coefficients). Large increments, show considerable theoretical cavitation zone movement and extreme variation in peak pressures. Furthermore, theory did not predict coefficients measured with higher increments (i.e. α, β not predicted). It is possible that in practice, under the specified oscillation the cavitation zone cannot re-locate as theory allows. This may mean that the oil film pressures depend on a preceding location and velocity in addition to the current values. This implies that for larger increments, the so-called "quasi-static" theory may be inadequate.

It is interesting that the incremental loading methods of determining displacement coefficients allow sufficient time during the experiment for any cavitation zone relocation. Therefore, in this case, both theory and experiment behave as "quasi-static," and give the better agreement between coefficient gradients obtained from the two sources.

It is important to recall that coefficients are required input data to rotor dynamic calculations, in which truly dynamic situations arise. Therefore, it is essential that oil film coefficients are valid for the dynamic and not the "quasi-static" condition. Furthermore, quite large velocities, comparable to the increments chosen for the significance criteria, are possible in the real machinery situation, thereby necessitating a more complex theory. Since oil film theories can only be verified by successful comparison with experimental results, it follows that more reliable theoretical coefficients of greater value to the rotor dynamicist, may be obtained by taking some preceding journal state into account. This concept offers the complicating prospect of producing coefficients whose values may vary with choice of previous history.

Conclusions

1. The experimental techniques are feasible and have enabled the nonlinearity of the eight dynamic oil film coefficients to be measured. Further significant improvement can only be achieved by introducing an on-line subtraction of the "origin" journal centre co-ordinates. Measurement of journal and bearing centres, displacement coefficients by incremental loading, and journal centre velocity combined with large velocity-based oil film forces were demonstrated.

2. No significant difference was detected between measured and predicted "zero" coefficients A_{xx0}, A_{xy0}, B_{yx0}, and B_{xy0}. The magnitude by which theory underestimates A_{yx0}, B_{xx0} and overestimates A_{yy0}, B_{yy0} was established. Apart from a few exceptions, coefficient gradients (α, β) were not accurately predicted.

3. No significant difference was distinguished between coefficients A_{yy} and A_{xy} obtained by incremental or dynamic loading techniques.

Variation of "zero" coefficients with eccentricity ratio, and the effect of vibration/rotation frequency ratio upon "zero" velocity coefficients was established.

4. Adjudged by the specified criteria observed non-linearity of A_{xy} and B_{xy} is significant $\epsilon/C_r > 0.78$. Measured non-linearity of all velocity and displacement coefficients is significant at $\epsilon/C_r > 0.86$ and 0.90, respectively. Less generous criteria would recognize significant coefficient nonlinearity at lower ϵ/C_r.

Acknowledgments

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DISCUSSION

W. E. ten Napel[1] and R. Bosma[1]

With much interest we have been reading this paper, particularly the description of the experimental part. With regard to the theoretical part, we have some questions and remarks on which we should welcome the author's comment.

First, a remark with regard to the nonlinear characteristics of the eight coefficients. It is well known, indeed, that at least the displacement coefficients are nonlinear. This immediately follows from the Reynolds equation.

With regard to the velocity coefficients, however, it can be remarked that $F_\perp$ and $F_\parallel$ are linear functions of v. Reinhoudt [8] remarks that it is better to take v fairly large in order to arrive at the desired numerical accuracy but that the occurrence of cavitation complicates matters. Our question with regard to this matter is whether cavitation is the only reason for the nonlinearity of velocity-coefficients or does the dependency of the viscosity on temperature and pressure also play an important role.

From Fig. 7 it follows that the left-hand and right-hand limit for A_{yy} and A_{xy} for $y \to 0$ show a large discrepancy, which in our opinion can only be explained in terms of truncation errors. These errors will tend to be even larger at higher eccentricities.

We are wondering whether truncation errors also play a role in the calculation of the remaining stiffness-coefficients. It would be very interesting to compare the theoretical results for the "zero" coefficients either with those of other investigators (e.g. Orcutt and Arwas [9] or Childs, et al. [10]) or with calculated values according to the equations of Christensen, et al. [11].

In the latter the displacement coefficients a_{xx} for instance has been calculated by applying:

$$a_{xx} = \frac{\partial F(x)}{\partial x} = \iint_A \frac{\partial p}{\partial x} \sin(\theta + \phi)\, dA,$$

instead of author's definition:

$$a_{xx} = \frac{F(x + \Delta x) - F(x)}{\Delta x},$$

where $\partial p/\partial x$ can be calculated by applying one of the equations given in reference [11].

