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C. Skarstrom, and J. W. Beams

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for each of our subscribers in every issue of this section. The Associate Editor will welcome reminders from our readers of instruments that have been overlooked or suggestions of appropriate items that should be included.

As an experiment, it is planned that the section "Current Literature of Physics" will be arranged with regard to a simple subject index, instead of being listed according to journals. The Editor will welcome comment on this change and suggestions for further improvements.

Many subscribers to the *Review* have remarked that they have missed the section "Physics News," which was a regular feature of this journal until January, 1939. In it appeared notices of meetings to be held by member societies of the Institute and by local groups devoted to physics, announcements of available fellowships and scholarships in physics, calendars of important lectures and symposia, news of appointments and changes in status of physicists, and death notices. This section is being reinstated in charge of Professor Louis N. Ridenour, of the University of Pennsylvania; and its coverage, interest, and usefulness will be in direct proportion to the cooperation our subscribers show in submitting news items for inclusion in it. Letters are being sent to many of the physics departments and research groups from which news items will frequently come, asking their help in developing this section, but inevitably many groups will be missed, and the assistance of our readers in gathering physics news is here requested.

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The Electrically Driven Magnetically Supported Vacuum Type Ultracentrifuge

C. Skarstrom and J. W. Beams
Rouss Physical Laboratory, University of Virginia, Charlottesville, Virginia

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The electrical motor drive and the magnetic support for the vacuum type ultracentrifuge have been revised and improved. The drive is a two-phase motor and the support a solenoid which attracts a solid steel cylinder fastened to the rotating parts. The armature of the motor consists of a solid steel cylinder and a magnetic core support mounted coaxially on a stainless steel tubular shaft. Cooling water passes through the tubular shaft. A two-phase salient pole stator produces the rotating magnetic field when actuated by the output of a transitron oscillator and power amplifier. Condensers in series with the motor field windings split the phase and match the load to the power amplifier. At an oscillator frequency of 1188 cycles per second and an input to the motor of 1 kw, the rotating magnetic field produces a torque of 600 g-cm throughout the starting period up to about 10 percent slip (about ½ hp at 1000 r.p.s.). A 7½-lb rotor (6¼″ diameter, moment of inertia of 81,000 g-cm^2) has been accelerated to 1000 r.p.s. in about 18 min. Upon reaching the desired operating speed, a slip speed control actuated by a magnetic pick-up on the centrifuge shaft sharply reduces the power input to the motor and automatically holds the rotational speed constant to within 0.05 percent. When the slip is not too large, the mechanism provides a satisfactory ultracentrifuge drive which is "run-away proof" and which automatically maintains its speed within ½ r.p.s. from day to day.

THE self-balancing air-driven vacuum type ultracentrifuge has found wide application, both as an analytical tool for the determination of particle or molecular size or weight, and as a means of purifying or separating substances of different densities. The principal reasons for this are as follows: First, the speed of sedimentation is a maximum because the centrifugal force available is limited only by the bursting speed of the centrifuge rotor. Second, the centrifuge is convection-free since, at its working speed, both vibrations and temperature gradients are absent. Also, experiments have shown that the rate of sedimentation obtained is in agreement with that predicted by the theory, assuming no remixing of the materials. Third, the centrifuge is self-balancing and spins in a vacuum. This avoids the necessity for extreme precision in dynamically balancing the rotor and eliminates the undesirable heating of the rotor and excess consumption of power resulting from air friction. Fourth, the cost of the apparatus is not excessive. On the other hand, the operation of the machine is not automatic and requires the constant attention of an operator unless special controlling apparatus is installed. Even then it is extremely difficult to hold the rotational speed constant to a few hundredths of a percent. Also, a supply of compressed air, which is not always available, is essential. In order to overcome these undesirable features, an electrical drive and magnetic support has been substituted for the air drive and support for the rotating parts, but the other features of the machine are left essentially the same.

