



ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO

PMR 3501
Engenharia de Precisão

A17
Mancais e guias aerostáticas

2020.2



Planejamento

Dia	S	Aula	Tópico	Prof.
08.10	5ª	A17	Elementos de máquinas de precisão - mancais e guias hidrostáticos	RS
14.10	4ª	A18	Elementos de máquinas de precisão - mancais e guias aerostáticos	RS
15.10	5ª	A19	Elementos de máquinas de precisão - mancais magnéticos	RS
21.10	4ª	A20	Elementos de máquinas de precisão - guias de molas	RS
22.10	5ª	A21	Elementos de máquinas de precisão - transmissores do movimento	RS
28.10	4ª			RS
29.10	5ª	A22	Elementos de máquinas de precisão - conversores do movimento	RS
04.11	4ª	A23	Elementos de máquinas de precisão - atuadores	RS
05.11	5ª	A24	Elementos de máquinas de precisão - acoplamentos	RS
11.11	4ª	A25	Exercícios -4	RS
12.11	5ª	A26	Estruturas de sistemas de precisão: Requisitos, Materiais e Fabricação	RS
18.11	4ª	A27	Estruturas de sistemas de precisão: configurações estruturais e laço estrutural	RS
19.11	5ª	A28	Estruturas de sistemas de precisão: considerações estáticas, dinâmicas e térmicas. Erros, propagação de erros / compensação de erros	RS
25.11	4ª	A29	Materiais para componentes de precisão	RS
26.11	5ª	A30	Exercícios -5	RS
02.12	4ª	A29	Apresentação de Estudo de Caso/Seminário	RS
03.12	5ª	A30	Apresentação de Estudo de Caso/Seminário	RS
09.12	4ª	A31		
10.12	5ª			
14.12	3ª		Encerramento do semestre 2020-2	
06.12			Mecedor tridimensional de coordenadas	



Fundamentos do projeto de precisão

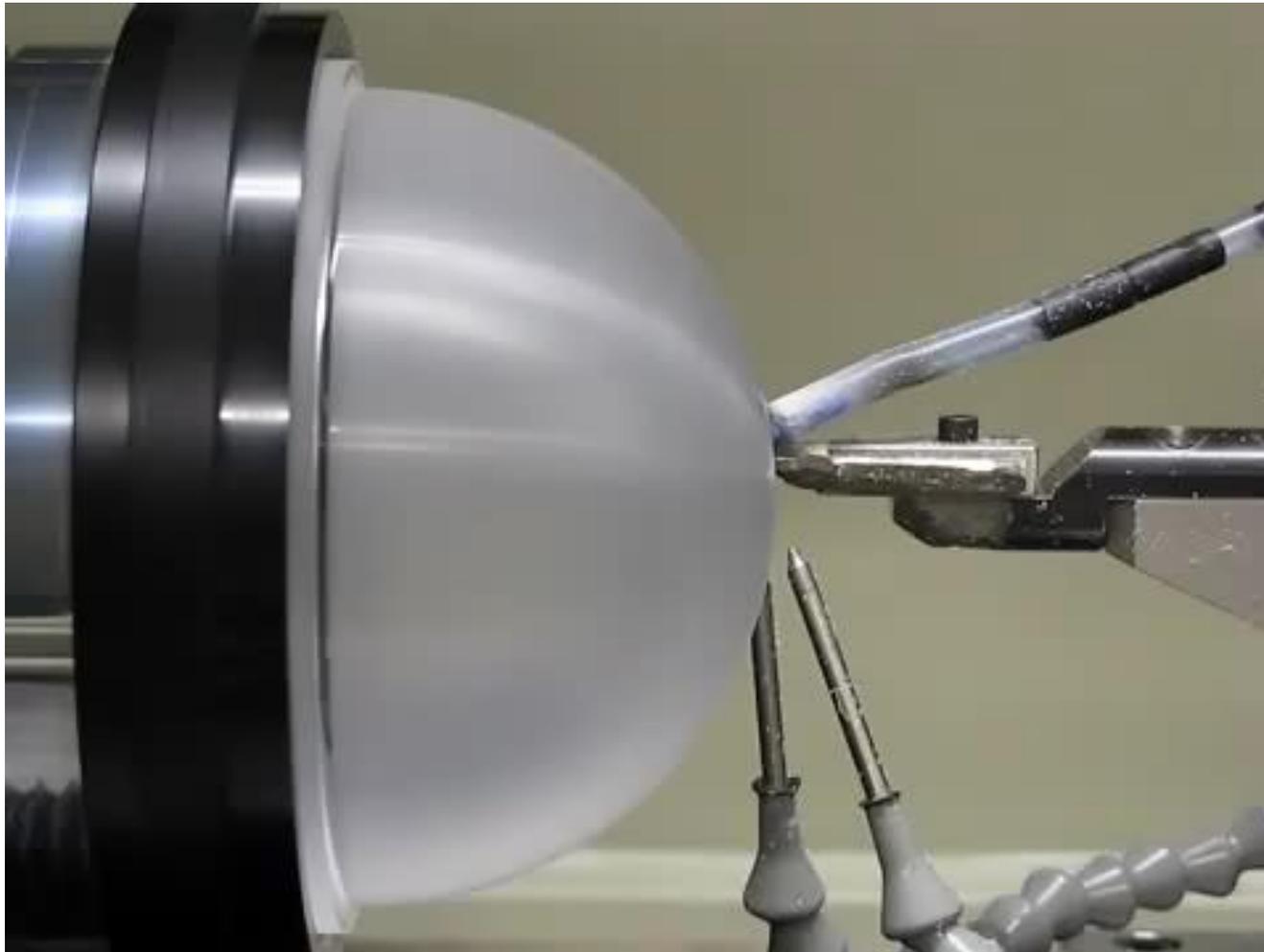
Pensamentos críticos

- Se você está **contente** com algo, contorne
- Se você está **descontente** com algo, contorne
- Sempre pode haver uma solução melhor, tente novas abordagens
- Você pode projetar um sistema para ser insensível ao meio, ou você pode isolar o sistema do meio
- Se você não consegue resolver um problema pelo seu começo, comece pelo fim e trabalhe no sentido reverso





Diamond turning an acrylic dome





Introdução

Mancais e Guias

Mancais

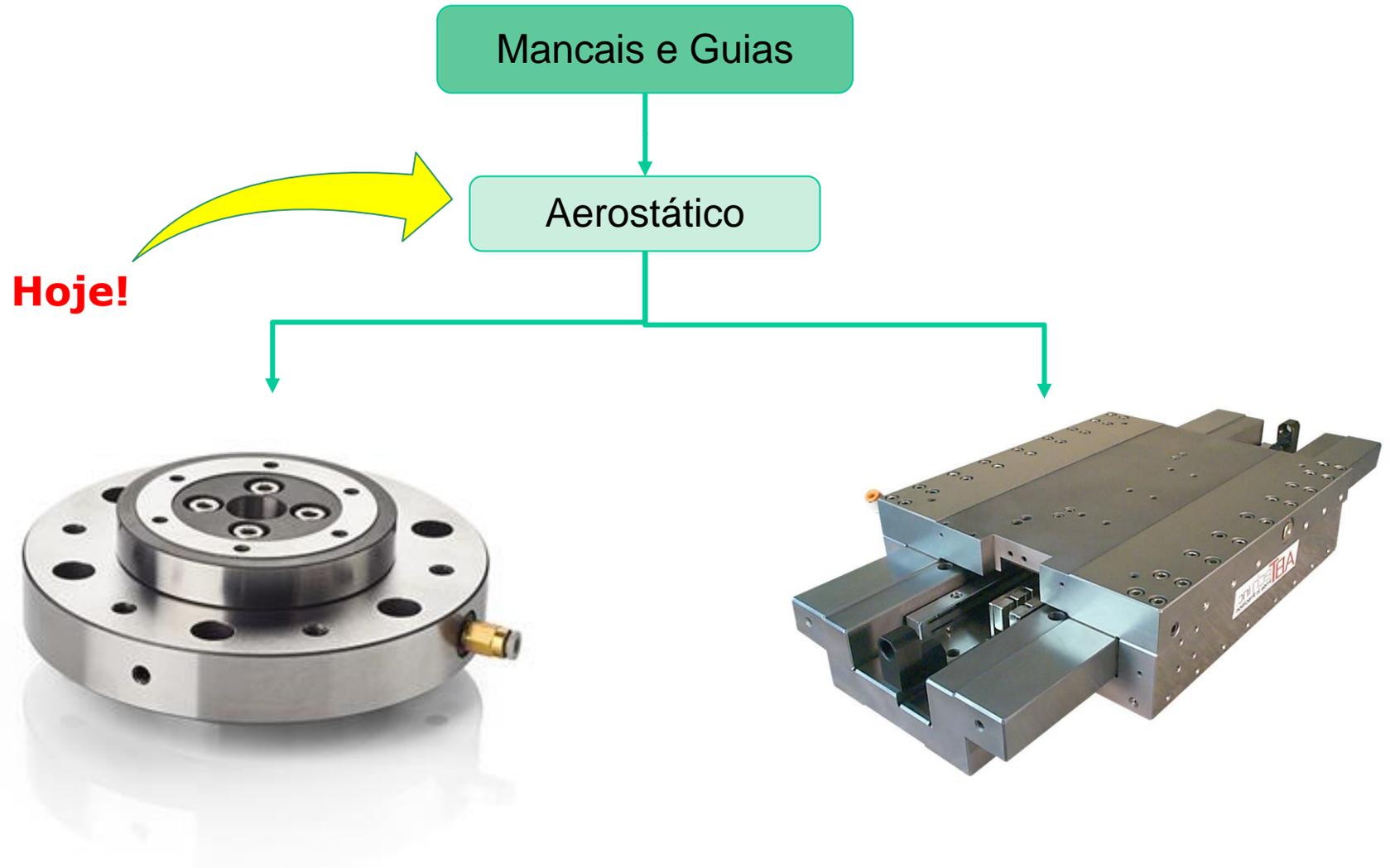


- **Mancais** são elementos de máquinas que tem por função básica absorver carregamentos, e onde o movimento de **translação** em qualquer direção deve ser minimizado, deixando **livre** somente a **rotação** em torno de um eixo.

Guias



- **Guias** são elementos de máquinas que tem por função básica absorver carregamentos, e onde o movimento de **rotação** em qualquer direção deve ser minimizado, deixando **livre** somente a **translação** ao longo de um eixo.

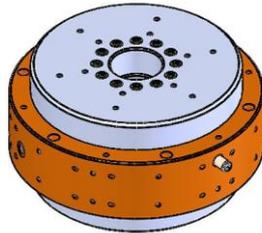






Mancais/Guias aerostáticas

Características

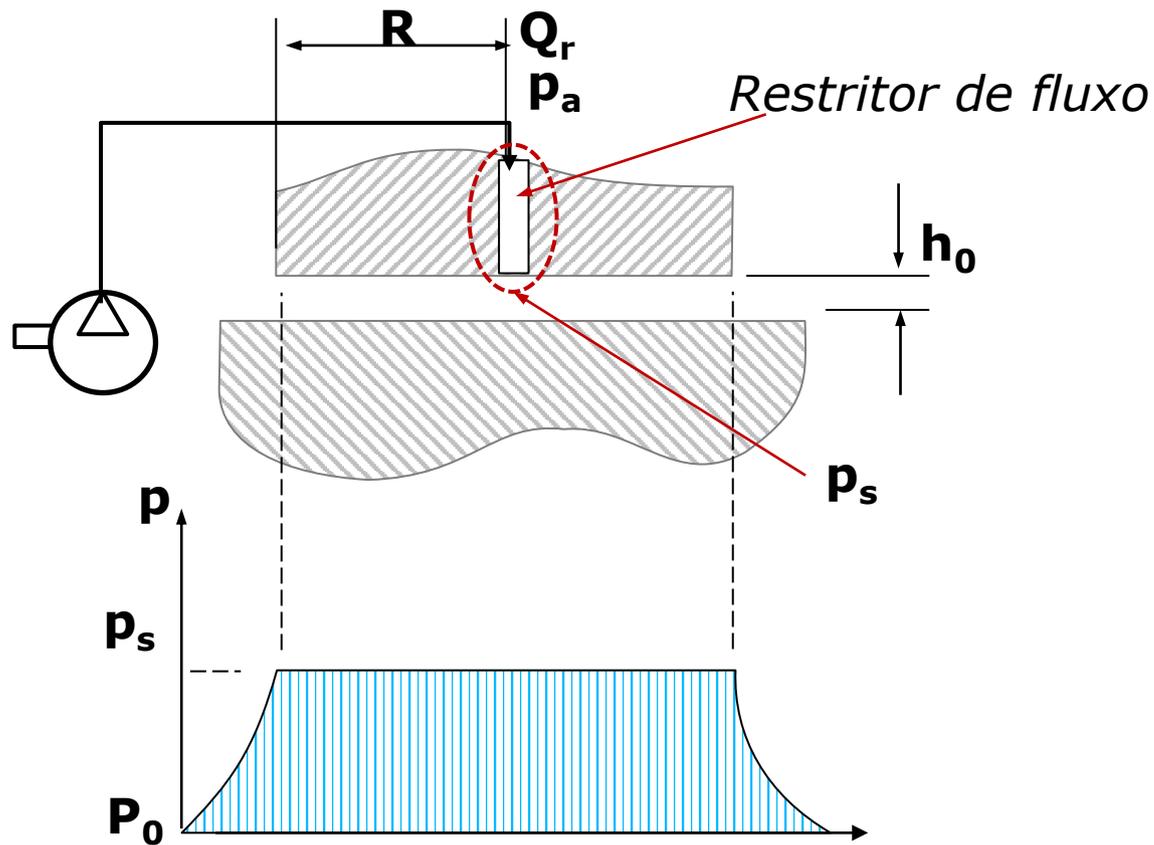


- Projeto complexo (mais do que os hidrostáticos)
- Fabricação complexa (mais do que os hidrostáticos)
- Baixa modularidade
- Sem atrito, desgaste e *stick-slip*
- Baixa capacidade de carga
- Não necessita de sistemas de retorno e resfriamento
- Baixa rigidez
- Elevado amortecimento
- Alta velocidade
- Elevada exatidão

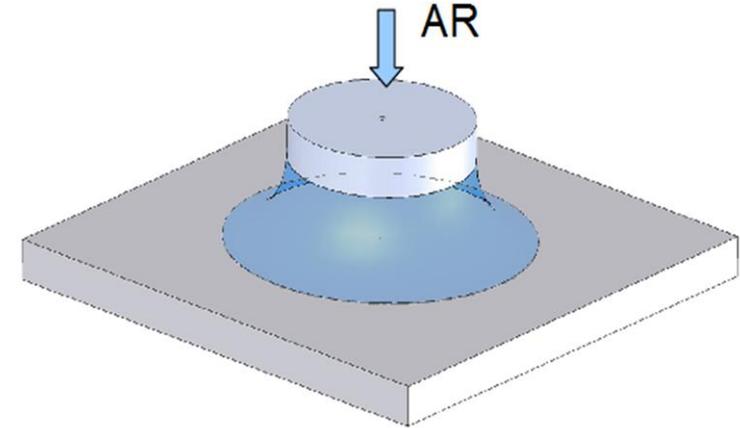
<https://www.physikinstrumente.com/en/products/air-bearings-stages/a-60x-piglidge-rt-rotary-air-bearing-module-900719/>



princípio de funcionamento



Pad circular e anular





Restritores de fluxo

Tipos

Orifício

Capilares

Flexíveis

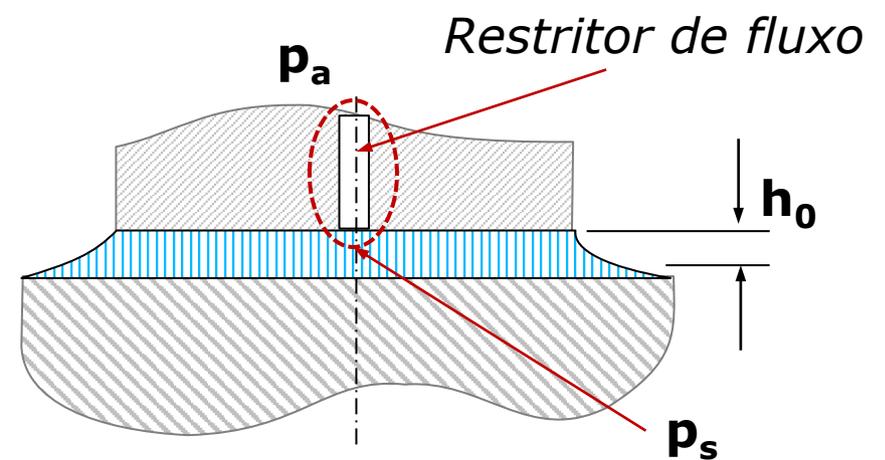
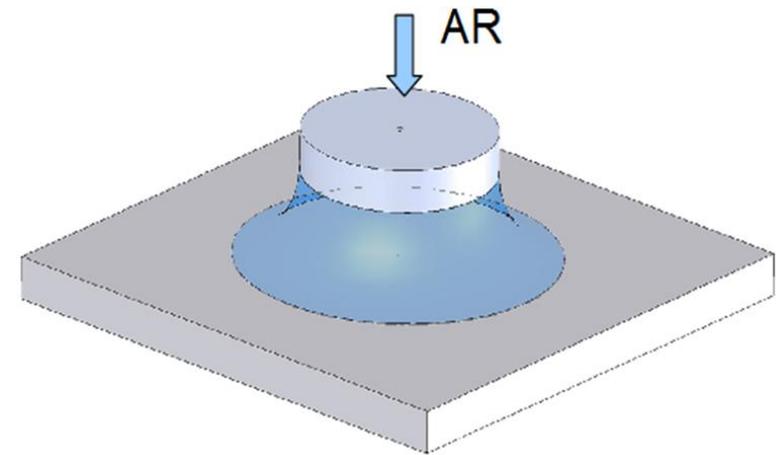
Porosos

