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The Experimental Approach to the Problems of Shaft Whirling

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The Experimental Approach to the Problems of Shaft Whirling

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SUMMARY

The theoretical and practical aspects of shaft whirling are discussed and a brief survey is given of past work.

A new experimental approach to the problem is suggested and discussed. A detailed programme of experiments is outlined.

The design of model test rigs is also considered and a description is given of a rig built at the R.A.E. for investigating the theory of shaft whirling.

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1 Introduction

The introduction of contra-rotating propellers with single and coupled engine installations and of axial flow compressor turbines with high rotational speed and complex structure has brought the old problem of shaft whirling once again into prominence. Not only has it become necessary to estimate critical speeds of individual power plants with great accuracy, but regard has to be paid to the flexibility of the mounting structure and the effect even momentary or incipient whirls may have on the aircraft structure.

Examination of the long history of the study of shaft whirling shows that although there has been much effort given to solving the many whirling problems theoretically, the experimental approach has been, by modern standards, neglected, and in particular full advantage has not been taken of modern electronic and photographic equipment. The result is that many different theoretical methods are at present in use for calculating critical whirling speeds which have never been confirmed experimentally and which take little account of the constraints peculiar to specific installations.

The major requirements for the solution of shaft whirling problems are discussed in the report. The first and most important is to establish experimentally an accurate method of calculating critical whirling speeds of complex systems having regard to the constraints in a particular installation. In many of the installations (e.g. contra-propeller systems) it is possible to have a number of critical whirling speeds covering a wide range of speeds often in the region of the operating speed range. Some of these criticals have been found to be of little importance as the resonant amplitudes are small. It is desirable therefore to be able to make an advance estimate of the severity of each whirling condition as well as to calculate the speed at which it occurs.

Small model rigs are considered to be suitable for testing theories of shaft whirling, but do not reproduce all the conditions occurring in practice which are required to be known if any theory is to be of use. These various conditions, of which degrees of constraint are most significant, need to be investigated by means of actual installations or large model rigs which closely represent them.

A suggested programme of investigations is included in the report, covering the most important problems which have been met with to date. A model rig has been built for the experimental verification of the basic theories relating to the single shaft system. The whirling shaft is supported on the cantilever principle with provision for an outrigger bearing of symmetric or unsymmetric flexibilities as required. A rotor adjustable to cover the two blade or four blade propeller problems is provided. The rig may be modified to cover the contra rotating propeller cases. A description is given of this rig together with a discussion of the design requirements associated with models of this form.

Finally the photographic recording technique developed for the measurement of whirl and shaft deflection forms is described. The shaft speed is measured electronically to ensure accurate plotting of the whirl amplitude frequency curves.

2 Historical Background

Since 1869 when Rankine[1] published one of the earliest theories on the whirling of rotating shafts, many explanations of this phenomenon have been propounded by various investigators. In 1883 Greenhill[2] in a paper communicated to the Institute of Mechanical Engineers, investigated the stability of a shaft between bearings when transmitting a thrust and a couple. Eleven years later in 1894 Dunkerley[3] provided an important contribution to the subject in his paper published in the Philosophical Transactions of the Royal Society. In this paper he describes experiments carried out with various arrangements of shafts, bearings and pulleys. The results of these experiments were applied to a theory suggested by Professor Osborne Reynolds, and an empirical formula was derived for the calculation of critical whirling speeds of shafts carrying a number of loads. Although Dunkerley observed critical whirling speeds on model shafts and using Professor Reynolds theory was able to estimate fairly accurately the values of these criticals, his basic conception of the physics of shaft revolution is now regarded as erroneous.

