



ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO

# **Engenharia de Precisão**

**PMR 3501 – A27**

**Mancais e guias aerostáticas**

**2023.2**



## 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





## Mancais e Guias

### Mancais

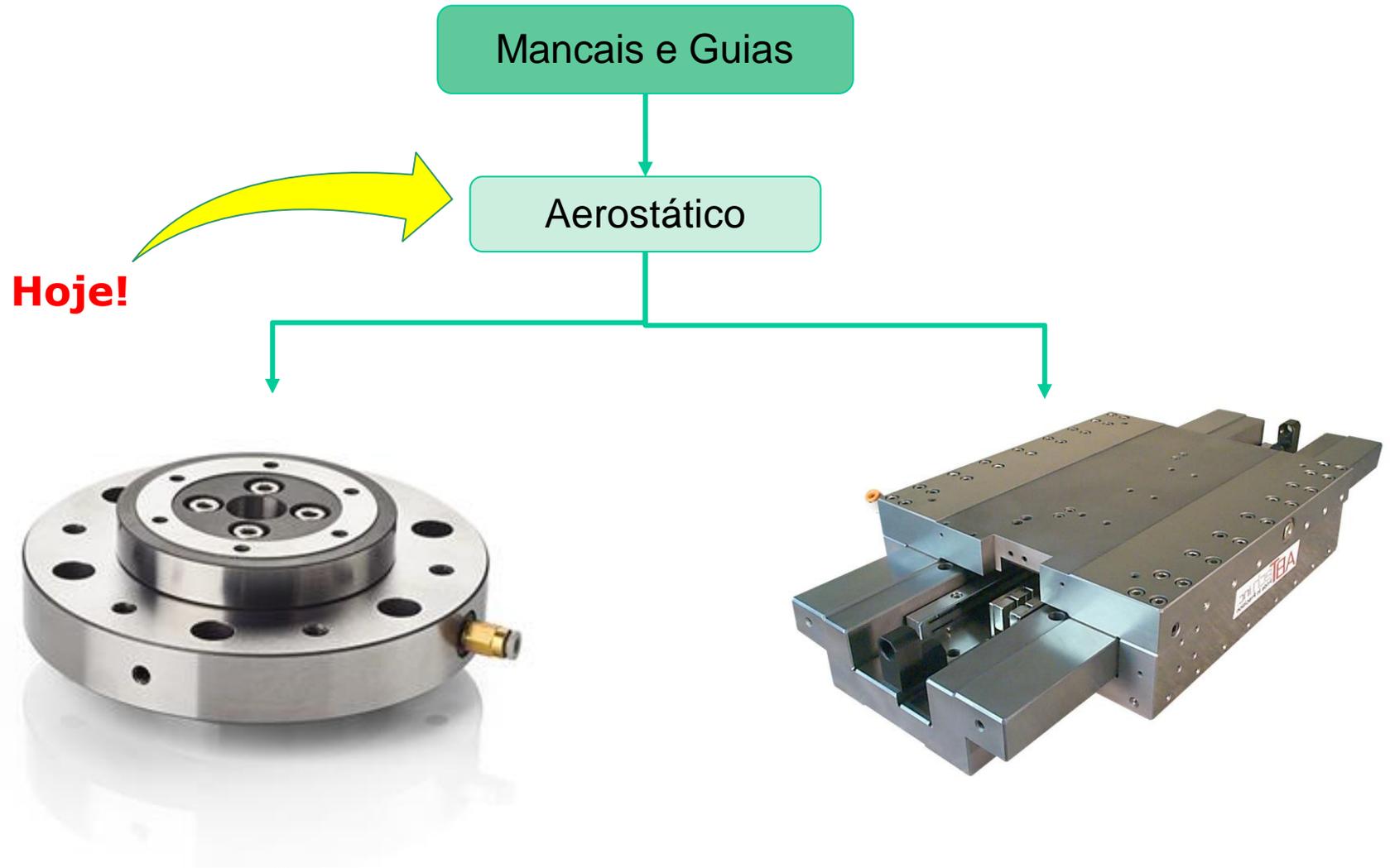


- **Mancais** são elementos de máquinas que tem por função básica absorver carregamentos, e onde o movimento de **translação** em qualquer direção deve ser minimizado, deixando **livre** somente a **rotação** em torno de um eixo.

### 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.





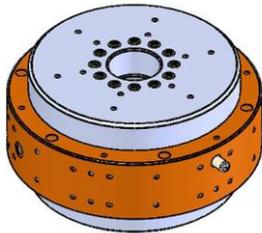
## Guias aerostáticas





## Mancais/Guias aerostáticas

### Características

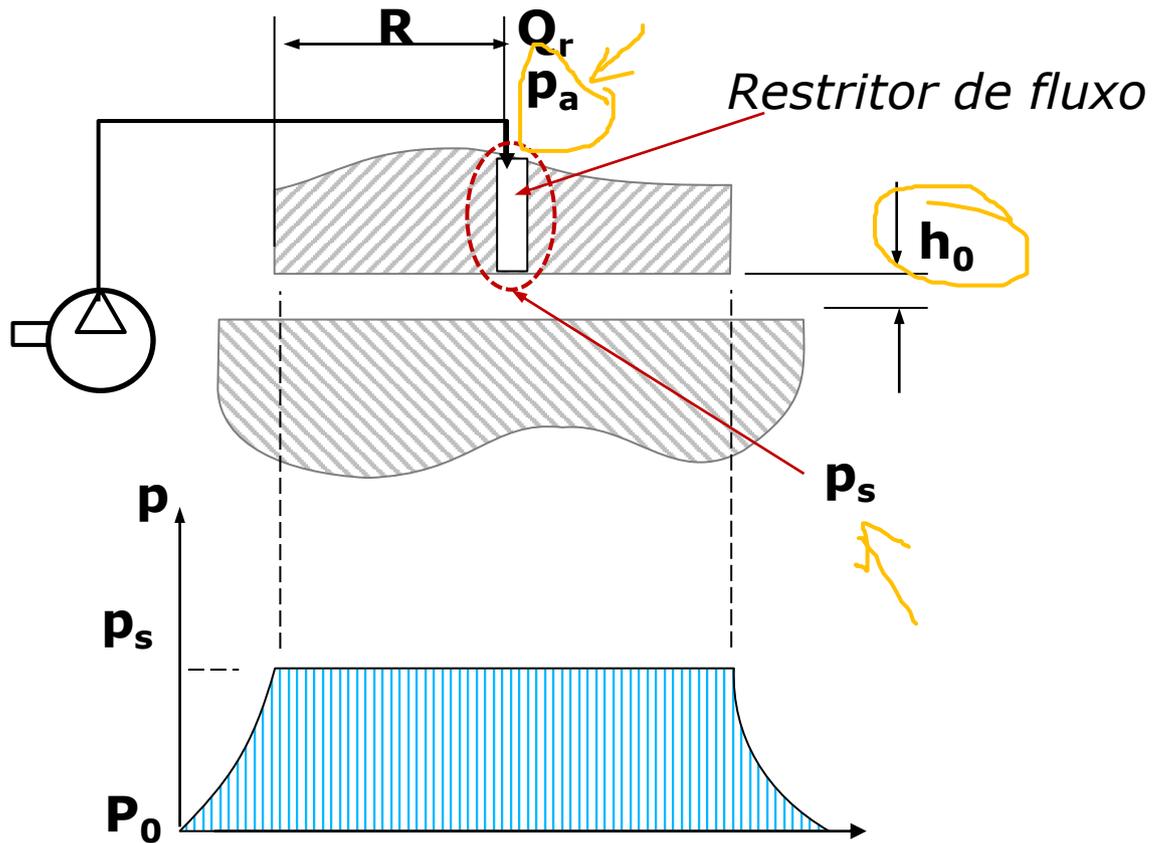


- Projeto complexo (mais do que os hidrostáticos)
- Fabricação complexa (mais do que os hidrostáticos)
- Baixa modularidade
- Sem atrito, desgaste e *stick-slip*
- Baixa capacidade de carga
- Não necessita de sistemas de retorno e resfriamento
- Baixa rigidez
- Elevado amortecimento
- Alta velocidade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

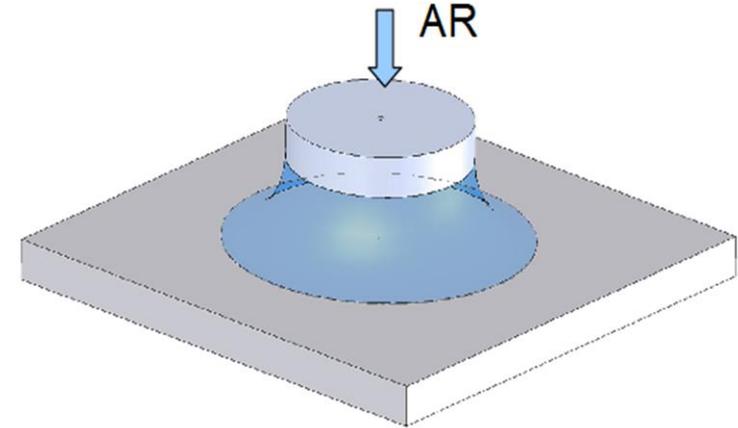
<https://www.physikinstrumente.com/en/products/air-bearings-stages/a-60x-piglode-rt-rotary-air-bearing-module-900719/>



princípio de funcionamento



Pad circular e anular





## Restritores de fluxo

### Tipos

Orifício

Capilares

Flexíveis

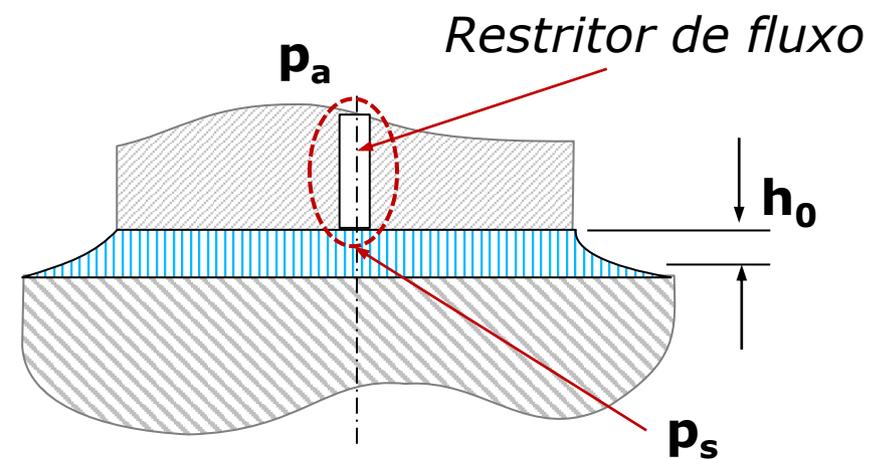
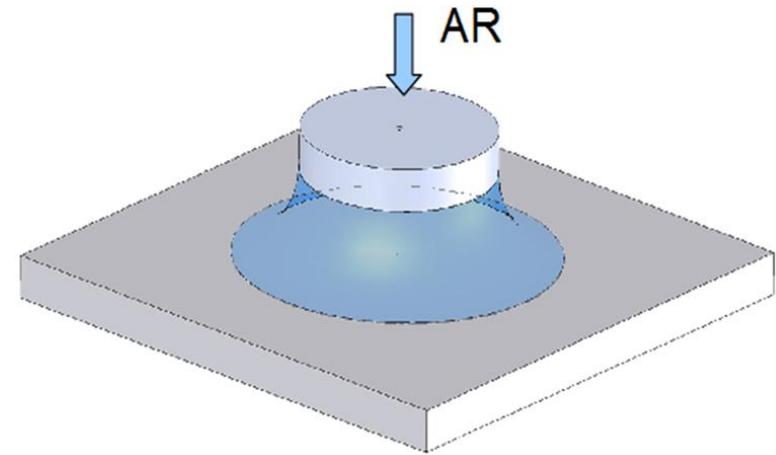
Porosos

