from the wrong place, and will introduce an out of dynamic balance, so that really, if a propeller is required to be in good running balance, the statical balance should be omitted, as it is not only unnecessary, but also most likely involves more metal being removed than is really necessary.

DISCUSSION

Mr. McEwin: Mr. President, Mr. King-Salter, and Gentlemen,—I have very great pleasure in moving a vote of thanks to Mr. King Salter for the valuable matter he has brought before us to-night. We are all indebted to him for coming here and giving us the benefit of his researches, which will, no doubt, be of far-reaching value, and will probably be very useful to many of us who are here. We are too apt to take for granted things that are happening around us; we travel in our ferry boats; we go to sea in large steamers, and we put up with vibration just as a matter of course—we put up with noisy trams in our cities; but after all, ships and trams and other appliances constructed by men are for the benefit of men—they are designed to secure his ease and comfort. As the general public is apt to take things for granted and make no attempt, and evidence no desire to improve existing conditions, so, too, is the engineer apt to take things like that put before us by Mr. King Salter as a matter of course. That makes the trouble he has gone to the more admirable, and makes us the more indebted to him; those who go to sea from now on will have reason to thank him for his patient research. The results of his work will always be appreciated by the engineering world.

I do not pretend to criticise the subject matter of the paper. The author set out to obtain certain definite results, and he undoubtedly attained his objective. The testimony of the naval officers mentioned in the paper is sufficient proof of that.

The paper has proved an exceedingly interesting one, and the experiments themselves must have been exceedingly interesting to those who carried them out.

With respect to the apparatus used in the balancing experiments, it is noteworthy that the shaft was free to move in one direction only, viz., vertically. The author suggests a method of providing for a horizontal instead of a vertical motion.

Naturally, one must recognise that there are limitations in such experiments as these, especially in dealing with propellers weighing two tons. Nevertheless, it would be interesting to know if it would be possible, by any means, to allow the rotating shaft to move freely in any direction.

The Curtis people balance some of their turbine discs by suspending the shafts by means of a cable, the lower end being steadied in a spring bearing that permits of a sideways motion. The shaft is rotated by means of the cable. After being marked, the rotor is stopped, and wire is twisted into the blades. This method is repeated until the balance is perfect. The balance of the disc is then adjusted and the wires removed. Some modification of this method might lead to interesting results if applied to the balancing of small, if not the larger, propellers.

Centrifugal dehydrators are usually driven from the heads of their vertical shafts, and are not supported or guided in any way at their lower extremities. Experience with such machines makes it appear possible that even comparatively heavy bodies could be suspended and balanced in a somewhat similar manner. However, the President is an expert in connection with such machines, and can doubtless make some valuable suggestions on this aspect of the subject.

An interesting problem in balancing was encountered by De Laval in connection with his turbine. It will be remembered that the smaller sizes ran at a velocity of 30,000 revolutions per minute. It was found difficult to balance the rotors with sufficient accuracy to enable them to run safely at such a high speed. Consequently De Laval adopted the flexible shaft running in ball and socket joints. As a result of this arrangement, the rotor reaches its "critical" speed when run up to about 1/6th of its normal number of revolutions, and after an instant of intense vibration, "settles" and runs quietly about its centre of gravity instead of about its theoretical axis.

In searching for some further information on this point, I came across an account of some interesting phenomena in Lester G. French's work on steam turbines that had been made with a disc rotated by means of a flexible shaft.

Fig. I.—Disc and Flexible Shaft.

The disc has a dense section at H, so that its centre of gravity is on the line C—D. When the disc is first rotated the flexibility of the shaft allows of it running eccentrically, as in the next figure, in which the centre of rotation is shown to be a point on that side of the theoretical axis which is remote from the dense section H.

Fig 2.—Rotation about the vertical axis.

As the speed of revolution approaches the point of so called "critical" speed already referred to, the vibration becomes very intense, then the rotor "settles," as it is called, and runs quietly. During the short period of intense vibration, the centre of gravity of the disc becomes the point about which rotation is made. This point, of course, is on that side of the theoretical axis which is close to the dense section H of the rotor.

