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# Discussion

## Steady-State Analysis of Mechanical Seals With Two Flexibly Mounted Rotors[1]

**S. Leefe.**[2] Dynamics has historically been somewhat underrepresented as a research topic in mechanical seals. Any contribution to our analytical toolbox or our state of understanding is therefore most welcome.

It is worth examining the applicability of the analysis, as presented, to cases of practical interest. In particular, the major explicit assumptions are:

- the sealed fluid is incompressible;
- there is no cavitation in the fluid film.

However, there are some significant additional assumptions carried over from the authors' previous work, in the cited references. These are:

- dynamic variation in film thickness distribution is small compared with its characteristic value (implied by the employment of linearized stiffness and damping coefficients);
- the seal is operating in the full-film noncontacting mode;
- the seal is plain-faced with coning but no waviness.

Plain-faced seals usually operate in the mixed friction regime, where film thickness is small and linearized fluid film stiffness and damping coefficients cannot be applied. Here, also, despite our best efforts, in-service waviness is ubiquitous and every bit as significant as coning in determining mean film thickness and leakage. This also gives rise, in most cases, to cavitation, unless the ambient hydrostatic pressure is high. In the discusser's opinion, in all but a limited number of cases, there is little alternative but to mount a full-frontal numerical assault on the problem of plain-faced seal dynamics, if the aim is to assess the impact of misalignment on seal performance.

The analytical framework laid out in this paper, after appropriate modification of detail, would in the discusser's opinion be of most practical benefit in the estimation of gas seal performance—where the typically high sliding speeds and low viscosity of the sealed medium often dictate seals specially designed for stable clearance operation (and the gaseous sealed fluid avoids the additional complication of cavitation). Unfortunately, this too is not without its problems since clearance operation is usually provided by means of hydrodynamic features such as grooves and Raleigh steps. This, and the presence of a gaseous sealed fluid as a mean that any stiffness and damping coefficients must be derived from a fluid film analysis based on the compressible Reynolds equation and cannot be taken from the formulas offered in this paper. However, in principle, having obtained these coefficients by whatever technique, one could justifiably apply the current approach to estimate dynamic response. It is the discusser's opinion that an estimate of performance might prove more reliable in these circumstances.

In conclusion, the real value of the work presented here in this most difficult of areas is that the authors have laid down the analytical framework for the most general dynamic analysis where both seal rings rotate and are flexibly mounted. For this they are to be congratulated.

## Authors' Closure

The authors would like to thank Dr. Leefe for his interest in the paper and for his thoughtful input. Dr. Leefe correctly states most of our assumptions, then makes two different points. The first is specific, regarding the applicability of the authors' assumptions to cases of practical interest, while the second is philosophical, regarding the relative merits of theoretical versus numerical analysis. We shall consider these two issues separately, then attempt to tie them together.

We agree that the most restrictive of our assumptions is the requirement of a full fluid film, which does not always exist in seals. However, in seals with operating speeds high enough to cause failure resulting from dynamic effects, contact would generally be a serious problem. Our model can predict the point at which contact occurs, and we assume that this contact constitutes seal failure.

The authors have also encountered the problem of waviness in their own experimental work and agree that it exists in most real seals. However, the computation of this waviness itself requires a number of assumptions regarding structural and heat transfer boundary conditions and heat generation within the film and support, so that its inclusion in the analysis often adds an additional series of questionable assumptions.

Finally, the authors maintain their assertion that small motions are the only motions possible in a seal for which failure has been defined as face contact, and that these motions must necessarily occur about an equilibrium position in steady-state operation.

Dr. Leefe then proposes that the only valid approach is often a ''full-frontal numerical assault.'' While the authors agree that numerical tools have an important place in seal analysis, we believe that a false dichotomy exists between theoretical and numerical analysis in the minds of many engineers, and that numerical analysis is not a panacea for resolving the unknowns in a seal analysis.

First, numerical analysis often presents similar problems with assumptions. For example, face contact, waviness, cavitation, and compressibility can be modeled numerically, but fall victim, as described above, to problems of choosing a contact model and assuming boundary conditions. Analysis, either numerical or theoretical, can only serve to provide a first approximation

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[1] By J. Wileman and I. Green published in the January 1997 issue of the JOURNAL OF TRIBOLOGY, Vol. 119, pp. 200–204.

