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Speed Control for the Air Driven Ultracentrifuge

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INTRODUCTION

THE method of speed control[1-3] described in this paper was developed in connection with our work on Svedberg's air driven ultracentrifuge. The necessity of control arises from the fact that by using pressure regulators alone it is impossible to keep the speed of rotation constant enough for any accurate experiments. In a typical experiment, air from a compressor passed in succession through two pressure regulators before impinging on the turbine of the centrifuge, and the pressure in the second regulator was so adjusted as to give a rotor speed of 1024 rev. per sec. It was found that the speed drifted a few rev. per sec. on either side. A rough application of the control, however, immediately brought the fluctuation of speed within 1/5th r.p.s. If due attention be paid to the details mentioned in the last section of the paper, it appears quite possible to keep the speed constant within 1/50th r.p.s. or a still narrower limit. Though in the usual sedimentation experiments it is not necessary to keep the speed constant within such a narrow limit, the method may be profitably used in other experiments where constancy of rotational speed is essential, for example, in the measurement of the velocity of light by the rotating mirror method.

[1] H. Kahler, Rev. Sci. Inst. **9**, 257 (1938).
[2] J. W. Beams, F. W. Linke, and P. Sommer, Rev. Sci. Inst. **18**, 57 (1947).
[3] T. Davis, Rev. Sci. Inst. **7**, 96 (1936).

SPEED MEASUREMENT

The method of speed control depends in principle on the method of speed measurement developed by one of us two years ago in this laboratory.[4] A brief description of this method will be given here. A narrow horizontal slit 2 (see Fig. 1) is placed at a distance of about 2 cm from the incandescent pole of a carbon arc carrying a current of about 8 amp. A magnified image of the slit is formed at a distance of about 2 meters from the slit 2 by a system of two condensing lenses 4 and 5. Two small plane mirrors 7 and 8 are clamped to the prongs of an electrically maintained tuning fork 6 with their reflecting surfaces facing each other. The fork is placed immediately after the two lenses, and the beam of light is multiply reflected from the two mirrors clamped to its prongs. By adjusting the inclination of the fork to the beam of light any desired number of reflections can be taken. If there are r reflections, then the amplitude of vibration of the image of the slit 2 is magnified r times. A much wider horizontal slit 10 is then placed so as to coincide with the image of slit 2. When the fork vibrates, the second slit allows light to pass through it only intermittently with a frequency double that of the fork which was 256 in the experiment performed. A condensing lens 11 of large aperture and about half a meter focal length is placed

[4] S. D. Majumdar, Ind. J. Phys. **19**, 153 (1945).

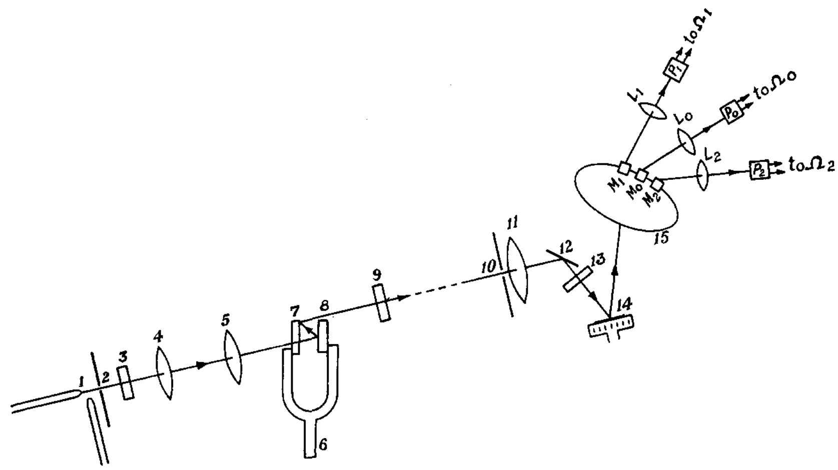

FIG. 1. 1—carbon arc; 2—narrow horizontal slit; 3, 9, 13—cylindrical lenses; 4, 5, 11, L_1, L_0, L_2—spherical condensing lenses; 6—electrically maintained tuning fork; 7, 8, 12, M_1, M_0, M_2—plane mirrors; 10—wider horizontal slit; 14—tilted mirror; 15—circle on which spots appear; P_1, P_0, P_2—photo-cells.

immediately after the slit 10, and the beam of light coming through it is bent downwards by a plane mirror 12 and reflected from a tilted plane mirror 14 (with its normal inclined at about 10° to the axis of rotation) fixed to the top of the turbine of the centrifuge. When the centrifuge is not rotating, a reduced image of the slit 2 is formed on a screen after reflection from the tilted mirror. A cylindrical condensing lens 13 of large focal length placed immediately before the tilted mirror with its axis perpendicular to the slit 10 contracts this image into a small spot of light. If the fork and the centrifuge are now both set in motion a circle 15 of bright spots will be formed on the screen. If the speed be p/q times 512 then q spots will be formed* and there will be only one spot if the speed be any integral multiple of 512. The spot of light thus obtained is extremely sensitive to any slight change of speed. If the speed deviates slightly from an exact multiple of 512 the spot will begin to move slowly in the clockwise or the anticlockwise direction, depending on whether the speed is increasing or decreasing.