Fig. III.—Rotation about axis of Gravity.

Now, if the disc had been marked with chalk when running, as in Figure 2, the chalk mark would have been on the heavy side of the disc. If, however, the marking were done at the higher rate of revolution, when running, as in Figure 3, the chalk mark would have been on the light or opposite side of the disc.

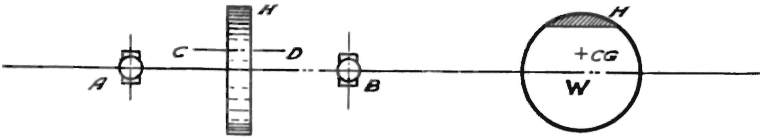


FIG 1. DISK & FLEXIBLE SHAFT.

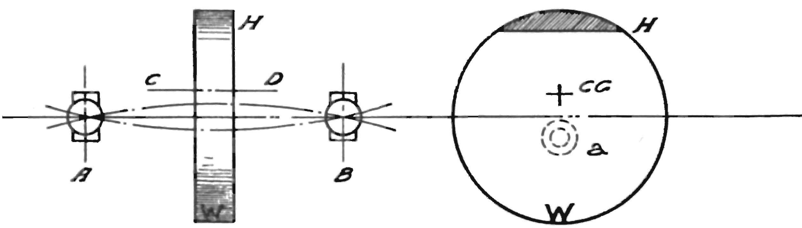


FIG 2. ROTATION ABOUT THE VERTICAL AXIS.

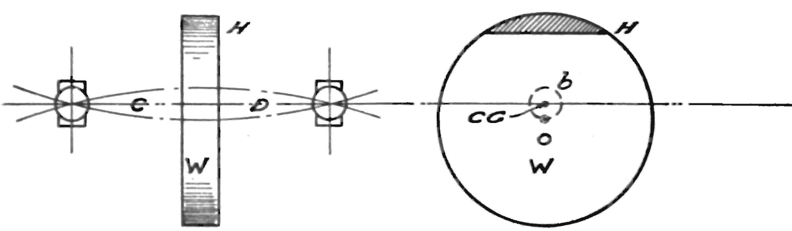


FIG 3. ROTATION ABOUT AXIS OF GRAVITY

Naturally it is not feasible to attempt to balance propellers or to run them on flexible shafts. The bearing of these remarks lies in the point that it is quite possible to strike unexpected results when working on problems of this character. I trust that what I have said may be of some service to those who are working on this particular problem.

I have great pleasure in proposing the vote of thanks.

Mr. Walter Reeks: It is with very great pleasure that I rise to second this vote of thanks—in fact, I regard it as a privilege. One cannot fail to be impressed with the importance of the subject Mr. King-Salter has so ably brought forward this evening. I take it that the out of dynamic balance due to conditions 5, 6 and 7, that is, irregularities of weight distributions, brings about a state of things analogous to those existing in the pinions of turbine reducing gears, in that case due to inequalities of tooth pressure, where the third stage of development seems to have been reached.

It will be remembered that De Laval, in his earlier small gears, turned down his driving shafts between bearings to obtain that small amount of freedom necessary to correct what was then thought to be want of dynamic balance.

Parsons followed with larger gears and obtained success by greater accuracy of tooth cutting, for which purpose he had himself to make special tools with a creep attachment.

Now we learn that Westinghouse is getting just as good results by mounting the pinions in a floating frame (see "International Marine Engineering," June, 1917, p. 259). The pinion tends to wobble, due to slight inequalities of tooth contact; the propeller tends to wobble, due to irregularities in weight distribution, and are up to that point alike.

Now, if it be true, as I believe it is, that a floating frame corrects the errors and irregularities of the pinion, why not mount the propeller in something similar? It is easy to conceive of, and would appear quite practicable. In point of fact, it has been done already years ago, in the "Umbria" and "Etruria," of the Cunard Co., where, in spite of the best known static balancing (dynamic balancing being then unknown), serious vibrations occurred, the ships were stiffened, and the vibrations increased; they were then reduced in local stiffening and the trouble cured or largely decreased. Surely that is the equivalent of a floating frame by virtue of the slight local movement thereby allowed.

