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Appendices
Al Resistances in Series

Assumptions:

(a) $C_d$ identical for all flow areas

(b) Incompressible flow i.e. low Mach Numbers

Equating flow through orifice area $A_1$, curtain area $A_2$ and the combined effective flow area $A_e$:

$$C_d A_1 \left[ \frac{2 \rho \{P_2 - P_i\}}{ho} \right]^\frac{1}{2} = C_d A_2 \left[ \frac{2 \rho \{P_1 - P_2\}}{ho} \right]^\frac{1}{2}$$

$$= A_e \left[ \frac{2 \rho \{P_1 - P_2\}}{ho} \right]^\frac{1}{2}$$

where $A_e = \text{effective flow area of the overall resistance}$

Cancelling, squaring and rearranging:

$$\left[ \frac{A_e}{A_1} \right]^2 \left[ 1 - \frac{P_2}{P_0} \right] = C_d^2 \left[ 1 - \frac{P_1}{P_0} \right]$$

$$= \frac{C_d^2}{\sigma_e^2} \frac{P_1}{P_0} \left[ 1 - \frac{P_2}{P_1} \right]$$

Therefore:

$$\frac{P_2}{P_1} = 1 - \frac{\sigma_e^2 \left( 1 - \frac{P_1}{P_0} \right)}{(P_1/P_0)}$$

...... (A.2)
and:

\[ C_d^2 \left[ 1 - \frac{P_1}{P_0} \right] = \left[ \frac{A_e}{A_1} \right]^2 \left[ 1 - \frac{P_1}{P_0} \cdot \frac{P_2}{P_0} \right] \quad \ldots (A.3) \]

Substituting Equation (A.1) into (A.2)

\[ C_d^2 \left[ 1 - \frac{P_1}{P_0} \right] = \left[ \frac{A_e}{A_1} \right]^2 \left[ 1 - \left\{ \frac{A_e}{P_0} - \delta_2 \left( 1 - \frac{P_1}{P_0} \right) \right\} \right] \]

\[ = \left[ \frac{A_e}{A_1} \right]^2 \left[ 1 - \frac{P_1}{P_0} \right] \left[ 1 + \delta_2^2 \right] \]

Rearranging gives:

\[ A_e = \frac{C_d A_1}{\sqrt{1 + \delta_2^2}} \quad \text{or} \quad \frac{C_d A_2}{\sqrt{1 + \delta_2^2}} \quad \ldots (A.4) \]

Using \( A_e \) in the isentropic flow equation:

\[ \dot{m}_0 = \frac{C_d A_1}{\sqrt{1 + \delta_2^2}} \sqrt{\frac{2 \gamma}{(\gamma-1)RT} \left\{ \left( \frac{\text{A}_k}{P_0} \right)^{\gamma/2} - \left( \frac{\text{A}_k}{P_0} \right)^{\gamma/2 + \delta_2^2} \right\}^{1/2}} \]

for pocketed orifices

\[ \dot{m}_0 = \frac{C_d A_2}{\sqrt{1 + \delta_2^2}} \sqrt{\frac{2 \gamma}{(\gamma-1)RT} \left\{ \left( \frac{\text{A}_k}{P_0} \right)^{\gamma/2} - \left( \frac{\text{A}_k}{P_0} \right)^{\gamma/2 + \delta_2^2} \right\}^{1/2}} \]

for inherently compensated orifices

Note: As \( \delta_2 \to 0; A_e \to C_d A_1 \)

As \( \delta_2 \to \infty; A_e \to C_d A_2 \)
A2 Entrance Loss Effects

Assumptions:

(a) Incompressible flow i.e. low Mach No.

(b) Pressure loss in bearing film dependent upon Reynolds' Number and dynamic pressure in the form obtained by previous studies.

(c) Flow completely fills secondary flow area.

Equating mass flow through overall resistance:

\[
\frac{C_d d_0^2}{4 \sqrt{1 + \frac{d_0^2}{C_d}}} \left[ \frac{2}{\varphi} \left\{ \rho_0 - \rho_c \right\} \right]^{1/2} = \frac{(C_0 LF) \times d_0^2}{4} C_d \left[ \frac{2}{\varphi} \left\{ \rho_0 - \rho_c \right\} \right]^{1/2}
\]

Cancelling, squaring and rearranging:

\[
(C_0 LF)^2 = \frac{1}{1 + \frac{d_0^2}{C_d}} \left[ \frac{1 - \left( \frac{\rho_c}{\rho_0} \right)}{1 - \left( \frac{\rho_c}{\rho_0} \right)} \right]
\]  

...... (A.5)

From assumption (b):

\[
\rho_0 - \rho_c = k' (\rho_0 - \rho_c)
\]  

Where \( k' = \frac{F}{N}(Re) \)

Rearranging Equation (A.6)

\[
\frac{\rho_c}{\rho_0} = \frac{\rho_0}{\rho_c} (1 - k') + \frac{k' \rho_c}{\rho_0}
\]  

...... (A.7)
From Equations (A.1) and (A.4):

\[ \frac{p_f}{p_o} = 1 - \left( \frac{\beta_s}{\rho_o} \right)^2 \frac{1}{1 + \frac{\delta^2}{\rho_o}} \]  

\[ \text{…… (A.8)} \]

Substituting Equation (A.8) into (A.7):

\[ \frac{p_c}{p_o} = \left[ 1 + \frac{1 - \frac{\rho_c}{\rho_o}}{1 + \frac{\delta^2}{\rho_o}} \right] \left( 1 - \frac{k'}{\rho_o} \right) + \frac{k' \delta}{\rho_o} 

\[ \text{…… (A.9)} \]

Substituting Equation (A.9) into (A.5):

\[ \text{CREF} = \sqrt{\frac{1}{1 + k' \delta^2 \rho_o}} \]

Using CREF in the isentropic flow equation:

\[ \dot{m}_o = \frac{c_d \alpha d^2}{4 \sqrt{1 + k' \delta^2 \rho_o}} \rho_o \left[ \frac{2V}{(\delta - 1)RT} \left\{ \left( \frac{p_c}{p_o} \right)^{(\gamma + 1)/(\gamma - 1)} - \left( \frac{p_c}{p_o} \right)^{(\gamma + 1)/\gamma} \right\} \right]^{1/2} \]
Equating mass flow rates through orifice with that through the bearing clearance gives:

\[ \frac{d^2 \delta}{d \xi^2} = C_d \left[ \frac{2 \delta}{(\delta-1)R^2} \left\{ \left( \frac{\rho_d}{\rho} \right)^{1/2} - \left( \frac{\rho_d}{\rho} \right)^{1/2} \right\} \right]^{1/2} \]

\[ = \left( \frac{\rho_d}{\rho} \right)^{1/2} - \left( \frac{\rho_d}{\rho} \right)^{1/2} \]  \hspace{1cm} \ldots \ldots (B.1)

Defining \( \phi \) as:

\[ \phi = \frac{C_d \left[ \frac{2 \delta}{(\delta-1)R^2} \left\{ \left( \frac{\rho_d}{\rho} \right)^{1/2} - \left( \frac{\rho_d}{\rho} \right)^{1/2} \right\} \right]^{1/2}}{\left( \frac{\rho_d}{\rho} \right)^{1/2} - \left( \frac{\rho_d}{\rho} \right)^{1/2}} \]

Equation (B.1) becomes:

\[ \phi = \frac{1}{\Lambda_s \xi} \]

For \( \xi_0 = 0 \)

\[ \frac{6 \eta \sqrt{kT} \, n \, a_0 \, \xi_0}{4 \, k} \phi = \lambda_0 \]

\[ \therefore \frac{d \phi}{d \lambda_0} = \frac{1}{\Lambda_s \xi_0} \cdot \frac{3}{\lambda_0} \]

\[ \frac{d \rho_d}{d \lambda_0} \] can be defined as:

\[ \frac{d \rho_d}{d \lambda_0} = \frac{d \rho_d}{d \phi} \cdot \frac{d \phi}{d \lambda_0} \]  \hspace{1cm} \ldots \ldots (B.2)
Substituting for \( \frac{d\phi}{dh_0} \) into Equation (B.2):

\[
\frac{d\phi}{dh_0} = \frac{d\phi}{d\phi} \cdot \frac{1}{\eta \xi} \cdot \frac{3}{h_0} \qquad \cdots \text{(B.3)}
\]

