SOME EXPERIMENTS ON THE BURSTING OF SPHERICAL ROTORS BY CENTRIFUGAL FORCES*

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Soc. Exp. Stress Analysis, New York (1948).

ABSTRACT

Experiments are described in which steel spherical rotors of various sizes are spun to speeds where explosion occurs. The rotors are supported in a vacuum by an axial magnetic suspension and are spun by rotating magnetic fields. Such an arrangement allows the rotors to be accelerated slowly in a vacuum without heating until they explode. A series of spherical rotors were made of the same kind of steel and heat treated in the same way. It was found that the maximum peripheral speed obtained was approximately the same (roughly 10^5 cm/sec) for the spherical rotors of various diameters. However, the probability of any particular rotor reaching this maximum speed increased as the size of the rotor decreased. The smallest rotor so far exploded (0.021 inch diameter) reached approximately 40 million rpm and gave a centrifugal acceleration of 430 million times gravity. The experiments are being extended to both smaller and larger rotors. The stresses developed are calculated by the method of Chree. The application of this technique to a number of other problems is discussed.

THEORETICAL ANALYSIS

With modern methods of spinning high speed rotors, the maximum rotor speed is determined by the mechanical strength of the rotor.(1)** This is a serious limitation since, with several rotor drives now in use, it would be possible to multiply the rotor speed severalfold if the rotors could be prevented from exploding. According to theory, the maximum stress produced in a homogeneous elastic spinning rotor is proportional to the square of the peripheral speed or to $(2\pi Nr)^2$, where N is the number of revolutions per second and r is the radius. That is, similarly shaped rotors made of the same kind of elastic material should explode when their peripheral speeds are roughly equal, regardless of the size of the radius. However, the bursting speed of a rotor made of a given elastic material can be greatly increased by making it in the proper shape. For maximum theoretical bursting speed it is customary so to shape the rotor that the radial and tangential stresses have a constant value throughout the rotor for any given rotor speed.(2) In actual practice this ideal situation is very difficult to attain, first because the rotor is either too thin near the periphery or too thick near the axis and, second, no rotor material is perfectly elastic. Also it is important to keep the fundamental vibration frequency of the rotor below the highest rotor speed used. As a result, in most solid rotors, the maximum stress usually occurs on the axis of rotation. With some plastic materials, such as nickel alloy steel, it is found that the maximum working speed can be obtained by first overstressing the rotor near the axis for a short time and permitting plastic flow to take place.(2) This plastic flow both increases the yield point and distributes the stresses in such a way that higher rotor speeds can be produced.

In centrifuging experiments, where the centrifuging is continued until the sedimentation is approximately balanced by diffusion, as in the case of the separation of gases, vapors, isotopes, etc., the separation factor depends directly upon the square of the peripheral speed in the exponent of e. Since the bursting strength of a rotor also is proportional to the square of the peripheral speed, a small increase in rotor strength greatly increases the separation factor obtainable. For this reason for any new design

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*The work described in this paper has been supported by the U. S. Navy Bureau of Ordnance under contract NOrd-7873.

**Superiors in parentheses refer to bibliography.

of rotor, it has become common practice, in our laboratory at Virginia, to spin a series of rotors until they explode in order to determine the highest possible working speed for a particular design. In other types of centrifuging experiments, it is necessary to produce a maximum centrifugal acceleration or $(2\pi N)^2r$. In this case the rotor is not only made as strong as possible but the radius is made as small as practicable.

In this paper a series of experiments on the bursting of small steel rotors designed primarily to give high centrifugal fields will be described. The rotors are supported in a vacuum by an axial magnetic suspension developed by several different workers(3,4) at the University of Virginia and are spun by a rotating magnetic field. Fig. 1 shows a schematic diagram of the apparatus used. This apparatus has been described in detail elsewhere(4) but an outline will be given here because of its rather wide possible application. The steel rotor R is supported in the axial magnetic field of the solenoid S. Its horizontal position is determined by the symmetrically diverging field of the solenoid and its vertical position is maintained by the automatic regulation of the current through the solenoid. The rotor R is spun by a rotating magnetic field produced by the two pairs of coils D. V is a glass chamber surrounding the rotor which is evacuated to a pressure of approximately 10^{-6} mm of mercury by the usual cold trap diffusion pump, forepump system. The small pickup coil L_1 is in the grid circuit of a radio frequency oscillator which regulates the current through S and thus maintains the vertical position of R. The small iron wire H mounted below the vacuum chamber V in a glass tube G filled with a liquid, aids in damping any horizontal motion of the rotor. In most of these experiments the solenoid S contained 20,500 turns of No. 30 enameled copper wire although, for rotors larger than 1/2", a larger solenoid and different support circuit was used. An iron tube I with 3/4" O.D., 3/32" wall thickness and 3-3/8" long was placed inside the solenoid to increase the magnetic field at R.