Válvulas sensoras de pressão

Rasgo

Fluxo constante

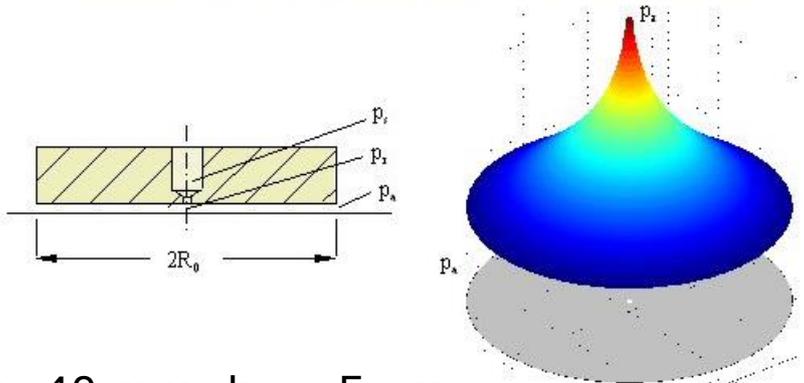
Estabilidade inerente





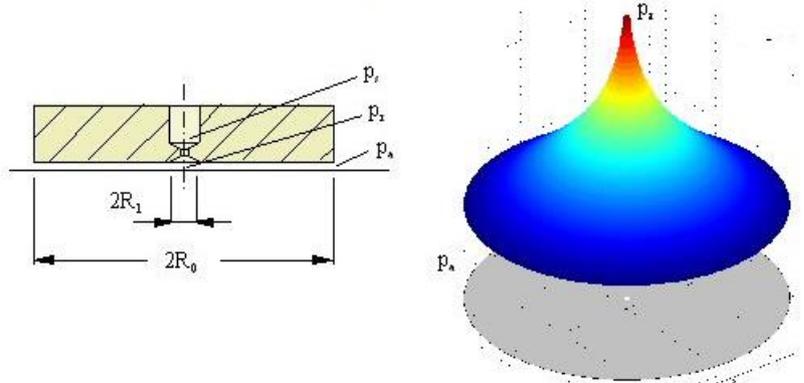
## Restritores de fluxo

Aerostatic thrust bearing fed through an inherent orifice restrictor



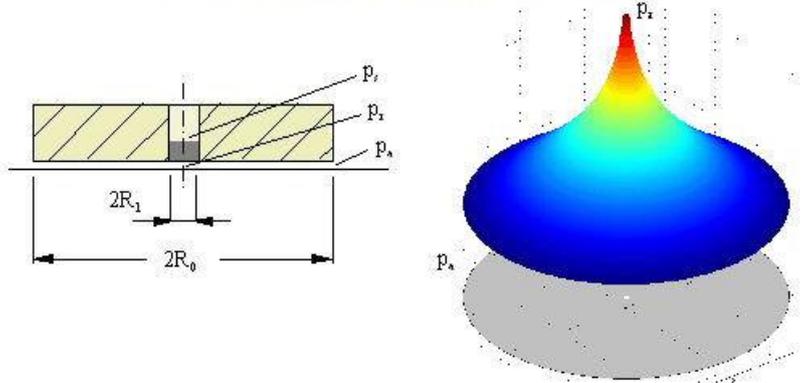
Dia. 40 mm,  $h_o = 5 \mu\text{m}$   
Load capacity = 46.2 N

Aerostatic thrust bearing with simple orifice restrictor



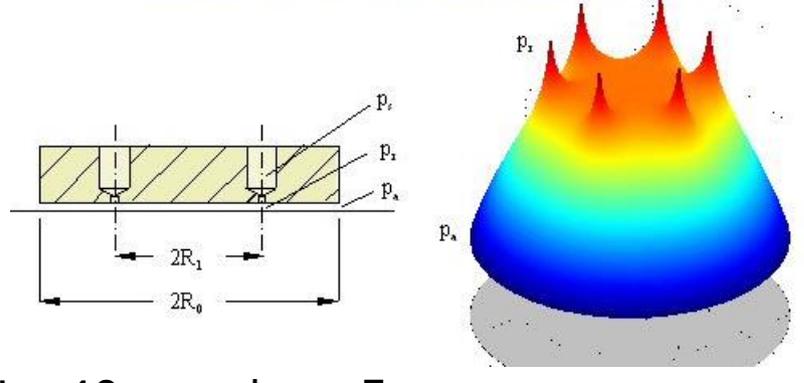
Dia. 40 mm,  $h_o = 5 \mu\text{m}$   
Load capacity = 91 N

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

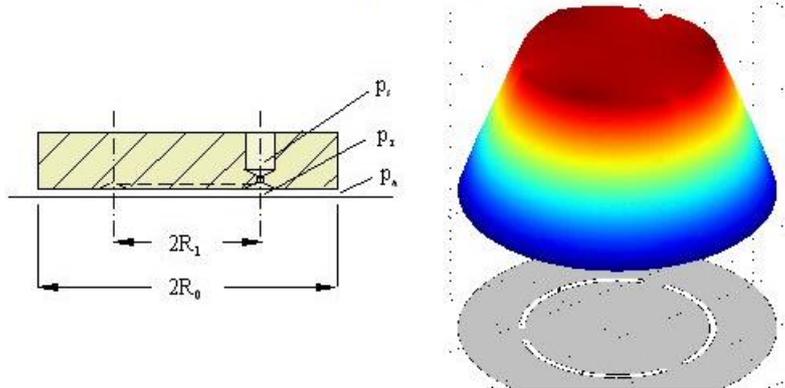


Dia. 40 mm,  $h_o = 5 \mu\text{m}$   
Load capacity = 150.8 N



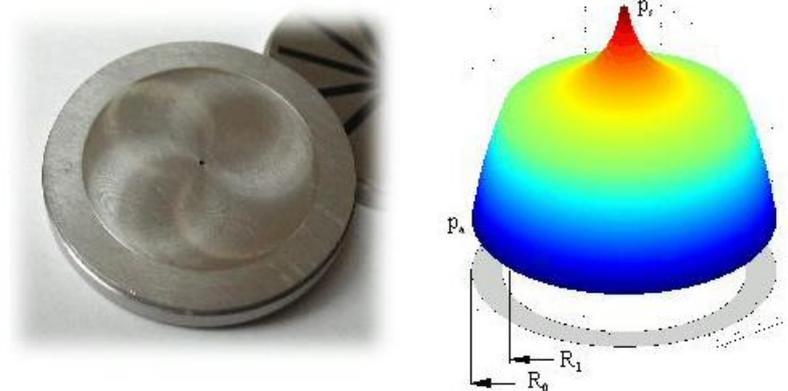
## Restritores de fluxo

Aerostatic thrust bearing fed through a narrow groove



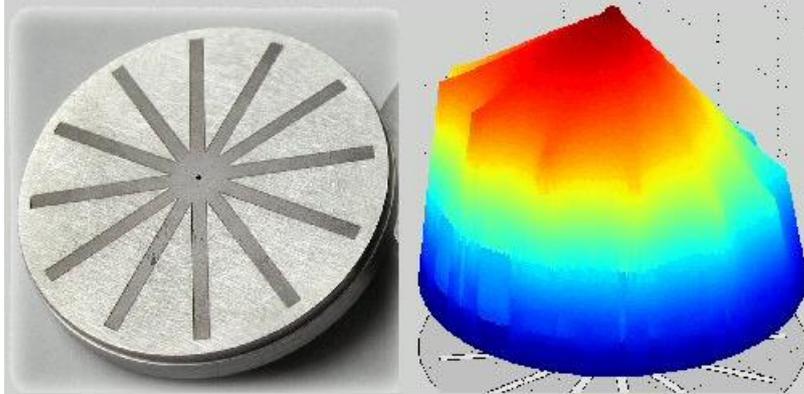
Dia. 40 mm,  $h_o = 5 \mu\text{m}$   
Load capacity = 208,3 N

Aerostatic shallow pocket thrust bearing



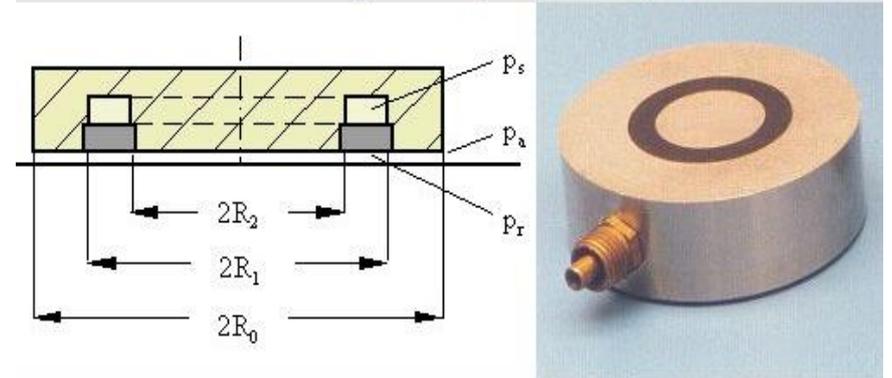
Dia. 40 mm,  $h_o = 5 \mu\text{m}$   
Load capacity = 240,7 N

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



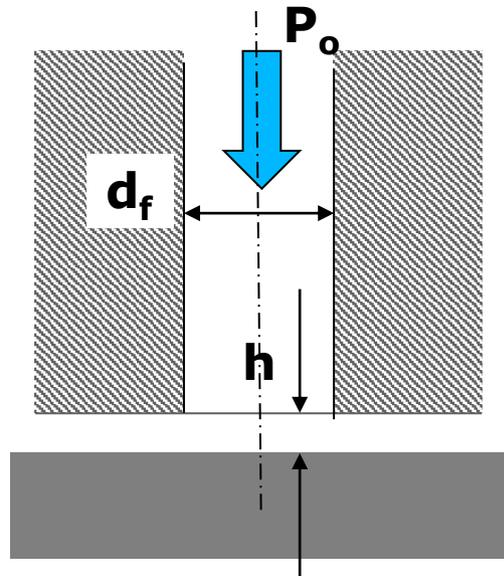
## Mancais aerostáticos



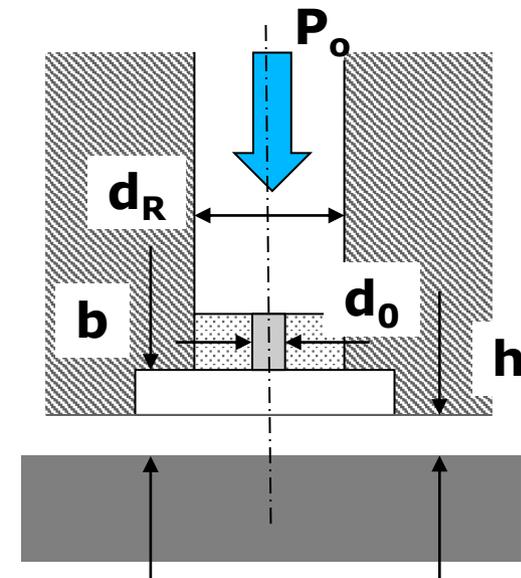


## princípio de funcionamento

### Análise do restritor



Orifício sem rebaixo

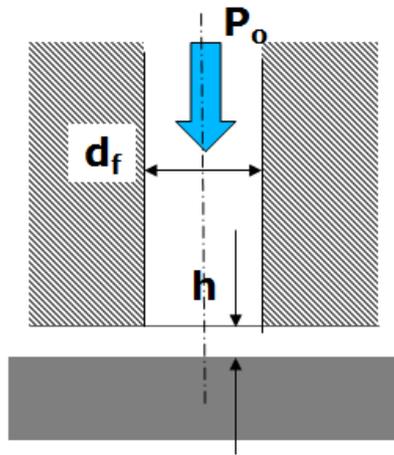


Orifício com rebaixo

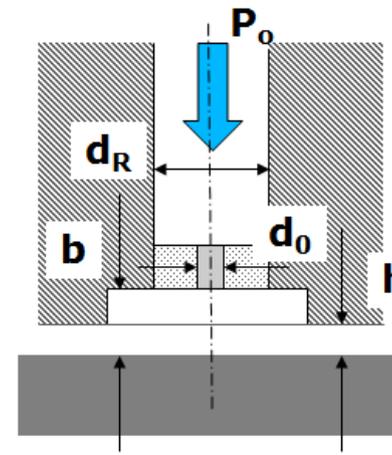


## princípio de funcionamento

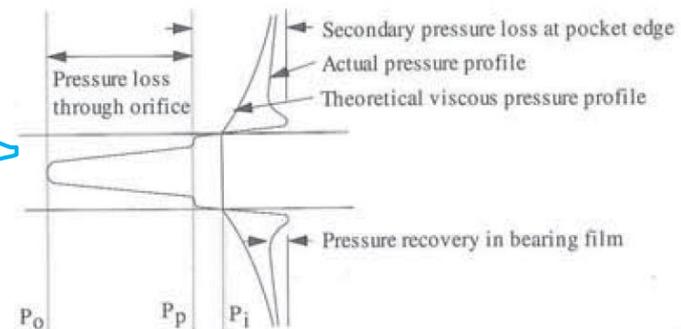
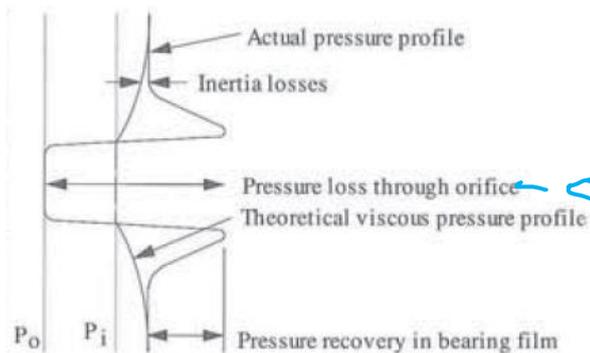
### Análise do restritor