For \( S_0 \neq 0 \):

\[
\frac{6\eta \sqrt{kT} \pi d_0^2 S}{4 h_0} \phi = h_0^3 \sqrt{1 + S_0^2}
\]

\[
\frac{d\phi}{dh_0} = \frac{1}{\eta \xi} \left[ \frac{3}{h_0} - \frac{S_0^2}{h_0 (1 + S_0^2)} \right]
\]

Substituting for \( \frac{d\phi}{dh_0} \) into Equation (B.2):

\[
\frac{d\phi}{dh_0} = \frac{d\phi}{dh_0} \cdot \frac{1}{\eta \xi} \left[ \frac{3}{h_0} - \frac{S_0^2}{h_0 (1 + S_0^2)} \right]
\]

\[\cdots \text{(B.4)}\]

The concentric bearing stiffness is dependent on \( \frac{d\phi}{dh_0} \). Thus the effect of \( S_0 \) on bearing stiffness is given by the ratio of Equation (B.3) to (B.4):

\[
\frac{\text{Stiffness } (S_0 = 0)}{\text{Stiffness } (S_0 \neq 0)} = \frac{\frac{d\phi}{dh_0} (S_0 = 0)}{\frac{d\phi}{dh_0} (S_0 \neq 0)} = \frac{1 + S_0^2}{1 + \frac{2}{3} S_0^2}
\]

In a similar manner, it can be shown that:

\[
\frac{\text{Stiffness } (S_0 = \infty)}{\text{Stiffness } (S_0 \neq \infty)} = \frac{2}{3} \cdot \frac{1 + S_0^2}{1 + \frac{2}{3} S_0^2}
\]
APPENDIX C - PROOF THAT: \[ \frac{\pi Z}{a'} \prod_{k=1}^{\infty} \left[ 1 + \frac{Z^2}{k^2 (a')^2} \right] = \sinh \left[ \frac{\pi Z}{a'} \right] \]

\[ \frac{\pi Z}{a'} \prod_{k=1}^{\infty} \left[ 1 + \frac{Z^2}{k^2 (a')^2} \right] \]

can be written as:

\[ \frac{\pi Z}{a'} \left[ 1 + \frac{Z^2}{(a')^2} \right] \left[ 1 + \frac{Z^2}{4 (a')^2} \right] \left[ 1 + \frac{Z^2}{9 (a')^2} \right] \left[ 1 + \frac{Z^2}{16 (a')^2} \right] \cdots \]

\[ \cdots \left[ 1 + \frac{Z^2}{\infty (a')^2} \right] \]

re-arranging gives:

\[ \frac{\pi Z}{a'} \left[ 1 + \frac{Z^2}{(a')^2} \right] \left\{ 1 + \frac{1}{4} + \frac{1}{9} + \frac{1}{16} + \cdots \right\} \]

\[ + \frac{Z^4}{(a')^4} \left\{ \frac{1}{4} + \frac{1}{9} \left( 1 + \frac{1}{4} \right) + \frac{1}{16} \left( 1 + \frac{1}{4} + \frac{1}{9} \right) + \cdots \right\} \]

\[ + \frac{Z^6}{(a')^6} \left\{ \frac{1}{4} + \frac{1}{9} \left( 1 + \frac{1}{4} \right) \right\} \]

\[ + \frac{1}{25} \left\{ \frac{1}{4} + \frac{1}{9} \left( 1 + \frac{1}{4} \right) + \frac{1}{16} \left( 1 + \frac{1}{4} + \frac{1}{9} \right) \right\} + \cdots \}

etc.

But:

\[ \left\{ 1 + \frac{1}{4} + \frac{1}{9} + \frac{1}{16} + \cdots \right\} = \frac{\pi^2}{3!} \]

\[ \left\{ \frac{1}{4} + \frac{1}{9} \left( 1 + \frac{1}{4} \right) + \frac{1}{16} \left( 1 + \frac{1}{4} + \frac{1}{9} \right) + \cdots \right\} = \frac{\pi^4}{5!} \]
Substituting these identities:

\[
\frac{\pi z}{a'} \prod_{k=1}^{\infty} \left[ 1 + \frac{z^2}{k^2 (a')^2} \right]
\]

\[
= \frac{\pi z}{a'} + \frac{\pi^3 z^3}{3! (a')^3} + \frac{\pi^5 z^5}{5! (a')^5} + \frac{\pi^7 z^7}{7! (a')^7} + \ldots
\]

which by definition equals \( \sinh \left[ \frac{\pi z}{a'} \right] \)

Therefore:

\[
\frac{\pi z}{a'} \prod_{k=1}^{\infty} \left[ 1 + \frac{z^2}{k^2 (a')^2} \right] = \sinh \left[ \frac{\pi z}{a'} \right]
\]
APPENDIX D

Listing of Computer Program Used for
Plotting the Flow Net of Single Admission Bearings
00100 $RESET-FREE
00200 $SET SUPRS
00300 $SET AUTOBIND
00400 $BIND=FROM (L)B00317/A, (L)B00317/B
00500 FILE 1(KIND=DISK,TITLE="PLOT/ISO1.")
00600 FILE 5=INPUT,UNIT=REMOTE
00700 FILE 3=OUTPUT,UNIT=REMOTE
00800 FILE 6=OUTPUT,UNIT=PRINTER
00900 C EP BEARINGS
01000 C CALCULATES AND PLOTS ISOBARS AND STREAMLINES
01100 C SINGLE PLANE COLLAR BEARING AND SINGLE ADM JOURNAL
01200 C
01300 COMMON X,Y,P1,P2,F1,PB,PD,ANG,XP(100),YP(100)
01400 CALL PLOTIN
01500 CALL DEVICE (1,0)
01600 CALL SHIFT2(150,100)
01700 WRITE(3,5)
01800 5 FORMAT(1HO,12H NE,NPBR,PD?)
01900 READ(5,/)P1,P2,PD
02000 WRITE(6,20)P1,P2,PD
02100 WRITE(3,20)P1,P2,PD
02200 20 FORMAT(1H,S5N*SW=,F7.2,7H N*PBR=,F8.5,4H PD=,F7.4)
02300 WRITE(3,21)
02400 21 FORMAT(1H,S42H SINGLE ADM JOURNAL = 1, COLLAR THRUST = 2)
02500 C READ TYPE OF BEARING
02600 READ(5,/)M
02700 IF(M.EQ.2)GO TO 22
02800 C TYPE 1 - SINGLE ADM JOURNAL
02900 WRITE(3,23)
03000 23 FORMAT(1H,S9H L,N,L/D?)
03100 READ(5,/)B1,N,SW
03200 WRITE(3,24)B1,N,SW
03300 24 FORMAT(1H,S3H L=,F6.1,3H N=,14,5H L/D=,F6.3)
03400 GO TO 28
03500 C TYPE 2 - COLLAR THRUST
03600 22 WRITE(3,25)
03700 25 FORMAT(1H,S11H RC,N,RORI?)
03800 READ(5,/)RC,N,RORI
03900 WRITE(3,30)RC,N,RORI
04000 WRITE(6,30)RC,N,RORI
04100 30 FORMAT(1H,S4H RC=,F6.1,3H N=,I4,6H RORI=,F6.3)
04200 SW=(ALOG(RORI))/2
04300 28 PI=3.142
04400 C CALCULATES AND PLOTS X AND Y FOR STREAMLINES
04500 DO 180 K=1,6
04600 ANG=(K-1)*PI/12
04700 Y=(K-1)*PI/6
04800 DO 190 I=1,39
04900 X=(40-I)/39.0
05000 CALL STR1
05100 IF(M.EQ.1)GO TO 26
05200 C TYPE 2 - COLLAR THRUST
05300 YP(I)=EXP(X*SW)*RC*Y/N
05400 XP(I)=(EXP(X*SW)*COS(Y/N)-1)*RC
05500 C MIRRORS STREAMLINES