Válvulas sensoras de pressão

Rasgo

Fluxo constante

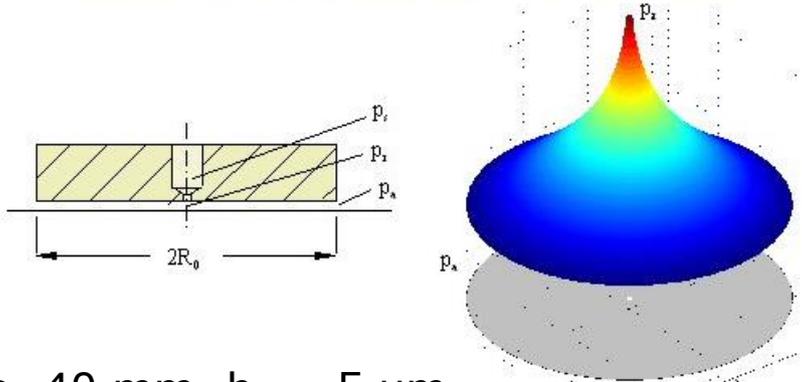
Estabilidade inerente





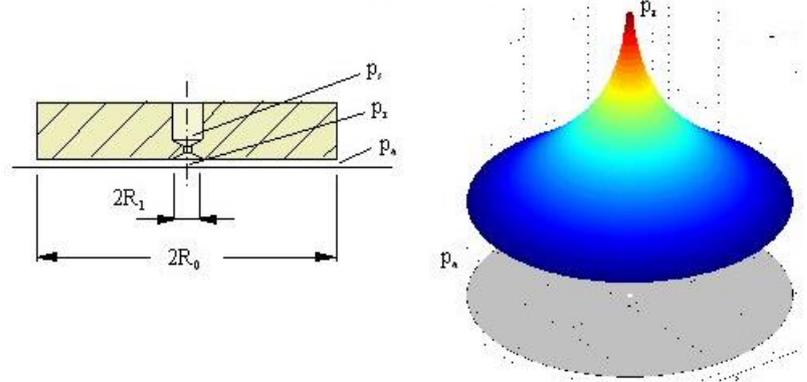
Restritores de fluxo

Aerostatic thrust bearing fed through an inherent orifice restrictor



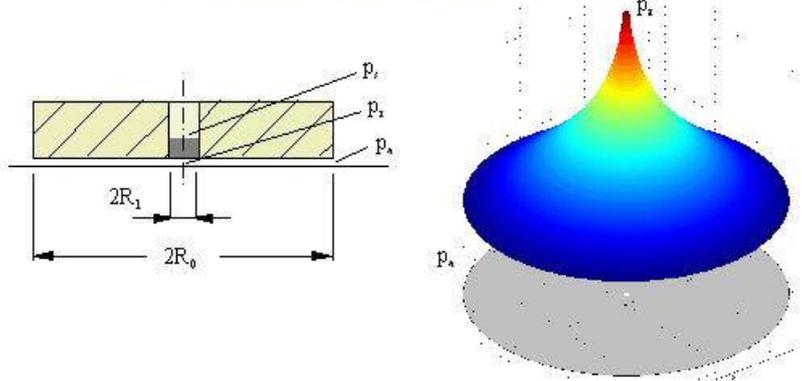
Dia. 40 mm, $h_o = 5 \mu\text{m}$
Load capacity = 46.2 N

Aerostatic thrust bearing with simple orifice restrictor



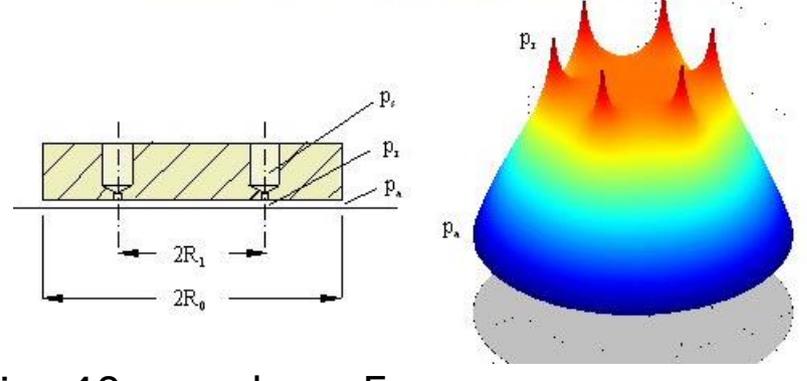
Dia. 40 mm, $h_o = 5 \mu\text{m}$
Load capacity = 91 N

Aerostatic thrust bearing with porous restrictor



Dia. 40 mm, $h_o = 5 \mu\text{m}$
Load capacity = 91 N

Aerostatic thrust bearing with grouped inherent orifices

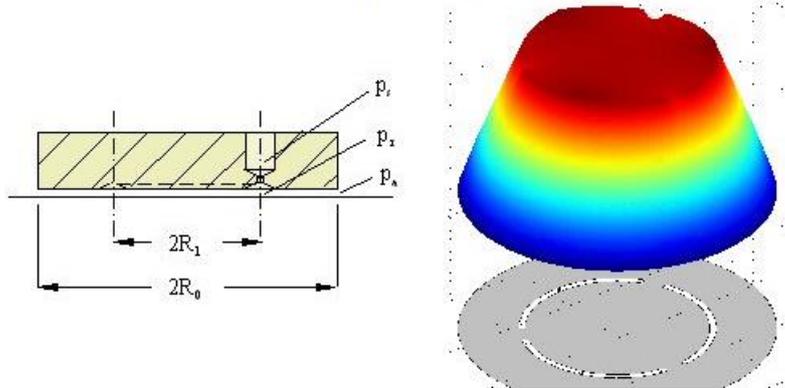


Dia. 40 mm, $h_o = 5 \mu\text{m}$
Load capacity = 150.8 N



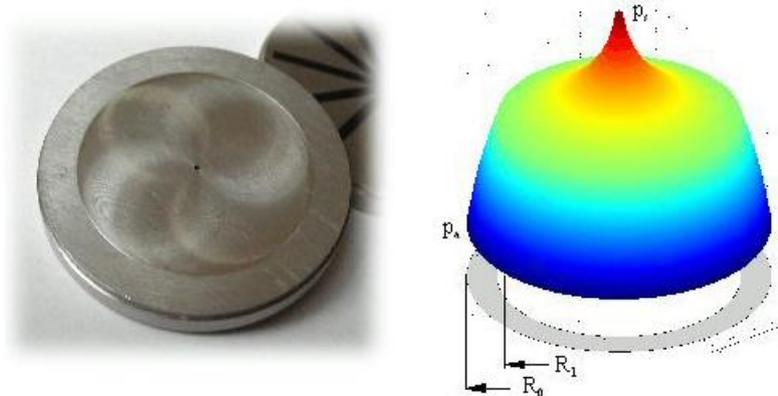
Restritores de fluxo

Aerostatic thrust bearing fed through a narrow groove



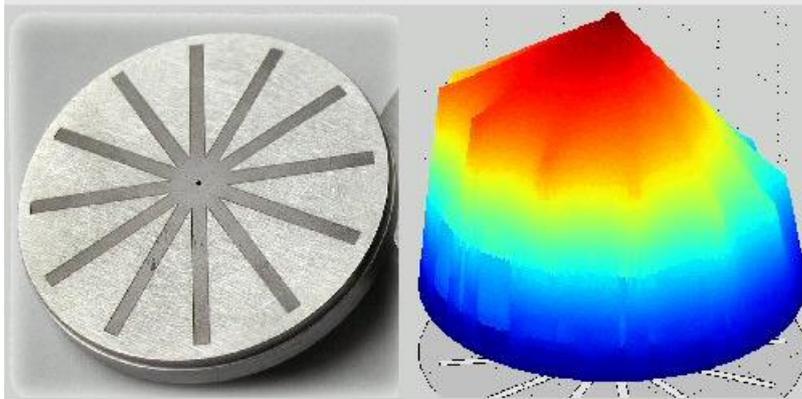
Dia. 40 mm, $h_o = 5 \mu\text{m}$
Load capacity = 208,3 N

Aerostatic shallow pocket thrust bearing



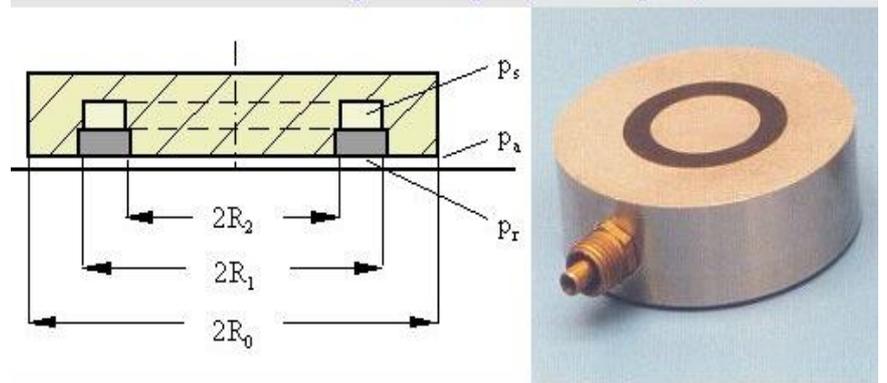
Dia. 40 mm, $h_o = 5 \mu\text{m}$
Load capacity = 240,7 N

GROOVE COMPENSATED AIR BEARINGS



Dia. 40 mm, $h_o = 5 \mu\text{m}$
Load capacity = 303,1 N

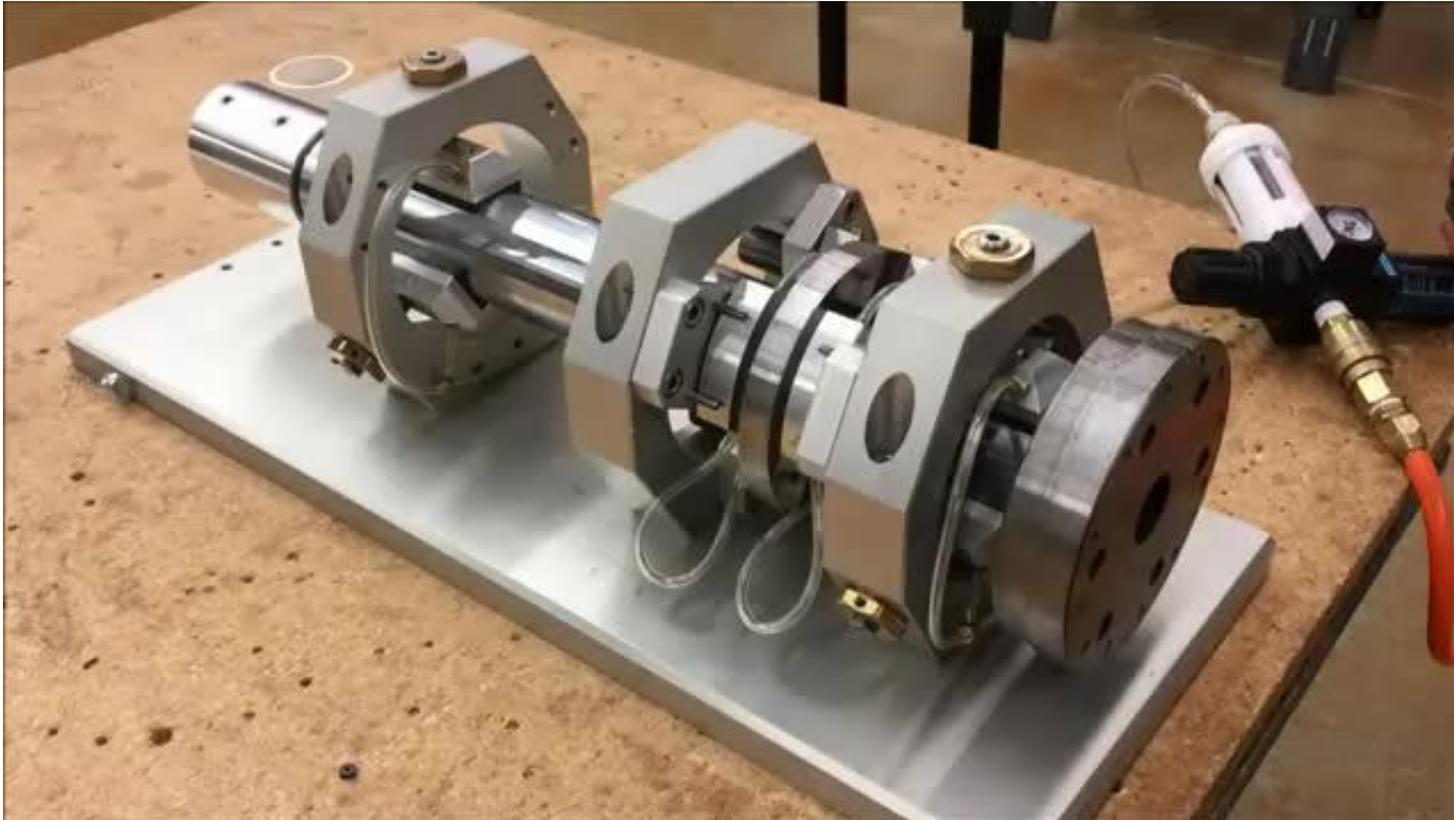
Aerostatic thrust bearing fed through a porous ring shaped area



Dia. 40 mm, $h_o = 5 \mu\text{m}$
Load capacity = 219 N



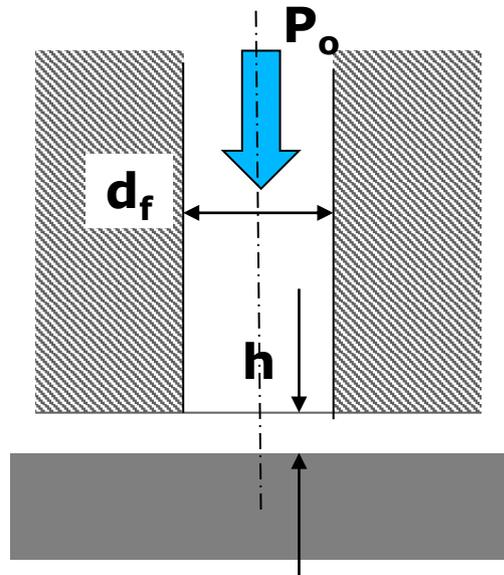
Mancais aerostáticos



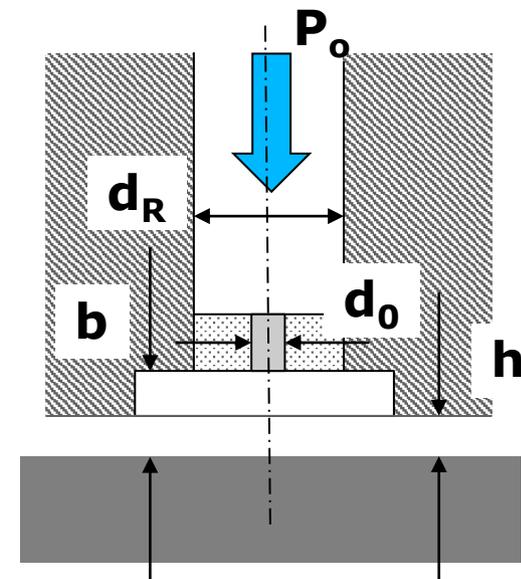


princípio de funcionamento

Análise do restritor



Orifício sem rebaixo

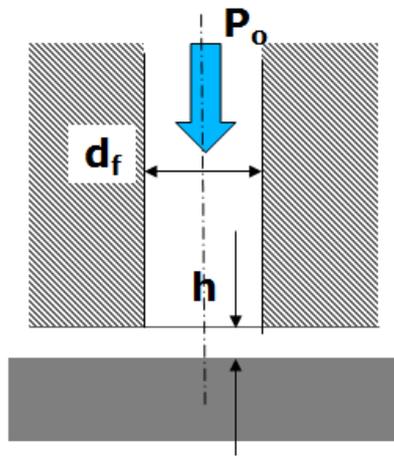


Orifício com rebaixo

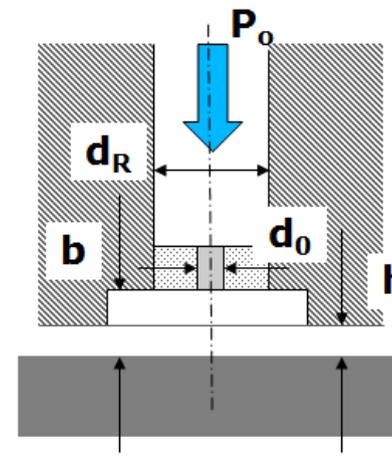


princípio de funcionamento

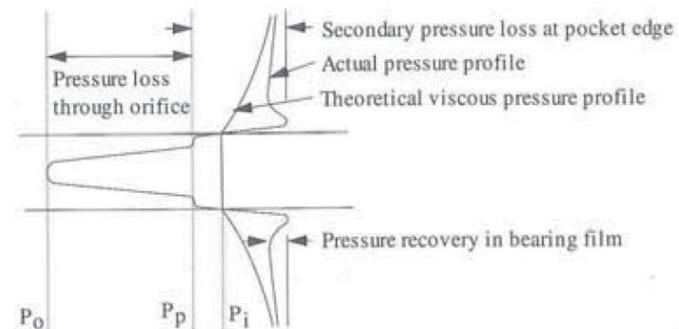
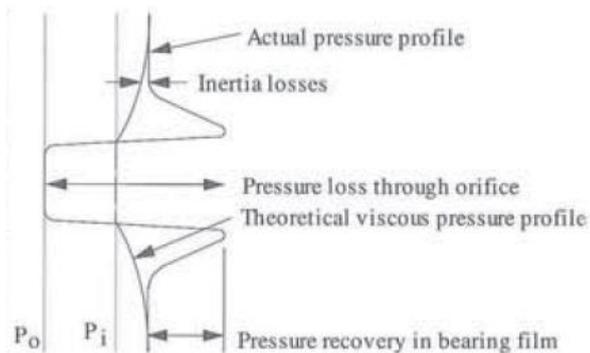
Análise do restritor