Orifício sem rebaixo



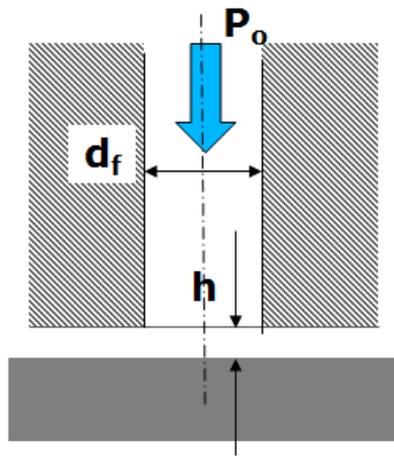
Orifício com rebaixo





princípio de funcionamento

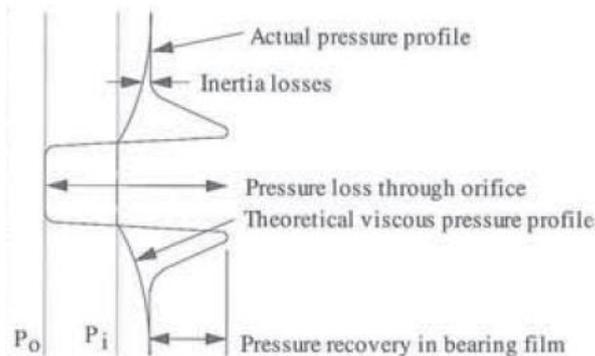
Fluxo de massa através do restritor do tipo orifício



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

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

Diferença de pressão

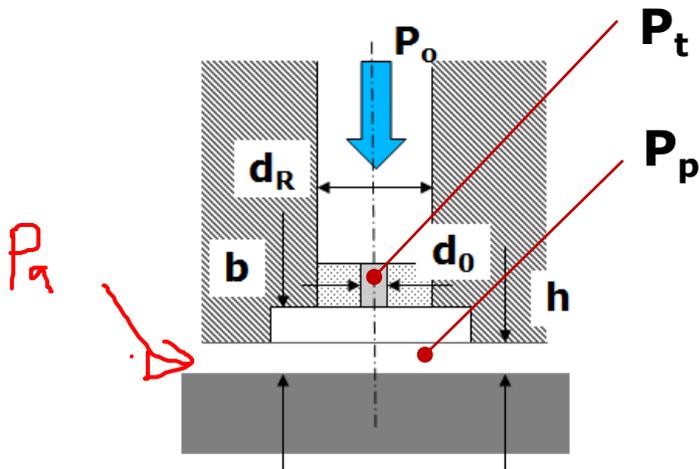


$$\frac{P_t}{P_o} = \left[ \frac{2\nu}{(\nu + 1)} \right] \frac{\nu}{\nu - 1}$$



princípio de funcionamento

Fluxo de massa através do restritor com rebaixo



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

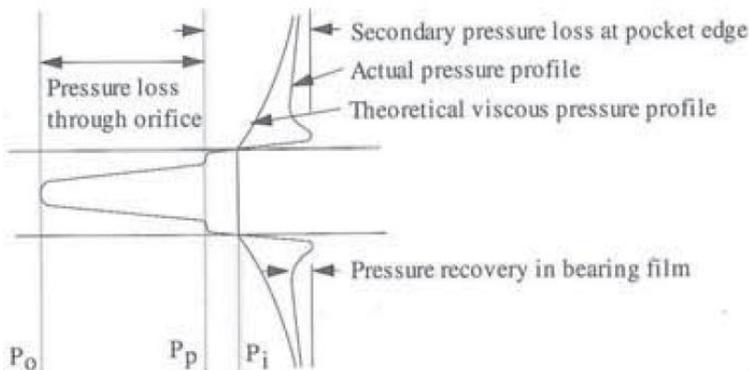
$$\dot{m}_0 = 1,87 \times 10^4 \cdot C_d \cdot d_0^2 \cdot \frac{P_0}{P_a}$$

Diferença de pressão

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

Fator de compensação

$$\delta_L = \frac{d_0}{4 \cdot d_R \cdot h}$$



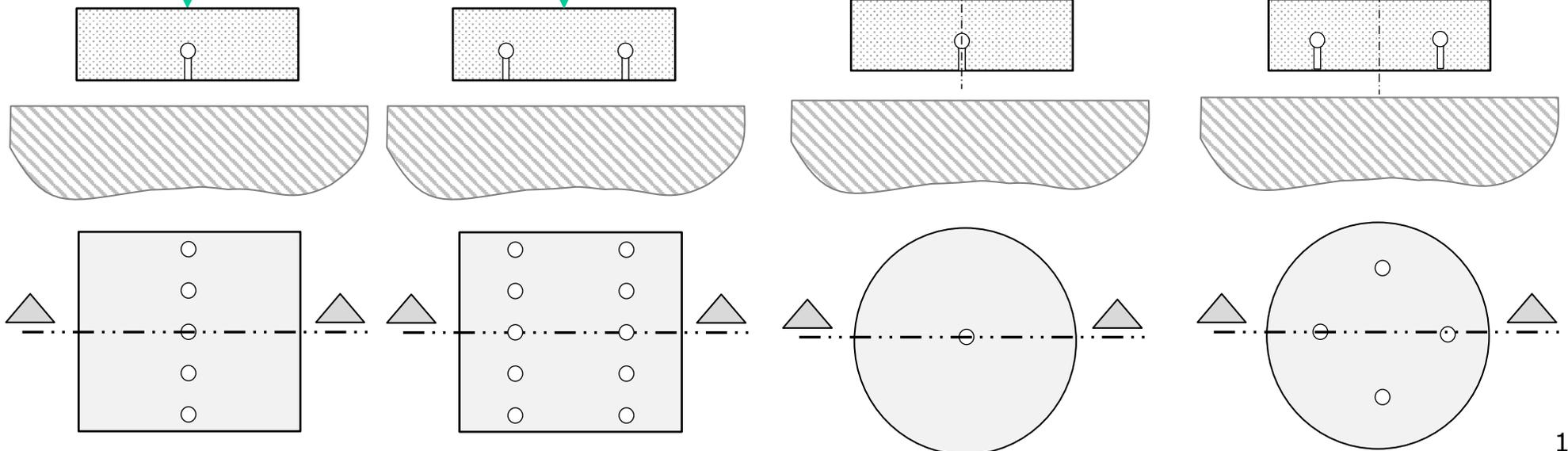


## Guias aerostáticas

*Pads / Sapatas*

Retangulares

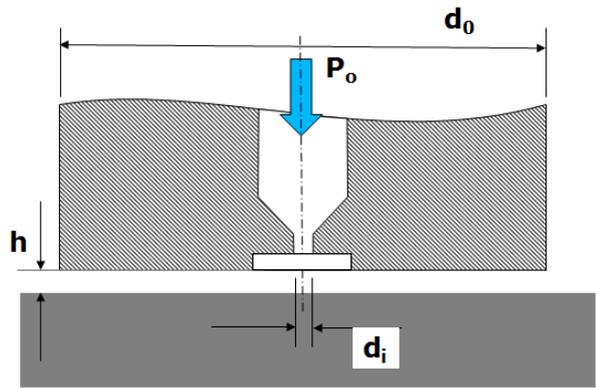
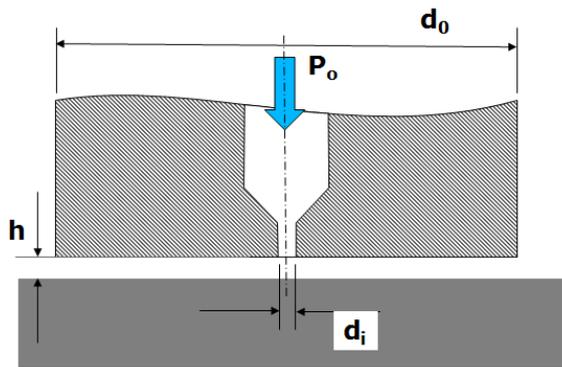
Circulares





**Princípio de funcionamento**

**Mancais de sapata circular**



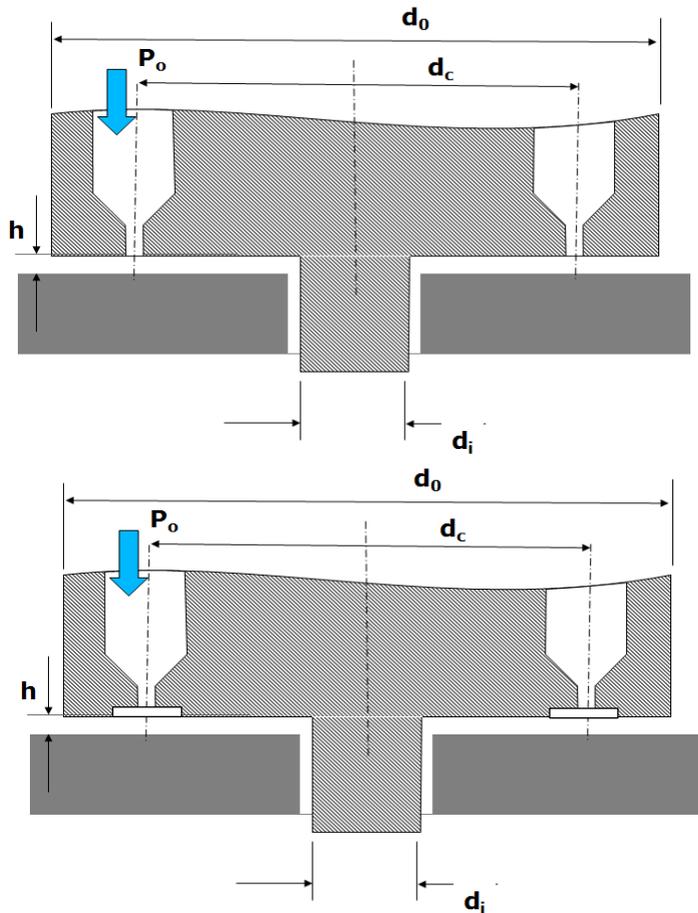
$$\frac{R_o}{R_i} = 20 \Rightarrow \text{recomendação}$$

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 <sup>3</sup> /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)	$d_o = \sqrt{\frac{\Lambda_s \xi P_o h_o^3}{7890 \times 2\log_e(R_o/R_i)}}$	$d_r = \frac{\Lambda_s \xi P_o h_o^2}{31.55 \times 2\log_e(R_o/R_i)}$
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

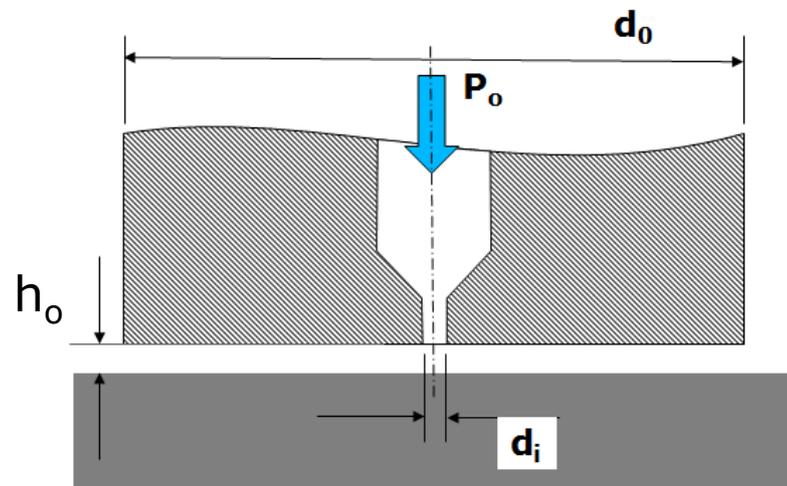


Parameter	Pocketed orifices	Inherently compensated orifice
Max. stiffness (N/μm)	$K = \frac{0.44\pi(R_o^2 - R_i^2) (P_o - P_a)}{h_o}$	$K = \frac{0.29\pi(R_o^2 - R_i^2) (P_o - P_a)}{h_o}$
Max. angular stiffness (Nm/rad)	$K_A = \frac{0.23\pi(R_o^2 - R_i^2)R_oR_i (P_o - P_a)}{h_o}$	
Max. load (N) @ $\epsilon = 0$	$W = 0.26\pi(R_o^2 - R_i^2) (P_o - P_a)$	
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 <sup>3</sup> /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

