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THE BALANCING OF ROTATING MASSES, WITH SPECIAL REFERENCE TO SCREW PROPELLERS.

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The use of high speed rotating masses in turbines, armatures, etc., has necessitated the question of their running balance being closely examined and rectified, and in recent years the methods of correcting the out of balance of such masses have been more perfected; but so far, within my knowledge, the literature on this particular part of the subject has been conspicuous by its absence.

The balancing of the out of balance weights in reciprocating engines has been most exhaustively dealt with by more than one writer, and especially by Professor Dalby in his book on the balancing of engines; but even this author makes no detailed reference to turbines, or armatures; he makes some reference to the vibration of ships, and the caues that produce such vibration, which are attributed to the engines, and in one part to want of symmetry in the propeller, and slight variations in the pitch of the blades; but the effect of want of running balancing in the propellers themselves has not been touched upon by him, nor anyone else that I have been able to discover.

The object of this paper is shortly to review the causes of the want of running balances in rotating masses, and what are the phenomena met with when correcting this, and the steps to be taken to do so, leading up to the balancing of propellers, and the effect of their want of balance in the vibration of ships.

I do not propose to enter into the mathematics of the subject, for which I would refer members to Prof. Dalby's and other authors' books.

It is assumed that it is well known a mass like the rotor of a turbine, or an armature, may not rotate at speed without vibration, i.e., in running or dynamic balance, even though it has been balanced on knife edges, and given standing or static balance. Let us examine briefly what are the conditions for standing or static balance, and dynamic or running balance.

Let A.B., Fig. I, be a weightless shaft running in bearings at either end A. and B., and assume two equal weights, W.W., are attached to it at equal distances from the axis of rotation, and that their centres of gravity lie in the same plane at right angles to the axis of rotation. Such weights will be in static balance, and if the shaft is rotated, there being no forces tending to cause the shaft to wobble, it will run also in dynamic balance.

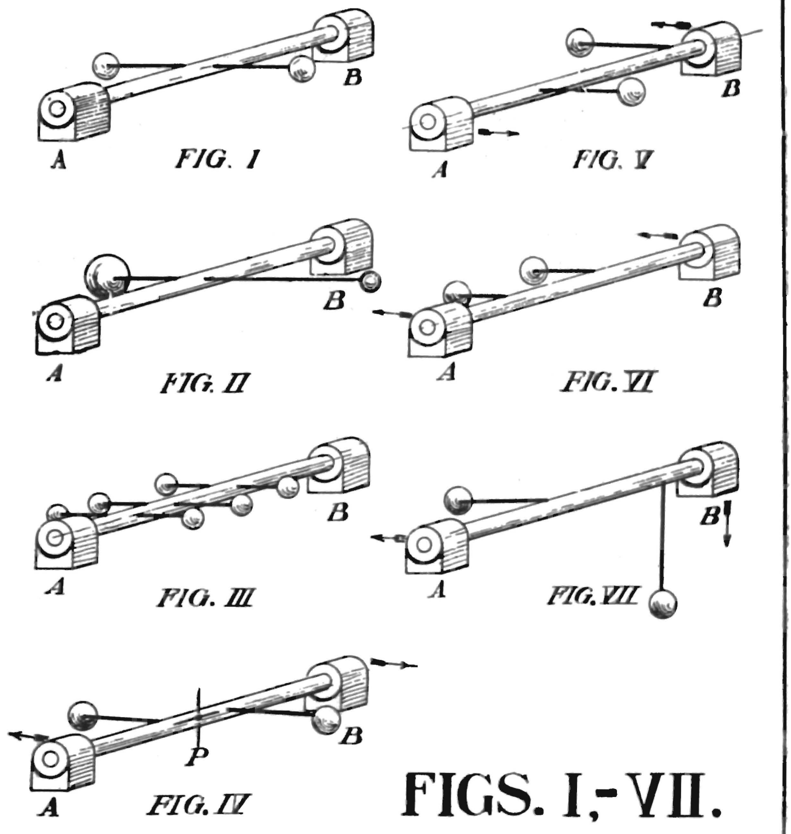
The same remarks hold good even if the weights W.W. are not equal, provided the moments of their weights about the axis are equal (vide Fig. II); if we had any number of weights at the same point in the length of the shaft forming a group, provided the sum of their moments about the axis is zero, and their centres of gravity all lie in the same plane at right angles to the axis, the static and dynamic balance will still be perfect.

