DYNAMICS OF FACE SEALS FOR HIGH SPEED TURBOMACHINERY

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ABSTRACT

Face seals in rocket engine fuel and oxidiser turbopumps have been the subject of intense investigation for over 25 years. Whilst advances have been made in the understanding of thin film lubrication between seal faces; valuable data has been produced on the friction and wear of material pairs in cryogenic environments; pioneering work has been done on the effect of lubricant phase change in seals; and many improvements have been made in mechanical seal design, relatively superficial attention has been given to the vibrational dynamics of face seals in high-speed turbomachinery.

BHR Group Ltd. (formerly BHRA) has recently completed the first stage of a study, commissioned by the European Space Agency, to investigate this area. This has involved the development of a two-dimensional adiabatic, turbulent lubrication model for thick gas film applications, the production of an integrated mathematical model of gas seal vibrational dynamics for thin film applications, implementation in software, the undertaking of an experimental programme to validate software against variations in operating conditions and design variables, and suggestions for improved seal design.
CURRENT PROJECTS

- Applications
  - rotary
  - reciprocating
  - static

- Technology
  - experimental
  - analytical
  - design studies

- Organisation
  - direct contract
  - consortium + Dept. of Trade and Industry
  - consortium + BBC
  - independent consortium
FLUID SEALING TECHNOLOGY

Independent facilities and expertise:

- Seal Analysis: thermal, mechanical, lubrication
- Seal testing: oil, water, gas, cryogens, contaminants
- Pump Loops: oil, water, slurry, water/air
- Site Measurements: fixed, portable
- Design Audit: analysis, critical review
- Rig Manufacture: design, build, modification

PROJECT STRUCTURE

FLUID FILM → SEAL TESTS

STRUCTURAL DISTORTION → INTEGRATED COMPUTER MODEL

SEAL RING DYNAMICS → PARAMETRIC STUDY

Data from → Validated by

RECOMMENDATIONS

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Leakage Buffer Gas

Bearings Buffer Seals Turbine Seal

FACE SEAL OPTIONS:

- Plain
- Hydrostatic
- Self-acting

LITERATURE SURVEY
MAIN FINDINGS - SEALING PRACTICE

Limit of demonstrated success of plain face seals in LOX (NASA 1979)

- Self-acting face-seals in LOX (NASA evaluation)
- Plain face-seals in LOX (demonstrated success)
- Plain face seals in LH2 (Japanese test programme)
- Plain face seals in GN2 (BiHRG test programme)
LITERATURE SURVEY
MODELLING - FILM LUBRICATION ANALYSIS

Laminar, isothermal - Reynolds equation
- Liquid films - treatment of cavitation
- Gas films - grid design (adaptive, graded, etc.)
  - algorithm design (implicit, alternating, multigrid, 'interior co-location', etc.)

Turbulent lubrication - Hirs' bulk flow
  - Constantinou
  - Ng & Pan

Non-isothermal (higher Mach number) compressible flow
- 1-D (radial) adiabatic model with radial taper
  and entrance effects - Zuk

Two-phase (boiling interface) films
- 1-D models
- Stability approached from consideration of equilibrium
  film thickness vs. opening force curves
  (i.e. not from dynamic analysis)

LITERATURE SURVEY
MODELLING - DYNAMICS

- [K] and [C] matrices from fluid film analysis
  then dynamics as a separate problem
- Integrated analysis - fluid film forces and moments
  calculated at each timestep
- Excitation mechanisms
- Number of vibrational degrees-of-freedom
- Thermal and vibrational transients - 3 or 4 orders of
  magnitude difference in timescale - separate problem
SCAPE OF MODEL

- Concentrate initially on DYNAMICS
- Gas seal assumed (2-D transient 2-phase prohibitive within commercial constraints)
- Transient structural distortions
- Full transient lubrication analysis
- Turbulent, adiabatic AND laminar, isothermal leakage flow
- Choked exit conditions catered for
- 4 vibrational degrees of freedom
- Mechanical damping

MATHKERNELICAL MODEL
TURBULENT, ADIABATIC FLOW

Radial and circumferential velocities:

\[ u_r = -\frac{6\nu^2}{r^2} (\frac{2p}{2r} - \frac{L_t}{r}) \]

where \( L_t = \frac{w^3}{r} \)

and

\[ u_\theta = -\frac{6\nu^2}{r^2} \frac{2p}{r} \]

(optimal inertia)

\( G_r \) and \( G_\theta \) from Hirs' bulk flow turbulent lubrication theory (or \( 1/12 \), laminar)

Given in terms of Reynolds numbers "as seen by" rotor and stator (different)

Shear stresses from these Reynolds numbers

2-D adiabatic energy equation relates pressure to circumferential shear stress for density at current timestep