Orifício sem rebaixo



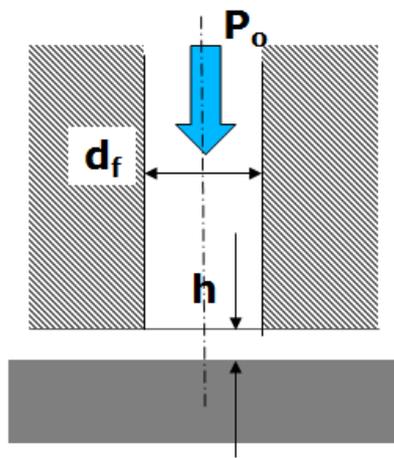
Orifício com rebaixo





princípio de funcionamento

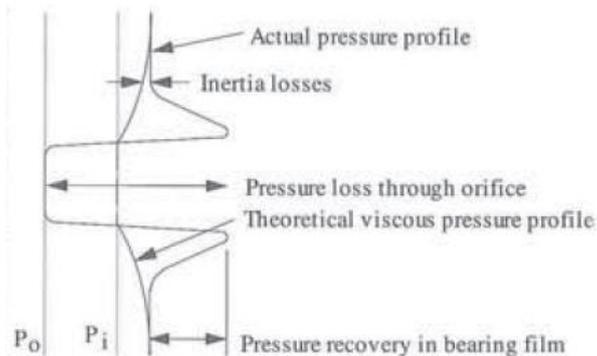
Fluxo de massa através do restritor do tipo orifício



$$\dot{m}_0 = \pi \cdot d_f \cdot h \cdot C_d \left[\frac{2\nu}{(\nu - 1)R \cdot T} \left\{ \left(\frac{P_t}{P_o} \right)^{\frac{2}{\nu}} - \left(\frac{P_t}{P_o} \right)^{\nu + \frac{1}{\nu}} \right\} \right]^{\frac{1}{2}}$$

$$\dot{m}_0 = 7,48 \times 10^4 \cdot C_d \cdot d_f \cdot h \cdot \frac{P_o}{P_a}$$

Diferença de pressão

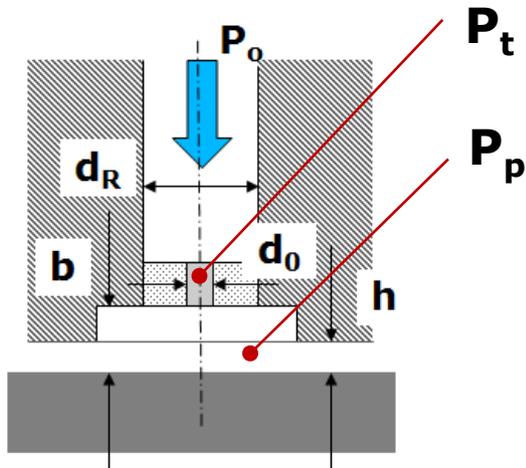


$$\frac{P_t}{P_o} = \left[\frac{2\nu}{(\nu + 1)} \right] \frac{\nu}{\nu - 1}$$



princípio de funcionamento

Fluxo de massa através do restritor com rebaixo



$$\dot{m}_0 = \frac{\pi \cdot d_0^2 \cdot P_0 \cdot C_d}{4\sqrt{1 - \delta_L^2}} \left[\frac{2\nu}{(\nu - 1)R \cdot T} \left\{ \left(\frac{P_t}{P_0}\right)^{\frac{2}{\nu}} - \left(\frac{P_t}{P_0}\right)^{\nu + \frac{1}{\nu}} \right\} \right]^{\frac{1}{2}}$$

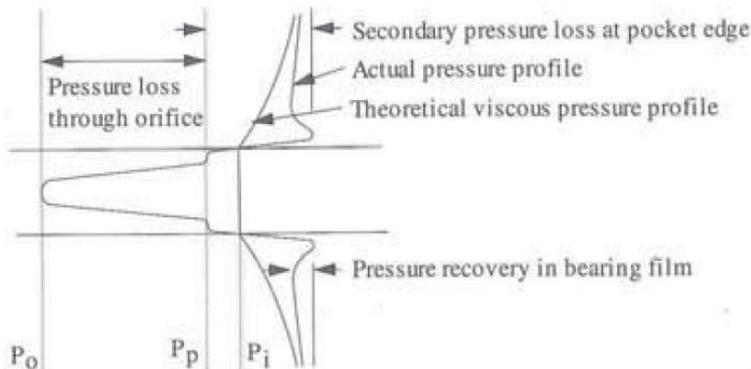
$$\dot{m}_0 = 1,87 \times 10^4 \cdot C_d \cdot d_0^2 \cdot \frac{P_0}{P_a}$$

Diferença de pressão

$$\frac{P_p}{P_0} = \left[\frac{2\nu}{(\nu + 1)} \right]^{\frac{\nu}{\nu - 1}}$$

Fator de compensação

$$\delta_L = \frac{d_o}{4 \cdot d_R \cdot h}$$



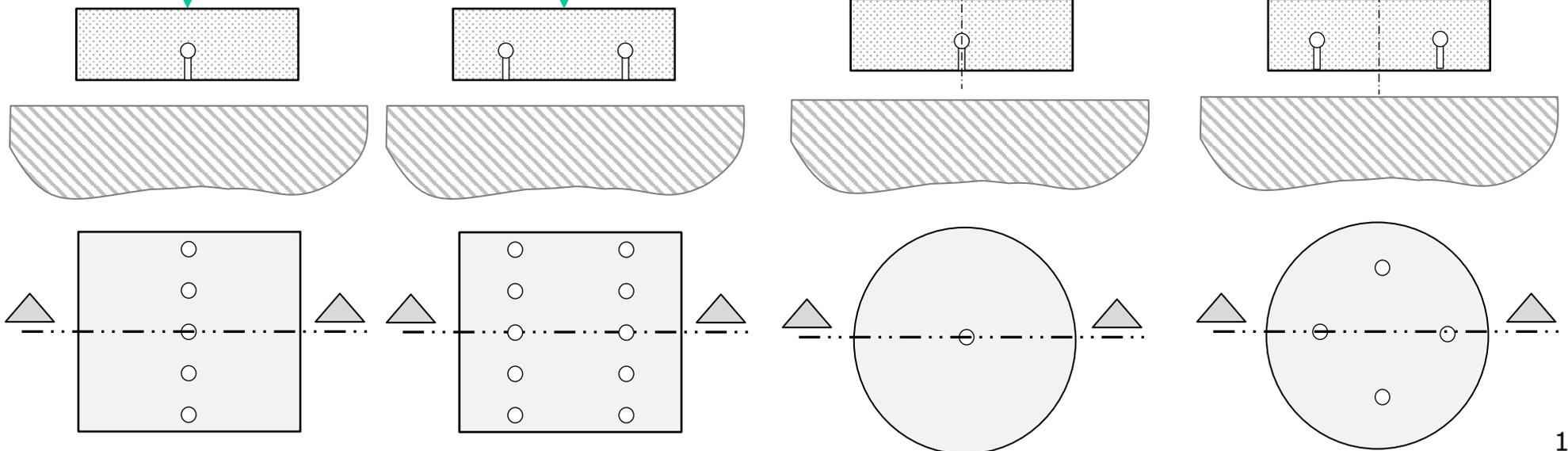


Guias aerostáticas

Pads / Sapatas

Retangulares

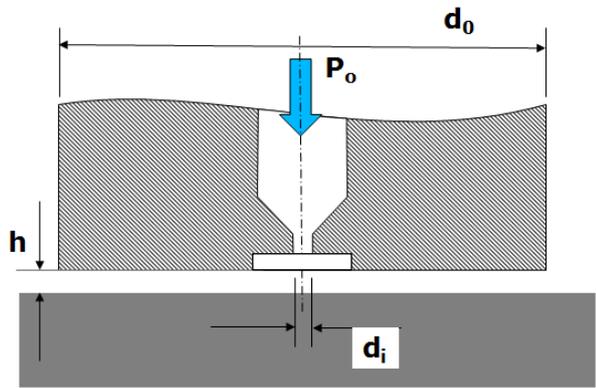
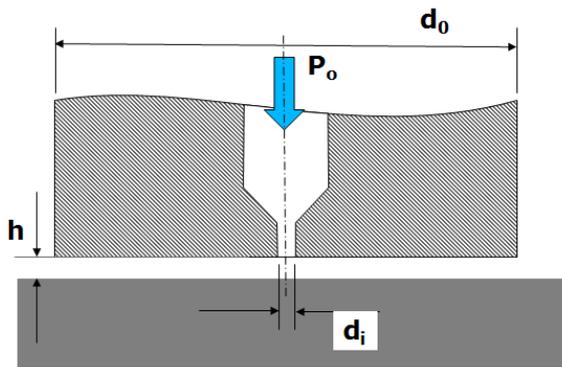
Circulares





Princípio de funcionamento

Mancais de sapata circular



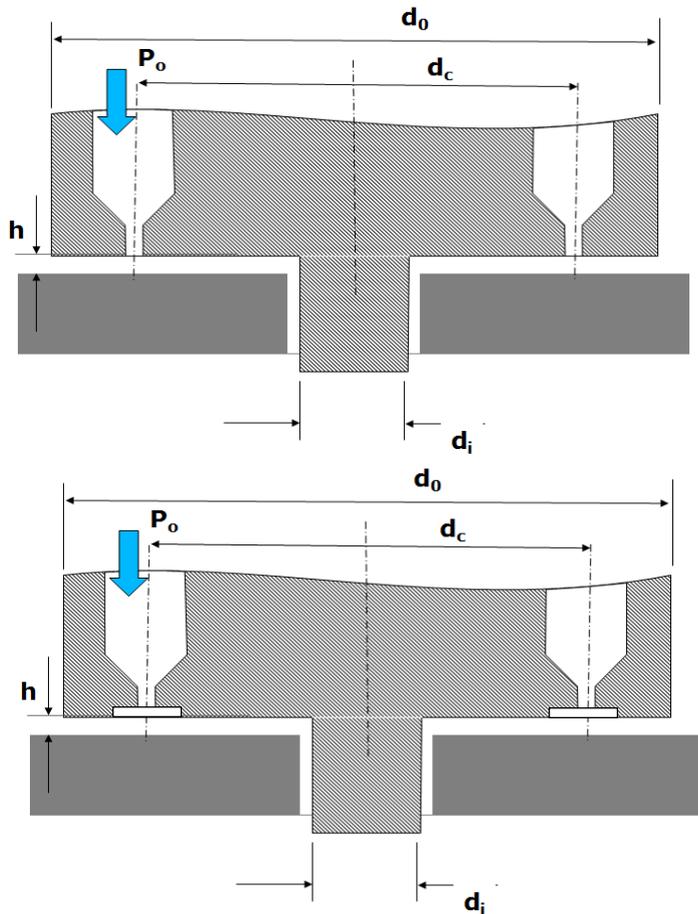
$$\frac{R_o}{R_i} = 20 \Rightarrow \text{recomendação}$$

Parameter	Pocketed orifices	Inherently compensated orifice
Max. stiffness (N/μm)	$K = \frac{0.27\pi R_o^2 (P_o - P_a)}{h_o}$	$K = \frac{0.18\pi R_o^2 (P_o - P_a)}{h_o}$
Max. Load (N) @ $\epsilon = 0$		$W = 0.15\pi R_o^2 (P_o - P_a)$
Max. Load (N) @ $\epsilon = -0.25$		$W = 0.21\pi R_o^2 (P_o - P_a)$
Max. Load (N) @ $\epsilon = 0.25$		$W = 0.11\pi R_o^2 (P_o - P_a)$
Air flow rate (m ³ /s)	$Q = \frac{0.34 h_o^3 P_o^2}{3.42 \times 10^6 \times 2\log_e(R_o/R_i)}$	
Orifice diameter (mm)	$d_o = \sqrt{\frac{\Lambda_s \xi P_o h_o^3}{7890 \times 2\log_e(R_o/R_i)}}$	$d_f = \frac{\Lambda_s \xi P_o h_o^2}{31.55 \times 2\log_e(R_o/R_i)}$
Pocket depth (mm)	$b \leq \frac{0.05h_o}{(R_i/R_o)^2 \times 10^3}$	Not applicable
Pocket compensation when:	$\frac{125d_o^2}{R_i h_o} < 0.5$	Not applicable



Princípio de funcionamento

Mancal anular

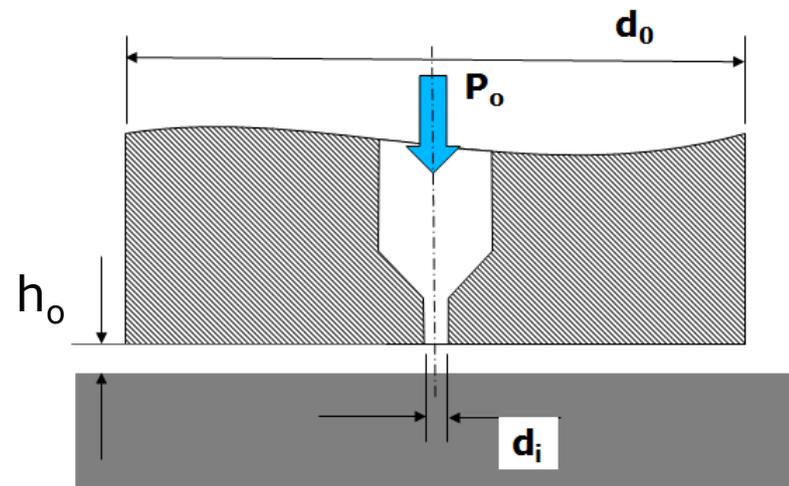


Parameter	Pocketed orifices	Inherently compensated orifice
Max. stiffness (N/μm)	$K = \frac{0.44\pi(R_o^2 - R_i^2) (P_o - P_a)}{h_o}$	$K = \frac{0.29\pi(R_o^2 - R_i^2) (P_o - P_a)}{h_o}$
Max. angular stiffness (Nm/rad)	$K_A = \frac{0.23\pi(R_o^2 - R_i^2)R_oR_i (P_o - P_a)}{h_o}$	
Max. load (N) @ $\epsilon = 0$	$W = 0.26\pi(R_o^2 - R_i^2) (P_o - P_a)$	
Max. load (N) @ $\epsilon = -0.25$	$W = 0.37\pi(R_o^2 - R_i^2) (P_o - P_a)$	$W = 0.35\pi(R_o^2 - R_i^2) (P_o - P_a)$
Max. load (N) @ $\epsilon = 0.25$	$W = 0.18\pi(R_o^2 - R_i^2) (P_o - P_a)$	$W = 0.20\pi(R_o^2 - R_i^2) (P_o - P_a)$
Air flow rate (m ³ /s)	$Q = \frac{0.27 h_o^3 P_o^2}{3.42 \times 10^6 \times 2 \log_e(R_o/R_i)}$	
Orifice diameter (mm)	$d_o = \sqrt{\frac{\Lambda_s \xi P_o h_o^3}{7890 \times n \times 0.5 \log_e(R_o/R_i)}}$	$d_f = \frac{\Lambda_s \xi P_o h_o^2}{31.55 \times n \times 0.5 \log_e(R_o/R_i)}$
Pocket depth (mm)	$b \leq \frac{0.2(R_o^2 - R_i^2)h_o}{nd_R^2 \times 10^3}$	Not applicable
Pocket compensation when:	$\frac{R_o^2 \times 10^3}{d_R h_o} < 0.5$	Not applicable



Exemplo de dimensionamento

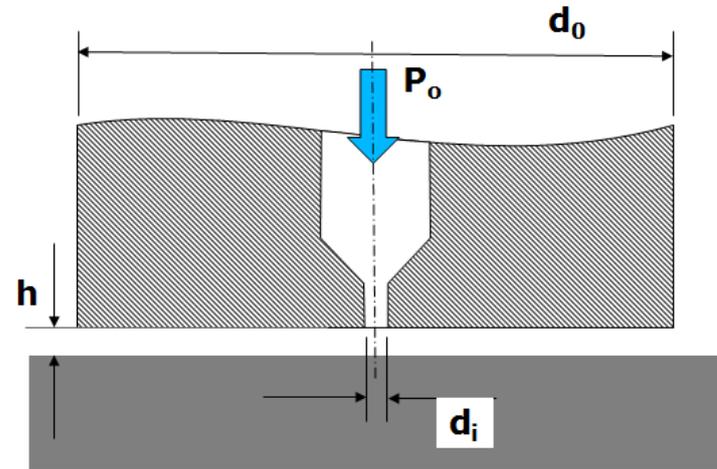
- Uma sapata circular aerostática de 140mm de diâmetro deve ser projetada para suportar 700N de carga, e ter uma rigidez de $70\text{N}/\mu\text{m}$.
- Dado que a razão de pressão $P_o/P_a = 5$, $h_o = 20\mu\text{m}$.
- Determinar a rigidez teórica e compare com a especificada, determine o consumo de AR e determine o diâmetro do restritor.





