved by allowing the rotor arms to intersect a laser beam which was set perpendicular to the plane of rotation. The physical arrangement of the rotor suspension magnet and the pump meant that the beam had to be set so that its interception took place near the tip of the rotor blade. At this point, the arm could be travelling at 2km/s and, as the arm is very thin at its tip (1mm) the black pulse only lasts for a short period of time, typically 500ns.

This meant that a fast detector had to be employed in conjunction with a comparatively fast amplifier. A P.I.N diode, type MRD510 (Motorola) was used, but it has a very low sensitivity of only 0.3μA/mW/cm² and hence large amplification was needed. Therefore, the amplifier has an input sensitive to current - as the diode is equivalent to a current source - with a D.C. voltage on the input to reverse bias the junction. The speed of the amplifier needed to be approximately 250ns
Figure 4.11  P.I.N. Diode Amplifier.

The circuit diagram shows a P.I.N. diode amplifier with various components and voltages labeled. The amplifier includes diodes, resistors, capacitors, and an operational amplifier (μA715). The input signal is applied to the circuit through a test point, and the output is connected to the amplifier's output terminal. The circuit utilizes voltage sources of +12, +15, +10, and -10V to power the components.
and would work down to D.C. to simplify setting-up. For convenience the output was made to drive a cable and the voltage swing was limited to standard TTL levels to allow easy interfacing with the phase control unit for locking the rotors.

4.3. B The circuit.

The amplifier is composed of two sections, a current-to-voltage converter providing a low input impedance with a D.C. bias on the input, and a second section which provides a small amount of voltage gain combined with output voltage damps and cable drive.

With reference to the circuit diagram 4.11, the first stage is built around a $\mu$A 715 high speed operational amplifier, which simplified the design but brought stability problems. The $\mu$A 715 was found to be very sensitive to phase lags or leads produced at its output and would break into oscillation very easily. Also, as the amplifier has a relatively high frequency response, of 65MHz bandwidth, the problem of internal phase changes producing positive feedback at high frequencies also had to be solved.

The output from the diode was taken directly to the inverting input and the feedback through $R_8$ was used to produce a virtual earth amplifier. The input impedance was low, about $R_8/A$, when $A$ is the open-loop gain of the $\mu$A 715. As the open-loop gain of the amplifier falls off at high frequencies, the input impedance of the amplifier increases and hence the capacitive shunting effect of the input cable becomes increasingly effective in limiting the response time of the stage.

To produce the D.C. offset at the input, the non-inverting input was taken through $R_7$ to the variable resistor $R_5$, which acted as a potential
divider with one end set at -6.8V and the other at -4.96V. As the non-inverting input has a high impedance, this pre-set divider could be used to set the non-inverting input at some negative potential with some adjustability. This was needed to set up the output voltage of the amplifier, as will be seen later. The output would be set by the voltage of the non-inverting input, but as a result of the current fed into the inverting input through R₃ from the -6.8V point, the output voltage is almost 0V and the input is held at -6.8V. The capacitor C₅ decouples the non-inverting input to ground. Diode D₃ produces the -6.8V point and holds it stable, so that the output voltage setting is mainly independent of supply line changes. The test input consists of a 1 MΩ resistor in series with a 10nF D.C. blocking capacitor. This enables input current pulses to be produced from a standard voltage pulse generator. The blocking capacitor is necessary to prevent the pulse generator from upsetting the D.C. conditions of the amplifier.

As this stage is a virtual earth amplifier with a current source feeding the input, then the gain, assuming sufficient open-loop gain, is dependent on the value of R₈, which is a 1 MΩ resistor and hence this gives a gain of 1V/μA.

There were various types of compensation attempted to give a stable configuration, the form of the compensation being taken from the literature supplied with the µA 715. However, various compensations were tried and all failed to give satisfactory stability and speed, so it was found necessary to produce compensation which was compatible with this circuit. Satisfactory stability was produced by a 470pF capacitor connected between pins 1 and 9 of the amplifier. The output of the µA 715, as already
stated, was very sensitive to the loading effects of subsequent stages; therefore $R_{11}$ and $R_{12}$ were used to produce a degree of isolation from any mildly reactive components appearing at the input of the next stage. This was found to be perfectly satisfactory and the output at point B gave a rise time of 60ns and minimal ringing.

The second stage consisted of a voltage amplifier with a gain of 4, this being defined by the ratio of $R_{19}/R_{13}$ and a push-pull cable driver. This stage is D.C. coupled like the first. Transistor TR$_1$ is used in a grounded emitter configuration, with the collector load 'bootstrapped' from the output via $C_9$ to give a large voltage gain. The diodes $D_6$ and $D_7$ produce the bias for TR$_2$ and TR$_3$ to prevent them both being turned off at the same time. TR$_2$ and TR$_3$ are emitter followers producing push-pull action to drive a cable. Voltage feedback is derived from their emitters through $R_{19}$ and back to the base of TR$_1$. Diode $D_5$ prevents the positive excursion of the base of TR$_2$ beyond 5.3V positive, which in turn prevents the output from exceeding +4.6V. Diodes $D_{10}$ and $D_{11}$ prevent the negative travel of the base of TR$_3$ to lower than -0.5V. However, $R_{15}$ is necessary to prevent the destruction of TR$_1$ by exceeding the current rating when TR$_1$ is fully conducting. These limits on positive and negative excursion enable TTL Schmitt trigger, SN7413, to be directly connected to the other end of the output cable without endangering the input of the TTL gate. Point B is free to swing in the positive or negative sense and, while a positive swing will only turn on TR$_1$, a negative swing could take the base of TR$_1$ more than 3V lower than the 3.3V of the emitter. This would cause breakdown of the base-emitter junction and so $D_9$ was included to prevent this.
The output stages of the three amplifiers built were designed to drive 50 Ω co-axial cable. All three amplifiers were found to give pulse rise times of 100ns at the other end of a 10m 50 Ω cable with correct termination. The output D.C. bias was adjusted to 0V by means of R₅. Further adjustment of R₅ has been found unnecessary as the bias is relatively insensitive to small supply rail and temperature changes.

The amplifiers were powered by the mains fail-safe power supply, which gave ±12V, but because small changes in the supply voltage were likely in the event of a mains failure, Zener diodes D₁ and D₂ were included to provide added regulation.

A 2mW HeNe laser was used to produce the light beam which was intercepted by the rotor arms. The intensity of the beam was sufficient to cause the output to be held on 4.5V unless the rotor intercepted the beam, in which case the voltage fell to -0.5V. If the voltage clamps were not present, the voltage swing would have been greater. Because the light output from the laser was sufficient to cause the output to be clamped, the large quantity of noise modulating the laser beam was not passed on to the logic units. This also made it possible for transition times of less than 40ns to be reached as the slew-rate of the amplifier was large enough to enable the output to change by 5V in a time less than 40ns, even though the rise time of the amplifier is 100ns.

One of the amplifiers was modified by the removal of diodes D₅, D₁₀ and D₁₁. This increased the output range by removing the voltage clamps and made it, therefore, a useful current amplifier which was not to be used on TTL inputs.
Figure 4.12  Rotor Speed Monitor.

5V regulated power supply

Rotor Speed Monitor
4.4. A  The rotor speed monitor.

The purpose of the rotor speed monitor is to perform simple digital functions on the two-pulse trains, one from each rotor, and channel the information to other apparatus. Also, in the event of a mains power failure, the simple monitoring of the rotors' speed can be made by converting the rotor pulses to sound.

4.4. B  Circuit description.

The circuit is shown in Figure 4.12 and consists of two inputs, A and B, and four outputs plus an audible outputs. The input pulse trains are fed to $G_1$ and $G_2$, which simply invert the TTL-compatible input pulses and produce a degree of isolation for the following stages. The signal is fed to gates $G_8$ and $G_9$, which again invert and hence output the input pulses of A on D and of B on E. Also, the $\overline{A}$ and $\overline{B}$ signals are fed to $G_7$, which is a two-input NAND gate. This superimposes both inputs on the same base line and then outputs them at F.

The output C produces a fixed width pulse of a repetition rate which is determined by earlier switch conditions. With the switch $S_2$ in the A-position, there is an output pulse whenever pulses from input A and input B overlap in time. The width of the input pulses corresponds to a $0.5^\circ$ arc of the rotor arms' orbit. These in-phase pulses are of great value when using counting equipment to measure the time of flight of pulses of atoms accelerated by the rotors. If the repetition rate of coincident pulses from C is equal to the rotor frequency, then the two rotors will be phase-locked to within $1^\circ$ arc. Switch $S_3$ set at A divides
the output frequency from $G_5$ by two and, in position B, by one. If output C is used to trigger an oscilloscope with output F on the y-axis, then the scope will be triggered whenever input pulses are in phase. If $S_2$ is set on B, then only one of the input pulses is fed out of C, the selection of which is made by $S_1$. This enables the switching of $S_1$ to allow the desired pulse train from output F to be selected and held stationary on the oscilloscope display. This is useful for observation of phase, as the two rotors become phase-locked. The frequency of the rotors is measured using a frequency meter, triggered by the oscilloscope time base and this makes it very convenient to trigger the oscilloscope from the output C to measure the frequency of input pulses from A or B.

The output from C is produced by using $G_5$, which is a two-input NAND gate which feeds a 4-bit scaler. The output from the least significant bit produces the frequency divide-by-two, which is useful as it corresponds to, in the case of a double-armed rotor, to the rotational frequency. The output from switch $S_3$ allows triggering of a monostable, which produces a fixed length pulse of 60μs. This was chosen so that, at maximum rotor pulse frequency, 10kHz, the period of the pulses is just greater than the pulse width. The potentiometer, $R_2$, controls the audible output level from the loudspeaker, which is merely fed by current pulses.
CHAPTER V

THE ELECTRONIC DRIVE FOR ACCELERATION OF THE ROTORS

5.1 Introduction.

The acceleration of the rotors is achieved using a rotating magnetic field, which drives them as an induction motor. The rotating magnetic field is produced by four coils forming the sides of a square with the axis of the coils intersecting with the rotor. Opposite coils are fed with the same sinusoidal current, forming a coil set, and the two sets are fed currents in quadrature. This produces a rotating magnetic field which accelerates the rotor by its interaction with the induced currents within the steel rotor boss. Rotors had previously been accelerated at Birmingham using ex-R.A.F. alternators which could provide rotating fields of 2,600Hz, but, because phase-lock between two rotors and, also, higher rotational speeds were required, it was necessary to produce a reliable electronic drive unit.

5.2 Rotor Drive Torque.

The torque on the rotor is produced, as previously stated, by the interaction of the induced electric currents within the rotor boss and the rotating magnetic field. If the rotor is considered as a small conducting sphere of radius \( R \), positioned in a uniform, rotating, magnetic field, then an approximate relationship can be produced for the drive torque \( T_r \).

If two pairs of coils are used to produce two time varying magnetic fields in quadrature, \( B_x \) and \( B_y \), then the rotating vector \( \vec{B} \) is given by

\[
\vec{B} = \hat{i}B_x + \hat{j}B_y
\]

(5.1)
where \( B_x = B \cos \omega t \) and \( B_y = B \sin \omega t \),

then \[
B = \hat{i}B \cos \omega t + \hat{j}B \sin \omega t
\] (5.2)

At some point in time \( B \) will lie in the \( x \)-direction and, if the coordinate system is allowed to rotate at the same angular frequency as \( B \), then \( B \) will always lie on the \( x \)-axis.

Now, to find the torque on the steel sphere in this uniform magnetic field, it is necessary to derive the magnitude and direction of the electric field vector \( E \). This can be achieved using the relationship

\[
\nabla \cdot E = \frac{\partial B}{\partial t}
\] (5.3)

Simplifying assumptions can be made at this point due to the choice of a rotating co-ordinate system.

Generally, \( E = \hat{i}E_x + \hat{j}E_y + \hat{k}E_z \), but as the currents that produce the torque in a loop are parallel to \( B \) and \( \omega \), then \( E_y = 0 \) and also, from equation 5.2

\[
-\frac{\partial B}{\partial t} = \hat{j}B_\omega
\] (5.4)

One of the solutions for \( E \), using equation 5.3, is

\[
E = \frac{1}{2}B_\omega [-\hat{i}z + \hat{k}x]
\] (5.5)

The electric field vector \( E \) gives rise to circulating currents within the conducting sphere and the current flowing in a conductor of cross-sectional area \( \Delta A \) is given by:

\[
I = \frac{\Delta A \cdot E}{\rho}
\] (5.6)

from \( E = \rho \cdot J \), where \( \rho \) is the resistivity of the material.

The force \( \Delta F \) on a length of loop \( dl \) is given by:

\[
\Delta F = \hat{J} \wedge \hat{B} (dl \cdot \Delta A)
\] (5.7)
which generally produces a force per unit length equal to $I \times B$.

Using the above equations, the torque on a general loop in the field can be found and this can then be used to integrate over the surface of a spherical, conducting shell of thickness $S$, to give the total torque $T_T$ on the shell of

$$T_T = \frac{3}{8} \frac{\pi^2 B^2 R^4 S}{c} (\omega_f - \omega_r)$$

(5.8)

where $\omega_f$ is the angular frequency of the magnetic field and $\omega_r$ is the angular frequency of the rotor.

As the rotor boss is made of solid steel, the time varying magnetic field only penetrates a limited depth into the material and hence the circulating current only flows in a shell. The thickness of the shell is approximately equal to the skin depth $S$. The low frequency approximation for skin depth is given by:

$$S = \left( \frac{2 \varepsilon_0 e^2}{\sigma (\omega_f - \omega_r)} \right)^{1/2}$$

(5.9)

where $\sigma$ is the conductivity of the material.

This low frequency approximation is only valid if $(\omega_f - \omega_r) \ll 1/t$ and if $(\omega_f - \omega_r) \ll \varepsilon/\varepsilon_0$, where $t$ is the average time between collisions of free electrons within the metal.

As the skin depth for steel is less than the radius of the rotor, the currents should flow mainly within a shell, governed by the skin depth. This means that the torque is approximately given by, from equation 5.8:

$$T_T = \frac{3}{8} \frac{\pi^2 B^2 R^4 c}{\varepsilon_0} \sqrt{\frac{2 \varepsilon_0}{c}} (\omega_f - \omega_r)$$

(5.10)

As it was very difficult to measure the magnitude of the rotating magnetic field with great accuracy, it was not possible to check the
Figure 5.1

Rotor rotational frequency in kHz.

Actual

Theoretic

Acceleration time $\times 10^2$ secs.
relationship given in equation (5.10). However, the torque $T_r$ is seen to be proportional to $(\omega_f - \omega_r)^{\frac{1}{2}}$ and a graph of rotor frequency as a function of time, during a rotor run, when the rotor was continuously accelerated, shows fairly close correspondence (Figure 5.1).

Because the material is ferromagnetic an extra torque is produced due to the rotating magnetic field directly inducing magnetization within the material, which lags behind the applied field. If the applied field is constant and the magnetic properties of the material are isotropic, then the hysteresis-torque per unit volume can be described by (Bozorth 1951, Jonas 1960):

$$T_h \propto B^2 \sin \theta$$  \hspace{1cm} (5.11)

where $\theta$ is the hysteresis angle between the applied field strength and the intensity of magnetization. This process produces only a small torque and may be considered negligible in this case.

The earlier derivation for the torque (equation 5.8) assumed the magnitude of $B_x$ to be equal to $B_y$ and hence the magnitude of the resultant vector $B$ would describe a circular orbit. If the two applied perpendicular fields are not equal, then the vector $B$ is given by:

$$B = \hat{i}B' \cos \omega t + \hat{j}B \sin \omega t$$  \hspace{1cm} (5.12)

where $B' = B + \Delta B$ and hence the vector $B$ is equal to:

$$B = \hat{i}B \cos \omega t + \hat{j}B \sin \omega t + \hat{i}^\Delta \Delta B \cos \omega t$$

The first two terms of equation 5.13 are the same as the initial case considered, but the extra term, $\hat{i}^\Delta \Delta B \cos \omega t$, is not a rotating term, merely oscillating between $\hat{i}^\Delta \Delta B$ and $-\hat{i}^\Delta \Delta B$. This is equivalent to two counter-rotating vectors of magnitude $\Delta B/2$. Considering the counter rotating terms and disregarding torque, produced by the primary terms
of equation 5.13, the rotor, rotating with some frequency \( \omega_r \), experiences two torques. The first is an accelerating torque proportional to \((\omega_f - \omega_r)^\frac{1}{2}\) and the second is a decelerating torque proportional to \((\omega_f + \omega_r)^\frac{1}{2}\). From this it can be seen that an imbalance in the applied magnetic fields produces a net braking torque on the rotor proportional to \([ (\omega_f - \omega_r)^\frac{1}{2} - (\omega_f + \omega_r)^\frac{1}{2} ]\). This can be approximated, if \( \omega_f/\omega_r \ll 1 \), to the retarding torque \( T_r \) being proportional to \( \Delta B^2 \omega_r/(\omega_f)^\frac{1}{2} \). Therefore, for maximum efficiency it is necessary to adjust the field contribution from each coil set so that the fields are as equal as possible.

The uniformity of the magnetic fields is limited because of the physical layout, the coils being far from the ideal Helmholtz criterion, i.e. the radius of the coil equal to the spacing of the coils. The radius of the coils equals 55mm and the spacing is 140mm. This means that the magnitude of the magnetic field at the centre of the configuration is reduced to 0.33 of the value produced by a true Helmholtz configuration, using the same diameter coils. This also reduces the uniformity of the magnetic field within the volume occupied by the rotor boss.

5.3 Rotor Heating.

The currents that cause the acceleration also cause heating and a calculation for heat dissipation, \( E_h \), within the rotor, assuming the heat input to be solely due to \( I^2 R \) losses within the steel, yields the relationship for a spherical conducting shell:

\[
E_h = \frac{3}{8} \frac{\pi^2 B^2 (\omega_f - \omega_r)^2 R^2 S}{Q} \tag{5.14}
\]

and by comparison with equation 5.8 gives:

\[
E_h = T_r (\omega_f - \omega_r) \tag{5.15}
\]
The torque $T_r$ is related to the angular acceleration, $a$, by the relationship $T_r = Ia$, where $I$ is the moment of inertia of the rotor. If the initial acceleration rate of the rotor is $a_0$ and the rotor is stationary and subject to an accelerating torque, then the average temperature rise per unit time $K_r$ is:

$$K_r = \frac{Ia_0 \omega_f}{M_r c}$$  \hspace{1cm} (5.16)

where $M_r$ is the mass of the rotor, $c$ is the specific heat capacity and $\omega_f$ is the angular frequency of the magnetic field, in Rad/sec. The initial temperature rise of the rotor was measured as a function of time, when $a_0$ equalled 0.8Hz/sec. This gave an initial temperature rise of 1.5K/min., which agrees closely with the initial temperature rise per unit time, given by equation 5.16, of 1.54K/min.

