

## DISCUSSION

### I. Etsion<sup>1</sup>

The authors are to be congratulated for presenting some aspects of a complex problem regarding possible mechanisms in face seals operation. Much effort is being devoted lately towards a better understanding of these mechanisms. Experimental work such as this reported by the authors is essential for that aim.

Some remarks concerning the test procedure and the conclusions may be helpful in further experiments of this kind. The initial waviness measured by probe A while the spindle is slowly rotated can be misleading unless the gimbal motion is subtracted. Gimbals tracing would eliminate first mode waviness which may be present on the rotor surface. On the other hand, if such first mode does not exist then the tendency of the gimbals to make three points contact between rotor and stator will result in an appearance of false first mode wave. The measurement of rotor surface waviness during operation is also affected by the gimbal motion. This measurement is not complete without an accurate knowledge of the exact motion of the gimbals.

The authors explain discrepancies between theory and experimental observation by the gimbal inertia which would not allow perfect tracking, and hence eliminating of first harmonic due to tilt. However, even with inertialess gimbals perfect tracking cannot be achieved because of a hydrodynamic transverse moment acting at 90 degrees out of phase from the tilt [16]. As a matter of fact it can be shown that angular misalignment of the stator would cause it to wobble at a frequency that is half the rotor speed. Indeed a wobble of such subharmonic nature was observed by the discussor on the very same apparatus when the glass stator was tilted by means of an eccentric load.

In conclusion, although TFI may affect seal's operation it is felt that the dynamics of seal motion is the key factor in studying seal stability. This motion should be carefully monitored and analyzed in any further experimentation.

### Additional References

16 Etsion, I. "Hydrodynamic Effects in a Misaligned Radial Face Seal," ASME Paper No. 78-Lub-12 presented at the ASME-ASLE Lubrication Conference, October 1978.

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## Authors' Closure

We wish to thank Dr. Etsion for his considered comments. In answering we must first say that we seem not to have communicated as clearly as we thought. Our film probe was not *intended* to give a representation of the cup but only of its relative penetration into the film. It was expected that the first mode or tilt would be eliminated by the tracking of the gimbals. In oscilloscope traces we find that this indeed appears to be the case. Furthermore we note that under the conditions of loading and speed encompassed in this study we found no evidence of half-speed or other subharmonic motions but found traces repeating quite clearly cycle to cycle.

Whereas it is true that if the stator and rotor are flat, tilting of the stator gives rise to moments shifted in phase relative to the tilt, and whereas we have witnessed this effect leading to self-excited low frequency oscillations, we note that synchronous motions of tilted rotor and tilted stator were both theoretically justified and observed here. In such motions the tilt of the rotor is not in phase with the stator. It would also appear as a first mode component in the displacement measured with the film probe. However, for reasonable stator inertia and for reasonable face loads, the first mode penetration into the film is extremely small relative to second mode waves which provide the lift.

We agree with Dr. Etsion now that future measurements should be supplemented by data on the motion of the gimbals. In fact we have included what we thought was a provocative plot of the changes of gimbals motion, and we have included some discussion of this in our text.

In Dr. Etsion's last comment let us note that the startling effects of the formation of the "thermal asperity" with its associated hot spot is the object of our study. We are convinced that it is responsible for many classes of failure and such phenomena as heat checking. For the liquid lubricated seal we recognize that it can only be studied in the light of the dynamic behavior. Indeed we are preparing for publication an analysis of dynamic and thermoelastic effects combined. The explanation of the observations reported here provided the incentive for this work.

As to his comment that gimbal motion may respond to a few peaks and give false first mode behavior, we concur that as an academic point it is valid. In practice the wavy surfaces we observe have gentle waves and, in the operation reported here, these do not penetrate deeply into the film. After transition the spikes appear, but then we are not interested in hydrodynamic behavior. It is the conditions before change and why they degenerate that concern us.