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THE DYNAMIC BALANCING OF ROTATING MASSES

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I had the honor to read a paper before the members of this Institution in November, 1917, on this subject, and this paper is practically a continuation and amplification of the former; I must therefore kindly ask members to carefully bear in mind my previous remarks.

In my previous paper I dealt with our experiences with a particular arrangement of balancing gear, as shown in Figs. 8 and 9 of my former paper, and, from the use of that machine, certain deductions were made as to the necessity for some instrument that would give the angle of lag accurately, and also the amplitude of vibration, and it was hoped, with such an instrument, that we should be able to deduce not only the position of the out of balance weight, but also its amount. The following remarks are the result of our further experiments. It will be noted from what follows that the problem has not been easy of solution, and it has been clouded by unsuspected phenomena, which, I regret, remain yet to be elucidated. Although two years have passed since my former remarks, there yet remains much to be done. I can only plead the pressure of other work, which has prevented our investigations being continued without interruption, as the reason for the present incomplete results. However, some advance has been made, which, it is hoped, may prove of interest.

Consider for a moment the balancing apparatus and the rotor being balanced, what forces are in action, and what means are adopted to control the unbalanced forces.

We have (1) W—the weight of the mass being balanced, and included in this is the weight of the shaft and its bearings; (2) a weight or weights—w—which constitute the out of balance portions of W, included in W, and which, when the mass is rotated, produces a force or forces, F, causing the rotating mass to vibrate; (3) R, the resistance or strength of the springs which a bsorb and balance the forces, F; and (4) f, the friction of the apparatus, which acts against the forces F.

Normally, under simple conditions, the vibration of a spring follows the same law as that of a pendulum, viz., $T = 2\pi\sqrt{\frac{l}{g}}$ (1), when T is the time of vibration and l is the length of the pendulum. In the case of a spring e, the extension or compression of the spring replaces l in the pendulum, so that the time of vibration of any given spring is not constant, but depends upon the amplitude of the extension or compression.

It has been assumed that the motion under review may be generally, neglecting friction, expressed by $T = C\sqrt{\frac{e\ w}{F\ g}}$ (2). when C is a constant.

Now, W may be considerable, depending upon the kind of rotor being balanced; it may be only a few pounds or it may be many tons. The out of balance weights producing F will, in most cases, not be large—anything from a few ounces up to a few pounds—and the strength of the spring which balances F should, presumably, be controllable if we want sensitiveness. F depends not only on the amount and radius of the out of balance weights, but also upon the speed of rotation, and increases directly as the radius at which it acts, and as the square of the revolutions, and that T should apparently be dependant upon e, the extension or compression of the spring, which in its turn gives us the measure of the amplitude of vibration. Therefore, to amplify F, we want a high speed of rotation, that is, we require to make T small; thus e must be small, but this should be reasonably large to enable it to be read without resorting to complicated methods of magnification. In this problem we are faced, therefore, with a number of conflicting factors—what is the best practical solution of these antagonistic elements?

This is the problem which I have been endeavouring to find a good working solution, and in doing so have come up against a number of other most perplexing phenomena.

I have stated that in our original balancing gear the whole weight was supported by the springs. This apparatus did not give much latitude as regards being able to vary the size and strength of the springs; the only variation that could be made was in lengthening or shortening them. Some experiments were made in this direction, but it was found that by using shorter springs T and e were reduced as was expected, but the practical result was that the reduction in e made it unsatisfactory, owing to e being so small. This result was obtained before the apparatus to be described for measuring e had been devised, but the objection, within limits, still holds good.

In the London "Engineer," Vol. XCIX., 15th January, 1915, page 64, is an article describing an apparatus applied in particular to the balancing of electric armatures. The vibratory motion in that gear was horizontal with side springs, and the rotor being balanced was supported on balls.

Again, a paper was read by Comr. F. S. Cleary, U.S. Navy, before the American Society of Naval Engineers (Vol. XXX., No. 1, Feb., 1918), entitled "Dynamic Balancing,'' in which the same method of mounting the rotating masses was adopted.

Apparently in both these cases this method of mounting was found to be satisfactory, but little mention is made of the effect that could or would result from using springs of different length and/or strength. Another important item is the method to be adopted of driving the mass—being balanced—to enable it to be driven freely without interfering with its freedom to vibrate. The methods adopted in the first mentioned paper are by means of a belt as shown in Fig. 1, reproduced from ''Engineering,'' and in Comr. Cleary's apparatus by another method employing a belt, as shown in Fig. II., reproduced from his paper.