The same conditions also hold good when there are any number of such groups around the shaft disposed at varying distances along the axis (vide Fig. III). For simplicity of illustration, the weights have been shewn in the same plane parallel to the axis.

Summing up, a general formula for the condition for static and dynamic balance may be thus enunciated, viz.:—

(a) That the mass centre of each unit length of mass along the shaft shall be coincident with the axis.

(b) The centres of gravity of each part of each such unit length of mass shall lie in a plane at right angles to the axis.



FIGS. I.-VII.

Suppose now we have two weights forming a unit placed as shewn in Fig. IV., and assume condition (a) is satisfied, i.e., it will be in static balance, clearly condition (b) is not, and if such a system is rotated, it will not be in dynamic balance, as the weights will set up centrifugal forces producing a couple tending to turn the shaft about some point P, causing the ends of the shaft, if they are free, to wobble about the point P. The extent of that wobble will be proportional—

(a) To the centrifugal forces generated by the two weights; and

(b) To their relative positions along the shaft.

The direction which the ends of the shaft will move instantaneously will be in the planes of weights, as indicated by the arrows in Fig. V, i.e., the ends of the shafts will be moving instantaneously in opposite directions.

Again, assume two weights as shewn in Fig. VI. Here we have a case of pure want of static balance, i.e., condition (a) is not, but condition (b) is fulfilled, and the shaft will tend to move instantaneously bodily in the direction of the arrows, i.e., the movement at each end will be in the same direction, the extent of the throw of each end being proportional to the weights, and their relative position along the shaft, but there will be no tendency for the shaft to wobble about a point P, as in Fig. IV.

The two cases given are for weights in the same plane parallel to the shaft. If they are not in the same plane a little consideration will show that the direction in which the end of the shafts will tend to move will be in the planes of those weights, and we there get what has been rather appropriately called a dog's hind leg (vide Fig. VII). Any combination of these conditions can be resolved into a case of either V, VI, or VII.

A little consideration will also show that even in the case given by Fig. VI, which is one of pure out of static balance, unless you know the position and amount of these out of balance weights, relative to the length of the shaft, in correcting them by weights at the ends or other parts of the shaft, you may introduce an out of dynamic balance condition.

It will thus be seen how the method of balancing rotors on a knife edge may not, and most probably will not, correct the want of static balance without disturbing the dynamic balance, and may even introduce a dynamic out of balance which previously did not exist.

It has been shown for perfect running balance that the centre of gravity of each part of each unit length of mass along the shaft must lie in a plane at right angles to the centre of the shaft; apply this to a 3-bladed propeller, and it will be seen how such a propeller, unless the centre of gravity of each blade lies in such a plane, may readily be out of running balance, although on the knife edges it may be in perfect static balance.

In the case of two- or four-bladed propellors each opposite pair of blades must fulfil the conditions for dynamic balance. This condition for perfect running balance in propellers is one which hitherto has not been given much attention, and was the unsuspected source of considerable vibration in the ship, as will be shewn later.

It is also evident that the rotating of the rotors, of whatever form, shows up the want of static and of dynamic balance, and that any combination of the two conditions resolves itself into one of pure want of dynamic balance, and can be corrected together as one, thus obviating the necessity for the static balancing on knife edges; but I do not say, in building up a rotor, of whatever form, that every care should not be taken, when assembling the parts, to ensure that each part should be separately in as good static balance as possible, otherwise the amount of vibration set up in the balancing machine may be excessive.

The next question is how to determine and correct the position and amount of out of balance weights.

The generally accepted practice has been to mount the rotor in bearings so that the rotor, its shaft and bearings, shall rest on springs, which carry the whole weight to be balanced, including the bearings and other non-revolving parts, and also so arranged that the whole arrangement resting on the springs shall be free to move only in the line of action of the axis of the springs.