5.4 The Electronic Drive Unit.

The electronic drive unit was initially designed by J.H.B. and constructed by the author. This initial design was modified by the author to increase certain aspects of reliability and also to allow digital control of the direction of the rotating magnetic field.

5.4A The Basic Unmodified Circuit.

The drive unit consisted of two identical channels which provided independent drive for two rotors. Therefore only one channel will be described.

A square-wave oscillator running at 10kHz was gated and the frequency divided by two. This produced two sets of square-wave pulses at 5kHz, with a phase difference of $\pi/2$. These pulses were then fed to a switch, which was used to change the relative phase of the two pulse trains and
then to an R. T. L. gate, which had an external input, allowing the pulses to be isolated from the next section.

The next stage comprised two variable pulse length monostables which enabled the length of the pulses to be varied from 0 to 0.1 ms. These were then used to pulse two banks of ten transistors each to drive the two coil sets, having a current phase relationship of $\pi/2$. The drive coils had a secondary which was tuned to 5 kHz using a capacitor bank and hence the primary windings in the collectors of the transistor banks appeared to be purely resistive and therefore large currents could flow through the coils.

5.4B A detailed description of the modified electronic drive unit.

The low power section of the drive unit is supplied by a 3.6 V, 10 A supply and the high power stages, producing the output drive currents, are supplied by a 30 V, 60 A DC supply. There is also a 5 V supply, which has been added to provide power for TTL, used in the modified sections.

Initially the drive oscillator at 10 kHz was powered by the 3.6 V supply but due to current pulses being drawn from it to provide base current for the output transistors, the oscillator frequency was 'pulled' and produced instability. When the frequency of the oscillator changed, the frequency of the current pulses did not trigger the tuned coils at the correct time and this resulted in phase shifts in current and voltage, which produced excessive dissipation in the output transistors and hence a proportional reduction of power transferred to the coils.

The drive unit was initially designed to drive the two rotors independently but with a common driving frequency of 5 kHz. However, it was found that, if two rotors were set up in the double rotor vessel with their
Figure 5.2

The diagram shows a circuit with various components and labels such as SN7413, 28kHz, 14kHz, 10kHz, 20kHz, and 1kHz. The circuit includes gates, resistors, capacitors, and other electronic components, with labels indicating their roles and connections. The figure illustrates the coupling that occurs between the components, highlighting the interaction and control of the circuit's signals.
respective drive coil sets, strong drive coupling took place between the rotors. This coupling made the independent control of the rotors impossible as the application of a driving field to one rotor caused the torque to be shared between both rotors. The strong coupling was mainly due to the fact that both rotor drive units used drive coils with their secondaries tuned to the same frequency and in close proximity to one another. Lack of space meant screening was very difficult, so it was decided to change the frequency of one of the rotor drives. This means that one rotor has a rotational field of frequency 5kHz and the other of 7kHz. Consequently the capacitor bank for tuning the 7kHz drive coil sets had to be changed and also an independent oscillator produced to run at 14kHz. Because of the frequency 'pulling' effect mentioned earlier, the 10kHz oscillator was also replaced and both were run off a stabilised 5V supply. The phase-shifting stage requires the oscillators to have an accurate 1:1 mark/space ratio and this was most easily accomplished by producing two oscillators running at 28kHz and 20kHz and then frequency dividing their outputs by two. The circuits of the oscillators are shown in figure 5.2. They use the four input NAND Schmitt trigger SN7413 with the output fed back through a resistor charging the input capacitor. Because the gate has temperature stabilised levels, the oscillators produced were found to be adequately stable. The pulses from the Schmitt trigger oscillators are then buffered, using $G_1$ and $G_3$, which are $\frac{1}{6}xSN7404$. The pulses then feed the clock inputs of two independent J-K flip-flops. The J and K inputs are held high, which causes the outputs $Q_1$ and $Q_2$ to toggle at half the frequency applied to the clock inputs $T_1$ and $T_2$. The outputs from the JK's are then buffered by gates $G_4$ and $G_2$ and the outputs
Figure 5.3

1:1 mark-to-space

A

MRTL
MC789P

0V

MC760

Q

C

D

E

S1 at A

E1

S1 at B

E2

S1 at B
fed to the next section. The frequency outputs show no 'pulling' effect when the drive unit is operational.

Only a description of the 5kHz drive channel will follow, as the 7kHz drive channel is merely a duplicate. The 5kHz channel does, however, include the drive reversing unit which is unnecessary in the other channel.

The next stage uses MRTL logic for producing digital phase shifting. In the process input pulses are used to produce two outputs at half the input frequency and at a relative phase of $\pi/2$. As in figure 5.3, the 10kHz output from the oscillator stage is fed into an inverter, which feeds pulses into the clock input of a J-K flip-flop and, in this case, the C and S inputs are held low to enable the output to toggle. On the negative transition of the T-input, the output $Q$ goes to the previous state of $Q$ and $Q$ goes to $\overline{Q}$. This simply produces the standard divide-by-two action used earlier with the TTL J-K's. The outputs $\overline{Q}$ and $Q$ are now fed via switch $S_1$ to the inputs of another J-K flip-flop, which has its clock connected to A, the input of the 10kHz pulses. When the input A changes from a high to a low state, the output E will produce 1 or 0 depending on the inputs of C and S. As can be seen from the pulse chart, figure 5.3, the output from E is either lagging behind or leading the output from C by $\pi/2$, depending on the state of the switch $S_1$. For reasons that will be described later in this section, the switch $S_1$ must not be thrown while the drive unit is producing/5kHz rotational field. The pulses to the output transistors must be inhibited first, then the switch thrown and finally the pulses started again. This was initially achieved by turning off power to the J-K flip-flops, but this has subsequently been changed and now a
switch in the next stage inhibits these pulses.

The next stage is one which enables the direction of the drive torque to be reversed, using a TTL logical level input, the direction of the rotating magnetic field being defined by the logic level. It will be seen from the pulse chart, Figure 5.3, that the action of the switch $S_1$ is merely to negate the output $E$ and hence reverse the direction of the driving field. However, the pulses must be isolated from the output stage during this change-over period. The first operation that must be performed by the logical reversing unit is therefore to inhibit the drive. After this has been done, the phase of the pulses can be altered and then a short period of time must elapse to allow oscillating currents in the tuned circuit to collapse before the inhibit is removed. The reason for inhibiting the pulses to the output transistors during phase-reversal is to prevent the pulsing of the output transistors at the wrong part of the oscillating current cycle, in the secondary of the drive coils. The power supply to the output transistor is derived from a 30V supply but because the collector load is a tuned circuit, it is possible for the collectors of the output transistors to reach 60V during the cycle. The voltage limit of the output transistors is 60V but if a sharp current pulse were drawn by the transistors, then this could cause secondary breakdown, resulting in the possible failure of ten transistors. The lower trace of plate 5.1 shows the decaying voltage on the collector of the drive transistors, when the drive pulses have been turned off. It can be seen that the amplitude of the oscillation has decayed to approximately $\frac{1}{5}$ of the peak amplitude after a time period of 2ms and this is then small enough to enable the output transistors to be turned on without being damaged. The oscillating
Figure 5.4

- From E, SN7413 -> G1
- From C, SN7486 -> G2
- +3.6V, Manual inhibit, D1
- Logical input inhibit
- Drive sense input, SN745
- Load, SN7486, G3
- G4, G5, SN745
- Up, down, load clear
- G6, G7
- E out, C out
voltage on the collector decays in approximately ten cycles of the 5kHz drive frequency and thus it can be used to time the period prior to turn-on.

With reference to Figure 5.4, the drive reversing stage functions as follows: A logical level is fed from an external input to A. This logical level can take one of two possible states, high or low, and for convenience it will be assumed that logical 1 signifies accelerate, and 0 decelerate. If the rotor is being accelerated and the drive unit has been applying an accelerating torque for some time, the output from the D-type latch SN7475 will be the same as the A input, i.e. the state of the drive will be equal to the required drive state. This means that a high will be present on the input of the exclusive OR gate, G2, which will therefore act as an inverter. Hence, pulses entering from input C will be Schmitt triggered by G1 and inverted, then fed to G2, which will also invert them, because the other input is high and then they will be fed to G9. The logical level on A is equal to the logical level on B, so the exclusive OR gate, G3, will produce a high output which feeds the two input NAND gate, G4.

The BCD 4-bit scaler is not counting and is set at zero. This means that the output from the BCD-to-Decimal converter, SN7442, will have a low on its decimal, zero output. The gate, G4, will consequently have two high inputs, which will cause G5 to inhibit pulses from G1 entering the scaler. This will also mean that the diode, D2, is not conducting and, provided that none of the other diodes is conducting, pulses entering G9 and G8 will be fed into the next section. The latch is prevented from loading because the output from the decimal-two output of the decoder is
high, which causes the load input to be held low. The latch will load the logic level that appears on the input A into the output at B, when the load input is high.

Now, if it is required to change the drive state to decelerate, then this will be indicated by the input of the latch becoming low. The actual drive torque now no longer agrees with the desired torque and therefore the output of G₃ goes low. This results in the output of G₄ going high and causes the diode, D₂, to conduct, inhibiting the output pulses and hence removing the torque applied by the drive unit. Also, pulses from G₁ can feed G₅, which inverts and then feeds them to the up input of the scaler. After the first pulse has entered the scaler, the decimal-zero output of the decoder goes high and this holds the output of G₄ high independent of the output from G₃. When the scaler has counted two pulses, the load on the input of the latch goes high and loads the new logic level present on input A. The output from the latch will now be low and therefore the output of G₃ will produce a high, because the two inputs are equal. This will not, however, change the output of G₄ and so the output pulses will still be inhibited. Because the output of the latch is now low, the gate G₂ no longer inverts pulses but merely feeds the input pulses to its output. Therefore, the phase reversal has been accomplished, but the output transistor cannot be turned on until the inhibit has been removed. The scaler counts up to '3' and this causes the load input on the latch to return to a low state. Counting continues up to '9' and then the scaler automatically sets itself on zero. As the scaler is once again on '0', the decoded output from the decimal-zero output goes low and this prevents subsequent pulses from entering the scaler. Also, because this is
Figure 5.5

+3.6V

[Diagram of a circuit with various components labeled with R1, R4, R5, R9, R10, R12, R14, R15, R16, R18, C1, C2, D1, D2, TR1, TR2, TR3, TR4, TR5, TR6, TR7, and connections to F and 0.]
accomplished by raising the output of $G_4$, the diode $D_2$ ceases conduction. Hence, the inhibit is removed from the driving pulses and the drive now produces a torque in the opposite sense. The time between the inhibit and turn-on is equal to ten pulses of the 5kHz oscillator (2ms) and hence this minimises the danger of secondary breakdown.

The Schmitt trigger, $G_1$, is necessary because the pulses have to be changed from RTL to TTL levels. However, TTL can satisfactorily drive RTL gates and so $G_2$ and $G_4$ can adequately drive the RTL gates, $G_8$ and $G_9$. The diodes $D_1$, $D_2$ and $D_3$, combined with the resistor $R_1$, form a type of OR gate, enabling the drive to be inhibited from one of three possible sources.

The next stage of the unit allows manual control of the mark/space ratio of pulses being used to drive the output transistors. This alters the amount of energy applied to the tuned circuit every cycle (Figure 5.5). There are four circuits in the drive unit of this form. Two are used for the 7kHz channel and two for the 5kHz channel. The input from E or C enters through diode $D_1$, which is conducting, if the logical input is low. Current flows through $R_4$ and $TR_1$, which together constitute a constant current source, feeding current into capacitor $C_1$. The magnitude of this current is defined by the voltage on the base of $TR_1$, this being adjusted by the variable control, $R_3$, which is manually operated and is accessible from the front of the unit. When the input is high, the capacitor $C_1$ is fed with a constant current which produces a voltage ramp. The rate of rise of this ramp is dependent on the setting of $R_3$. A voltage will be reached across $C_1$ such that $TR_2$ will conduct and, when the base voltage has risen, a further base-emitter voltage, $TR_5$, will be turned on. This
Figure 5.6

+30V

L1

L2

C1

R1

R2

R3

R4

N1

R5

R6

R7

R8

R9

R10

R11

R12

R13

R14

R15

R16

R17

R18

R19

R20

R21

R22

R23

R24

R25

F1

F2

F3

F4

F5

F6

F7

F8

F9

F10

0V
will cause the base of TR_3 to fall and the resulting signal to be amplified by the long tail pair produced by TR_3 and TR_4. As the input from E or C is an even mark/space ratio pulse train, the maximum time that TR_2 can conduct is half the period of the pulses. When E or C is low, the diode D_1 conducts and turns off TR_2. The capacitor, C_2, produces a time constant of 30\mu s to slow down the turn-off time of the current in TR_7. This, combined with the capacitor C_3, reduces the amount of radio-frequency interference produced by the fast switching of high currents in the output transistors.

The current pulses produced by TR_7 are now used to feed the bases of ten power transistors, mounted on a large copper, water-cooled heat sink (Figure 5.6). The voltage on the collectors of the output transistors is shown in the upper half of plate 5.1. This shows the waveform when the transistors are producing drive. It can be compared with the lower trace, which shows the voltage on the collectors when the output transistors have just been turned off. Note the voltage on the secondaries of the drive is sinusoidal in both cases. The pulsed base current turns on all ten transistors and this causes the voltage across L_1 and L_2, the primaries of a coil set, to increase to nearly 30V. Current starts to flow in the primary and also in the secondary, rising to a maximum. Then the voltage collapses as the tuned circuit resonates at the tuned frequency and causes the collectors of the transistors to rise above the +30V rail and approach 60V. During this time the transistors should be turned off and not turned on until the voltage on the collectors is again +30V or less and falling. This is arranged by the pulse width of the base driving current. The output stage operates in class C mode. This
Output transistors producing drive.

Output transistors turned on

Output transistors turned off

50μs/cm

Output transistors immediately after inhibition

10V/cm

0.75ms/cm

PLATE 5.1 Voltage waveform on collector of output transistors.
mode of operation is very efficient as the transistors are either turned fully on or fully off. However, the base current pulses are slowed down to prevent r.f. interference, as previously stated, and as the power transistors have a limited frequency response, there is a finite transition time between the two states. This causes dissipation within the transistors and hence a considerable heating effect.

Resistors, \( R_{16} \) to \( R_{25} \) are included in the emitters to compensate for variations in the current gain of the power transistors and also to allow for variations in base-emitter voltages. The resistors, \( R_{5} \) to \( R_{14} \) are used to ensure that the output transistors are turned off when \( TR_7 \) is not conducting. Base current flows through diodes \( D_1 \) to \( D_{10} \), which prevents all the transistors being held 'on' if a short should develop in one of the transistors between collector and base. If a short were to develop between collector and emitter, the relevant fuse would fail and the diodes would again prevent current flowing from collector to emitter and then through the base resistors, thereby turning on the transistors. This circuit is repeated for the other drive coil set, using 5kHz pulses but with a different phase.

Each drive coil consists of 2.5 turns of \( \frac{1}{8} \)" copper pipe, to constitute the primary, while the secondary is made up of 100 turns of 18 gauge, enamel-covered, copper wire. The primary has cold water flowing through it to provide cooling. The secondaries are potted in epoxy resin. This is necessary to provide added insulation as the voltage, on the secondary, peaks at over 1kV. This high voltage also provides problems for \( C_1 \), which has to be a high voltage type. The value of \( C_1 \) is approximately 0.29\( \mu F \) for the 5kHz drive and is composed of a series-parallel
Figure 5.7

Drive coil set select

Drive coil select

Read normally open

Thermistors

Temp. cal.

0-80°C

10V

18V

Standard resistor

Set cal.

1k

10k
configuration of 1000pF capacitors rated at 600V, the inductance of the coils being approximately 1.8mH each. Mica capacitors are used as the heating effect, due to the loss angle of the dielectric, at high frequencies and currents would make many other types impracticable. Neon indicators, N₁ and N₂, are set to trigger at 300V and 600V, indicating that the drive coil set is functioning correctly.

Final adjustment of each drive channel is achieved by connecting two AC volt meters to the secondary circuit of each coil set. Adjustment is then made of the relevant oscillator frequency, such that both voltages are at a maximum. This has to be done with great care as the output transistors can easily be destroyed if the oscillator frequency differs greatly from the tuned frequency of the coils.

The total RMS current flowing in the primaries of one complete drive channel operating with a fifty percent duty cycle, is 24A and if the tuning is correct, such that the load appears to be purely resistive, then the total power delivered by one rotor drive channel to the coils, is approximately 600W. Due to the currents and the powers involved, a water pressure-sensing switch was fitted to the water supply, cooling the heat sink. This ensures that the electronic drive unit cannot be used unless the water supply is cooling the transistors. The voltage rating of the transistors is reduced if their temperature rises above 25°C and hence the water-cooling is essential. Also, in consideration of the high currents flowing in the primaries and secondaries of the drive coils, causing a large heating effect, calibrated thermistors were attached to the drive coils and, with the aid of a simple circuit (Figure 5.7) the temperature of each coil can be measured during a rotor run. This is necessary as the
Figure 5.8: Acceleration of rotor as a function of time for continuous accelerating drive.
Figure 5.9  Deceleration of rotor as a function of time for continuous decelerating drive.
epoxy resin, in which the drive coils are potted, has a temperature limit of just over 100°C and so the temperature of the coils is not allowed to exceed 80°C, allowing some margin of safety.

5.5 General Operation of the Drive Unit.

The electronic drive unit successfully accelerates rotors of the form shown in Chapter II at acceleration rates of 1Hz/sec in the 5kHz rotating field and also in the 7kHz field. The moment of inertia of the rotors is approximately 4.3 x 10^-6 Kg m² and this means that a torque of 2.7 x 10^-5 Nm is produced up to angular frequencies of 2000 revolutions/sec. Graphs of rotational frequency as a function of time are given in Figures 5.8 and 5.9, showing the rates of acceleration and deceleration respectively.
INITIAL PHASE LOCK SYSTEM FOR HIGH SPEED ROTORS

6.1 Introduction.

As previously stated, it is necessary to phase-lock one rotor with respect to the other to maximize the number of high velocity molecular encounters per second. This is achieved by measurement of the angular velocities of the two rotors and their respective phases, this information being used to control the applied drive torque.