In previous reports[1,2] descriptions have been given of such machines which, although in many respects superior to the air-driven apparatus, required considerable care and attention during the period of acceleration and were only semiautomatic in operation. Furthermore, the torque was very small when the slip was large. In this paper, a description of an electrically driven, magnetically supported vacuum type ultracentrifuge which is completely automatic and possesses sufficient torque with large slips for rapid acceleration is given. It operates from the 110-volt power lines. The centrifuge starts from rest and accelerates to a predetermined rotational speed, then remains at this speed within at least 0.05 percent for as long as desired. The electrical drive may then be used to bring the rotor to rest quickly if this is desirable. The operator's attention is required only for setting the controls at the beginning and end of the run.

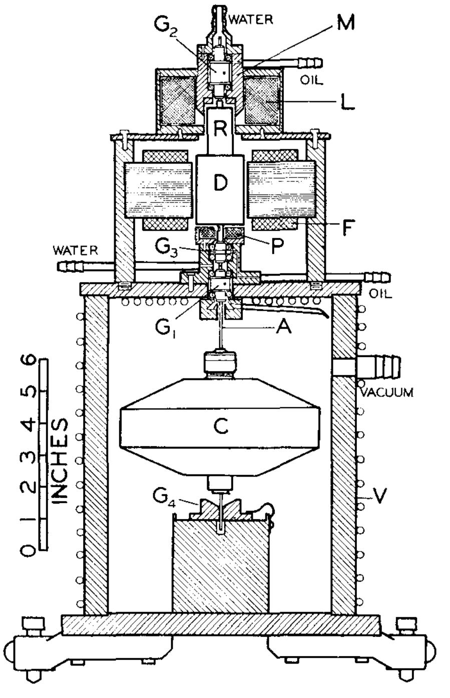

FIG. 1. Partial section of assembled electric ultracentrifuge.

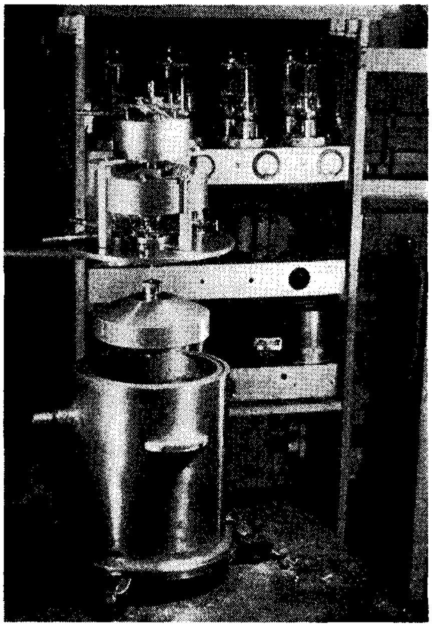

FIG. 2. Photograph of the machine. The power amplifier rack is shown in the background.

DESCRIPTION OF THE MACHINE

A partial section of the machine is shown in Fig. 1. The rotating system comprises the motor armature *D*, $1\frac{1}{2}''$ O.D., the magnetic support core *R*, $\frac{13}{16}''$ O.D., and the rotor *C*, $6\frac{1}{4}''$ O.D. *R* and *D* are made from cold-rolled steel, while *C* is made from forged Duralumin ST14. These are mounted coaxially on the tubular stainless steel shaft *A*, $\frac{1}{8}''$ O.D., through which cooling water passes. Two small holes (No. 56 drill) in the shaft *A*

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[1] J. W. Beams and L. B. Snoddy, Science **85**, 185 (1937).
[2] J. W. Beams and S. A. Black, R. S. I. **10**, 59 (1939).