The next important contribution to the subject was made by Chree[4] in 1904 in a theoretical investigation concerned mainly with the behaviour of a rotating shaft near its critical whirling speed. Although Chree's theory enabled him to calculate whirling speeds which agreed with those of Dunkerley he failed to explain the stability of a shaft above its critical whirling speed. Chree's basic theory which is essentially the same as Rankines has since been shown to be fallacious. Subsequent writers on the subject were numerous but their contributions were of less importance until 1919 when a rational theory of shaft revolution was presented by Jeffcott[5]. None of the investigators previous to Jeffcott had realised, what has since been recognised as a fundamental principle, that a true running shaft supported on bearings does not necessarily rotate about the axis of the bearings, and that if the shaft whilst stationary deflects under its own weight then it will rotate about its statically deflected axis. This phenomena was first observed by Duffield, a professor of physics at University College, Reading, who in about 1916 noticed that, when a straight piece of wire was rotated in the chuck of a lathe and was disturbed by plucking or striking, it could vibrate in the plane containing the shaft and the line of application of the disturbing force. It was the independent appreciation of this phenomena which prompted Jeffcott to submit his theory of shaft revolution. He showed that in consequence of a forced vibration, caused by lack of balance, a shaft whirls in steady motion about its elastic axis and not about the axis of its bearings

Following the Jeffcott theory the principles of shaft whirling began to be appreciated to a fuller degree and in the early 1920's Stodola[6] published an account of his experimental investigations of the critical whirling speeds of a shaft with a number of discs uniformly distributed along the shaft, the effect of loosely mounted discs and also secondary disturbances occurring during shaft rotation. This was one of the first series of experiments where actual whirl amplitudes and patterns were recorded. This was done by attaching a lever to the shaft supported by a linkage at some intermediate point and carrying a pencil at the end.

Further experimental work was carried out by Robertson[7,8] in the 1930's who, by means of optical methods, made visual observations of whirl amplitudes and patterns mainly with regard to transient whirls.

Apart from the work of Stodola and Robertson, very little fundamental experimental work has been carried out on shaft whirling especially with regard to the complex shaft systems in use at the present time where such factors as the inertia effects of rotating masses, flexibility of bearings and masses, and contra-rotating systems have to be considered. There is, however, no lack of theoretical matter on the subject. Probably the most comprehensive treatment of the subject at the present time is due to Morris[9,10].

3 The experimental Approach

Shaft whirling presents a complex dynamic problem and although the fundamentals are now understood, the theoretical approach to the whirling of complex systems has never been confirmed experimentally. The first requirement, therefore, for a complete understanding of whirling problems, is for planned experiments to check the theory relating to shaft systems supported in small flexible bearings and carrying rotors of appreciable moments of inertia. It is considered that this requirement can be met by a series of experiments on small model shaft systems, designed to present the least possible number of unknown constraints, so that the effect of any imposed constraint in the system can be readily assessed.

With the theoretical approach to the subject established it is necessary to determine the effects of the constraints which are to be found in practical installations and which are mostly ignored in the general theoretical treatment. The most important to be considered is that imposed by bearings for single and multi span shaft systems. Present day whirling calculations are based on the assumption that a bearing has either no constraint or maximum constraint depending on its length and construction. Accurate calculations are not possible until a closer estimate of bearing constraints can be made. The use of small models in the experimental approach to this problem is impracticable as bearing clearances cannot be made representative. Valuable information can be obtained from experiments on larger models but it is essential that the results of such experiments be correlated with confirmatory tests on full scale installations. Hence, although the majority of the work is done on the larger model test rigs the results obtained may be applied with confidence to the full scale installation.

4 Details of the Problem and Proposed Programme of Experiments

The problems to be investigated may be divided into two main groups (4.1) those relating to single shaft systems and (4.2) those relating to contra rotating shaft systems. Under these headings the particular problems in each group are as follows:-

4.1 Single Shaft Systems

(a) The effects of symmetric and unsymmetric bearing flexibilities on critical whirling speeds.

(b) The effects of symmetric and unsymmetric rotor inertias on critical whirling speeds and free vibrations (two blade and four blade propeller analogies).

(c) The effect of propeller blade flexibilities on the critical whirling speeds and free vibrations.