* To obtain the numerator of the ratio p/q the slit 10 is slowly moved away from the zero position of vibration of the image of the slit 2. Each spot then splits up into two which again coincide. The displacement of the slit 10 from the zero position necessary to get this coincidence is measured, and from this the numerator p is calculated with the help of a formula given in the previous paper (see reference 1).

INCREASING THE INTENSITY OF LIGHT

The central idea of the controlling device is to prevent both the clockwise and the anticlockwise motion of the spot. Before proceeding to describe this method we shall lay stress on certain points which are essential for the success of the experiment. Since the intensity of light is a factor of great importance, two cylindrical condensing lenses 3 and 9 were used to make full use of the fan-shaped beam of light coming through the slit 2. The first lens 3 (with a short focal length and large aperture) was placed between the slit 2 and the spherical lens 4 with its axis vertical so as to concentrate all the light coming through the slit on the mirrors attached to the fork. The second lens (with a large focal length and large aperture) was placed after the fork with its axis vertical so as to concentrate all the light on the slit 10. At high speeds the shortening of the duration of flashes by multiple reflections at the mirrors attached to the fork becomes indispensable. This leads to a considerable diminution of the intensity of light owing to absorption at the silvered surfaces and the increased amplitude of vibration of the image of the slit 2. The silvering of all the mirrors should therefore be as perfect as possible. Finally, the spherical lenses 4, 5 and the cylindrical lenses 3, 9 should be free from aberration in order that a sharp well defined image of the slit 2 may be formed on the slit 10. The other lenses used in the experiment need not be accurate.

SPEED CONTROL

In the first experiment the pressure regulators were adjusted to give a rotor speed of 1024 r.p.s. The frequency of the fork was 256 and only one spot of light was formed on the screen which moved slowly in a circle 15 of about 6 in. in diameter. Three small mirrors M_1, M_0, M_2 were then placed as close to one another as possible to cover a portion of the circle 15 in which the spot moved. When the spot in its motion reached these mirrors light was reflected to fall on three corresponding photoelectric cells P_1, P_0, P_2 through three condensing lenses L_1, L_0, L_2. The currents in the photo-cells were amplified and operated three sensitive relays R_1, R_0, R_2. Each relay was wound with very fine wire of a total resistance of about 2000 ohms. The operating current was 5 ma and the release current 3.5 ma.

The two amplifier circuits Ω_1 and Ω_2 were symmetrically interconnected as shown in Fig. 2. The coil of each relay was connected to the output of the final valve of the corresponding amplifier circuit. The H.T. voltage was supplied to Ω_1 and Ω_2 from the same battery. The connections to the negative terminal of the H.T. battery were not, however, given directly but through the movable contacts T_1 and T_2 of the relays R_1, R_2. Both T_1 and T_2 were permanently connected to the negative terminal of the H.T. battery. The fixed contact A_1 of R_1 was connected to the negative terminal of the L.T. battery of Ω_2, and the fixed contact A_2 of R_2 was similarly connected to the negative terminal of the L.T. battery of Ω_1. The plates of the final valves of Ω_1 and Ω_2 were connected, respectively, to the fixed contacts B_1, B_2 of the relays R_1, R_2 through a key (K_1, K_2) and a resistance of about 10,000 ohms.

With these arrangements when no current is passing through the relay coils T_1 and T_2 remain in contact with A_1 and A_2, respectively. If light now falls on the photo-cell P_1, the relay R_1 is excited, and as a result the contact A_1T_1 is broken and the contact B_1T_1 made. The current through the relay coil now finds an alternative path through the contact B_1T_1 to the negative terminal of the H.T. battery, and so this contact is not broken even when light is cut off. If light now falls on the photo-cell P_2, it is easily seen that the amplifier circuit Ω_2 will not operate since the connection to the negative terminal of the H.T. battery is given through the contact A_1T_1 which is broken. To operate the circuit Ω_2 the key K_1 has got to be opened. Exactly the opposite thing will happen if light falls *first* on the photo-cell P_2 and *then* on the photo-cell P_1.

