High-Constant-Speed Rotating Mirror

By J. W. BEAMS, E. C. SMITH and J. M. WATKINS

The rotating mirror is magnetically suspended in a high vacuum and spun by a rotating magnetic field. The mirror is accelerated to full speed in a way similar to that of the armature in an induction motor, but at running speed it performs as an armature of a synchronous motor. The frequency of the rotating field is determined by a piezoelectrically controlled circuit. Also it is free of hunting. The maximum rotational speed of the mirror is determined only by the strength of the mirror. Mirrors are described which rotate at 20,000 rps.

In a great many problems, where it is necessary to study accurately phenomena which occur in very short intervals of time, it is desirable to have a high-constant-speed rotating mirror.[1,2] It is particularly important that not only the number of revolutions per second of the mirror must be known with high precision, but the mirror must be free of so-called hunting or rapid variations in speed. This latter requirement of freedom from hunting is usually almost impossible to attain in practice, especially where the friction on the mirror or bearings requires that the drive deliver considerable power, i.e., when the frictional torques and the driving torques are large, small asymmetries in either give rise to hunting of the rotor. In the rotating mirror arrangement described in this paper, the total frictional torque is very small with the result that the speed can be made extremely constant and hunting, if present, is too small to be observable.

Experimental Arrangement

Figure 1 is a schematic diagram of the apparatus, while Fig. 2 is a photograph of the suspended mirror with the vacuum chamber and one drive coil removed. This arrangement is the outgrowth of a series of experiments, using magnetically suspended rotors or centrifuges in a vacuum, carried out at the University of Virginia over a number of years.[3–7] The mirror R made of high-strength ferromagnetic material is suspended inside a glass vacuum chamber by the axial magnetic field of the solenoid S situated above the chamber. The vertical position of the rotor is

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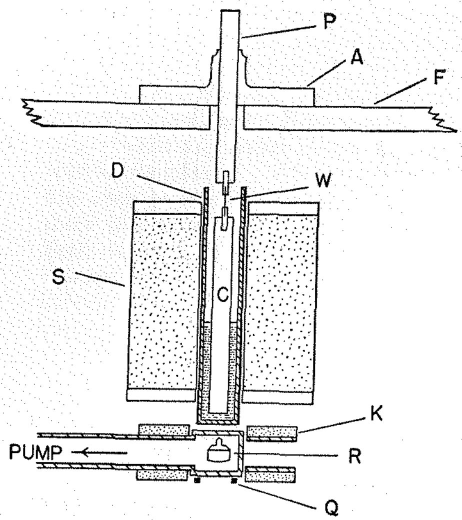

Fig. 1. Schematic diagram of high-constant-speed rotating mirror arrangement.

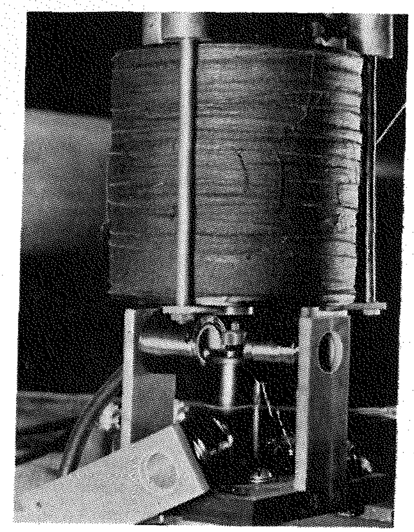

Fig. 2. Suspended mirror, with vacuum chamber and one drive coil removed.

maintained by the automatic regulation of the current through the solenoid S, while its horizontal position is determined by the symmetrically diverging magnetic field. The mirror R is spun by two pairs of coils K which produce a rotating magnetic field. The small coil Q is part of a tuned grid–tuned plate radiofrequency oscillator (Fig. 3) which regulates the current through S. It is so arranged that when the rotating mirror rises, the current through S decreases, while when it falls, the current in S increases in such a way as to maintain the mirror at the desired height without observable hunting. The steel cylindrical core C of the solenoid S is suspended by a small wire W from the adjustable support P. The core C is surrounded by a damping fluid as shown and serves to damp any horizontal motion of the rotor.