(d) The whirling of a shaft carrying a number of rotors and supported by more than two bearings.

(e) The whirling of shafts of unsymmetric section.

4.2 Contra-rotating Shaft Systems

(a) The effects of symmetric rotor inertias on the critical whirling speeds.

(b) The effects of symmetric and unsymmetric bearing flexibilities on critical whirling speeds with rotor of appreciable inertia.

4.3 Bearing Constraints

The accurate calculation of the deflection coefficients constitutes the greatest difficulty when estimating critical whirling speeds, as in most cases the effect of the bearings on the shaft stiffness can only be assumed.

The constraints in plain bearings can be investigated by experiments on models which must, however, be larger than those used for theoretical confirmations in order that more practical sized bearings can be investigated. Valuable information can be obtained by investigating the critical whirling speeds and transverse free vibrations of a shaft in bearings of varying length/diameter ratios and varying clearances. To be of greatest value, however, such results would have to be applied to full scale installations. This may be achieved by carrying out simple experiments on existing systems.

The effective constraint provided by ball bearings can best be assessed by experiments on actual installations or on test rigs of much larger sizes where the bearings are of the same order of size as those used in practice.

The suggestions so far are mainly applicable to an engine-propeller installation. There are still to be considered the problems associated with the gas turbine in which complex axial flow compressors are being used. The calculation of deflection coefficients and equivalent inertias for such systems has proved to be extremely difficult. The calculated critical whirling speeds for some such installations have been found to be more than 50% above the actual critical with subsequent failures on test.

For such cases model experiments are of little value and each installation must be treated separately until sufficient practical information is available on the characteristics of these complex systems. By carrying out model and full scale experiments it may be possible to devise a simple experimental technique for investigating the whirling characteristics of these complex installations without actually running through the critical speeds, thereby avoiding possible destruction of the particular installation on test.

5 Details of Model Experimental Rig

5.1 Basic Requirements

In order to carry out the experiments a rig has been constructed to fulfill the following basic requirements for work of this kind namely:-

(1) The shaft on which measurements are to be taken shall be of sufficient flexibility to permit large amplitudes of whirl to be forced without its being strained beyond the elastic limit. The system is then arranged so that the maximum whirl amplitude will occur at the end of the shaft thus facilitating the development of a photographic technique for recording purposes. Using a magnifying camera, it is thus possible to obtain photographs of whirl paths, large enough to enable accurate measurements to be made. When necessary, visual observations of the whirl paths can be made using stroboscopic light. Fulfillment of these conditions enabled an efficient experimental technique to be developed by means of which the accuracy of the fundamental physical theory could be investigated.

(2) It was considered to be most important that the initial conditions of shaft support and balance should present the least number of unknown parameters. An attempt was therefore made to start with a true running shaft, accurately balanced. By exercising great care in the initial fitting of the shafts used this was achieved to such a degree that it was possible in most cases to run the loaded shaft at its critical whirling speed without its striking the guard ring.

5.2 The Model Shaft System

Photographs of the rig are shown in Fig. P.1. The basic system consists of a cantilever shaft 12" long made from $\frac{1}{4}$" diameter silver steel rod The shafts used were selected from standard rods, with particular care as to their straightness. The test piece is fitted by means of a split collet into the end of a 1" diameter driving shaft. This driving shaft is carried by two taper roller bearings set 6" apart in the main bearing block. By making the clearances in the taper roller bearings as small as practicable a condition was reached whereby it was possible to assume the end conditions for the cantilever to be perfectly encastre.

Provision is made to support the free end of the shaft by means of a flexible outrigger bearing 10" from the face of the collet. The outrigger bearing consists of a $\frac{1}{4}$" self aligning bearing supported by four springs disposed at 90° about the axis of the shaft. The springs could be arranged to provide either equal or unequal stiffness in the two principal planes.