D - 1
YP(79-I) = -EXP(-X*SW)*RC*Y/N
XP(79-I) = (EXP(-X*SW)*COS(Y/N)-1)*RC
GO TO 27
C TYPE 1 - SINGLE ADM JOURNAL
26 YP(I) = Y*B1/(2*SW*N)
XP(I) = X*B1/2
C MIRRORS STREAMLINES
YP(79-I) = -YP(I)
XP(79-I) = -XP(I)
GO TO 27
27 CONTINUE
190 CONTINUE
CALL MOVTO2(XP(1), YP(1))
CALL POLTO2(XP, YP, 78)
IF (K .EQ. 1) GO TO 202
C MIRRORS STREAMLINES
DO 200 I = 1, 78
YP(I) = -YP(I)
XP(I) = XP(I)
CALL MOVTO2(XP(1), YP(1))
CALL POLTO2(XP, YP, 78)
202 CONTINUE
180 CONTINUE
C CALCULATES AND PLOTS X AND Y FOR ISOBARS
WRITE(3,6)
6 FORMAT(1H0,9H PB, YMAX?)
READ(5,/) PB, YM
WRITE(3,50) PB, YM
50 FORMAT(1HO, 4H PB=, F7.4,6H YMAX=, F7.4)
X = (PD-PB)/(PD-1)
DO 160 I = 1, 20
IF(YM .LT. 1.0) GO TO 70
C NOT OF CLOSED FORM AROUND INLET
Y = YM*PI*(20-I)/19
70 CALL PRE2
IF(M .EQ. 1) GO TO 31
C COLLAR THRUST
YP(I) = EXP(X*SW)*RC*Y/N
XP(I) = (EXP(X*SW)*COS(Y/N)-1)*RC
C MIRRORS ISOBARS
YP(40-I) = -XP(I)
XP(40-I) = XP(I)
YP(39+I) = -EXP(-X*SW)*RC*Y/N
XP(39+I) = (EXP(-X*SW)*COS(Y/N)-1)*RC
YP(79-I) = -YP(39+I)
XP(79-I) = XP(39+I)
GO TO 32
C SINGLE ADM JOURNAL
31 YP(I) = Y*B1/(2*SW*N)
XP(I) = X*B1/2
D - 2
C MIRRORS ISOBARS
YP(40-I)=-YP(I)
XP(40-I)=XP(I)
YP(39+I)=-YP(I)
XP(39+I)=-XP(I)
YP(79-I)=YP(I)
XP(79-I)=-XP(I)
32 CONTINUE
160 CONTINUE
YP(79)=YP(1)
XP(79)=XP(1)
CALL MOVT02(XP(1), YP(1))
CALL POLTO2(XP, YP, 79)
GO TO 15
C PLOTS CENTRE LINES
161 I=1, 39
Y=1.2*PI*(39-I)/38
IF (M .EQ. 1) GOTO 61
YP(I)=RC*Y/N
YP(79-I)=-YP(I)
XP(I)=(COS(Y/N)-1)*RC
XP(79-I)=XP(I)
GO TO 62
XP(I)=0.0
XP(79-I)=0.0
YP(I)=Y*B1/(SW*N^2)
YP(79-I)=-YP(I)
62 CONTINUE
60 CONTINUE
CALL MOVT02(XP(1), YP(1))
CALL POLTO2(XP, YP, 78)
IF(M .EQ. 1) GO TO 65
YP(1)=EXP(SW)*RC*PI/N
XP(1)=(EXP(SW)*COS(PI/N)-1)*RC
YP(2)=EXP(-SW)*RC*PI/N
XP(2)=(EXP(-SW)*COS(PI/N)-1)*RC
GO TO 66
65 YP(1)=PI*B1/(2*SW*N)
XP(1)=B1/2
YP(2)=YP(1)
XP(2)=-XP(1)
66 CALL MOVT02(XP(1), YP(1))
CALL POLTO2(XP, YP, 2)
YP(1)=-YP(1)
YP(2)=-YP(2)
CALL MOVT02(XP(1), YP(1))
CALL POLTO2(XP, YP, 2)
CALL DEVEND
STOP
1600 END
16100 C
16200 C
16300 C
16400 SUBROUTINE STR1
16500C STREAMLINES - ITERATES Y FOR GIVEN X AND ANGLE
16600 COMMON X, Y, P1, P2, F1, PB, PD, ANG, XP(100), YP(100)
16700 1300 BL=0.0
16800 DO 2000 J=1,13
16900 P3=P1*(X+2*(J-7))/2
17000 A2=TANH(P3)
17100 A1=TAN(Y/2)
17200 TP=A1/A2
17300 GO TO 2002
17400 2001 TP=TAN(Y/2)
17500 2002 BL=BL+((-l)**(J-7))*ATAN(TP)
17600 2000 CONTINUE
17700 D1=ANG-BL
17800 TP=0.0
17900 DO 2100 J=1,13
18000 A1=TAN(Y/2)
18100 A3=(1/COS(Y/2))**2
18200 P3=P1*(X+2*(J-7))/2
18300 A2=TANH(P3)
18400 GO TO 2004
18500 2003 A2=1.0
18600 2004 A4=1+(A1/A2)**2
18700 D2=A3/(A4*A2*2)
18800 2100 TP=TP+((-l)**(J-7))*D2
18900 YNEW=Y+D1/TP
19000 IF (ABS(YNEW-Y) LE. 0.0001) GO TO 2005
19100 Y=YNEW
19200 GO TO 1300
19300 2005 RETURN
19400 END 
19500 C
19600 C
19700 C
19800 SUBROUTINE PRE2
19900 C PRESSURES - ITERATES X FOR GIVEN Y AND PRESSURE
20000 COMMON X, Y, P1, P2, F1, PB, PD, ANG, XP(100), YP(100)
20100 1103 TP=0.0
20200 BL=0.0
20300 DO 1000 J=1,13
20400 P3=P1*(1+2*(J-7))
20500 IF(ABS(P3) .GE. 50) GO TO 1001
20600 P4=COSH(P3)
20700 A2=ALOG(P4-1)
20800 GO TO 1002
20900 1001 A1=ABS(P3)-ALOG(2)
21000 1002 P5=P1*(X+2*(J-7))
21100 IF(ABS(P5) .GE. 50) GO TO 1003
21200 P6=COSH(P5)
21300 A2=ALOG(P6-COS(Y))
21400 GO TO 1004
21500 1003 A2=ABS(P5)-ALOG(2)
21600 1004 TP=TP+((-l)**(J-7))*(A1-A2)
21700 P7=P1*(2*(J-7))
21800 IF(ABS(P7) .GE. 50) GO TO 1005
P8 = COSH(P7)
A3 = ALOG(P8 - COS(P2))
GO TO 1006
1005 A3 = ABS(P7) - ALOG(2)
1006 CONTINUE
1000 BL = BL + ((-1)**(J - 7)) * (A1 - A3)
F1 = TP / BL
D1 = (F1**2 - 1) / (F2**2 - 1) - F1
TP = 0.0
DO 1100 J = 1, 13
P5 = P1 * (X + 2*(J - 7))
IF (ABS(P5) .GE. 50) GO TO 1101
A1 = P1 * SINH(P5)
A2 = COSH(P5) - COS(Y)
A3 = A1 / A2
GO TO 1102
1101 A3 = P1
1102 TP = TP + ((-1)**(J - 7)) * A3
1100 CONTINUE
D2 = TP / BL
XNEW = X - D1 / D2
IF (ABS(XNEW - X) .LE. 0.0001) GO TO 1104
X = XNEW
GO TO 1103
1105 RETURN
1104 RETURN
1103 RETURN
1102 RETURN
1101 RETURN
1100 RETURN
END
SUBROUTINE PPT
COMMON X, Y, P1, P2, F1, PB, PD, ANG, XP(100), YP(100)
DO 3000 J = 1, 13
WRITE(3, 3001) J, XP(J), YP(J)
3001 FORMAT(1H I = , I4, 3H X = , F8.2, 3H Y = , F8.2)
3000 CONTINUE
RETURN
END
SUBROUTINE PPT
COMMON X, Y, P1, P2, F1, PB, PD, ANG, XP(100), YP(100)
DO 3000 J = 1, 13
WRITE(3, 3001) J, XP(J), YP(J)
3001 FORMAT(1H I = , I4, 3H X = , F8.2, 3H Y = , F8.2)
3000 CONTINUE
RETURN
END
Appendix E

Equations Describing Bearing Clearance

No Errors
\[ h_{e,x} \approx h_0 \left\{ 1 + \epsilon \cos \theta \right\} \]

Bearing Taper
\[ h_{e,x} \approx h_0 \left\{ 1 + \epsilon \cos \theta - \frac{\%h_0 \text{ taper} \cdot (L-2x)}{100} \right\} \]

Bellmouthing
\[ x \leq \frac{L}{2} \]
\[ h_{e,x} \approx h_0 \left\{ 1 + \epsilon \cos \theta + \frac{\%h_0 \text{ bellmouth} \cdot (L-4x)}{100} \right\} \]
\[ \frac{L}{2} \leq x \leq L \]
\[ h_{e,x} \approx h_0 \left\{ 1 + \epsilon \cos \theta - \frac{\%h_0 \text{ bellmouth} \cdot (3L-4x)}{100} \right\} \]