Suspending Circuit

The circuit, which automatically regulates the current through the solenoid S in such a way as to maintain the rotor at the desired vertical position, is shown in Fig. 3. The pickup coil Q is in the grid circuit of a 5-mc partially neutralized tuned grid–tuned plate oscillator. If the rotating mirror R moves downward and approaches the coil Q, the latter's impedance, with the proper setting of the oscillator, is changed in such a way as to lower the amplitude of oscillation in the circuit. This gives rise to a so-called error signal which is detected by a cathode-follower detector and appears as a reduction in potential across the resistance R_{12}. A portion of this potential change appears on the grid of a 6SJ7 which is one-half of a two-pentode mixer. Subsequently, this signal increases the potential on the grids of the three 6L6's in parallel, which increases the current through the solenoid S and in turn raises the rotating mirror R.

In order to prevent vertical oscillation of the rotor R the "error" signal is differentiated by the resistance R_{11}-capacity C_7 combination and mixed with the original error signal. Also,

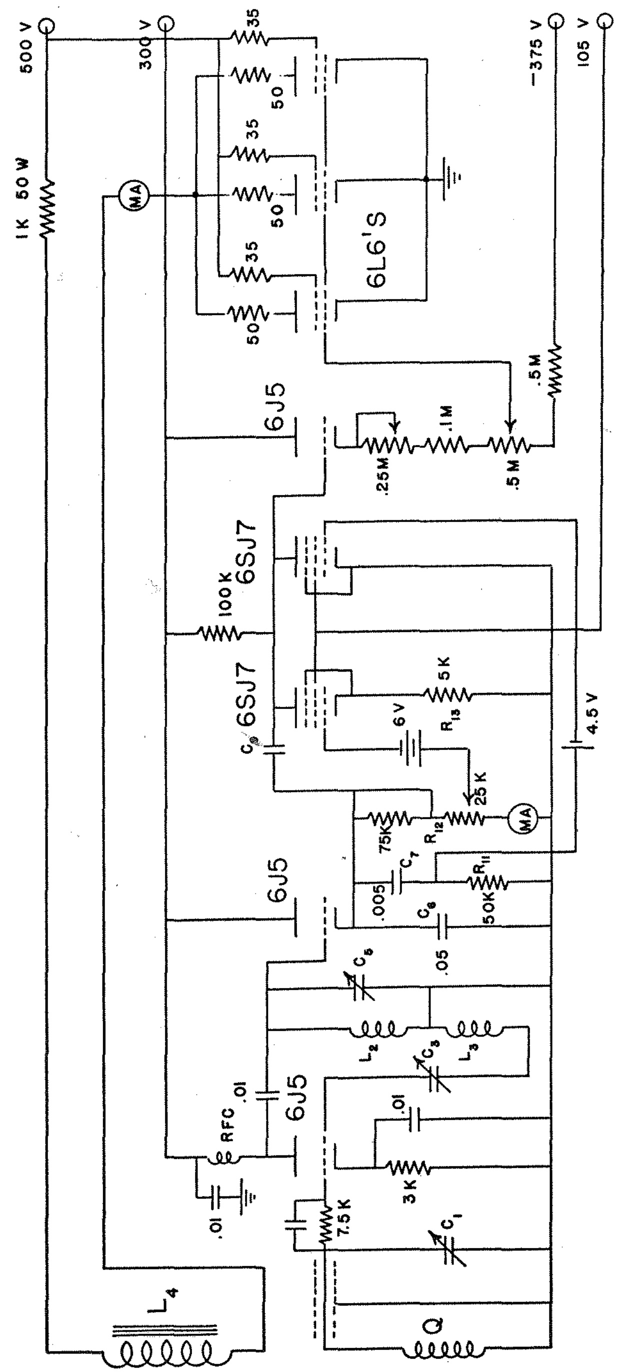

Fig. 3. Diagram of tuned grid-tuned plate radiofrequency oscillator and support.

the use of two 6SJ7 pentodes as mixers together with the negative feedback through resistor R_{13} and condenser C_9 produces increased stability. The power supplies were of the conventional regulated degenerative type.[8] The regulation of the 500-v supply is less critical than that of the 300-v supply so the latter is stabilized from the former. A variation of from 100 v to 135 v in the line voltage produces less than a 10-v change in the 500-v supply which in turn produces less than 0.02 v in the 300-v supply. The −375-v supply is obtained from a conventional transformer rectifier with condenser input filter system and stabilized with two VR 150's and one VR 75 in series.