Exemplo de dimensionamento

- $d_o = 140\text{mm}$, $R_o = 70\text{mm}$
- $K_{proj} = 70\text{N}/\mu\text{m}$
- $P_o/P_a = 5$ (atm)
- $P_a = 1$ atm
- $h_o = 20\mu\text{m}$



$$K_{\max} = \frac{0,27 \cdot \pi \cdot R_o^2 (P_o - P_a)}{h_o}$$

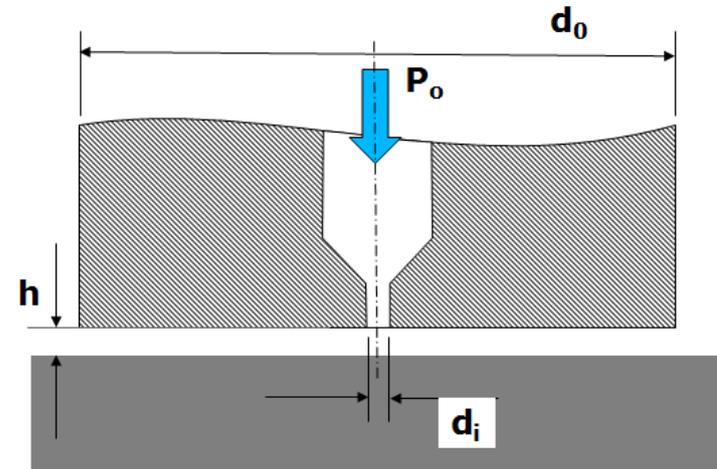
$$K_{\max} = \frac{0,27 \cdot \pi \cdot (70)^2 (0,405 \text{ N/mm}^2)}{20}$$

$$K_{\max} = 84,17 \text{ N}/\mu\text{m} \quad \longleftrightarrow \quad K_{proj} = 70 \text{ N}/\mu\text{m}$$



Exemplo de dimensionamento

- $d_0 = 140\text{mm}$, $R_0 = 70\text{mm}$
- $K_{\text{proj}} = 70\text{N}/\mu\text{m}$
- $P_0/P_a = 5$ (atm)
- $P_a = 1$ atm
- $h_0 = 20\mu\text{m}$



$$Q = \frac{0,34 \cdot h_0^3 \cdot P_0^2}{3,24 \times 10^{-6} \cdot 2 \log_e \left(\frac{R_0}{R_i} \right)}$$

$$Q = 3,4 \times 10^{-5} \text{m}^3/\text{s}$$

$$\frac{R_0}{R_i} = 20 \Rightarrow \text{recomendação}$$



Exemplo de dimensionamento

- $d_0 = 140\text{mm}$,
- $R_0 = 70\text{mm}$
- $K_{\text{proj}} = 70\text{N}/\mu\text{m}$
- $P_0/P_a = 5$ (atm)
- $P_a = 1$ atm
- $h_0 = 20\mu\text{m}$
- $d_f = ?$

$$d_f = \frac{\Lambda_s \cdot \xi \cdot P_0 \cdot h_0^2}{31,55 \times 10^6 \cdot 2 \log_e \left(\frac{R_0}{R_i} \right)}$$

$$\Lambda_s \cdot \xi = \text{????}$$

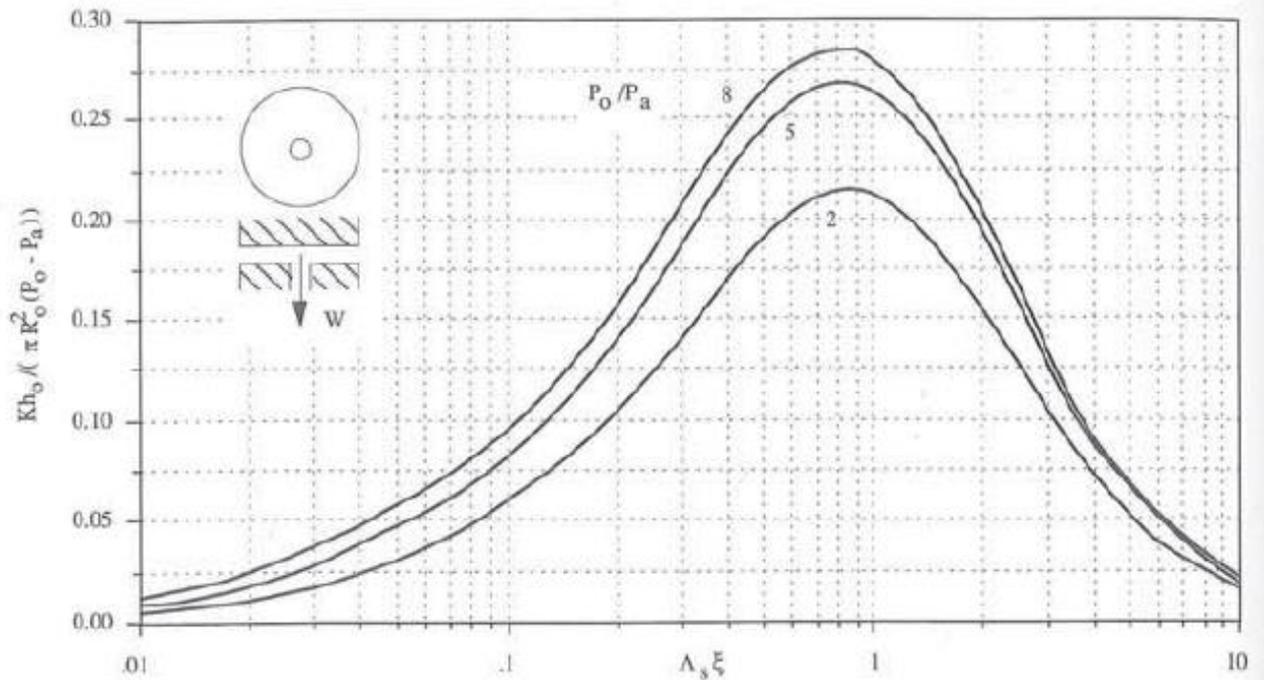


Figure 9.3.28 Pocketed circular thrust bearing stiffness where $R_i/R_0 = 0.05$, $C_d = 0.8$, and $\nu = 1.4$. For inherently compensated bearings, multiply the ordinate by $2/3$.



Exemplo de dimensionamento

$$\frac{K \cdot h_0}{\pi \cdot R_0^2 (P_0 - P_a)} = \frac{70 \text{ N} \cdot \mu\text{m}^{-1} \cdot 20 \mu\text{m}}{\pi \cdot 70^2 (0,405 \text{ N/mm}^2)}$$

$$\frac{K \cdot h_0}{\pi \cdot R_0^2 (P_0 - P_a)} = 0,27$$

$$\frac{P_0}{P_a} = 5 \text{ atm}$$

$$d_f = \frac{\Lambda_s \cdot \xi \cdot P_0 \cdot h_0^2}{31,55 \times 10^6 \cdot 2 \log_e \left(\frac{R_o}{R_i} \right)}$$

$$\Lambda_s \cdot \xi = 0,85$$

$$d_f = \frac{0,85 \cdot 0,506 \text{ N} \cdot \text{mm}^{-2} \cdot (20 \times 10^{-3})^2 \text{ mm}^2}{31,55 \times 10^6 \cdot 2 \log_e (20)}$$

$$d_f = 0,91 \text{ mm}$$

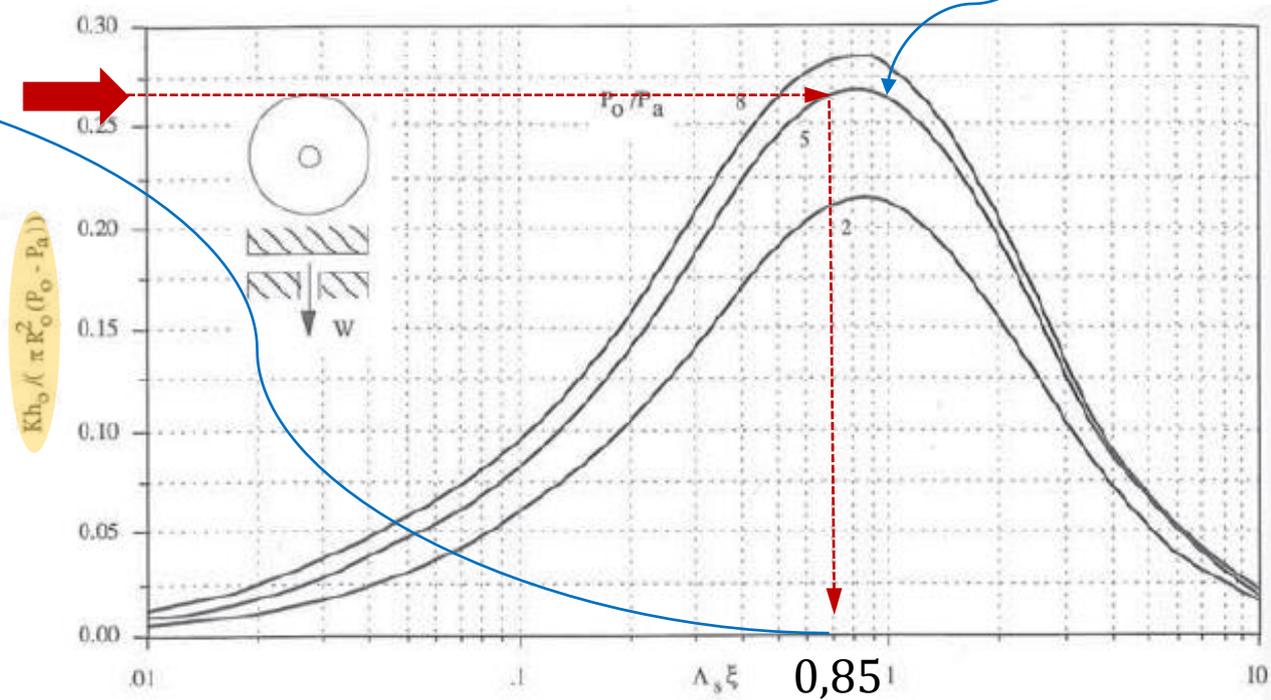
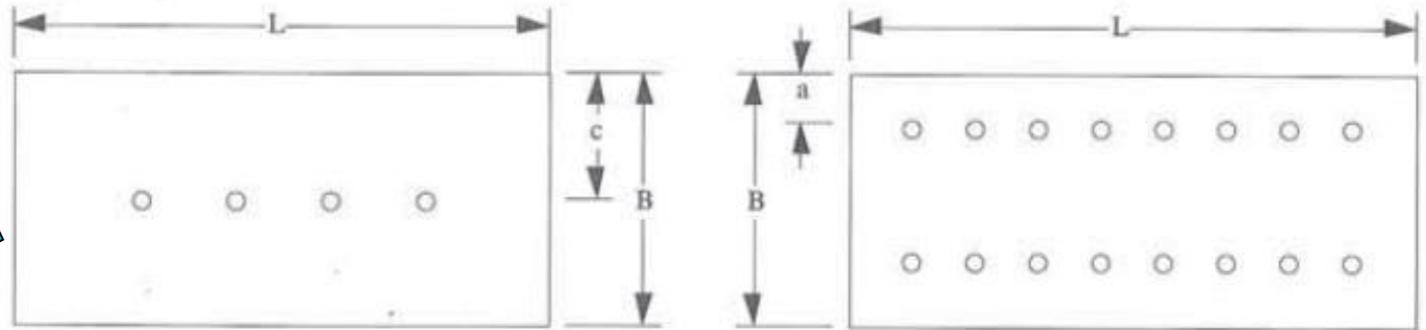
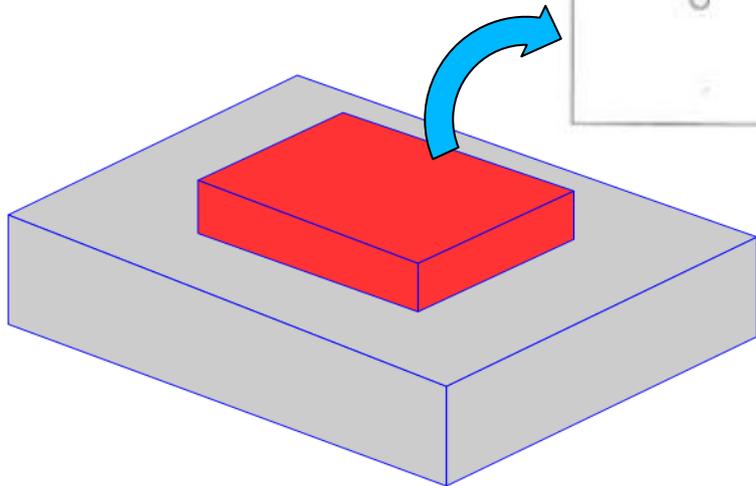


Figure 9.3.28 Pocketed circular thrust bearing stiffness where $R_i/R_o = 0.05$, $C_d = 0.8$, and $\nu = 1.4$. For inherently compensated bearings, multiply the ordinate by $2/3$.



Sapatas aerostáticas retangulares



$$\frac{\pi B}{L} \quad (\text{single entry bearings}) \quad (9.3.42a)$$

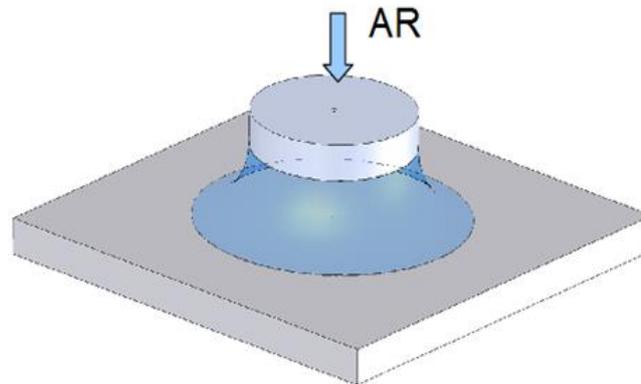
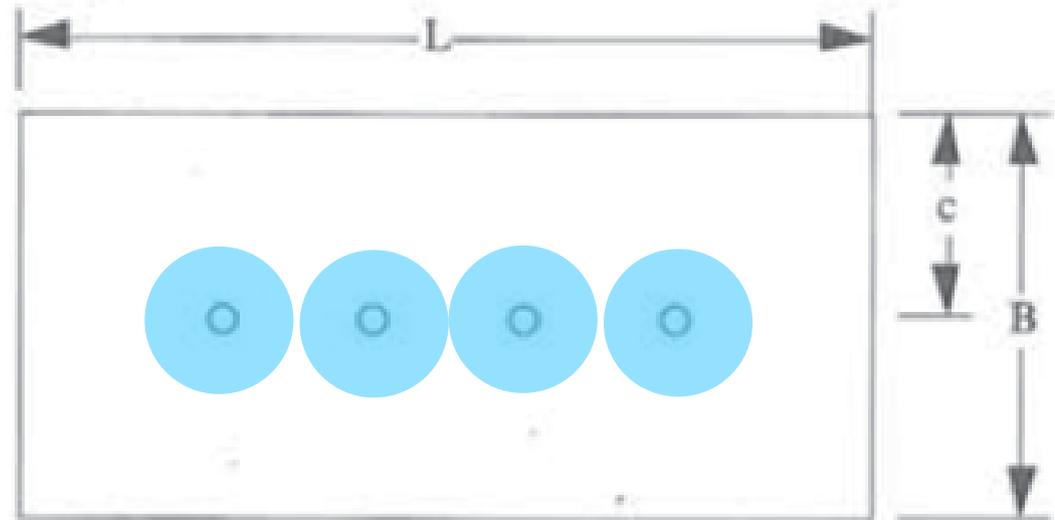
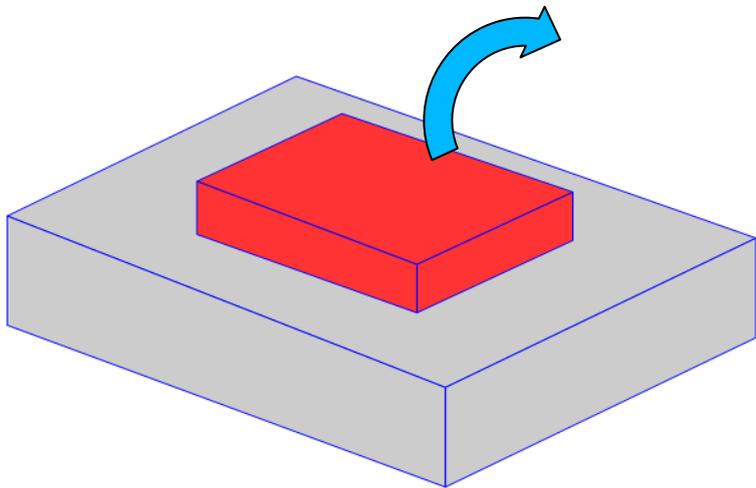
$$\xi = \frac{\pi 2a}{L} \quad (\text{double entry bearings}) \quad (9.3.42b)$$

- n = number of orifices per row.
- N = number of orifices per bearing (where there are two rows of inlets N = 2n).
- d = d_f for inherently compensated bearings
- d = d_R for pocket-compensated bearings



