DAMPING SEALS FOR TURBOMACHINERY

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Abstract

The paper addresses rotor whirl stabilization of high performance turbomachinery which operates at supercritical speed. Basic whirl driving forces are reviewed. Stabilization and criteria are discussed. Damping seals are offered as a solution to whirl and high vibration problems. Concept, advantages, retrofitting, and limits of damping seals are explained. Dynamic and leakage properties are shown to require a rough stator surface for stability and efficiency. Typical seal characteristics are given for the case of the high pressure oxidizer turbopump of the Space Shuttle. Ways of implementation and bearing load effects are discussed. Feasibility was first proven analytically in a Center Director Discretionary Fund project in fiscal year 1981. The Rocketdyne Division of Rockwell International has since installed such seals in the high pressure oxidizer turbopump for development to raise the speed limit and thus achieve higher thrust for the Space Shuttle Main Engine.

Introduction

High performance turbomachinery operates supercritically, i.e. with speeds above rotor resonances (critical speeds). Thus more power is being packed into lightweight units unless speed must be limited to prevent a rotor from whirling and causing damage. The speed limit challenged many as well as the writer to find a solution, not without earnest prayer (which God answered), and not without the foundation laid by others such as Dr. Henry Black from Scotland, who is well remembered.1-4

* Deceased January 17, 1980.
Constant Whirl Forces

Whirl is an orbital motion, superimposed upon the rotation of a rotor. Whirl forces are conceptually known, but accurate data are not readily available. Whirl forces (Fig. 1) are constant or increase with rotor motion.

Synchronous constant forces are caused by mass unbalance, runout rubbing, and seal runout. Subsynchronous constant forces are generated by rotating Coulomb friction forces in rotor joints. The constant forces produce a forward whirl limit cycle response at synchronous or subsynchronous frequencies. Well balanced rotors with minute runout yield low vibrations, however, Coulomb friction in rotor joints can cause damaging rotor vibrations. Coulomb friction whirl can be reduced with lubricating the rotor joints and splines. The whirl can be avoided with tight but nonlubricated interference fits. Joint locking with a high rotor unbalance is not recommended.

Proportional Whirl Forces

Increasing whirl forces can be most destructive. The simplest representation of the forces is a proportional relationship which couples rotor deflections by skewed-symmetric matrices to transverse whirl forces. Rotor hysteresis, seal gaps, journal bearings, turbine blade bypass, and impeller interactions drive usually subsynchronous forward whirls. External rotor rubbing drives a backward whirl that for hard rubbing can become supersynchronous (Fig. 1).

Rotor Stabilization

The purpose of rotor stabilization is to negate the whirl regeneration of proportional forces while reducing the whirl limit cycle caused by constant forces. Rotor suspension damping, stiffness, and asymmetry are whirl stabilizers ordered after their efficiency. Natural damping is usually too low to prevent whirl in high pressure applications. Therefore, squeeze film dampers are used in turbomachinery.
Figure 1. Principal Whirl Cases.

$\omega < \omega_1$ and $\omega > \omega_1$. Force and Speed Premises.

External Whirl.
Symmetrical whirl.
$\omega > \omega_1$.
$\omega < \omega_1$.

Internal Premises.
Symmetrical whirl.
$\omega > \omega_1$.
$\omega < \omega_1$.

Backward whirl.
Forward whirl.
$\omega > \omega_1$.
$\omega < \omega_1$.

$u < 0$.
$u > 0$.

Unbalance $u$.
not only for vibration attenuation but also for whirl prevention. However, such dampers are unsuitable for cryogenic applications. The difficulties prompted the development of damping seals.

Damping seals are like annular seals, except for rough inner surfaces on stators (Fig. 2). Annular seals are a first step and were implemented to eliminate whirl from the high pressure turbopump (HPFTP) of the Space Shuttle Main Engine (SSME). However, such seals can destabilize a rotor resonance below 1/2 the speed frequency. Damping seals improve this ratio to < 1/4, reduce leakage, and increase damping. Damping seals were recently installed in a high pressure oxidizer turbopump (HPOTP) for SSME development as shown in Figure 3.

**Stability Criterion**

The stability condition of a single mass rotor (Fig. 4) suffices to examine the seal effect. Also, more complex models are represented, considering one resonant mode that is only negligibly detuned by the seal. Equation (1) describes the internal seal whirl effect with the whirl factor $Q$ proportional to the seal damping $C$. The Couette factor $c$ of equation (2) is the ratio of circumferential bulk flow velocity $v$ to rotor surface velocity $w$. $\Omega$ is the rotor speed in rad/s.