A phase lock system was designed by J. H. B. and tested using one rotor, attempting to lock it in phase to a standard oscillator. This was unsuccessful owing to limitations of the rotor drive and control information used to correct the angular velocity of the rotor.

The circuitry utilized analogue sampling of the input frequencies and phase relationship between the two pulse sources and then, using only the phase error information, adjusted the applied drive torque. Unfortunately insufficient 'natural friction' of the rotor system resulted in insufficient damping and hence instability.

If the rotor drive was manually controlled it was possible to put the rotor nearly into lock with the standard; however, if the locking electronics were allowed to take over control there was a build up of oscillation about the mean phase lock point until the amplitude of the phase variations exceeded $360^\circ$, after which the phase information produced positive feedback for the next period of $360^\circ$ and thus the system completely lost control.

The conclusions drawn from the unsuccessful attempt to phase lock
the rotor enabled a new locking system to be developed, having damping information present to control the torque in the form of frequency difference information. Also the driving system, at this stage, was only a two-state drive, either on or off. There was no provision to apply a decelerating torque controlled by an auxiliary unit; therefore it was necessary to provide some form of proportional control to prevent excessive over-shoot.

6.2 Partial Analogue Phase Lock System with Proportional Control

The following system was designed and built by the author to lock a slave rotor to a master rotor or to a standard, with a phase error of less than 3° arc. The circuit diagrams are given in Figures 6.1, 6.2 and 6.3, and a block diagram in Figure 6.4.

6.2A Basic mode of operation.

Input pulses could be derived from two rotors or one rotor and a standard, and applied to inputs A and B (Figure 6.1). The input pulses could have a frequency range 500Hz to 5kHz, with standard T.T.L. logic levels. Pulses entering input A were fed into a variable time delay unit which enabled delays of up to 80% of the period of the A input pulses.

Pulses from the time delay unit and input B were then shaped (1μsec. duration) and fed to a scaler. Counting was arranged with the scaler such that additional logic, in conjunction with the scaler, could detect a frequency difference between inputs A and B, and also the sense of the difference. The frequency difference condition was sensed only after a new condition had remained constant for some short period of time, determined by the absolute frequency difference. This delay in the scaler system detecting a frequency difference crossing zero and
Figure 6.1

Load input BCD zero

Load input BCD five
changing sign meant that a control arrangement using only this information for frequency lock would always produce over-shoot. However, it served to turn the drive fully on or off to produce a form of coarse frequency lock.

The signal from the scaler was used to produce a ramp, which could take either sign of gradient. This was differentiated and produced an analogue voltage proportional to the frequency difference. Also, pulses were taken from the inputs to the scaler and gated, such that a variable mark/space ratio waveform was produced. The mark/space ratio was dependent on the phase relation of the input pulses at A and B. With the two inputs equal in phase and frequency, and the time delay unit set such that the time delay equalled half the period of the input pulse period, an even square wave was produced. The square wave was then integrated and this produced a voltage proportional to phase difference.

The two variable voltages were then added to a constant voltage and an output produced which was the sum of frequency-difference, phase information and a constant. This voltage was now used to modulate the mark/space ratio of a 200Hz clock, which could then control the electronic drive unit. The mark/space ratio fed to the drive unit, defined the on/off period of the accelerating torque, giving some degree of proportional control. This control signal could, however, be overridden by the coarse frequency lock from the frequency scaler; however, there was a 'dead zone' in the coarse frequency lock which enabled proportional control of phase and frequency.

6.2. B Detailed circuit operation.

(24, 25) Input pulses were fed to A and then to switch S₁ and G₁. The mono-stable G₁ was fired on the rising edge of the pulses and caused the
output $\overline{Q}$ to go low for a period of time defined by the setting of $R_1$ and $R_2$. If $S_1$ was set to position A, then $G_2$ would fire at the end of the period and produce an output pulse of 1$\mu$s duration, delayed by the period of time that $\overline{Q}$ was low. If the switch $S_1$ was set to position B, then the input pulses were not delayed. Pulses from B were also shaped and fed to one input of the dual input NAND gate $G_9$ and the output from $G_2$ fed to $G_8$. These gates were used to stop scaler ST from overflowing or underflowing. The outputs from $G_8$ and $G_9$ fed into the up and down inputs respectively of the scaler ST.

The scaler was composed of two cascaded SN74192's which gave a capacity of eight Binary Coded Decimal (BCD) bits. Gates $G_{10}$ and $G_{11}$ were fed into the other inputs of $G_9$ and $G_8$ respectively and used to stop 'up'-counts if the scaler was set on '99' and down-counts if the scaler was set on '1'. A pre-set BCD '50' could be loaded into the scaler by means of switch $S_2$ and corresponded to half the scaler capacity. The scaler counted up on the rising edge of a pulse applied to the 'up' input, while the 'down' input was high, and down for rising edges applied to the 'down' input, while the 'up' input was high. For this reason the input pulses were made equally short (1$\mu$s) compared with the input repetition rate because the shorter the period of time that the input pulses spent holding the scaler inputs down, the lower the probability of error counts due to both inputs being down simultaneously.

If the input frequency of pulses from A was less than the frequency of pulses from B, then there was an excess of down-counts resulting in the scaler counting to '1' and holding. If the two input-frequencies became equal, the scaler would remain on '1' as there would be no
Figure 6.3

The diagram shows a circuit with various components and connections. The components include resistors (R41, R43, R44, R46, R47, R49, R50), a 74121 SN74121G15 integrated circuit, and diodes (D3, D4, D5) with labels indicating angles (≥90). The circuit includes a 5V power supply and connections to switches and manual/auto inhibit features.

The diagram illustrates the flow of electrical signals through the circuit, with arrows indicating the direction of signal propagation. The specific connection points and logical gates (G16, G18, G19, G20, G21) are shown to highlight the circuit's operation.
resultant counts into the scaler. However, if the frequency of pulses from input A was greater than input B, then there was an excess of up-counts which resulted in the scaler counting up.

Outputs C and D detected greater than '90' and less than '10' and provided non-proportional control limits, giving full drive or no drive (coarse frequency lock) when the scaler was not within this range. During proportional control the scaler had to be within the range '10' to '90'. This was achieved by the momentary loading of BCD '50' into the scaler. A digital display was used to show the number existing in the scaler at any time.

Connected to the scaler was an eight bit Digital-to-Analogue Converter (DAC) which converted the digital number held in the scaler into a current and later a voltage. If the scaler was set on '50' and the input-frequencies were equal, then there would be no change on the output of the DAC. However, if the relative frequency of the input pulses changed, then the output current from the DAC would also change, the time differential giving the frequency difference. As the system would control the frequency difference, the 'walk' towards the non-proportional limits of the scaler range would be halted.

The phase information was derived by gates G₄, G₅, G₆ and G₇. This group constituted an 'S-R flip-flop' which was set by one input from the scaler and reset by the other. As previously stated, the output, E, was an even square wave if the input pulses to gates G₄ and G₅ had a 180° phase relationship. If it was necessary to have zero phase error between the input pulse sources, the time delay unit, G, could be used to provide the required correction.
Figure 6.4 Block diagram of analogue phase-lock unit.

A input

Pulse delay

Monostable

B input

Monostable

8-bit BCD up down scaler

8-bit BCD DAC

Current to Voltage

Integrate

Integrate

Integrate

Phase to Voltage

Integrate

Sum

Constant

Voltage to mark/space ratio

Drive inhibit

Inhibit

200Hz clock

D

dx/dt

C

x
The digitized information was then converted into analogue voltages, conversion of frequency information being achieved by the DAC and stage A (Figure 6.2). The current from the DAC was fed to $R_1$, $R_2$, $R_3$ and $R_4'$. These converted the current to a voltage and allowed adjustment of the output current to produce zero volts when the scaler was set on '50', thus enabling equal positive and negative voltage swings. The small voltage was amplified by $A$ and then smoothed using a 1 sec. time constant. The integration was necessary to remove the 'stepped' output from the DAC and hence stop the 'edges' of the steps causing transients in the differentiator. The configuration of the integrator was not of the usual form, using a 741, because owing to the speed of the edges a passive form, followed by a buffering stage, gave better integration than the more usual form, similar to $A_4'$. Stage $A_3$ was a standard differentiator circuit with integration to limit the upper frequency gain and hence the noise level. The output from $A_3$ was a voltage proportional to the frequency difference of the two input pulse sources, producing zero volts for zero frequency difference. Offset null adjustment was included in the differentiator to ensure the output setting. The signal was then fed to $A_4$ which provided some voltage amplification and integration, the output being fed to $R_{23}$ which provided adjustment of phase-derivative (frequency-difference) information used for control.

The phase-difference information was fed from $E$ to $R_{38}$ and integrated by $R_{36}$ and $C_{13}$. Stage $A_5$ supplied voltage amplification and level adjustment, finally feeding $R_{26}$. The input pulse-train had levels, 0 volts to 4 volts, standard T. T. L., but this had to be arranged so that
a 1:1 mark/space ratio would produce a d.c. voltage on $C_{13}$, which produced 0 volts on the output of $A_5$. The level change was achieved by $R_{35}$ and the adjustment of $R_{38}$. The whole stage effectively produced a voltage proportional to the mark/space ratio of the input from $E$. $R_{26}$, $R_{23}$ and $R_{28}$ provided independent level adjustment for phase, phase-derivative and constant information. These three voltages were added by $A_6$ to produce a control voltage at $G$. The constant was included to provide correction for the retarding torque on the slave rotor caused by 'rotational friction'.

The signal from $G$ (Figure 6.3) was fed to the base of $TR_1$ via $R_{41}$. This converted the voltage into a current which charged $C_{19}$. This charging current defined the 'on' period of pulses fed into $G_{15}$ from the oscillator, composed of an SN7413 dual NAND Schmitt trigger, which has its output fed back to the input and used to charge $C_{20}$. This oscillator produces pulses at 200Hz which then had a mark/space ratio defined by the voltage from $G$. This gave a continuous adjustment of the time for which the accelerating torque from the drive acted. The diodes $D_1$ and $D_2$ were included to protect the base-emitter junction of $TR_1$ from an over positive potential appearing at the input $G$. This is possible as a result of the 'swing' of the output of the previous 741.

Because the power controlled by the voltage from $G$ only had a limited range of mark/space ratios available, not extending to 1:0 or 0:1, the outputs from $G_{16}$ and $G_{19}$ enabled these two extremes to be realized by gating with the outputs from $ST$, this addition producing the coarse frequency-lock.
6.2C Phase lock tests.

The locking system was never used to lock a slave rotor to a master rotor; it was, however, used to lock a slave rotor to a standard frequency, derived by digitally dividing the 100kHz output from a Hewlett-Packard 545 frequency meter. The output frequency had a short term stability of 1 part in $10^9$ and the frequency meter was used to measure the period of the slave rotor pulses when locked. The frequency-locking produced average deviations from the standard of 1 part in $10^7$ sampled over 0.5 sec. at a rotational speed of 1,000 revolutions/sec. The controls were adjusted so that with zero phase and phase-derivative information the constant was adjusted to produce as near zero resultant torque on the rotor as possible. Then the phase-derivative information was increased to ensure frequency lock with the standard. Finally, phase information was increased to allow full phase lock to be established. The voltage output from $A_4$ was fed to the y-axis of a chart-recorder and this gave a plot of frequency-difference against time, the x-axis being driven by a voltage ramp. The manual control switch, $S_4$, was then used to decouple the control pulses from the rotor drive unit; this resulted in a loss of lock. Then $S_4$ was set to the auto position, which enabled the lock to be established again. The uncontrolled time was made short so that the rotor did not cause the frequency scaler ST to leave the proportional section. Observation of the frequency-lock recovery time enabled the best level setting of phase-derivative information. The unit produced phase-locking to the standard to better than $1^\circ$ arc, and it could maintain this under fairly constant medium vacuum (10^-6 torr) for several hours.
6.2D Limitations.

The unit had several disadvantages, one of which was the limited torque range of the proportional section. Sudden changes in vacuum pressure or, which is more relevant, gas load variations when the rotor would have been used as a molecular accelerator, would have caused a loss of phase-lock and if the impulse was severe enough, a loss of frequency-lock. Recovery of the lock position would have taken place, provided no further impulses were applied, but if repeated impulses produced a loss of frequency lock, then the proportional section would have been unable to correct, and only coarse frequency-lock would have been possible.

The absolute phase setting tended to drift over many hours, due mainly to changes in the time delay of $G_1$ and drifts generally within the analogue section. Also because of the analogue nature of the unit, considerable setting up of levels was necessary and this added generally to the problems of use.

As a result of these limitations a new design of locking-unit was required. The drift problem was eliminated by using a totally digital sampling system and full drive torque capability was included over the whole control range. Modifications to the drive unit enabled a digital input signal to control acceleration or deceleration.

The author's design for the Digital Locking Unit follows in Chapter VII.
CHAPTER VII

DIGITAL PHASE-LOCK FOR HIGH SPEED ROTORS

7.1 Introduction.

The following discussion will deal mainly with the phase-lock unit designed and built by the author to supersede the locking unit described in the previous chapter. The reasons for the change to a digital system are given under the section Limitations (Figure 6.2D).

One of the main differences between this system and the partially analogue system lies in the mode of sampling. The proportional section of the previous unit had a continuous control signal, proportional to the state of the inputs at that time. This digital unit uses a sample and correct system. Two inputs are required, as in the previous unit, but there are also two outputs. These convey two sets of information to the drive unit: the sense of the driving magnetic field, and drive or inhibit information. The commands are conveyed by standard T. T. L. logical levels and enable a large degree of flexibility. The modification to the drive unit enabled the direction of the rotating magnetic field to be controlled by a single logical input, which greatly increases the control capability of any drive servo unit. Passive deceleration was the primary limitation of the previous system, this being produced by gas loads and frictional couples as a result of interaction between the steel rotor body and the suspending magnetic field.

The state of the two drive control outputs is determined by the frequency difference and phase relation of the two inputs, or by manual override.
Figure 7.1

\[ \phi_s > \phi_m \]

\[ F_m \neq F_s \]

Figure 7.5
7.2 Mode of Operation.

The logical operations of the unit will be described under the heading Detailed Circuit Operations (7.3) but the method by which the parameters are measured will be described here.

7.2A Measurement of frequency.

During the following discussion the two inputs will be labelled input M and input S and the two inputs will be assumed to have continuous independent pulse trains entering each input, referred to as M-pulses and S-pulses.

With reference to Figure 7.1, the frequency difference of the two inputs is measured by subtracting the time period for nine M-pulses from the period for nine S-pulses, the time taken to perform this operation being called the sample time. At the end of each sample, a signal is fed to the relevant section to update the drive control information, held in a short-term memory. To achieve good stability of lock, it is necessary to perform the subtraction with sufficient accuracy to enable the frequency-difference unit to determine differences between the repetition rates of M-pulses and S-pulses to within 1 Hz, at frequencies of 5kHz. This repetition rate would produce approximately 500 samples of the frequency difference every second, and hence a possibility of 500 slave-rotor drive corrections every second.

To achieve the accurate subtraction, the time period of the nine pulses has to be accurately measured (.02%). Two possible methods for producing the result of the subtraction are, firstly, to simply measure the time for nine periods of pulses from each input and then subtract them. However, as one of the simplest method of measuring time, digitally is to
of count the number/high frequency pulses which can be fitted into the time interval, a very large number of counts would be produced and hence this would necessitate the use of large capacity scalers. It would also require two scaler banks, because of simultaneous counting and a unit to perform the subtraction.

The second method, devised by the author, requires only one scaler bank, of modest size, 20-BCD bits, and the subtraction performed by the up/down option within it.

If the two inputs have pulse trains of repetition rates $F_m$ and $F_s$ and an arbitrary pulse from one of the inputs is used to start a sample — say input $M$ — then the time between the zeroth pulse from input $M$ and the next pulse into input $S$ will give a time period $T_1$, and if this time period is subtracted from the period between the ninth pulse from input $M$ and the ninth pulse from input $S$, $T_2$, then:

$$T_2 - T_1 = 9(1/F_s - 1/F_m)$$  \hspace{1cm} (7.1)

This is equivalent to nine times the average period of $M$-pulses subtracted from nine times the average period of $S$-pulses, the average being taken over the sample period (Figure 7.1). As measurements of $T_1$ and $T_2$ are made at different times one scaler can be used, and the subtraction can be accomplished using the count-up, count-down facility.

The time periods are measured using clock pulses of frequency 12MHz, which feed into a 20-bit scaler and are gated such that counting is only done during $T_1$ and $T_2$. Steering logic has to be used to define the direction of counting and to determine which pulse train starts the sample. The result of the subtraction is then compared with the value loaded in the scaler, prior to the entry to the zeroth pulse. The
absolute magnitude of the subtraction is not required, but it is necessary to know whether the result is greater than, less than or equal to zero.

This information directly indicates the frequency relationship of the input pulses, $F_m > F_s$, $F_m = F_s$, $F_m < F_s$, indicating which of the three possible drive states has to be applied.

Because the frequency difference unit measures discrete intervals of time, using the high frequency pulses of period $T_c$, the duration of the time interval $T_1$ or $T_2$ is not an integral number of periods of $T_c$. Thus it is possible, depending on the phase relationship of the time period and the clock pulses, to produce one of two possible counts in the scaler. However, this does not produce any problems when the value of the subtraction $|T_2 - T_1|$ is much greater than the period $T_c$; but when the two input frequencies $F_m$ and $F_s$ are nearly equal, i.e.

$$\frac{1}{F_s} - \frac{1}{F_m} \ll \frac{2T_c}{9} \quad (7.2)$$

then the results of the subtraction do not always yield the same result.

The average result of the subtraction produces an automatic, proportional control section over a narrow range of frequency differences (± 25Hz at 4kHz).

To consider this aspect further it is necessary to simplify the counting system. Assuming that the scaler does not miss counts and the oscillator clock, used to measure time, produces delta-function type pulses, and possesses a completely random phase relationship to the beginning of the period to be measured, the probability $P_m$ of counting $m$ counts, during the time period $T_m$ is given by:
\[ P_m = \frac{(T_m - zT_c)}{T_c} \]  
(7.3)

for \( mT_c \gg T_m \gg zT_c \), \( m = 1 + z \).

Also the probability \( P_z \) of counting \( z \) counts during the time period \( T_m \) is given by:

\[ P_z = \frac{(mT_c - T_m)}{T_c} \]  
(7.4)

Therefore \( P_z + P_m = 1 \)

For any time interval \( T_m \), there are two possible results of a count, their probabilities being governed by the function \( P_m \) and \( P_z \).

