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Citation: Review of Scientific Instruments **18**, 57 (1947); doi: 10.1063/1.1740818
View online: https://doi.org/10.1063/1.1740818
View Table of Contents: http://aip.scitation.org/toc/rsi/18/1
Published by the American Institute of Physics

THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 18, NUMBER 1 JANUARY, 1947

Speed Control for the Air-Driven Centrifuge*

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(Received September 17, 1946)

A method based on some work of Thomas Davis is described for controlling the rotor speed of an air-driven ultracentrifuge. A permanent magnet mounted on the shaft of the centrifuge induces an e.m.f. in a series inductance, capacity resistance circuit which has the same frequency as the rotor. When the rotor speed approaches the resonance frequency of the circuit, energy is absorbed, and the driving air pressure *versus* rotor speed relation increases abruptly. By regulating the driving air pressure at a few lbs./in.^{2} above that necessary to maintain the speed of the centrifuge where resonance begins, the rotor speed is held constant to roughly 0.1 percent over the range of speeds employed.

In many types of experiments in which a high speed centrifuge is employed, it is necessary to maintain the rotor speed as constant as possible.[1,2] This is especially true where the self-balancing, convection-free centrifuge is used as an analytical tool for the determination of molecular weights or as a means of purifying or separating substances of almost the same density. Some time ago, an electrically driven vacuum type self-balancing ultracentrifuge was developed,[3] which had excellent speed control and operated from the regular 110-volt, 60-cycle power lines. However, up to the present time these electrically driven centrifuges have not been used extensively because there has been no adequate source of supply. On the other hand, the air-driven self-balancing ultracentrifuges[2,4] have been widely used principally because of their greater availability and ease of construction. These air-driven vacuum type ultracentrifuges will produce a maximum rate of sedimentation because they are convection free and can give a centrifugal field which is limited only by the mechanical strength of the rotor. However, usually considerable trouble is encountered in holding their speed constant enough for the experiments unless the air pressure valves are controlled manually or by quite an elaborate automatic mechanism. Also, there is always the danger that the centrifuge will over speed and explode the rotor.

The purpose of this paper is to describe a comparatively simple device which will maintain the speed of the air-driven centrifuge constant to the order of 0.1 percent for as long as desired. It is based directly upon some work of Thomas Davis[5] carried out in this laboratory about ten years ago. It consists in removing the excess driving energy electrically when the desired rotor speed is attained, and thus maintaining the speed constant. A magnet attached to the centrifuge shaft induces an alternating e.m.f. in a series inductance capacity resistance circuit whose frequency is equal to the frequency of rotation of the centrifuge. If this circuit is tuned to resonance at just above the desired running speed, the circuit will absorb a negligible amount of energy until the rotor speed reaches the frequency where resonance begins. At this speed, the current in the circuit rises abruptly with increase in speed, and hence holds the speed constant if the driving pressure to the air turbine is greater than necessary to maintain the speed.

Figure 1 shows a diagram of this speed control attached to an air-driven vacuum type ultracentrifuge, the essential parts of which have been previously described.[2,4] However, in order to explain the action of the electromagnetic speed control, a brief description of the complete apparatus will be given. The rotating parts consist of the flexible steel shafts $A(0.1'')$ and $A'(0.1'')$, the driving air turbine T, the centrifuge rotor RA, and the magnet M of the control. The shaft is

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* This work was supported by the Bureau of Ordnance of the Navy, contract NOrd-7873.

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[2] J. W. Beams, Rev. Mod. Phys. **10**, 245 (1938); J. App. Phys. **8**, 795 (1937).

[3] C. Skarstrom and J. W. Beams, Rev. Sci. Inst. **11**, 398 (1940).

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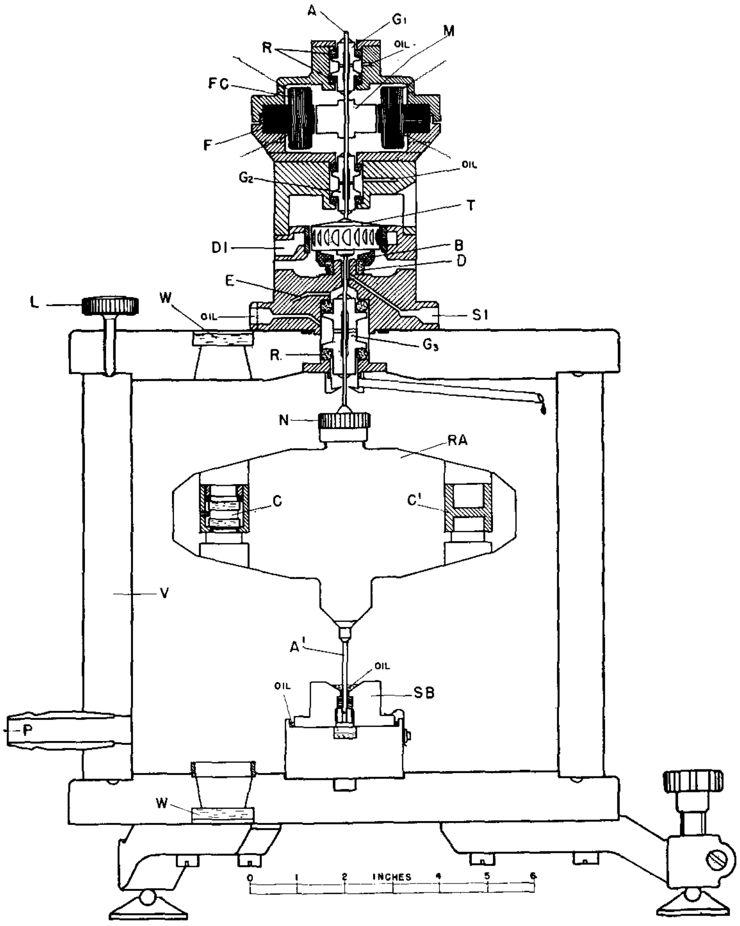