It is customary in large ships to fit rigid "A" brackets or to plate right out to the spectacle frame, by which any vibrations are passed through to the ship direct. In small craft it is not unusual to hold the stern bearing by means of a single hanging bracket, which goes a long way to fulfilling the condition of a floating frame, as, being itself flexible, it absorbs much of the vibration, and dissipates most of it before reaching the hull. While these hanging brackets are usually of metal, they have also been made locally of selected tough, hard wood, with great success as vibration absorbers.

Where facilities exist for balancing propellers dynamically, by all means do so. The efficiency of such balancing has been amply shown by Mr. King-Salter, but his diagram shows there is still some vibration, due probably to causes outside that of dynamic balance. These could, I think, be still further reduced by some such method as I have suggested. We are not all so happily placed as to have the means of dynamically balancing our propellers, and cannot always afford the cost, so have to be content with the next best means—a floating or flexible bearing.

MR. TOURNAY-HINDE: It gives me exceedingly great pleasure to have an opportunity this evening of supporting the motion which has been proposed by Mr. McEwin and seconded by Mr. Reeks in appreciation of Mr. King-Salter's paper in connection with the balancing of propellers.

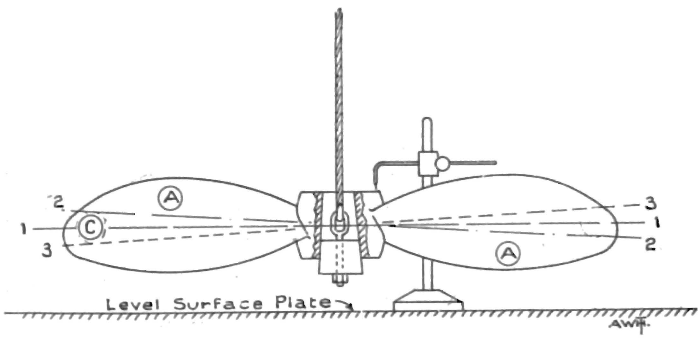
It is a subject in which I myself have been very much interested, not in connection with propellers, but in connection with large fan impellers up to 5ft. and 6ft. in diameter, running at speeds up to 1,000 R.P.M. If a paper containing the information that has been disclosed in Mr. King-Salter's paper to-night had been available at that time, it might have been of very material assistance indeed to the work I then had in hand.

There has really been very little contributed towards the dynamic balancing of rotating masses by way of our text books or by any papers that have been read before the Engineering or kindred societies in the world; but there are two papers I came across which might perhaps interest Mr. King-Salter to look through: one is in the "Transactions of the Engineers and Shipbuilders in Scotland" of November, 1902; the other will be found in the Proceedings of the Engineering Association of West Pennsylvania of November, 1900. There is also an article in the publication "Machinery" of February, 1905, which contains an excerpt from the matter which Mr. McEwin presented to you to-night, and also other information which is of value.

The principal difficulty in balancing any rotating mass, as Mr. King-Salter pointed out, is that it always has length as well as diameter or size in its diametrical direction, and it is this fact which usually makes any attempt at static balancing quite useless when the speeds are at all high, or where—to put it in more correct phraseology—the peripheral speed is high, because small weights on large diameters product just as great vibratory results on the shaft as large weights on small diameters.

I notice that Mr. King-Salter rather decries any attempt at static balancing prior to carrying out the dynamic balance. I agree with him entirely there, if static balancing is confined to the usual method of balancing on knife edges.