The solenoid S consists of 25,000 turns of No. 28 insulated copper wire wound on a bakelite frame. Its inductance is 19.5 h (henrys) and its resistance, 1010 ohms. The cold-rolled steel, cylindrical core C of the solenoid ($\frac{7}{16}$ in. in diameter and $3\frac{7}{8}$ in. long) is suspended by a $\frac{5}{16}$-in. length of hardened 0.018-in. diameter piano wire W. The height of the core C is adjusted with a brass plunger P which fits into a brass disk A. The disk, which slides on the frame F, is adjusted by setscrews to the proper axial position so that the core remains approximately on the axis of the solenoid S when the current is raised to maximum value. The length of the core C and wire W are adjusted so that the period of the pendulum so formed is approximately that of the rotor S when given a horizontal displacement. The core hangs in a "dash pot" (a glass test tube flattened at the lower end and filled with SAE No. 10 motor oil) and damps any horizontal motion of the rotating mirror R. No motion of the rotor either in a horizontal or vertical direction can be detected by a 50× microscope focused on the scratches of the suspended mirror.

Rotating Mirror

For greatest stability of magnetic support it is desirable (although not absolutely necessary) to make the rotor as long or longer in the direction of the axis of spin than in the radial direction. On the other hand, for rotational stability, the moment of inertia around the axis of spin should be larger than that around the radial or perpendicular direction. Added to this, the rotor should be symmetrical around the axis of spin. It was found that a sharp cone on top of a short cylinder proved to be a very stable configuration. The faces of the mirror were ground on the cylindrical surface and the sharp cone concentrated the magnetic flux in the proper way to give stability. The edges of the top and bottom of the cylindrical portion were slightly beveled to prevent discontinuities (resulting from the mirror faces) from affecting the pickup coil Q.

The first mirrors were made of magnetic stainless steel (Carpenter 2B stainless 400). They were machined to shape and then heat-treated by the standard procedure to give good mirror surfaces and high strength. They were next ground to exact shape and the mirror surfaces lapped and polished. They were flat to roughly 0.2 wavelength of sodium light. Rotors of 0.5-in. diameter with mirror faces $\frac{1}{4}$ in. × $\frac{1}{4}$ in. were used successfully for long periods at 16,000 rps, but exploded at 18,500 rps. As a result the stainless steel has been replaced by hard high-strength alloy steel with the mirror faces covered with a very thin coating of aluminum. Ball bearings ground to the proper shape were found to be satisfactory when care was taken not to remove the temper during the grinding process. The mirror used at 20,000 rps was 0.5 in. from the bottom to tip of the cone and each of the six mirror faces was 0.25 in. in diameter. The first type of mirror is shown in Fig. 2. The rotating mirror was surrounded by an all-glass vacuum chamber with an optically flat glass window, through which the light passes, sealed on with low-vapor-pressure vacuum cement or wax. The chamber was evacuated by a standard forepump, diffusion-pump, cold-trap arrangement.

Driving Circuits

A schematic diagram of the drive circuit is shown in Figs. 4 and 5. The drive frequency is determined by a piezoelectric crystal-controlled electron-coupled oscillator operating at a frequency of 100,000 cycle/sec (Fig. 4). The crystal operates in a thermostat-controlled oven to improve stability. The oscillator is calibrated by zero-beating the 100th harmonic with the 10-mc wave broadcast by radio station WWV of the National Bureau of Standards. The oscillator may be tuned over a very narrow range and, in practice, set to give the lowest practical beat frequency. This procedure allows the oscillator frequency to be determined to about one part in 10^8. However, the published precision of WWV is only five parts in 10^8, so that when radio transmission irregularities are considered, the precision of the oscillator is not known to perhaps better than one part in 10^7. In practice, the oscillator circuit is operated for long periods of time and the drift is extremely small. If it becomes necessary to determine the frequency to better than one part in 10^7, it will be necessary to have a laboratory standard.