Sapatas aerostáticas retangulares

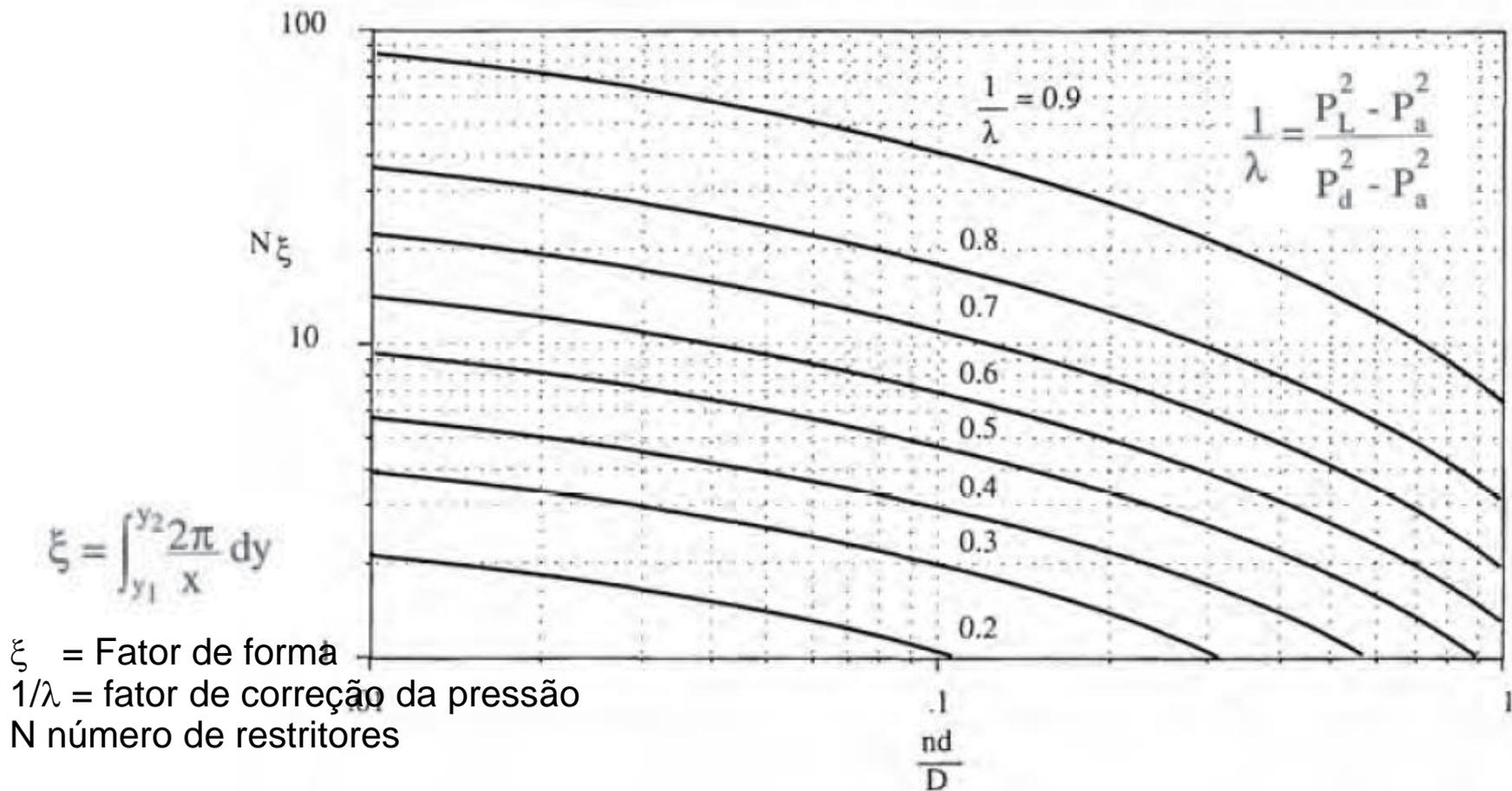
Aproximação por sapatas unitárias circulares





Sapatas aerostáticas retangulares

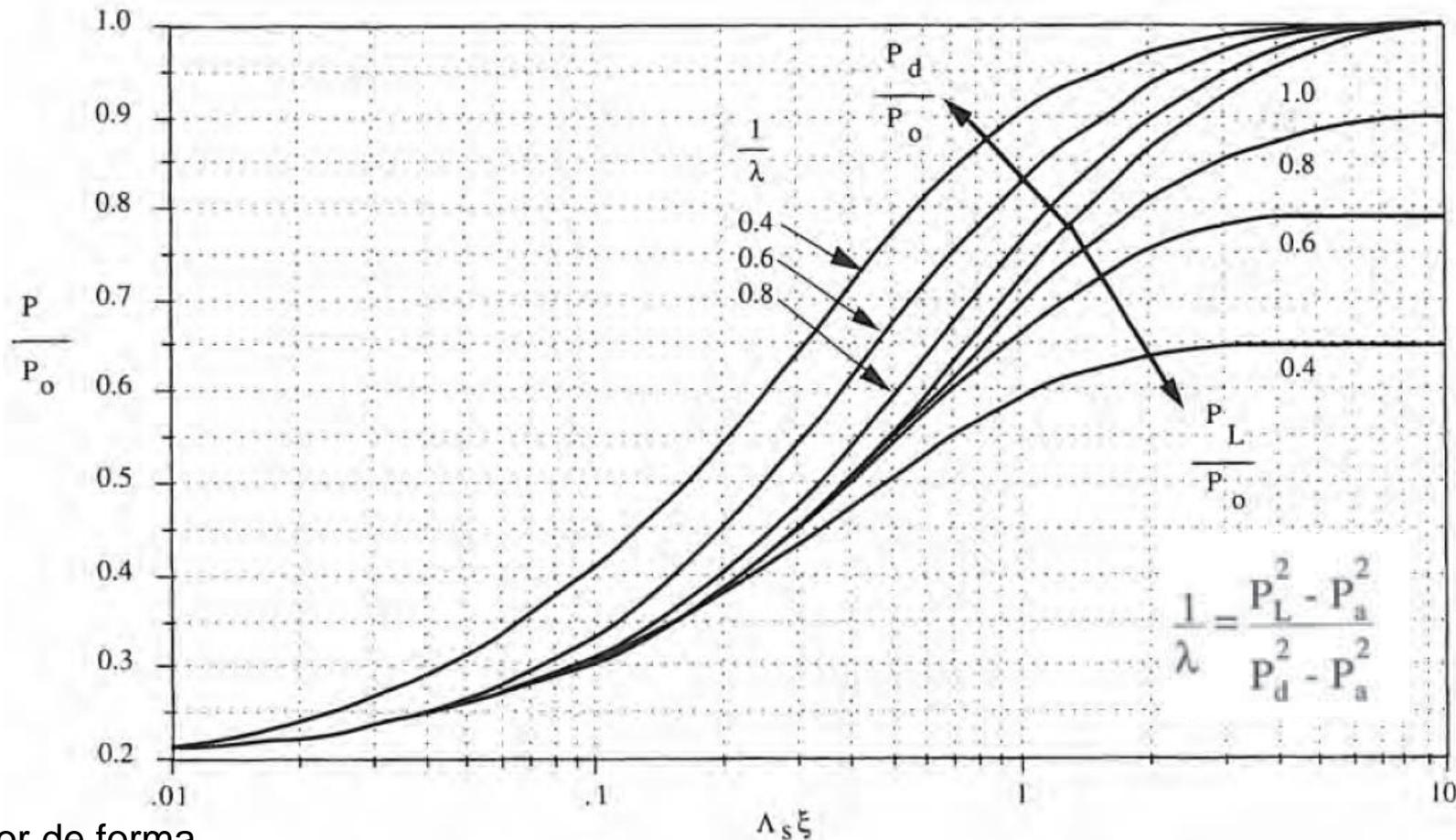
dimensionamento





Sapatas aerostáticas retangulares

dimensionamento



ξ = Fator de forma

$1/\lambda$ = fator de correção da pressão

N número de restritores



Guias aerostáticas - dimensionamento

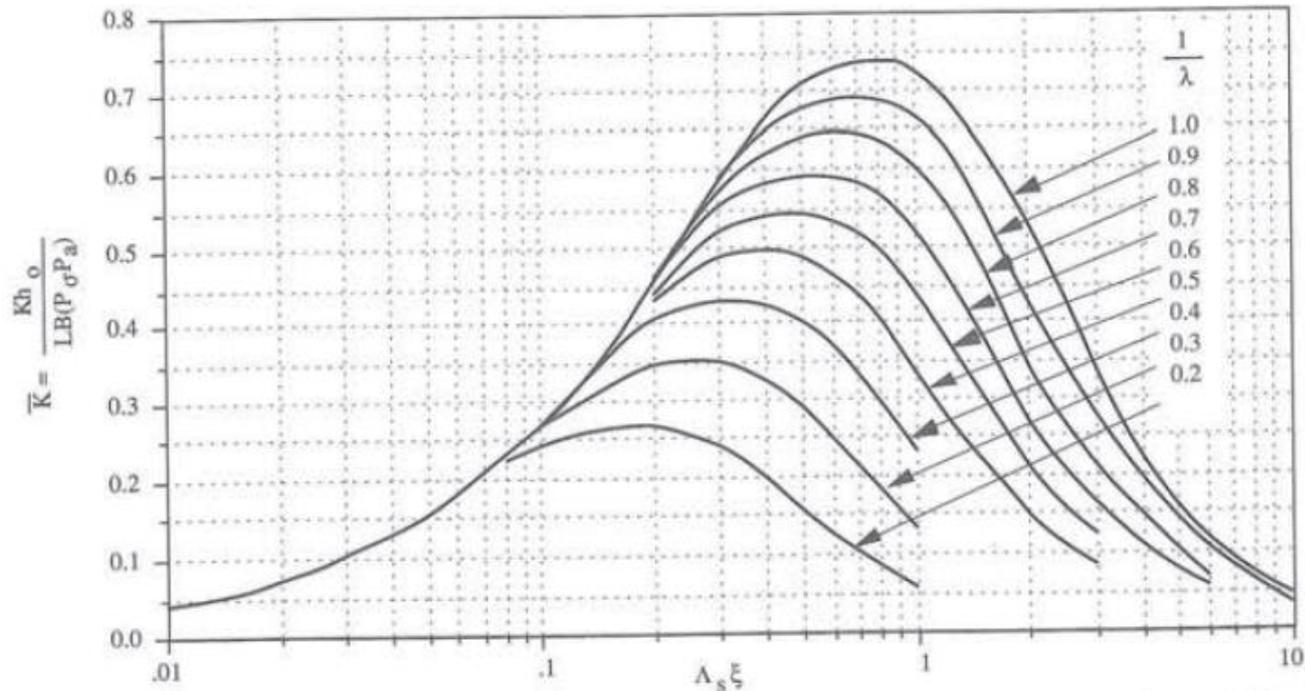


Figure 9.3.32 Stiffness parameter for rectangular double-entry thrust bearings with pocketed orifices where $a/B = 0.25$, $P_0/P_a = 5$, $C_d = 0.8$, and $\nu = 1.4$. For inherently compensated orifices, multiply the ordinate by 0.67. For single-entry bearings, multiply the ordinate by 0.75.

\bar{K} = parâmetro adimensional de rigidez

$\Lambda_s \xi$ = Fator de alimentação (feeding parameter)

$1/\lambda$ = fator de correção da pressão

N = número de restritores

$$\Lambda_s \xi = \frac{31.55 n d_r \pi B}{P_o h_o^2 L}$$



Guias aerostáticas - dimensionamento

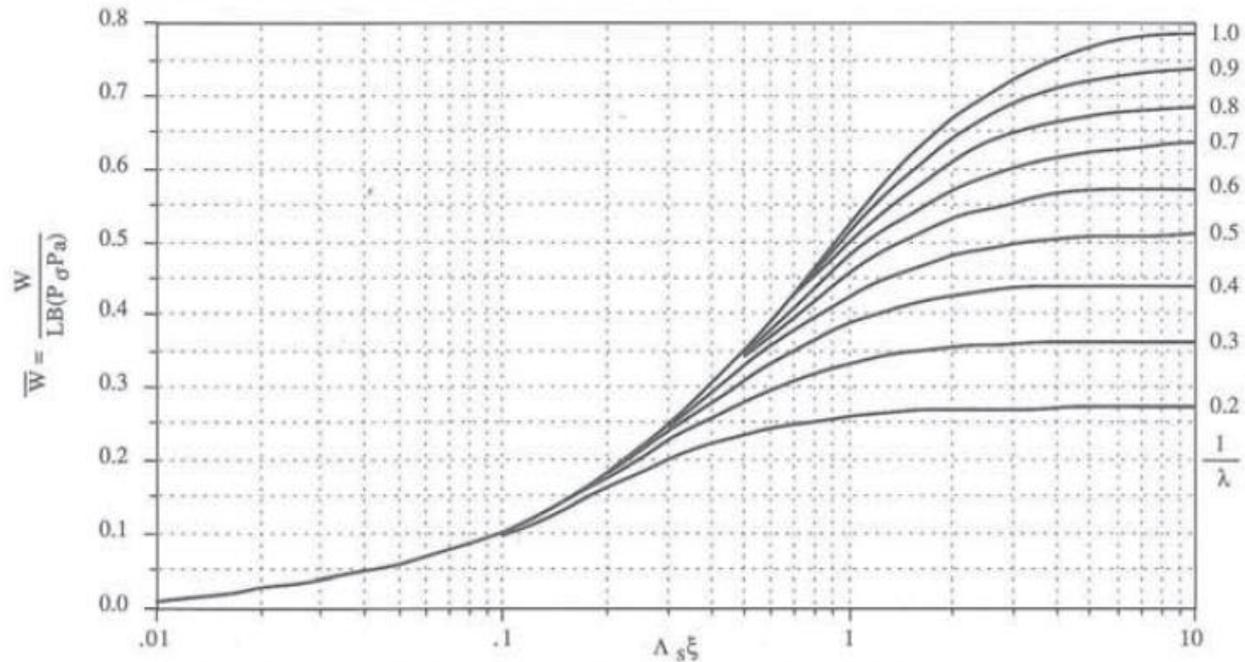


Figure 9.3.33 Load parameter for rectangular double-entry thrust bearings with pocketed orifices where $\varepsilon = 0$, $a/B = 0.25$, $P_0/P_a = 5$, $C_d = 0.8$, and $\nu = 1.4$. For single-entry bearings, multiply the ordinate by 0.75.

\bar{K} = parâmetro adimensional de rigidez

$\Lambda_s \xi$ = Fator de alimentação (feeding parameter)

$1/\lambda$ = fator de correção da pressão

N = número de restritores

$$\Lambda_s \xi = \frac{31.55 n d_r \pi B}{P_0 h_o^2 L}$$



Guias aerostáticas - dimensionamento

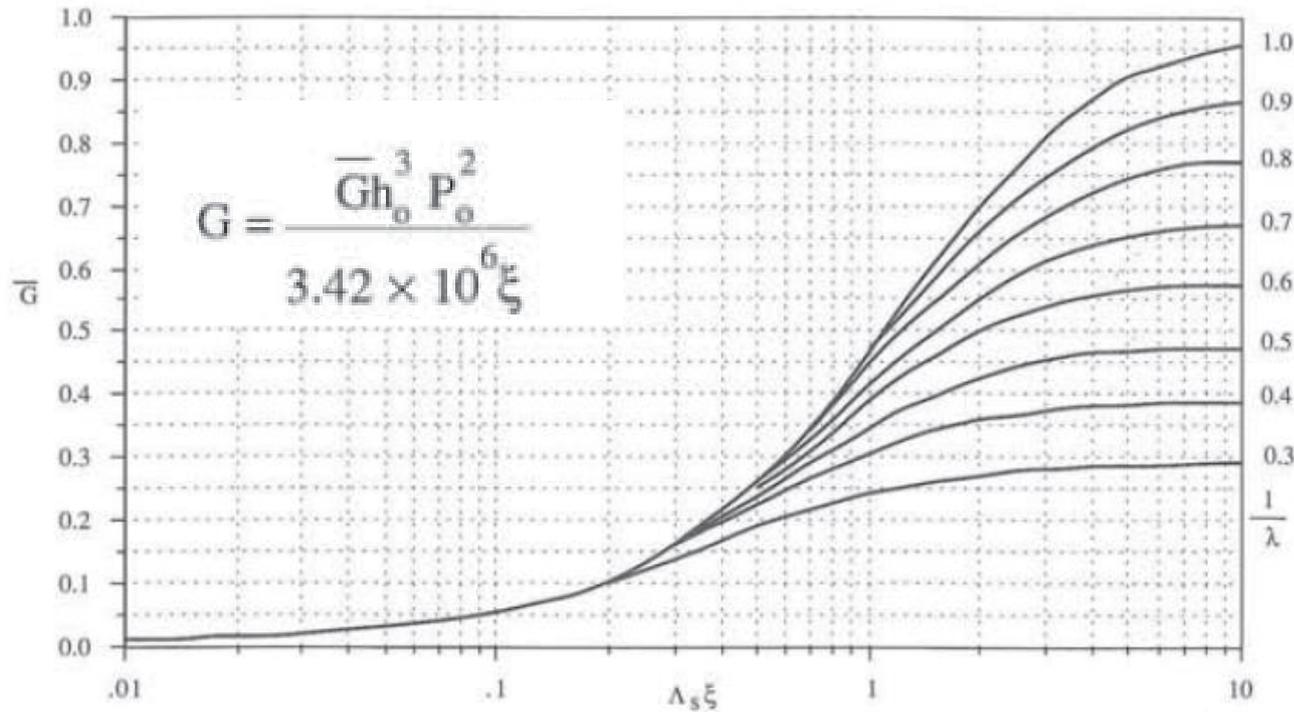


Figure 9.3.34 Nondimensional flow rate for rectangular double-entry thrust bearings with pocketed orifices where $a/B = 0.25$, $P_o/P_a = 5$, $C_d = 0.8$, and $\nu = 1.4$. For single-entry bearings, multiply the ordinate by 0.5.