Barrelling
\[ x \leq \frac{L}{2} \]
\[ h_{e,x} \approx h_0 \left\{ 1 + \epsilon \cos \theta - \frac{\%h_0 \text{ barrel} \cdot (L-4x)}{100} \right\} \]
\[ \frac{L}{2} \leq x \leq L \]
\[ h_{e,x} \approx h_0 \left\{ 1 + \epsilon \cos \theta + \frac{\%h_0 \text{ barrel} \cdot (3L-4x)}{100} \right\} \]
Ovality

\[ h_{o,x} \approx h_o \left\{ 1 + \epsilon \cos \theta + \frac{h_o \cdot \text{MOC} \cdot \sin(2\theta + \pi/2)}{200} \right\} \]

Bearing Tilt

\[ h_{o,x} \approx h_o \left\{ 1 + \left[ \frac{e_1 - e_t}{h_o h_o} \right] \left( \frac{L - 2x}{L} \right) \cos \theta \right\} \]

Local Burring at Pockets

\[ h_{\text{pockets}} \approx h_o \left\{ 1 + \epsilon \cos \theta - \frac{b_R}{h_o} \right\} \]

Combined Taper, Ovality, Tilt and Burring

\[ h_{o,x}^{\text{film}} \approx h_o \left\{ 1 + \left[ \frac{e_1 - e_t}{h_o h_o} \right] \left( \frac{L - 2x}{L} \right) \cos \theta + \frac{h_o \cdot \text{MOC} \cdot \sin(2\theta + \pi/2)}{200} - \frac{\% h_o \cdot \text{taper} \cdot (L - 2x)}{100 \cdot 2L} \right\} \]

\[ h_{o,x}^{\text{pockets}} \approx h_o \left\{ 1 + \left[ \frac{e_1 - e_t}{h_o h_o} \right] \left( \frac{L - 2x}{L} \right) \cos \theta + \frac{h_o \cdot \text{MOC} \cdot \sin(2\theta + \pi/2)}{200} - \frac{\% h_o \cdot \text{taper} \cdot (L - 2x)}{100 \cdot 2L} - \frac{b_R}{h_o} \right\} \]
APPENDIX F - RELATED PUBLICATIONS

The papers listed below have been published by the Author during the period of this study.


Figures

Figure 1.1: Principles of Operation

(a) Typical or Universal Design

(b) Specialized Design

Figure 1.2: Typical Vertical Design
Figure 1.1 Principles of Operation

Figure 1.2 Typical Orifice Designs

(a) Annular or Inherently Compensated
(b) Pocketed Compensated
Figure 2.1  Pressure Losses Local to an Inherently Compensated Restrictor.

Pressure loss through orifice area $\pi d_f h$

Inertia losses

Theoretical viscous pressure profile

Pressure recovery in bearing film
Figure 2.2  Pressure Distribution Local to an Inherently Compensated Restrictor for Choked Flow Conditions.

(a) Supersonic pressure profile [zero friction]
(b) Post-shock pressures [single normal shock]
(c) Typical laminar pressure profile
Figure 2.3 Comparison of Various Theoretical Pressure Profiles with Experiment - Inherently Compensated Thrust Bearing.

\[ \frac{2R_0}{d_f} = 30 \]
\[ d_f = 2 \text{ mm} \]
\[ \frac{P_o}{P_a} = 5 \]

- Experimental data by Mori et al. (Ref. 2.4)

Various theories (see text)
Figure 2.4  Pressure Losses Local to a Pocketed Orifice

Pressure Loss through Orifice  Area $\pi d_o^2 / 4$

Secondary Pressure Loss at Edge of Pocket  Area $\pi d_r h$

Theoretical Viscous Pressure Profile

Pressure Recovery in Bearing Film

$P_0$  $P_p$  $P_r$  $P_a$
Figure 2.5  Experimental \( C_d^* \) at Choked Conditions Against \( d_o \)  
- Ruby Jewels

Figure 2.6  Correlation of \( C_d \) with Pressure Ratio Based on Recovered Conditions in Pocket
Figure 2.7 Comparison of Various Theoretical Pressure Profiles with Experiment - Pocketed Compensated Thrust Bearing.

2 \( \frac{R_o}{d_R} \) = 7.5
\( d_R = 8.0 \text{ mm} \)
\( d_o = 0.8 \text{ mm} \)
\( b = 1.0 \text{ mm} \)
\( \frac{P_o}{P_a} = 3 \)

- Experimental data by Mori et al. (Ref. 2.4)
- Various theories (see text)

\( h = 29 \mu m \)
\( h = 90 \mu m \)
Figure 3.1  Flow Element

Figure 3.2  Relationship of Feeding Parameter with $K_{go}$

$C_d = 0.8, \gamma = 1.4$
Figure 3.3 $\frac{P_d}{P_o}$ Against Feeding Parameter

Figure 3.4 $\overline{G}$ Against Feeding Parameter
Figure 3.5  Sensitivity of Orifice Pressure $P_d$ with Changes in Film Clearance.

$C_d = 0.8$
$\delta = 1.4$

pocketed orifices

(for inherently compensated:
$\frac{dB}{dh} = \frac{3}{2}$ that shown)
Figure 4.1 Elemental Cube

Figure 4.2 Flow Net of Two Sources Close to Each Other
Figure 4.3 Single Admission Journal Bearing
Figure 4.4 Annular Thrust Bearing

Figure 4.5 Conformal Transformation
(a) Source and Sink Arrangement

(b) Flow Network

Figure 4.6 Annular Thrust Bearing
(a) Source and Sink Arrangement

(b) Flow Network

Figure 4.7 Double Admission Journal Bearing
Figure 4.8 Effect of the Number of Summing Terms on Calculated Film Pressures
Figure 4.9  Flow Diagram for the Computer Program Used for Plotting the Flow Net of Single Admission Bearings
\[ \frac{1}{\lambda} = \frac{p_d^2 - p_a^2}{p_a^2} \]

Figure 5.1  Line Feed Correction Factor $\frac{1}{\lambda}$

Figure 5.2  Determination of $\frac{1}{\lambda}$
Figure 5.3 Effect of $\lambda$ on Orifice and Film Pressures

Figure 5.4 Orifice and Film Pressures Against $\Lambda_s \xi$
Figure 5.5  \( \bar{G} \) Against \( \Lambda_s \xi \) for Various \( \gamma / 2 \)

\[
C_d = 0.8 \\
\gamma = 1.4
\]

Figure 5.6  Sensitivity of Film Pressures with Changes in Clearance for Various \( \Lambda_s \xi \)

\[
\frac{dP_d}{dh} = \frac{P_0 - P_a}{C_d} \\
\text{for inherently compensated:} \\
\frac{dP_d}{dh} \text{ is } \gamma / 2 \text{ that shown}
\]
Figure 6.1 Elemental Area

$$GA = \frac{\Delta X}{\Delta Y}$$

Figure 6.2 Grid Network Used in Finite Difference Analysis
assign pressure values to pockets

set film pressures

relax film pressures sequentially downstream of pockets

film pressure convergence test

calculate flow from each pocket to surrounding grid points and through the respective orifice

calculate new pocket pressure from Newton Raphson iteration to give flow rate equality

pocket pressure convergence test

Figure 6.3 Routine for Evaluation of Film Pressures
Figure 7.1  Typical Journal Bearing Designs
Figure 8.1  Geometry of Tilted Bearing

Figure 8.2  Axial and Circumferential Divisions
Figure 8.3 Grid Network
central admission
\[ a/L = 0.5 \]
\[ P_b / P_d = 5 \]
\[ \Lambda_s \xi = 0.5 \]
\[ \varepsilon = 0 \] pocketed orifices
\[ \epsilon = 0.5 \]

Figure 9.1 Circumferential and Dispersion Losses

(a) Single Admission
Double admission
\( a/L = 0.25 \)
\( P_0/P_a = 5 \)
\( \Lambda \xi_0 = 0.5 \)
\( \xi_0 = 0 \) pocketed orifices
\( \epsilon = 0.5 \)

Figure 9.1 (cont.)
Figure 9.2 Effect of $\frac{h}{\lambda}$ on Load/Deflection Characteristics
**Figure 9.3** Effect of L/D on Load/Deflection Characteristics

