

7 The investigation shows that a logical specification regarding the acceptable location of critical speeds could be arrived at by means of such a steady-state unbalance response analysis in all cases rather than basing the specification on the calculated rigid support critical speeds [7].

8 A technique remains to be developed to specify the amount and location of unbalance along the axis of the rotor which will more closely simulate the response of an actual unbalanced rotor-bearing system.

## Acknowledgments

The authors are indebted to the Elliott Company, A Division of Carrier Corporation, for permission to publish this paper, and to the many individuals within the company who contributed to these investigations.

## References

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## DISCUSSION

### R.G. Kirk.<sup>2</sup>

The authors have presented an interesting summary of a number of machines that are typical of the compressor industry. Of major interest and concern to this industry is the influence of bearing damping on rotor forced response and stability. The discussor would like to see a common nomenclature to distinguish among damped natural frequencies, undamped natural frequencies (critical speeds), and peak response speeds (damped critical speeds). This is especially important since methods are now available to calculate damped eigenvalues and eigenvectors of rotors including bearing and support damping. It must be made clear that these damped eigenvalue frequencies are *not* the speeds at which peak response from rotor imbalance will occur.

The assumption of rigid pedestals is a good simplifying assumption for presentation purposes, but could be very misleading in many cases. For the heavy rotor in the authors' presentation, the vertical stiffness is on the order of 10-20 million lb/in. and probably above, near, or at least approaching the bearing support structure equivalent stiffness.

The plotting of undamped critical speeds versus static stiffness in order to predict peak response speeds can be very misleading. This is especially true when trying to specify the location of second and third modes (see Fig. 2) for the purpose of meeting specification on their closeness to maximum continuous operating speeds (see reference [7]).

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The discussor has several questions which relate to the authors' presentation. The authors have only plotted experimental data for the vertical direction. (1) Are the probes really at the vertical, or are they rotated to 45 deg and 135 deg (which are the locations of many job probes and are better orientations to give maximum response readings directly)? The horizontal predicted amplitudes are much larger than those for the vertical response. (2) Is experimental data available to compare to the predicted responses and if so, does the response agree, especially for the case of the light rotor (Figs. 9, 10)? (3) Since the paper is treating the influence of damping, could the authors please give the values of the damping coefficients, the cross-coupling terms for the heavy rotor bearing, and the damping values used for the light rotor tilting pad bearing? This would make the analytical results presented much more meaningful and would permit a better understanding of the observed response. (4) For tilting-pad bearing machines, is it not more appropriate to plot a dynamic stiffness characteristic versus rotor speed instead of the static stiffness of the bearing? For example, something as simple as  $K_{dyn} = \sqrt{K^2 + (c\omega)^2}$  for the case of symmetric bearing characteristics might be used. (5) For rotors with high damping and large cross-coupled stiffness terms, have the authors observed cork screwing and mixed mode response in the vicinity of apparent second- or third-mode speed ranges? (6) And finally, have the authors taken note of experimental or analytical phase angle data and if so, does the occurrence of a forward phase shift always indicate the presence of a "peak response speed?" The discussor is particularly concerned about modes having over 50 percent critical modal damping.

If the authors can supply this information and answers, the value of this paper to technical literature will be greatly increased.

## Authors' Closure

The authors have gone through the discussion with interest. The content of the paper is related only to the steady-state response of the rotor due to unbalance at specified locations along the rotor and the effect of fluid film bearing damping on the undamped lateral critical speeds. The assumptions pertaining to such an analysis and also the definition of lateral critical speeds as used in the paper have been stated clearly in the introduction of the paper. The synchronous system response has been investigated.

The fact that the predicted peak response correlated closely with the experimental results shows that the assumption of rigid supports is valid for the cases presented in the content of the paper. Strictly speaking, no physical system is infinitely stiff. The undamped critical speeds obtained from the plotting of static stiffness on the critical speed maps have not been used to predict peak response. This, in conjunction with the mode shape plots at the undamped critical speeds, aid the designer in evaluating qualitatively the possible effect of fluid film bearing damping on the undamped lateral critical speeds. Note the conclusions.

Analytical phase angle data for the vertical and horizontal responses were obtained for some cases, but the authors are unable to make any conclusive remarks, as suggested by the discussor, at this point in the investigation. More work needs to be done in this area.

The probes were placed in the vertical direction.

The lubricant used in all cases is DTE light at an inlet temperature of 120°F (49°C). Since all other relevant data (e.g., steady-state bearing reactions, bearing dimensions, etc.) are supplied in the text of the paper, the discussor should have no difficulty in computing the fluid film bearing stiffness and damping coefficients at different required speeds for the type of bearings used in the rotor-bearing systems presented in the paper.

As one would normally expect, cork screwing of the rotor has been observed in several cases. For the case of mixed mode response, the authors suggest that the discussor go through the section on System 1, Table 1.