The output of the buffer amplifier of the oscillator is fed to a multivibrator frequency divider. The output of the multivibrator is a square wave of frequency $1/n \times 10^5$ cycle/sec, where n is an integer. The divider was designed for $n = 5$ or 6, i.e., frequencies of 20 kc or $16\frac{2}{3}$ kc, but other division ratios are easily obtained. This square wave is fed through an amplifier which serves as a filter. The resultant sine wave is passed through a phase-splitter and buffer-amplifier. The output (Fig. 5) is then amplified and transformer-coupled to the power tubes which operate as class C amplifiers with the drive coils resonant with the proper capacitors as the plate load.

The speed is measured by a method shown schematically in Fig. 6. Light is reflected from the mirror faces into a photomultiplier cell. This signal is amplified and applied to one pair of plates of an oscilloscope. The comparison frequency is applied to the other pair of oscilloscope plates so that the resultant Lissajous figure gives the frequency relationship. The comparison frequency was usually a standard audio-frequency oscillator except at operating speed, where the drive frequency or WWV was used as a comparison.

Operation

The procedure in starting the rotating mirror is to turn on the crystal oscillator in the drive circuit several hours before operation so that it will have sufficient time to reach thermal equilibrium. In the meantime, the pumps are started and the chamber surrounding the rotor evacuated to 10^{-6} mm Hg pressure or below. The mirror is then supported and the power applied to the driving circuit. In practice the support circuit approaches equilibrium in a relatively short time. The rotating field produced by the two pairs of coils K (Fig. 1) induces eddy currents in the mirror and it starts spinning. Consequently, the mirror acts as a high-resistance armature of an induction motor and continues to accelerate.

When the mirror speed approaches within about 40 rps of the frequency in the coils K, the rate of acceleration falls off, but if the pressure in the vacuum chamber is below 10^{-6} mm Hg the rotating mirror will continue to accelerate until its rotational speed approaches closely enough to the frequency of the rotating magnetic field to "lock in." When this occurs, the rotating mirror operates as an armature of a synchronous motor and spins without observable hunting at a rotational speed equal to the drive frequency. Consequently,