Equation (3) is the characteristic equation of the model in Figure 4. Conformal mapping, substituting with equation (1), and reordering produce the inequality (4) which sets the speed limit. $K_y$ and $K_z$ are the lateral suspension stiffnesses in $y$ and $z$, $m_s$ is the rotor mass, and $s$ is the Laplace operator. $\Omega_1$ in equation (5) defines the first critical speed or resonance.

\[
Q = c\Omega C \hspace{1cm} (1)
\]

\[
c = \frac{v}{w} \hspace{1cm} (2)
\]

\[
K_yK_z + Q^2 + sC(K_y+K_z) + s^2[C^2 + m_s(K_y+K_z)]
+ s^3 2Cm_s + s^4 m_s^2 = 0 \hspace{1cm} (3)
\]

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Figure 2. Damping Seal Concept.
Figure 3. HPOTP Damping Seal Retrofit.

Figure 4. Simple Rotor Model.
The stability limit of inequality (4) is high for low c values, high rotor resonances, and asymmetric rotor suspensions. Asymmetry can be coincidental which makes symmetry a safer assumption for predicting speed limits. External whirl effects, such as turbine blade bypass, can be lumped into Q by raising c. Conversely, external damping, such as from bearings, can be lumped into C by reducing c to maintain the same Q. Thus external effects are equivalently represented internally by the Couette factor c which becomes a measure of stability for comparing seals and other rotor dynamic components.

**Flow Friction**

The flow velocities relative to the rotor and the stator differ because of rotation. The velocities describe bulk flow so turbulent flow can be treated similar to pipe flow. Equations (6) and (7) describe shear stresses $\tau_R$ and $\tau_S$ respective to the rotor and stator. $f_R$ and $f_S$ are respectively the rotor and stator surface frictions which generally differ. $u$ is the axial bulk flow velocity and $\rho$ is the fluid mass density. The seal gap pressure gradients are given in equations (8) and (9) for the axial and circumferential directions $x$ and $q$ respectively. $h$ is the gap thickness, $\rho$ the pressure, and $t$ the time. Note the projections of the shear stresses from equations (6) and (7). The Reynolds numbers $R_R$ and $R_S$ in equations (10) and (11) are taken in the respective bulk flow directions of the rotor and the stator. $\mu$ is the fluid viscosity. The respective rotor and stator friction factors $f_R$ and $f_S$ of equations (12) and (13) are Moody's approximation with $2h$ as hydraulically equivalent pipe diameter $D$.

The effective roughnesses $k_R$ and $k_S$ reach pocket depth values for well circulating pockets. The triangular pockets of Figure 2 should be best for obtaining high $k_S$ values.
The rotor generates a Couette flow which is established downstream of the seal inlet according to equation (14) which follows from equation (9) for the case of negligible circumferential pressure gradients and flow accelerations. Equations (15) and (16) are the asymptotes for $u = 0$ and $u = \infty$ which enclose the Couette factor $c$ for all surface friction ratios. Figure 5 shows $c$ as a function of surface friction ratio and the axial velocity ratio $u/w$. $c$ is low for high stator friction. The friction ratio is approximately the cubic root of the roughness ratio, as the equations (12) and (13) indicate. Therefore, large roughness ratios are required.

\[
\tau_r = \rho \frac{[u^2+(v-w)^2]}{f_r}/8
\]

\[
\tau_s = \rho \frac{(u^2 + v^2)}{f_s}/8
\]

\[-\partial p/\partial x = \rho [u f_r (u^2+(v-w)^2)^{1/2} + v f_s (u^2 + v^2)^{1/2}] / 8h
\]

\[-\partial p/\partial q = \rho [(v-w)f_r (u^2+(v-w)^2)^{1/2} + v f_s (u^2 + v^2)^{1/2}] / 8h
\]

\[R_r = \rho 2h [u^2+(v-w)^2]^{1/2}/\mu
\]

\[R_s = \rho 2h (u^2 + v^2)^{1/2}/\mu
\]

\[f_r = 0.0055 + 0.55(k_r/100h + 1/R_r)^{1/3}
\]

\[f_s = 0.0055 + 0.55(k_s/100h + 1/R_s)^{1/3}
\]

**Couette Flow**

The rotor generates a Couette flow which is established downstream of the seal inlet according to equation (14) which follows from equation (9) for the case of negligible circumferential pressure gradients and flow accelerations. Equations (15) and (16) are the asymptotes for $u = 0$ and $u = \infty$ which enclose the Couette factor $c$ for all surface friction ratios. Figure 5 shows $c$ as a function of surface friction ratio and the axial velocity ratio $u/w$. $c$ is low for high stator friction. The friction ratio is approximately the cubic root of the roughness ratio, as the equations (12) and (13) indicate. Therefore, large roughness ratios are required.
\[ u = c = 1/(1+f_s/f_r) \]  \hspace{1cm} (16)

Figure 5. Couette factor \( c = v/w \) versus the friction and axial velocity ratios.