It is quite evident, where one has a mass, even of much less weight than those referred to by Mr. King Salter, the out-of-balance amount is quite insufficient to produce any rotary motion along a straight edge—that is to say, the indentation of the shaft on the straight edge, although it may be microscopically small, will, if you look into it, be quite sufficient to hold, say, an ounce weight on a diameter of 5 or 6ft. without having an appreciable effect on the static balance, while the same weight on the same diameter running at 1,000 R.P.M. would produce several pounds radial pull and show quite a marked vibration in the shaft.



At this stage Mr. Tourney-Hinde described, by means of diagrams (see figure), a method of balancing a two-bladed propeller by supporting it on a wire in a horizantal position, when it could be corrected for static out-of-balance. He stated that a wire should be attached to somewhere about the centre of gravity of the mass being balanced, and this should be done by fitting into the boss a cylindrical plug, which was split in two, and a wire (bicycle spoke) run up a groove cut in the centre of the two halves of the bush. If weights were added or metal removed from the blades until the propeller hung in a horizontal position it would remove possibly 60 or 70 per cent. of the out-of-balance weight before dynamic balancing the propeller by placing it on a rotating shaft between two flexible bearings.

I was very much interested, also, in Mr. King-Salter's reference to the lag that takes places—that is to say, the marking on the shaft does not indicate the radius at which the out of balance weight is. During the course of the work I was engaged in carrying out we came across the same phenomena. Our method of balancing, since we were not dealing with such heavy weights as Mr. King-Salter dealt with, was somewhat different. The total weight of the impeller would not be more than about 1½ cwt. or 2 cwt. We used a 3in. shaft, about 8 or 9ft. long, on rigid bearings, and we placed the impellers which had to be balanced, and which had a total width of about 8in., at the centre, and gradually increased the speed by means of a variable speed electric motor.

On spotting a shaft of that sort, if scribers were placed at several points along the shaft, instead of the spots being in the one position they would make a curve, thus showing that the lagging effect was more marked the further you got away from the rotating mass. It might have been slightly due to the torsion in the shaft, but this seems hardly likely, because the total amount of power required to drive it would not be much more than 8 or 9 horse-power. To prevent fan resistance we provided plates for closing the sides of the impeller to prevent the air from entering, and therefore we only had a weight of about 1½ cwt. to 2 cwt. running. This lagging effect was most marked. We used to run in both directions and try and hit the mean between them. To give you some idea how little a weight would correct an error in an impeller of that size and weight, a matter of perhaps a quarter of a pound altogether—say 2 ounces on one side and 1½ ounce on the other at some other portion of the fan—wherever it was required, according to the twist of the shaft, would be quite sufficient to enable the propeller to run and bend the shaft and throw the whole mass out of the bearings.

There is one matter I should like to refer to before I sit down, and that is this: Reference has been made by one or two speakers to the fact that some vibration still remains in the diagrams after the dynamic balancing has been carried out. With propellers of the size Mr. King-Salter is dealing with it is quite possible that a little difference in displacement or a change of position in relation to the mass of the propeller to the shaft may exist as compared with that which existed at the time he balanced it in the shop and when it was placed in the ship. By that I mean it is almost physically impossible, after having once got a satisfactory dynamic balance in the testing machine, to remove the propeller and place it upon the shaft of the turbine or the engine in exactly the same position it occupied in relationship to the shaft, and that slight deflection, or slight difference, although it may seem insignificant to one who has had no experience of balancing large revolving masses at high speeds, is quite sufficient to introduce the tremor that still remains on the diagram.

There is one other interesting phase in connection with balancing: I do not know whether Mr. King-Salter has come across it, possibly he has; he has certainly made a very deep study of the question—and that is this: If three eccentrics are made, having a fairly good fit on the shaft—friction fit—and placed on the shaft in any position before the shaft is rotated, and the shaft is rotated free to move after a few moments the eccentrics will shift to some position of themselves, and the whole mass will become so that the centre of gravity of the mass, if the eccentrics are large enough in proportion to what you are balancing, will run in the axis of rotation and all vibration will cease. Exactly the same thing takes place in hydro extractors used for drying various things. The bucket will run with very great vibration empty, but the moment you put water into it it will so fill the bucket eccentrically to the necessary degree that the whole thing will run perfectly true on the centre of axis of the shaft.