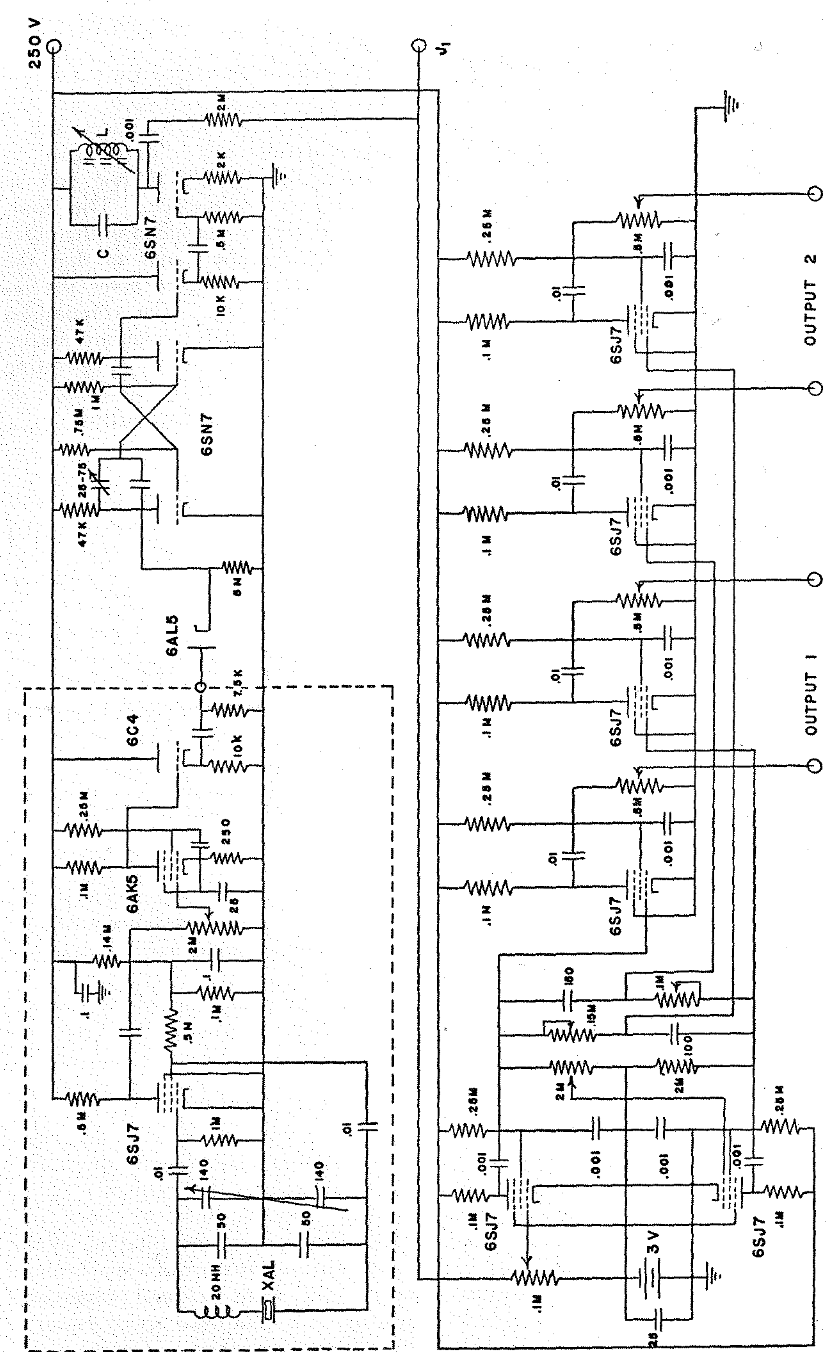

Fig. 4. Drawing of crystal-controlled oscillator and multivibrator frequency divider.

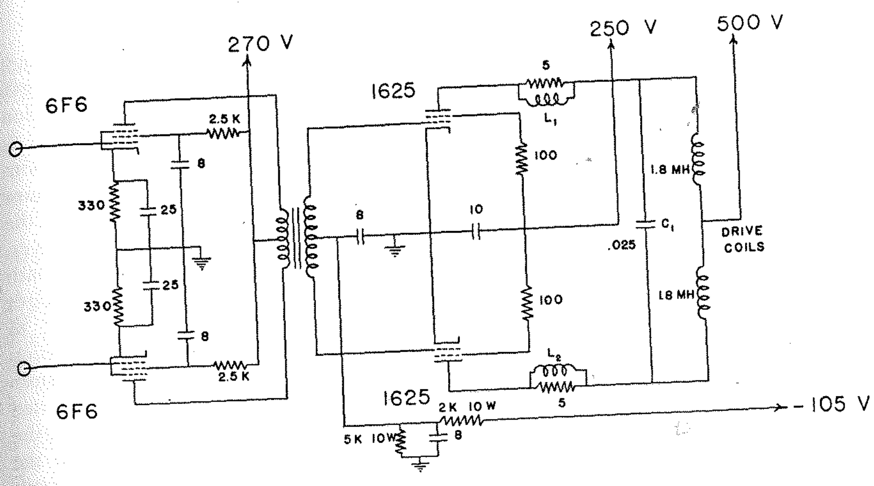

Fig. 5. Drive amplifier.

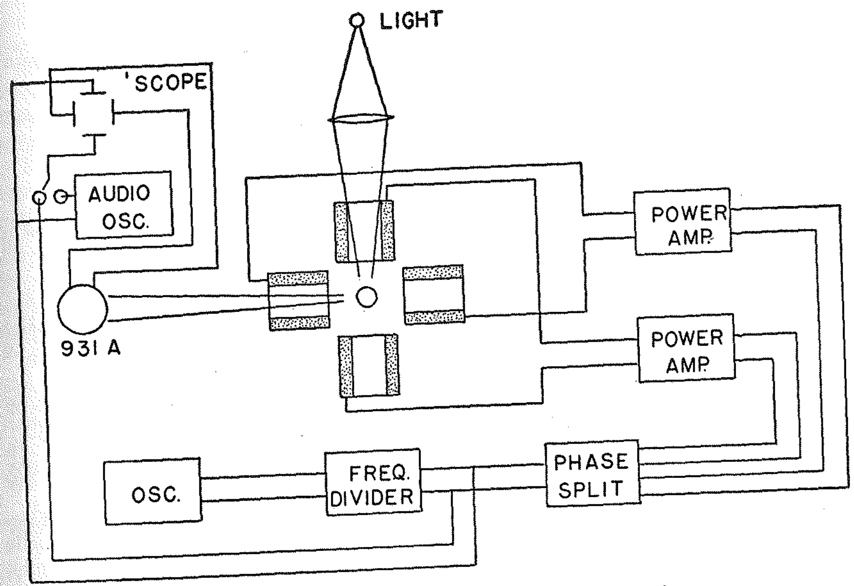

Fig. 6. Scheme of speed-measuring method.