To obtain the required frequency information, two counts are required. The first to obtain \( T_1 \) and the second to remove counts governed by \( T_2 \), hence producing the subtraction. If \( T_1 \) is such that \( nT_c > T_1 > (n-1)T_c \), and \( T_2 \) such that \( (n+1)T_c > T_2 > (n+2)T_c \), then the measured period \( T_1 \) would yield either \( n \) or \( (n-1) \) counts, and the measurement of \( T_2 \) would yield either \( (n+1) \) or \( (n+2) \) counts. If \( T_1 \) counts are subtracted from \( T_2 \) counts, the result must always be greater than zero. If \( nT_c > T_1 > (n-1)T_c \) and \( T_2 > (n+1)T_c \) or \( T_2 \leq (n-2)T_c \), then only one possible resultant drive state is possible and hence, outside of this range, the frequency difference measurement produces non-proportional control, in which the maximum drive torque is applied to accelerate or decelerate, according to the sign of the subtraction \( T_2 - T_1 \).

Within the proportional section there are three intervals, which are governed by the possible results of the subtraction. If \( T_1 \) is such that \( nT_c > T_1 > (n-1)T_c \), this being held constant for the rest of the description, then if \( T_2 \) is \( (n+1)T_c > T_2 > nT_c \), then there are two
possible results of the subtraction \((T_2 - T_1)\). The first possible result is zero, when \(n\) counts are produced by \(T_1\), and \(n\) counts being produced by \(T_2\). If the probabilities of \(T_1\), producing \(n\) counts in \(P_1^n\) and of \(T_2\) producing \(n\) counts in \(P_2^n\), then the probability \(P_o\) of the subtraction resulting in zero is:

\[
P_o = P_1^n \cdot P_2^n
\]  

and the probability \(P_1\) of the subtraction producing a result of greater than zero is \(P_1 = 1 - P_1^n \cdot P_2^n\). The values of \(P_1^n\) and \(P_2^n\) being given by equations 7.3 and 7.4 assuming that the probability of producing a given count for \(T_2\) is not related to the probability produced by \(T_1\).

A variable \(T_q\) (called the average torque fraction), can be used to express the proportion of time for which the drive would be applied as a result of the subtraction giving a result greater than zero. The value of \(T_q\) ranges from +1 to -1 to cover reverse drive, and is equal to 1 or -1 when the frequency difference is large enough to put the frequency difference sample outside the proportional range. The value of \(T_1\) and \(T_2\) is set by the relative phase relationship of the input pulses (Figure 7.1), but for simplicity the value of \(T_q\) given in the following relationships assumes the measurement of \(T_1\) is always performed with the same phase relationship. For a fixed time, \(T_1\), the value of \(T_q\) will vary as a function of \(T_2\), which is proportional to the difference frequency \(\Delta F\) of the input. When \(P_1^n = (T_1 - (n-1)T_c)/T_c\), \(T_q\) is given by:

\[
T_q = (1 - P_2^n \cdot P_1^n)
\]  

for \(T_2\) within the range \((n+1)T_c > T_2 > nT_c\) and in terms of the frequency difference \(\Delta F\):

\[
T_q = \frac{P_1^n}{P_1^n} \left[ \frac{9 \Delta F}{F^2 T_c} - 2 \right] + 1
\]  

\(1P_n \neq 1\) or 0  

(7.7)
\[ P_n = 1 \]
\[ P_{n-1} = 0 \]

Figure 7.2

$F = 4\text{kHz}$
\[ P_n = .5 \]
\[ P_{(n-1)} = .5 \]

Figure 7.3

\( F = 4\text{kHz} \)

\( \Delta F \text{ in Hz} \)
$P_n = 0.75$

$P_{n-1} = 0.25$

$F = 4\text{kHz}$

Figure 7.4
and the range of $\Delta F$ is $F^2 T_c (2 - \frac{1}{P_n}) / 9 \geq \Delta F \geq F^2 T_c (1 + \frac{1}{P_n}) / 9$. 

$F$ is equal to the frequency of the input pulses when $F_m$ is approximately equal to $F_s$.

For $T_2$ such that $(n - 1) T_c > T_2 > (n - 2) T_c$, there is a probability of the subtraction producing 0 or -1. This changes the relationship equation 7.7 to:

$$T_q = (1 - \frac{1}{P_{(n-1)}}) \cdot P_{(n-1)}$$

$$= (\frac{1}{P_n} - 1) \left[ \frac{9 \Delta F}{F^2 T_c} + \frac{1}{P_n} + 1 \right] + 1$$

where the range of $\Delta F$ is $F^2 T_c \frac{1}{P_n} / 9 \geq \Delta F \geq -F^2 T_c (1 + \frac{1}{P_n}) / 9$.

For $T_2$ within the same range as $T_1$, there is a probability of the subtraction producing +1, 0 or -1. This gives:

$$T_q = \frac{2}{P_n} - \frac{1}{P_n}$$

$$= \frac{9 \Delta F}{F^2 T_c}$$

when the range of $\Delta F$ is $(1 - \frac{1}{P_n}) F^2 T_c / 9 \geq \Delta F \geq -F^2 T_c \frac{1}{P_n} / 9$.

Derivation of the formulae for $T_q$ are given in Appendix 1 and the graphs of variation of $T_q$ with $\Delta F$ for various values of $\frac{1}{P_n}$ are given in Figures 7.2, 7.3 and 7.4.

7.2B Measurement of phase.

The measurement of the phase difference between the two inputs is also accomplished by two measurements of time. The measurements are as in Figure 7.5. Inputs M and S are assumed to have input pulses of the same, or very nearly the same, frequency. This is not unreasonable as the frequency difference information is dominant in the control of the
rotor, until the subtraction of \((T_2 - T_1)\) yields a zero, and for the following sample the phase information is used to control the rotor. The time periods between the eighth pulse of M-input and the ninth pulse of S-input is subtracted from the time between the ninth pulse of S-input and the ninth pulse of M-input. This subtraction produces zero when the input pulses are \(\pi\) out of phase. However, the rotors have two arms and it is important to phase lock the arms so the input pulses are divided by two just prior to the inputs of the locking unit. The input pulses are locked with a phase relationship of \(\pi\), which results in the rotor arms being locked in phase. If \((T_3 - T_4)\) is greater than \(3T_c\) then results of phase measurements will not be proportional to phase difference, but will only indicate when the relative phase of the slave rotor is lagging behind or leading the master rotor. Within time differences of \(3T_c\) the phase also produces a form of probabilistic proportional control. The range of the proportional control of phase is of the order of \(\pm 18^\circ\) for input pulses of 5kHz.

The next stage produces a form of integration for the frequency and phase data. This process is used to independently compare present and previous phase and frequency information. A memory stores the frequency information from the previous sample and compares it with the results of the present sample. If the two sets of results are equal, then the results of the present sample are loaded into the output memory, which is then read by the gating logic, which controls the drive. If the new data is not equal to the previous data, then the output memory is loaded with \(F_m = F_s\) or in the case of phase, by phase difference = 0. This means that only consistent samples are allowed to be stored in the output
memory and this reduces the effects of the proportional section of frequency and phase. As it is generally useful to have limited proportional control, the integration facility can be switched off. The way the interaction between phase and frequency information affects the control of the slave rotor drive is shown in the truth table, Figure 7.20.

Neutralisation of systematic errors was accomplished by a type of multiplexing of the inputs and the phase and frequency results every sample.

7.3 Detailed Circuit Operation.

(28, 25) With reference to the circuit diagrams (Figures 7.6 to 7.13), and the block diagram (Figure 7.14), the operation of the digital phase-lock unit is as follows:

Pulses from the two rotors enter inputs \( R_m \) and \( R_s \) (Figure 7.6). These pulses come from the P.I.N. diode amplifiers which amplify the pulses produced by the rotors intersecting the laser beam twice every rotation. These pulses are shaped by the DUAL NAND SCHMITT TRIGGERS, SN7413, \( G_1 \) and \( G_2 \). The pulses entering \( R_m \) come from the master rotor, with frequency \( F_m \), and those entering \( R_s \) come from the slave-rotor, with frequency \( F_s \).

The pulses are fed from their respective Schmitt triggers to the scalers \( S_A \) and \( S_B \). These are synchronous 4-bit counters, the outputs from the least significant bit giving a pulse train of equal mark/space ratio and of half the input frequency. This frequency is therefore equal to the rotational frequency of the relevant rotor, as the rotors produce two pulses per revolution. These two signals are fed to the outputs \( M \) and \( S \).
which feed the next section. Other outputs are available at this point, for monitoring the rotor frequencies. The mono-stables $M_1$ and $M_2$, SN74121, with pulse lengths longer than the repetition rate of the input pulses, provides light outputs to indicate the presence of input pulses.

The two input NAND gate $G_3$ is used to gate the two output signals from the Schmitt triggers so that an output pulse results when the two input pulses overlap in time. The signal is then fed to $M_3$ and the output of $M_3$ to an L.E.D. indicator to show when the rotors are in phase.

The outputs $M$ and $S$ are now fed to the multiplexing unit $G_{10}$ (Figure 7.7) composed of a Quad 2-Line-To-1-Line Data Selector/Multiplexer, SN74157. This integrated circuit is used to switch pulses from $M$ and $S$ to its outputs $1y$ and $2y$. However, the input that appears on the output is defined by the select input $T$. The purpose of this unit is to reverse the input to the next section after every sample, and thereby neutralise systematic errors. The select input $T$ has a square wave applied to it, with a period equal to two sample periods. The square wave is derived in another part of the circuit and the effect of this switching will be described later.

If the input to the select input $T$ is low it allows pulses from $M$ to feed $G_{11}$ and from $S$ to feed $G_{12}$, these being simply inverter buffers. This section controls the sample and the use of the acquired data, having a sequence of operations which is not affected by any other part of the system except the inputs. This section has three scalers, $S_1$, $S_2$ and $S_3$, of which $S_3$ is the time sequence control scaler. The scalers are all type SN74192, synchronous BCD 4-bit up/down counters. Because this section has a closed sequence of operations it is necessary to start the description
at some arbitrary point in the cycle. For convenience, this point will be the end of a sample cycle; this means that the data has been stored and the unit is ready to begin the next sample cycle.

At this point scaler $S_3$ has just counted to BCD '5' and this output has been decoded into decimal by the SN7442. The other scalers, $S_1$ and $S_2$, are both on '9' which is detected by the two input NAND gate $G_{24}'$, inverted by $G_{15}$ and fed to one of the inputs of the two input NAND gate $G_{22}'$. Scaler $S_3$ is not on '6', therefore the other input to $G_{22}$ is high and because $S_1$ is on '9' then the other input is also high. This means that the output of the NAND gate $G_{15}$ is held high and this stops the scaler $S_1$ counting, and hence locks it on '9'.

In connection with scaler $S_2$, gates $G_{30}$ and $G_{29}$ produce a high into $G_{27}$ because the scaler is set on '9'. As the output from the NAND gate $G_{36}$ is high, the input to $S_2$ is also high and hence is locked on '9'. As a result of both scalers being on '9', the output from $G_{23}$ which is fed from $G_{26}$ and detects that both scalers are on '9', feeds a high to $G_{14}$ which is a three input NAND gate feeding the up input of scaler $S_3$. As scaler $S_3$ is set on '5', the decoded six output is high, so that the pulses produced by the 100 kHz oscillator $G_{13}$ are inverted by $G_{14}$ and fed to $S_3$. This results in the scaler counting to '6'. At '6' the output from the decoder goes low on the decimal six output, and this forces the output of $G_{14}$ high, preventing further counting by $S_3$. However, this also means that the output from the decoder to $G_{22}$ will force the output high and enable the next pulse coming from $G_{11}$ to be fed into the scaler $S_1$. This will cause it to count to '10', which will clear the output to zero and send out a carry pulse, which is not used. $S_1$ is not on '9' and hence the out-
Figure 7.8

Frequency scaler

12MHz in

G31

G32

G33

G34

G35

G36

G37

G38

G39

G40

G41

P

D

C

F

H

G

L

M

N

O
put from $G_{25}$ will be low, holding the output of $G_{22}$ high irrespective of its other input. As both scalers are not set on '9', the output from $G_{23}$ is low, which means that gate $G_{14}$ has two inputs inhibiting pulse counting by $S_3$. Both low inputs must be removed to enable the scaler to continue counting.

The output from $G_{37}$ will be high because the output from $G_{25}$ has gone low. The double inversion of the output of $G_{24}$ by $G_{25}$ and $G_{37}$ is used to buffer the heavily loaded output of $G_{24}$. As $S_3$ is set on '6', the output from the inverter $G_{28}$ is high and, as a consequence, $G_{36}$ has a low output which makes the output from $G_{27}$ high, enabling scaler $S_2$ to count pulses from $G_{12}$ inverted by $G_{16}$. Scaler $S_2$ then counts to '10', clears, as in the case of $S_1$, resulting in the output of $G_{29}$ becoming low and hence ensures that the input pulses to $S_2$ cannot be inhibited until the scaler has reached '9'. Meanwhile, the output from $G_{43}$ must go high, this happening almost immediately as neither of the scalers $S_1$ nor $S_2$ are on '9' and $S_3$ is on '6'. As a result, the three input NAND gate $G_{18}$ has all inputs high, making the clear input high. The scaler is cleared and, because it is no longer on '6', the output of $G_{17}$ returns to a low state.

One of the inputs to $G_{14}$ is driven high in consequence, but the other input, which was low, will not go high until both scalers $S_1$ and $S_2$ are on '9'. Therefore, $S_3$ cannot count pulses from $G_{13}$ until both scalers have counted nine pulses from their respective inputs 1y and 2y. Also, the output from the decimal six digit of the decoder is high and the output from $G_{36}$ is high, which means that both scalers $S_1$ and $S_2$ can count their respective inputs until they reach '9', and then they will be inhibited, for reasons given above.
Figure 7.9
When both scalers have reached '9', they stop and the output of $G_{26}$ which has detected this state, now lifts the inhibition on scaler $S_3$ and enables pulses from $G_{13}$ to be counted by $S_3$.

During the count, timing and loading information is taken from digit outputs two and four of the decoder to control other stages. Scaler $S_3$ counts to '6' and then the whole cycle is repeated.

To simplify the cycle, $S_3$ counts up to '6' enabling $S_1$ to be cleared and begin counting pulses from $G_{11}$. $S_2$ can be cleared only after $S_1$ has been cleared and then counts pulses from $G_{12}$. Both count to '9' and stop. Meanwhile, $S_3$ has been cleared and, when $S_1$ and $S_2$ are both '9', begins counting pulses from the 100kHz oscillator. $S_3$ then counts unhindered to '6', when it is stopped and the cycle is repeated.

During the cycle other stages have been counting and subtracting.

For the frequency-difference measurement, the time interval $T_1$ is equal to the time that scaler $S_1$ is not on '9' and $S_2$ is '9', and the interval $T_2$, at the end of the cycle, is equal to the time that scaler $S_1$ is '9' and $S_2$ is not '9'. It is possible for the situation to occur, at the end of the cycle, that $S_2$ is '9' and $S_1$ is not '9'. This happens when the frequency of the pulses being fed to $S_1$ is much less than the frequency of pulses being fed to $S_2$. If $F_m \gg F_s$ then this situation will occur every alternate sample governed by the multiplexing unit $G_{10}$ but will not produce any errors in the frequency-difference measurement.

The frequency scaler $S_6$ (Figure 7.11) is a 20-bit BCD scaler composed of 5x SN74192's, synchronous up/down counters (dual clock with clear) in cascade. These scalers have up/down facilities and, therefore, subtraction is accomplished by feeding pulses in the up-input and into the down-
Scaler capacity = $10^5$

BCD No.

$5 \times 10^4 = 0101, 0000, 0000, 0000, 0000, 0000, 0000, 0000$

Figure 7.10
input. Because the down count could be larger than the up count, the scaler is not cleared before counting begins but is loaded with a pre-set number. The scaler has a decimal range of $10^5$ so the scaler is loaded with the BCD word equivalent to $5 \times 10^4$ prior to the sample, giving an equal counting range up and down. The load command is produced by scaler $S_3$ which outputs a low state to output 'K' when the scaler is set on '4'.

Output K is gated with the underflow and overflow outputs from the scaler $S_6$. These outputs are fed into mono-stables which produce 500nsec pulses. Normally the outputs from $M_7$ and $M_5$ are high; therefore loading occurs only when the K output goes low. But if during the sample, counting is such that the scaler overflows or underflows, then the scaler is re-loaded with $5 \times 10^4$ and outputs are produced from U and V to show that the scaler count is in error and hence the frequency information produced during the sample is incorrect.

Steering logic is required to feed pulses to the correct input, to measure the times $T_1$ and $T_2$, and a diagram of the logic is shown in the upper half of Figure 7.8 and a truth table relating the states of the scalers $S_1$ and $S_2$ to the count up /down inputs is shown in Figure 7.15. The scaler $S_6$, therefore, counts up for the period that $S_1$ is '9' and $S_2$ is '9' and down for the period that $S_1$ is '9' and $S_2$ is '9'. If the two time periods are equal, then after the sample the scaler will most probably be set on the initially loaded number, i.e. $5 \times 10^4$.

Wired to the scaler bank is a 20-bit BCD MAGNITUDE COMPARATOR composed of $5 \times SN7485$'s in cascade. These compare the number held in $S_6$ at the end of a sample with $5 \times 10^4$. The comparator has a three-
Scaler capacity = $10^5$

BCD No.
$5 \times 10^4 = 0101, 0000, 0000, 0000, 0000, 0000$

Figure 7.11

- AC Comparator
- AC > BC
- AC = BC
- AC < BC
- Select
- y1
- y2

- Load input
- G42
- G41
- +5V

- underflow
- overflow

- T
- BCD No.
- L
- N
- U
- V
- W
- X
- Y

- M5
- M4
- +5V
state output and this is shown in Figure 7.11. The extreme frequency conditions are shown in Figures 7.16, 7.17 and 7.18. At this stage it is still necessary to ignore the effect of the multiplexing gate $G_{10}$ and assume the $T$ input is low.

Figure 7.16 shows the input condition $F_m > F_s$. As the select input on $G_{10}$ is low, then the number above the $R_m$ input refers to the state of scaler $S_1$ and the number above the $R_s$ input, the state of $S_2$. The time period $T_1$ corresponds to down-counts in the frequency scaler Figure 7.15, but $T_2$ produces a larger up count, $T_2 > T_1$, therefore the frequency scaler has a count in excess of $5 \times 10^4$ at the end of the sample. The result, as far as the comparator is concerned, is that $AC > BC$. Therefore, if the comparator outputs the state $AC > BC$, then this corresponds to $F_m > F_s$ as long as the $T$ input is low. Following this, Figure 7.17 shows $T_2 = T_1$, and this is most likely to produce down-counts equal to up-counts, indicating an equality in the input frequencies and also shown by the comparator. Finally, Figure 7.18 shows $T_1 < T_2$, which is the same relationship as Figure 7.16 but the steering logic detects that the scaler $S_2$ started the period $T_2$ and this causes down-counts for both $T_1$ and $T_2$, thereby causing the output of the comparator to indicate $AC < BC$.