\bar{K} = parâmetro adimensional de rigidez

$\Lambda_s \xi$ = Fator de alimentação (feeding parameter)

$1/\lambda$ = fator de correção da pressão

N = número de restritores

$$\Lambda_s \xi = \frac{31.55 n d_f \pi B}{P_o h_o^2 L}$$



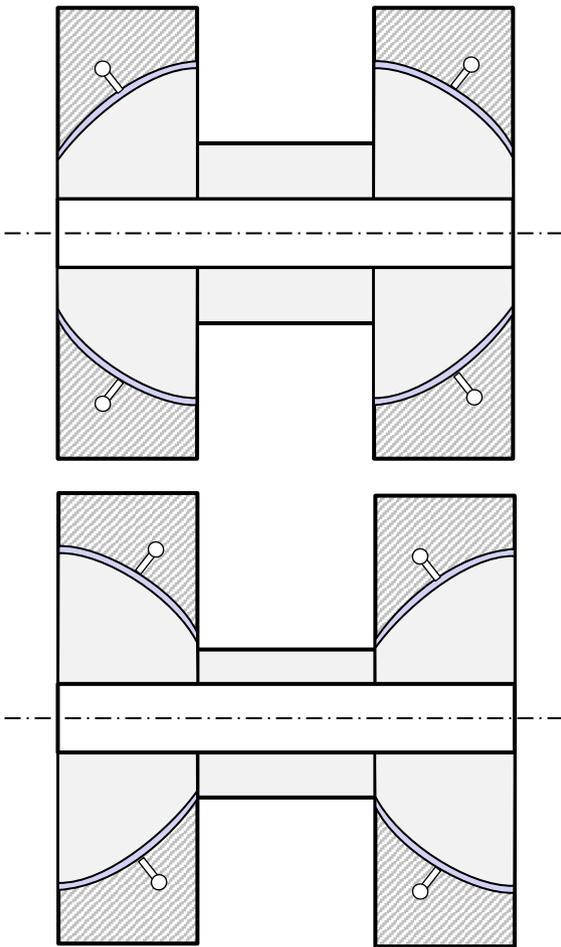


PI

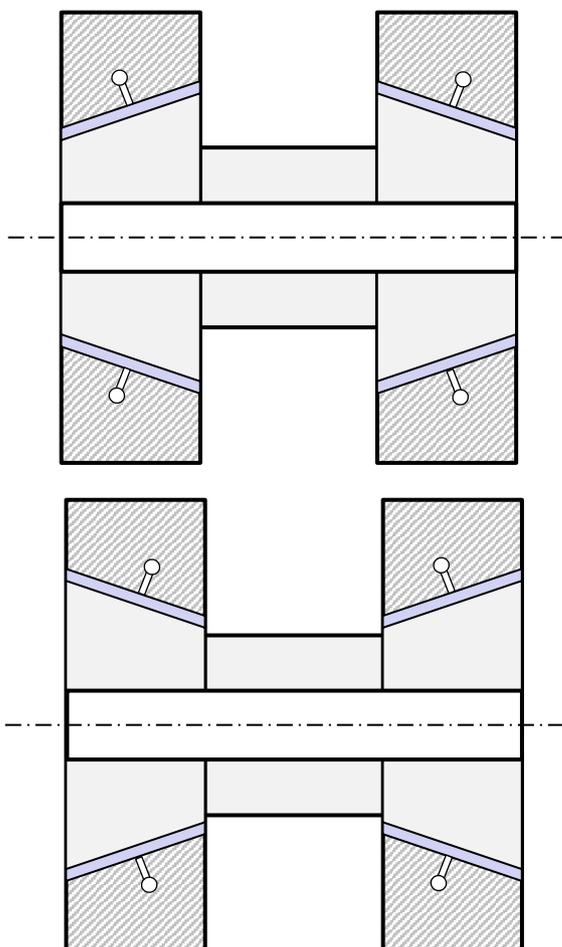


Formas construtivas

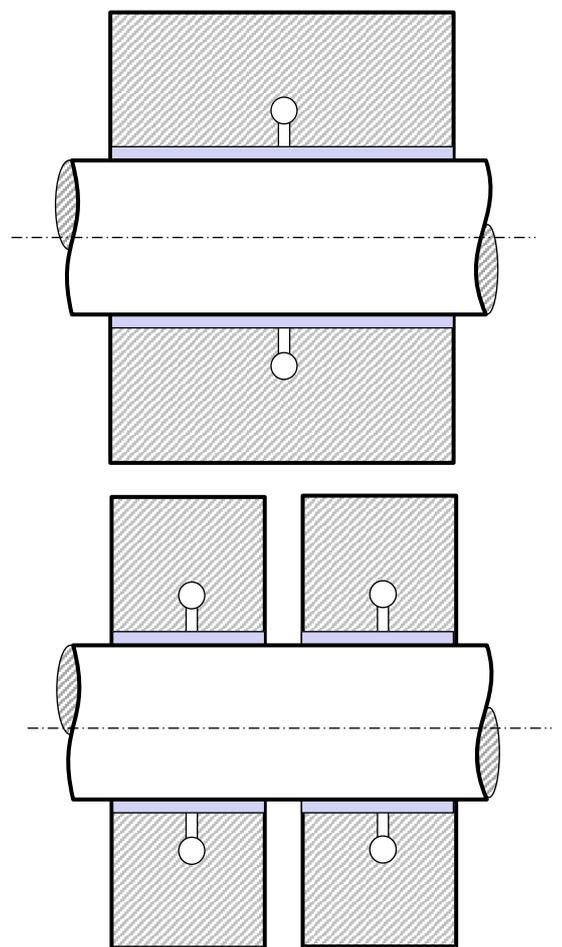
Semiesférico



Cônicos



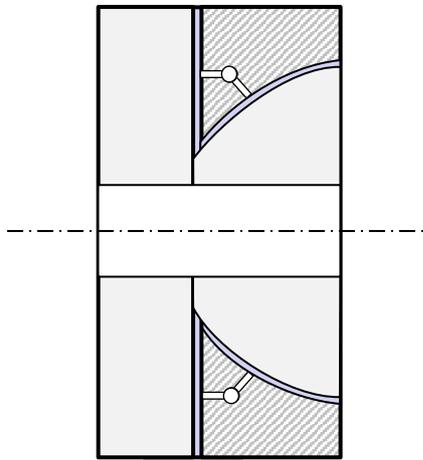
Cilíndricos



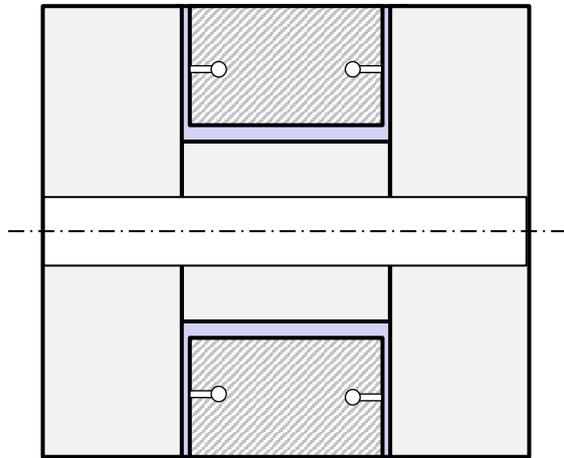


Formas construtivas

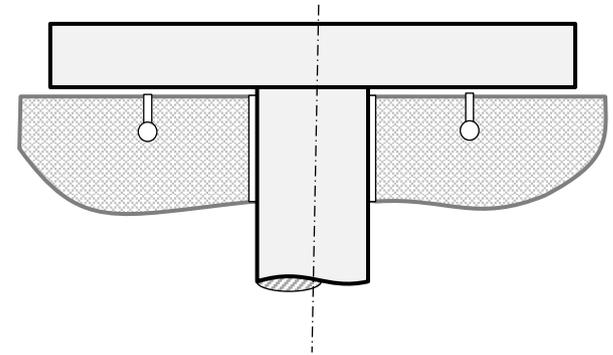
Semiesférico / plano



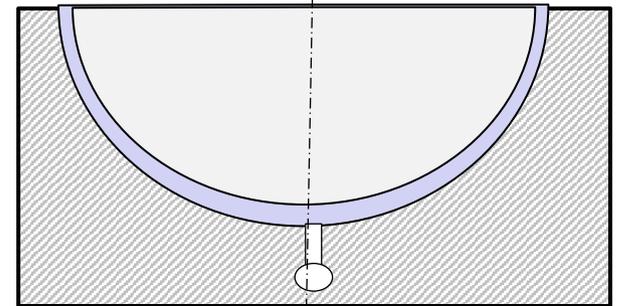
Yates



Axial

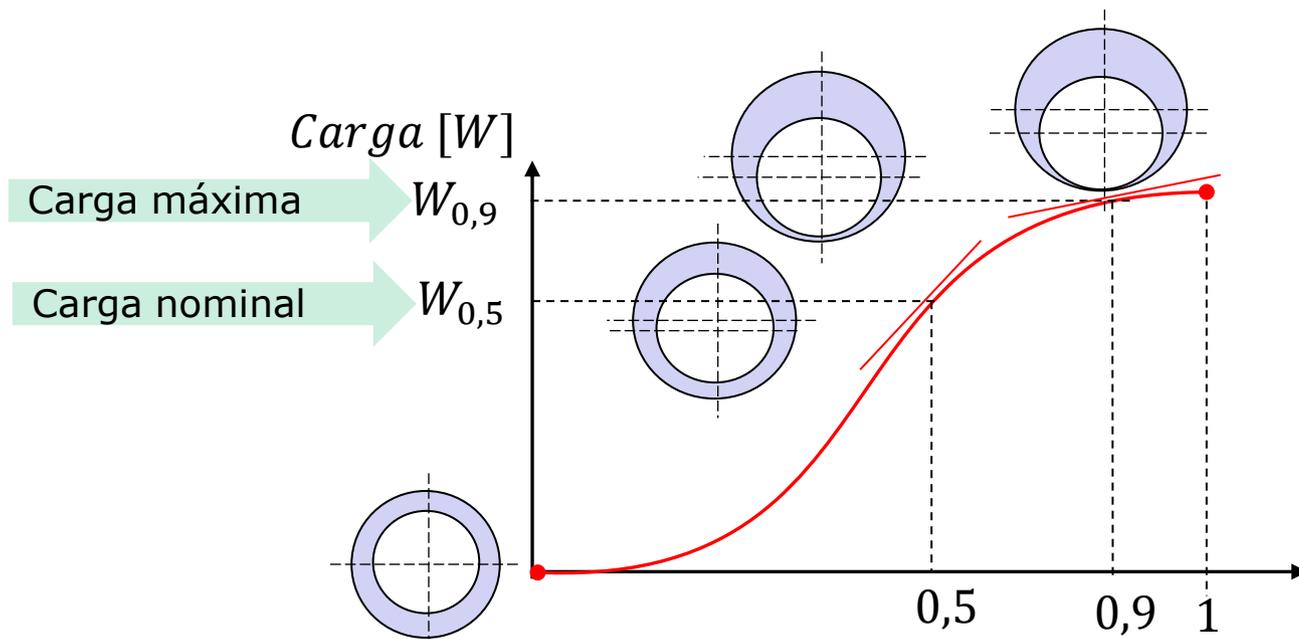
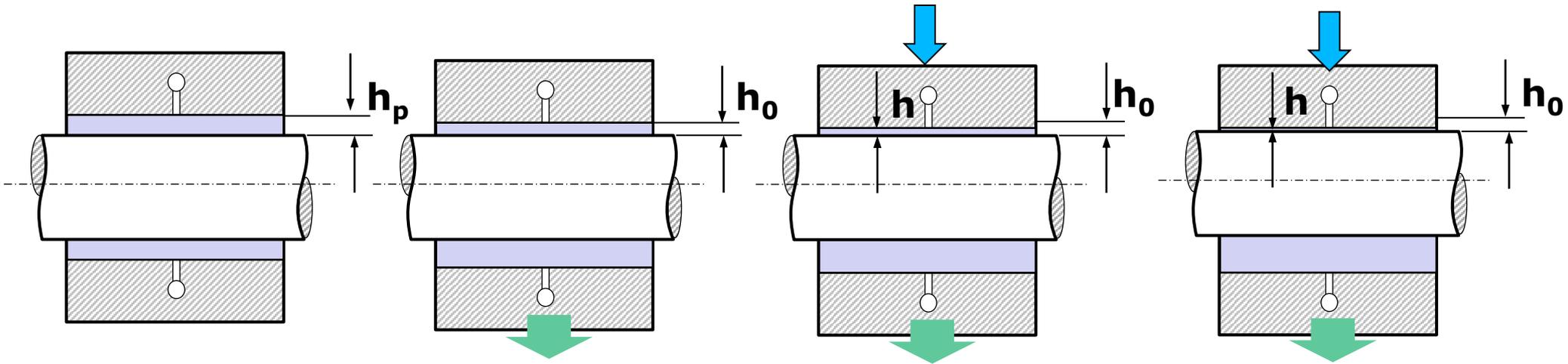


Atitude





Mancais radiais



$$K = \frac{dW}{d\varepsilon}$$

$$K_{0,5} = \frac{dW_{0,5}}{d\varepsilon_{0,5}}$$

$$K_{0,9} = \frac{dW_{0,9}}{d\varepsilon_{0,9}}$$

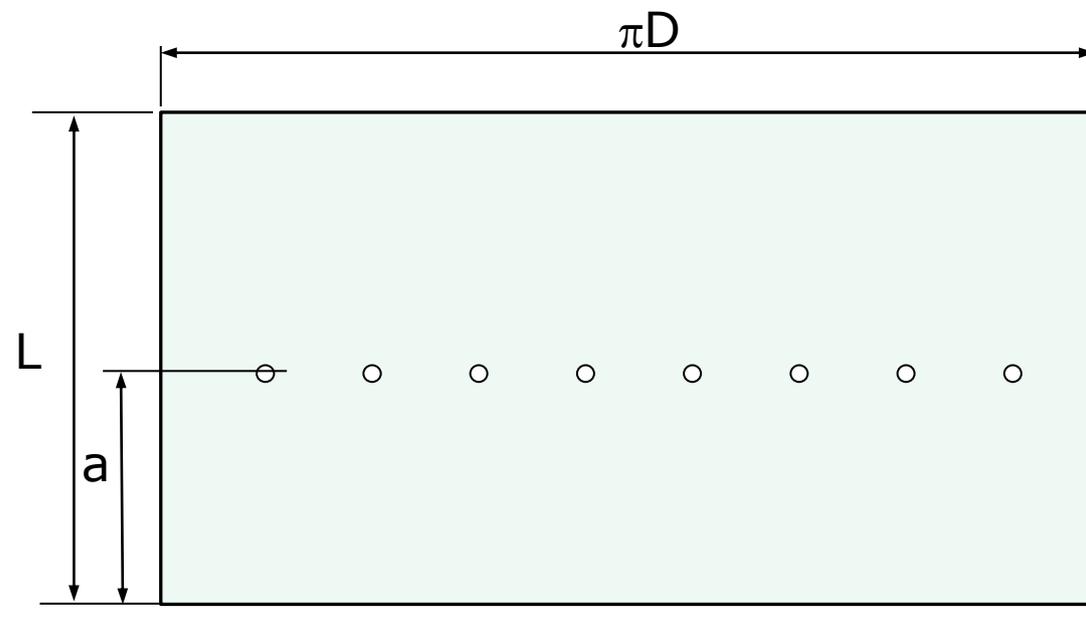
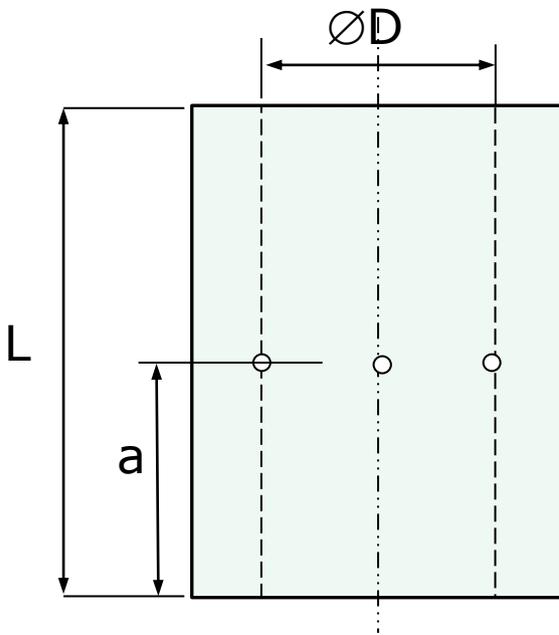
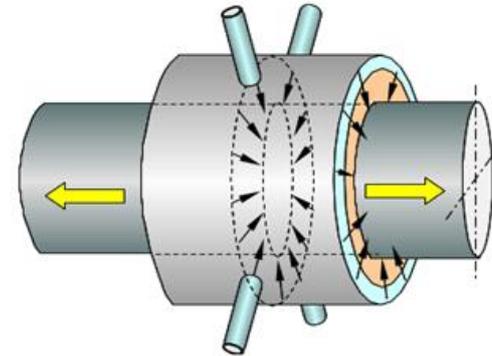
$$\varepsilon = 1 - \frac{h}{h_0}$$