- Double admission
- $a/L = 0.25$
- $P_0/P_0 = 5$
- $\Lambda_s \xi = 0.5$
- $\xi = 0$ pocketed orifices
- $\Lambda \alpha = 1$
double admission
$\frac{a}{L} = 0.25$
$\frac{P_0}{P_a} = 5$
$\Lambda_s \xi = 0.5$
$\delta_s = 0$ pocketed orifices
$\frac{A_y}{A_s} = 1$

Figure 9.4 Bearing Film Pressures
Figure 9.5 Load Capacity Against $\Lambda s \xi$
Figure 9.6 Load Capacity Against $\varepsilon$ - Various $\Lambda_s$, $\xi$
Figure 9.7 Load Capacity Against $\Lambda_s \xi$ - Various $\Lambda_s$
Figure 9.8 Load Capacity Against $E$ - Various $P_0/P_a$
Figure 9.9  Load Capacity Against $\xi$ - Various $a/L$
Figure 9.10  Load Capacity Against \( \xi \) — Various Types of Compensation
Figure 9.11 Mass Flow Rate Against $\varepsilon$
Figure 9.12 $\overline{T_q}$ Against $\Lambda_s \xi$ - Various $\nu_\lambda$

(a) Single Admission
Double Admission

Figure 9.12 (cont.)
Figure 9.13 $\frac{T_q}{(P_0-P_a)LD^2}$ Against $\varepsilon_T$ - Various $\Lambda_5 \xi$

$L/D=1$ double admission
$a/L=0.25$
$P_0/P_a=5$
$\xi_0=0$ pocketed orifices
$\frac{1}{\kappa}=1$. 
Figure 9.14 \( \frac{T_q}{(P_0 - P_0)LD^2} \) Against L/D Ratio

- \( P_0/P_0 = 5 \)
- \( \Lambda_s \xi = 0.5 \)
- \( \frac{1}{\lambda} = 1 \)
- \( W = 0 \)
- \( \xi_T = 0.5 \)

- a/L = 0.25
  - Pocketed orifices \( \xi = 0 \)
  - Inherently compensated orifices \( \xi = \infty \)

- a/L = 0.5
  - Pocketed or inherently
    compensated orifices
Figure 9.15 $\overline{T_q}$ Against $\varepsilon_T$ - Various $P_0/P_a$

- $L/D = 1$ double admission
- $a/L = 0.25$
- $\Lambda_\varepsilon = 0.5$
- $\xi = 0$ pocketed orifices
- $\Lambda_\alpha = 1$
Figure 9.16 $\bar{T}_q$ Against $\varepsilon_T$ - Various Types of Compensation

- $L/D = 1$ double admission
- $a/L = 0.25$
- $P_0/P_a = 5$
- $\Lambda_s \xi = 0.5$
- $\lambda = 1$

- Pocketed orifices $\xi = 0$
- Inherently compensated orifices $\xi = \infty$
Figure 9.17  Comparison Between Corrected Line Feed Model and Finite Difference Solution - Varying n
Figure 9.18 Comparison Between Corrected Line Feed Model and Finite Difference Solution - Varying $d_p/D$
$L/D = 1$ double admission
$a/L = 0.25$
$P_o/P_a = 5$
$\Lambda_s \xi = 0.5$
$\xi_o = 0$ pocketed orifices
$\varepsilon = 0.5$

Figure 9.19 Combined Effect of $n$ and $d_{R}/D$ on Load Capacity
L/D = 0.5
a/L = 0.5
n = 16
P'/P = 3.04
d_L = 0.09 mm
h_o = 10.5 \mu m
d_R = 1.2 mm
\delta = 0.16
D/d_0 = 0.031
\Lambda_2\xi = 1.41

Figure 10.1 Experimental and Theoretical Pressure Profiles
- Concentric Conditions
Figure 10.1 (cont.)
Figure 10.1 (cont.)

- experiment
- complex potential theory
- finite difference solution

L/D = 1  
a/L = 0.5  
n = 8  
B/R = 3.04  
C = 0.12 mm  
h = 16 μm  
d = 1.2 mm  
ε = 0.19  
d/D = 0.031  
Λ = 0.71
Figure 10.1 (cont.)
Figure 10.1 (cont.)
Figure 10.1 (cont.)

L/D = 1
a/L = 0.25
n = 8
P/P_a = 5.08
c_s = 0.26 mm
h_o = 21.1 μm
d_o = 1.8 mm
s = 0.53
d_o/D = 0.047
Λ_oξ = 0.77

---

experiment
complex potential theory
finite difference solution

Figure 10.1 (cont.)
Figure 10.1 (cont.)
Figure 10.1 (cont.)

- experiment
- complex potential theory
- finite difference solution
Figure 10.1 (cont.)

L/D = 1  double adm
a/L = 0.25
n = 8
P_0/P_a = 3.67
d_0 = 0.31 mm
d_R = 2.5 mm
b = 0.08 mm
d_R/D = 0.05
C_d = 0.92

finite difference
--- h_0 = 31.5 μm  ξ = 0.75  Λ_s ξ = 0.43
--- h_0 = 35.5 μm  ξ = 0.72  Λ_s ξ = 0.30

o experiment

Figure 10.1 (cont.)
Figure 10.2 Experimental and Theoretical Pressure Profiles
- Eccentric Conditions

---

**Table 10.2**

<table>
<thead>
<tr>
<th></th>
<th>Load Capacity W Newtons</th>
<th>Mass Flow Rate $G \times 10^{-5} \text{kg/s}$</th>
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</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>28.6</td>
<td>17.8</td>
</tr>
<tr>
<td>Finite Difference Solution</td>
<td>29.7</td>
<td>15.8</td>
</tr>
<tr>
<td>Corrected Line Feed Model</td>
<td>30.7</td>
<td>15.0</td>
</tr>
</tbody>
</table>
L/D = 1
a/L = 0.25
n = 8
P_0/P_0 = 3.04
\bar{d}_0 = 0.26\, \text{mm}
h_0 = 21.1\, \mu\text{m}
d_R = 1.8\, \text{mm}
\delta = 0.53
d_R/D = 0.047
\Lambda_4\Xi = 1.30

(b)

<table>
<thead>
<tr>
<th>load capacity W Newtons</th>
<th>mass flow rate G \times 10^5 \text{kg/s}</th>
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</thead>
<tbody>
<tr>
<td>70</td>
<td>31.8</td>
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<tr>
<td>73.9</td>
<td>29.3</td>
</tr>
<tr>
<td>81.2</td>
<td>27.5</td>
</tr>
</tbody>
</table>

Figure 10.2 (cont.)
L/D = 1
a/L = 0.25
n = 8
P_0/P_a = 5.08
d_0 = 0.26mm
h_o = 21.1 μm
d_R = 1.8mm
ε = 0.53
d_R/D = 0.047
Λ_sε = 0.77

<table>
<thead>
<tr>
<th>Load capacity W Newtons</th>
<th>mass flow rate G x 10^5 kg/s</th>
</tr>
</thead>
<tbody>
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<td>168</td>
<td>62.7</td>
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<tr>
<td>168.9</td>
<td>62.1</td>
</tr>
<tr>
<td>183.2</td>
<td>58.7</td>
</tr>
</tbody>
</table>

Figure 10.2 (cont.)
$$L/D = 1$$
$$a/L = 0.25$$
$$n = 8$$
$$P_0/P_a = 7.8$$
$$d_0 = 0.26\text{mm}$$
$$h_0 = 21.1\ \mu\text{m}$$
$$d_R = 1.8\text{mm}$$
$$\delta = 0.53$$
$$d_R/D = 0.047$$
$$\Lambda_1\delta = 0.51$$

<table>
<thead>
<tr>
<th>load capacity $W$ Newtons</th>
<th>mass flow rate $G \times 10^3$ kg/s</th>
</tr>
</thead>
<tbody>
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<td>286</td>
<td>107</td>
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<tr>
<td>285.9</td>
<td>108.2</td>
</tr>
<tr>
<td>330.2</td>
<td>101.2</td>
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</table>

Figure 10.2 (cont.)
L/D = 1
a/L = 0.25
n = 8
\( P_0/P_a = 5.08 \)
df = 0.66 mm
h0 = 30 \( \mu \)m
\( \delta = 5.5 \)
dR/D = 0.017
\( \Lambda \xi = 0.359 \)