**Dynamic Seal Parameters**

The integral dynamic effect of a seal is described by stiffness \( K \), damping \( C \), mass \( m \), whirl coupling \( c\Omega C' \), and gyro coupling \( c\Omega m' \) as shown in vector equation (17).

\[
\begin{bmatrix}
F_y \\
F_z
\end{bmatrix} = 
\begin{bmatrix}
K + s^2C + s^2m & c\Omega(C' + sm') \\
-c\Omega(C' + sm') & K + s^2C + s^2m
\end{bmatrix}
\begin{bmatrix}
y \\
z
\end{bmatrix}
\]  \hspace{1cm} (17)

The detailed derivations are given in reference 9, except for minor differences in rearranging frequency square terms herein. Some parts of the derivation are repeated for continuity. Equations (18) through (22) define the dynamic parameters and their response to the whirl frequency \( \omega \). The time constants are small. The basic stiffness \( K_0 \), damping \( C_0 \), and induced mass \( m_0 \) are given in equations (23) through (25) for inlet loss \( f_1 \); resistivities \( F, G, \) and \( H \); dimensions \( h, L, \) and \( r \) of seal gap, seal length, and seal radius; axial velocity \( u \); and mass density \( \rho \). The resistivities are
given by the equations (26) through (32). The time constants are defined by the equations (33) through (36).

\[ K = \frac{[K_o - (c\Omega)^2 m_o]}{(1 + \omega^2 \tau^2)} \]  
\[ C = \frac{[C_o (1 + \omega^2 \tau_a^2) + m_o \omega^2 (\tau - \tau_b) - \tau K_o]}{(1 + \omega^2 \tau^2)} \]  
\[ m = \frac{[m_o (1 + \tau \tau_b (\omega^2 + (c\Omega)^2)) - C_o (\tau - \tau_a)]}{(1 + \omega^2 \tau^2)} \]  
\[ C' = \frac{[C_o (1 + \omega^2 \tau_b^2) + 2m_o \omega^2 (\tau - \tau_b)]}{(1 + \omega^2 \tau^2)} \]  
\[ m' = \frac{[2m_o (1 + \omega^2 \tau_b^2) - C_o (\tau - \tau_a)]}{(1 + \omega^2 \tau^2)} \]  
\[ K_o = \frac{(\pi r/h)u^2(1 + f \tau_1)\tau L (F + H)/2}{(\tau / \tau_a)} \]  
\[ C_o = \frac{(\pi r/h)(\tau / \tau_a) L^3 (F + G)/12}{(\tau / \tau_a)} \]  
\[ m_o = \frac{C_o \tau_0}{\tau_b} \]  
\[ F = \rho [f_x (u^2 + (v-w)^2)^{1/2} + f_s (u^2 + v^2)^{1/2}]/8h \]  
\[ G = \rho u^2 [f_x - g_x]/(u^2 + (v-w)^2)^{1/2} \]  
\[ + f_s - g_s)/(u^2 + v^2)^{1/2}]/8h \]  
\[ H = \rho [h_x (u^2 + (v-w)^2)^{1/2} + h_s (u^2 + v^2)^{1/2}]/8h \]  
\[ g_x = h_x/(1 + R_{x} k_{x}/100h) \]  
\[ g_s = h_s/(1 + R_{s} k_{s}/100h) \]  
\[ h_x = (0.55/3) \cdot (k_{x}/100h + 1/R_{x})^{1/3} \]  
\[ h_s = (0.55/3) \cdot (k_{s}/100h + 1/R_{s})^{1/3} \]
The flow induced masses in equation (17) are dipol masses that are negligible against the rotor mass. The whirl coupling is indeed proportional to the Couette factor c as shown earlier in equation (1). Table 1 gives the dimensions of diverse inlet and outlet seals of the HPOTP preburner pump impeller (Fig. 3). Table 2 lists the analytical results for labyrinth, damping, and smooth annular seals. Table 2 shows that the leakage rates of labyrinth and damping seals are comparable, while the smooth annular seals leak 1.6 times more. Tests by Rocketdyne produced the same ratio. The whirl ratio of damping seals is $\frac{1}{4}$ but 0.5 for the other seals. Damping seals have the highest damping while the smooth annular seals show the highest stiffness.