There is another matter in connection with the ingenious recording apparatus that Mr. King-Salter has set up between the decks to which I would like to refer, and that is this: Since that is to record vibrations, I take it Mr. King-Salter very carefully saw to it that the period of vibration of the springs he referred to was a long way outside of the range of the vibrations he was trying to measure, otherwise they may have possibly introduced some little errors due to synchronising with the speed of the vibrations of the propellers themselves. It is very difficult to measure vibratory measurements, on account of having generally to use some other vibratory apparatus to measure it with, and that is usually attempted to be reduced as much as possible by making the periods of the vibrations to be measured with the steadying apparatus differ as far as possible.

I should like again to express my deep appreciation of Mr. King-Salter's work. It is, as Mr. McEwin said, highly original matter, and the fact that there is so very little reliable information of the kind available makes a paper of this description exceedingly valuable to us all.

Speaking for myself, I feel quite privileged to have heard Mr. King-Salter's very able descriptions of his experiments, and I feel quite sure my fellow members feel the same.

Mr. Fildes: Although this address to-night particularly appertained to propellers, I should like to know whether Mr. King-Salter has made any experiments with regard to crank shafts under high speed.

My recollection carries me back to two balancing machines—one was called, I think, the Norton Balancer, and the other the Ackenoff. These were devised and used primarily for the determination of the vibrations due to the leverage and mass thrown on crank shafts of automobiles. I noted particularly the radial load that was imparted on the basis of a mass weighing 7½ lbs. at a radius of 2½ inches. To show how light weights will produce big forces I will, with the President's permission, show on the board some figures which will perhaps be of interest to members of the Association.

7½lbs. AT 2½in. RADIUS.

R.P.M.	Centrifugal force. lbs.
100	5.3
200	21.3
300	47.9
400	85.2
500	133.1
1,000	532.5
1,500	1,198.3
2,000	2,130.3
2,500	3,328.6
3,000	4,793.3

It seems to me, therefore, when you are dealing with small masses, small leverages, and high velocities, you have something there that needs to be taken seriously into consideration.

I have very much pleasure in supporting the eulogistic remarks which have been made respecting Mr. King-Salter's most valuable paper.

Mr. Oram: I should like to ask Mr. King-Salter whether the deflection of the shaft, due to the deadweight of the propeller, which is there constantly, is taken into account in balancing the propeller when it is in motion—I mean the flexibility of the shaft?

Mr. Vicars: I wish to ask for a little information with regard to the balancing of propellers. What I want to know is this: After you have dynamically balanced them in the test room and fixed them on the steamer, a tremor still passes through the vessel. Is it not possible that some of that may be due to two causes: firstly, to the possibility of the propeller shaft being slightly out of alignment, and secondly, to the fact that the water has its greatest density at the bottom of the propeller and its lightest at the top, and would not that be equivalent to working continually with a slight out-of-balance load?

MR. CHALMERS: I have listened with very great pleasure to Mr. King-Salter's interesting paper. I have no wish to say anything at all in regard to it; but I think it is one of those matters that have never been very clearly stated. It is a peculiar thing that the vibration should show an increase and then go off again. Some time ago, you will remember, I tried these sort of experiments with a vessel in regard to rolling and pitching. As you will easily understand, the period of the rolling of the ship and the period of the sea-way were not quite in agreement; different ships, of course, have different periods of rolling and pitching, with the result that, as the vessel would get into motion, the one action would presently counterbalance the other, and so there would be a lessened degree of vibration. The thought came into my mind, as Mr. King-Salter was speaking, in the case of a twin-screw steamer, would not the vibration of one propeller have a tendency, at various times, to counteract that of the other?

I have very great pleasure in endorsing the remarks that have been made in regard to the vibration, and I thank Mr. King-Salter for his very able address.