The opening of the keys K_1, K_2 was done by the third photo-cell P_0 with the amplifier circuit Ω_0 operating the relay R_0 which simultaneously broke the two contacts K_1, K_2 when light fell on P_0. H.T. voltage was supplied to Ω_0 from a separate battery.

With these arrangements when the speed of

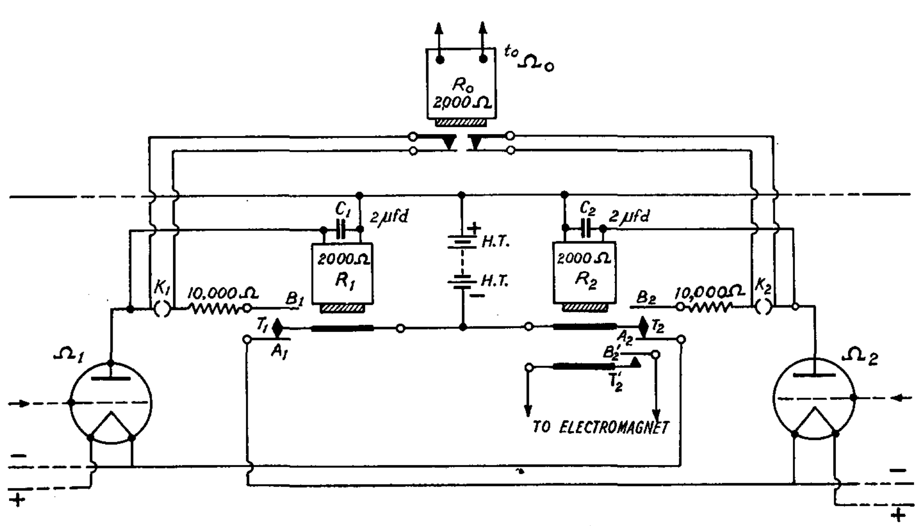

FIG. 2.

rotation was a little higher than 1024 r.p.s. and consequently the light spot was rotating in the circle in the clockwise direction, it traversed the mirrors in the succession $M_1M_0M_2$, and owing to the above interconnections the circuit Ω_1 was completely put out of action and a current almost always passed through the relay coil R_2 except for the short interval between the operations of the relays R_0 and R_2. Exactly the opposite thing happened when the light spot was rotating in the anticlockwise direction and traversed the mirrors in the order $M_2M_0M_1$. The relay R_2 had an additional pair of contacts B_2', T_2' insulated from the ones (A_2, B_2, T_2) mentioned above. When R_2 was excited a current of about 0.2 amp. was established through the contact $B_2'T_2'$ in the coil of a heavy current relay R_3. The relay R_3 established a current of about 2.5 amp. in an electromagnet which partially closed a stopcock, thus reducing the pressure of the air impinging on the turbine.

With the above arrangements when the air pressure was kept a little higher than necessary to keep the spot of light stationary, speed could be automatically controlled for any length of time within a very narrow limit of fluctuation.

DISCUSSION

It will be seen that if the light spot be rotating in the clockwise direction it will be accelerated in passing from M_0 to M_2 along the shorter arc and retarded in passing from M_2 to M_0 along the longer arc of the circle. The mirrors M_1, M_0, M_2 should therefore be placed as close to one another as possible to ensure a resultant retarding effect.

A much narrower limit of fluctuation can be obtained by using, instead of one set of three mirrors, n identical sets symmetrically distributed along the circle in which the spot moves. If there are n such sets then the control will operate n times during one revolution of the light spot, and consequently the limit of fluctuation will be brought down to *roughly* $1/n$th of that obtained by one set. The same result can be achieved by using, instead of n sets of mirrors, n light spots which will be formed at a speed of $512 \times p/n$ r.p.s. if p/n be a fraction in its lowest terms. The second method is certainly more advantageous so long as the intensity of the individual spots does not fall below that necessary to excite the relays.

In trying to obtain extremely small fluctuations of speed in this way the remark made in the first paragraph of this section should be borne in mind. If there are n sets of mirrors and one spot of light (or, n spots of light and one set of mirrors), then the spot will be alternately accelerated and retarded n times during one revolution in the clockwise direction. The distance between the mirrors should therefore be much less than $1/2n$th of the circumference of the circle in order to ensure a resultant retarding effect on the spot. In a typical experiment using one set of mirrors and four spots we succeeded in keeping the speed constant within 1/20th r.p.s.

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