FIG. 1.

vertical and turns in the bearings G_1, G_2, G_3, and a very loose (15-mil clearance) sliding guide *SB*. G_1, G_2, and G_3 are mounted in flexible neoprene rings and are oil sealed. G_3 is lubricated and sealed with a low vapor pressure oil so that a good vacuum can be maintained in the steel vacuum chamber *V*. The guide bearing *SB* serves to prevent "swinging" of the rotor at low speed during acceleration. At running speed, the shaft *A′* runs free in the 15-mil clearance without touching. The rotating members are supported by an air cushion formed between the Bakelite collar *B* and the turbine *T*. This collar is fastened to a flexible neoprene support *D*. The centrifuge rotor *RA* is an ordinary oval shaped analytical rotor with the center of the cell *C* which contains the solution to be centrifuged 65 mm from the axis. The cell *C′* is a counterbalance for *C*. The windows *W* are for observing optically the sedimentation of the material in *C* which, in turn, gives a measure of the molecular weight of the substance in solution. A so-called "quantity" or "preparative" type rotor may be substituted for the analytical rotor *RA* without other changes in the apparatus. The permanent magnet *M* is a hardened steel rectangular bar $1\frac{1}{4}''$ long, $\frac{1}{2}''$ wide, and $\frac{9}{16}''$ high, which is magnetized. It has a hole in the center for the shaft *A*, to which it is rigidly attached by set screws on opposite sides of the shaft. The field coils *FC* consist of a large number of turns of copper wire wound on a laminated field core. The wire must be well insulated, and the material of the laminations suitable for use without appreciable loss at frequencies in the range of rotor speeds used. We have used 0.02″ to 0.0075″ thick silicon steel laminations to give a thickness of $\frac{9}{16}''$. The copper wire was No. 21 enameled. Sufficient turns were used to give an inductance greater than 30 millihenrys for the coils connected in series.

The two field coils *FC* were connected in series to give maximum magnetic flux through the field core. In these experiments, two opposite poles were employed for the field, but a larger number may be used if desired. The two field coils are connected to condensers to give a series resonant circuit with a frequency just above the running speed of the centrifuge. The condensers should be free from loss at the desired resonant frequency and, of course, should be able to withstand voltages in excess of those developed. In most of these experiments, three or more 2000 v condensers were connected in series since this gave frequency flexibility as well as reduced the voltage developed across any one condenser.

To operate the machine, oil is forced into G_1, G_2, and G_3, and the vacuum chamber *V* evacuated through *P*. Compressed air is then applied through *SI* to the air support at a pressure (10 to 15 lbs./in.^{2}) which allows the rotating members to turn freely. The driving air is then admitted through *DI* to the turbine *T*, and the centrifuge starts spinning. The centrifuge will continue to accelerate until electrical resonance starts in the circuit. The rotating magnet *M* induces an e.m.f. in the field coils equal to its frequency of rotation. However, the current in the circuit is very small until the circuit starts resonating. When this occurs, the current increases abruptly with frequency, and the reaction is such as to brake the magnet, thus preventing it from further angular acceleration. If, now, the driving air pressure is set a few lbs./in.^{2} above that necessary to maintain this speed of the centrifuge (determined with the field coils *FC* open circuited), the resonance circuit will absorb the surplus energy, and the rotor speed will be maintained constant.

Table I gives the observed values of the driving pressure, rotor speed, current, and power consumed by the electrical circuit just after the circuit starts resonating in a typical experiment.

The resonance frequency of the circuit with which the data of Table I were taken was between 925 and 930 r.p.s. The two field coils in series had an inductance of about 50 millihenrys and a resistance of 3.7 ohms. The effective resistance of the whole circuit was 4.55 ohms. The driving air pressure required to maintain the centrifuge rotor speed between 900 r.p.s. and 930 r.p.s. with the electrical circuit open, was between 20 and 25 lbs./in.^{2}.

