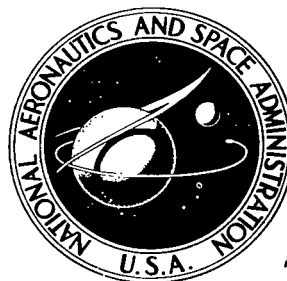


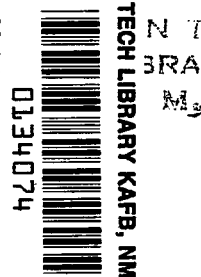
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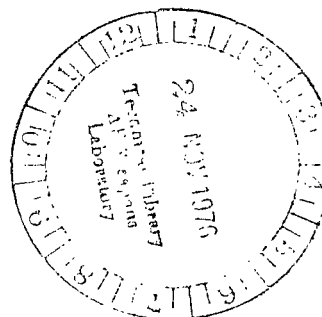
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NONAXISYMMETRIC INCOMPRESSIBLE HYDROSTATIC PRESSURE EFFECTS IN RADIAL FACE SEALS

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NONAXISYMMETRIC INCOMPRESSIBLE HYDROSTATIC

PRESSURE EFFECTS IN RADIAL FACE SEALS

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SUMMARY

A flat seal having an angular misalignment is analyzed, taking into account the radial variations in seal clearance. An analytical solution for axial force, tilting moment, and leakage is presented that covers the whole range from zero to full angular misalignment (surfaces in contact). It is shown that nonaxisymmetric hydrostatic pressures due to the radial variations in the film thickness have a considerable effect on seal stability. When the high pressure is on the outer periphery of the seal, both the axial force and the tilting moment are nonrestoring. This causes the seal surfaces to wear at the outer diameter. Instability and wear at the inner diameter can occur when angular misalignment is combined with radial distortions and the high pressure is on the inner periphery.

The case of high-pressure seals where cavitation is eliminated is discussed, and the possibility of dynamic instability is pointed out.

INTRODUCTION

Axial forces in excess of those theoretically predicted for aligned flat seal faces are now well established by many experiments (e. g., refs. 1 to 3). These axial forces are crucial in providing the mechanism that separates the seal faces and controls the gap between them.

A considerable amount of fundamental research has been done in the last two decades in an attempt to understand the origin of these axial forces and how they relate

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to the mechanism of seal operation. Many theories have been suggested, but there is no generally accepted mechanism. In a recent report (ref. 4), the various models and theories are listed. It seems that most of them relate the separating axial force to hydrodynamic effects.

To generate hydrodynamic pressures with relative circumferential motion, the geometry of the seal faces must deviate from being absolutely alined or perfectly flat. This deviation can be in the form of angular misalinement (ref. 5), microasperities (ref. 6), and various forms of waviness (refs. 2, 7, and 8). It was postulated (ref. 9) that cavitation must be associated with the production of net forces greater than the hydrostatic forces. In the absence of cavitation, a hydrodynamic pressure increase in the circumferentially converging portions of the seal clearance is counterbalanced by an equal pressure decrease in the diverging portions, with the result of zero net hydrodynamic force. Although it explains the existence of hydrodynamic generated forces, cavitation is not likely to occur in high-pressure seals. In some experiments (refs. 10 and 11) where regions void of fluid were observed, the applied pressure was usually less than 3 atmospheres. In reference 11, where temperatures in the seal clearance were measured, it was found that boiling rather than cavitation was the reason for the appearance of gas in the seal interface.

Considering all these facts, it is not likely that hydrodynamic effects are the only mechanism that is responsible for maintaining a lubricated gap in face seals. Some investigators (refs. 1, 12, and 13) studied the effects on seal behavior of hydrostatic pressures caused by radial variations in seal clearance. Such variations, which can be caused by thermal and mechanical distortions, generate a net force that is different from the hydrostatic one that is related to flat, alined seal faces.

When the clearance decreases in the direction of flow, the pressures are greater than those for parallel surfaces. Also positive stiffness and hence a stable fluid film are related to such configurations. When the clearance increases in the direction of flow the result is a decrease in pressure, negative stiffness, and a statically unstable fluid film.

In all the literature dealing with hydrostatic effects, with the exception of reference 14, the deviation from the flat, alined geometry is always axisymmetric. The inevitable result is axisymmetric pressure distribution in the seal clearance. Some experimenters report surface rubbing in a form that is most unlikely to occur when pressure symmetry prevails. In reference 1 it is shown that the seal surfaces rub on either the outer or the inner boundaries, depending on the direction of flow. The wear is always such that film convergence in the direction of flow is produced. Obviously, such wear could be a result of an angular misalinement combined with nonrestoring moments.

In reference 14 a misaligned hydrostatic seal with an orifice bypass is analyzed. For the case of zero orifice flow, which is no more than a conventional face seal, it is found that the seal always produces restoring tilt moments. This result contradicts the experimental evidence of surface wear (ref. 1), which suggests nonrestoring tilt moments.

Considering the misaligned face seal of figure 1, it is clear that, while the clearance converges in the radial direction over one-half of the circumference, over the other half it diverges. Hence, when the flow is outward, the hydrostatic pressure distribution around the seal tends to reduce the tilt and restore alignment. On the other hand, when the flow is inward, the result is a nonrestoring moment, which tends to increase misalignment.