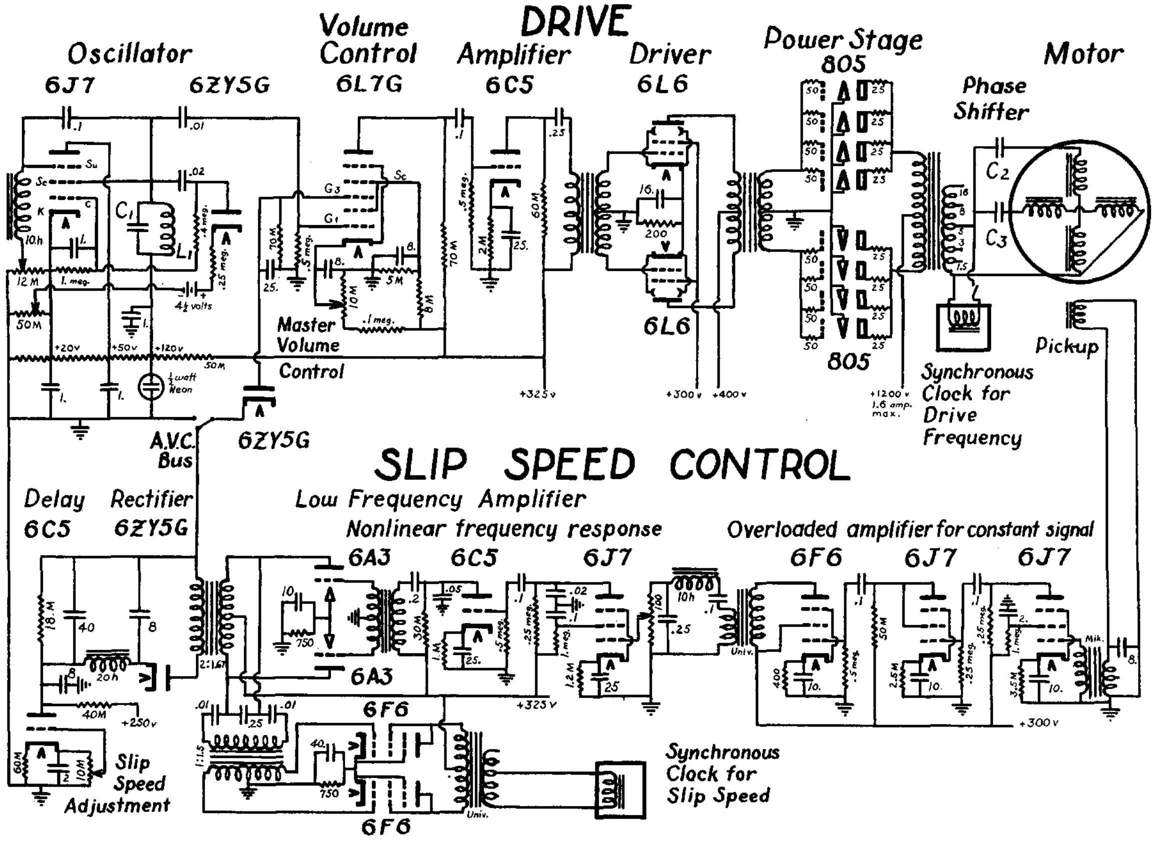

FIG. 3. Electric ultracentrifuge drive and control circuits less power supply. Resistance in ohms, in $M=10^3$ ohms, and in meg $=10^6$ ohms. Inductance in henries. Capacitance in microfarads. For drive frequency $=1188$ cycles per second: $L_1=0.32$ H; $C_1=0.06$ mf; and with opposite stator coils connected in parallel $C_2=3.9$ mf 2000 V D C; $C_3=7$ mf 2000 V D C. These constants may be adjusted for other drive frequencies by switching.

allow passage for the cooling water in the region between G_1 and G_3. The Babbitt-lined bearings G_1, G_2, and G_3 are set in Neoprene rings and supplied with oil[3] under pressure. G_1 is a friction slide bearing whose function is to inhibit precession and damp vibrations at the critical frequencies. G_2 seals off the open upper end of the tubular shaft A. Figure 2 is a photograph of the machine taken before the vacuum chamber V had been water-jacketed.

The nine-pound weight of the rotating system is almost carried by the lifting action of the iron-sheathed solenoid L upon the rotating core R. The remaining weight is borne between the upper Babbitt surface of G_3 and the rotating "pick-up" armature ¼″ O.D. immediately above G_3. This latter bearing is able to support the entire weight of the rotating system with negligible wear in case of failure of the power supply for the lifting solenoid.