<table>
<thead>
<tr>
<th>load capacity</th>
<th>mass flow rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>W Newtons</td>
<td>G x 10^5 kg/s</td>
</tr>
<tr>
<td>experiment</td>
<td>138</td>
</tr>
<tr>
<td>finite difference solution</td>
<td>142.3</td>
</tr>
<tr>
<td>corrected line feed model</td>
<td>144.0</td>
</tr>
</tbody>
</table>
$L/D = 1$ double adm
$a/L = 0.25$
$n = 8$
$P_p/P_a = 3.67$
$d_o = 0.31 \text{mm}$
$d_R = 2.5 \text{mm}$
$b = 0.08 \text{mm}$
$d_R/D = 0.05$
$C_d = 0.92$
$e = 18.9 \mu \text{m}$

Figure 10.2 (cont.)
L/D = 1 double admission
a/L = 0.25
n = 8
P_o/P_o = 3.67
d_o = 0.31 mm
d_R = 2.5 mm
b = 0.08 mm
d_R/D = 0.05
C_d = 0.92
e = 18.9 \mu m

![Diagram](image)

- experiment
- finite difference

- $h_0 = 31.5 \mu m$, $\xi = 0.75$, $\Lambda_s \xi = 0.43$, $\varepsilon = 0.6$
- $h_0 = 35.5 \mu m$, $\xi = 0.72$, $\Lambda_s \xi = 0.30$, $\varepsilon = 0.53$

Figure 10.2 (cont.)
Figure 10.3 Experimental and Theoretical Load/Deflection Curves

(a) Pocketed Compensated Orifices

\[ \begin{align*}
L/D &= 1 \text{ double admission} \\
a/L &= 0.25 \\
n &= 8 \\
\varphi/\beta &= 7.8 \\
d_0 &= 0.11 \text{ mm} \\
h_0 &= 11.9 \text{ \(\mu\)m (air gauge)} \\
d_0 &= 1.2 \text{ mm} \\
\delta &= 0.21 \\
d_0/D &= 0.031 \\
\Lambda \xi &= 0.55
\end{align*} \]
L/D = 1 double admission
a/L = 0.25
n = 8
P_a/P_b = 5.08
d_f = 0.66 mm
h_o = 30 µm (air gauge)
S = 5.5
d_b/D = 0.017
Λ₁ξ = 0.359

(b) Inherently Compensated Orifices

Figure 10.3 (cont.)
Figure 10.4 Load Capacity Against $\Lambda_s \xi$
- Experimental and Theoretical Values

(a) Pocketed Compensated Orifices
Figure 10.4 (cont.)

(b) Inherently Compensated Orifices

\[ \frac{W}{L/D(P_0-P_a)} \]

- Theory
- Experiment \( \frac{P_0}{P_B} = 3.0-7.8 \)
  - \( \varepsilon = 0.25 \)
  - \( \varepsilon = 0.5 \)
  - \( \varepsilon = 0.8 \)

\[ \Lambda_s \xi \]

\[ L/D = 1, n = 8 \]
\[ d_B = 0.008, 0.017 \]
$L/D = 1$ double admission
$a/L = 0.25$
$n = 8$
$P_0/P_s = 3.67$
$d_o = 0.31\text{mm}$
$d_R = 2.5\text{mm}$
$b = 0.08\text{mm}$
$d_R/D = 0.05$
$C_d = 0.92$

Figure 10.5 Load Capacity Against Deflection
- Experimental and Theoretical Values

Figure 10.6 Mass Flow Rate Against Deflection
- Experimental and Theoretical Values
Figure 10.7 Radial Stiffness Against Deflection

- Experimental and Theoretical Values
Figure 10.8  Torque Against Tilt
- Pink's Experimental Data and Theoretical Values

(a) Double Admission

\[ \frac{T_q}{(P_0-P_1)LD^2} \]

\[
\begin{align*}
L/D &= 1 \\
a/L &= 0.25 \\
n &= 8 \\
P_1/P_0 &= 4 \\
d_0 &= 0.26\text{mm} \\
h_0 &= 30\mu\text{m} \\
d_R &= 1.8\text{mm} \\
 \xi &= 0.42 \\
d_R/D &= 0.047 \\
\Lambda_s\xi &= 0.42
\end{align*}
\]
Figure 10.8 (cont.)

(b) Single Admission
Figure 10.9 Torque Against Tilt
- Grewal's Experimental Data and Theoretical Values
L/D = 1.5 double admission
a/L = 0.25
P_L/P_a = 4
n = 12 slots/row
h_0 = 24.5 μm
K_g_0 = 0.49

(a) Film Pressures

Figure 10.10 Film Pressure Characteristics (Slot Bearing) Against Deflection - Experimental and Theoretical Values
Figure 10.10 (cont.)

(b) Pressure Differential

\[ \frac{P_H - P_L}{P_0 - P_a} \]

- experiment
- line feed model (Ref. 6.2)
Figure 10.11 Film Pressure Characteristics (Orifice Bearing) Against Deflection - Experimental and Theoretical Values
Figure 10.11 (cont.)
L/D = 1 double admission
a/L = 0.25
n = 8
P_o/P_a = 3.67
d_o = 0.31 mm
d_R = 2.5 mm
b = 0.08 mm
d_R/D = 0.05
C_d = 0.92

Figure 10.12 Pressure Differential Against Load Capacity
- Experimental and Theoretical Values
Figure 11.1  Variation of Load Capacity Due to the Departure of $h_0$ from Optimum

- $L/D = 1$
- $a/L = 0.25$
- $A_s \xi (\text{opt}) = 0.42$
- $P_r / P = 5$
- $\xi_s = 0.25$
- $c_r / D = 0.03$
- $n = 8$

$h_s / h_0 (\text{opt}) = 0.7$

$h_s = D - D_s / 2$

$h_s = \frac{D - D_s}{2}$
Figure 11.2 Variation of Load Capacity Due to the Departure of $d_0$ from Optimum
Variation of Load Capacity

Figure 11.3 Effect of Mismatched Orifices
(b) Variation of Eccentricity at Null Position
Figure 11.4  Effect of Non-Parallelism on Load Capacity
Figure 11.5  Effect of Out-of-Roundness on Load Capacity
Figure 11.6 Effect of Bearing Tilt on Load Capacity
Figure 11.7 Effect of Local Burring at Edge of Pocket on Load Capacity
L/D = 1, double admission
a/L = 0.25
n = 8
P/Pa = 7.8

d₀ = 0.11 mm
h₀ = 11.9 µm (air gauge)

d_R = 1.2 mm
δ = 0.21
d_R/D = 0.031
Λ_sξ = 0.55

<table>
<thead>
<tr>
<th>Burr</th>
<th>Bearing Geometry</th>
<th>Loading Orientation</th>
<th>Absolute Error in h₀</th>
<th>Error in δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>No Burr</td>
<td></td>
<td>-6%</td>
<td>all -5%</td>
</tr>
<tr>
<td>L</td>
<td>No Burr</td>
<td></td>
<td>+6%</td>
<td>all +5%</td>
</tr>
<tr>
<td>H</td>
<td>0.05</td>
<td>With Burr</td>
<td>-6%</td>
<td>all -5%</td>
</tr>
<tr>
<td>L</td>
<td>0.05</td>
<td>With Burr</td>
<td>+6%</td>
<td>all +5%</td>
</tr>
</tbody>
</table>
L/D = 1 double admission
a/L = 0.25
n = 8
P_0/P_a = 5.08
d_f = 0.66 mm
h_o = 30 μm (air gauge)
S = 5.5
d_R/D = 0.017
Λ_sξ = 0.359

---

Figure 11.8 (cont.)
Figure 13.1  Typical Bearing Geometry

\[ e_{res} = \sqrt{e_y^2 + e_x^2} \]

\[ \phi = \tan^{-1}\left[\frac{e_y}{e_x}\right] \]
Figure 14.1 Effect of $C_n$ on Aerodynamic Performance
Figure 14.2 Load Capacity Against $\varepsilon$ - Aerodynamic Bearings $L/D = 1$
Figure 14.3  Load Capacity Against $\varepsilon$ - Aerodynamic Bearings
$L/D = 2$
**Suffices**

A – aerodynamic contribution  
s – aerostatic  
res – resultant

**Force Diagram**

Figure 14.4  Vector Addition of Aerodynamic and Aerostatic Loads
Figure 15.1  Theoretical Predictions for Hybrid Bearings
- Various $C_n$

(a) Load Capacity
(b) Attitude Angle/Shaft Locus

Figure 15.1 (cont.)
Figure 15.2  Theoretical Predictions for Hybrid Bearings
- Various L/D
Figure 15.3  Theoretical Predictions for Hybrid Bearings
- Various $P_0/P_a$
Figure 15.4  Theoretical Predictions for Hybrid Bearings
- Various a/L
Figure 15.5  Theoretical Predictions for Hybrid Bearings
- Various $\Lambda_5 \xi$