Nonaxisymmetric hydrostatic pressure distribution may affect not only the tilting moment, but also the separating force and the leakage across the seal. Such effects have been overlooked in other investigations. The objective of this work is to study these effects, aiming at a better understanding of radial face seal operation.

SYMBOLS

C	seal clearance along centerline
C_1, C_2	constants of integration
F	axial force
F_d	hydrodynamic force
F_s	axial force contributed by nonaxisymmetric hydrostatic pressure
\overline{F}_s	nondimensional force, $F/\pi(p_i - p_o)r_o^2$
H	nondimensional film thickness, h/C
h	film thickness
I	given by eq. (15)
M	tilting moment
\overline{M}	nondimensional tilting moment, $M/\pi(p_i - p_o)r_o^3$
p	pressure
Q	leakage

\bar{Q} nondimensional leakage, $Q / \frac{C^3}{12\mu} \left(\frac{P_i - P_o}{r_i - r_o} \right) \pi(r_o + r_i)$

R nondimensional radius, r/r_o

r radial coordinate

β angle of distortion

γ angle of tilt

ϵ tilt parameter, $\gamma r_o / C$

$\bar{\epsilon}$ ϵR_m

θ angular coordinate

μ viscosity

ω rotational angular velocity

Subscripts:

i at inner radius

m at midradius

o at outer radius

ANALYSIS

Figure 1 describes the geometry of the misaligned seal. In most applications the radius ratio r_i/r_o is very close to unity. Hence, the narrow-seal approximation results in the one-dimensional incompressible Reynolds equation

$$\frac{\partial}{\partial r} \left(rh^3 \frac{\partial p}{\partial r} \right) = 6\mu\omega r \frac{\partial h}{\partial \theta} \quad (1)$$

The film thickness distribution for the misaligned seal is given by

$$h = C + \gamma r \cos \theta \quad (2)$$

where γ is the angular tilt and θ is measured from the point of maximum clearance.

The boundary conditions for equation (1) are

$$p = p_i \quad \text{at } r = r_i$$

$$p = p_o \quad \text{at } r = r_o$$

Because of its linear nature, equation (1) can be solved separately for the hydrostatic and hydrodynamic pressure components. Hence, the hydrostatic component is obtained from the solution of

$$\frac{\partial}{\partial r} \left(rh^3 \frac{\partial p}{\partial r} \right) = 0 \quad (3)$$

A common assumption for narrow seals is that curvature effects may be neglected. When applied to equation (3), this must be carefully examined. In some works this assumption results in a modified expression for the film thickness having the form

$$h = C + \gamma r_m \cos \theta$$

This is, of course, an unrealistic, warped surface that if substituted into equation (3) will result in hydrostatic pressure distribution identical to that in the case of parallel seal surfaces.

Hence, when neglecting curvature effects, equation (3) becomes

$$\frac{\partial}{\partial r} \left(h^3 \frac{\partial p}{\partial r} \right) = 0 \quad (4)$$

but the film thickness h remains a function of both θ and r , as given by equation (2). Integrating twice with respect to r gives for the pressure

$$p = \frac{C_1(\theta)}{h^2} + C_2(\theta)$$

For the boundary conditions, the constants of integration become

$$C_1 = (p_i - p_o) \frac{(h_o h_i)^2}{h_o^2 - h_i^2}$$

and

$$C_2 = p_o - \frac{C_1}{h_o^2}$$

Hence, the hydrostatic pressure in the seal clearance is

$$p = (p_i - p_o) \left(\frac{h_i}{h} \right)^2 \frac{h_o^2 - h^2}{h_o^2 - h_i^2} + p_o \quad (5)$$

Using the film thickness expression given by equation (2) yields

$$\frac{h_o^2 - h^2}{h_o^2 - h_i^2} = \frac{r_o - r}{r_o - r_i} \frac{h_o + h}{h_o + h_i}$$

Substituting this into equation (5) yields

$$p = (p_i - p_o) \frac{r_o - r}{r_o - r_i} \left\{ 1 + \left[\left(\frac{h_i}{h} \right)^2 \frac{h_o + h}{h_o + h_i} - 1 \right] \right\} + p_o \quad (6)$$

The first term in the braces of equation (6) represents the well-known axisymmetric solution for parallel surfaces. The second term is the contribution of misalignment. This contribution is not axisymmetric and depends on the gap.

Axial Force

The axial force, which tends to separate the seal surfaces, is obtained from

$$F = 2 \int_{r_i}^{r_o} \int_0^\pi pr \, dr \, d\theta \quad (7)$$

The nondimensional film thickness

$$H = \frac{h}{C} = 1 + \epsilon R \cos \theta \quad (8)$$

is introduced where

$$R = \frac{r}{r_o}$$

and the tilt parameter ϵ is given by

$$\epsilon = \frac{\gamma r_o}{C}$$

Equation (5) can be written in the form

$$p = (p_i - p_o) \frac{H_i^2}{H_o^2 - H_i^2} \left(\frac{H_o^2}{H^2} - 1 \right) + p_o \quad (9)$$

A direct integration of equation (7) is very difficult. A perturbation technique (ref. 5) could be used where the pressure is expanded in powers of ϵ . However, such a solution is restricted to very small values of the tilt parameter ϵ and is inadequate when nonrestoring moments exist since this situation may lead to surface contact. In that case the solution has to cover the whole range of misalignment through $\epsilon = 1$.