In the appliances made at Cockatoo,, as stated in my former paper, the drive is through a flexible shaft and a couple of hook joints.

Further reference will be made to this matter later, as the method of driving has been found to be a most important matter.

Referring again to formula (2), it will be seen that sensitiveness will be increased if W is reduced, as it is evident that that portion of the energy, produced by the unbalanced forces F, used in causing the weights made up of the bearings and its supports to vibrate, will be so much wasted energy. But not much can be done in this direction other than to reduce the bearings and other portions, revolving and non-revolving, which are not part and parcel of the mass being balanced, but in designing a balancing apparatus this point should be carefully borne in mind.

Summarising the above remarks, in order to obtain sensitiveness and the best results, (a) W must be kept

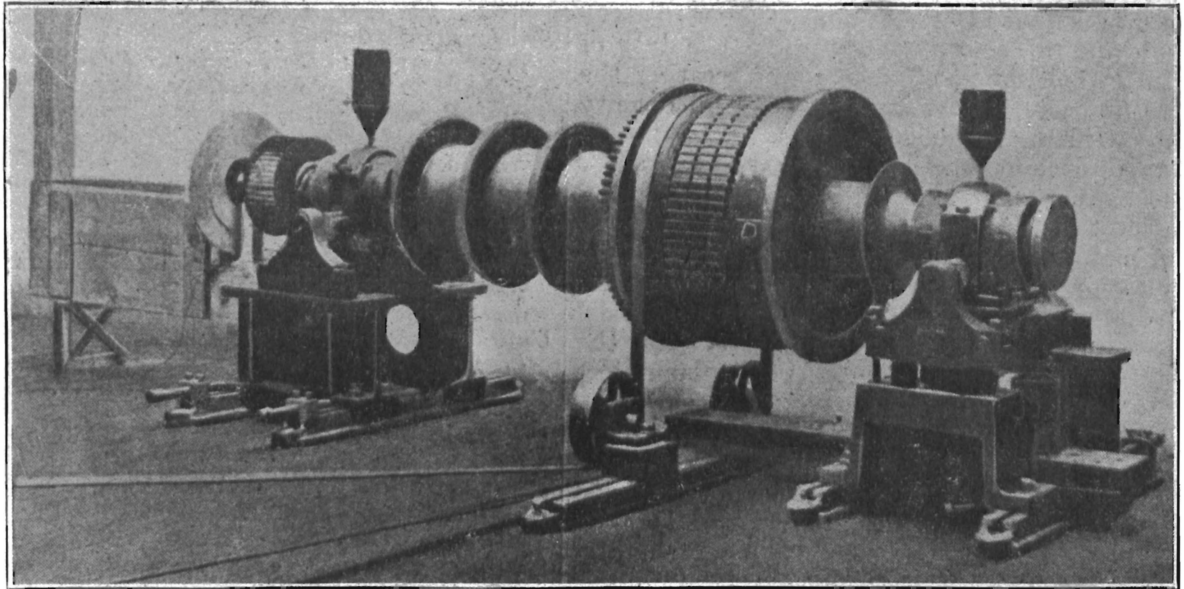


Fig. 1.