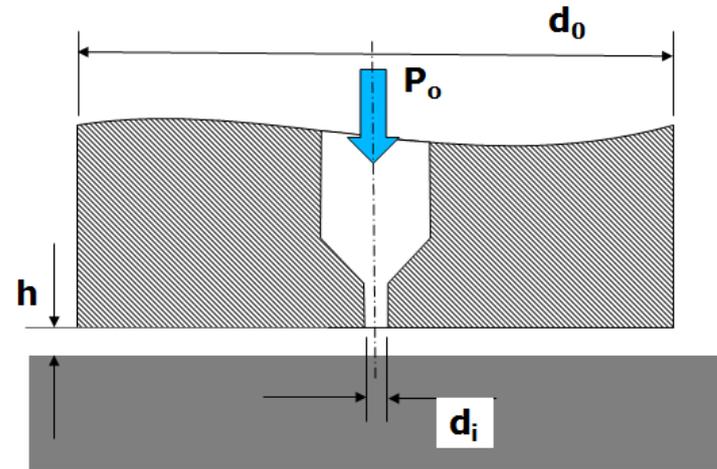
- Uma sapata circular aerostática de 140mm de diâmetro deve ser projetada para suportar 700N de carga, e ter uma rigidez de  $70\text{N}/\mu\text{m}$ .
- Dado que a razão de pressão  $P_o/P_a = 5$ ,  $h_o = 20\mu\text{m}$ .
- Determinar a rigidez teórica e compare com a especificada, determine o consumo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



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

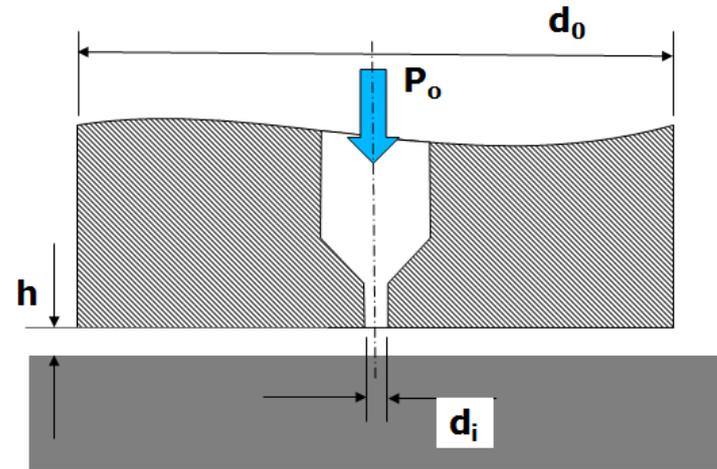
$$K_{\max} = \frac{0,27 \cdot \pi \cdot (70)^2 (0,405 \text{ N/mm}^2)}{20}$$

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



## 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
- $h_0 = 20\mu\text{m}$
- $d_f = ?$

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

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

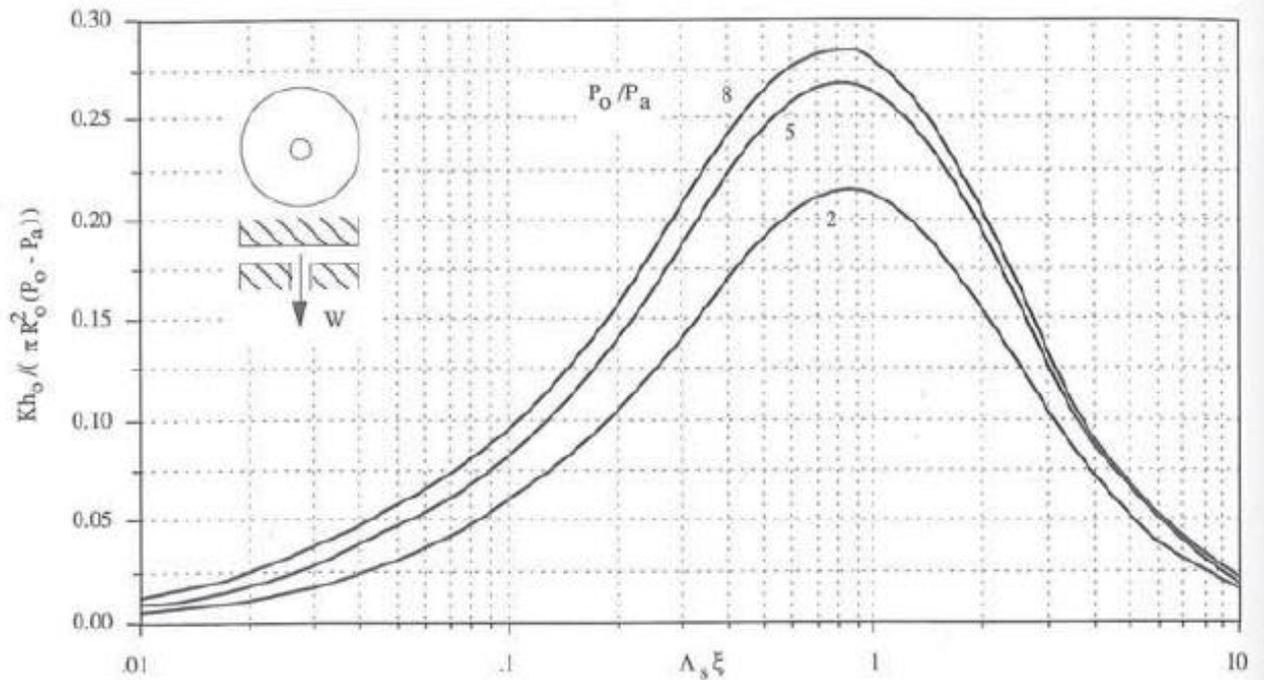


Figure 9.3.28 Pocketed circular thrust bearing stiffness where  $R_i/R_0 = 0.05$ ,  $C_d = 0.8$ , and  $\nu = 1.4$ . For inherently compensated bearings, multiply the ordinate by  $2/3$ .



**Exemplo de dimensionamento**

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

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

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

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

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

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

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

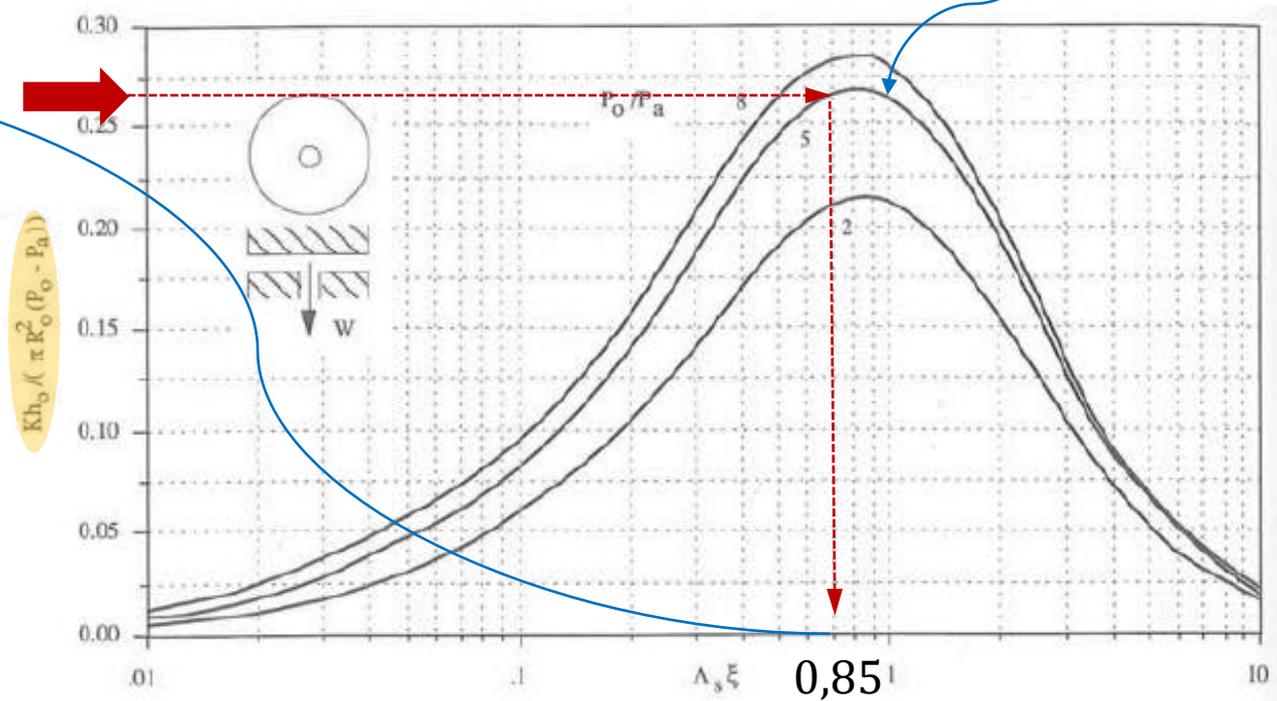
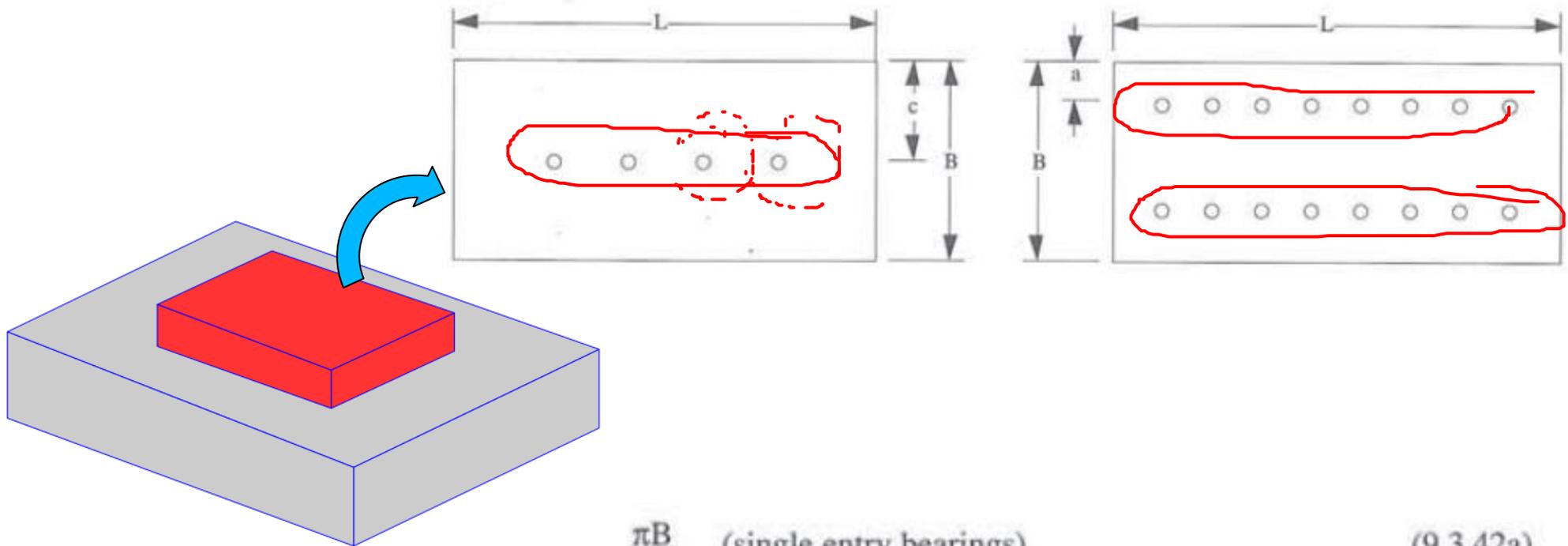


Figure 9.3.28 Pocketed circular thrust bearing stiffness where  $R_i/R_o = 0.05$ ,  $C_d = 0.8$ , and  $\nu = 1.4$ . For inherently compensated bearings, multiply the ordinate by  $2/3$ .