With the assumption of negligible curvature effect, that is, $r \approx r_m$, equation (7) becomes

$$F = 2r_m r_o \int_0^\pi \int_{R_i}^1 p \, dR \, d\theta \quad (10)$$

Integrating by parts we have

$$\int_{R_i}^1 p \, dR = pR \Big|_{R_i}^1 - \int_{R_i}^1 R \frac{\partial p}{\partial R} \, dR \quad (11)$$

From equations (9) and (8) we have

$$-\frac{\partial p}{\partial R} = (p_i - p_o) \frac{2H_i^2 H_o^2}{H_o^2 - H_i^2} \frac{\epsilon \cos \theta}{H^3} \quad (12)$$

Substituting equation (12) in equation (11) and using the integral

$$\int \frac{\epsilon R \cos \theta}{H^3} \, dR = \frac{1}{\epsilon \cos \theta} \left(-\frac{1}{H} + \frac{1}{2H^2} \right)$$

we have

$$\int_{R_i}^1 p \, dR = p_o - p_i R_i + (p_i - p_o) I \quad (13)$$

where

$$I = \frac{1}{\epsilon \cos \theta} \left(\frac{2H_i H_o}{H_o + H_i} - 1 \right) \quad (14)$$

Since

$$H_o + H_i = 2H_m$$

and

$$1 + R_i = 2R_m$$

the expression for I becomes (by using eq. (8))

$$I = \frac{R_m + \epsilon R_i \cos \theta}{1 + \bar{\epsilon} \cos \theta} \quad (15)$$

where

$$\bar{\epsilon} = \epsilon R_m \quad (16)$$

The axial force thus becomes

$$F = 2r_m r_o \left[\pi(p_o - p_i R_i) + (p_i - p_o) \int_0^\pi I \, d\theta \right] \quad (17)$$

From the journal bearing integrals (ref. 15),

$$\int_0^\pi \frac{d\theta}{1 + \bar{\epsilon} \cos \theta} = \frac{\pi}{(1 - \bar{\epsilon}^2)^{1/2}} \quad (18a)$$

and

$$\int_0^{\pi} \frac{\cos \theta d\theta}{1 + \bar{\epsilon} \cos \theta} = -\frac{\pi}{\bar{\epsilon}} \left[\frac{1}{(1 - \bar{\epsilon}^2)^{1/2}} - 1 \right] \quad (18b)$$

Hence, from equations (15) to (18)

$$F = 2\pi r_m r_o \left\{ p_o - p_i R_i + (p_i - p_o) \left[\frac{R_m - \frac{R_i}{R_m}}{(1 - \epsilon^2 R_m^2)^{1/2}} + \frac{R_i}{R_m} \right] \right\} \quad (19)$$

This can be further developed into

$$F = 2\pi r_m r_o \left\{ p_o (1 - R_m) + p_i (R_m - R_i) + (p_i - p_o) \left(R_m - \frac{R_i}{R_m} \right) \left[\frac{1}{(1 - \epsilon^2 R_m^2)^{1/2}} - 1 \right] \right\}$$

Noting that

$$1 - R_m = R_m - R_i = \frac{1}{2} (1 - R_i) \quad (20a)$$

and that

$$R_m - \frac{R_i}{R_m} = \frac{1}{R_m} \left[\left(\frac{1 + R_i}{2} \right)^2 - R_i \right] = \frac{(1 - R_i)^2}{4R_m} \quad (20b)$$

we finally have for the axial force

$$F = \pi r_m (r_o - r_i) (p_i + p_o) + \pi r_o^2 (p_i - p_o) \frac{(1 - R_i)^2}{2} \left[\frac{1}{(1 - \epsilon^2 R_m^2)^{1/2}} - 1 \right] \quad (21)$$

The first term on the right side of equation (21) is the axial force for the case of parallel flat surfaces. The second term presents the contribution of the nonaxisymmetric hydrostatic pressure distribution due to seal misalignment. Denoting that con-

tribution by F_s , we have

$$F_s = \pi r_o^2 (p_i - p_o) \bar{F}_s$$

where \bar{F}_s is a nondimensional force given by

$$\bar{F}_s = \frac{F_s}{\pi r_o^2 (p_i - p_o)} = \frac{(1 - R_i)^2}{2} \left[\left(1 - \epsilon^2 R_m^2\right)^{-1/2} - 1 \right] \quad (22)$$

From equation (22) it is clear that, for any angular misalignment, \bar{F}_s is positive. Hence, the deviational force F_s depends on $p_i - p_o$. For $p_i > p_o$, F_s is positive and thus yields axial forces in excess of the hydrostatic force for aligned flat surfaces. Since ϵ is given by $\gamma r_o / C$, it can also be seen that a decrease in C increases ϵ and hence increases \bar{F}_s . Thus, when $p_i > p_o$, the axial force F_s increases when the clearance decreases, producing positive stiffness and a statically stable film. On the other hand, when $p_i < p_o$, the axial force F_s and the axial stiffness become negative and thus result in unstable operation.