The output of the comparator consists of a three-bit word which can be considered as a binary code indicating the result of the comparison. The three possible results are coded (001) for $AC > BC$, (010) for $AC = BC$ and (100) for $AC < BC$.

One of the disadvantages of a system which always uses the same scalers, say $S_1$ and $S_2$, for sampling the inputs and using the control logic
to produce the same steering logic in every sample, is that it is very
liable to systematic counting errors and so the gate $G_{44}$, which performs
the same function as $G_{10}$, is included. Until now the 'T' select input
has been held low, but, if this input is now 'toggled' at a frequency equal
to half the sample frequency, then $T$ will also go high and this causes
input pulses from $M$ to be fed to scaler $S_2$ and input pulses from $S$ to be
fed to scaler $S_1$. This result produces a reversal of the unequal outputs
of the comparator for the same frequency inputs at $R_m$ and $R_s$. Thus the
output of the comparator must be reversed in phase with the multiplexing
gate $G_{10}$. This is done by $G_{44}$ which reconstructs the correct information
relating to the input frequency conditions. If the bits of the
frequency word are considered in the order $YXW$ (Figure 7.11), then the
result $(001)$ indicates $F_m > F_s$, $(010)$ indicates $F_m = F_s$, and $(100)$
indicates $F_m < F_s$. The multiplexing waveform is produced by the
least significant bit of scaler $S_5$, which is a SN74193, binary scaler, fed
from the decimal four digit of scaler $S_3$.

The phase measurements are made using scaler $S_4$ (Figure 7.10) and
the steering logic is shown on the lower half of Figure 7.8. The scaler
$S_4$ is also a 20-bit BCD scaler, basically the same as the frequency scaler
but with the exception that the loading of the scaler is not gated with the
overflow and underflow outputs. As with the frequency scaler, the
description of the operation will assume that the $T$ select input it low so
that pulses from $R_m$ will be fed into scaler $S_1$, etc. As previously
stated, the results of the phase sample are not used to servo the slave
rotor, unless the input frequencies are equal. Therefore the following
description will assume equal input frequencies.

The zero phase position of the inputs is when $T_3 = T_4$ (Figure 7.5),
Figure 7.13

Diagram showing electrical components and connections:
-标注了各个元件和信号路径。
-包含逻辑门、电阻、电容等元件。

Drive sense output
Drive inhibit
as the phase of the input pulses before frequency division will be zero. If \( T_3 > T_4' \), then the phase of the slave rotor leads the phase of the master and hence, under these conditions, a retarding torque is necessary to restore the zero phase condition. If \( T_3 < T_4' \), then the phase of the slave rotor lags behind the phase of the master, and under these conditions, an accelerating torque is required to restore zero phase.

The steering logic produces an up or down count dependent on the state of \( S_1 \) and \( S_2 \); this is shown in the truth table Figure 7.19. The scaler will count incorrectly during the beginning of the sample cycle due to scaler \( S_1 \) or \( S_2 \) being '9' when the other is '6'. This means that the phase scaler must be loaded later in the sample cycle than the frequency scaler. This is done when scaler \( S_1 \) is set on '5', which is detected by the inverter \( G_{20} \) and the three input NAND gate \( G_{21} \).

The output from the scaler \( S_4 \) is fed to a 20-bit comparator and then to a multiplexing gate \( G_{45} \), which performs the same function as in the frequency case.

The phase information is also set in a 3-bit word and the coding of QRS is (001) indicating that the phase of the slave rotor leads the master rotor, denoted by \( \phi_m < \phi_s' \) (010) indicating the in-phase condition, denoted by \( \phi_m = \phi_s' \), and (100) indicating the phase of the slave rotor lagging behind the master rotor, denoted by \( \phi_m > \phi_s' \).

The 12 MHz clock used by the scalers \( S_3 \) and \( S_6 \) is shown in Figure 7.9. It consists of two FET's used to produce the required positive voltage gain and a simple LC tuned circuit. The FET gate connected to the top of the tuned circuit produces low loading of the aforesaid and hence the Q of the circuit is limited to the resistance of the inductor and the losses...
Divide
input
pulses
by 2

Divide
input
pulses
by 2

100kHz
clock

12MHz
clock

Sample
control
and timing
logic

Multiplex

Freq.
scaler

Comparator

Demultiplex

Integ.
by compar

Error pulses
Control pulses

Logical
sum

Phase
scaler

Comparator

Demultiplexer

Integ.
by compar

Short-term
memory

Auto-
manual

Drive
sense

Drive
inhibit

Error inhibit

Figure 7.14.
in the mica capacitors. There is stray capacitance from the gate of the FET to the source and to the drain, but as the drain is held by the supply rail there is no Miller amplification of the gate-drain capacitance. The capacitor \( C_1 \) was made large enough to swamp the stray capacitance but this meant that the inductor had to be small. The 2.5\( \mu \)H coil was potted in epoxy resin to prevent microphonic effects producing frequency modulation. It is necessary for the oscillator to have a fairly small short term frequency drift, typically less than 1 part in \( 10^6 \) over a sample period, as the frequency of the oscillator will affect the count rates for the time periods \( T_1 \) and \( T_2 \), \( T_3 \) and \( T_4 \). Because the time measurements are comparative, the absolute frequency of the clock is not important but needs to be as high as is reasonable for the scalers to accurately count. Measurements of the frequency drift of the oscillator gave drifts of 1 part in \( 10^5 \) over one second, the drift usually being in the same sense and hence over a sample period the change in frequency was very small. A crystal-controlled oscillator could be used but would not significantly improve the counting efficiency as the multiplexing removes systematic errors due to the drifting clock. For example, if the clock were gradually slowing down, then the measurement of \( T_2 \) would give, on average, a smaller number of counts than \( T_1 \), even if the two intervals were equal; but because the multiplexing causes alternate rotors to start the samples, the average effect of a constant drift in the clock cancels out and produces no bias in the frequency measurement. It will, however, decrease the control sensitivity. A certain amount of clock drift is desirable to reduce beat effects between the clock frequency and the rotor frequencies when the rotors are locked and hence the time periods \( T_1 \) and \( T_2 \) occur at
Figure 7.15

<table>
<thead>
<tr>
<th>S_1</th>
<th>S_2</th>
<th>L up input</th>
<th>M down input</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>9</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>$\overline{9}$</td>
<td>9</td>
<td>H</td>
<td>P</td>
</tr>
<tr>
<td>$\overline{9}$</td>
<td>$\overline{9}$</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>9</td>
<td>$\overline{9}$</td>
<td>P</td>
<td>H</td>
</tr>
</tbody>
</table>

Truth table for frequency steering logic.

P = clock pulses
H = no input pulses

Figure 7.16

Figure 7.17

Figure 7.18
regular intervals. One fairly simple solution to these problems is the use of a random pulse generator. This would alleviate the beat effects and also ensure that the probability of producing a given count due to $T_1$ does not influence the probability of producing a given count due to $T_2$. The amount of clock drift was found to be totally satisfactory for the lock required and hence no changes were found necessary.

Both phase and frequency data are fed to a stage which compares the present sample result of frequency with the previous result (Figure 7.12). If the frequency comparison shows the two sample results to be equal, the result is loaded into the frequency memory $G_{52}$. The method of comparison is as follows: When scaler $S_3$ counts to decimal two, $G_{52}$ which is a D-type latch, loads the output from $G_{51}$, but the output that is produced by $G_{51}$ is dependent on the logical state of the select input. If switch $TS_1$ is set on A, the select input is held low and this means that data presented on the A input is carried through to the y outputs. This mode of operation produces no integration, but if the switch $TS_1$ is set to B then the output of $G_{51}$ is defined by the state of $G_{50}$, an OR gate. During the J pulses from $S_3$, the D-type latch $G_{46}$ is also loaded with the results from the present sample and when $S_3$ counts to decimal four, a K pulse loads that data into $G_{47}$, which is another D-type latch. This means that during the J pulse, $G_{47}$ contains the previous sample state of W and Y inputs and $G_{46}$ contains their present states. If the states stored in $G_{47}$ are the same as $G_{46}$, then the exclusive OR gate (EXOR) will yield a low on the select input of $G_{51}$ and hence load the present data into the frequency memory $G_{52}$; but if the results are not the same, then the frequency memory is loaded with (010) which corresponds to $F_m = F_s$. The operation
### Figure 7.19

<table>
<thead>
<tr>
<th>Scaler 1</th>
<th>Scaler 2</th>
<th>Scaler 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N up</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>H</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>H</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>H</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>P</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>H</td>
</tr>
</tbody>
</table>

P = clock pulses
H = no input pulses

Truth table for phase steering logic.

### Figure 7.20

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Phase</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fm &gt; Fs</td>
<td>Fm = Fs</td>
<td>Fm &lt; Fs</td>
</tr>
<tr>
<td>Aw</td>
<td>Ax</td>
<td>Ay</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

x = irrelevant
of the phase section is the same but with different data. If \( W_t, X_t \) and
\( Y_t \) correspond to the results of the previous sample and \( W_{t+1}, X_{t+1} \)
\( Y_{t+1} \) correspond to the results of the present sample, then the stored word
\( A_wA_xA_y \) in the frequency memory will be as follows:

If \( W_{t+1}, X_{t+1}, Y_{t+1} = W_t, X_t, Y_t \)
then \( A_wA_xA_y = W_t, X_t, Y_t \)

If \( W_{t+1}, X_{t+1}, Y_{t+1} \neq W_t, X_t, Y_t \)
then \( A_wA_xA_y = 010 \)

If the input frequencies \( F_m \) and \( F_s \) are equal, then with a systematic
error, the multiplexing would cause an oscillation every sample between
\( F_m > F_s \) and \( F_s < F_m \) at the input of the integrator. This would be
expressed on the output of the memory \( G_{52} \) as 010 \( (F_m = F_s) \). Without
the integration the inertia of the rotor can provide the necessary integra-
tion of the torque, but this digital form could be useful if a very low
moment of inertia rotor were used. Light emitting diodes are used to
indicate the frequency and phase relationship of the master and slave
rotors.

The final stage of the locking unit deals with the gating process to
produce the correct drive conditions to put the slave-rotor into lock with
the master rotor. Priority is given to the frequency information to
drive the rotors into frequency lock, and then, when \( F_m = F_s \) the phase
information controls the rotor. If the phase information pushes the rotor
out of frequency lock, the frequency information again dominates. The
control switches \( V_1 \) and \( V_2 \) enable the drive to be applied for a discretely
variable fraction of a sample period, such that a balance can be set.
between the average torque produced when the phase information is dominant, and the average torque when the frequency information is dominant. The frequency torque level adjustment was made by $V_2$ and was found to give the best control when set on 7, while the phase adjuster $V_1$ was best set on 2 or 3 as the phase-lock only required small bursts of torque. The truth table for the drive outputs is shown in Figure 7.20. Switch $T_4$ enables the two outputs to the drive unit to be manually controlled. The manual control for the drive sense is made by $T_3$ and for drive-inhibit by $T_5$. Error counts produced by the frequency scaler are fed to the S-R Flip-Flop composed of $G_{76}$ and $G_{77}$. The setting of this flip-flop inhibits the drive via $G_{78}$. If $T_5$ is set on A, then the inhibit holds until the switch is momentarily set to B, but if the switch is permanently set to B, then the drive will only be inhibited for one sample and will then clear, unless another error pulse is received. These errors can occur for one of two reasons. As previously stated, if the input frequency of the two inputs are so low that the time period $T_1$ or $T_2$ causes the frequency scaler to overflow or underflow, then a count error will be produced ($T_1$ or $T_2 > 5\text{ms}$). The second possible cause of error would be the loss or partial loss of input pulses from one of the inputs. When the two input frequencies are approximately equal, the number of possible torque corrections per sec. is of the order of $F_m/10$.

In the situation when the master rotor and the slave rotor are locked in phase, and both rotors are subject to a constant deceleration or acceleration, with the locked phase condition holding, then the time period $T_2$ sampled at some time later than $T_1$ will give $T_2 - T_1 \neq 0$, even though the rotors have an average difference frequency of zero. This produces
within the unit an error equivalent to a systematic error and is neutralized by the multiplexing. Provided the deceleration is not too large, i.e. less than $2.5 \times 10^2 \text{Hz/ sec.}$ for rotors at $5 \times 10^3 \text{Hz}$, there will be sufficient information to produce frequency control, but for the best phase lock the common deceleration rate must be kept to a minimum. This can be done by simply applying a small torque to the master rotor to reduce its time rate of change of frequency.

Adjustment for locking the slave rotor to the master rotor at any phase difference other than zero has not been built into the unit but it can easily be achieved by changing the number used by the phase comparator to produce the phase word, and the removal of the phase multiplexing gate to the input of the phase scaler $S_4$.

7.4 Results of Phase-Lock Tests.

The phase-lock unit was tested by locking one rotor to a simulated rotor, produced by a frequency standard, stable to $1 \text{ in } 10^9$. This offered the most convenient method of measuring the degree of frequency and phase-lock for various frequencies of a master rotor. The main difference between locking the slave rotor to a frequency standard, rather than a master rotor, is that there is no decrease of the frequency of the standard, which would be present to some small degree with a coasting rotor. Adjustments for this, however, can be made such that the deceleration rate is very slow, by applying a small amount of drive to the master rotor.

Measurements of frequency lock only for rotational speeds of up to $3,500 \text{ revolutions/s.}$ showed frequency locking to better than $5 \times 10^{-2} \text{Hz.}$
No. of samples = 177
Frequency lock only
Rotational frequency 1000rev/
Width of proportional section = 
\[+ 13 \times 10^{-3} \text{ Hz.}\]
Figure 7.22

No. of samples = 224
Frequency and phase-lock
Sample period = 0.5s
Rotational frequency = 1000 rev/s
Average change in phase during sample = 0.054° arc/sample period for a frequency difference of $0.3 \times 10^{-3}$ Hz.
Figure 7.21 shows, in histogram form, the results of many samples of frequency difference when the rotor is frequency-locked. Figure 7.22 shows the degree of frequency-lock when the rotor is phase-locked.

The frequency drift can be used as an indication of the degree of phase-lock. As the frequency difference was measured over a set period of time, 0.5 seconds, the result was an average over this time. Hence this result can be used to determine the average change of phase during the sample. A change of $0.3 \times 10^{-4}$ Hz corresponds to a change in phase of $0.054^\circ$ arc per sample period. Thus the maximum change of phase during a sample period is $0.3^\circ$ arc. This agrees with direct oscilloscope observations of phase difference. The width of the frequency histogram shows that locking is well within the limits of the proportional range of the control unit, as this limit is $\pm 13 \times 10^{-3}$ Hz with input pulses of 1kHz.

The unit was also tested by locking the rotor at 3,500Hz, this corresponding to 1.75km/s, where the control unit was sampling the phase and frequency condition of the rotor 350 times per second. This gave phase-lock to within $1^\circ$ arc, even under conditions of vacuum pressures of $10^{-4}$ torr.

The rotor was locked at 3,000Hz to a standard and was used to produce a beam of mercury atoms. This is described in Chapter VIII. It was necessary to observe its locking behaviour under gas load conditions as it will be under these conditions that the unit must operate. The rotor was producing a beam of approximately $10^{13}$ atoms/s with a power of approximately 5µW and produce locking to less than $1^\circ$ arc.

As yet the unit has not been tested by locking two rotors at high speed but this merely awaits the completion of two high-speed rotors. There seems every reason to believe that it will successfully achieve this.
CHAPTER VIII

EXPERIMENTAL RESULTS AND FUTURE PROSPECTS

8.1 A Successful High Speed Rotor.

After many problems associated with the carbon fibre composite and the bonding of the composite to the rotor boss, a rotor was finally made which, when spun at 4,250 revolutions per second, attained the tip speed of 2 km/s. This had arms and a boss of the design described in Chapter II and a photograph of the rotor is shown in Plate 2.1. Taking into account the breaking strength of the carbon fibre composite, the theoretical breaking speed of this rotor was calculated to be 2.47 km/s. This rotor was safely brought back to rest and showed no physical damage.

A second rotor was made of slightly weaker composite and run to 1.75 km/s and subsequently used to produce a mercury beam, as will be described in the next section.

8.2 Using a High Speed Rotor to Produce a Beam of Mercury Molecules.

Using the 1.75 km/s rotor just mentioned, a simple experiment was undertaken to produce a beam of mercury atoms and measure the velocity distribution.

The single rotor unit was employed and set up as indicated in Figure 8.1, using a beam unit, described in Chapter III, to produce the primary beam of atoms. These were arranged to strike the rotor tip and then evaporate, or possibly bounce, such that the resultant beam travelled freely within the vessel for \(1.34 \times 10^{-1}\) m and then entered a glass tube which served to collimate the beam. At the end of the tube was placed an ionisation gauge, type IG6, which is a vacuum measuring gauge. This
Figure 8.1

Laser beam

Copper screening -30°C

Anode

$7.5 \times 10^{-2} \text{ m}$

$1.2 \times 10^{-2} \text{ m}$

$1.5 \times 10^{-2} \text{ m}$

$13.4 \times 10^{-2} \text{ m}$

$5.7 \times 10^{-2} \text{ m}$

$24.2 \times 10^{-2} \text{ m}$

$30^\circ \text{C}$
consisted of a cylindrical anode and within this a thin wire grid. On the axis of the anode was a tungsten filament and surrounding the whole unit was a copper cylinder, which was cooled and earthed to provide electrostatic screening and some degree of cryogenic pumping through the glass envelope.

Connected to the gauge head was a modified version of the P.I.N. diode amplifier. The modified amplifier merely had the output voltage clamps removed so that the output voltage swing was linear for an applied input current. The circuit diagram for the ionisation gauge is shown in Figure 8.2.