- $L/D = 2$
- $a/L = 0.25$
- $P_2/P_1 = 5$
- $d/D = 0.03$
- $n = 8$

$1 - \Lambda_5 \xi = 0.25$
$2 - \Lambda_5 \xi = 0.7$
$3 - \Lambda_5 \xi = 5.0$

hybrid $C_n = 2$
hybrid $C_n = 2$
aerostatic
Figure 15.6  Theoretical Predictions for Hybrid Bearings
- Pocketed and Inherently Compensated Orifices
Figure 15.7  Theoretical Predictions for Hybrid Bearings
- Pocketed Orifices and Slot Entry Bearings
Figure 15.8  Theoretical Predictions for Aerostatic and Hybrid Bearings - Effect of Orifice Orientation with Respect to Load
Figure 15.9  Typical Pressure Profiles for Hybrid Bearings
(b) Circumferential at the plane of orifices

--- Aerodynamic $C_n = 2$
- --- Aerostatic ($C_n = 0$)
- --- Hybrid $C_n = 2$

(c) Circumferential at the bearing centreline
Figure 15.10 Hybrid Bearings - Comparison Between Finite Difference Solution and Powell's Superposition Method
Figure 15.10 (cont.)
\[ \frac{W}{D^2 P_a} \]

- Hybrid \( C_f = 2 \)
- Finite Difference
- Superposition \( \frac{W_S + k W_A}{W} \)
- Aerostatic

\[ L/D = 1 \]
\[ a/L = 0.25 \]
\[ P_1/P_2 = 5 \]
\[ d/D = 0.03 \]
\[ n = 8 \]
\[ \Lambda_s S' = 0.42 \]

Figure 15.10 (cont.)
Figure 15.10 (cont.)
Figure 15.10 (cont.)
Figure 15.10 (cont.)

- L/D = 2
- a/L = 0.25
- \( P_0/P_a = 8 \)
- \( d/D = 0.03 \)
- \( n = 8 \)
- \( \Lambda_s \Sigma = 0.7 \)

- Hybrid \( C_n = 2 \)
- Finite Difference
- Superposition
- \( W_0 + W_a \)
- Aerostatic
I.4

Figure 15.10 (cont.)

Aerostatic

Hybrid \( C_N \) = 2

Finite Difference

Superposition

\[ \frac{W}{D^2 (P_0 - P_a)} \]

inherently compensated orifices

Hybrid \( C_N = 2 \)

Finite Difference

Superposition

\[ \frac{W}{W_S + KW_A} \]

(g)
Figure 15.11  Hybrid and Aerostatic Bearings - Comparison Between Finite Difference Solution and Results from M.T.I.
Figure 15.12 Hybrid Bearings - Comparison Between Finite Difference Solution and Modified Superposition Method
Figure 15.12 (cont.)
Figure 15.12 (cont.)
Figure 15.12 (cont.)

\[ \frac{W}{D^2(P_0 - P_1)} \]

- \( \frac{L}{D} = 2 \)
- \( \frac{a}{L} = 0.25 \)
- \( \frac{P_0}{P_1} = 5 \)
- \( \frac{d}{D} = 0.03 \)
- \( n = 8 \)
- \( \Lambda_s \frac{\delta}{x} = 0.7 \)

Inherently compensated orifices

Hybrid
\( C_n = 2 \)

Aerostatic
Figure 16.1 Schematic Diagram of Test Rig

KEY
1 - Test Shaft
2 - Sleeves
3 - Hydrostatic Slave Bearings
4 - Test Bearing
5 - Pneumatic Load Cylinder
6 - Load Adjusting Mechanism
7 - Pressure Transducer
8 - Capacitance Probes
9 - Pulley
Figure 16.2  Test Bearing Mounting Arrangement
Figure 16.3 Test Rig Instrumentation
Figure 16.4  Pneumatic Load Cell Transducer Calibration Curve
Figure 16.5  Calibration Curves for the Outputs of the Wayne Kerr Amplifier and the Analogue Computer
Figure 16.6  Circuit Diagram for Analogue Computer
Figure 16.7  Output Curves from Analogue Computer
Figure 16.8  Set-Up for Calibrating the Tacho-Generator
Figure 16.9  Air Supply Circuit
Figure 16.11  Diaphragm Valves
Figure 16.12  Typical Test Bearing
Jewel placed over hole.
Rolled Flush with Bore.

0.08mm thick spacer placed over jewel & sellotaped in position.
Rolled Flush with Bore.

Spacer, of thickness equal to the required pocket depth, placed over jewel & sellotaped in position.
Rolled Flush with Bore.

Sellotape & spacer removed.

Figure 16.13  Procedure for Mounting Jewels in Pockets
Figure 16.14  Roundness Traces for L/D = 1 Bearing
Figure 16.15 Axial Profile Traces for L/D = 1 Bearing
Figure 16.16  Test Shaft Assembly
Figure 17.1  Aerodynamic Performance (Without Holes) for L/D = 1 - Theory and Experiment
(b) Attitude Angle/Shaft Locus
Figure 17.2 Aerodynamic Performance (Without Holes) for $L/D = 2$ - Theory and Experiment

(a) Load Against Deflection

$h_0 = 12.7 \mu m$

<table>
<thead>
<tr>
<th>speed rpm</th>
<th>$C_n$</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>1320</td>
</tr>
<tr>
<td>2</td>
<td>2000</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
</tr>
<tr>
<td>4</td>
<td>4000</td>
</tr>
</tbody>
</table>
Figure 17.2 (cont.)

(b) Attitude Angle/Shaft Locus
(c) Deflection Against Speed

(d) Attitude Angle Against Speed

Figure 17.2 (cont.)
Figure 17.3 Aerodynamic Performance (With Holes) for L/D = 1
- Theory and Experiment
(b) Attitude Angle/Shaft Locus

Figure 17.3 (cont.)
Figure 17.4  Aerodynamic Performance (With Holes) for L/D = 2, $h_0 = 12.7 \mu m$ - Theory and Experiment
(b) Attitude Angle/Shaft Locus

Figure 17.4 (cont.)
(c) Deflection Against Speed

(d) Attitude Angle Against Speed

Figure 17.4 (cont.)
Figure 17.5  Aerodynamic Performance (With Holes) for L/D = 2,
h0 = 17.9 μm — Theory and Experiment

(a) Load Against Deflection
Figure 17.5 (cont.)

(b) Attitude Angle/Shaft Locus
Figure 17.6 Hybrid Performance for L/D = 1
- Theory and Experiment

(a) Load Against Deflection

-实验
-有限差分解
-修改的叠加

-速度 rpm | Cn
---|---
1 aerostatic | 0
2 2000 | 0.93
3 5000 | 2.32

a/L = 0.25
h_o = 12.3 μm
P_e/P_e = 2
\lambda_s = 1.24
d_L/D = 0.036
n = 8
Figure 17.6 (cont.)

(b) Attitude Angle/Shaft Locus
Figure 17.7 Hybrid Performance for $L/D = 2$, $h_o = 12.7 \mu m$, $P_o/P_a = 2$
- Theory and Experiment

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>$C_n$</th>
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</thead>
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<tr>
<td>1 aerostatic</td>
<td>0</td>
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<tr>
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<td>0.57</td>
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<tr>
<td>3 3000</td>
<td>1.30</td>
</tr>
<tr>
<td>4 5000</td>
<td>2.17</td>
</tr>
</tbody>
</table>
(b) Attitude Angle/Shaft Locus
Figure 17.7 (cont.)

(c) Deflection Against Speed

(d) Attitude Angle Against Speed
Figure 17.8 Hybrid Performance for $L/D = 2$, $h_o = 12.7 \mu m$, $P_o/P_a = 5$
- Theory and Experiment
(b) Attitude Angle/Shaft Locus

Figure 17.8 (cont.)
(c) Deflection Against Speed

(d) Attitude Angle Against Speed

Figure 17.8 (cont.)
Figure 17.9  Hybrid Performance for $L/D = 2$, $h_o = 12.7 \mu m$, $P_o/P_a = 0$  
- Theory and Experiment
Figure 17.9 (cont.)

(b) Attitude Angle/Shaft Locus
Figure 17.9 (cont.)