Tilting Moment

The tilting moment due to the nonaxisymmetric component of the hydrostatic pressure is

$$M = - \int \int p r^2 \cos \theta \, dr \, d\theta$$

The (-) sign is used in order to obtain restoring moments as positive values. Again, when the curvature effect is neglected, the moment becomes

$$M = -r_m^2 r_o \int_{R_i}^1 \int_0^{2\pi} p \cos \theta \, dR \, d\theta \quad (23)$$

The same procedure as for the axial force is repeated here, giving the tilting moment in a form similar to equation (17):

$$M = -2r_m^2 r_o (p_i - p_o) \int_0^\pi I \cos \theta \, d\theta \quad (24)$$

From reference 15 we have

$$\int_0^{\pi} \frac{\cos^2 \theta}{1 + \bar{\epsilon} \cos \theta} d\theta = \frac{\pi}{\bar{\epsilon}^2} \left[\frac{1}{\left(1 - \frac{\bar{\epsilon}^2}{\epsilon^2}\right)^{1/2}} - 1 \right] \quad (25)$$

Substituting equation (15) into equation (24) and using equations (16), (18b), and (25) give the tilting moment as

$$M = (p_i - p_o) \pi r_o^3 \bar{M} \quad (26)$$

where the nondimensional tilting moment \bar{M} is given by

$$\bar{M} = \frac{(1 - R_i)^2}{2} \frac{1}{\epsilon} \left[\left(1 - \epsilon^2 R_m^2\right)^{-1/2} - 1 \right] = \frac{\bar{F}_s}{\epsilon} \quad (27)$$

As in the case of the axial force, the nondimensional moment \bar{M} is always positive and vanishes only for $\epsilon = 0$, as expected. For $p_i > p_o$ the tilting moment as given by equation (26) is positive and hence is a restoring moment. For $p_i < p_o$ the tilting moment is a nonrestoring one, the angular stiffness is negative, and the seal is unstable.

Leakage

The leakage across the seal is obtained from

$$Q = 2 \int_0^{\pi} - \frac{h^3}{12\mu} \frac{\partial p}{\partial r} r d\theta \quad (28)$$

If we use the nondimensional terms H and R , substitute equation (12) into equation (28), noting that $H_o^2 - H_i^2 = (H_o + H_i)(1 - R_i)\epsilon \cos \theta$, and neglect the curvature effect, equation (28) becomes

$$Q = (p_i - p_o) \frac{C^3}{6\mu} \left(\frac{R_m}{1 - R_i} \right) \int_0^{\pi} \frac{H_i^2 H_o^2}{1 + \bar{\epsilon} \cos \theta} d\theta \quad (29)$$

$$H_i^2 H_o^2 = 1 + 2(1 + R_i)\epsilon \cos \theta + \left[(1 + R_i)^2 + 2R_i \right] \epsilon^2 \cos^2 \theta + 2R_i(1 + R_i)\epsilon^3 \cos^3 \theta + R_i^2 \epsilon^4 \cos^4 \theta \quad (30)$$

Again, from reference 15 we have

$$\int_0^\pi \frac{\cos^3 \theta}{1 + \bar{\epsilon} \cos \theta} d\theta = \frac{\pi}{\bar{\epsilon}^3} \left[1 - \frac{1}{(1 - \bar{\epsilon}^2)^{1/2}} + \frac{\bar{\epsilon}^2}{2} \right] \quad (31a)$$

and

$$\int_0^\pi \frac{\cos^4 \theta}{1 + \bar{\epsilon} \cos \theta} d\theta = \frac{\pi}{\bar{\epsilon}^4} \left[\frac{1}{(1 - \bar{\epsilon}^2)^{1/2}} - 1 - \frac{\bar{\epsilon}^2}{2} \right] \quad (31b)$$

Using equations (18), (25), (31), and (30), we have from equation (29)

$$Q = \pi(p_i - p_o) \frac{C^3}{6\mu} \left(\frac{R_m}{1 - R_i} \right) \left\{ \frac{1}{(1 - \bar{\epsilon}^2)^{1/2}} + 2 \frac{R_i}{R_m^2} \left[\frac{1}{(1 - \bar{\epsilon}^2)^{1/2}} - 1 \right] + 4 \frac{R_i}{R_m^2} \left[1 - \frac{1}{(1 - \bar{\epsilon}^2)^{1/2}} + \frac{\bar{\epsilon}^2}{2} \right] + \frac{R_i^2}{R_m^4} \left[\frac{1}{(1 - \bar{\epsilon}^2)^{1/2}} - 1 - \frac{\bar{\epsilon}^2}{2} \right] \right\}$$

After rearranging this becomes

$$Q = \frac{C^3}{12\mu} \left(\frac{p_i - p_o}{r_o - r_i} \right) \pi(r_o + r_i) \bar{Q} \quad (32)$$

where the nondimensional leakage \bar{Q} is given by

$$\bar{Q} = 1 + \left[\frac{1}{(1 - \epsilon^2)^{1/2}} - 1 \right] \left(1 - \frac{R_i}{R_m} \right)^2 + \frac{\epsilon^2}{2} \frac{R_i}{R_m^2} \left(1 - \frac{R_i}{R_m} \right) + \frac{3}{2} \frac{\epsilon^2}{R_m^2} \frac{R_i}{R_m^2}$$