MR. SNASHALL: A point occurred to me with regard to the vibrations which is evident after dynamic balancing has been taken care of, and that is the question of the errors of pitch of various blades. Personally I am not acquainted with the degree of accuracy in setting out propeller blades or finishing them; but it seems possible to me that the vibration may be due to what may be called a state of want of hydraulic balance—one blade may have been of slightly greater pitch than another, thus causing a deflection which would be responsible for this continued state of vibration. I should like to know whether that is a possible cause of the continued vibration.

Mr. Fraser: There is just one question I should like to ask, and that is in regard to the lag shown in the testing machine. Although Mr. King-Salter has not mentioned the degrees of lag, that, I take it, is the angle. Say we take a radial line between the centre of rotation and the weight that is out of balance, that is where you would expect the mark of the scriber to appear on the shaft; but it occurs somewhere later. That, I presume, is the angle of lag. Mr. King-Salter mentioned casually that angle—varying somewhere from 90 to 180. Does that mean the mark would be on the opposite side of the shaft at times? It seems rather extraordinary that such a big angle should be recorded.

The President: There is no question that the discussion to-night, and the manner in which Mr. King-Salter's paper has been received, speak for our appreciation of him and his work, and nothing I can add can emphasise that fact. I will now ask you to carry the motion of thanks that has been moved and seconded and so fully supported to-night in the usual way before I convey to Mr. King-Salter our sense of appreciation. (Acclamation).

I have now very much pleasure, Mr. King-Salter, in conveying to you a vote of thanks for coming here to-night and delivering your valuable and interesting paper, and I now ask you to reply to the discussion.

MR. KING-SALTER'S REPLY.

Mr. President and Gentlemen,—I am sure I am extremely grateful to you for the way in which you have received my paper to-night. One gentleman said it was a privilege to him to hear it. I can assure you it is a privilege on my part to be here to put it before you, and I appreciate very much your kind remarks.

With regard to Mr. McEwin's remarks, I am afraid I should be rather loath to attempt to mount a heavy propeller in a bearing which would allow it to wobble in any direction, nor do I think that it would be necessary, for as I have tried to explain in my paper, what we want to find out is the direction in which the out of balance weight is acting, and it appears to me, if we constrain the motion to one direction, that would be the best way to obtain the result required.

The Curtis De Laval methods of suspending a wire are very interesting, and no doubt have served their purpose very well, but I hardly think they are applicable to heavy weights like a propeller or turbine rotor.

Mr. Walter Reeks' remarks about the vibration in the "Umbria" and "Utruria" confirm what, in my paper, I have endeavored to bring out, viz., the necessity for dynamical balancing. Had those propellers been thus balanced, I have little doubt the vibration would have been most materially reduced. I venture to suggest that his proposal to fit flexible "A" brackets is not the true cure for the vibration; it does not eliminate them, but only hides them from observation. The better way is to balance the propellers, and thus remove the tendency to vibrate.

The vibrations in the ship that still remained after the propellers had been balanced were probably caused by those water complexities, set up by the propellers, of which there were four, interfering with each other, and working in water which passes through them with varying velocities at different points of the disc area. I would also suggest that Mr. Reeks would probably find it cheaper to have his propellers balanced than go to the expense of fitting flexible "A" brackets.

As Mr. Tournay-Hinde remarks, the literature on the subject of my paper is meagre, and I am glad to hear of the papers he refers to, which I had not seen. No doubt the point raised, as to the indentation of the weight of the propeller or other mass being balanced on the knife edges, reduces its sensitiveness, which is only another argument in favor of the rotational balance, where the forces developed by centrifugal action can manifest themselves in the way Mr. Fildes' figures show they do. I am afraid, though, the ingenious method of obtaining a better balance by a static method, which he described, would be rather a risky performance with heavy weights, and it would, with the ordinary static balance, which is in itself a lengthy process, be in the end more costlythan the process I propose of dealing with both the static and dynamic out of balance in one by the rotational method. The method Mr. Tournay-Hinde employed for his impellers is ingenious, but here again, as he says, it is hardly applicable to heavy weights.