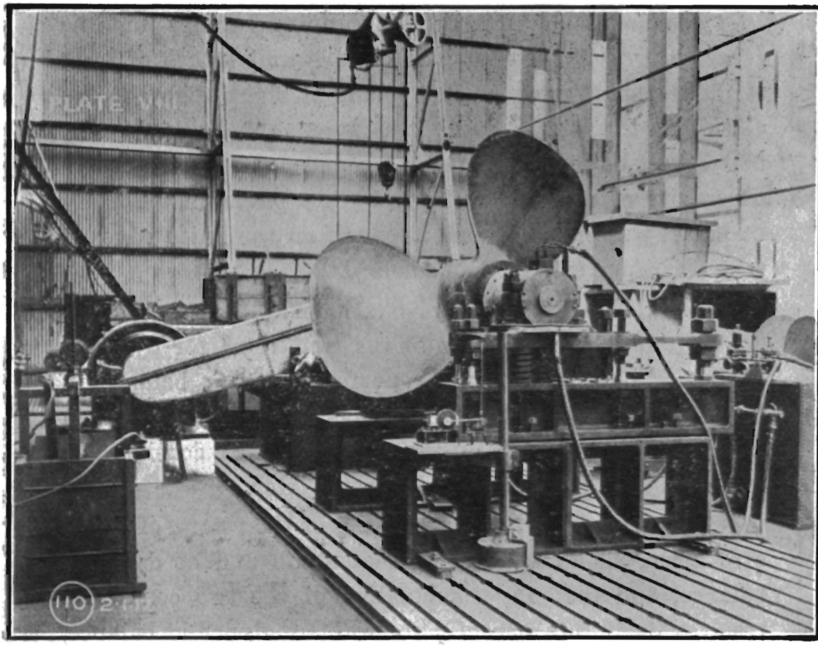


Fig. 8.

Figs. VIII and IX show such an appliance, with a propeller weighing nearly two tons mounted on it, ready for balancing. Motion is imparted to the mass to be balanced by an electric motor, by means of a shaft and a couple of Hook's joints, so that the mass, whilst revolving, is free to move in the constrained direction; in this case such motion is vertical.

If the motor is started, and the rotor, which in this particular case is a propeller, is caused to revolve, and if it is not in perfect running balance certain phenomena are observed: it will be found that, as the speed increases, the rotor will vibrate vertically up and down, and the amplitude of these vibrations will gradually increase till they reach a maximum at a certain speed; the vibrations will then, as the speed of rotation is increased, decrease, till at another certain speed they will be very much diminished, and in some cases practically nil; and if the speed is still further increased, the vibrations will again grow to another maximum at a third certain speed, but the amplitude of the vibrations at this particular speed will be considerably less than the first maximum obtained.

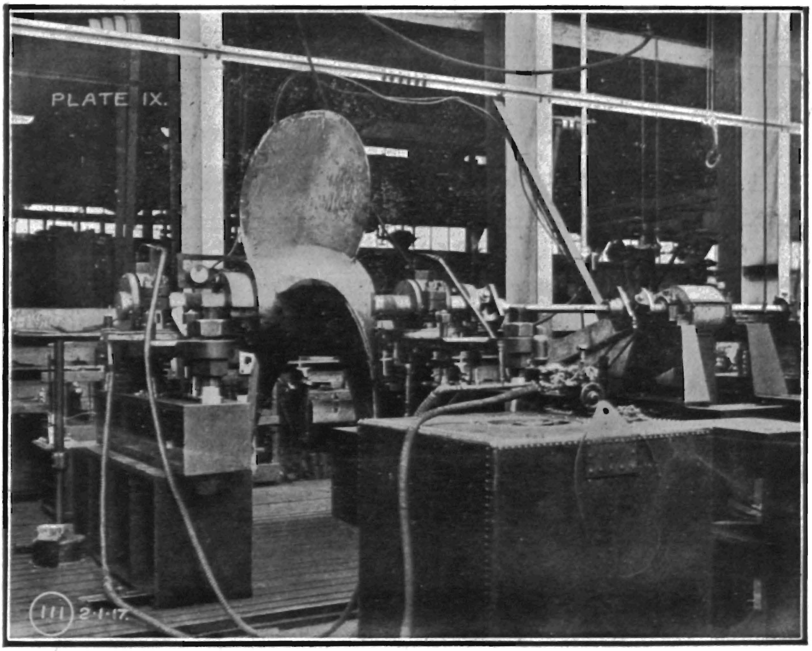


Fig. 9.

Fig. X shows a vibrometer record of these events. It will also be found that the amplitude of the vibrations may not be the same at either end of the shaft carrying the rotor.