From equation (20b), \bar{Q} can be written in the form

$$\bar{Q} = 1 + \frac{3}{2} \epsilon^2 R_i + \frac{1}{4} \left\{ \left[(1 - \epsilon^2 R_m^2)^{-1/2} - 1 \right] \left(\frac{1 - R_i}{R_m} \right)^4 + \frac{\epsilon^2}{2} R_i \left(\frac{1 - R_i}{R_m} \right)^2 \right\} \quad (33)$$

From equation (33) it is clear that for the aligned seal, where $\epsilon = 0$, \bar{Q} will equal 1, as expected. As the misalignment increases, the leakage increases too. For very narrow seals, where $1 - R_i < 0.1$, it is seen from equation (33) that the increase is most affected by the term $(3/2)\epsilon^2 R_i$. The nondimensional leakage, given in the form

$$\bar{Q} = 1 + \frac{3}{2} \epsilon^2 R_i \quad (34)$$

is obtained when the radial variations in the film thickness h (eq. (2)) are neglected. Hence, it can be seen that, with regard to leakage, the simpler expression $h = C + \gamma r_m \cos \theta$ can be used in the analysis.

RESULTS AND DISCUSSION

Values of the nondimensional parameters \bar{F}_s , \bar{M} , and \bar{Q} are presented in table I and figures 2 to 4 to cover the whole range of tilt parameters from $\epsilon = 0$ to $\epsilon = 1$. An interesting result is the axial force at $\epsilon = 1$. In the case of radially inward flow, this force adds to any unbalanced closing force and increases substantially the friction between the rubbing surfaces. A seal of 10-centimeter outer diameter, 0.9 radius ratio, and 10-atmosphere seal pressure, will experience at $\epsilon = 1$ an unbalanced axial force of 86 newtons and a tilting moment of 430 newtons per centimeter.

The radius ratio r_i/r_o affects very much the axial force and tilting moment. As this ratio decreases, the axial force and tilting moment increase quite rapidly.

As can be seen from table I the differences between the values of \bar{Q} calculated by equation (33) and those calculated by equation (34) are negligible. Hence, the simpler expression (eq. (34)) can be used for any practical radius ratio.

The analysis presented in the previous section has indicated unstable seal operation under radially inward flow when $p_i < p_o$. Such instability is confirmed by the experiments of Denny (ref. 1). The nonrestoring moment in the case of radially inward flow causes the surfaces to contact and wear at the outer diameter of the seal. However, Denny also found that with the flow radially outward the wear was greatest at the inner diameter. Such a wear appearance is unlikely for a flat misaligned seal but can be a result of combined misalignment and coning due to thermal and mechanical distortions.

In figure 5, a misaligned distorted seal is shown. It is clear from the figure that, whenever the distortion angle β is larger than the tilt angle γ , the seal surfaces can come into contact at the inner diameter. Moreover, since an unstable film is related to diverging clearances in the direction of flow, it can be seen that, when $\beta > \gamma$, an instability will result from a radially outward flow.

A word should be added with regard to the effect of the hydrodynamic pressure generated due to angular misalignment. Figure 6 shows the resultant hydrodynamic force F_d for a misaligned seal. While the hydrostatic pressure distribution is symmetric about the line BB and therefore produces moments only about the line AA, this is not the case with the hydrodynamic pressure. If the sealed pressure is high enough to eliminate any cavitation, the hydrodynamic pressure distribution becomes antisymmetric about the line BB. This results in a net zero hydrodynamic axial force but produces a couple that lags the hydrostatic tilt moment vector by 90° . Such a system is prone to dynamic instability that can damage the seal.

CONCLUDING REMARKS

Contrary to the common belief that hydrodynamic effects are mainly responsible for proper seal operation, it is shown that hydrostatic effects play an important role in seal performance. The hydrostatic pressure distribution is very sensitive to radial variations in film thickness. Hence, these variations cannot be neglected even when dealing with radius ratios close to unity.

The analytical solution for a flat radial face seal having an angular misalignment shows that hydrostatic axial forces and tilting moments can be generated because of the misalignment. These forces and moments can be either restoring or nonrestoring, depending on the location of the high pressure with respect to the seal boundaries. When the high pressure is on the inside, the seal is stable. When the high pressure is on the outside, static instability occurs.

The stability condition can be reversed when coning, due to thermal and mechanical distortions, is combined with angular misalignment. Finally, hydrodynamic pressures due to seal misalignment can well be the origin of dynamic instability.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 30, 1976,
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TABLE I. - MISALIGNED-SEAL PERFORMANCE PARAMETERS