With regards to the remnants shown in the vibration records in Fig. 20, this is not due to any change in the shafts, as this remnant was taken with the same shaft as that with which the main balancing was done, but is simply due to the fact that the balancing was intentionally stopped short of perfection, as it was not considered worth the extra cost that would have had to be expended had the last trace of vibration been eliminated.

That part of the shaft on which the propeller fits, and on which it is balanced in the shop, is an exact replica of the end of the tail shaft on which the propeller fits in the ship, so that there is very little chance of there being any difference due to this cause: the vibrations in the ship are due to other causes—water ones—already referred to.

I do not think there is any likelihood of the periodicity of the springs in the vibrometer interfering with the records, so long as it is stiff and quick enough to keep the recording lever up close against the rod, which was fastened to the deck over. We found that we had to make that spring stronger than the light one we originally fitted to ensure this being done.

Mr. Fildes asks whether I have made any experiments with crank shafts under high speed. Such work has not hitherto come under my experience. The balancing machines referred to have been under my notice, but as they are designed for only comparatively light work, they were quite useless for propellers or heavy turbine rotors. The figures quoted by Mr. Fildes illustrate very clearly what a powerful force there is in centrifugal action, and is one which we were fully alive to and had ample evidence of in our work on propellers, and of which full use is made in the rotational balance.

Mr. Oram asks whether the flexibility of the shaft was taken into account. The length and size of the shafts we use in our work are such that there is ample rigidness against any flexibility which is worth noticing.

Mr. Vicars raises two points—to the first I would say that with the care exercised in building the ships there is little possibility of any want of alignment, and as regards the second the difference in density between the upper and lower tips of the propeller blades is so small that I do not think there can be much vibration due to it, but there are other water complications, which I have already referred to. I may say also that I have made no attempt to solve any of these complex problems, and have confined myself entirely to the want of dynamical balance in the propellers themselves, and have only considered steady motion in a straight line. It is well known that as a vessel pitches or rolls in a sea way, or where the helm is put over, considerable additional vibrations are set up. These, however, have nothing to do with the question I have dealt with.

Mr. Chalmers raises somewhat similar points. The curves obtained were taken in a vessel fitted with four propellers, all of which were revolving at different speeds varying some 15 revolutions per minute in about 500, so that under such conditions it is not difficult to conceive that you could have periods when the vibrations set up by each propeller would at one moment tend to cause maxima and at another moment minima vibrations, i.e., when the vibrations of the separate propellers synchronised and when they were in opposition. There would naturally be less tendency for these variable vibrations in a twin screw ship than in the case of the vessel we tested, but we would still have to contend with the variable water and other problems.

Mr. Snashall asks about errors of pitch. In all the propellers dealt with, the driving faces were machined accurately to a true helix, and the backs were chipped and graded as accurately as possible to designed thicknesses, and as the metal is removed from the backs of the blades, if any alteration in the pitch of the driving faces is found it is carefully corrected.

Mr. Fraser may rest assured that what I said about the variability of the lag is quite correct. I will go further, and say that in some experiments I have made the angle of lag has varied between 0° and 330°. As stated in my paper, the greatest difficulty we have to contend with is in determining what is the lag. Theoretically, it would appear that at the moment of synchronisation of the centrifugal forces, which depend upon the speed of rotation, with the period of vibration of the springs, the lag should be 90° behind the actual position of the weight, but only a few revolutions below or above this period causes the lag to vary enormously, and up to the present time I have been unable to find out any law for this variation. The chief difficulty is to mark the position on the shaft at the exact moment of maximum vibration.

I think that concludes the remarks I have to make in reply to the questions raised, and I can only repeat I am grateful to you for the way in which you have received my paper, and I assure you it has been a very great pleasure for me to be here to-night.

THE PRESIDENT: Before closing the meeting, I should like to say, on behalf of the Association, that it has given us great pleasure to see such a satisfactory attendance of visitors here to-night, and I desire to assure them a hearty welcome is always extended to them. We are always glad to see at our meetings engineers or others interested in the subjects presented.