## Sapatas aerostáticas retangulares



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

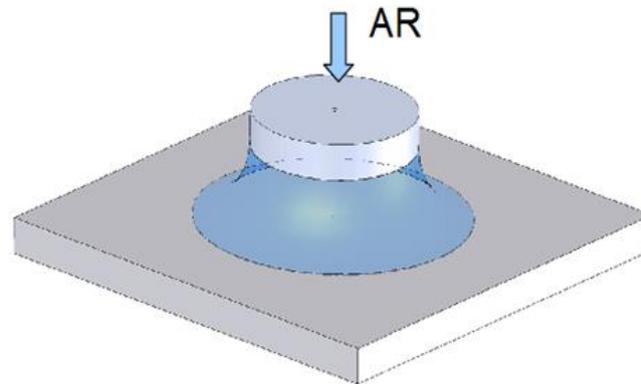
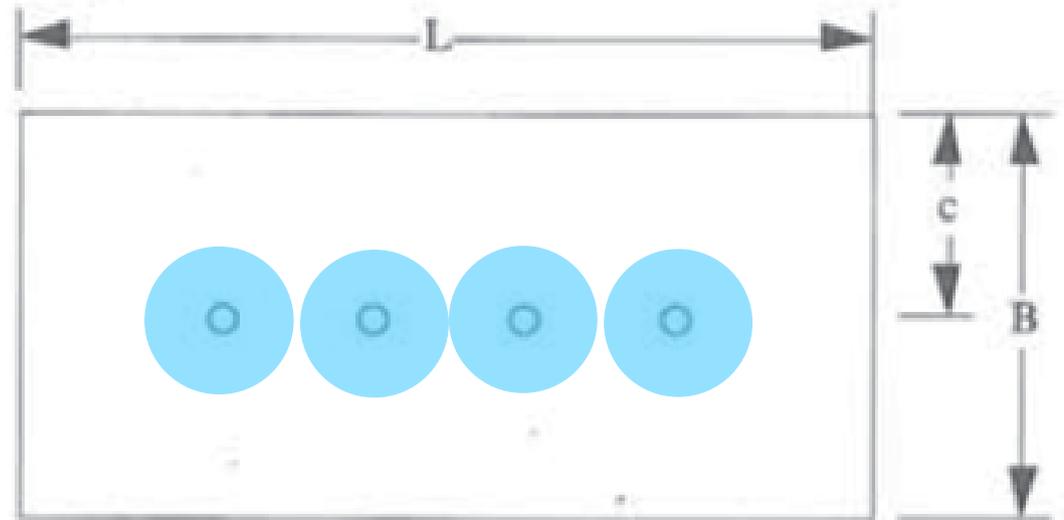
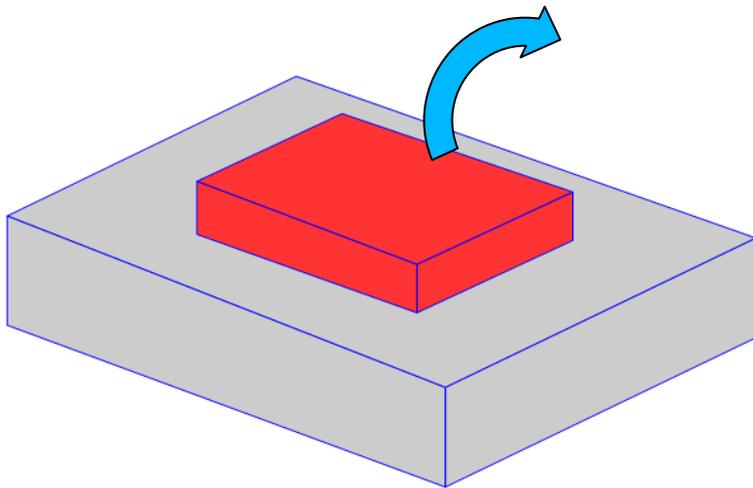
$$\xi = \frac{\pi 2a}{L} \quad (\text{double entry bearings}) \quad (9.3.42b)$$

- 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

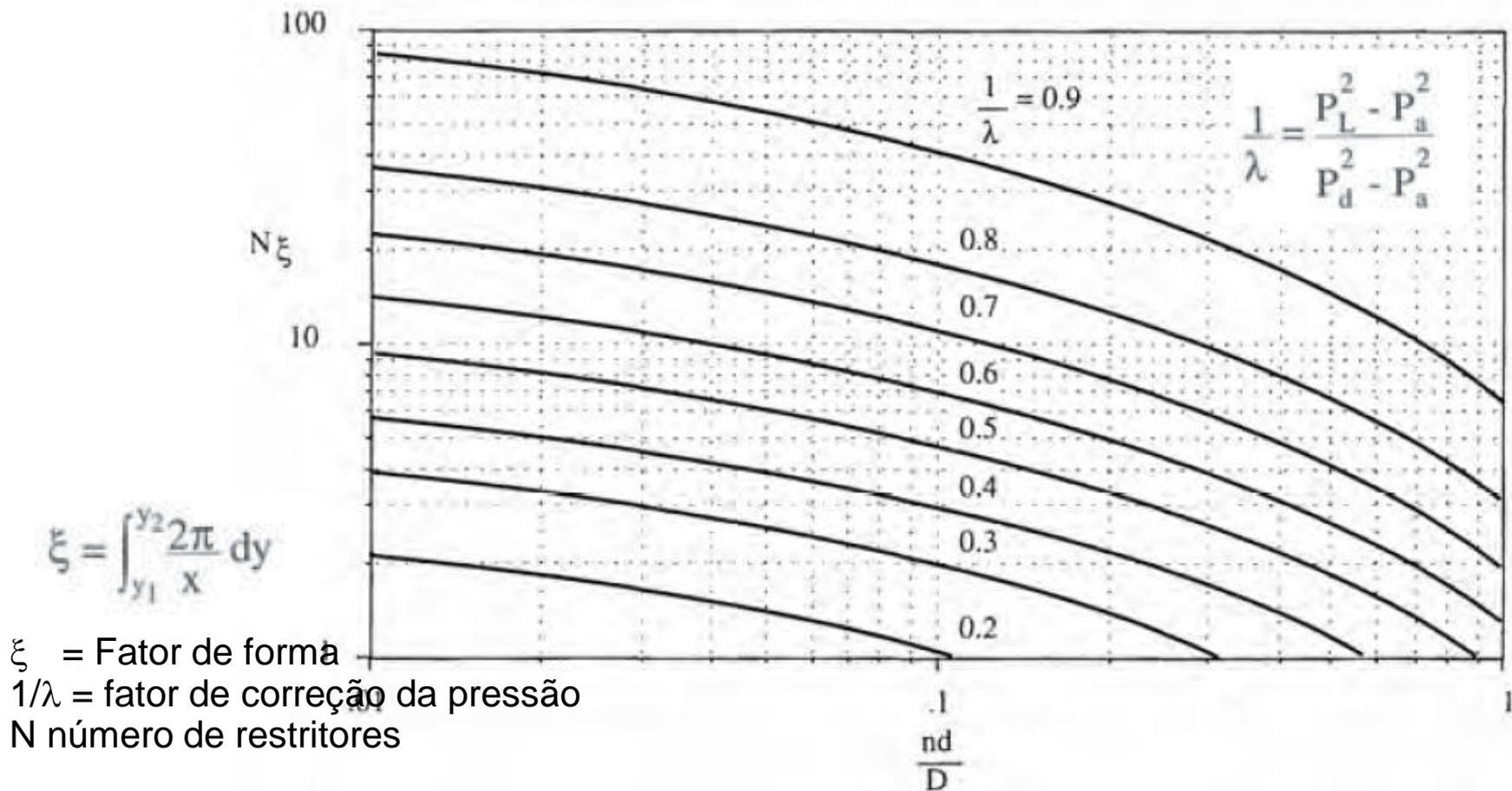
### Aproximação por sapatas unitárias circulares