The gauge was calibrated by comparison with another gauge placed within the vessel and connected to a standard vacuum measuring unit. With no rotor running and no cooling applied to the detector, the pressure in the vessel \( \sim 10^{-6} \) Torr was compared with the voltage appearing on the output of the amplifier. The beam detector gauge was operated in the same mode as if it were used as a normal vacuum gauge; thus the output current was directly proportional to the number of nitrogen atoms within the volume of the detector. From this statement, the number of molecules, \( N_d \), within the detector is given by:

\[
N_d = I_d \cdot m
\]  

(8.1)

where \( I_d \) is the current from the detector and \( m \) is the constant of proportionality. This assumes that the number of ionised atoms detected does not change the density of molecules within the detector. Using the manufacturer's literature and comparative measurements using the other ionisation gauge, it was possible to produce a value of \( m \) for nitrogen of \( 1.29 \times 10^{19} \) molecules/detector volume/\( \Lambda \). However, it was necessary
Figure 8.2

Grid

Mercury molecules in.

Filament

Collector

2.2μF

4.7k

-90V

2.2μF

12V DC supply

90V

0-10mA

A
to know the value of \( m \) for mercury, this being deduced by using handbook
data for ionisation cross-sections for Hg and \( N_2 \). These showed that
Hg had twice the ionisation probability of \( N_2 \) and, thus, the above figure
was halved, giving \( m \) a value of \( 6.45 \times 10^{18} \) molecules/detector volume/A.

Now, if molecules of Hg are travelling through the detector with a
velocity \( V \) and, if the detector volume is defined by a cylinder of length
\( L_d \) then in one second a cylinder of molecules of length \( V \) will have to
pass through the detector to produce a current of \( I_d \) lasting one second.
Therefore, the number of molecules which must pass through the detector
in one second must be \( \frac{m \cdot V \cdot I_d}{L_d} \). Thus if a pulse of current of
amplitude \( I_d' \), lasting only for a period of time, \( T \), then the number of
molecules, \( N_p \), within the pulse is given by:

\[
N_p = \frac{V \cdot I_d \cdot m \cdot T}{L_d}
\]  

As the laser beam is positioned such that the time when the molecular
pulse began is known, the time-of-flight can be measured and, hence, by
dividing any given shaped pulse into small squared pulses of length \( \triangle t \)
and height \( I \), the number of molecules \( \triangle A \) of a given velocity within that
range of time \( \triangle t \), can be approximately deduced from:

\[
\triangle A = \frac{I \cdot \triangle t \cdot k}{T_f}
\]

where

\[
k = \frac{m}{L_d} \cdot S
\]

where \( S \) is the distance of flight and \( T_f \) is the time of flight.

The efficiency of the detector was low, of the order of \( 10^{-3} \% \) and
hence noise was a problem and will be discussed later.
PLATE 8.1 Mercury pulses produced by rotor with rotational speed of 1,500 rev/s.
The rotor was run in a vacuum of $10^{-5}$ Torr and the beam unit temperature set on $140^\circ$C. The laser beam was so positioned that the rotor blade intercepted the beam when in a direct line of sight with the detector. This pulse was used for measuring the frequency of rotation of the rotor and also for the time-of-flight measurements. Further to this point, it was used as a reference signal in the Boxcar detector unit discussed later. Next, the rotor was run up to 1,500 revolutions/s, producing a tip speed of 700 m/s. The output from the amplifier is shown in Plate 8.1. The upper frame shows pulses of mercury and below there is the pulse from the laser to show the 'shooting position'. The lower trace shows the output from the amplifier when the rotor is spinning in the wrong direction, but all other conditions being the same as for the upper trace. Plate 8.2 shows mercury pulses produced by the rotor at 3,000 revolutions/s, equivalent to a tip speed of 1.4 km/s. As will be seen from the photographs, the signal to noise ratio is approximately 2:1, making it very difficult to obtain useful information directly from these photographs. However, the noise can be substantially reduced by the use of a linear gate with integration, combined with a triggerable delay sweep generator, to form a Boxcar detector, a brief description of which will follow.

The Boxcar detector can be used to reduce noise in any signal provided the signal is periodic and some reference signal can be produced at the same repetition rate. The reference signal needs to be fairly noise-free, but the actual shape of its waveform is not important. This reference signal is used to trigger a pulse with an adjustable width, which can be made to occur at some delayed period after the trigger point.
PLATE 8.2  Mercury pulses produced by rotor with rotational speed of 3,000 rev/s.
Figure 8.3

Path length equals
2.42 x 10^{-1} m

\( t = 1.666 \times 10^{-4} \text{ s} \)
This delay can be set as a constant or it can vary as a linear function of time. It is in this latter state that the unit is operated. Thus, a pulse occurs at some time-delay after the reference pulse and this delayed pulse then occurs at a steadily increasing time-delay with respect to the reference. This pulse is then used to open the linear gate and allow the noisy signal to be fed into an integrator. The width of the pulse is much less than the repetition of the waveform and hence the gate opens for a very short time and samples only a very small part of the waveform. Also, the period of the delay only varies slowly with time; therefore, the position on the noisy waveform, where the gate opens, only moves slowly along it. Hence, each point on the noisy waveform is sampled and integrated many thousands of times, so that the noise is substantially removed. Noise is any signal that appears with the required signal, which is not periodic with the reference signal.

The output from this unit was fed to a graph plotter and over a period of 15 minutes the waveform was scanned and 'cleaned up'. The output is shown in Figure 8.3. The waveform was then measured and calculations made of the number of atoms within a given velocity band (Figure 8.4) and the number of atoms within a given energy band (Figure 8.5).

From simple considerations given in Chapter I, one would not expect molecules within the beam to have a velocity less than the tip speed. However, it will be seen from Figure 8.4 that molecules possess the speed of the rotor tip plus and minus the thermal velocity for a rotor at about 370°K. This can be partly explained by the molecules coming from an area of the rotor blade, where the speed is less than the tip speed. As the
Figure 8.4  Graph of number of atoms/pulse unit velocity bin as a function of velocity for H₂ molecules.

Rotational Rotor speed = 3,000 rev/s
Total no. of molecules per pulse = 2.4 x 10⁹
Figure 8.5  Graph of number of atoms per unit energy per pulse as a function of energy for H₂ molecules.

Energy of a molecule travelling with rotor tip speed

Rotational rotor speed = 3,000 revs/s.
Total number of atoms per sec. = $1.43 \times 10^{13}$
Total energy of beam per sec. = $4.5 \mu W$ (after collimation)
acceptance angle of the beam collimation will only allow a 6mm length of the rotor blade from the tip to be in a line-of-sight with the detector, this is not sufficient to produce an effect of this magnitude. Another possibility is that the collected mercury molecules on the rotor tip do not only lie on the leading curve of the cone but, due to surface diffusion, some reside on the flat truncated tip of the rotor blade. This means that molecules leaving the tip could have speeds of plus or minus the thermal speed of the molecules in addition to the tip speed. Observation of the oscilloscope photographs and the Boxcar-processed signal shows no sign of elastic collisions between the rotor arm and mercury molecules.

The beam intensity was approximately $5 \times 10^{15}$ molecules/sr/s but this would increase with higher rotational speeds and also by changing the shape of the tip as outlined in Chapter II. The rotor was used to produce this beam for a continuous period of six hours and after this observation of the rotor tip indicated that the fast molecular collisions of the mercury with the arm had not damaged the fibres or the resin at the rotor tip. The inside surface of the beam detector was found to be covered in a thin metallic layer, which appeared to be mercury. The surface was not uniformly covered but tended to have the thickest layer where the copper cooling jacket was in good contact with the glass envelope over a sizeable area.

The experiment to observe the effect of mercury-mercury collisions has not as yet been performed due to material problems. These are not fundamental and therefore the experiment should be possible as outlined in Chapter III. The optical resonance which it is hoped to excite is the so-called forbidden transition $^3P_1 \rightarrow ^1S_0$, which gives a wavelength
of 253.7nm. Thus the reaction would be of the form:

\[ \text{Hg} + \text{Hg} \rightarrow \text{Hg}^* + \text{Hg} \rightarrow \text{Hg} + \text{Hg} + hV \]

As the value for the cross-section for this resonance is not known, it is difficult to know the degree of sensitivity required for the photon-counting system. However, cooling of the photo-multiplier cathode is provided to reduce the dark current and the general light background can be reduced by using U-V transmission filters.

8.3 Conclusions.

The results which have been achieved during the last three years indicate that rotors are a practical proposition for producing molecular beams with energies between 1 and 10eV. The techniques used for making the rotors and the control electronics have proved reliable. The equipment built during this time is to be transferred to the Department of Chemistry, where modified apparatus will be built and rotors used to study the chemical properties of molecules. Also, at Heriot-Watt University carbon fibre rotors are to be used to investigate molecule surface phenomena.

The principles are simple and the apparatus is less costly in manpower and finance than alternative methods. However, the enormous forces created by high speed rotation require great precision in manufacture and assembly of the rotors if they are to be used with confidence in the future. Yet it would seem that rotors, and carbon fibre-armed rotors in particular, have a future as molecular beam producers.
CHAPTER IX

SUPPLEMENT TO THE THESIS

The following work does not constitute a part of the thesis but is a supplement to conclude the work presented within it. This work was accomplished by the author in the period between the submission of the thesis and the oral examination.

M. P. Ralls.
9.1 Introduction.

The following work was carried out mainly by the author and is divided into three sections: firstly, the testing of the rotor synchronization electronics using two high-speed rotors; secondly, the colliding mercury beam experiment, in which it was hoped to excite atoms of mercury and observe the 253.7 nm intercombination line; and, thirdly, a re-examination of the velocity-intensity results produced by the single rotor experiment.

9.2 Rotor Synchronisation.

After some delay, two rotors were accelerated in the double rotor apparatus, which has already been described in Chapter III. The rotors had previously been individually tested to a rotational speed of 3,750 rev/s. The purpose of this double rotor acceleration was to ascertain the effectiveness of the phase locking electronics described in Chapter VII. The electronics had already been tested using one rotor and a frequency standard, but this could not be made to simulate two phase-locked, slightly decelerating rotors.

The mercury ovens were run at a temperature of 140°C producing a vessel pressure of $10^{-5}$ Torr, and hence a gas load on the rotors. The rotors were first locked at 1,000 rev/s and then at 2,300 rev/s. Both attempts were completely successful and produced an approximate R.M.S. phase lock of 1.5° arc. Following this successful locking, the rotors were deliberately un-locked and re-locked several times to enable observations to be made of the damping characteristics of the control system. There appeared to be no significant phase overshoot, indicating sufficient damping. The relative phase condition of the two rotors was
Figure 9.1 Arrangement of Apparatus Scale 0.5

Rotor A  Laser Beam for radial detector

Collision volume

Rotor B  Laser Beam for radial detector

Detector B

Detector A

1.8 x 10^{-2} m

37.8 x 10^{-2} m

10.8 x 10^{-2} m

35.2 x 10^{-2} m
observed oscilloscopically using pulses derived from the interrupted laser beams.

The rotors were also run and phase-locked when performing the colliding beam experiment to be discussed in Section 9.3. In this case the rotors were accelerated to a rotational speed of 3,600 rev/s and were phase-locked. The phase-lock was established as easily as at the lower speeds but the phase wander was slightly smaller at the higher speed.

9.3 The Colliding Beams Experiment.

9.3A Introduction.

The colliding-beam experiment outlined in Chapter III and Chapter VIII was attempted using two conical, carbon fibre composite rotors of the same design as those used in the production of a mercury beam described in Chapter VIII. The object of the experiment was to convert the kinetic energy released in a head-on collision of two Hg atoms to excite one into the $^3P_1$ state, and hence observe the singlet-triplet inter-combination line at 253.7nm.

9.3B Apparatus.

The physical layout of the components is shown in Figure 9.1. The photomultiplier (P.M.) was mounted as in Figure 3.2. Unfortunately it was not possible to use the end-window P.M. as described in Chapter III due to its failure and so this was replaced by a side-window version, type IP28 with a quantum efficiency of 20% at 254nm. As a result of the P.M. having a side window, it was not possible to mount it in direct contact with the spectrosil light pipe. This meant that there was a space of 15cm between the P.M. and the light pipe, thus significantly reducing the solid angle of the detecting system. A further undesirable feature of
Figure 9.2  Spectral Response of Ultra-Violet Transmission Filter
Figure 9.3

Detector A

Collector

Detector B

Filament

Grid + 90 V

2.2 μF

90 V

2.2 μF

Rotor B

Rotor A

Oscil.

Timebase Trigger

Rotor A

8 V

B

A

A

B

2

4.7 k

0-10 mA

9.0 V

V c I

V

A

Rf
this was that the cathode of the P. M. could not be cooled and hence the background count rate from the P. M. was limited by the dark current. Between the light pipe and the P. M. was placed an ultra-violet transmission filter with a spectral response shown in Figure 9.2. This had a transmission of 35% at 254nm. Taking the geometry of the system into account, in addition to the above factors, the arrangement had an optical detection efficiency of 0.0056%, compared with 0.22% for the original arrangement.

Beam monitors were wired up as shown in Figure 9.3. Either of the beam monitors could be selected for displaying the pulses from a given rotor, by switching the relevant heater-current on and hence producing an ionising electron current. The output from the current amplifier was fed to an oscilloscope which was triggered by the radial detector of the relevant rotor. Thus it was possible to check that the observed pulses were phase-locked to the rotor which was producing them.

A schematic diagram of the photon-counting circuit is given in Figure 9.4. During a measurement period, scaler $S_1$ would count pulses from the P. M. continuously while scaler $S_2$ only counted photons when the gate input allowed. The signal for the gate input was derived indirectly from a pulse which was produced when the two rotors were in phase (blades parallel) and hence in a shooting position. To produce this gate pulse the in-phase pulse was fed to a variable time delay unit and lengthened before being fed to the gate input. Thus a pulse would activate scaler $S_2$ some pre-set time after the rotor blades were parallel. The set delay interval could be adjusted by integral steps of $1/7.6$ of the period between successive in-phase pulses. These delayed pulses were
Figure 9.4

- Photomultiplier
- Amp.
- Descrim.
- Variable Delay Unit
- Gate Width Adjust
- Gate
- Scaler S₂
- Scaler S₁
- T₁
- Rotor Pulses
- In phase pulses
- Oscil.
then lengthened to 1/7.6 of this time period and fed to the gate input of scaler $S_2$. Thus when switch $T_1$ is closed, assuming the photon flux to be constant, the count/unit time produced in scaler $S_1$ should be 7.6 times the count in scaler $S_2$. However, should an increased number of photons arrive at the P.M., to coincide with the time that $S_2$ is counting and should this occur consistently, then the ratio of $S_2/S_1$ would show an increase value compared with that produced when these are not correlated.

In this way it was possible to observe the photons collected from the collision volume at various times after the production of the beams. If during a period of time comparable with the gate pulse, there was an increase of $\Delta N$ counts in the number of photons detected and $N$ was the number of non-correlated photons counted by $S_1$ between two successive parallel blade positions, then after $(M + 1)$ parallel blade positions, scaler $S_1$ will have counted $M(N + \Delta N)$ and scaler $S_2$ will have counted $M(N P_s + \Delta N)$. $P_s$ is the average ratio of $S_2/S_1$, when $\Delta N = 0$, this being equal to the gate width of the pulses fed to scaler $S_2$ divided by the period between successive gate pulses fed to scaler $S_2$. For large $M$ the ratio of counts collected by $S_2$ divided by counts collected by $S_1$, $P_s$, is given by:

$$P_s = \frac{N P_s + \Delta N}{N + \Delta N}$$  \hspace{1cm} (9.1)

9.3C Results.

The rotors were accelerated to an angular velocity of 3,600 rev/s.

The beam detector filament for rotor A was turned on and the output from the current amplifier was displayed on the oscilloscope with the time base triggered by radial pulses from rotor A. At this stage the rotors were
not synchronised. With an electron ionisation current of 5mA, small pulses could be seen above the noise locked to the timebase, but the pulses were too small to allow sensible measurements to be made. The primary beam units were at a temperature of $140^\circ C$ comparable with the temperature used in the single Hg beam experiment. Observation of rotor B pulses with the timebase locked to radial pulses from rotor B yielded similar results. However, when detector pulses were displayed with the timebase triggered by the other rotor's radial pulses, there was no observable waveform locked to the timebase. This indicated that pulses of atoms were, in fact, being produced by the rotors and were travelling through the collision volume. The size of the pulses could be attributed to the distance the beams had to travel and the fact that the beam had to pass above the other rotor's mercury vent and possibly through a volume of relatively high pressure where the chances of collision were increased.