The force producing the vibrations is the centrifugal action of the unbalanced weight; this increases as the square of the revolutions in accordance with a well-known law of centrifugal force.

Why, then, do not the vibrations increase as the speed increases—which we have seen reach a maximum, at a certain comparatively low speed, which is not again obtained?

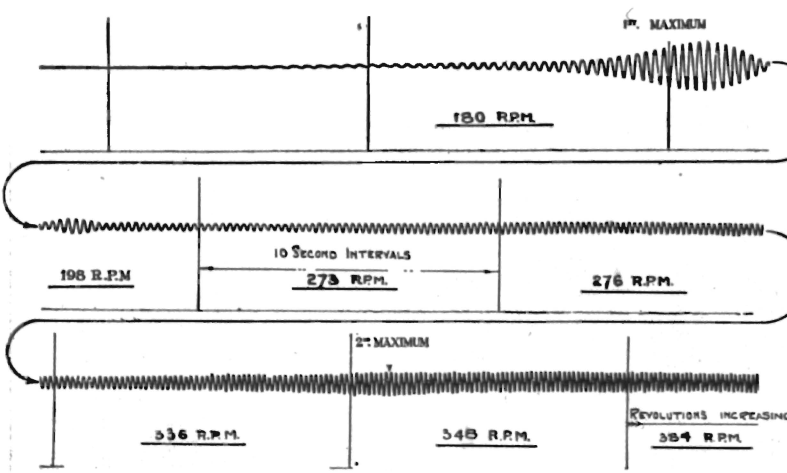


FIG. X

Fig. 10

The answer to this question will be found, after little consideration, to be that the motion is entirely controlled by the supporting springs.

It will also be found that the speed at which the maximum amplitude of vibrations is reached is higher the smaller the out of balance weight. Now the law of vibration of a spring is the same as that of a pendulum; and the time of vibration is a function of the amplitude of vibration of the spring; hence the greater the amplitude of vibration the slower will be its period.

Hence the first large vibration, due to the out of balance weight, which produces a large amplitude of vibration, will occur at a lower speed, as this period of maximum vibration must synchronise with the natural period of vibration of the springs, and, consequently, coincidence of the periodicity of the centrifugal forces with that of the springs will only occur at one particular speed, and at the higher speeds when the period of the forces producing the vibration is so much higher, and although these forces are much greater on account of the higher speed, yet that period can only synchronise with a small vibration of the spring, and will not produce larger vibrations owing to the two forces not synchronising. We see, therefore, why the first maximum must be greater than any succeeding maxima, and also that the periods of the succeeding maxima are harmonics of the first.

In what way can the balancing apparatus be made more sensitive? We know that the disturbing forces are greater at the higher speeds and increase as the square of the speed; but in the balancing apparatus illustrated the springs have to be stiff enough to carry the weight, and cannot be made lighter; but they could be made shorter, so that their period is higher, but then their amplitude will be smaller, nothing much will apparently be gained. Some experiments made in this direction showed that the speed of coincidence is higher, and also that when the out of balance weights are small the amplitudes of vibration are proportionately greater—that is, that the shorter spring is more sensitive.

From the results of these experiments it would appear that by altering the arrangement of the balancing apparatus, so that instead of supporting the weight of the rotor on the springs, it is supported on rollers, or other means, which allow of its vibrating horizontally, instead of vertically, and by damping the vibrations by light and short horizontal springs we shall obtain a more sensitive appliance; but the amplitude of vibration should be kept short to take advantage of the greater forces at the higher speeds.

It would appear, therefore, that in the type of balancing apparatus shewn, that if the rotor is found to be in balance at the first period of synchronisation, no better results will be obtained by running up to much higher speeds. Up to the time of writing, all the cases that have been balanced go to prove that this is true.

A rotor then, which is out of balance, when revolved vibrates up and down. How is the position of the out of balance weight to be determined? The means adopted hitherto have been to mark the rotating shaft, which has been smoked to make the marks clear, by means of scribers which are screwed up, and just touch the shafts at the apex of their amplitudes, one scriber at each end of the rotor. Suppose this is done, more or less long marks will be found on the shaft. You obtain the middle points of these marks. Now suppose the direction of rotation is reversed, and other two marks, one at each end, are obtained, and their middle points determined. It will be found that the first middle point obtained and the second will not probably coincide by many degrees. The explanation of this is that the position on the shaft—which, as it rotates, reaches its apex of amplitude—lags behind the position of the out of balance weight, so that when the direction of rotation is reversed this lag is also reversed. The correct position for the out of balance weight will therefore be in the centre between the two positions thus obtained.

