Journal of Tribology

Discussions

Discussion: ''Operation of Foil Bearings Beyond the Bending Critical Mode'' [ASME J. Tribol., 122, No. 1, pp. 192–198 (2000)][1]

I. Green
School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332

The author associates the (integer multiple of) harmonics shown in Fig. 19 with rigid body frequencies. Would the author elaborate on this, and perhaps provide a theoretical foundation that supports such an association? It is our experience that integer multiple of harmonics may be present at any rotational frequency (unrelated to rigid body modes/frequencies) because of misalignment and deflection that cause intermittent rub between rotor and stator (see also Vance, [1] p. 356). In the author's experiment the speed is supercritical and the harmonics shown are integer fractions of that speed. Rub will also cause the same phenomenon in subcritical speeds only that the harmonics will occur at integer multiples of the rotational speed. This has been observed by Lee and Green [2] in experiments of a flexibly mounted rotor face seal (the association with journal bearings and particularly trust bearings is, of course, trivial). The analysis by Lee and Green [2] reveals that the integer multiples result from a Fourier series expansion of signals that are contaminated with rubbing characteristics. That analysis also gives an explanation for the varying harmonics magnitudes (where some may not even show up). In fact there is a clear envelope in Figure 19 of the harmonic magnitudes which may disclose the arc extent of rub. Not only that this rubbing phenomenon can be monitored (Zou and Green [3]) it can also be eliminated by either passive (Lee and Green [2]) or active control (Zou et al. [4]). It is worth of note that the power generated by such rubs is not high. Rough estimates of some of the parameters, and assuming a generous coefficient of friction of 0.2, reveals that the power generated in such a case would be fairly low (perhaps 50 Watts), which is insufficient to cause a ''major system melt-down.'' But rub over time has a detrimental effect on the bearing surfaces that would ultimately lead to their failure.

References

[1] Vance, J. M., 1988 *Rotordynamics of Turbomachinery*, Wiley, New York.
[2] Lee, A. S., and Green, I., 1994, ''Higher Harmonic Oscillatoins in a Noncontacting FMR Mechanical Face Seal Test Rig,'' ASME J. Vibra. Acoust. **116**, No. 2, pp. 161–167.
[3] Zou, M., and Green, I., 1997, ''Real-time Condition Monitoring of Mechanical Face Seal,'' *Proceedings of the 24th Leeds-Lyon Symposium on Tribology*, London, Imperial College, pp. 423–430.

[1]H. Heshmat, 2000, ''Operation of Foil Bearings Beyond the Bending Critical Mode,'' ASME JOURNAL OF TRIBOLOGY, Vol. 122, No. 1, pp. 192–198.

[4] Zou, M., Dayan, J., and Green, I., 1999, ''Feasibility of Contact Elimination of a Mechanical Face Seal Through Clearance Adjustment,'' accepted for publication in ASME Transactions, Preprint 99-GT-147, presented at the ASME Turbo Expo 98' (ASME International Gas Turbine Institute).

Closure to ''Discussion of 'Operation of Foil Bearings Beyond the Bending Critical Mode' '' [ASME J. Tribol., 122, No. 2, p. 478 (2000)]

Hooshang Heshmat, Ph.D.

Dr. Green has inquired as to whether some theoretical explanation for the particular experimental observation that I have reported in my paper is available. We have for some time been investigating the observed phenomena in foil bearing systems both theoretically and experimentally. The program is fundamental in nature and is well underway. Once conclusive evidence and correlation is complete to the author's satisfaction, it is our intention to publish the results. Incidentally, this peculiar phenomenon is most relevant to foil bearing systems. Investigators, skilled in the field of foil bearing technology, have been reporting similar situations for more than two decades; unfortunately such information has not been published, but privy to those intimately involved in foil bearing development.

Dr. Green's discussion of rub phenomena and harmonic excitation is consistent with experience related to more conventional systems such as ball bearing supported rotors. However, I believe that this reviewer has misinterpreted the brief discussion referring to Fig. 19. First, it should be noted that we are talking about fractional subharmonic vibrations which lock onto the rigid body natural frequencies (a subharmonic resonance). The discussion states that in rub phenomena the harmonics will occur at integer multiples of the rotational speed. In contrast, the author has stated that the phenomena observed in gas foil bearing systems is strictly related to conditions when the operating speed is an odd multiple of a rigid body critical speed. If the reviewer would review Fig. 18 it can be seen that the subharmonic vibrations do not track or follow the operating speed as would be expected if this were a rub induced phenomena. To carry the discussion further and respond to the reviewer's comments regarding the arc extent of the rub and potential heat generation in the bearing, the author totally disagrees with the reviewer's hypothesis. The occurrence of even intermittent high speed rubs in a foil bearing can lead to major bearing performance degradation, if not outright bearing failure. Addressing first the potential for rub, it should be noted that the largest peak-to-peak amplitude of vibration occurred at approximately 570 Hz (34,200 rpm) as the rotor decelerated through the rotor bending critical speed. If a rub were to occur it would be expected during critical speed transition, not when overall vibrations were experienced at the operating speed of 747 Hz (44,820 rpm). Regardless of the vibration condition experienced, during post test examination of the bearings, no evidence of a high speed rub was detected.