## Sapatas aerostáticas retangulares

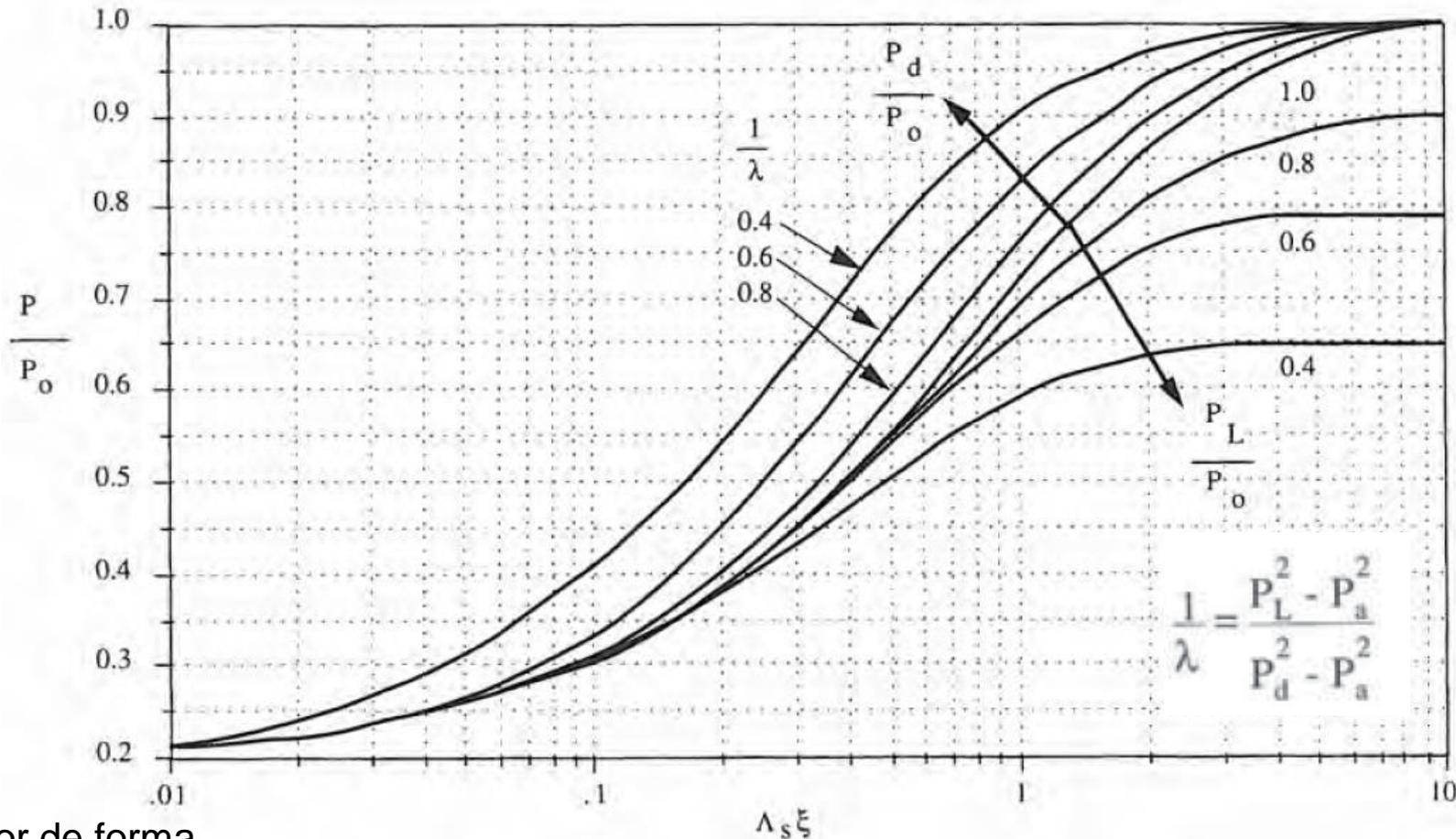
### dimensionamento





## Sapatas aerostáticas retangulares

### dimensionamento



$\xi$  = Fator de forma

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

N número de restritores



## Guias aerostáticas - dimensionamento

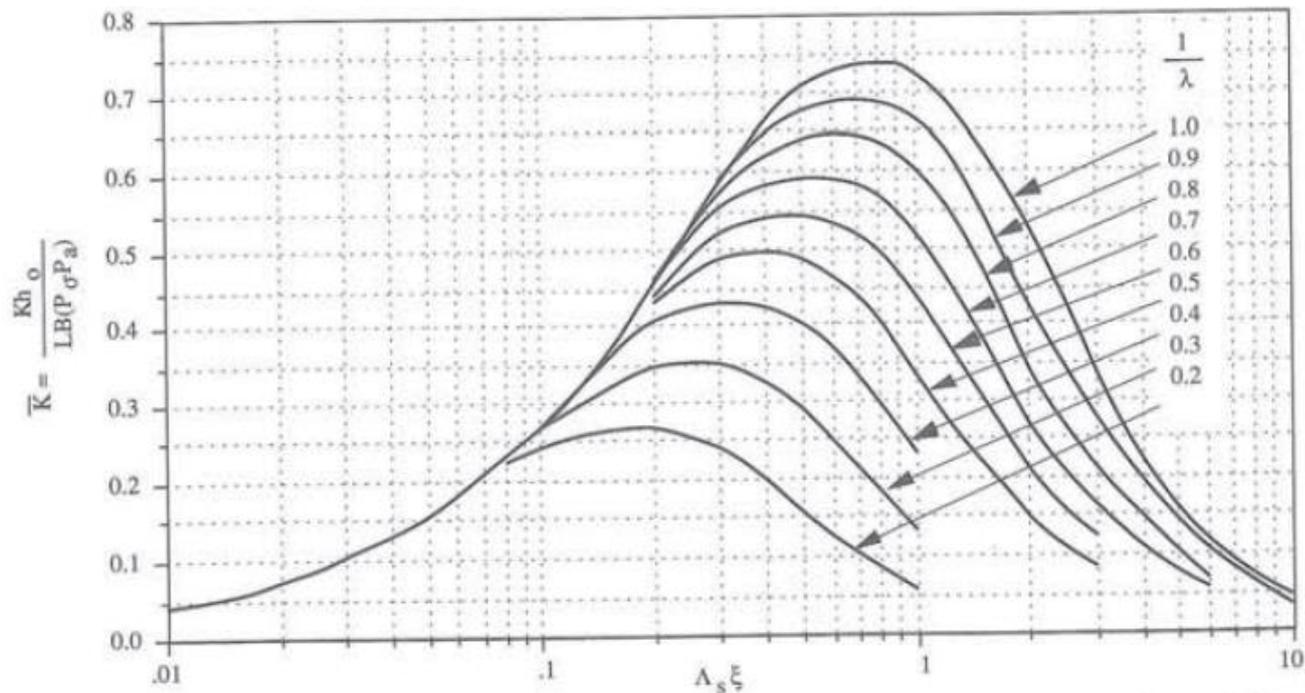


Figure 9.3.32 Stiffness parameter for rectangular double-entry thrust bearings with pocketed orifices where  $a/B = 0.25$ ,  $P_o/P_a = 5$ ,  $C_d = 0.8$ , and  $\nu = 1.4$ . For inherently compensated orifices, multiply the ordinate by 0.67. For single-entry bearings, multiply the ordinate by 0.75.

$\bar{K}$  = 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

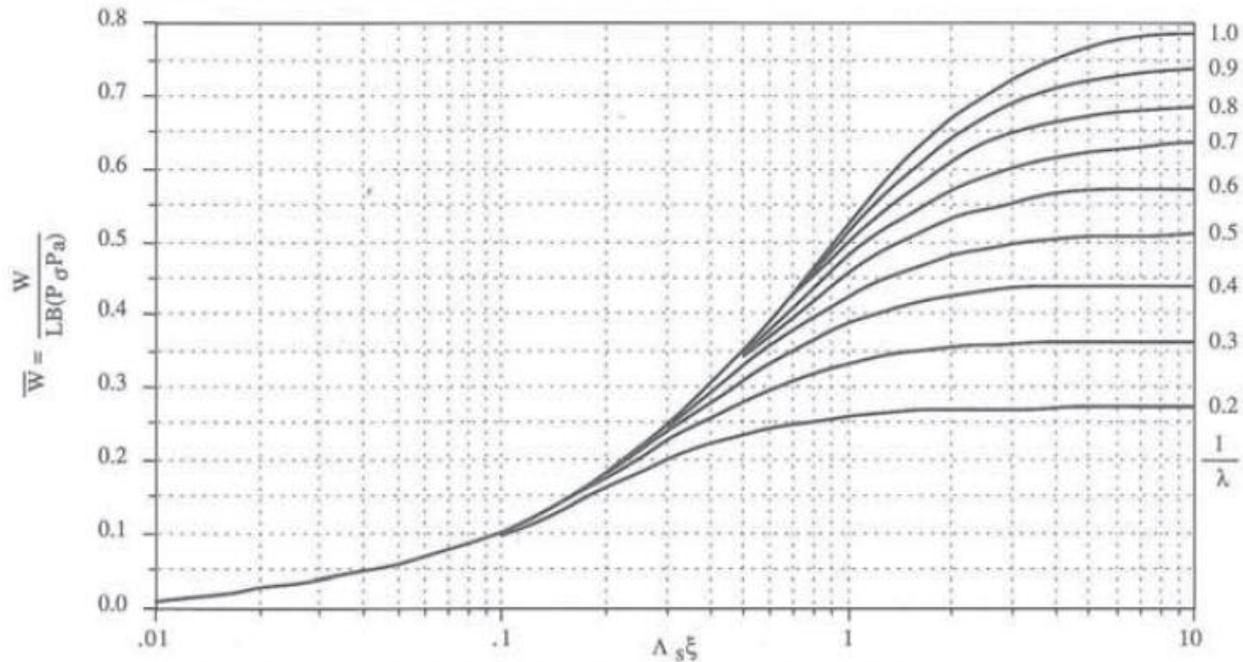


Figure 9.3.33 Load parameter for rectangular double-entry thrust bearings with pocketed orifices where  $\varepsilon = 0$ ,  $a/B = 0.25$ ,  $P_0/P_a = 5$ ,  $C_d = 0.8$ , and  $\nu = 1.4$ . For single-entry bearings, multiply the ordinate by 0.75.

$\bar{K}$  = parâmetro adimensional de rigidez

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

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

$N$  = número de restritores

$$\Lambda_s \xi = \frac{31.55 n d_r \pi B}{P_0 h_0^2 L}$$



## Guias aerostáticas - dimensionamento

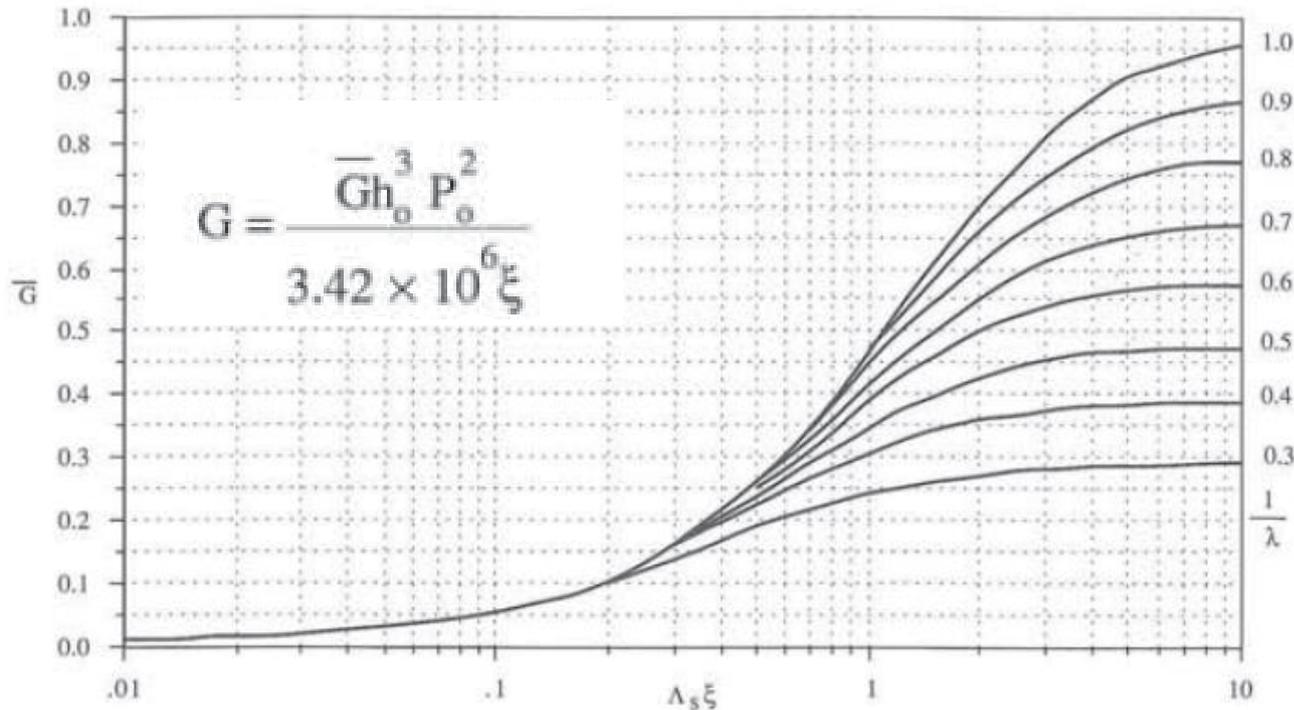


Figure 9.3.34 Nondimensional flow rate for rectangular double-entry thrust bearings with pocketed orifices where  $a/B = 0.25$ ,  $P_o/P_a = 5$ ,  $C_d = 0.8$ , and  $\nu = 1.4$ . For single-entry bearings, multiply the ordinate by 0.5.

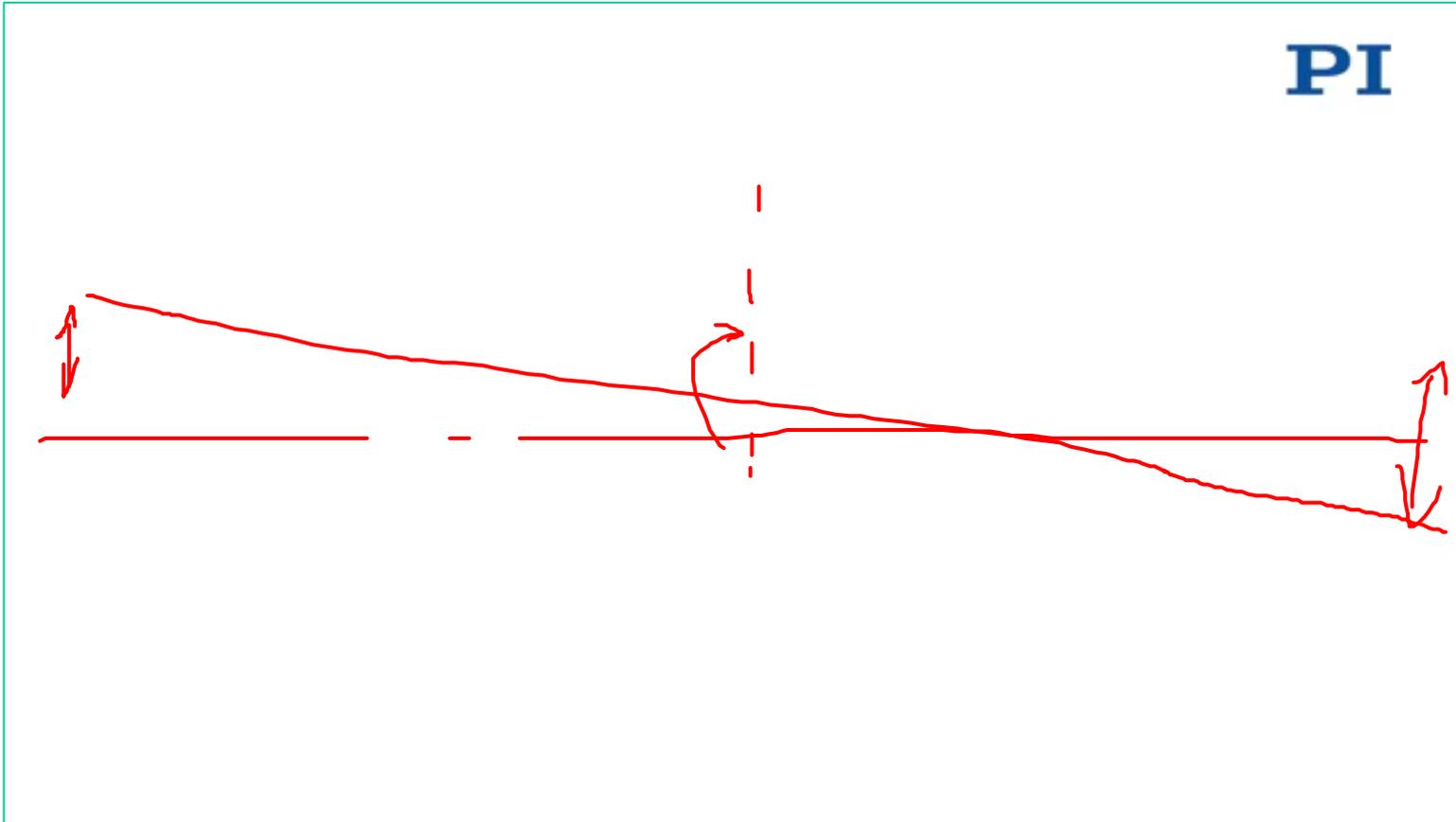
$\bar{K}$  = parâmetro adimensional de rigidez