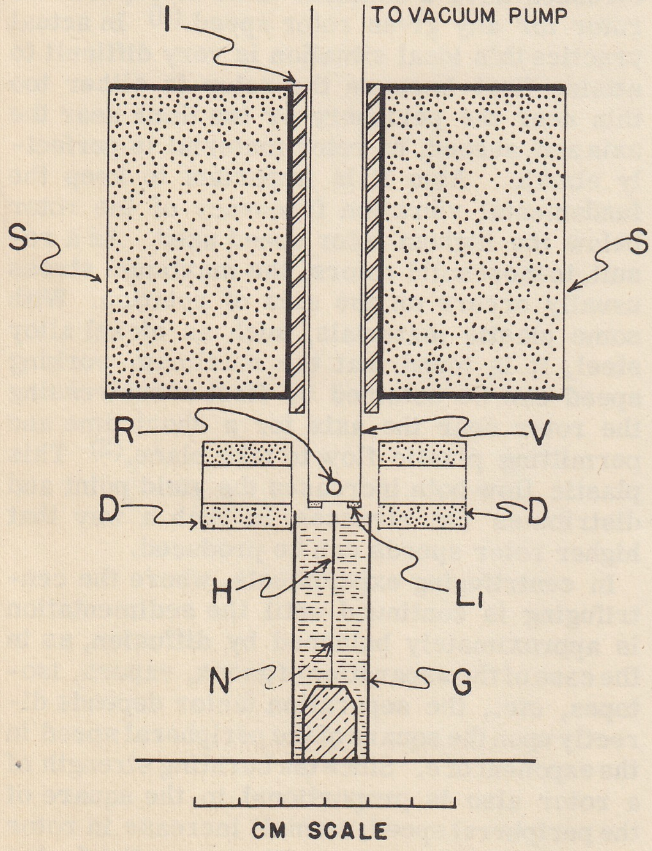

Fig. 1. Schematic Diagram.

Several different types of electronic circuits have been used successfully to regulate the current through S but the one employed in most of these experiments is shown in Fig. 2. It will be observed that the pickup coil L_1 is in the grid circuit of a tuned plate tuned grid radio frequency (10 megacycles) oscillator. When the rotor R approaches L_1 the "Q" of the grid circuit of the oscillator is changed in such a way that the current through the solenoid S is increased. When R rises, the current through S is decreased. In order to prevent vertical hunting of the rotor, a derivative of the signal from S is also introduced into the circuit in such a way as to produce complete damping. For example, with this circuit no observable "hunting" of the rotor can be seen with a 30-power microscope focused upon scratches in the rotor.

The rotating magnetic field which caused the rotor to spin was produced by a standard electronic power oscillator arrangement. The frequency of this generator was set equal to the highest rotor speed required and was usually regulated by a piezoelectric crystal. As a result, during the period of acceleration, the