The pick-up coil P is a small iron-sheathed solenoid, the armature of which rotates with the shaft. A slight depression is filed half-way around the armature and a corresponding semicircular enlargement is made in the hole through the iron sheath. Stray magnetic flux from the supporting solenoid L is sufficient for the production of an alternating e.m.f. in P equal in frequency to the speed of rotation.

The 6″ O.D. motor stator F is built up from about two hundred 0.0075″ thick silicon steel laminations. Each of the four poles is wound with 106 turns No. 18 copper wire. The poles may be connected either in series or in parallel to make, essentially, two crossed solenoids. A rotating magnetic field is produced when this stator is connected to a two-phase a.c. source. The

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[3] Hyvac pump oil No. 93050B.

speed of rotation of the magnetic field is equal to the frequency of the source.

The clearance between the pole face and the armature is $\frac{1}{8}''$. This was determined for this stator by testing armatures of different sizes, shapes, and materials. The criterion for excellence was minimum centrifuge starting time with a fixed power input to the motor.

DESCRIPTION OF DRIVE AND CONTROL CIRCUITS

The a.c. to drive the motor is obtained from an electronic power amplifier excited by an independent audiofrequency oscillator as shown in Fig. 3. Change of the one-phase output of this power amplifier into two phases is accomplished by capacitor phase shifting. One of the motor fields is series tuned above resonance, while the other field winding is series tuned below resonance until the two motor current phases are 90° apart. In this way maximum torque is developed by the motor and the power tubes may be operated at their maximum ratings into practically a resistive load.

This resonant type of phase shifting acts as an independent safety speed control in that it gives maximum motor torque only for the drive frequency for which it is adjusted. Thus an accidental increase in the oscillator drive frequency unbalances the phasing network and sharply reduces the motor torque.

A "transitron"[4] oscillator is used as a simple and inexpensive source of constant audiodrive frequency. After operation for about an hour, the drift of the oscillator becomes negligible and has a frequency stability of 20 parts per million per a.c. service line volt change. This is due to the inclusion of a compensating delayed automatic amplitude control in the oscillator circuit, the net delay voltage being obtained from the difference between the e.m.f. of a small "C" battery and the voltage drop across a resistance in the supply bleeder circuit.

The constant signal from the oscillator passes through a volume control tube in which its magnitude may be varied either manually or electronically by a constant speed control circuit. The controlled signal is then amplified and fed to a pair of 6L6's in push pull. These supply 24 watts to drive the four pairs of RCA 805's operating at zero bias in class *B*. The output of this power stage drives the motor through a suitable impedance matching transformer.

In operation, the speed controlling action occurs as follows: Both the drive frequency and a frequency equal to the speed of rotation appear as alternating e.m.f.'s in the pick-up coil *P* (Fig. 1). As the motor accelerates, these two frequencies approach each other. It is possible to combine them into a single slip frequency equal to their difference. This is accomplished by rectification of the output of the pick-up coil in an overloaded amplifier (Fig. 3). The overloading also constitutes a simple automatic volume control for this slip frequency.

From here the constant amplitude slip frequency passes into another audioamplifier with a rising response in the base. As the motor speeds up, the slip frequency becomes smaller, producing a larger and larger control voltage from the rectified output of this amplifier. When the magnitude of this rectified slip frequency exceeds an adjustable delay voltage, the resulting difference of a few volts is applied to the electronic volume control tube in the main drive circuit. This sharply reduces the power input to the motor so as to maintain a preassigned slip speed and, hence, a constant rotational speed of the ultracentrifuge.