According to the flow diagram, Fig. 3 in the paper, the viscosity fields have been updated after each pressure field convergence. Since the pressure distribution influences the velocity distribution in the oil film and since the velocity distribution influences the heat dissipation we are wondering whether the assumed temperature profile for the load and speed combinations as specified have also been updated after each iteration.

We do agree with the author that calculations with linear coefficients are restricted to small journal displacements and velocities.

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However, when the coefficients are described, as proposed by the author, by:

$$a_{xx} = a_{xxo} + \alpha_{xx} . x \text{ (etc.)}$$

rotor dynamic calculations can only be performed by computer simulation. Can the author give some indications when his approach is to be preferred as compared to the existing methods for computer simulation like the mobility [12] or impedance method [10], which both have the advantage of not being restricted to small journal displacements at all.

Additional References

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R. Holmes[2]

This paper presents an interesting and painstaking contribution in the field of bearing coefficient estimation, but once again, through no fault of the author, the results are bedevilled by scatter. I wonder if the time has come to apply to a journal bearing, identification techniques developed in the field of control[3] in an effort to reduce such scatter and to speed up the process of investigation.

Two specific points may be raised in connection with the paper. The first relates to the use of equations (7) and (8) as an alternative to the author's main approach. If separate incremental loadings ΔF_x and ΔF_y are applied then the appropriate equations should surely be

$$\Delta x = \alpha_{xx}\Delta F_x + \alpha_{xy}\Delta F_y$$

and

$$\Delta_y = \alpha_{yx}\Delta F_x + \alpha_{yy}\Delta F_y,$$

where α's are flexibility influence coefficients. The stiffness coefficients would then be obtained by inversion.

The other point relates to the equations (under "Results") such as

$$a_{xx} = a_{xxo} + \alpha_{xx}x \text{ etc.}$$

Why, for example, does the author not write

$$a_{xx} = a_{xxo} + \alpha_{xx}x + \alpha_{xy}y + \beta_{xx}\dot{x} + \ldots$$

since there appears to be no reason why the second order terms should not depend on y etc, just as much as on x?

[2] Applied Science Laboratory, The University of Sussex, Sussex, England.

[3] Stanway, R., Burrows, C. R., and Holmes, R., "PRBS Forcing in Journal and Squeeze-Film Bearings", ASLE reprint no. 78-AM-2A-1 presented at Dearborn, Mich., Apr. 1978.

C. H. T. Pan[4]

The importance of dynamic phenomena in rotor-bearing systems has been recognized for some time. Much has been published in calculation methods and/or numerical characteristics of various fluid-film bearings. Credibility of these studies is often not totally convincing because of the necessity for invoking one or more of the following measures of expedience:

- Viscosity is assumed to be uniform in the fluid film.
- A simple model for the "cavitation" condition, e.g. that due to Swift-Stieber, is assumed.
- Inertia effects are neglected.
- Numerical accuracy is most of the time accepted on the basis of heuristic arguments.

This paper is a welcome addition to the literature in representing the systematic evaluation of the dynamic characteristics of a fluid-film bearing simultaneously by theoretical and experimental methods.

Upon reading this paper, the following questions came to this reader's mind:

1. How was the temperature field determined?
2. Can the author provide an illustrative comparison of the "zero" coefficients as calculated by the "fully variable theory" with those obtained by simpler method such as the "iso-viscous, short-bearing thoeory"?
3. If the instantaneous total displacement, e.g. $x_0 + x$, is used as a state variable, is it equivalent to the inclusion of the corresponding "gradient" coefficient x_0?
4. What is the rationale for omitting the cross-coupling velocity gradient coefficients γ_{xxy} etc. by assuming

$$b_{xx} = b_{xx0} + \beta_{xxx}\dot{x} + \beta_{xxy}\dot{y}?$$

5. Why should an apparent discontinuity exist at $y = 0$ in A_{yy} as shown in Fig. 7?

Elucidation of these questions by the author will be greatly appreciated.

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Author's Closure

Since some topics have been raised by more than one discusser, it will be more convenient to reply under subject heading.