The rotors were then synchronized using the phase-locking electronics described in Chapter VII. Lock was maintained to within 1.5° arc. The beam unit filaments were turned off to prevent light entering the collision volume. For a given delay time the scalers were allowed to count for 60s and then the delay increased until 7 delay periods had been used to sample the ratio of scaler $S_2$/scaler $S_1$. The scaler counts are shown in Figure 9.5 and the ratios shown in Figure 9.6. Figure 9.7 is a histogram showing the ratios as a function of delay time. The marked bin denotes the delay time which would be expected to have a greater ratio than the others if photons were produced by the return of excited Hg atoms from the $^3P_1$ state to the ground state.
<table>
<thead>
<tr>
<th>Average Delay of Bin $\mu$s</th>
<th>$S_1$</th>
<th>$S_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1</td>
<td>38,191</td>
<td>4,901</td>
</tr>
<tr>
<td>27.3</td>
<td>40,276</td>
<td>5,357</td>
</tr>
<tr>
<td>45.5</td>
<td>40,097</td>
<td>5,303</td>
</tr>
<tr>
<td>63.7</td>
<td>84,069</td>
<td>11,079</td>
</tr>
<tr>
<td>81.9</td>
<td>41,818</td>
<td>5,403</td>
</tr>
<tr>
<td>100.1</td>
<td>42,966</td>
<td>5,666</td>
</tr>
<tr>
<td>118.3</td>
<td>38,400</td>
<td>5,078</td>
</tr>
</tbody>
</table>

Figure 9.5

<table>
<thead>
<tr>
<th>Average Delay of Bin $\mu$s</th>
<th>$S_1/S_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1</td>
<td>0.1283</td>
</tr>
<tr>
<td>27.3</td>
<td>0.1330</td>
</tr>
<tr>
<td>45.5</td>
<td>0.1322</td>
</tr>
<tr>
<td>63.7</td>
<td>0.1318</td>
</tr>
<tr>
<td>81.9</td>
<td>0.1292</td>
</tr>
<tr>
<td>100.1</td>
<td>0.1318</td>
</tr>
<tr>
<td>118.3</td>
<td>0.1322</td>
</tr>
</tbody>
</table>

Figure 9.6
The results shown in Figure 9.7 show no obvious effect, as the delay of the observation time-window is increased. The adjusted standard deviation for the ratios $S_2/S_1$ is $1.75 \times 10^{-3}$. This compares favourably with a standard deviation of $1.76 \times 10^{-3}$ calculated using random counting fluctuations expected from counting typically 5,000. Using the criterion of a statistically significant ratio being greater than $3\sigma$, from the mean of all the ratios, where $\sigma$ is the standard deviation, there are no bins which produce a significant result. However, it is of interest to know how many photons, emitted during every beam interaction, would be needed to produce a ratio which would be greater than $3\sigma$. If $P_s$ is the observed ratio in one bin and $\bar{P}_s$ is the average ratio of all the bins, then the ratio will be significant if:

$$P_s \geq \bar{P}_s + 3\sigma$$  \hspace{1cm} (9.2)

Combining this with equation 9.1 to give the minimum number of detected events/beam interaction, $\Delta N$,

$$\Delta N \geq 3\sigma' \frac{N}{[1 - (\bar{P}_s + 3\sigma')]^{-1}}$$  \hspace{1cm} (9.3)

With the rotors rotating at 3,600 rev/s this gives 7,200 beam interactions/s. The dark current counting-rate was determined when the rotors were spinning at much slower speeds and gave a count-rate of 660 counts/s. Using this and knowing the period between successive parallel blade positions and the values of $\bar{P}_s$ and $\sigma'$, a minimum count of $5.57 \times 10^{-4}$ events/beam interaction would be necessary before they could be considered significant. However, the optical collection system was only 0.0056% efficient and hence the minimum number of events/beam interaction must be increased to 9.85 events/beam interaction.
Figure 9.7  Graph of delay time from parallel position against scaler Ratio $S_2/S_1$
The results of this experiment can be used to arrive at an approximate upper limit for the cross-section for the excitation and decay of the 253.7nm intercombination line of Hg. Firstly it is necessary to estimate the sensitivity of the detection arrangement and this has been achieved in the previous section. Secondly, it is necessary to estimate the number of atoms in each pulse. Unfortunately the beam detectors were not sensitive enough to enable accurate measurements to be made of the beam characteristics. However, the temperature of the ovens was comparable with the temperature of the oven used in the single mercury beam experiment, as was the vessel pressure. The design of the rotors was the same and so it is reasonable to use the beam characteristics measured in the single beam experiment to estimate the characteristics of the beams in the double experiment. The data produced by the single rotor experiment does, however, require a small modification before it is reasonably compatible with the double rotor experiment. The results given in Chapter VIII were taken for a rotor rotating at 3,000 rev/s while the double rotor experiment was performed with rotational speeds of 3,600 rev/s. Thus the results of the single beam experiment shown in Figure 9.8 have to have a constant velocity added to them in order that they should be reasonably compatible with a rotor of the same radius rotating 600 rev/s faster. With reference to Figure 9.8, the 5eV threshold for the reaction is just exceeded by bin 6. Bins 1 and 2 contain only a relatively small number of atoms and hence, with the contents of bins 1 and 2 added to bin 3, each beam can be considered to be a uniform beam with a velocity spectrum ranging from 1.813 km/s to 1.55 km/s. Thus the total number of atoms/pulse is approximately
Figure 9.8  
Results of Single Rotor Hg Beam exp.  
with rotor at 3,000 rev/s

<table>
<thead>
<tr>
<th>Bin No.</th>
<th>Velocity Range km/s</th>
<th>Number of Atoms in Bin x 10^8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.22 - 2.02</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2.02 - 1.85</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1.85 - 1.71</td>
<td>0.16</td>
</tr>
<tr>
<td>4</td>
<td>1.71 - 1.59</td>
<td>1.12</td>
</tr>
<tr>
<td>5</td>
<td>1.59 - 1.48</td>
<td>3.36</td>
</tr>
<tr>
<td>6</td>
<td>1.48 - 1.39</td>
<td>5.58</td>
</tr>
<tr>
<td>7</td>
<td>1.39 - 1.31</td>
<td>5.72</td>
</tr>
<tr>
<td>8</td>
<td>1.31 - 1.23</td>
<td>3.89</td>
</tr>
<tr>
<td>9</td>
<td>1.23 - 1.17</td>
<td>2.03</td>
</tr>
<tr>
<td>10</td>
<td>1.17 - 1.11</td>
<td>1.03</td>
</tr>
<tr>
<td>11</td>
<td>1.11 - 1.06</td>
<td>0.53</td>
</tr>
<tr>
<td>12</td>
<td>1.06 - 1.01</td>
<td>0.26</td>
</tr>
<tr>
<td>13</td>
<td>1.01 - 0.966</td>
<td>0.11</td>
</tr>
<tr>
<td>14</td>
<td>0.966 - 0.926</td>
<td>0.04</td>
</tr>
<tr>
<td>15</td>
<td>0.926 - 0.889</td>
<td>0.007</td>
</tr>
<tr>
<td>16</td>
<td>0.889 - 0.854</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>0.854 - 0.822</td>
<td>0</td>
</tr>
</tbody>
</table>
equal to $2 \times 10^9$ with an average velocity of $1.68 \text{ km/s}$. As this beam travels from the 'shooting position' to the collision volume, a distance of $1.08 \times 10^{-1} \text{ m}$, the beam will spread out along the flight path, such that the time taken by the fastest molecules to reach the centre of the collision volume will be $59.5 \mu s$ and in this time the slowest molecules will have travelled $9.225 \times 10^{-2} \text{ m}$. Thus the length of the pulse is approximately $1.6 \times 10^{-2} \text{ m}$. Using this information it is possible to conclude that the interaction time is about $10.1 \mu s$ and this interaction will occur $64 \mu s$ after the parallel blade position. The total number of atoms in each pulse is approximately $2 \times 10^9$. This is the number of atoms detected in the single rotor experiment where the detector presented a solid angle of $0.0031 \text{ sr}$. However, in the double apparatus the collision volume had a solid angle of $0.0218 \text{ sr}$ relative to the shooting position. It would be reasonable to scale up the number of atoms detected in the single rotor experiment by the ratio of these solid angles, provided the beam produced by the rotor expanded into a greater solid angle than the collision volume. The solid angle into which the atoms from the tip expand is approximately given by $\pi \frac{V_T^2}{V_R^2}$ where $V_T$ is the thermal speed and $V_R$ is the rotor tip speed. This produces a beam solid angle of approximately $0.1 \text{ sr}$; thus it is valid to scale up the number of atoms/pulse entering the collision volume by the factor 7, giving $1.4 \times 10^{10}$ atoms/pulse.

Considering two cylindrical volumes of atoms of length $L_p$ with a cross-sectional area, $A$, travelling towards one another, as in Figure 9.9, if they both enter the collision length, $X_c$, at the same instant, then the pulses will begin the interaction at a point $X_c/2$ along the collision
Figure 9.9  Simplified form of the Hg pulses

\[ L_p = 1.566 \times 10^{-2} \text{ m} \]

\[ A = 2.5 \times 10^{-4} \text{ m}^2 \]

\[ N_p = 1.4 \times 10^{10} \text{ atoms} \]

\[ X_c = 1.8 \times 10^{-2} \text{ m} \]

\[ v = 1.68 \text{ km/s} \]
length and the two volumes will then move through one another and separate at $X_c/2$. Provided the length of the pulses, $L_p$, is shorter than $X_c$, the detection system observing all the distance $X_c$ will observe all parts of the interaction. This was the case in the colliding beams experiment and hence the P.M. was capable of observing the whole interaction. The volume of the pulse was $L x A_p$ and the probability of an atom from pulse A interacting with an atom from pulse B is given by $1 - \left( \frac{\sigma}{A} \cdot N_p \right)$, where $\sigma$ is the cross-section for the interaction and $N_p$ is the number of atoms/pulse. As the probability of an interaction is very small in this case for the excitation and emission of the intercombination line, $e^{-\left( \frac{\sigma}{A} \cdot N_p \right)}$ is very close to unity and hence the probability of interaction is given approximately by $\sigma N_p / A$. This means that, if there are less than $\Delta N$ observed interactions, then the cross-section for the interaction will be:

$$\sigma < A \cdot \frac{\Delta N}{N_p^2} \quad (9.4)$$

The cross-section area ($A$) of the beam, which is equal to $2.5 \times 10^{-4} \text{ m}^2$, is governed by the diameter of the collision volume. Using the minimum detectable count required to produce a statistical result of 9.35 photon events/pulse interaction and the estimate of the number of atoms/pulse of $1.4 \times 10^{10}$, an upper limit of the cross-section for the excitation by collision of the $^3P_1$ state and return to the ground state by emission of a 253.7nm photon, can be calculated, this being equal to $1.27 \times 10^{-23} \text{ m}^2$. If the radius of a mercury atom in a metal or non-ionic solid is used to estimate the geometric cross-section, then the ratio of the cross-section for collisional excitation and decay mentioned above, to the geometric cross-section yields a factor of $5 \times 10^{-5}$. 
9.3D Summary and Conclusions.

The experiment was hoped to give some information about the head-on impact of two Hg atoms, both being in the ground state. As the atomic collision was produced by atoms with the same speed but opposite direction, all of the kinetic energy of the pair could be used to energize some type of excitation. The characteristics of the colliding beams were that each beam pulse had an average speed of 1.68 km/s relative to the laboratory, with a result that the average available reaction energy/atom pair was 5.84eV. In the event of a two-beam collision, the first interactions would occur between the fastest members of the two pulses, giving a reaction energy of 6.88eV/Hg$_2$; this being equivalent to 660kJ/mole. Later collisions would involve lower available reaction energies until the lowest energy interaction of 5eV/Hg$_2$, equivalent to 480kJ/mole, would take place between the slowest members of the pulses.

Of the approximately $2.3 \times 10^5$ interactions that took place during one pulsed beam interaction, calculated using the geometric cross-section, less than 10 of these resulted in the emission of the 253.7nm intercombination line, even though the available energy for each interaction was above the threshold of 4.9eV. Therefore, it is necessary to consider some of the other routes of the interaction. The two ground state ($^1S_0$) Hg atoms could simply collide and form the molecular state $^10_g$ (see Figure 9.10). This would not produce a bound state, but would dissociate very shortly after the initial impact. The potential energy, built up as the two atoms became closer together, would then be re-converted to kinetic energy and hence this interaction would be purely elastic. This process is likely to be the most dominant of the
B was the highest attainable point on the potential energy curve.

* Possible extension of the $^1_{0^+}$

Figure 9.10  Potential energy curves for some of the lower energy states of Hg$_2$
interactions. However, during the formation of the $^{10}_{g}$ state, the molecular state may intersect with one of the following triplet states $^{3}_{2}_{u}$, $^{3}_{1}_{u}$ or $^{3}_{0}_{u}$. If the potential energy of the ground state pair does not quite reach the crossing points, or if the curves do not actually cross but come very close to one another, there is a possibility, restricted by selection rules, of tunnelling between the states, such that $^{10}_{g}$ transfers to $^{3}_{2}_{u}$, $^{3}_{1}_{u}$ or $^{3}_{0}_{u}$. The singlet - triplet restriction is relatively weak compared to the $g - u$ selection rule. The change from a symmetric wave function, when the interaction is homo-nuclear, to an anti-symmetric result is very strongly forbidden unless the symmetry of the interaction can be broken. One possibility is to have a three-body collision which will allow a radiationless transition from a $g$ to a $u$ state, but this is a very unlikely occurrence. A second possible reason for a breakdown in this selection rule is that the collision of the two-body system is not completely homo-nuclear. The two atoms may not be identical due to isotope effects. In particular, mercury has seven stable, naturally occurring isotopes of which six have abundances greater than 6.5%. Thus, the chances of a homo-isotopic collision are small and hence the collision is not strictly homo-nuclear. However, the effect on the $g - u$ selection rule of lowering the symmetry of the interaction is difficult to estimate.

Once in the new molecular state, there can still be no bonding as the potential energy of the pair is greater than the dissociation energy and, hence, the molecule dissociates to form two unbound atoms, but one of the atoms will not now be in the ground state. Depending on which
Figure 9.11 Possible reaction routes.

\[ \text{Hg} \left( ^1S_0 \right) + \text{Hg} \left( ^1S_0 \right) + \text{KE} \]

\[ \text{hv} 184.9 \text{nm} \]

\[ \text{Hg} \left( ^1S_0 \right) + \text{Hg} \left( ^1S_0 \right) \]

\[ \text{hv} 550 \text{nm} \]

\[ \text{Hg}_2 \left( ^3S_u \right) \]

\[ \text{hv} 485 \text{nm} \]

\[ \text{Hg}_2 \left( ^3S_u \right) \]

\[ \text{Hg} \left( ^1S_0 \right) + \text{Hg} \left( ^3P_1 \right) \]

\[ \text{hv} 253.7 \text{nm} \]

\[ \text{Hg} \left( ^1S_0 \right) + \text{Hg} \left( ^1S_0 \right) \]
of the three molecular states, $^3_2 u$, $^3_1 u$, or $^3_0 u$, the molecule has changed to, one of the unbound pair will be in the $^3 P_2$, $^3 P_1$, or $^3 P_0$ state respectively. The atomic states $^3 P_2$ and $^3 P_0$ are forbidden, to decay by electric dipole radiation to the $^1 S_0$ state and these, if they are formed, would most likely be brought to the ground state by collisional deactivation. This process could also de-activate the $^3 P_1$ state and prevent the radiative decay to the $^1 S_0$ state. While it is a triplet-singlet transition, it is not as strongly forbidden as the $^3 P_2$ and the $^3 P_0$ transition and, hence, if the average time before a collision is greater than the lifetime of the state ($1.06 \times 10^{-7}$ s), then $6s^1, 6p^1, \quad ^3 P_1 \rightarrow 6s^2, ^1 S_0$ by the emission of a 253.7 nm photon.

Another possible decay mode is by molecular vibrational band emission. This is a transfer from one of the vibrational levels in the $^3_2 u$, $^3_1 u$, or $^3_0 u$ states, to any other, energetically lower level of these three. This is a fairly unlikely decay route as the time spent in the vicinity of the potential well would be much less than the typical lifetime of the level (1 ms).

It was possible in a few cases, where the available energy of the two, colliding atoms exceeded 6.67 eV, that the molecular state $^1_1 u$ could be formed, which would mean that after separation, one of the pairs would be in the $^1 P_1$ state and thereafter emit the 1.849 nm line with a radiative lifetime of 1 ns. This U-V line would have been absorbed by the oxygen in the air and hence would not have been detected. A diagram of the decay routes is given in Figure 9.11.
This was a fairly simple experiment which, while it needs to be performed with greater sophistication, highlights the possible use of double rotors to observe atomic/molecular interactions.

9.4. Simple Mercury Beam Analysis.

9.4.A. Re-Measurement of the observed data.

When the mercury pulses shown in Chapter VIII, Figure 8.3, were first analysed, the time axis was divided into equal intervals. This made it possible to determine how many atoms arrived in the detector within a flight time from \( t \) to \( t + \Delta t \). These results were then converted into velocity ranges, which inevitably led to unequal width velocity intervals see Figure 8.4., and the need to normalize each bin height to take account of the varying width. This type of plotting also meant that the number of bins/unit velocity range varied as the bin velocity increased and hence, there was a loss of information concerning the shape of the pulse at the higher velocities. In view of these limitations, the author decided to re-measure the results shown in Figure 8.3. such that the time-axis was divided into twenty bins, which gave 20 velocity bins of equal width of 50 m/s. Figure 9.12 shows a histogram of the re-measured pulses. The mercury pulse shows a peak at a velocity of 1.36 km/s, which can be compared to an absolute tip velocity of 1.42 km/s. The error on the velocity-axis is approximately \( \pm 4\% \), the main contribution being due to the uncertainty in the position along the flight path within the detector, where a molecule is ionised and collected. The pulse appears to have a high degree of symmetry about its maximum, which is surprising in view of the method of producing the pulse.
Figure 9.12.A. Velocity profile of the Single Hg Beam Experiment using equal sized velocity bins.
9.4.B. Simple Pulse Shape and Position Considerations.

If the rotor position for emission is simplified such that the rotor arm is perpendicular to the line joining the tip of the rotor to the detector, then the time taken by any molecule to reach the detector will be inversely proportional to the velocity imparted to it by the rotor arm, added to the component of thermal velocity parallel to the flight path. Taking into account the apparent symmetry of the observed pulse and this last point, the author considered a Gaussian curve as a fit to the shape of the pulse. A possible explanation for the apparent Gaussian shape is revealed if one considers the function produced by taking a volume of gas and resolving all the molecular velocities along one axis. This gives the familiar result that the number of molecules within the velocity range \( V_x \rightarrow (V_x + \Delta V_x) \) is proportional to \( e^{-\frac{mV_x^2}{kT}} \), which has its maximum centred on \( V_x = 0 \). Relating this to the shape of the re-measured pulses suggested that the observed pulse was the result of displacing all the \( x \)-components of velocity by an amount comparable to the tip-speed of the rotor. Also, the width of the pulse agreed with that which would be expected from a gas at a temperature of 400\(^{\circ}\) K, which is compatible with earlier measurements of rotor-body temperature.

Initial ideas on the rotor-produced gas pulses suggested that the molecules would leave the advancing face of the rotor with a velocity distribution that resembled a displaced Maxwellian speed distribution, namely a displaced exponential term multiplied by a velocity function.
However, this would have the effect of shifting the maximum of the pulse to higher speeds compared with a simple displaced Gaussian and would also destroy the symmetry of the pulse. On the other hand, emission from the back face would also produce another peak, slower than the rotor tip, thus producing an overall distribution with two peaks separated by about 360 m/s, this being twice the value calculated using the "most probable speed" for a simple Maxwellian speed distribution given by

\[ \sqrt{\frac{2kT}{m}} \]

It would be possible to fill the space between the peaks and thus make it appear as one pulse, but this requires very elevated temperatures.

In Chapter VIII is discussed the possibility of the mercury atoms moving to the very tip of the rotor arm and evaporating. Under these circumstances, one could expect a Gaussian distribution centred on the tip velocity. However, the tip speed was 1.42 km/s while the pulse peak lies at 1.36 km/s. The difference between these two velocities can barely be accounted for by the 4% measurement error. It may not be necessary to assume that the emission is from the very tip, but at some point, 2-3 mm, displaced from the tip, the emission mimics a gas cloud.

When the rotor tip is travelling with a speed of 1.4 km/s and is passing through a gas at a low pressure, \( \sim 10^{-5} \) torr, it could be considered to be comparable with a space vehicle re-entering the upper atmosphere. At this pressure, the mean free path is many metres, but the velocity of the tip is about four times the speed of sound and
hence, it may be possible for the gas just in front of the advancing edge of the rotor to be compressed and produce an effect similar to the compression wave produced by supersonic objects in normal pressures. However, as the pressure is lower than atmospheric by several orders of magnitude, the degree of the compression will be considerably reduced. The fact that the mean free path would appear to be longer than the dimension of the apparatus does not preclude the possibility of local, relatively high pressure areas existing within the vessel, especially as the diameter of the rotor is comparable with the diameter of vacuum vessel. Therefore, the observed pulse may be a small part of a shock wave produced by the rotor blade, from the general gas within the rotor vessel.