The entirely automatic action of the slip speed control may best be described by example. As the machine accelerates with 1 kw input to the motor, the controlling action is inoperative until the speed of the ultracentrifuge reaches about 2 r.p.s. less than the desired operating speed. Within one minute, the acceleration is progressively reduced to zero by the action of the slip speed control in diminishing the motor power input to that just necessary to keep the slip speed constant. At this operating speed of the machine, a change of one revolution per second in the actual speed is equivalent to a change of one cycle per second in the slip speed. Because of the nonlinear frequency response of the slip speed amplifier, this change of frequency produces in turn a change of one volt in the speed control bias on the control grid (G_3) of the volume control tube in the main drive circuit. This modifies the power fed into the motor by 250

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[4] C. Brunetti, R. S. I. 10, 85 (1939).

watts. Thus, since the motor being described requires about 500 watts to maintain 1000 r.p.s., a speed change of 0.1 percent produces a 50 percent counteracting change in motor power input. The sharpness of the slip speed control is evident.

The field windings of two synchronous household electric clocks[5] were removed and each replaced by 200 turns No. 22 copper wire. One clock operates on the drive frequency when connected to the output of the power stage. The other clock operates on the slip frequency when connected by a separate 10-watt amplifier to the slip speed control. The difference in the rates of these two synchronous clocks measures the speed of the ultracentrifuge.

OPERATION

With 1-kw input at 1188 cycles per second the motor alone accelerates to 1000 r.p.s. in 15 seconds. When the seven and one-half pound rotor *C* is attached and spun in a vacuum, the starting time is from 18 to 25 minutes, depending upon the condition of the bearings. A typical torque-speed curve is shown in Fig. 4. The total torque developed by the rotating magnetic field is shown as the sum of that absorbed by friction and that appearing as angular acceleration of the system whose moment of inertia is 82,100 g-cm^2. The frictional torque is obtained from deceleration measurements as the machine coasts to rest. The acceleration measurements were made with 1-kw input to the motor. The total torque is fairly constant throughout the starting period, falling off sharply when the speed of the machine reaches 90 percent of synchronous speed.

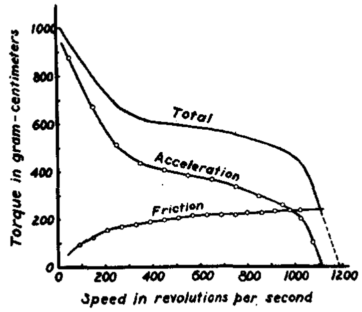

FIG. 4. Torque-speed relation with 1188 cycles per second drive frequency and 1 kw motor input power.

In Fig. 5 the action of the machine as it approaches its limiting speed is shown. In this figure, the power input to the motor necessary to hold the slip constant is plotted against the amount of the slip so maintained. It is to be noted that with a maximum input of 1 kw, the motor speed is inherently limited to about 70 r.p.s. less than the synchronous speed (1188 r.p.s. in this case).

While the motor may be operated using the full output of the power amplifier, it is more economical to select a running condition at which the power input for constant speed is less, i.e., in the region where the slip speed is between 100 and 180 r.p.s. (Fig. 5). This is accomplished by the inclusion of the slip speed control in the electric circuit which automatically adjusts the power delivered to the motor so as to maintain a constant and preassignable slip speed. Because the ultracentrifuge rotor *C* (Fig. 1) is usually operated just below its bursting speed, it is well for reasons of safety to have the inherent speed limit of the motor kept close to the operating speed. In this way, failure of the slip speed control for any reason can only result in a small increase in the absolute speed of the machine (30 to 110 r.p.s.). This is in contrast to other types of drive and control methods with which failure of the controlling mechanism may result in an explosion if not prevented by the operator.

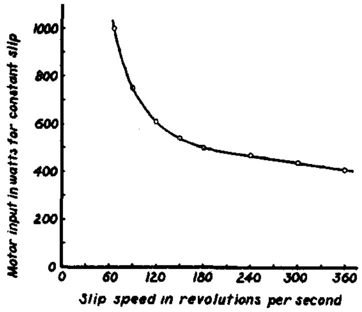

FIG. 5. Motor power input necessary to maintain constant centrifuge speed *versus* the slip speed. Drive frequency = 1188 cycles per second.

A further advantage of having the speed control operate on the slip speed rather than on the actual speed lies in the precision of the control obtainable with inexpensive and relatively non-precision equipment.