[2] BHR Group Limited, The Fluid Engineering Centre, Cranfield, Bedford, MK43 OAJ, United Kingdom.

to a seal design or a hint as to why a design in use has failed. Testing will always be necessary to validate the analysis.

Second, the leap from a completely theoretical analysis to a ''full-frontal'' numerical analysis should not be made without considering the myriad possibilities of combining the two to provide analyses which are highly accurate for a specific case. The computation time can be dramatically reduced by the introduction of concepts from the theoretical work into the numerical algorithm.

The authors agree with the discusser that the main value of the present work is in the analytical framework it provides for dynamic analysis, but feel that it is important not to lose sight of its overall applicability by focusing too narrowly upon the details. Neither theoretical nor numerical analysis can be a substitute for a designer's understanding of the processes at work in the seal, and this understanding should allow the designer to easily adapt those parts of the method useful in his application.

As promised, the authors would like to tie together the question of the applicability of the assumptions and the appropriateness of theoretical versus numerical analysis. To do this, it is necessary to note the division into several discrete steps of the theoretical analysis, and the way that the linearization allows these steps to be separated from one another. The steps are the following: 1) The Reynolds equation is solved in closed form for a pressure solution, and this solution is integrated to obtain the applied forces and moments; 2) the applied forces and moments are expressed in terms of linearized rotor dynamic coefficients and used to write the equations of motion; 3) the equations of motion are solved (in closed form) for the steady-state response and for the stability analysis.

Now contrast this with the ''brute force'' numerical method. With this technique, the pressure solution is obtained by a numerical solution of the Reynolds equation, which is in turn integrated numerically to determine the forces and moments which are substituted into equations of motion valid for a single time step. These equations of motion are integrated over one time step, and the process is repeated again for the next time step, starting again at the Reynolds equation solution. For each time step, it is necessary to iterate to obtain the pressure solution, and again to obtain the simultaneous solution to the equations of motion for the time step, all this iterated over hundreds or thousands of time steps. Anyone who has done this knows that the solution is slow and computationally expensive even with modern computing equipment. If the energy equation is included in the analysis, then the solution becomes even more complex.

This complexity and computational expense can be radically reduced by combining the two methods. For example, we can solve the Reynolds equation numerically, but only once, then use this numerical solution to obtain rotor dynamic coefficients which can be used in a closed-form solution for the steady-state response of the equations of motion (see Person and Tournerie, 1996) for an example of this technique in a seal with grooves and waviness). If the transient response is desired, then the same equations of motion can be solved numerically, using either theoretically or numerically derived rotor dynamic coefficients. Separating the fluid film analysis from the dynamic analysis dramatically reduces the computational effort required, particularly if one of the two is performed theoretically. Even if both parts of the analysis are performed numerically, the separation of the two solutions using the framework presented in this work yields dramatic savings resulting from the elimination of the pressure solution for each time step. This reduction in computational effort is especially important when, as discussed above, the waviness or the thermal boundary conditions in the seal are unknown so that it is necessary to calculate the solution for several different possibilities. Further, if the results of the numerical analysis closely match those of the completely theoretical solution, as in the case of Person and Tournerie (1996), then it may be justified to completely eliminate the numerical analysis. A large divergence between the numerical and theoretical results, on the contrary, may indicate the omission of an important effect in the analysis.

The tool which allows the cheapest and quickest seal assessment is obviously the best. In this regard, when it can be used, a closed-form solution is superior to a numerical analysis because it provides insight, allows instantaneous parametric investigation, and facilitates optimization. Even if some assumptions are not completely valid, a closed-form solution should usually be the first step in the design process and should be incorporated to the extent possible into any succeeding numerical analysis.

## Additional Reference

Person V., Tournerie, B., and Frêne, J., 1996 ''A Numerical Study of the Stable Dynamic Behavior of Radial Face Seals with Grooved Faces,'' ASME Paper No. 96-Trib-40, ASME JOURNAL OF TRIBOLOGY, Tribology Conference, San Francisco, Oct.