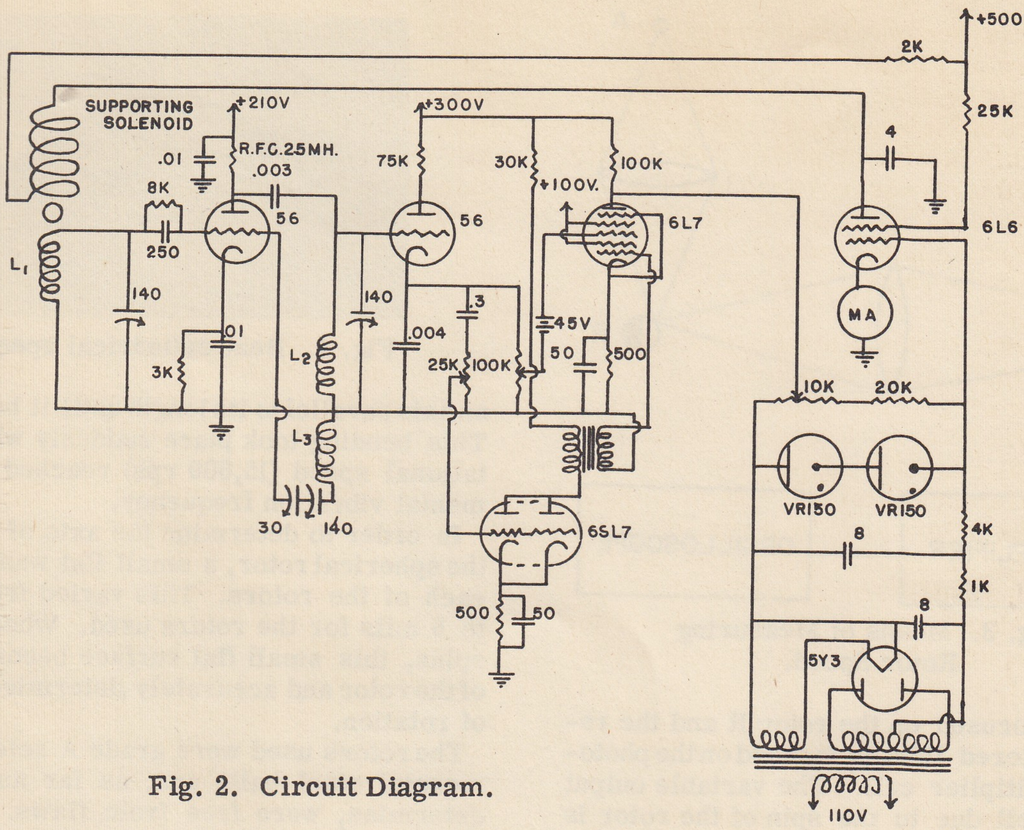

Fig. 2. Circuit Diagram.

rotor acts similarly to the armature of an induction motor. However, when the gas pressure surrounding the rotor is low enough (order of 10^{-6} mm of hg) the rotor accelerates until its speed equals the speed of rotation of the rotating magnetic field. It then "locks in" with this rotating field and operates similarly to the armature of a synchronous motor but without "hunting." This property of locking in with the frequency of the generator makes it possible to maintain very constant rotor speed since, with proper precautions, the frequency of a piezoelectrically controlled circuit can be held constant to one part in from 10^8 to 10^9. When the rotor is accelerated slowly, as was done in these experiments, its temperature remains approximately constant and less than 5°C above room temperature, especially if the temperature of the coils is kept at approximately room temperature.

The low frictional torque of this type of magnetic suspension results from the fact that the magnetic field is symmetrical about the axis of rotation and, consequently, for a symmetrical rotor, the electromagnetic drag should be nonexistent or negligible. In practice, this is found to be the case and the total observed drag can be accounted for as due to air friction alone, even when the pressure is as low as 10^{-6} mm of hg pressure. For example, with a 1.59 mm spherical rotor "coasting" freely at 120,000 rps, with the driving power removed, it required 10 hours to lose one percent of its speed when the air pressure surrounding the rotor was of the order of 5×10^{-6} mm hg, a result in agreement with calculations based on air friction.

The rotor speed was measured by the apparatus shown schematically in Fig. 3. About one-half of the rotor is polished and the other half darkened by dipping in dilute H_2SO_4 which had been in contact with metallic antimony. This gives a very thin, tenacious, dark layer which is not removed until the centrifugal fields reached the order of 400 million times gravity. Several other black deposits and films were tried but were destroyed before the rotors reached full speed. Light from an incandescent

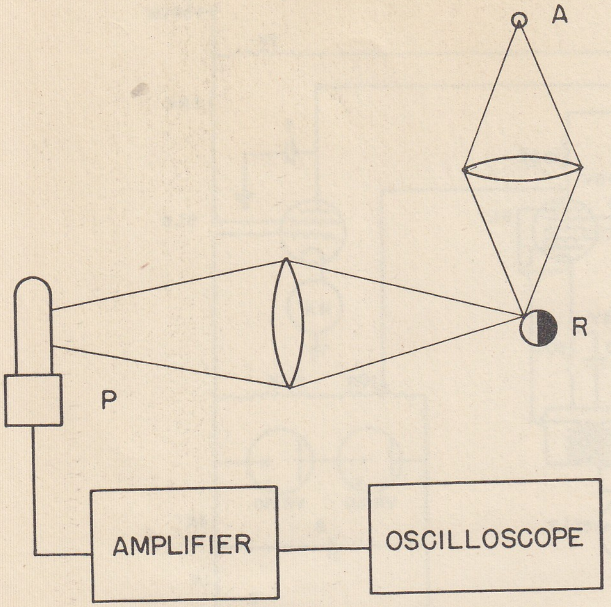

Fig. 3. Means of Measuring Rotor Speed.

lamp A is focused on the rotor R and the resulting scattered light is focused on the photoelectron multiplier cell. The variable output from this cell due to the spin of the rotor is amplified and fed to one pair of plates of a cathode-ray oscillograph. A known frequency from a standard calibrated oscillator is placed on the other pair of plates of the oscilloscope in such a way that the two frequencies can be compared. In this way the frequency is determined to at least three significant figures. The glass vacuum chamber V and the driving coils are surrounded by a wooden barricade which protects the observer and auxiliary apparatus from damage when a rotor explosion occurs.