A Schrage motor is used to drive the test rig through a ten to one ratio step up gear box giving a speed range of 0 - 20,000 r.p.m. if desired. A fine speed control is obtained by means of a friction brake fitted to the main bearing block between the two taper roller bearings. By setting the motor speed control to give a shaft speed slightly higher than the critical speed being investigated and then controlling the speed by means of the brake it is possible to explore whirl amplitudes and patterns at shaft speeds very close to the critical, where the whirl amplitude is very sensitive to shaft speed.

The accuracy of this method is evidenced by the small degree of scatter of the experimental points plotted near the critical speeds.

Preliminary investigations deal with the effects of unbalance of a rotor of small moments of inertia. The rotor used is made from aluminium, it is 2" diameter and composed of two eccentric rings, one inside the other so adjusted that by rotating the outer ring the c.g. of the complete rotor can be offset from the centre of the shaft, on which the rotor is fitted by as much as 0.2". The actual position of the c.g. can readily be fixed by means of a graduated scale engraved on the inner ring and corresponding to a datum line on the outer ring.

5.3 Recording Equipment

The whirl paths at the free end of the shaft are recorded on film. This is done by means of standard F.24 aerial camera carrying a K.24 lens on the end of an extension tube. This arrangement gives an optical enlargement of 5.6 times. The whirl amplitudes at the end of the shaft are kept to within approximately $\pm\frac{1}{4}$" by means of a guard ring behind the outrigger bearing, recorded amplitudes are therefore of the order of 1.25" maximum. For moderate amounts of rotor unbalance, at $\frac{1}{4}$" whirl amplitude, the slopes of the resonance curve above and below the critical speed are practically the same. It is therefore considered reasonable to assume that the critical speed lies midway between the values given by the two curves at this amplitude.

The recording technique found to be most suitable for the optical system described above was one whereby the rig was normally operated in subdued lighting and a small highly polished 'pip' or the centre of the shaft at the free end was intensely illuminated for a controlled period of time with an open shutter on the camera.

For this purpose the normal 'roller blind' shutter in the camera was removed and replaced by a solenoid operated shutter of the 'Venetian blind' type.

The light source is controlled by a relay system operated by sliding contacts on the motor shaft in such a way that, independent of shaft speed, the end of the shaft can be illuminated for any desired number of shaft revolutions up to five by operating the recording switch.

To facilitate the operation of the rig, the camera is also fitted with an automatic film winding mechanism operated from the control panel. To compare the shaft deflection forms for the static, transverse vibration and whirling cases a second light source has been designed to illuminate the whole length of the shaft along the top edge. Using a half plate camera a photograph is taken timed to include at least one vibration cycle. An enlargement four times shaft size is then obtained by projecting the plate negative onto a white screen, amplitudes at different points along the shaft being measured direct and plotted on an enlarged scale. The results thus obtained are found to be very satisfactory.

When plotting amplitude frequency curves it is essential to record the speed of the shaft simultaneously with the recording of the whirl amplitude. This is done by means of an inductance proximity pickup, placed behind the main bearing block near a clip which rotates with the shaft. The pickup is connected to a single channel C.R.T. recording trolley, speed records being taken at the same time, as the whirl records. The shaft speed can then be measured against a fifty cycle per second timing mark.

6 Conclusions

Preliminary tests have already been made on the model rig described with satisfactory results. These preliminary tests are to be published in a later report. The object of the proposed programme of experiments is to establish the theory of shaft whirling and give some idea of practical design effects but it is considered that, apart from supplying valuable information on the whirling of complex shaft systems, a simple technique may be devised for investigating the whirling characteristics of existing full scale installations without actually causing such systems to whirl, a process which is often impossible due to the remoteness of critical whirling speeds from operating speed ranges. In this way model and full scale installations could be correlated and the final results safely applied in the design stage of future installations.