Ratio of inner to outer radius, r_1/r_0	Tilt parameter, ϵ	Nondimensional force, \bar{F}_s	Nondimensional tilting moment, \bar{M}	Non-dimensional leakage, \bar{Q}	Simplified nondimensional leakage, $1 + \frac{3}{2} \epsilon^2 R_1$
0.80	0.1000E 00	0.8148E-04	0.8148E-03	1.012	1.012
	0.2000	0.3321E-03	0.1660E-02	1.048	1.048
	0.3000	0.7714E-03	0.2571E-02	1.108	1.108
	0.4000	0.1437E-02	0.3593E-02	1.193	1.192
	0.5000	0.2396E-02	0.4791E-02	1.301	1.300
	0.6000	0.3762E-02	0.6271E-02	1.434	1.432
	0.7000	0.5753E-02	0.8219E-02	1.591	1.583
	0.8000	0.8819E-02	0.1102E-01	1.771	1.763
	0.9000	0.1410E-01	0.1567E-01	1.976	1.972
	1.0000	0.2588E-01	0.2588E-01	2.206	2.200
	0.85	0.1000E 00	0.4843E-04	0.4843E-03	1.013
0.2000		0.1976E-03	0.9880E-03	1.051	1.051
0.3000		0.4599E-03	0.1533E-02	1.115	1.115
0.4000		0.8594E-03	0.2148E-02	1.204	1.204
0.5000		0.1439E-02	0.2877E-02	1.319	1.319
0.6000		0.2274E-02	0.3790E-02	1.460	1.459
0.7000		0.3513E-02	0.5018E-02	1.626	1.625
0.8000		0.5476E-02	0.6845E-02	1.818	1.816
0.9000		0.9056E-02	0.1006E-01	2.035	2.033
1.0000		0.1836E-01	0.1836E-01	2.278	2.275
0.90		0.1000E 00	0.2271E-04	0.2271E-03	1.014
	0.2000	0.9277E-04	0.4638E-03	1.054	1.054
	0.3000	0.2163E-03	0.7211E-03	1.122	1.121
	0.4000	0.4055E-03	0.1014E-02	1.216	1.216
	0.5000	0.6819E-03	0.1364E-02	1.338	1.337
	0.6000	0.1085E-02	0.1809E-02	1.486	1.486
	0.7000	0.1695E-02	0.2421E-02	1.662	1.661
	0.8000	0.2693E-02	0.3367E-02	1.865	1.864
	0.9000	0.4641E-02	0.5156E-02	2.095	2.093
	1.0000	0.1101E-01	0.1101E-01	2.351	2.350
	0.92	0.1000E 00	0.1485E-04	0.1485E-03	1.014
0.2000		0.6066E-04	0.3033E-03	1.055	1.055
0.3000		0.1416E-03	0.4719E-03	1.124	1.124
0.4000		0.2657E-03	0.6643E-03	1.221	1.221
0.5000		0.4477E-03	0.8954E-03	1.345	1.345
0.6000		0.7146E-03	0.1191E-02	1.497	1.497
0.7000		0.1121E-02	0.1602E-02	1.677	1.676
0.8000		0.1796E-02	0.2246E-02	1.884	1.883
0.9000		0.3156E-02	0.3506E-02	2.118	2.118
1.0000		0.8228E-02	0.8228E-02	2.381	2.380

TABLE I. - Concluded.

Ratio of inner to outer radius, r_i/r_o	Tilt parameter, ϵ	Nondimensional force, \bar{F}_s	Nondimensional tilting moment, \bar{M}	Non-dimensional leakage, \bar{Q}	Simplified nondimensional leakage, $1 + \frac{3}{2} \epsilon^2 R_1$
0.94	0.1000E 00	0.3528E-05	0.8528E-04	1.014	1.014
	0.2000	0.3486E-04	0.1743E-03	1.056	1.056
	0.3000	0.8142E-04	0.2714E-03	1.127	1.127
	0.4000	0.1530E-03	0.3825E-03	1.226	1.226
	0.5000	0.2583E-03	0.5166E-03	1.353	1.352
	0.6000	0.4135E-03	0.6892E-03	1.508	1.508
	0.7000	0.6519E-03	0.9312E-03	1.691	1.691
	0.8000	0.1054E-02	0.1317E-02	1.903	1.902
	0.9000	0.1891E-02	0.2101E-02	2.142	2.142
	1.0000	0.5604E-02	0.5604E-02	2.410	2.410
	0.96	0.1000E 00	0.3869E-05	0.3869E-04	1.014
0.2000		0.1582E-04	0.7912E-04	1.058	1.053
0.3000		0.3699E-04	0.1233E-03	1.130	1.130
0.4000		0.6960E-04	0.1740E-03	1.230	1.230
0.5000		0.1177E-03	0.2354E-03	1.360	1.360
0.6000		0.1890E-03	0.3151E-03	1.518	1.518
0.7000		0.2995E-03	0.4279E-03	1.706	1.706
0.8000		0.4887E-03	0.6109E-03	1.922	1.922
0.9000		0.8976E-03	0.9973E-03	2.167	2.166
1.0000		0.3220E-02	0.3220E-02	2.440	2.440
0.98		0.1000E 00	0.9872E-06	0.9872E-05	1.015
	0.2000	0.4039E-05	0.2020E-04	1.059	1.059
	0.3000	0.9451E-05	0.3150E-04	1.132	1.132
	0.4000	0.1781E-04	0.4451E-04	1.235	1.235
	0.5000	0.3018E-04	0.6036E-04	1.368	1.367
	0.6000	0.4861E-04	0.8102E-04	1.529	1.529
	0.7000	0.7742E-04	0.1106E-03	1.720	1.720
	0.8000	0.1276E-03	0.1595E-03	1.941	1.941
	0.9000	0.2405E-03	0.2672E-03	2.191	2.191
	1.0000	0.1218E-02	0.1218E-02	2.470	2.470
	0.99	0.1000E 00	0.2493E-06	0.2493E-05	1.015
0.2000		0.1020E-05	0.5102E-05	1.059	1.059
0.3000		0.2388E-05	0.7961E-05	1.134	1.134
0.4000		0.4503E-05	0.1126E-04	1.238	1.238
0.5000		0.7639E-05	0.1528E-04	1.371	1.371
0.6000		0.1233E-04	0.2054E-04	1.535	1.535
0.7000		0.1968E-04	0.2812E-04	1.728	1.728
0.8000		0.3260E-04	0.4076E-04	1.950	1.950
0.9000		0.6234E-04	0.6927E-04	2.207	2.203
1.0000		0.4506E-03	0.4506E-03	2.485	2.485