the rotational speed of the mirror is known with the same precision as that of the master driving oscillator. Usually it requires more time to accelerate the rotating mirror the last 40 rps than to bring it up to this speed since the torque falls off very rapidly as the "slip" becomes small. As a result, it is usually advantageous to disconnect the crystal oscillator from the phase-inverter and substitute an audio oscillator during the acceleration period. In this way the drive frequency is set at 50 or 60 cycles above the desired running speed. When the speed of the mirror slightly exceeds the desired running speed, the audio oscillator is disconnected and the crystal control substituted. The mirror then decelerates slowly and "locks in." When the mirror first "locks in" it hunts with a considerable amplitude, but in a few minutes this damps out and becomes too small to observe (less than 10^{-3} radian/sec). Since the rotor speed is over 10^5 radian/sec the error introduced by hunting is less than one part in 10^8.

With the circuit of Fig. 5 and a power input to the coils K of 150 w or 1.6 amp in the coils, the mirror accelerated at the rate of approximately 1000 rps/min until the "slip" frequency became about 50. However, with this much power input it is necessary to cool the coils with a small fan. On the other hand, when running speed is obtained, the power in the drive coils should be considerably reduced. The temperature of the mirror increases a few degrees during the acceleration period if the power input is not greater than indicated above. At running speed the rotor temperature decreases slowly to practically that of the surrounding walls. By removing the driving torque and permitting the mirror to "coast" freely, the deceleration is found to be extraordinarily small. As a matter of fact, the measured deceleration can be accounted for as due only to the friction of the residual gases surrounding the rotor. As a result, in order to bring the mirror to rest, it is necessary to reverse the direction of the rotating magnetic field and drive it down, otherwise it would take a very long time for the rotor to come to rest.

The above rotating-mirror arrangement is especially useful when phenomena which occur in very short periods of time must be studied with precision. It was developed for photographing the successive stages of sparks in different gases and the various stages of vacuum sparks. Also, it is being applied in a study of the velocity of light through liquids as a function of the wavelength of the light. Due to the high precision with which the rotational speed is known (one part in 10^7) and its freedom from hunting, the arrangement is almost ideally suited to the measurement of the velocity of light in a vacuum. However, for highest precision, the light path should be of the order of a mile in length and this distance is very difficult to measure and maintain with a precision of one part in 10^7. The maximum rotational speed of the mirror is limited only by the mechanical strength of the mirror. Consequently, by reducing the size of the rotating mirror higher speeds can be obtained. At the present time, a rotating mirror which spins at 10^5 rps is under development.

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Discussion

M. L. Sandell: If you wanted to slow up the rotor faster than happens directly from friction, could you do it by reversing the field?

Dr. J. W. Beams: Yes, that is the best way of doing it.

E. Salzberg: I would like to know whether the techniques you have developed in supporting a rotating object have found any application in industry or commerce?

Dr. Beams: Well, I don't know. This is a research tool as far as I know. Besides, in the spinning of mirrors, I think probably it will be very useful as an aid in producing a new type of centrifuge. I believe that it is going to allow us to increase the precision of the measurement of molecular weights, especially of the proteins.

The magnetic suspension used for supporting the mirror in these experiments may be slightly modified to make it into an excellent magnetic balance. We have succeeded in weighing weights of one milligram with a precision of about one billionth of a gram. This, of course, may find considerable use in industry.

Mr. Salzberg: Would it be possible to eliminate the use of the vacuum in rotating at relatively low speed?

Dr. Beams: Yes. However, the air friction goes up pretty rapidly with rotor speed.

Kenneth Shaftan: What material do you use?