The theoretical discontinuity in Ayy at $y \to 0$ was questioned by both Professors ten Napel and Bosma and Dr. Pan. All available data, including some not in the paper, but in reference [5], showed that this discontinuity was exhibited by displacement coefficients Axy and Ayy only, and its magnitude increased with eccentricity ratio. Both coefficients are those which require a finite vertical increment for their computation. It was established that this discontinuity was not due to the inclusion of the variation of viscosity with pressure or the choice of temperature field. Results were computed (but not illustrated) using the Short Bearing Approximation and a uniform viscosity field. These were, of course, nonlinear functions of displacement, but did not exhibit the discontinuity. Therefore, it was concluded that a prominent contribution to this discontinuity arose from the choice of circumferential boundary condition, the location and extent of the cavitation zone and the method by which it was evaluated. Fig. 7 shows the experimental support for the theoretical curve for Ayy, in the region of positive x, and at its discontinuity.

Responding to Professors ten Napel and Bosma's request for a comparison of zero coefficients with those of other workers, Fig. 13

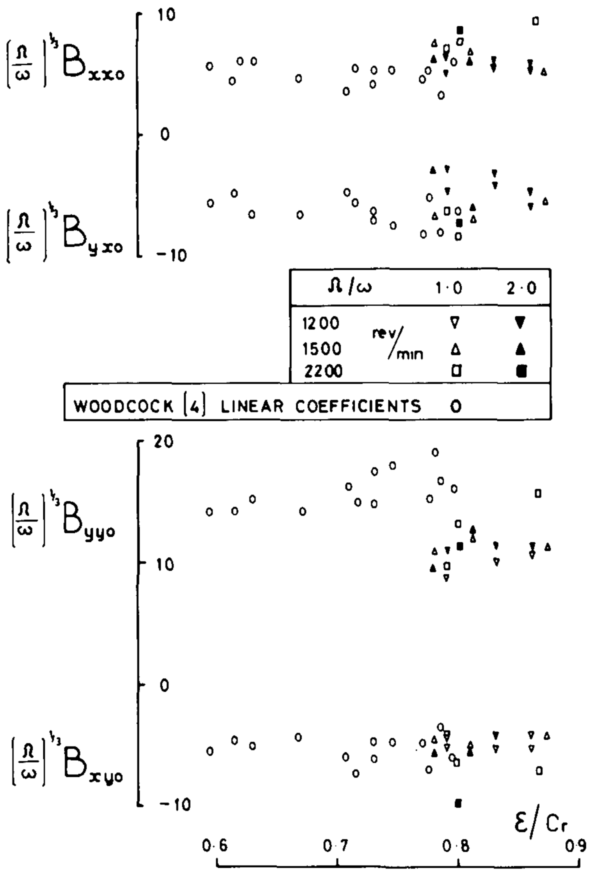

Fig. 13 "Zero" velocity coefficients

shows nondimensioned "zero" velocity coefficients compared to those measured by Woodcock [4]. Reference [5] gives comparisons with the Short Bearing Theory as suggested by Dr. Pan.

Published, measured temperature fields for bearings of comparable size and rotational speed were examined and all found to have:

(*a*) *negligible axial variation*

(*b*) circumferential temperature given by $T_\theta = aT_1\ (1 + \sin \theta/2)^b$ where a, b depend on test conditions and T_1 was the measured inlet temperature.

These relationships were incorporated into the computer program, and a, b, adjusted for the particular test condition. Reference [5] gives full details.

Temperature fields were not revised after each iteration.

Drs. Holmes and Pan both referred to further cross coupling coefficients. I agree with Dr. Holmes that other terms may also be important. However, coefficients obtained theoretically were restricted to those which could be measured by the methods described in the paper.

Dr. Holmes suggests an alternative approach to the determination of displacement coefficients by the incremental load method. By his procedure, horizontal and vertical incremental loads are separately applied in the presence of the large vertical steady state load. In the method described in this paper, horizontal and vertical incremental loads are separately applied with the large steady state load at some angle midway between horizontal and vertical. Hence the incremental loads each apply a different set of component forces in directions parallel and perpendicular to that of the steady state load.

This feature imparts some valuable advantages at the higher eccentricity ratios used in this work. Theory showed that the nonlinearity of the velocity coefficients at eccentricity ratios greater than 0.89 depended upon both cavitation zone movement and the influence of pressure upon viscosity. At lesser eccentricity ratios this nonlinearity depended only upon the cavitation zone.

Finally, may I thank the discussers for their thoughtful study of the paper and very helpful comments.