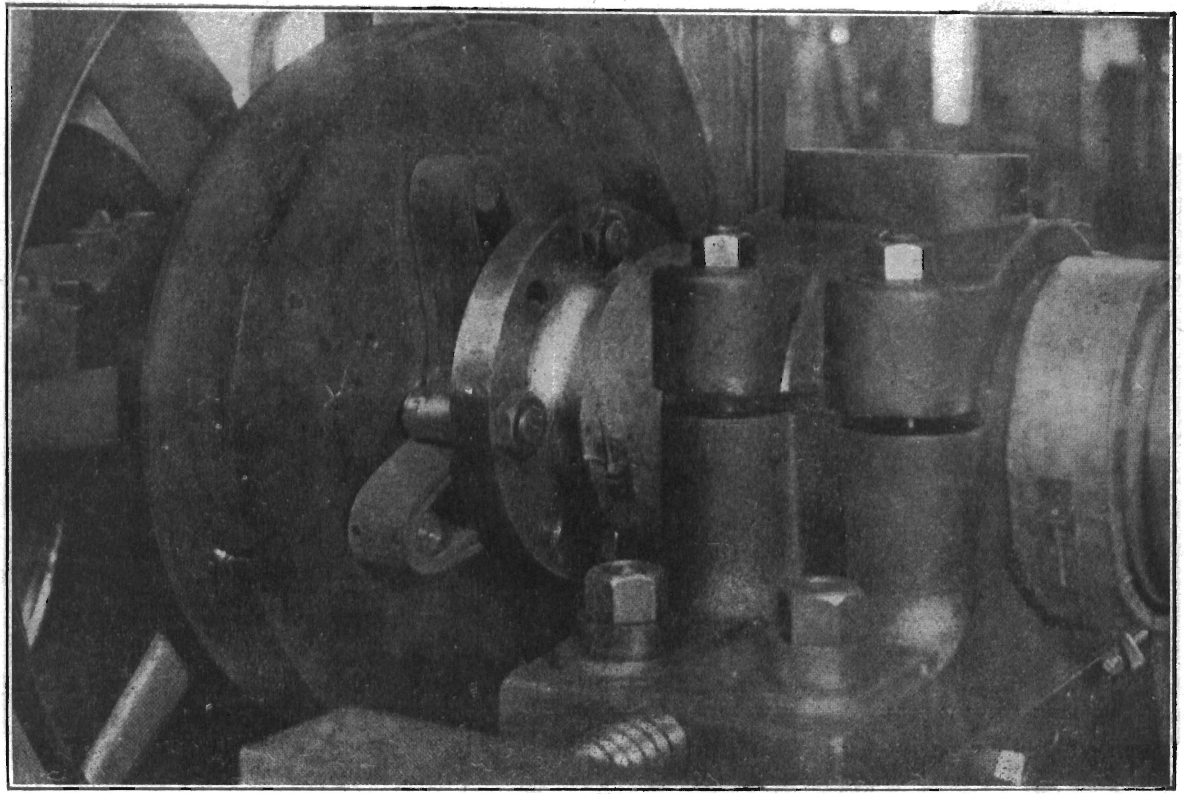


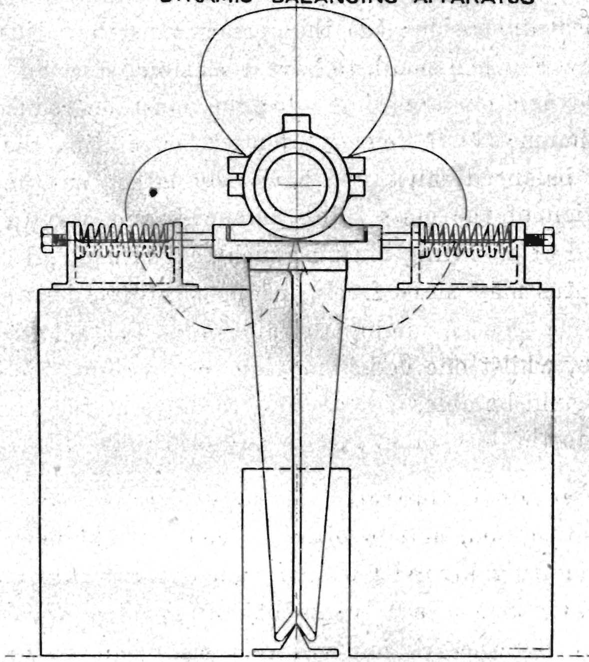
Fig. 2

as low as possible; (b) T must be small to enable the forces F to be utilised at the highest speed possible; (c) e must be as large as possible to obtain readings of a practical dimension; (d) the springs must be adjustable to allow F, when small, to have a sensible effect on them; (e) the friction opposing vibration must be reduced to a minimum; (f) the means adopted for rotating the gear being balanced must not have any effect on the free vibration of the mass being balanced, and also (g) the method of mounting must be such that either end of the apparatus may move freely in opposite directions at the same time, i.e., assuming the apparatus has a horizontal motion, whilst one end is moving to the right, the other one should be able, if necessary, to move at the same instant to the left, or in fact in any other direction.

The original apparatus, as previously stated, had a vertical motion, and in order to control that movement the mounting involved weight which it was desirable to eliminate, and also adjustment of springs was most limited, but the friction was very small, and it fulfilled condition (g) above. On the whole, very satisfactory results were obtained by its use. E.g., the weight of a particular propeller and its shaft was 2.45 tons, and the weight of the reciprocating and non-revolving parts was .8 tons. With a smaller propeller the weights were .725 and .8 tons respectively. Note how heavy the non-revolving parts are compared with the weight being balanced in the latter case.