EXPERIMENTAL RESULTS

In these experiments, spherical alloy steel rotors were used because carefully hardened and accurately ground rotors were available in the form of commercial balls used for ball bearings. Also, spherical rotors have their fundamental vibration frequency well above the rotor speed at which they should explode.(5) The importance of this latter requirement is shown in Fig. 4, which is a photograph of a steel rod 1.5" long, 3/16" in diameter, which was magnetically supported and spun around an axis parallel to its length until it bent double. This bending took place suddenly when its rotational speed (15,600 rps) reached the fundamental vibration frequency.

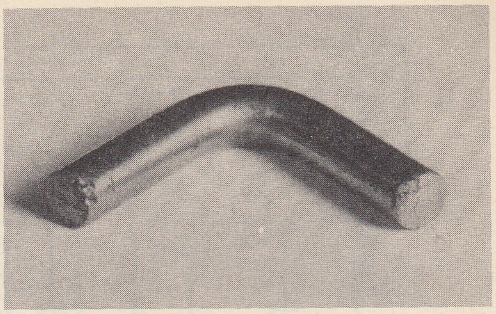

Fig. 4. Bent cylindrical specimen.

In order to determine the axis of rotation of the spherical rotor, a small flat was ground on each of the rotors. This varied from 0.5 mil to 5 mils for the rotors used. When the rotor spins, this small flat surface becomes the top of the rotor and accurately determines the axis of rotation.

The rotors used were grade A selected commercial steel balls and, as far as one could determine, were free from flaws. However, quite a number of them exploded at comparatively low rotor speeds. Upon examination of the fragments of these exploded rotors, definite flaws were observed in almost every case. Fortunately, a large number of the rotors required very high rotor speeds (high calculated stresses) to explode them.

In practice, although the two rotors may be made of the same kind of material, accurately ground to the same dimensions, and apparently free from major flaws at least, they do not explode at exactly the same rotor speed. In other words, the bursting speed is a statistical value. Table I gives some of the results obtained for a series of rotors just before the rotors exploded.

It will be noted that all of these rotors exploded when the peripheral speed reached approximately 10^5 cm/sec, which is in agreement with the theory that assumes the rotors are elastic.(6) This elastic theory shows that the maximum stress in the rotor occurs at the center.

The maximum calculated radial stress values are recorded in the fifth column of Table I and are seen to be quite large. These calculated