Iterate round instantaneous equations

Substitute \( u_r \) and \( u_\theta \) in continuity equation as "knowns" and find density at next timestep

Timestopping

Use film thickness, \( h \), at mid-timestep throughout procedure

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MATHEMATICAL MODEL
LAMINAR, ISOTHERMAL FLOW

Compressible Reynolds equation with ideal gas assumption

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \frac{\partial}{\partial x_i}(\rho \mathbf{u} \otimes \mathbf{u}) = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 \mathbf{u}}{\partial x_i \partial x_j}$$

Time discretisation:

$$\frac{\partial}{\partial t}(\rho \mathbf{u}^{n+1}) + \frac{\partial}{\partial x_i}(\rho \mathbf{u}^{n+1} \otimes \mathbf{u}^{n+1}) = -\frac{\partial p^{n+1}}{\partial x_i} + \mu \frac{\partial^2 \mathbf{u}^{n+1}}{\partial x_i \partial x_j}$$

No energy equation required.

Velocities and shear stresses from pressure gradients

- Check exit Mach number distribution for condition
  $$\mathbf{M} < \frac{1}{\sqrt{\gamma}}$$
  (isothermal flow)

- Check Reynolds number distribution for condition
  $$\text{Re} < \text{Re}_{critical}$$
  (laminar flow)
MATHEMATICAL MODELLING
FACE CONING

Sources:
- Pre-lapped taper and clamping forces
- Bellows load
- Rotor centrifugal inertia
- Change in ambient temperature for seal ring assemblies
- Sealed pressure differential
- Interfacial heat generation
- Interfacial pressure distribution

1. P.H. Analysis

2. Pressure distn. over P.H. grid - circumfl. average

3. Use influence coefficients to calculate face coning

\[ V = \sum_{k} c_k P_k \]
VIBRATIONAL DEGREES OF FREEDOM

MATHEMATICAL MODELLING DYNAMICS

Equations of motion time-discretised by Newmark's method:

\[
[M]^{-1} \dot{\ddot{\mathbf{u}}} = \frac{1}{\Delta t^2} \left( \mathbf{f} \right)_{\text{int}} - \frac{1}{\Delta t} \left( \mathbf{f} \right) \left( t \right)_{\text{int}} - \left( \mathbf{f} \right)_{\text{int}}
\]

Collect terms in \([\mathbf{x}]_{\text{int}}\) and solve:

\[
[\mathbf{x}]_{\text{int}} = \left[ (1) - \frac{3}{\Delta t} \Delta t^{2} [M]^{-1} [K] \left( 1 + \frac{1}{2 \Delta t} \right) \right]^{-1} [\mathbf{f}]_{\text{int}} + \Delta t [\mathbf{f}] \left( t \right)_{\text{int}} = \left( \mathbf{u} \right)_{\text{int}}
\]

Inertia and stiffness matrices, \([M]\) and \([K]\), are diagonal
in the absence of lateral stiffness, so that inverses are trivial.
### MATHMATICAL MODELLING

#### TIME-STEPPING

<table>
<thead>
<tr>
<th>COMPUTATION</th>
<th>USES</th>
<th>TO PREDICT</th>
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<td>Fluid film shape</td>
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\(\square\) = Output of fundamental importance

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### MATHMATICAL MODELLING

**APPROACH TO THERMAL TRANSIENT CONING**

**PROBLEM**

Thermal diffusion timescale

2-4 orders of magnitude slower than timescale of vibrational dynamics

**SOLUTION**

- Off-line thermal transient F.E. analysis provides coning as a function of time
- Coning-time curve "sampled" at user-specified intervals to provide quasi-steady coning for vibrational analysis
- Plain-faced balanced mechanical seals
- Bellows-type flexibly-mounted stator ring
- Rigidly-clamped rotor ring
- Coulomb friction vibration dampers
TEST PROGRAMME

SCOPE

- 42 tests covering:
  - face coning
  - rotor eccentricity
  - rotor out-of-squareness
  - degree of damping
- Effects of high and low temperature investigated
- Tests at high speed (60,000 rpm)
- All tests on typical plain face seal, modified to suit required conditions (face diameter = 30 mm)

FACILITY

- Hot gas (to around 220°C) supply
- Cold gas supply (boiling to room temp)
- Liquid cryogen supply possible
- High pressure (rated to 20 bar) up to 14000 rpm
- High speed (60,000 rpm) at lower pressure
TEST PROGRAMME
MISALIGNMENT AND ECCENTRICITY

MISALIGNMENT

ECCENTRICITY

Accurate tracking of run-out

Stability reached quickly
**Areas Suitable for Further Development**

- Liquid lubricant film
- Cavitating film
- Mechanical contact
- Circumferential EHD
- Different spring and secondary seal types
- Floating rotor types
- Ring seal geometries