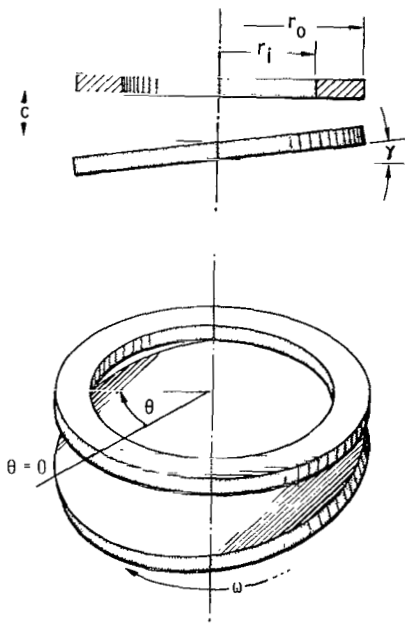


Figure 1. - Face seal with angular misalignment.

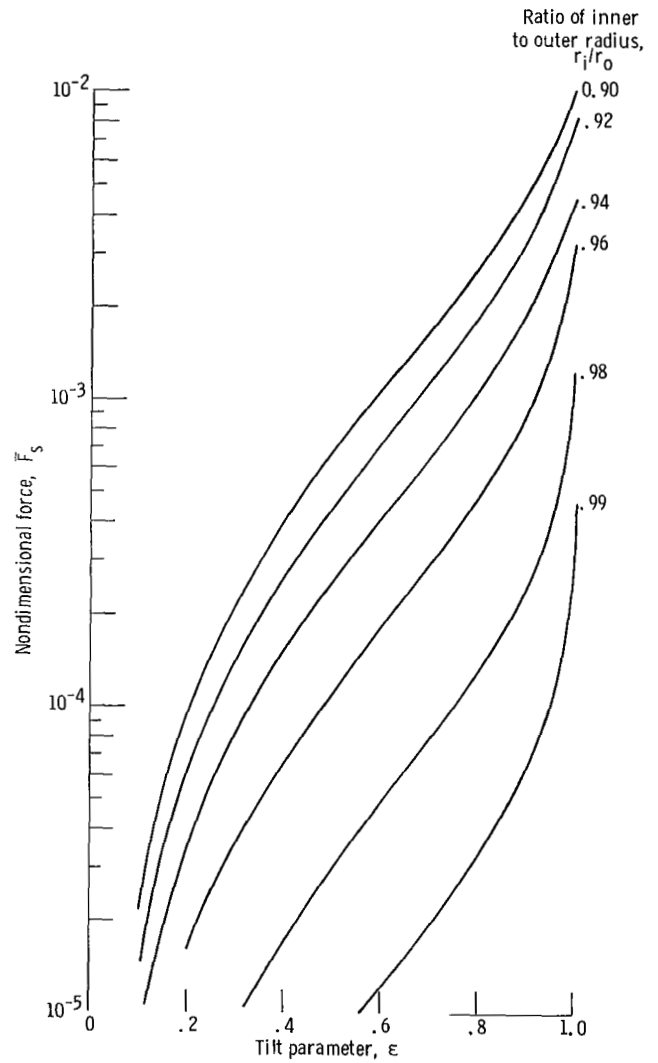


Figure 2 - Nondimensional force as function of tilt parameter for various radius ratios.