It will be observed that, with the electrical circuit connected, the driving air pressure *versus* rotor speed relation rises abruptly between 25 and 35 lbs./in.^{2}. As a matter of fact, an increase from 35 lbs./in.^{2} to 70 lbs./in.^{2} or doubling the driving pressure increased the rotor speed by less than 1.5 percent. Also, it will be noted that the current and power absorbed by the circuit increases rapidly with rotor speed. Sufficient air pressure was not available to drive the centrifuge through the resonance frequency, consequently it was impossible to over-speed the rotor. However, by disconnecting the electrical circuit, the centrifuge was easily spun to a speed well above the resonance frequency (about 1050 r.p.s.). The circuit was then closed, the driving air turned off, and the centrifuge allowed to "coast" down through the resonance frequency. The current in the circuit at resonance was approximately 6 amp., and the potential across the condensers was over 1000 volts (effective). The power dissipated at resonance was about 165 watts. As a result the centrifuge decelerated very rapidly down to about 900 r.p.s.

With a pressure regulator (Foster) in the driving pressure line, observations were made on the constancy of the centrifuge speed with the regulator valve set at a number of different driving pressures between 35 and 50 lbs./in.^{2}. It was found that the speed remained more constant than that of the audiofrequency oscillator available (0.2 percent) with which it was compared, so a re-wound electrical clock (Hammond Jr) was placed across one of the condensers in the circuit, and the number of revolutions made during several minutes was counted. From this the rotor speed was found to remain constant for long periods of time to roughly 0.1 percent. Also, the

TABLE I.

Driving pressure gauge lbs./in.^{2}	Rotor speed r.p.s.	Current amps.	Power consumed watts
22	892.0	0.01	0.0004
35	902.3	1.15	6.0
40	904.9	1.33	8.0
50	911.0	1.50	10.05
60	914.9	1.65	12.3
70	915.2	1.85	15.6

air pressure was cut off in front of the regulating valve and the centrifuge allowed to stop. After several hours, the air pressure was turned on again (without disturbing the regulating valve) and the centrifuge accelerated to the same speed as in the previous experiment, to about 0.1 percent, and then remained constant. This of course is very useful when centrifuging experiments are to be duplicated. The presence of the clock in the circuit changes the effective resistance, resonance frequency, etc., of the circuit, but this can be allowed for. However, it is an unnecessary complication if accurate frequency standards are available, since the frequency of the circuit (rotor frequency) can be compared directly with the known frequency by means of Lissajous figures on an oscilloscope screen.

In the above tests, the high pressure line was regulated roughly so that the Foster regulator could maintain the driving air pressure constant to about 0.5 lbs./in.^{2} at the various pressures used. With the electrical circuit disconnected and the driving pressure adjusted to give a rotor speed of approximately 900 r.p.s., the speed drifted a little less than 2 percent. This drift, of course, depends upon the period of fluctuation of the driving pressure as well as its magnitude. It is dependent, also, upon the characteristics of the turbine and the relation of the air friction on the turbine and spinning magnet *M* to the bearing friction, etc. However, in the above case, the speed regulation was improved almost 20 times by the electromagnetic control. Also it should be noted that if desired, the speed regulation can be much increased by decreasing the effective resistance in the electrical circuit or by adding more field coils *FC*. That is, it is possible to secure speed regulation considerably better than the 0.1 percent obtained in these experiments.

Since the field coils and magnet absorb energy, they must be cooled. This is accomplished by the "fanning" action of the rectangular shaped magnet. The housing around the field has open spaces so that air can circulate freely through it. In practice, it quickly reaches an approximate equilibrium temperature which is not much above that of the room, also, as shown in Fig. 1. The coils and magnet are insulated thermally from the centrifuge rotor by the driving turbine where comparatively large quantities of escaping air carry off any heat conducted downwards.

If variable condensers or inductances and variable resistances are placed in the electrical circuit, the circuit can be made to decelerate the centrifuge at almost any rate desired. This is often a considerable advantage where the energy stored in the centrifuge rotor is large.

In the above experiments, a simple two-pole field was used and since this decelerates the magnet only twice during each revolution, a slight hunting (in each revolution) might possibly be expected to occur. However, no hunting was observable. The large centrifuge rotor and flexible shaft evidently prevented it from taking place. If hunting should occur, say with a small rotor, more poles of course can be used, which should eliminate it. It is clear that this type of circuit may be used as a source of alternating power or that it may be applied to any type of rotating machinery where constant rotational speed is required.

Members at Large of the Governing Board of the American Institute of Physics

(Three to be Elected by Mail Ballot)

THE amended Constitution of the American Institute of Physics Incorporated (see page 7 of this issue) provides that there shall be three directors elected by a mail ballot of the Members and Associate Members of the Institute. The first election will be held in 1947 to choose three directors whose terms, commencing with the Annual Meeting of the Corporation in February, 1948 will expire, one at the Annual Meeting in 1949, one in 1950, and one in 1951.

The Rules provide for appointment, by the Governing Board, of a Nominating Committee to present at least three candidates for each of these officers. Moreover, the name of any person recommended in writing prior to May 1, 1947 by 15 or more Members or Associate Members shall be included on the ballot as a nominee.

The suggestions of Members and Associate Members, addressed to the Nominating Committee, American Institute of Physics, 57 East 55 Street, New York 22, New York, will be received with appreciation.