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FIG. I

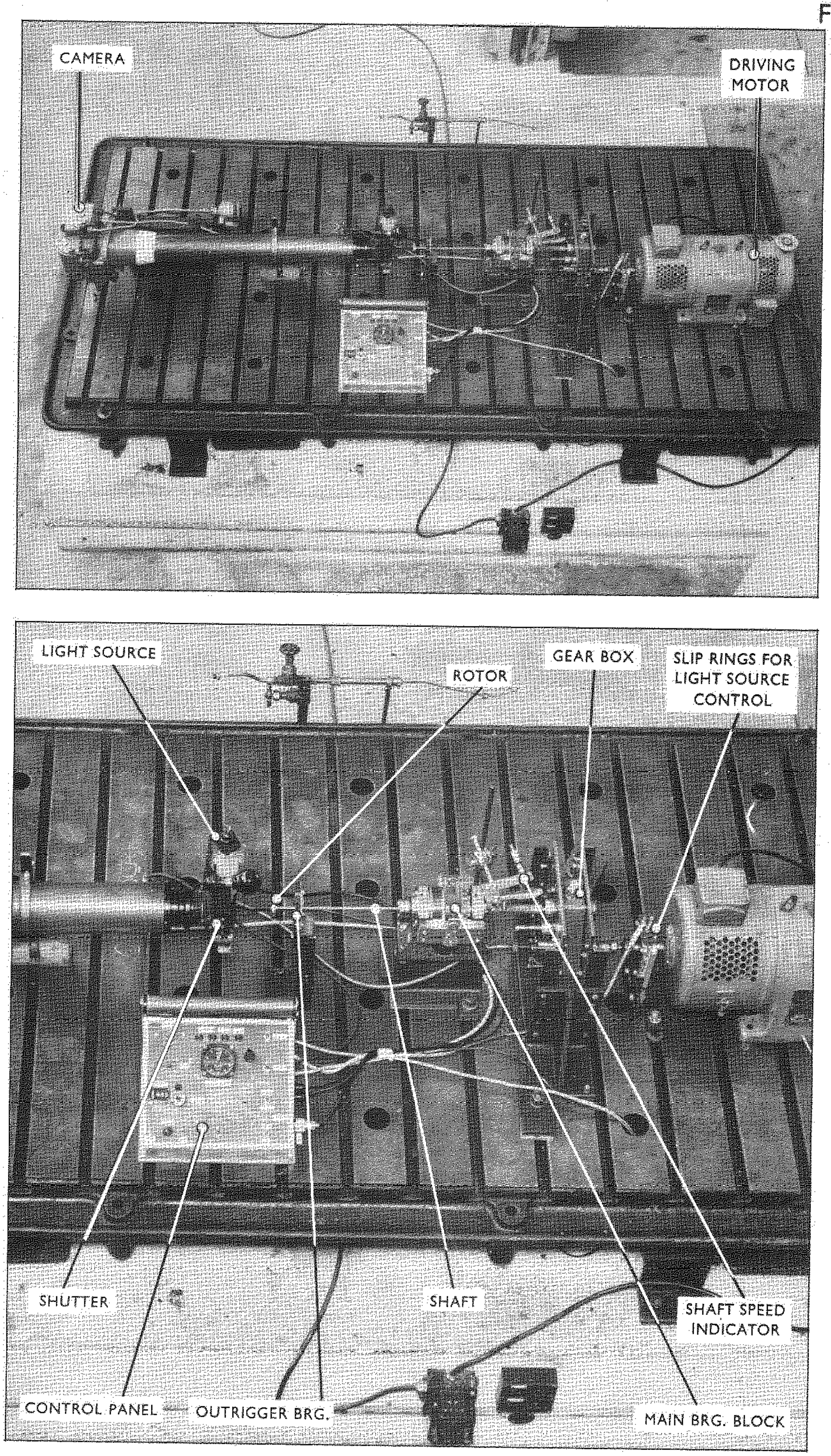

FIG. I. DETAILS OF THE EXPERIMENTAL RIG FOR THE INVESTIGATION OF SHAFT WHIRLING

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