Mancais radiais

$$F_{radial} = 0,3(L - a)DP_d$$

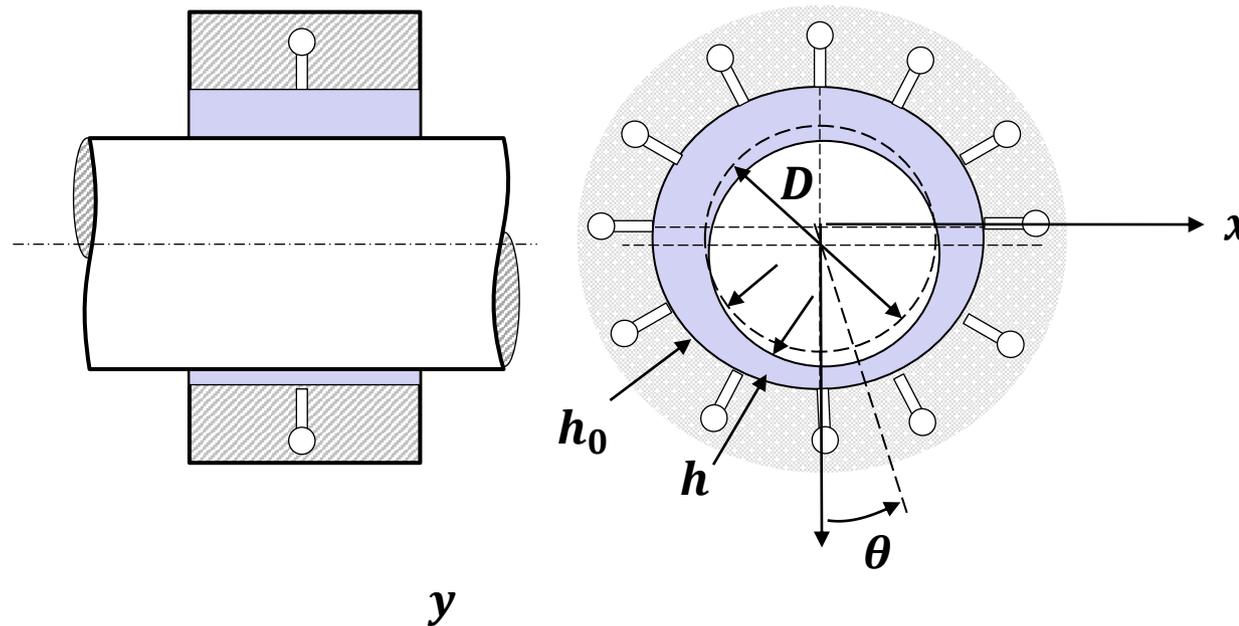
$$K_{radial} = 0,6(L - a) \frac{DP_d}{h_0}$$





Mancais radiais

$$\frac{\partial}{\partial \theta} (PH^3 \frac{\partial P}{\partial \theta}) + \frac{\partial}{\partial \zeta} (PH^3 \frac{\partial P}{\partial \zeta}) = \Lambda \frac{\partial}{\partial \theta} (PH) + 2\Lambda \frac{\partial}{\partial T} (PH)$$

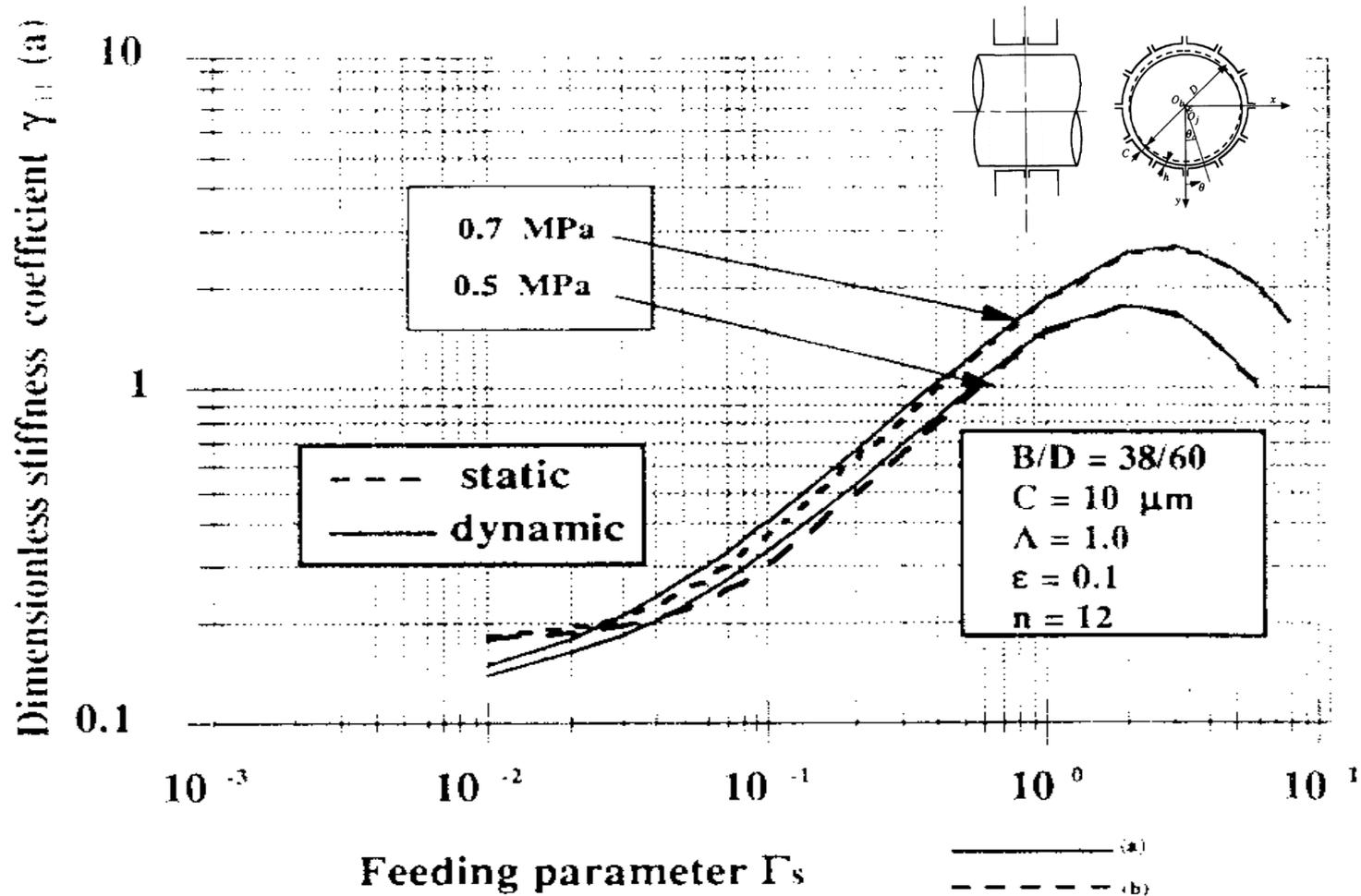


Dong-chul Han, Sang-shin Park, Woo-jung Kim, and Jong-won Kim; A study on the characteristics of externally pressurized air bearings. PRECISION ENGINEERING JULY 1994 VOL 16 NO 3



Mancais radiais

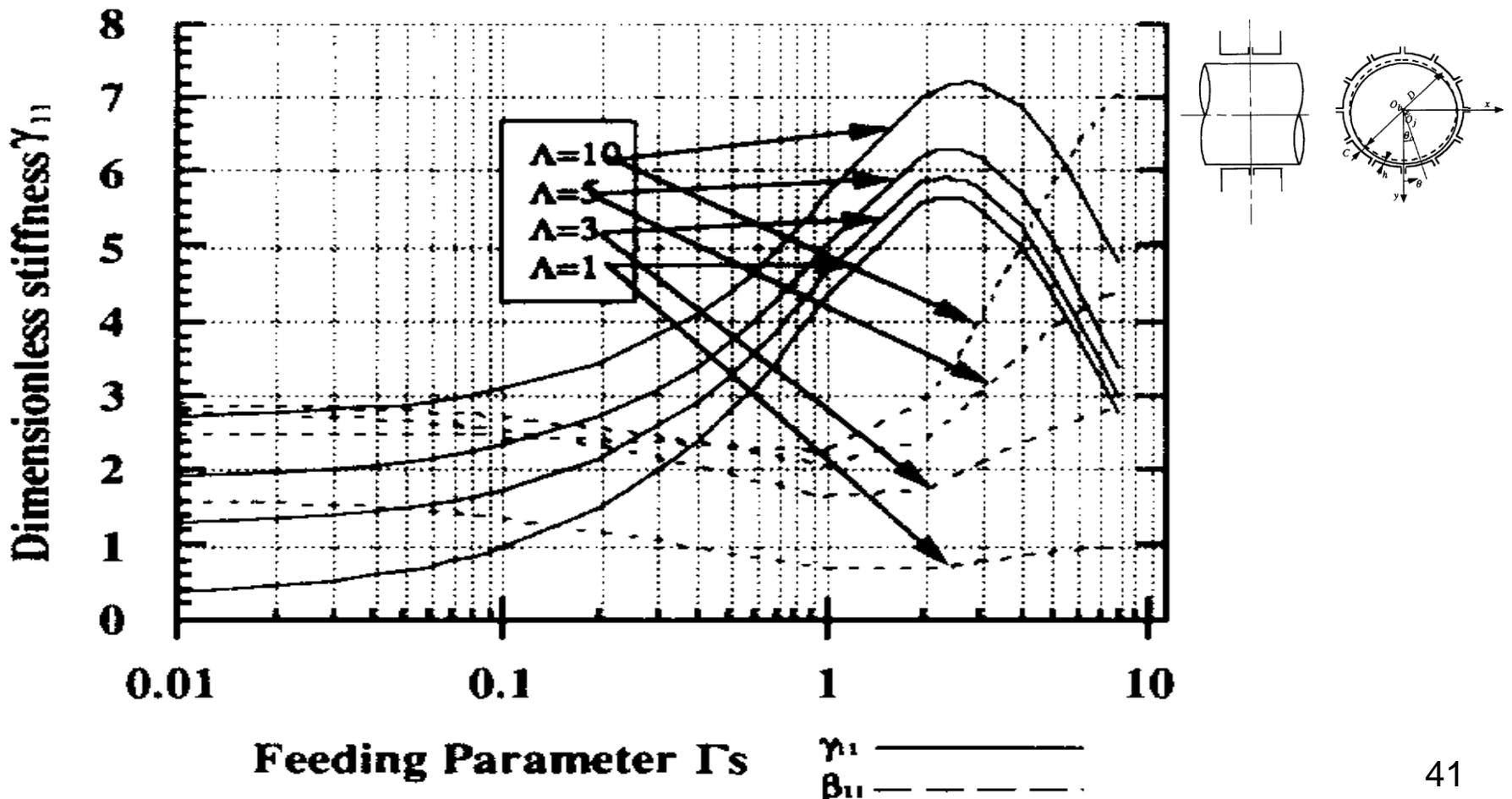
Comparison of static stiffness between dynamic stiffness coefficients





Mancais radiais

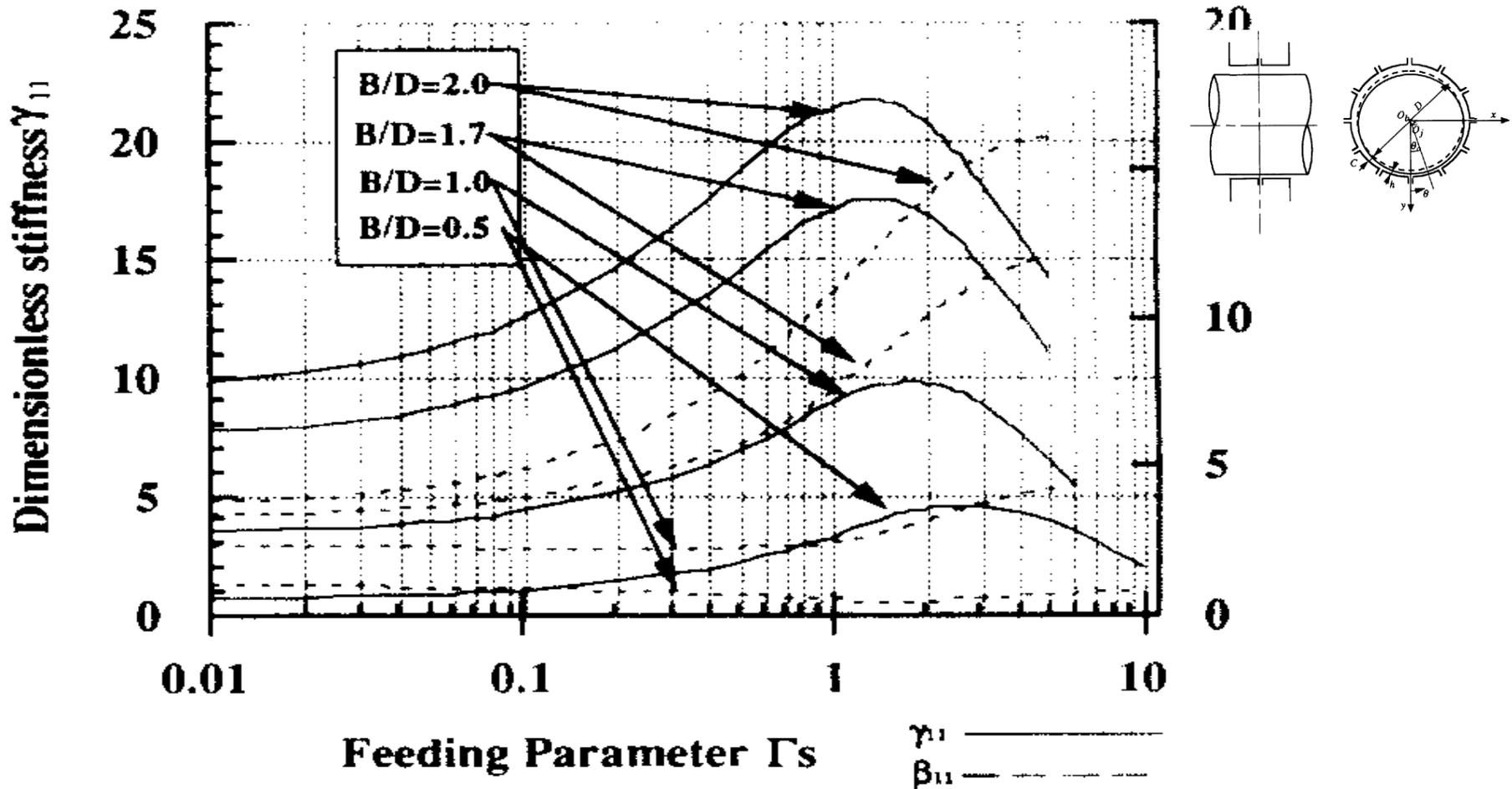
Feeding parameter versus stiffness and damping coefficients ($P_s = 6$)