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

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

$N$  = número de restritores

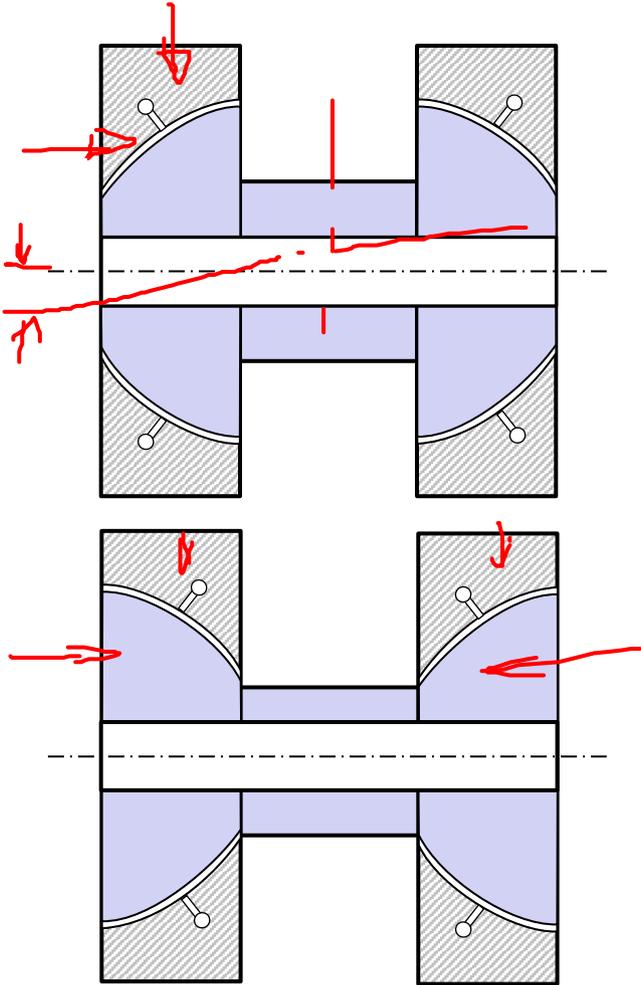
$$\Lambda_s \xi = \frac{31.55 n d_f \pi B}{P_o h_o^2 L}$$



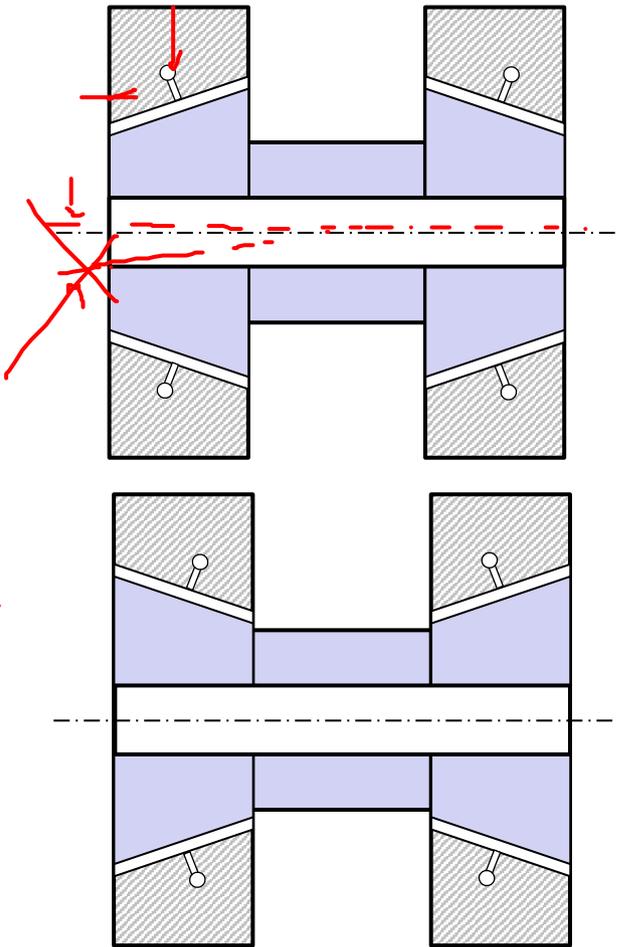


**Formas construtivas**

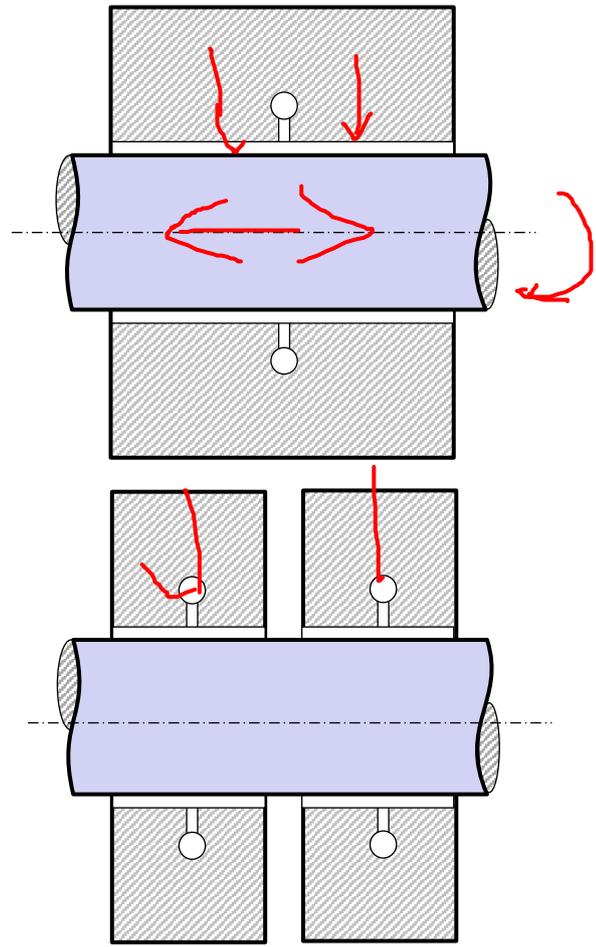
Semiesférico



Cônicos



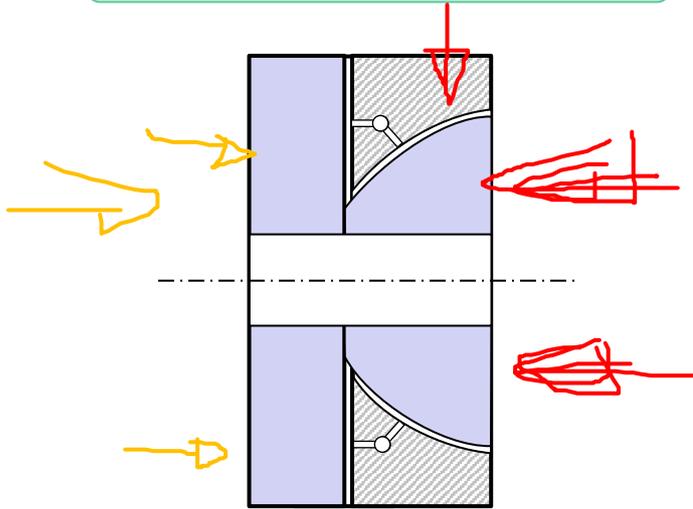
Cilíndricos



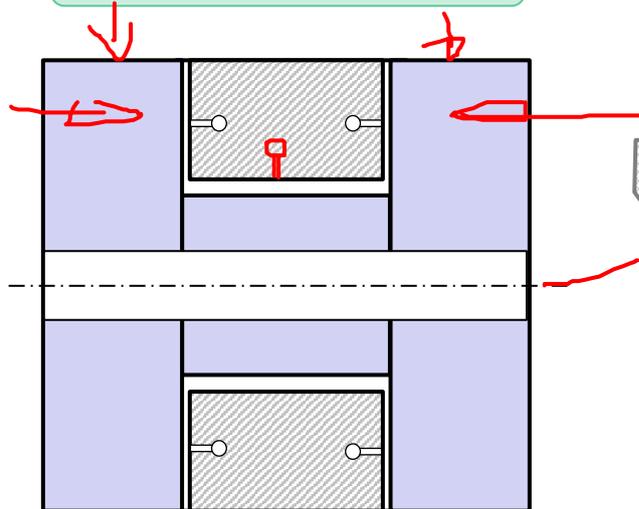


**Formas construtivas**

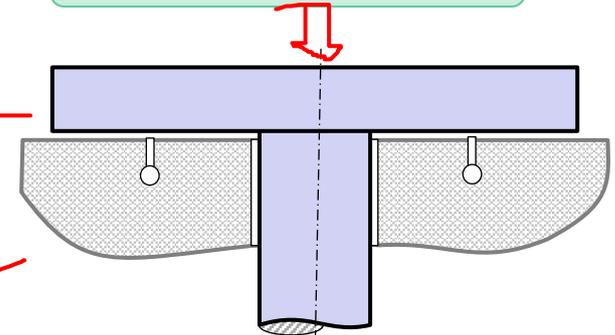
Semiesférico / plano



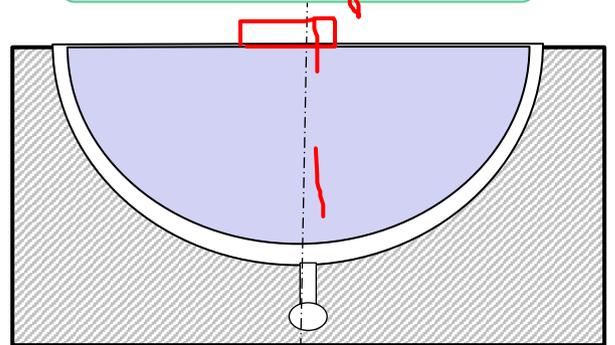
Yates



Axial

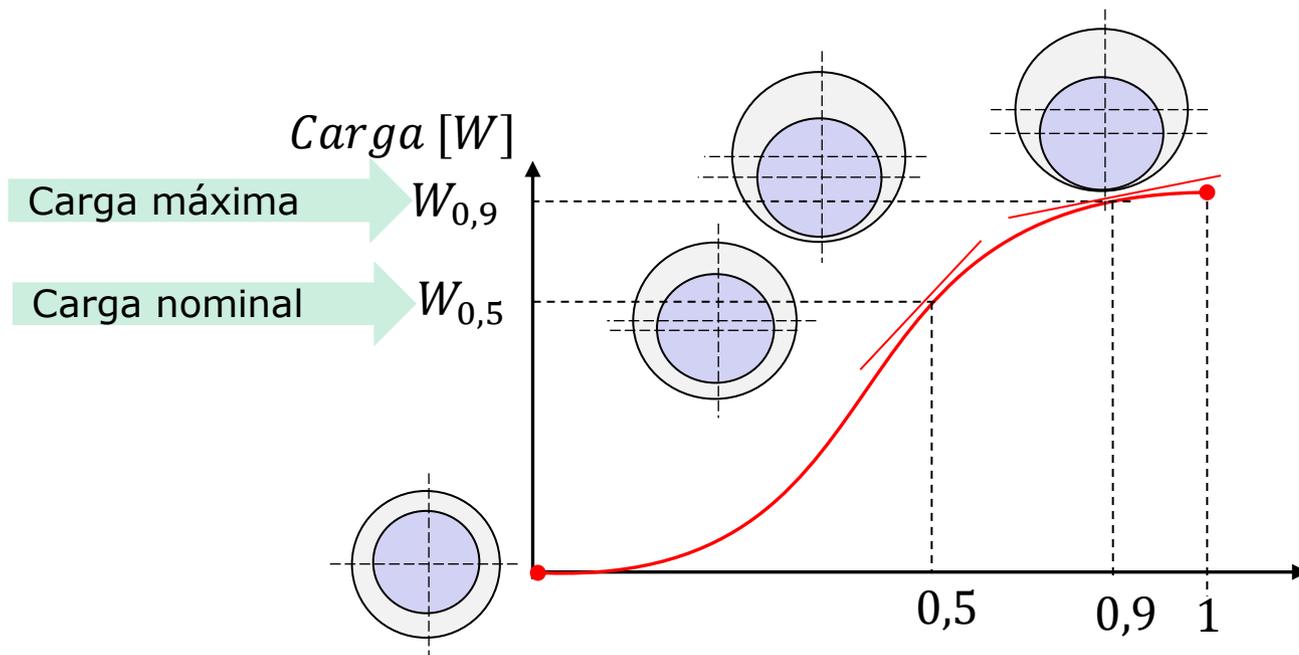
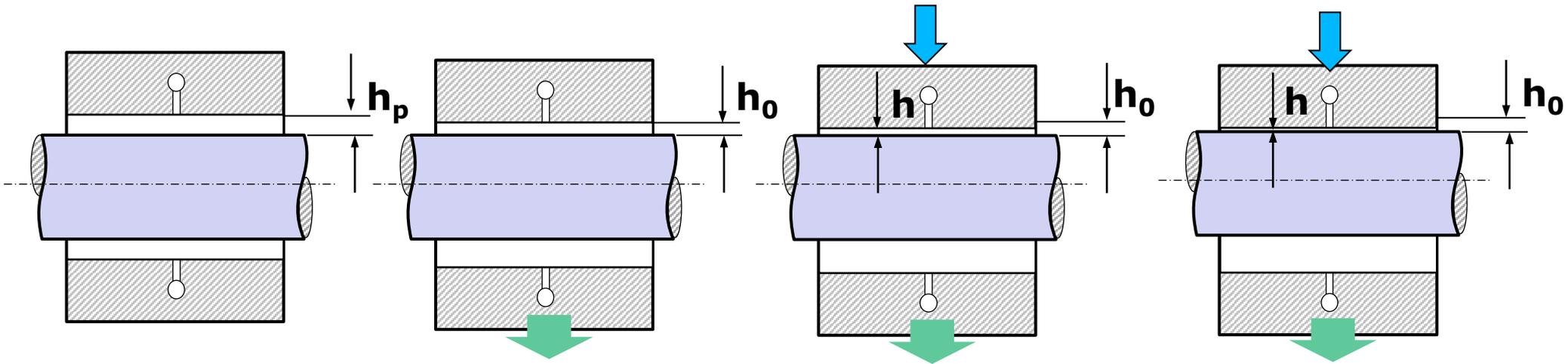