Dr. Beams: We are using steel mostly. The rotor is made of the best steel we can get. We made some experiments on the bursting of different steels and we ran a long series on ordinary commercial ball bearings and on selected ball bearings. It turned out the ball bearings burst at the same peripheral speed if made of the same material. There were a great many flaws in the larger ball bearings. The probability of the rotor going up to full speed was roughly inversely proportional to the diameter of the rotor. I think that this result can be explained metallurgically.

Anon: What was the measurement between the solenoid field and the rotor itself?

Dr. Beams: Do you mean what distance?

Anon: Yes.

Dr. Beams: All the way from a few millimeters to 6 or 8. It is a variable thing, depending upon the field in the solenoid and its gradient at the rotor position.

Anon: What order of magnitude of power inversely is required to spin the bearing rotor?

Dr. Beams: Now, this is a relative matter, of course. I had one that was small, near $\frac{1}{16}$ in. in diameter, which started spinning slowly when the light from a Western Union electric arc was focused on its periphery. In other words, the light pressure was sufficient to spin it.

In this rotating mirror we had 1.6 amp to the coil and it accelerated at the rate of 1000 rpm. We try in most of our experiments to bring the rotor up as slowly as we can; by accelerating it faster, more heat is generated in the rotor. But under about one ampere in the coil the rotor increases in temperature less than 10°.

A. W. Carpenter: In bursting ball bearings could you tell me offhand within what angle it proved to be splaying or clipping?

Dr. Beams: Well, they sort of powdered and completely disintegrated. One also notices a little yellow light, like on a grinding wheel. You, of course, look through a right-angle mirror to see the yellow light.

E. A. Andres, Sr.: If I understood you correctly, you said you had 1.6 amp accelerated at 1000 rps...

Dr. Beams: No, 1000 rpm.

Mr. Andres: I would like to know how you made the measurement.

Dr. Beams: By photoelectron multiplier tube and a light-beam arrangement.

C. D. Miller: Dr. Beams, as you know at NACA we used a system similar to the one developed by you for supporting and driving a rotor used in a camera with which we took pictures at speeds up to 800,000 frame/sec. We used a rotor weighing about two-thirds of a pound, about three inches long and about an inch in diameter.

I was interested in your remarks about the heating effect. We were not able to get an extremely good vacuum, as you have, because of certain mechanical limitations involved in our optical system. Because of the consequent high slip and resulting eddy currents, we ran into very serious heating of the rotor.

We eliminated the heating by resorting to what I call a self-synchronous motor. We cross-magnetized the rotor and drove it up to a few revolutions per second as an induction motor. Then, with two small coils alongside the lower end of the rotor, 90° apart, we picked up a four-phase voltage induced by the cross magnetization. We amplified this four-phase pickup, through both voltage and power amplifiers, and fed the output into the driving coils. We adjusted the positions of the pickup coils so that the rotating field was a little ahead of the cross magnetization of the rotor. The rotor then accelerated as a synchronous motor, and we avoided the heating altogether.

Dr. Beams: Yes. Yours was a very beautiful experiment. The method you used was certainly a good one. We have had to use a similar sort of scheme where we cannot have any temperature rise. The only reason we did not do it here is that the small mirrors do not get too hot. On the other hand, for larger rotors this is necessary.

Mr. Miller: I was wondering whether you found that the cross magnetization of the rotor would cause any undesirable effects in your experiments.

Dr. Beams: No, the cross magnetization seems not to upset anything else.

Anon: Mr. Miller, how much temperature rise did you encounter in the rotor when attempting to drive it up to full speed as an induction motor?

Mr. Miller: I did not measure the temperature rise except by touching the rotor with the hand. It was obviously excessive.

R. O. Painter: I wonder why the supporting field does not introduce eddy current flow. As I have it, there would be eddy current loss caused by this field since it fans out in the rotor.

Dr. Beams: Well, you see the magnetic field comes down uniformly across the rotor since the latter has a high permeability. Hence, there is no current flow.

Mr. Painter: Is it not generating eddy currents in the rotor periphery? You have a radial magnetic field.

Dr. Beams: You have a radial electrical field as it works out in practice. On the other hand, you have no closed circuit for the current unless the spin axis of the rotor makes a sizable angle with the direction of the magnetic field.

Mr. Painter: Between the center and the outside?

Dr. Beams: There is an electrical potential between the center and periphery of the rotor, but no current can flow.

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