Table 1. HPOTP Preburner Pump Seal Dimensions for Inlet and Outlet at Full Power 30,367 RPM

<table>
<thead>
<tr>
<th>PBP Seals</th>
<th>Gap</th>
<th>Diam.</th>
<th>Leng.</th>
<th>Pocket</th>
<th>Press</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>mils</td>
<td>inch</td>
<td>inch</td>
<td>mils 2</td>
<td>psi 3</td>
</tr>
<tr>
<td>Inlet Laby.</td>
<td>6</td>
<td>2.85</td>
<td>0.63</td>
<td>230</td>
<td>2006</td>
</tr>
<tr>
<td>Inlet Damp.</td>
<td>6</td>
<td>2.898</td>
<td>0.66</td>
<td>10(20)</td>
<td>2006</td>
</tr>
<tr>
<td>Inlet Smooth</td>
<td>6</td>
<td>2.898</td>
<td>0.66</td>
<td>0.032</td>
<td>2006</td>
</tr>
<tr>
<td>Outlet Laby.</td>
<td>4</td>
<td>3.345</td>
<td>0.87</td>
<td>80</td>
<td>6505</td>
</tr>
<tr>
<td>Outlet Damp.</td>
<td>4</td>
<td>3.3371</td>
<td>0.88</td>
<td>10(20)</td>
<td>6505</td>
</tr>
<tr>
<td>Outlet Smooth</td>
<td>4</td>
<td>3.3371</td>
<td>0.88</td>
<td>0.032</td>
<td>6505</td>
</tr>
</tbody>
</table>

NOTE: 1 = radial gap, 2 - effective pocket depth (actual depth), 3 = pressure difference.
Table 2. HPOTP Preburner Pump Seals' Dynamic for Inlet and Outlet at Full Power 30,367 RPM

<table>
<thead>
<tr>
<th>PBP Seals</th>
<th>Stif.</th>
<th>Whirl</th>
<th>Damp.</th>
<th>Ratio</th>
<th>Leak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>Klb/in</td>
<td>Klb/in</td>
<td>Lbs/in</td>
<td>%</td>
<td>Lb/s</td>
</tr>
<tr>
<td>Inlet Laby.</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>50</td>
<td>4.94</td>
</tr>
<tr>
<td>Inlet Damp.</td>
<td>106</td>
<td>46</td>
<td>57</td>
<td>23</td>
<td>5.18</td>
</tr>
<tr>
<td>Inlet Smooth</td>
<td>151</td>
<td>105</td>
<td>53</td>
<td>50</td>
<td>7.90</td>
</tr>
<tr>
<td>Outlet Laby.</td>
<td>20</td>
<td>36</td>
<td>23</td>
<td>50</td>
<td>5.13</td>
</tr>
<tr>
<td>Outlet Damp.</td>
<td>447</td>
<td>281</td>
<td>388</td>
<td>22</td>
<td>5.09</td>
</tr>
<tr>
<td>Outlet Smooth</td>
<td>935</td>
<td>544</td>
<td>302</td>
<td>50</td>
<td>8.51</td>
</tr>
</tbody>
</table>

NOTE: % ratio times maximum speed must be below 1st critical speed. Analysis is for 0.25 inlet loss, 2.59E-8 psi-s lox viscosity, and 1.05E-4 psi(s/in.)^2 lox density.

Seal Installation

Figure 3 illustrates a retrofitting case where inlet and outlet labyrinth seals were replaced by damping seals to inhibit a 450 Hz whirl at 30,000 RPM. Damping seals fit always into the space of labyrinth seals. Leakages are comparable, but stiffness and damping are much higher as seen in Table 2. Both changes inhibit whirl, lower vibrations, and increase critical speed. Damping seals seem to be more effective than squeeze film dampers, simpler, and smaller. Damping seals are suggested instead of smooth annular seals to reduce leaks and to suppress whirl.

The high stiffness of damping seals must be, however, considered when replacing labyrinth seals. Eccentricities between bearings and seals can cause unexpected side loads.

Soft Seals

The side loads can be reduced with small eccentricities, if tight tolerance costs are not prohibitive. Soft seals are another concept worth
considering. Damping seals become softer as roughness is increased. Axial flow is thus reduced and the fluid compressibility much enhanced. Another way is the insertion of a labyrinth seal downstream to shorten a damping seal without changing leakage.

**Hard Seals**

The hard seal approach takes advantage of high seal stiffness and uses the seals for supporting the rotor. Critical speeds are so increased and loads of pump and turbine discharges are shared by the seals. Tight tolerances (eccentricities) can be circumvented by loose fittings for the bearings' outer races. The bearings support the rotor at startup and cutoff when the seals are unpressurized or soft. At operation speed the seals are stiff and can take over. Good bearing life is expected because the bearings float mostly during their operation in a loadless condition. Outer race spinning due to floating can be prevented with antirotation devices.

**Conclusion**

Damping seals are new technology for improving turbomachinery operations. The shown properties encourage many applications from retrofitting machines that are beset by whirl problems to new and more efficient designs. We are grateful and do not take this progress for granted—be blessed the same way.

**References**