Now it has been proved by experiment that the angle of the lag varies very much indeed, and depends very much not only on the position of the out of balance weights, but also on the speed of rotation. It has been the tester's great bugbear, as unless he happens to mark the shaft at exactly the same speed when rotating the rotor, first in one direction and then in the other, the angles of lag will not be the same, and it has only been by a good deal of experience that the tester has been able to determine the correct position to place a weight or weights on the rotor to correct the out of balance. The amount of weight necessary also has had to be guessed at, and a correct result obtained only by experience and by trial and error.

I have made a few experiments with a rotor which was in good running balance, and then adding known weights at known radii, and measuring the amplitudes of the vibrations obtained, and determining the position of the lag by the scriber process. These experiments so far point towards shewing that, in some instances, the amplitude of vibration is proportional to the amount of out of balance weight, but the angles of lag obtained by this method were so erratic I have, up to the present time, been unable to discover any law for them; but I am inclined to think that the scriber method of determining the lag is by far too rough, as it is almost impossible to mark the shaft exactly at the moment the rotor is rotating at its period of maximum vibration, and a few revolutions on either side is ample to throw the angle of lag out many degrees.

It would appear, therefore, that some instrument is needed that will not only give the amplitude of vibration, but also mark the shaft at the exact moment when this ampltiude is reached. It is thought that if this can be done, and a similar position obtained in the reversed direction of rotation, as the two maximum amplitudes will probably occur at the same speed, that not only will the measure of the amplitude be a guide to the amount of out of balance weight, but also that the true position of the lag will be determined. I am at present working at this problem, and if satisfactory results are obtained, I shall hope to place them before this Association.

Fig. XI shows a propeller which was not in dynamic balance. It also shows where the two weights, A. and B., had to be placed, one at either end of the fore and aft length, to neutralise the out of balance, and the white patches show the amount and where the weight has to be taken off the blades to correct the balance. It will be seen that these patches are opposite to, but at the same fore and aft end, as the weights A. and B. It will also be noted that more weight has to be removed from one side than the other. This is due to the propeller being also not in static balance. This correction was automatically obtained during the dynamical balancing process.

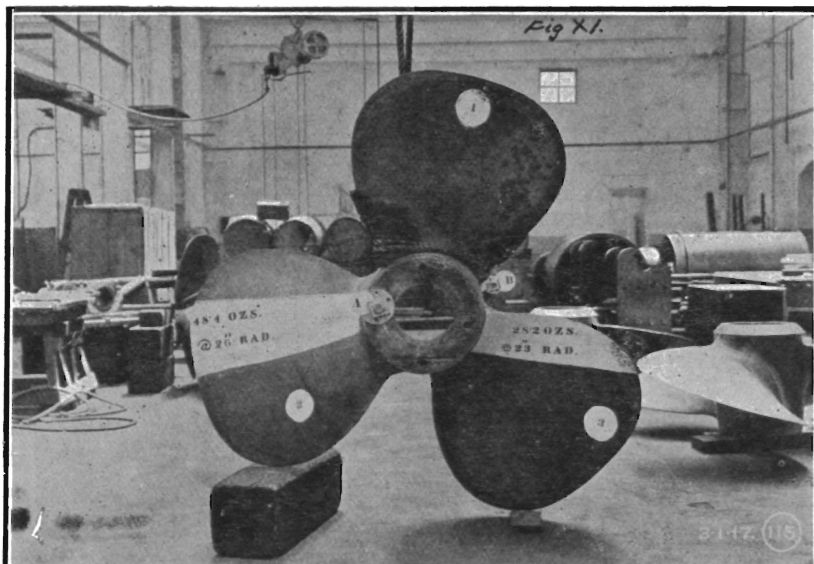


Fig. 11

The above remarks on balancing generally have entered into greater length than it was anticipated, but it is hoped that they may not be of no interest. Attention will now be given to the effect of the out of balance in propellers on the vibration of ships.