The next type of apparatus tried took the form of mounting the gear on a sort of hinge as shown in Fig. III., but this was unsatisfactory—being too heavy—and condition (g) was not fulfilled, so that it was finally decided to adopt the method referred to in the two papers mentioned above. This arrangement is shown in Figs. IV. and V.

DYNAMIC BALANCING APPARATUS



HORIZONTAL PIVOTED TYPE

FIG. III

I may observe that this conclusion was arrived at before Comr. Cleary's paper was seen. It consists of two pedestals, on top of each of which are secured hardened steel ball races, carefully levelled, and with guides to control any lengthwise motion; on these ball races rest the bearings on the under side of which are secured races corresponding to those on the pedestals, with a number of steel balls in between the two races. On either side of bearings, at right angles to the axis of the revolving shaft, springs are placed butting up against the bearings, so that when the apparatus is set in motion and vibrates, the springs absorb the forces produced by the out of balance weights,

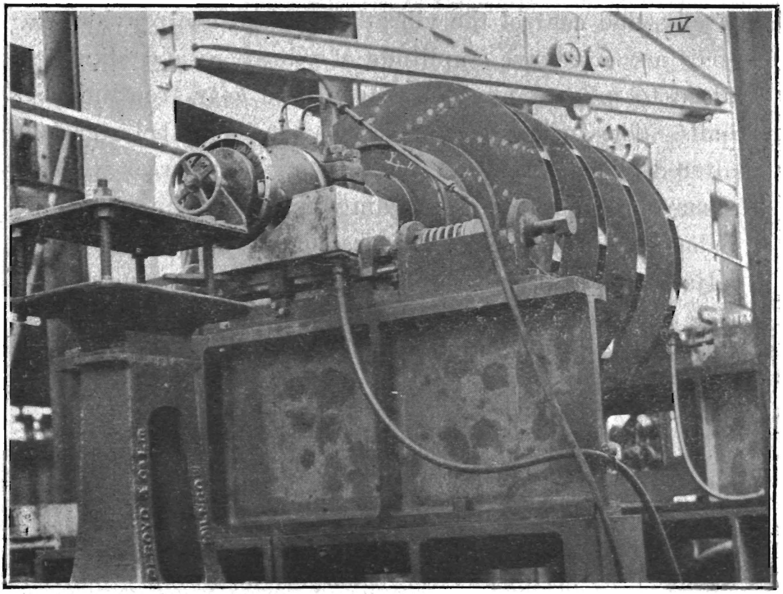


Fig. 4

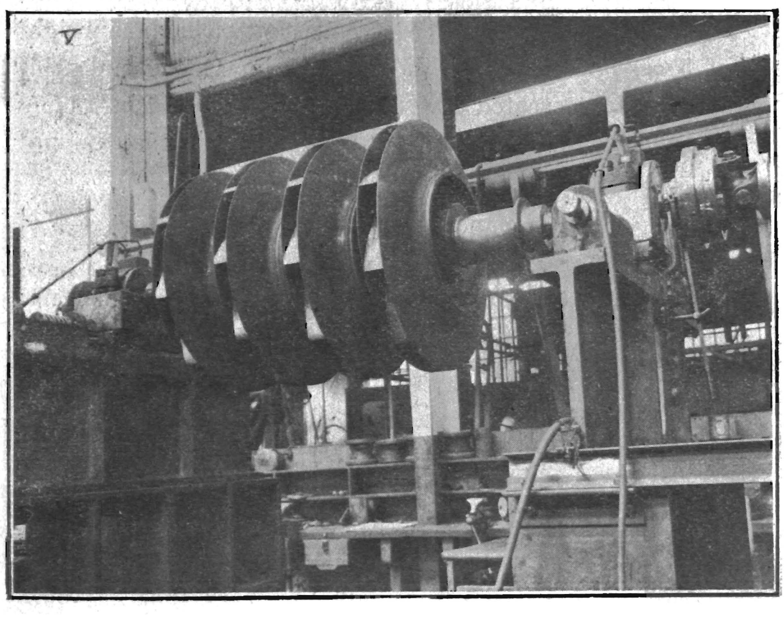


Fig. 5

if any, and control the vibration. Stops are provided to limit any excessive amplitude of vibration, and clips are fitted to prevent any jumping of the gear from off the balls. The springs can be screwed up, and their tension altered by set screws, or other springs—stiffer or weaker—may be substituted, according to the amount of out of balance. Four springs are used, and they are all four adjusted to the same length, and to have the same extension with the same given load. The appliance is driven by an electric motor through the flexible shaft and hook joints previously referred to in the original apparatus. This apparatus has been found to be very sensitive, as the friction is very small, and the weights of the non-revolving parts are reduced to a minimum, and by altering the springs very small out of balance weights can be detected, as practically the whole of the forces produced by the out of balance weights can operate on the springs. A test was made on a rotor weighing over two tons, which, after being balanced, had an out of balance weight of 5 oz. put on at a radius of 11½ in. at one end; this small weight created a vibration of .12 in., and balancing can and would be carried out to well within that amount of vibration.