(c) Deflection Against Speed

(d) Attitude Angle against Speed
Figure 17.10 Hybrid Performance for $L/D = 2$, $h_o = 17.9 \, \mu m$
- Theory and Experiment
(b) Attitude Angle/Shaft Locus

Figure 17.10 (cont.)
Figure 17.11  Comparison Between Theoretical Results and Experimental Data by Powell
Figure 17.12 Comparison Between Theoretical Results and Experimental Data by Cunningham et al.
experiment (Cunningham et al. Ref. 13.8)

- O 10,000 rpm \( C_n = 1.1 \)
- \( \times \) 25,000 rpm \( C_n = 2.8 \)

--- finite difference solution

(b) Shaft Locus

Figure 17.12 (cont.)
L/D = 2
a/L = 0.25
n = 8
h₀ = 20.3 µm
D = 25.4 mm
pocketed orifices

(a) Pressure Profiles

Figure 17.13 Comparison Between Theoretical Results and Experiment
Figure 17.13  Comparison Between Theoretical Results and Experimental Data by McFarlane and Reason
Figure 17.13 (cont.)

(b) Eccentricity and Attitude Angle

experiment (Mcfarlane and Reason Ref. 13.10)
finite difference solution
Tables
Table 2.1 Values of Experimental $C_d^*$ for Inherently Compensated Restrictors (Choked Flow Conditions)

(a) Pink (Ref. 2.2)

<table>
<thead>
<tr>
<th>$d_f$ mm</th>
<th>$h$ μm</th>
<th>$P_o/P_a$</th>
<th>$C_d^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.265</td>
<td>22.7</td>
<td>7.8</td>
<td>0.84</td>
</tr>
<tr>
<td>0.265</td>
<td>31.6</td>
<td>5.1</td>
<td>0.79</td>
</tr>
<tr>
<td>0.265</td>
<td>31.6</td>
<td>7.8</td>
<td>0.80</td>
</tr>
<tr>
<td>0.310</td>
<td>21.1</td>
<td>5.1</td>
<td>0.80</td>
</tr>
<tr>
<td>0.310</td>
<td>21.1</td>
<td>7.8</td>
<td>0.80</td>
</tr>
<tr>
<td>0.310</td>
<td>30.0</td>
<td>5.1</td>
<td>0.78</td>
</tr>
<tr>
<td>0.335</td>
<td>19.7</td>
<td>7.8</td>
<td>0.79</td>
</tr>
<tr>
<td>&quot;</td>
<td>28.6</td>
<td>5.1</td>
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<td>&quot;</td>
<td>7.8</td>
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<td>0.350</td>
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<td>0.80</td>
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<td>&quot;</td>
<td>33.0</td>
<td>7.8</td>
<td>0.73</td>
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<td>0.660</td>
<td>30.0</td>
<td>5.1</td>
<td>0.79</td>
</tr>
<tr>
<td>0.660</td>
<td>30.4</td>
<td>7.8</td>
<td>0.81</td>
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<tr>
<td>0.660</td>
<td>31.6</td>
<td>7.8</td>
<td>0.79</td>
</tr>
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</table>

$C_d^*$

Min Value = 0.67

Max Value = 0.84

Mean Value = 0.788
Table 2.1 (cont.)

(b) Mori and Miyamatsu (Ref. 2.4)

<table>
<thead>
<tr>
<th>df (mm)</th>
<th>h (μm)</th>
<th>$P_0/P_a$</th>
<th>$C_d^*$</th>
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<tbody>
<tr>
<td>1.0</td>
<td>54</td>
<td>3.0</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>62</td>
<td>3.0</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>68</td>
<td>3.0</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>3.0</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>3.0</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>104</td>
<td>3.0</td>
<td>0.78</td>
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<tr>
<td></td>
<td>129</td>
<td>3.0</td>
<td>0.76</td>
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<td>54</td>
<td>2.5</td>
<td>0.85</td>
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<td>62</td>
<td>2.5</td>
<td>0.83</td>
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<tr>
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<td>68</td>
<td>2.5</td>
<td>0.85</td>
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<tr>
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<td>80</td>
<td>2.5</td>
<td>0.83</td>
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<tr>
<td></td>
<td>91</td>
<td>2.5</td>
<td>0.81</td>
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<tr>
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<td>104</td>
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<td></td>
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<td>80</td>
<td>3.0</td>
<td>0.85</td>
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<tr>
<td></td>
<td>104</td>
<td>3.0</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>54</td>
<td>2.5</td>
<td>0.80</td>
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<td>61</td>
<td>2.5</td>
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<td>2.5</td>
<td>0.81</td>
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<td>2.5</td>
<td>0.84</td>
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<tr>
<td></td>
<td>90</td>
<td>2.5</td>
<td>0.85</td>
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</table>

$C_d^*$ Min = 0.76
$C_d^*$ Max = 0.86
$C_d^*$ Mean = 0.788
### Table 10.1: Comparison of Experimental and Theoretical Load Capacity

<table>
<thead>
<tr>
<th>$P/P_0$</th>
<th>$\Lambda E$</th>
<th>$d_0=0.11 \text{ mm}$</th>
<th>$C_d=0.8$</th>
<th>$\bar{R} (\varepsilon=0)$</th>
<th>$\bar{W} (\varepsilon=0.5)$</th>
<th>$\bar{W} (\varepsilon=0.8)$</th>
<th>$d_0=0.26 \text{ mm}$</th>
<th>$C_d=0.89$</th>
<th>$\Lambda E$</th>
<th>$\bar{R} (\varepsilon=0)$</th>
<th>$\bar{W} (\varepsilon=0.5)$</th>
<th>$\bar{W} (\varepsilon=0.8)$</th>
</tr>
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<tbody>
<tr>
<td>1.68</td>
<td>2.60</td>
<td>0.270</td>
<td>0.300</td>
<td>+11.1</td>
<td>0.128</td>
<td>0.150</td>
<td>+17.2</td>
<td>0.196</td>
<td>0.216</td>
<td>+10.2</td>
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<tr>
<td>3.04</td>
<td>1.44</td>
<td>0.552</td>
<td>0.581</td>
<td>+5.3</td>
<td>0.225</td>
<td>0.239</td>
<td>+6.2</td>
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<td>0.682</td>
<td>0.692</td>
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<td>0.274</td>
<td>0.279</td>
<td>+1.8</td>
<td>0.333</td>
<td>0.334</td>
<td>+0.3</td>
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<tr>
<td>7.80</td>
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<td>0.660</td>
<td>0.696</td>
<td>+5.8</td>
<td>0.278</td>
<td>0.292</td>
<td>+6.1</td>
<td>0.345</td>
<td>0.359</td>
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<td>1.68</td>
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<td>0.264</td>
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</tbody>
</table>

- $\bar{R}$: Experimental load capacity
- $\bar{W}$: Theoretical load capacity
- Error: Percentage error
<table>
<thead>
<tr>
<th>$P_r$</th>
<th>$h_0$</th>
<th>$K = 0$</th>
<th>$\bar{W}_{(e = 0.5)}$</th>
<th>$\lambda$</th>
<th>$\lambda W_{(e = 0.5)}$</th>
<th>$\bar{W}_{(e = 0.48)}$</th>
<th>$\lambda W_{(e = 0.48)}$</th>
<th>$\lambda W_{(e = 0.5)}$</th>
<th>$\lambda W_{(e = 0.48)}$</th>
<th>$\lambda W_{(e = 0.5)}$</th>
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<td>0.019</td>
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<td>7.80</td>
<td>0.270</td>
<td>0.677</td>
<td>0.439</td>
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Table 10.2 Comparison of Experimental and Theoretical Load Capacity
- Inherently Compensated Orifices
<table>
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<tr>
<th>$\frac{P_2}{P_1}$</th>
<th>$d_0 = 0.11 \text{mm}$</th>
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<tr>
<td></td>
<td>$\lambda_{S,E}$</td>
<td>$\lambda_{S,E}$</td>
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<tr>
<td></td>
<td>exp</td>
<td>theo</td>
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<td>1.68</td>
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Table 10.3  Comparison of Experimental and Theoretical Mass Flow Rates
- Pocketed Compensated Orifices
Table 10.4 Comparison of Experimental and Theoretical Mass Flow Rates
- Inherently Compensated Orifices

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<th>$P_a/P_s$</th>
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Plates
Plate 1  The Experimental Test Rig and Instrumentation

Plate 2  Test Bearing Assembly
Plate 3  Instrumentation Panel

Plate 4  Calibration Rig for Capacitance Probes
Plate 5  Compensating Valves

Plate 6  Slave Bearing
Plate 7  Test Bearings

Plate 8  Lapping Equipment
Plate 9  Air Gauging Equipment

Plate 10  Test Shaft