DISCUSSION

W. A. Gross[4]

Dr. Ausman has shown that, by making three plausible simplifications, he is able to obtain solutions for the steady self-acting gas-lubricated journal bearing which yield good results for both small and large eccentricity ratios. We congratulate Dr. Ausman for recognizing and employing these approximations.

Dr. Ausman raises the question of convergence of iterative solutions to the nonlinear Reynolds equation. This is certainly a fair question to raise, but so is the question involving the justification of the plausible assumptions used in this paper. Convergence and, of equal importance, uniqueness of iteration solutions are indicated by test. We find that, by beginning our iteration with various initial values, both larger than and less than the correct solution to a steady gas bearing film example, we converge to a solution which is unique to the number of decimal places required. Furthermore, iteration solutions for small bearing numbers approach the results for an incompressible film, while for large bearing numbers the results approach those for purely compressible films as theory predicts. These results provide solid evidence of convergence, even though a precise mathematic proof is missing.

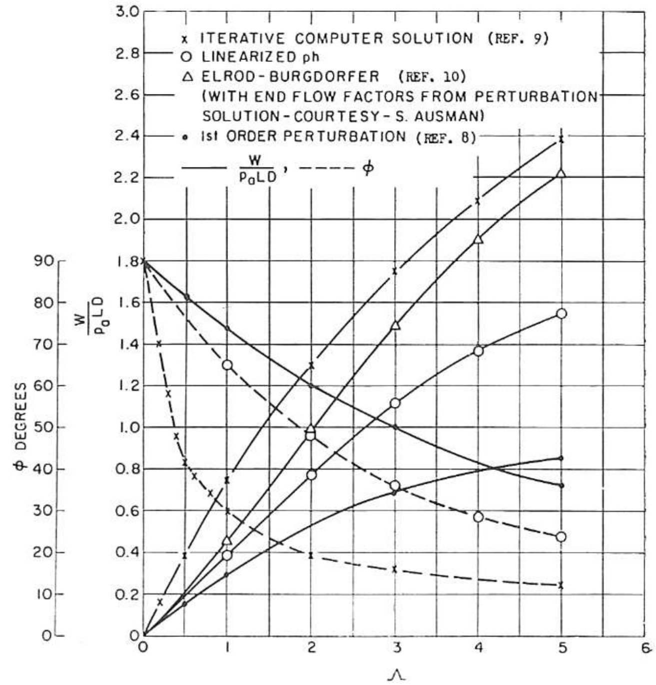
It is of interest to compare iteration solutions obtained by beginning the iteration with ambient pressure over the bearing with those solutions obtained by beginning the iteration with approximate solutions. We have carried out such investigations in co-operation with Dr. Ausman, who supplied us his approximate values for journal bearings with eccentricity ratio 0.8, bearing number 0.5, and slenderness ratio 1. Using an IBM 650 tape unit and an iteration scheme comparable to that described by Michael,[5] we find that 34 minutes are required to obtain a solution which is accurate to four places for an 8×12 grid when we start with ambient pressure over the grid. It should be noted that an 8×12 grid is too coarse for such a problem. The grid should be at least 12×24. The 8×12 grid was chosen strictly for comparison purposes. When we start with the Ausman linearized ph solution, we find that 49 minutes are required to converge to a solution which is accurate to four places. When we begin with the linearized ph solution with only five instead of eight digits specified, we find that 52 minutes are required. When we begin with an iteration solution supplied by Dr. Sternlicht of General Electric, we find that, starting with five place digits, we converge to a solution in 45 minutes. Finally, when we begin with our own solution, in which only five digits are used for input, we converge to a solution in $3^1/_2$ minutes. For the particular case chosen ($\epsilon = 0.8$, $\Lambda = 0.5$, $L/D = 1$), $W' = W/BLp_a = 0.386$ attitude angle $\phi = 43$ deg.

From the preceding, it is clear that the digital computer solution is very sensitive to the pressure gradient and, although the pressure profile may be well approximated, there are usually angular shifts in pressure maxima and, consequently, pressure gradients are significantly in error at many parts of the grid. The consequence is that the iteration takes longer with the approximate solution as an input than it does with purely ambient conditions supplied as an input.

Beno Sternlicht[6]

The author should be complimented for his valuable contribution to the theory of gas bearing lubrication. In this paper as in the previous one (Ref. [7]) the author uses analytical method for the solution of the Reynolds equation. These methods even though applicable only over a limited range of eccentricity ratios provide good physical insight into the problem and consume considerably less effort in computations than do the numerical methods.

To add to some of the comparisons that Dr. Ausman uses in his paper, I am taking the liberty of adding two figures. The first of these was chosen for a high value of eccentricity ratio $\epsilon = 0.8$ to accentuate the difference between the various methods of analysis. Eccentricity ratio of 0.8 is around the limit of good design practice. For lower eccentricity ratios there is closer agreement between the linearized ph and the iterative solutions. Note from Fig. 10 that the author was quite correct in stating in his title that this is an improved analytical solution over the first-order perturbation results.