In my former paper I drew attention to the need of some instrument that would indicate the position on the shaft where the maximum amplitude occurred and also record the extent of that amplitude, as, owing to the rapid change in the lag, as the speed increased or decreased, it was essential that the position of the lag would be determined accurately at the exact instant that the vibration reached its maximum amplitude, also that that maximum once reached was not again attained at any higher speed. This fact has been repeatedly proved during our experiments, and in the work that has been carried out in balancing propellers and other rotors of varying kinds. I further stated, that if the rotor which was being balanced was corrected at that first maximum it would be in correct balance for all higher speeds. This has also been proved in practice. As an instance, I may quote the case of some compound high speed rotary blowers which we were asked to balance, and which, when working, ran at 4000 revs. per minute. These blowers were balanced at a speed of about 180-200 revs. per minute at the first period of maximum vibration in the balancing machine, and after they were put to work they ran perfectly without the slightest out of balance being detected at any speed.

Returning to the matter of the instrument which we desired, several designs have been tried. The first one consisted of a series of multiplying mechanisms, which

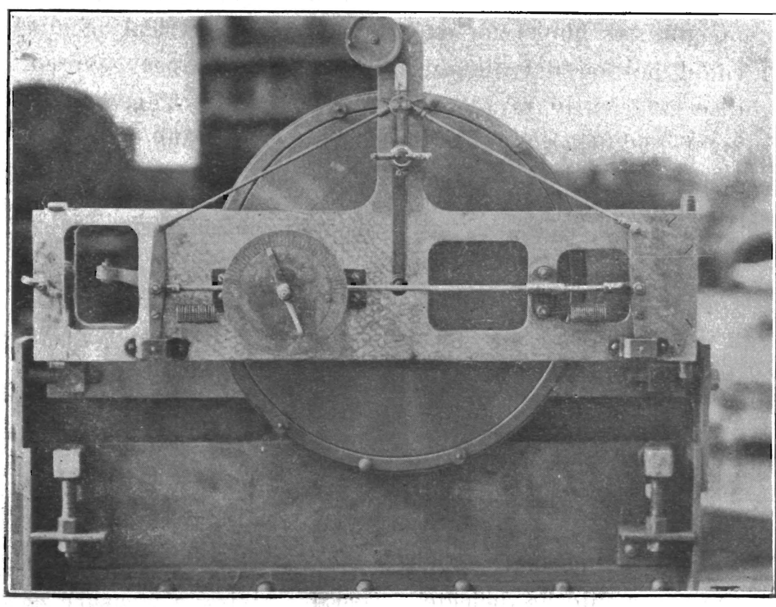


Fig. 6

consisted of a rack and pinion operating cams and levers, which had movements given to them by a pin projecting from the end of the revolving shaft. At each vibration this pin actuated the mechanism step by step, till the maximum amplitude was reached, and having been pushed thus far remained at that point. The other end of the mechanism and levers was situated opposite a disc, which was covered with a sheet of paper, and was made to revolve by means of chain gearing from the revolving shaft at the same speed as that shaft. This disc was about 13 in. in diameter, and it was thought if at the moment the pin on the end of the revolving shaft came in contact with the lever, which it was made to push over, an electric spark or an electrically operated pen could be made to mark the revolving disc, we should obtain the information we required. The mechanical portion of this apparatus worked quite satisfactorily, but, unfortunately, in spite of numerous experiments, no electrical means could be found which would mark the paper covered disc sufficiently rapidly or satisfactorily. This instrument had, therefore, to be abandoned. Figs. VI. and VII. show this instrument.