In Fig. 6 are shown two 10-hour runs made on successive days. The operating technique for these runs was as follows: The bearings were supplied with oil under 12 lb./in.^{2} pressure and the

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[5] Hammond Junior Synchronous Electric Clock, non-self-starting; Hammond Clock Company, Chicago, Illinois.

chamber *V* surrounding the rotor was evacuated to 10^{-4} mm of Hg. Cooling water was passed through the armature at the rate of 200 cc/min. The magnetic supporting solenoid was supplied with 0.19 amp. d.c. at 29 volts.[6] The power amplifier was then turned on and the master volume control set so that the motor input was 1 kw. Without further adjustment the centrifuge performed as shown by *A*, Fig. 6. Within 22 minutes the machine had accelerated to 1026.3 r.p.s. This speed was maintained by the action of the slip speed control within $\frac{1}{2}$ r.p.s. throughout the 10-hour run. At the conclusion of the run, one of the motor fields was reversed and the machine was brought to rest in 10 minutes. Repetition of this procedure in a subsequent 10-hour run, *B*, without any readjustment of the slip speed control shows that the speed of the machine may be duplicated on successive runs. It can be seen in Fig. 6 that the variation of speed throughout one run is about the same as that between successive runs. This is of importance in any planned program of centrifugation, wherein it is desired to subject successive batches of material to the same centrifugal field. The residual variations of speed are due to thermal drift in the electric circuits, variation of the voltage of the a.c. service mains, and variation of bearing friction in the machine.

DISCUSSION

The machine described herein has all the advantages of the air-driven vacuum type ultracentrifuge plus the following features: the motor is inherently speed limited and consequently runaway-proof; the speed control makes possible a simple operating and speed measuring technique; the speed is automatically maintained within at least $\frac{1}{2}$ r.p.s. of a desired speed; the motor may be reversed electrically for rapid deceleration; and failure of the power supply cannot damage the machine.

The slip speed control may be used with a variety of drive frequencies without readjustment because its speed controlling action depends only upon the difference between the drive frequency and the speed of the machine. Thus since it has been desirable to have several intermediate speeds at which the machine is automatically controlled, switching arrangements have been provided to change the frequency of the independent oscillator and to readjust the phase-shifting condensers for the new drive frequency. Drive frequencies from 800 to 1500 cycles per second have been used with this motor and it was found that the average total starting torque was roughly inversely proportional to the drive frequency for the same motor input power. With sufficient power there appears to be no limit to the rotational speed attainable by this driving method other than that determined by the bursting speed of the rotating system.

While the motor has been developed primarily for use as a drive for ultracentrifuges, it should find immediate application as a drive for high speed spindles for drilling, grinding, routing, etc.; for constant high speed rotating mirrors and optical shutters; for the rotating element of small gyroscopic instruments; or for a wide speed range constant torque pulley.

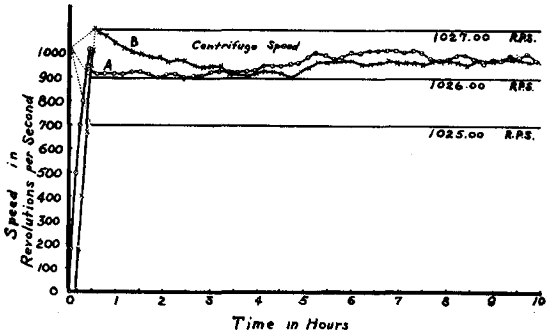

FIG. 6. Two successive runs with the slip speed control in operation. Drive frequency = 1188.0 cycles per second.

We would like to take this opportunity to acknowledge our appreciation to Messrs. Fritz Linke and Ph. Sommer, instrument makers, for their great care in the construction of the centrifuge. Also we are greatly indebted to the Division of Natural Sciences of the Rockefeller Foundation for a grant which has made this work possible.

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[6] It is, of course, possible to replace the supporting solenoid completely or in part by a properly designed permanent magnet.