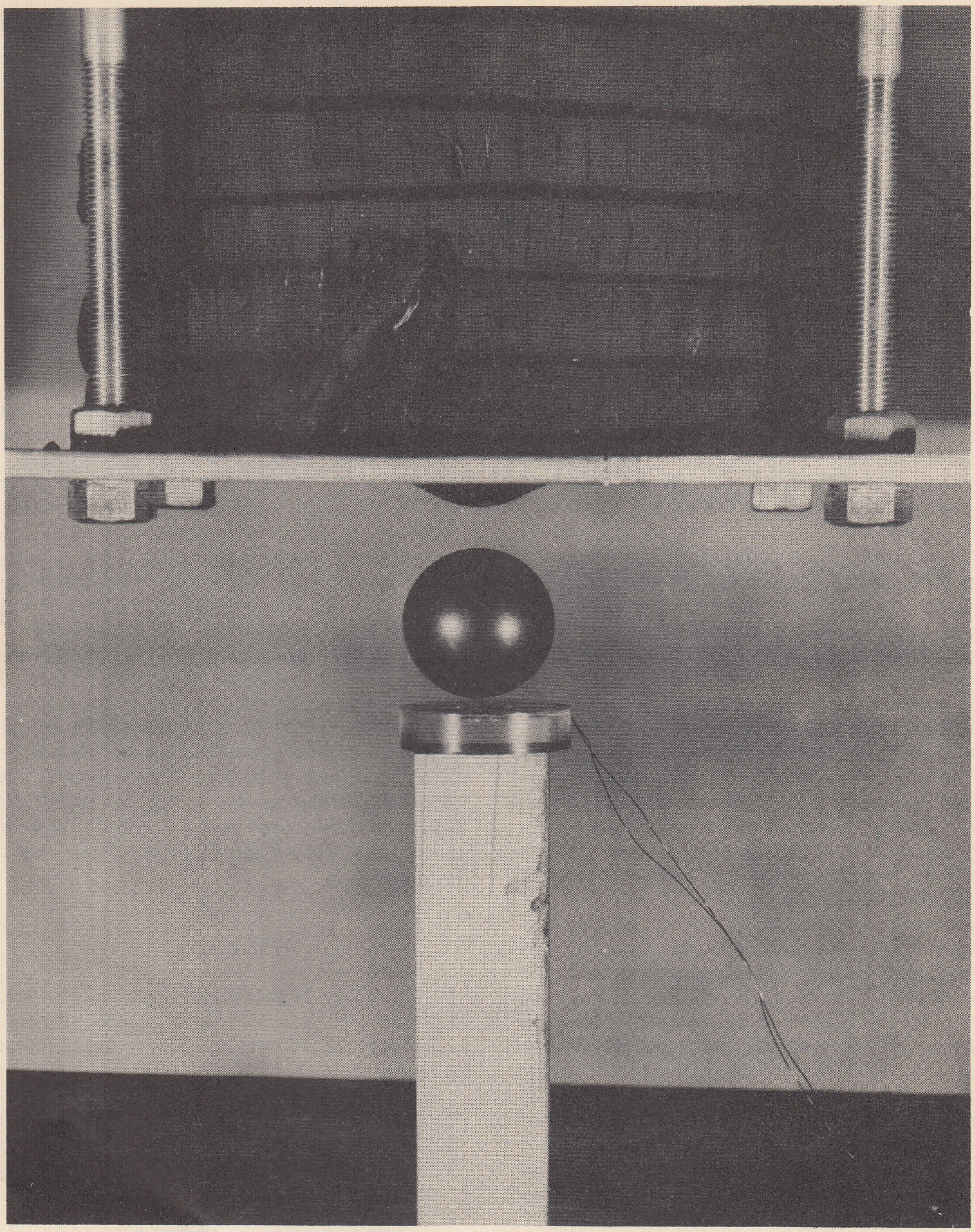

Fig. 5. Two-inch diameter spherical steel rotor supported by magnetic suspension.

TABLE I

Diameter rotor mm	Rotor speed r.p.s.	Peripheral speed cm/sec	Centrifugal acceleration x gravity	Maximum calculated stress lb/in^2
3.97	77,000	9.60×10^4	4.71×10^7	410,000
2.38	123,500	9.25×10^4	7.20×10^7	385,000
1.59	211,000	1.05×10^5	1.43×10^8	498,000
.795	386,000	9.65×10^4	2.40×10^8	420,000
.521	633,000	1.04×10^5	4.28×10^8	488,000

stresses may be larger than those actually existing, because of plastic flow in small regions around the center. This would redistribute the stresses. The fourth column gives the values of the centrifugal acceleration on the periphery and it will be noted that it varies from about 47 to 428 million times gravity, as the diameter is reduced from 3.97 mm to .521 mm.

Although a sufficient number of rotors have not yet been exploded to allow reliable conclusions to be drawn, the data indicate that the probability of a given rotor reaching a maximum peripheral speed, such as recorded in the table, increases with decreasing size of rotor. This probably arises from the fact that as the size of the rotor decreases, the relative volume of metal which receives the maximum radial stress, such as recorded in the table, decreases with decreasing size of rotor. Consequently, the probability of finding a flaw in this region is decreased.

If windows of plane optical glass are mounted in the walls of the glass vacuum chamber and an enlarged image of the spherical rotor is projected on a screen, the change in shape of the rotor can be observed as its speed changes. The diameter of the elastic rotor perpendicular to the axis of rotation should increase, while that along the axis should decrease as the rotor speeds up. It is hoped that a precise study of these values can soon be undertaken, as it should afford a direct method of testing the calculations. Also it is hoped that experiments on the bursting of spherical rotors larger than those shown in Table I can be carried out. Fig. 5 shows a photograph of a two-inch diameter spherical steel rotor suspended by magnetic suspension. Single crystals of iron have been supported and spun and an investigation of their elastic properties is in progress.

It is well known that if a steel fiber is stretched, its strength increases in the direction of its length. The question naturally arises as to how much, if any, of the strength increases perpendicular to its length. Experiments are under way at Virginia with the view of determining this by spinning short sections of the fibers (1 mil diameter) until they explode. In order to support these small fibers in a magnetic suspension, the scattered light from the suspended rotor fiber is made to actuate a photocell control circuit which is used to regulate the current through the solenoid, rather than the method shown in Fig. 2. Incidentally, this experiment provides a method of producing centrifugal fields many times those recorded in Table I.

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