The author next takes exception to the reviewer's heat generation calculations and conclusion that ''no major-system melt down'' would be expected. The rough estimate of power generation does not include the dynamic force contribution which is often significantly higher than the static component. However, even assuming the reviewer's value of 100 watts heat generation, and taking a typical high speed rub contact area as examined by the author in numerous other foil bearing systems, the expected power density for such a rub would be on the order of 1 Kilowatt/sq-cm. Clearly this localized heating would cause great distress to the very thin foil material and should be readily evident in post test examinations. Again no evidence of high speed rubs was detected which would lend credence to the reviewer's contentions that the observed phenomena is rub induced.

In summary, the subsynchronous integer harmonics of rigid body critical speeds have been experimentally observed to occur when the rotor spin speed is seven times the rigid body critical speed. This author believes that it is related to nonlinear bearing system. No evidence of an intermittent rub has been detected as the reviewer contends. It is the author's intention to bring to light this experimentally observed phenomena so that our understanding of foil bearing performance may be enhanced and to guide direction for future investigations.

Discussion: ''An Asperity Microcontact Model Incorporating the Transition from Elastic Deformation to Fully Plastic Flow'' [ASME J. Tribol., 122, No. 1, pp. 86–93 (2000)][1]

Izhak Etsion
Technion, Haifa, 32000, Israel

The authors have presented an elegant way to overcome a shortcoming of the CEB model by smoothing the transition from elastic to plastic state in a single asperity. Their physical interpretation of the results, however, may be misleading.

On several occasions the authors criticize the CEB results as being ''physically unreasonable'' e.g., when discussing the differences between the GW and CEB results in Fig. 5 for $\Psi=0.7$, the authors state that '' . . . The asperity yielding would require increased contact area to support a given contact load than otherwise . . . ''. This statement is a common mistake often made in connection to the contact of rough surfaces. In fact asperity yielding, or fully plastic contact, means that the asperity mean contact pressure has reached the value of the material hardness (see Eq. (9)). The mean contact pressure in the case of an elastic contact is certainly less than the hardness. **Obviously with a higher contact pressure a smaller contact area is required to support a given contact load.** Hence, for a given hardness, **asperity yielding would require less contact area to support a given contact load.**

Smaller contact area for a given surface roughness means that fewer asperities are required to carry the load. Hence, higher separation would be expected when the contact is more plastic. This physically realistic behavior contradicts another statement made by the authors in discussing their Fig. 4 that '' . . . the plastic deformation, which is the main feature of the CEB model, should yield a lower separation due to the plastic deformation of the contacting asperities . . . ''. In fact, even the authors present model results in Fig. 4 show increasing separation at a given load, as the contact becomes more plastic and the plasticity index increases.

The experimental and theoretical results of Kucharski et al. were obtained for extreme loading conditions, deep into the plastic regime, when ω is much larger than ω_2. Under these extreme plastic conditions the measured experimental approach (which is the opposite of the mean separation), and real contact area should be smaller than the prediction of any elastic-plastic model like the CEB model. Indeed, in Figs. 11 and 12 of Kucharski et al. this is the case. The results that are shown in these figures for the GW model are completely false since the GW model breaks down much before ω_2 is obtained and hence should not be considered for comparison with the other models. Again, the CEB model is very much physically reasonable.

Finally, it is interesting to note the similar results of the present model and the CEB model as shown in Figs. 4 and 5. This is probably due to the fact that selecting the mean pressure KH in the CEB model for plastically deformed asperities is not such a bad choice after all. Indeed, it overestimates the mean contact pressure of asperities in their early elastic-plastic state where ω is close to ω_1 but at the same time it underestimates the mean contact pressure of asperities deep into the plastic state where ω is close to ω_2. Using an average contact pressure in a statistical model like the CEB for the entire population of plastically deformed asperities seems to have a global smoothing effect equivalent to the empirical smoothing of the contact pressure on individual asperities in the present model.

[1]Yongwu Zhao, D. M. Maietta, and L. Chang, 2000, ''An Asperity Microcontact Model Incorporating the Transition From Elastic Deformation in Fully Plastic Flow,'' ASME JOURNAL OF TRIBOLOGY, Vol. 122, No. 1, pp. 86–93.

Closure to ''Discussion of 'An Asperity Microcontact Model Incorporating the Transition From Elastic Deformation to Fully Plastic Flow' '' [ASME J. Tribol., 122, No. 2, p. 479 (2000)]

Yongwu Zhao, David M. Marietta, and L. Chang

The authors thank Dr. Etsion's interest in the paper. We agree with Dr. Etsion that *with a higher contact pressure a smaller contact area is required to support a given load.* However, whether *asperity yielding would require less contact area to support a given contact load* depends on what particular problem one studies and what assumptions one makes. This statement is clarified by two types of problems described below.

The first type of problems is a rigid flat in contact with two rough surfaces (i.e., two separate contact problems). Both the rough surfaces have the same material properties but different roughness. Then, for a given load applied to the two contact systems, the one that generates more plastic deformation is likely to (but not always) yield less real area of contact. The result is consistent with Dr. Etsion's assertion.

The second type of problems is a rigid flat in contact with two rough surfaces, where both the rough surfaces have identical roughness, but one is elastic-plastic and the other is assumed to be perfectly elastic regardless of contact pressure. Then, for a given load applied to the two contact systems, the one that generates plastic deformation would yield larger area of contact. The result is against Dr. Etsion's assertion but meets the fact that *with a higher contact pressure a smaller contact area is required to support a given load.*

The results presented in Fig. 5 of the current paper are for the second type of problems. For this type of problems, it is necessary that any micro-contact models with plastic deformation yield larger contact area than the GW elastic model. It is this analysis that leads us to conclude that the CEB model could yield physically unreasonable results.