Another method—a flashlight vibrometer, designed by Mr. Dudley, of the Dockyard Engineering Drawing Office Staff—is shown diagrammatically in Fig. VIII. it is on the principle of the Flashlight Torsionmeter. It depended upon passing a ray of light through two slots in the circumference of a drum attached to the end of the revolving shaft, which ray was projected on to an adjustable screen with an eye piece. When the drum was revolving, and there was no vibration, the ray of light would not be deflected, but when the vibration occurred the ray would be deflected—thereby giving a measure of the amplitude of the vibration. By placing a series of

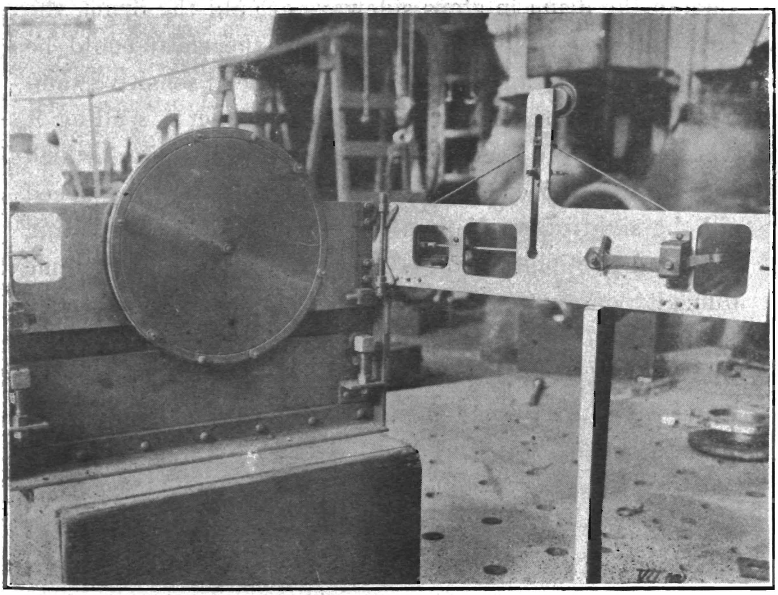


Fig. 7

DYNAMIC BALANCING
FLASHLIGHT RECORDING APPARATUS

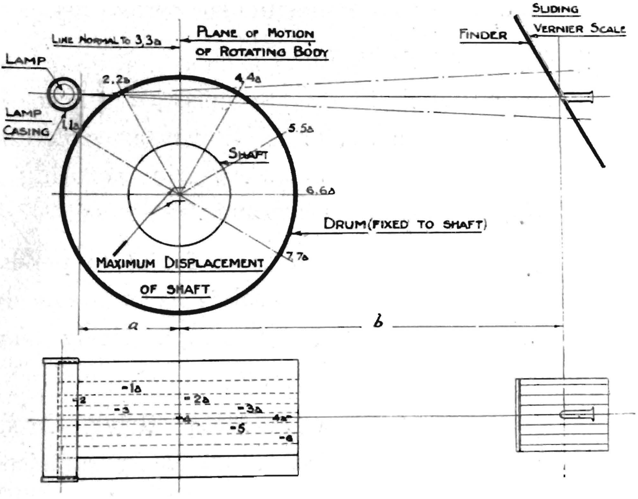


FIG. VIII

slots in the drum in steps sideways around the drum, the position of the vibration relative to the shaft could be obtained. This apparatus was extremely sensitive, and gave accurate readings, but in order to get a reading it was necessary to accurately ascertain the speed at which the vibration occurred, and maintain it at that speed till the sighting appliances were adjusted and a reading of the deflection obtained. On account of the extreme difficulty of fixing the revolutions at a period of a constant amplitude and the time taken to obtain a reading, this apparatus had also to be abandoned, but, owing to its sensitiveness, some of the complications that occur were revealed. Some of these were:—

(1) **Effect of Friction** of rotating body in its bearings was to increase apparent deflection of springs beyond that due to unbalanced mass when turning in one direction, and to reduce deflections when rotation reversed.

(2) **Gyroscopic action** of rotating body had a tendency under certain conditions to damp deflections.

(3) **Forced lubrication** (by means of a reciprocating force pump) tended to upset calculations by introducing a wedge of oil of measurable dimensions between shaft and bearing, causing temporary deflection of springs.

(4) **Synchronistic periods** were found to persist in apparently constant revolutions of motor drive, although separated by comparatively lengthy spaces of time.

(5) **Variation in Speed of Motor Drive.**—A slight acceleration or deceleration being sufficient to produce abnormal vibrations of springs.