L/D = 1, ε = 0.8

Fig. 10

In Fig. 11 a comparison is given of theoretical and experimental results for low eccentricity ratios. These eccentricity ratios are commonly used in practice. For the theoretical results iterative and first-order perturbation solutions are given. The linearized ph results fall between these two methods of analysis and were omitted from the graph to avoid confusion. There are very few accurately conducted experimental results available. The ones presented in this figure are among the best. Note that the experimental results fall between the two theoretical results. This points out the need for more accurately conducted experiments in order to see which theory correlates better with experiments. This comparison is given in order to reaffirm the value of Dr. Ausman's contribution.

References

8 J. S. Ausman, "Finite Gas Lubricated Journal Bearing," The Institute of Mechanical Engineers, Proceedings of the Conference on Lubrication and Wear, 1957, pp. 39–45.

9 B. Sternlicht, "Gas-Lubricated Cylindrical Journal Bearings of Finite Length, Part I: Static Loading," August 15, 1960, ONR Report, Contract No. NONR 2844(00).

10 H. G. Elrod and A. Burgdorfer, "Refinement of the Theory of Gas Lubricated Journal Bearings of Infinite Length," Proceedings

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[5] W. A. Michael, "A Gas Film Lubrication Study, Part II, Some Theoretical Analyses of Slider Bearings," *IBM Journal of Research and Development*, vol. 3, 1959, pp. 256–259.

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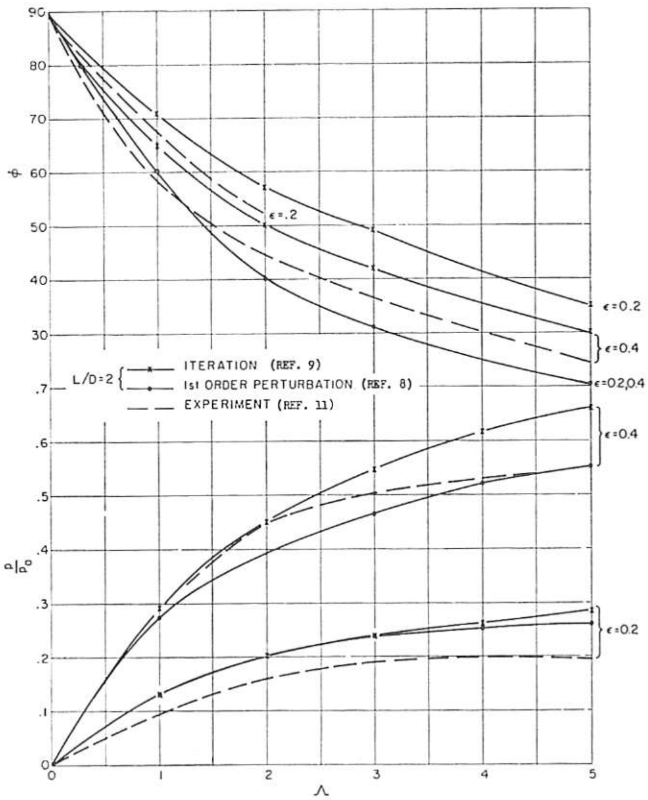

Fig. 11

of the First International Symposium on Gas Lubricated Bearings, Washington, D. C., October, 1959.

11 S. Whitley and C. Betts, "A Study of Gas-Lubricated Hydrodynamic Full Journal Bearings," *British Journal of Applied Physics*, vol. 10, October, 1959, pp. 455–463.

Author's Closure

The author is once again grateful to Dr. Sternlicht and Dr. Gross for their constructive remarks and additional comparative data. The convergence time experiments conducted by Dr. Gross were carried out to check the presumption that the linearized ph solution used as an initial starting point might reduce the costly computer time required for finite difference iterative solutions. Dr. Gross's example shows that such is not necessarily the case. In this instance, it actually took longer to converge from the analytical approximation than from an initial constant pressure grid. The author has had similar experience since first writing this paper and agrees with Dr. Gross that there is no advantage to be gained in starting a finite difference iteration program from the linearized ph solution.

One of the best uses for the linearized ph solution is for preliminary design of self-acting gas-lubricated bearings. Steady-state load characteristics can be estimated quickly and easily from equations (16) and (17) with the aid of Fig. 4. The accuracy of these estimates is comparable to the accuracy to which the bearing can be manufactured and tested. Dr. Sternlicht's comparisons re-emphasize this point, often overlooked, that even the best experimental data to date do not agree exactly with iterative computer solutions which presumably are nearly exact solutions of Reynolds equation.

Manufacturing tolerances and experimental error are the most likely sources of this apparent discrepancy. Bearing clearance has a critical effect on bearing performance. Uniform clearance bearings are difficult to manufacture when the nominal clearance itself is about 100 microinches, and accurate measurement of the minimum clearance of such a bearing loaded and operating is also difficult.

For these reasons one could not afford to design to the ultimate load indicated by an exact solution to Reynolds equation even if such a solution were available. It would still be necessary to include some margin of safety. In this regard Figs. 9, 10, and 11 show that the linearized ph solution yields a conservative design (predicts less load) in comparison with finite difference iterative solutions.