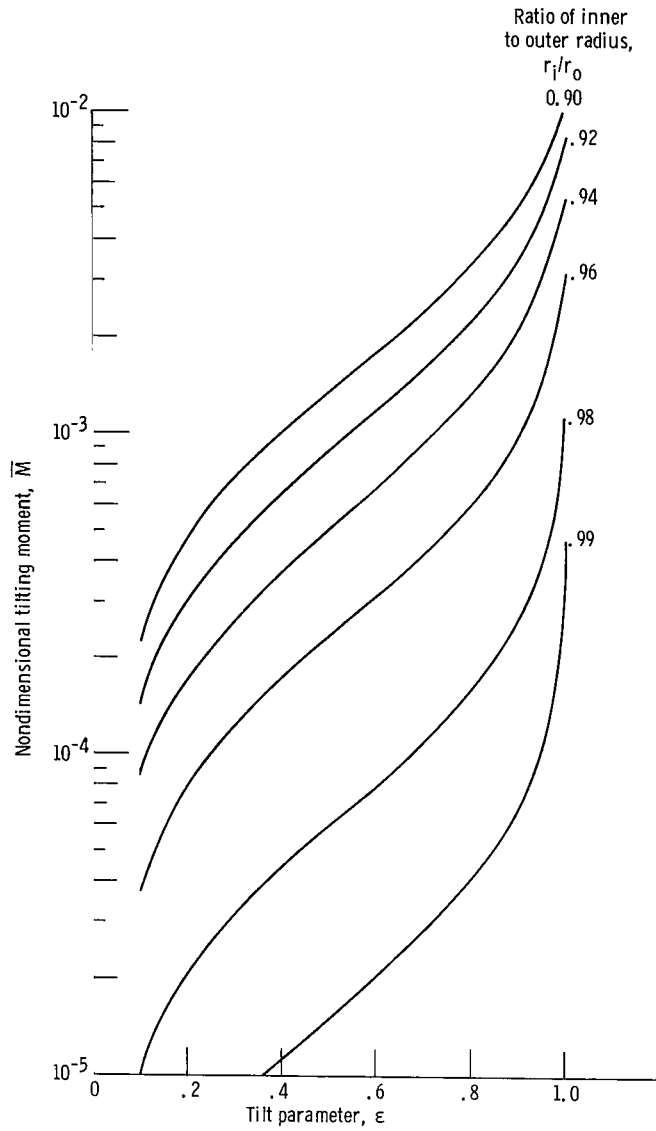


Figure 3. - Nondimensional tilting moment as function of tilt parameter for various radius ratios.

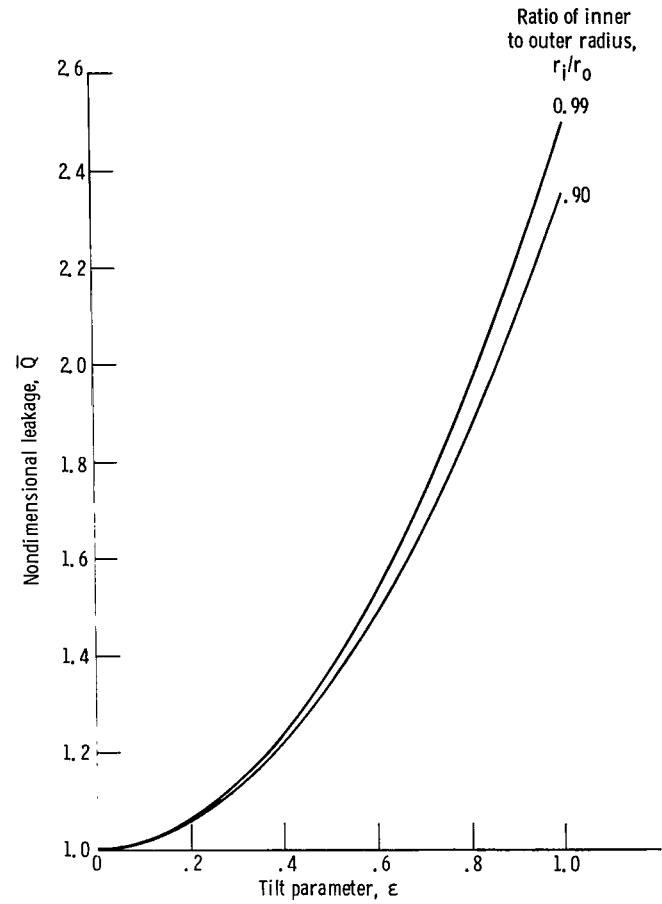


Figure 4. - Nondimensional leakage as function of tilt parameter for radius ratios of 0.9 and 0.99.

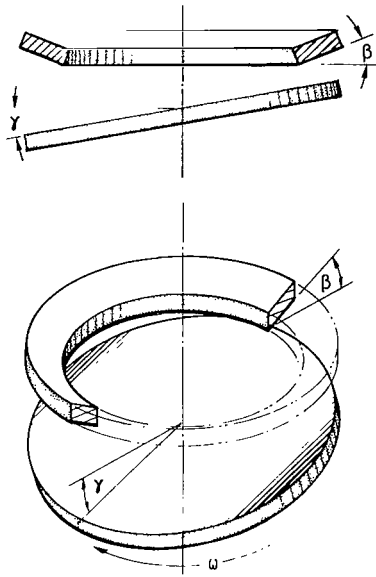


Figure 5. - Face seal with angular misalignment and coning.

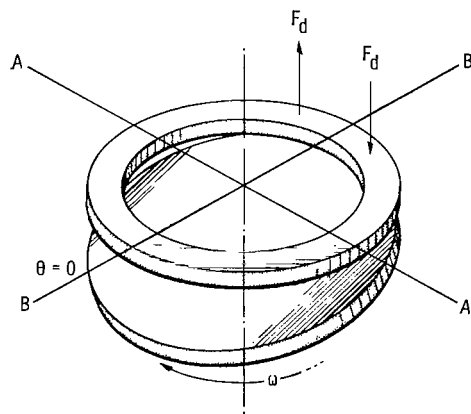


Figure 6. - Hydrodynamic forces in face seal.



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