Mancais radiais

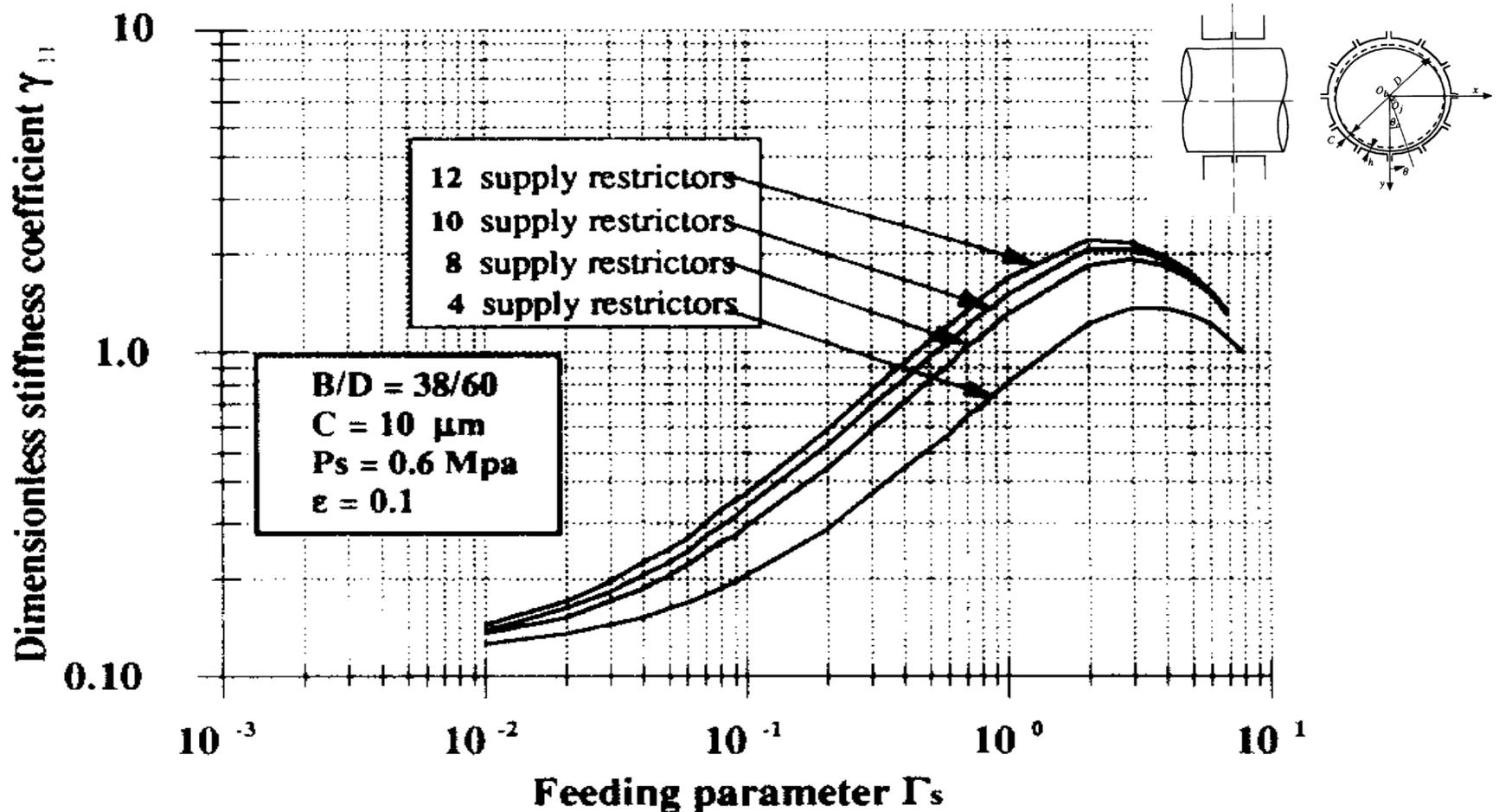
Influence of B/D ratio





Mancais radiais

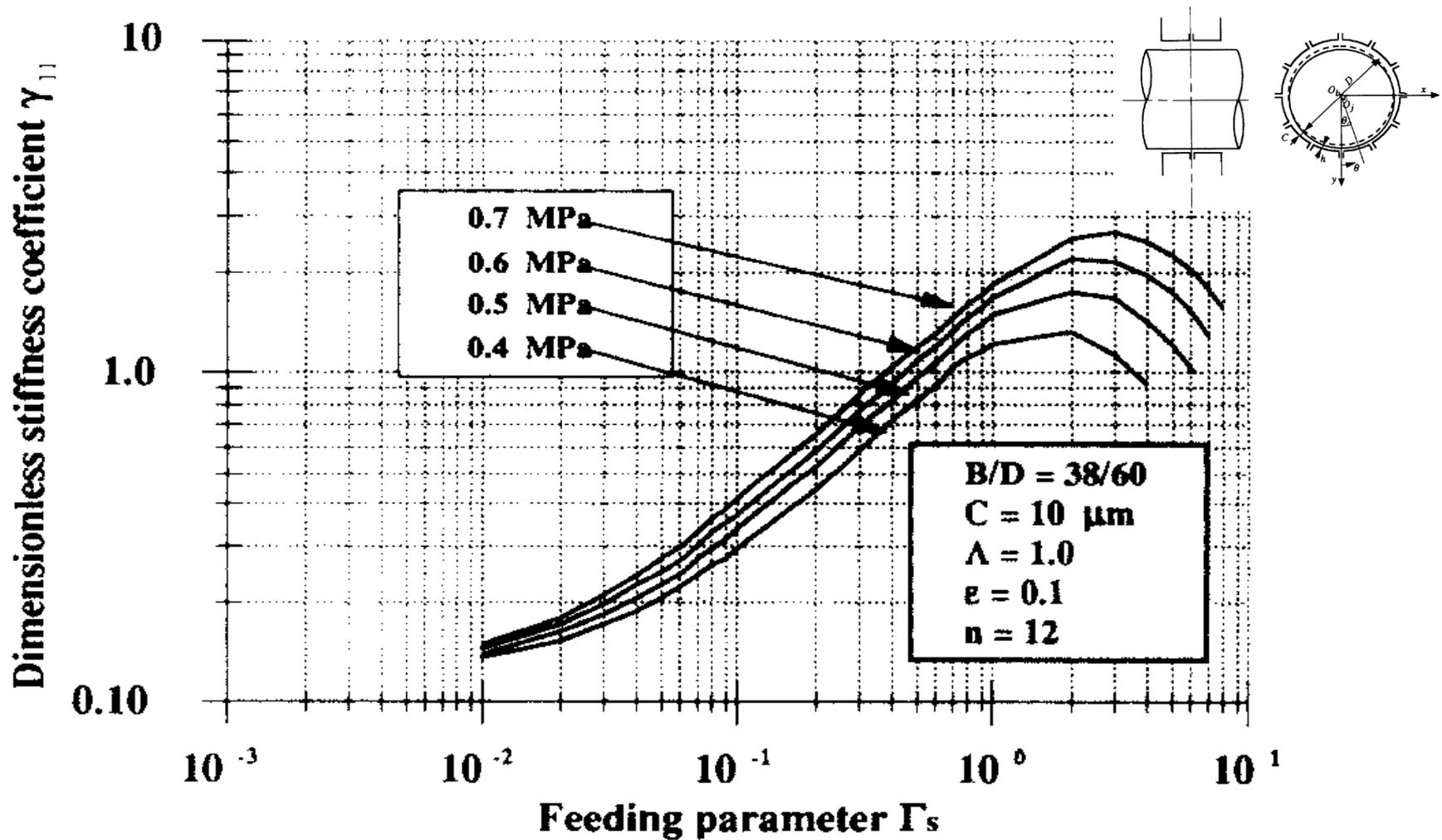
Influence of number of supply restrictors ($\Lambda=1$, $P_s=6$)





Mancais radiais

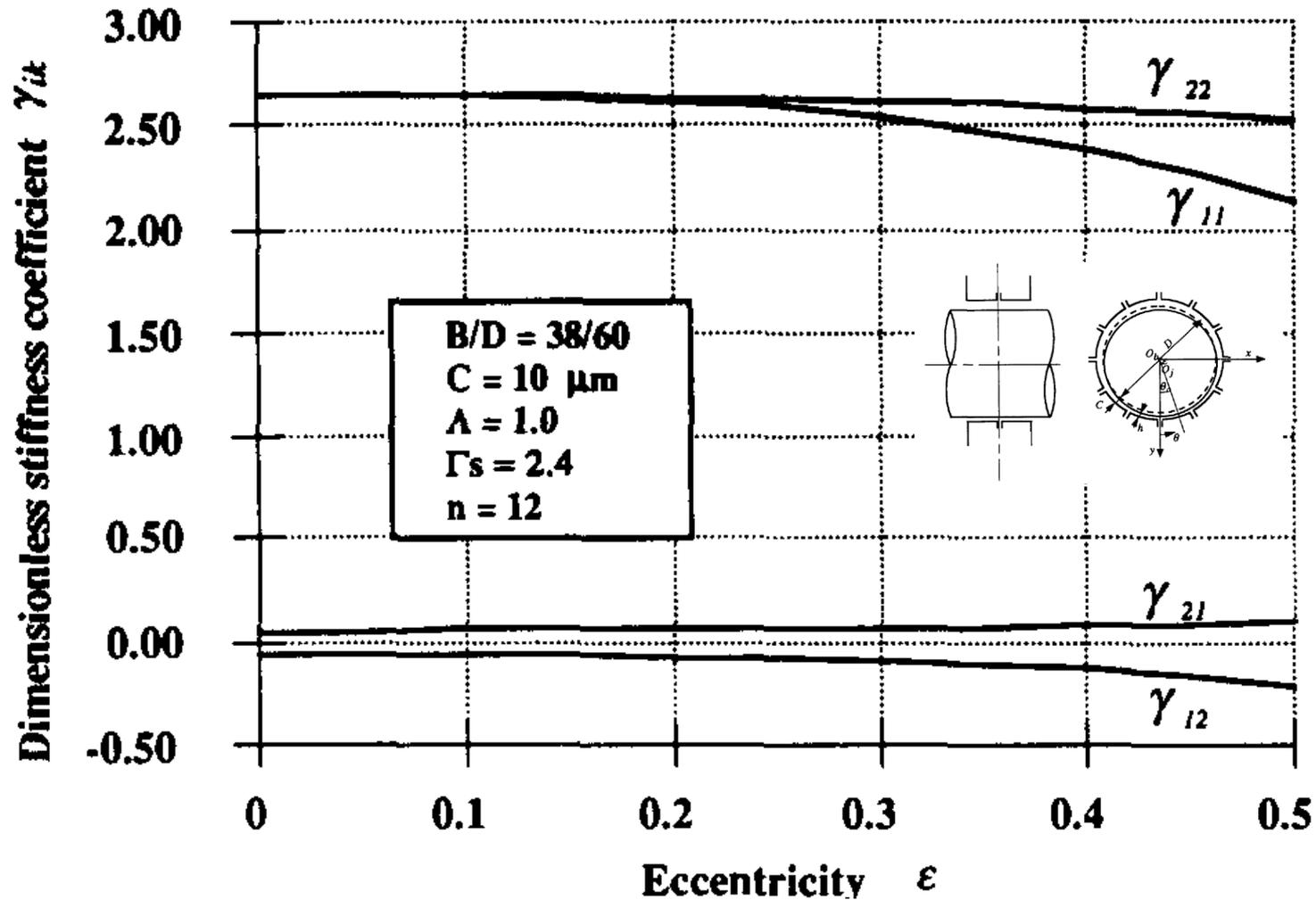
Influence of supply pressure ($\Lambda=1, n=12$)c





Mancais radiais

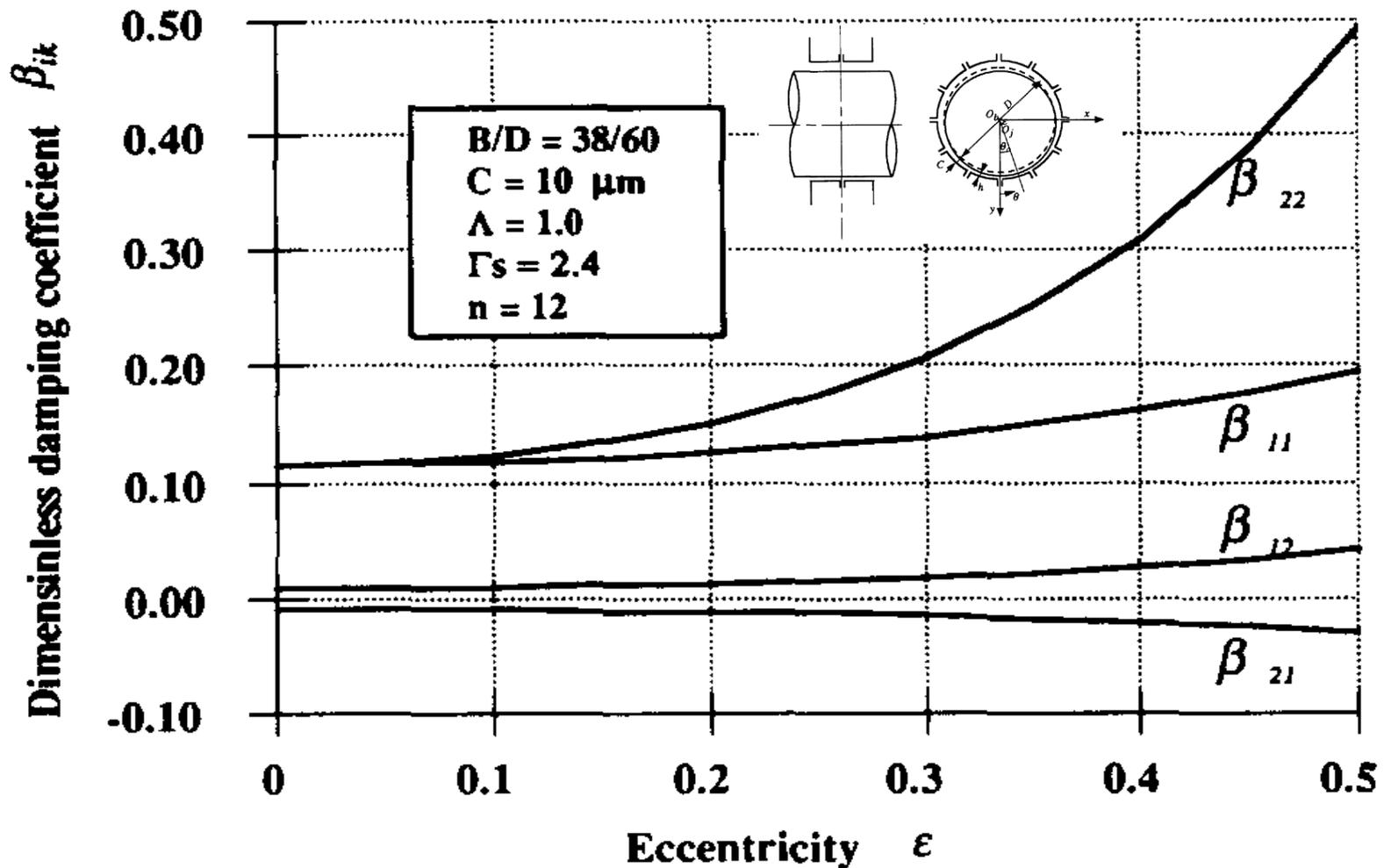
Stiffness coefficients versus eccentricity ($\Lambda=1$)

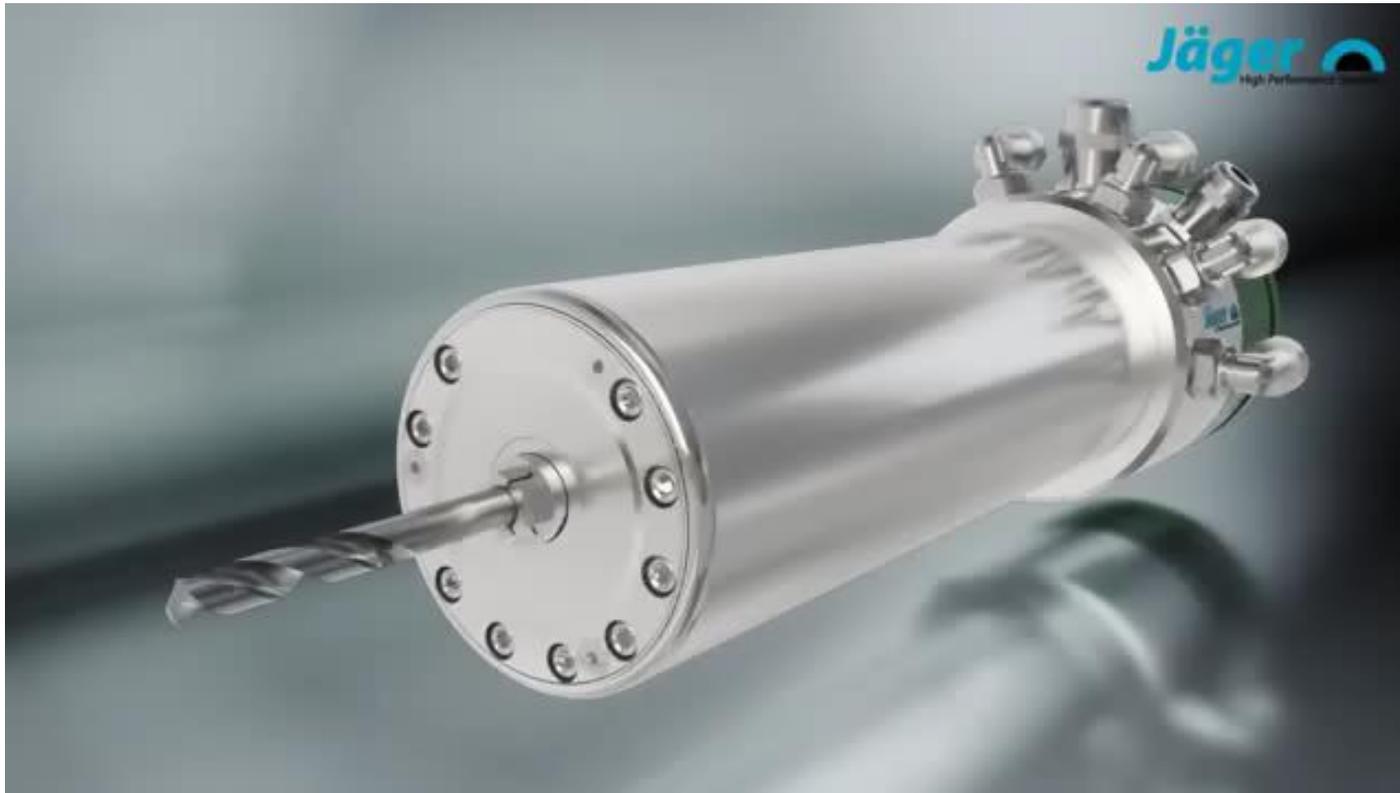




Mancais radiais

Damping coefficients versus eccentricity ($\Lambda=1$)







Comprando Hidrostáticos vs Aerostáticos

LUBRIFICANTE A FILME FLUIDO			
CARACTERÍSTICAS	Líquido	Líquido / AR	AR
NÍVEL DE VIBRAÇÕES	😊😊😊	😊😊	😊😊😊 *
CAPACIDADE DE CARGA	😊😊😊	😊	😞
AMORTECIMENTO	😊😊	😊😊	😊😊😊
RIGIDEZ	😊😊😊	😊	😞
AQUECIMENTO	😞😞	😊	😊😊😊
DESEMPENHO EM BAIXA VELOCIDADE	😞	😊😊	😊😊😊
DESEMPENHO EM ALTA VELOCIDADE	😊😊	😊😊	😊😊😊

Onde: 😊😊😊 – excelente, 😊😊 – bom, 😊 – moderado, 😞 – regular, 😞😞 – ruim e 0 – não aplicável.

* se bem projeto e fabricado



ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO

FIM DA AULA