The author attempted to refine the comparison between the displaced Gaussian and the observed pulse by producing a simple, mathematical model and least-squares-fitting it to the observed pulse. This model consisted of two parts, the first being simply a re-write of the Gaussian function, such that the Gaussian was displaced. The resultant equation then gives the number of atoms within the velocity range \( V_x \to V_x + \Delta V_x \), accelerated as a result of some interaction with a very small area of the rotor arm, proportional to \( e^{-\frac{m}{kT}(V_x - V_R)^2} \Delta V_x \), where \( V_R \) is the speed of that point on the rotor arm which was responsible for the acceleration of the molecules. The second part attempts to account for the possibility that at different distances from the tip the number of molecules available for acceleration may change. The criterion which defines the form of the function of proportionality was based
on the fact that whatever the nature of the molecule/arm interaction, it is likely to be one in dynamic equilibrium and hence, the number of atoms leaving any small area of the arm per rotation is equal to, or at least proportional to the number collected per rotation. This produces a simple function of proportionality of \( 2 \pi \Delta x (mx + c) x \), where \( x \) is the distance from the centre of the rotor to the element of the arm, which is of length \( \Delta x \) and height governed by the profile function of the rotor arm. This expression represents the volume swept out by the element \( \Delta x \), during one rotation of the rotor arm. Thus, for each element of the rotor arm extending a few millimetres from the tip, there corresponds a displaced Gaussian curve. To re-create the shape of the pulse produced by the above expressions, it is necessary to perform a convolution of them. This was done using a computer to perform a numerical convolution. The result was then normalized, requiring that the number of molecules in the model pulse be equal to the number of molecules in the observed pulse. Once this had been done, the curve was compared with the observed pulse using a "least-squares" criterion. Two variables were adjusted in the convolution exercise to produce the best fit. These were the temperature of the gas, \( T \), and the effective length of the arm that the detector would have been able to "see". The best fit is shown in Figure 9.12 C., while Figure 9.12 B, is a smooth curve drawn through the histogram. The "best fit" was produced with a value for \( T \) of 405°K and an effective length of 5.9 mm. These values are quite compatible with previous expectations of temperature and of geometry of the detection system. The positions of the two centroids for the
Figure 9.12.B. Velocity profile of observed pulse
Centroid at $X = 1.358 \times 10^3$ m/s
$Y = 2.58 \times 10^6$

Figure 9.12.C. The pulse produced using the model.
Figure 9.12.C. The pulse produced using the model.

Centroid at
\[ \bar{X} = 1.361 \times 10^3 \text{ m/s} \]
\[ \bar{Y} = 2.59 \times 10^6 \]
two curves also show a high degree of correspondance. While this model may seem rather simplistic, the correspondance suggests that it is worthy of consideration.
This is the end of the supplement to the thesis.
APPENDIX 1

Derivation of counting probability for digital drive unit
(See Chapter VII)

\[ T_1 = (n - 1)T_c + \frac{1}{P_n} T_c \quad \text{for } nT_c > T_1 > (n-1)T_c \]
\[ T_2 = nT_c + \frac{2P_{(n+1)}}{T_c} \quad \text{for } (n+1)T_c > T_2 > nT_c \]

Therefore:
\[ T_2 - T_1 = T_c \left[ \frac{2P_{(n+1)}}{T_c} - \frac{1}{P_n} + 1 \right] \]

Also:
\[ T_2 - T_1 = 9 \left[ \frac{1}{F_s} - \frac{1}{F_m} \right] \]

And if \( F_s \sim F_m \), then:
\[ T_2 - T_1 = \frac{9 \Delta F}{F^2} \]

where \( \Delta F = F_m - F_s \) and \( F = F_s \) or \( F_m \)

Therefore:
\[ \Delta F = \frac{F^2 T_c}{9} \left[ \frac{2P_{(n+1)}}{T_c} - \frac{1}{P_n} + 1 \right] \]

Average torque fraction \( T_q = \frac{1 - 2P_n}{P_n} \) in this case

and as
\[ 2P_n = 1 - 2P_{(n+1)} \]
\[ T_q = 1 - \frac{1}{P_n} \left[ 1 - 2P_{(n+1)} \right] \]

Hence:
\[ T_q = \frac{1}{P_n} \left[ \frac{1}{P_n} + \frac{9 \Delta F}{F^2 T_c} - 2 \right] + 1 \]

for \( \frac{1}{P_n} \neq 0 \) or 1

\( 2P_{(n+1)} \) range from 1 \( \rightarrow 0 \)
Therefore:
\[ \Delta F \text{ must be } \frac{F^2 T}{9} \left( 2 - \frac{1}{P_n} \right) \Delta F \geq \frac{F^2 T}{9} (1 - \frac{1}{P_n}) \]

if \( \frac{1}{P_n} = 1 \) then \( \frac{F^2 T}{9} \Delta F \geq 0 \)

Therefore:
\[ T_q = \frac{9 \Delta F}{F^2 T} \]

For \( nT_c \gg T_1 \gg (n - 1)T_c \)

and \( (n - 1)T_c \gg T_2 \gg (n - 2)T_c \)

\[ T_1 = (n - 1)T_c + \frac{1}{P_n}T_c \]
\[ T_2 = (n - 2)T_c + \frac{2P_{n+1}}{T_c} \]

Therefore:
\[ T_2 - T_1 = T_c \left[ \frac{2P_{n-1}}{T_c} - \frac{1}{P_n} - 1 \right] \]

Hence:
\[ \Delta F = \frac{F^2 T}{9} \left[ \frac{2P_{n-1}}{T_c} - \frac{1}{P_n} - 1 \right] \]

This gives for the average torque fraction \( T_q \)

\[ T_q = (1 - \frac{1}{P_{n-1}}) \cdot \frac{2P_{n-1}}{T_c} \]
\[ = 1 + (\frac{1}{P_n} - 1)\left[ \frac{9 \Delta F}{F^2 T} + \frac{1}{P_n} + 1 \right] \]

for \( \frac{1}{P_n} \neq 0 \) or 1

For the range of \( \Delta F \)

\[ - \frac{F^2 T}{9} \frac{1}{P_n} \Delta F \geq - \frac{F^2 T}{9} (\frac{1}{P_n} + 1) \]

if \( \frac{1}{P_n} = 1 \)

\[ 0 \geq \Delta F \geq - \frac{F^2 T}{9} \]
Hence \[ T_q = -\frac{9 \triangle F}{F^2 T_c} \]

For \[ nT_c \gg T_1 \gg (n-1)T_c \]
and \[ nT_c \gg T_2 \gg (n-1)T_c \]

\[ T_1 = (n-1)T_c + \frac{1}{P_n} T_c \]

\[ T_2 = (n-1)T_c + \frac{2}{P_n} T_c \]

\[ T_2 - T_1 = T_c \left(\frac{2}{P_n} - \frac{1}{P_n}\right) \]

\[ \triangle F = \frac{F^2 T_c}{9} \left(\frac{2}{P_n} - \frac{1}{P_n}\right) \]

\[ T_q = \left(\frac{2}{P_n} - \frac{1}{P_n}\right) \]

Therefore: \[ T_q = \frac{9 \triangle F}{F^2 T_c} \quad \frac{1}{P_n} \neq 0 \text{ or } 1 \]

for \[ \triangle F \text{ such that } (1 - \frac{1}{P_n}) \frac{F^2 T_c}{9} \gg F \gg -\frac{F^2 T_c}{9} \frac{1}{P_n} \]

Generally if \( \frac{1}{P_n} \neq 0 \text{ or } 1 \), then width of proportional section
\[ = \frac{3F^2 T_c}{9} \]

but if \( \frac{1}{P_n} = 1 \text{ or } 0 \), the width of proportional section
\[ = \frac{2F^2 T_c}{9} \]

See Figures 7.2, 7.3 and 7.4.
## APPENDIX 2

Component values for circuit diagrams

**Figure 4.2 The Rotor Suspension Circuit.**

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Figure 4.11  P.I.N. Diode Amplifier.

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<tr>
<td>R&lt;sub&gt;6&lt;/sub&gt;</td>
<td>680 ohms</td>
</tr>
<tr>
<td>R&lt;sub&gt;15&lt;/sub&gt;</td>
<td>1k</td>
</tr>
<tr>
<td>R&lt;sub&gt;24&lt;/sub&gt;</td>
<td>2.7k</td>
</tr>
<tr>
<td>R&lt;sub&gt;7&lt;/sub&gt;</td>
<td>10k</td>
</tr>
<tr>
<td>R&lt;sub&gt;16&lt;/sub&gt;</td>
<td>1k</td>
</tr>
<tr>
<td>R&lt;sub&gt;25&lt;/sub&gt;</td>
<td>47 ohms</td>
</tr>
<tr>
<td>R&lt;sub&gt;8&lt;/sub&gt;</td>
<td>1M</td>
</tr>
<tr>
<td>R&lt;sub&gt;17&lt;/sub&gt;</td>
<td>5.6k</td>
</tr>
<tr>
<td>R&lt;sub&gt;18&lt;/sub&gt;</td>
<td>5.6k</td>
</tr>
<tr>
<td>R&lt;sub&gt;9&lt;/sub&gt;</td>
<td>100 ohms</td>
</tr>
<tr>
<td>D&lt;sub&gt;1&lt;/sub&gt;</td>
<td>10 VZ</td>
</tr>
<tr>
<td>D&lt;sub&gt;5&lt;/sub&gt;</td>
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<tr>
<td>D&lt;sub&gt;9&lt;/sub&gt;</td>
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<td>4.7 VZ</td>
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<td>D&lt;sub&gt;8&lt;/sub&gt;</td>
<td>3.3 VZ</td>
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<td>D&lt;sub&gt;12&lt;/sub&gt;</td>
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<tr>
<td>C&lt;sub&gt;1&lt;/sub&gt;</td>
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<tr>
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<tr>
<td>TR&lt;sub&gt;2&lt;/sub&gt;</td>
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<tr>
<td>C&lt;sub&gt;2&lt;/sub&gt;</td>
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</tr>
<tr>
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<td>10µF Tant.</td>
</tr>
<tr>
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<tr>
<td>C&lt;sub&gt;9&lt;/sub&gt;</td>
<td>10µF Tant.</td>
</tr>
<tr>
<td>C&lt;sub&gt;4&lt;/sub&gt;</td>
<td>10µF Tant.</td>
</tr>
<tr>
<td>C&lt;sub&gt;10&lt;/sub&gt;</td>
<td>10µF Tant.</td>
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<tr>
<td>C&lt;sub&gt;5&lt;/sub&gt;</td>
<td>10µF Tant.</td>
</tr>
<tr>
<td>C&lt;sub&gt;11&lt;/sub&gt;</td>
<td>10µF Tant.</td>
</tr>
<tr>
<td>C&lt;sub&gt;6&lt;/sub&gt;</td>
<td>470pF</td>
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Figure 4.12  Rotor Speed Monitor

<table>
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<tr>
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<tbody>
<tr>
<td>R₁</td>
<td>39k</td>
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<tr>
<td>R₂</td>
<td>10k</td>
</tr>
<tr>
<td>R₃</td>
<td>1k</td>
</tr>
<tr>
<td>R₄</td>
<td>100 ohms</td>
</tr>
<tr>
<td>C₁</td>
<td>0.1μF Disc.</td>
</tr>
<tr>
<td>G₅</td>
<td>1/4 SN7400</td>
</tr>
<tr>
<td>G₆</td>
<td>1/4 SN7400</td>
</tr>
<tr>
<td>G₇</td>
<td>1/4 SN7400</td>
</tr>
<tr>
<td>G₈</td>
<td>1/6 SN7404</td>
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<td>G₉</td>
<td>1/6 SN7404</td>
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<td>G₁₀</td>
<td>1/6 SN7404</td>
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Figure 5.5  Pulse Length and Base Current Drive Circuit

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<tbody>
<tr>
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<tr>
<td>R₂</td>
<td>1k</td>
</tr>
<tr>
<td>R₃</td>
<td>2.5k</td>
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<tr>
<td>R₄</td>
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</tr>
<tr>
<td>R₅</td>
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<tr>
<td>R₆</td>
<td>1.5k</td>
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<tr>
<td>R₇</td>
<td>27 ohms</td>
</tr>
<tr>
<td>R₈</td>
<td>270 ohms</td>
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<tr>
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<tr>
<td>R₁₀</td>
<td>470 ohms</td>
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<tr>
<td>R₁₁</td>
<td>12 ohms</td>
</tr>
<tr>
<td>R₁₂</td>
<td>150 ohms</td>
</tr>
<tr>
<td>R₁₃</td>
<td>68 ohms</td>
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<tr>
<td>R₁₆</td>
<td>470 ohms</td>
</tr>
<tr>
<td>R₁₇</td>
<td>0.22 ohms</td>
</tr>
<tr>
<td>R₁₈</td>
<td>680 ohms</td>
</tr>
<tr>
<td>R₁₉</td>
<td>680 ohms</td>
</tr>
<tr>
<td>D₁</td>
<td>IN4148</td>
</tr>
<tr>
<td>TR₁</td>
<td>V405A</td>
</tr>
<tr>
<td>TR₂</td>
<td>P346A</td>
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<td>TR₃</td>
<td>P3468</td>
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<tr>
<td>TR₄</td>
<td>BC182</td>
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<td>TR₅</td>
<td>BC182</td>
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<tr>
<td>TR₆</td>
<td>BC212</td>
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<td>C₂</td>
<td>0.1μF</td>
</tr>
<tr>
<td>C₃</td>
<td>470pF</td>
</tr>
</tbody>
</table>
Figure 5.6  
Electronic Drive Output Stage

\[ R_5 \rightarrow R_{14} \quad 68 \text{ ohms} \quad R_{16} \rightarrow R_{25} \quad 0.22 \text{ ohms} \]

\[ TR_2 \rightarrow TR_{1} \quad \text{MJE2801} \]

\[ D_1 \rightarrow D_{10} \quad \text{IN4148} \]

Figure 6.2  
Rotor Analogue Phase-Lock Circuit.

\begin{align*}
R_1 & = 10k & R_{17} & = 10 \text{ ohms} & R_{33} & = 10 \text{ ohms} \\
R_2 & = 18k & R_{18} & = 1k & R_{34} & = 10k \\
R_3 & = 820 \text{ ohms} & R_{19} & = 100k & R_{35} & = 10k \\
R_4 & = 1k & R_{20} & = 10k & R_{36} & = 1\text{M} \\
R_5 & = 10k & R_{21} & = 10k & R_{37} & = 1k \\
R_6 & = 1k & R_{22} & = 1k & R_{38} & = 10k \\
R_7 & = 10 \text{ ohms} & R_{23} & = 10k & R_{39} & = 100k \\
R_8 & = 10k & R_{24} & = 100k & R_{40} & = 100k \\
R_9 & = 10 \text{ ohms} & R_{25} & = 100k & R_{41} & = 100k \\
R_{10} & = 1\text{Mohm} & R_{26} & = 10k & R_{42} & = 2.2k \\
R_{11} & = 10 \text{ ohms} & R_{27} & = 33k & R_{43} & = 39k \\
R_{12} & = 10 \text{ ohms} & R_{28} & = 10k & R_{44} & = 390k \\
R_{13} & = 2.2k & R_{29} & = 5.7k & R_{45} & = 68 \text{ ohms} \\
R_{14} & = 1\text{Mohm} & R_{30} & = 50k & R_{46} & = 10k \\
R_{15} & = 10 \text{ ohms} & R_{31} & = 50k & R_{47} & = 1k \\
R_{16} & = 1\text{Mohm} & R_{32} & = 10 \text{ ohms} & R_{48} & = 100 \text{ ohms} \\
\end{align*}
Figure 6.2 continued.

<table>
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<tr>
<th>Component</th>
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</thead>
<tbody>
<tr>
<td>C_1</td>
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</tr>
<tr>
<td>C_2</td>
<td>22μF Tant.</td>
</tr>
<tr>
<td>C_3</td>
<td>1μF</td>
</tr>
<tr>
<td>C_4</td>
<td>22μF Tant.</td>
</tr>
<tr>
<td>C_5</td>
<td>22μF Tant.</td>
</tr>
<tr>
<td>C_6</td>
<td>1μF</td>
</tr>
<tr>
<td>C_7</td>
<td>22μF Tant.</td>
</tr>
<tr>
<td>C_8</td>
<td>22nF</td>
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<tr>
<td>C_9</td>
<td>22μF Tant.</td>
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<tr>
<td>C_10</td>
<td>22nF</td>
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<td>C_11</td>
<td>22μF Tant.</td>
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<td>C_12</td>
<td>22μF Tant.</td>
</tr>
<tr>
<td>C_13</td>
<td>1μF</td>
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<tr>
<td>C_14</td>
<td>22μF Tant.</td>
</tr>
<tr>
<td>C_15</td>
<td>22μF Tant.</td>
</tr>
<tr>
<td>C_16</td>
<td>1μF</td>
</tr>
<tr>
<td>C_17</td>
<td>22μF Tant.</td>
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<td>C_18</td>
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Figure 6.3  Rotor Analogue Phase-Lock

<table>
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<tbody>
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<tr>
<td>D_2</td>
<td>IN4148</td>
</tr>
<tr>
<td>D_3</td>
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</tr>
<tr>
<td>D_4</td>
<td>L.E.D.</td>
</tr>
<tr>
<td>D_5</td>
<td>L.E.D.</td>
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</table>
APPENDIX 3

Logic Symbols Used in Circuit Diagrams

NOT (inverter)     \[ A \rightarrow X \quad X = \overline{A} \]

BUFFER           \[ A \rightarrow X \quad X = A \]

NAND gate        \[ A \quad B \rightarrow X \quad X = \overline{A \cdot B} \]

AND gate         \[ A \quad B \rightarrow X \quad X = A \cdot B \]

OR gate          \[ A \quad B \rightarrow X \quad X = A + B \]

NOR gate         \[ A \quad B \rightarrow X \quad X = \overline{A + B} \]

Exclusive OR gate \[ A \quad B \rightarrow X \quad X = A \cdot \overline{B} + \overline{A} \cdot B \]

Exclusive NOR gate \[ A \quad B \rightarrow X \quad X = A \cdot \overline{B} + \overline{A} \cdot B \]
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