Atitude





**Mancais radiais**



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

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

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

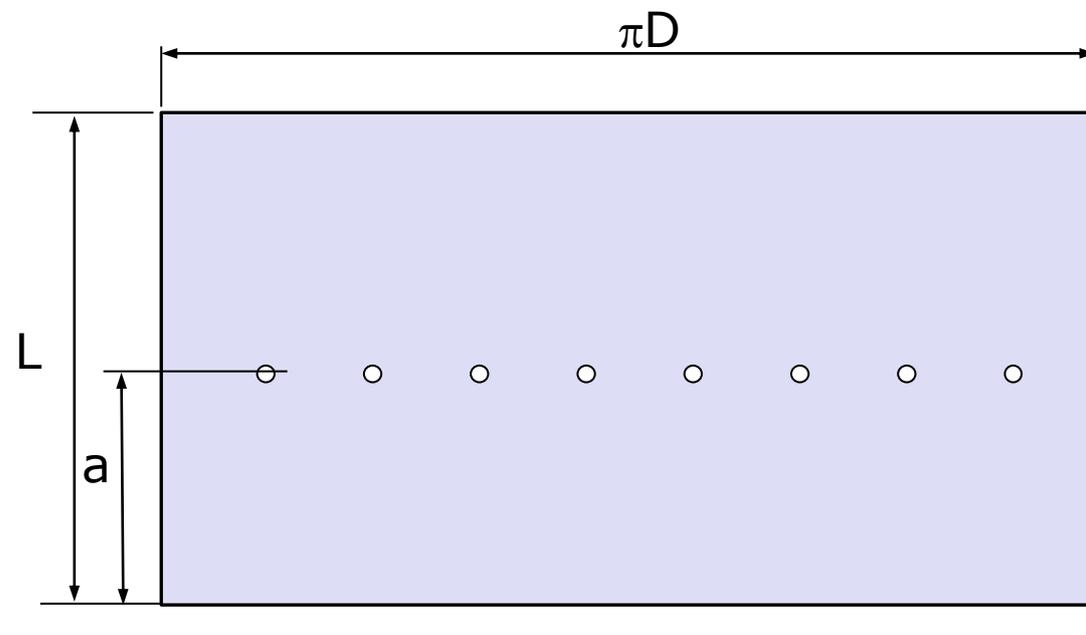
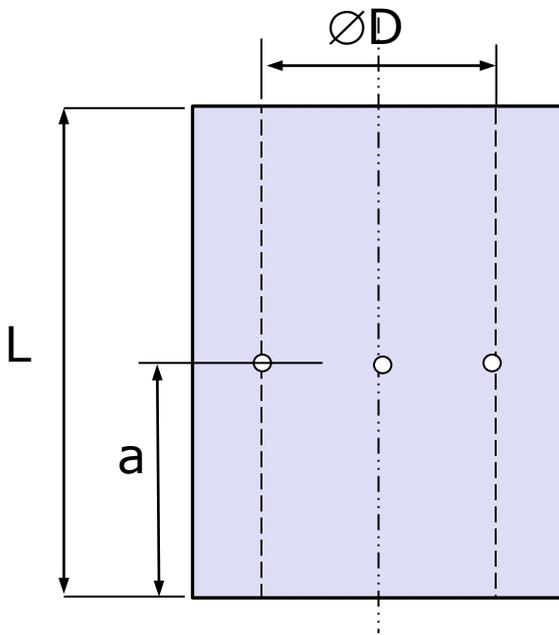
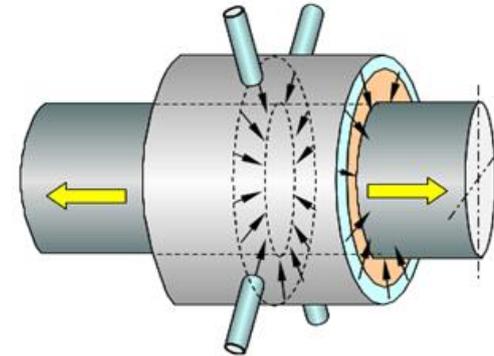
$$\varepsilon = 1 - \frac{h}{h_0}$$



## Mancais radiais

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

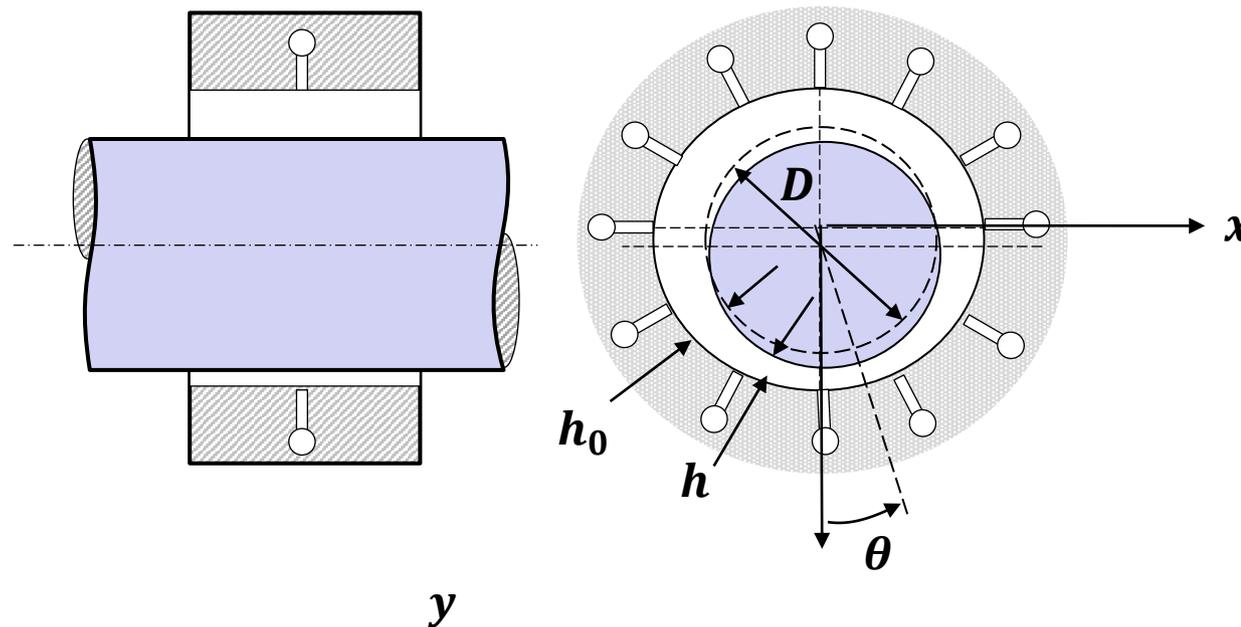
$$K_{radial} = 0,6(L - a) \frac{DP_d}{h_0}$$





Mancais radiais

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

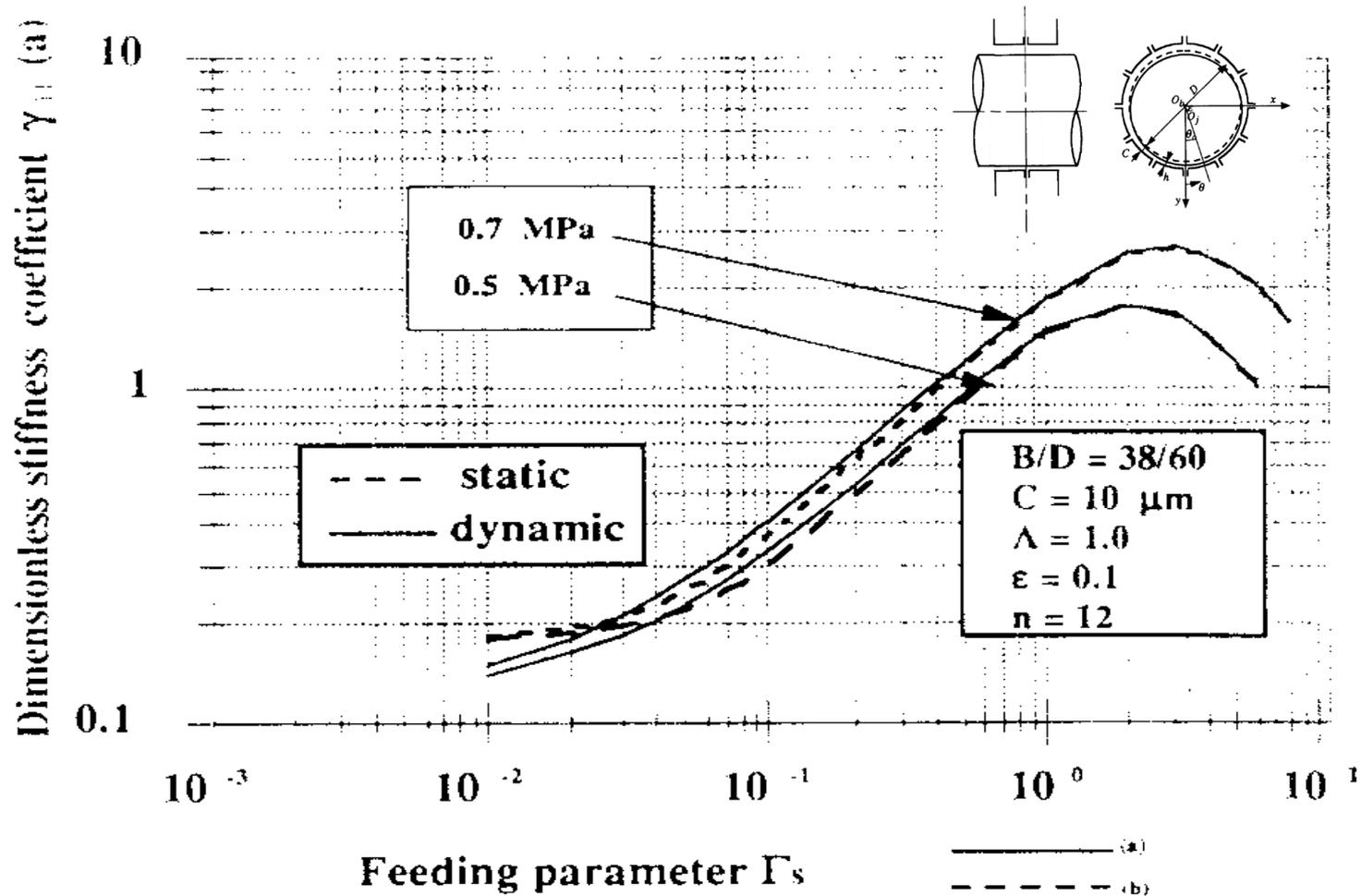


Dong-chul Han, Sang-shin Park, Woo-jung Kim, and Jong-won Kim; A study on the characteristics of externally pressurized air bearings. PRECISION ENGINEERING JULY 1994 VOL 16 NO 3



## Mancais radiais

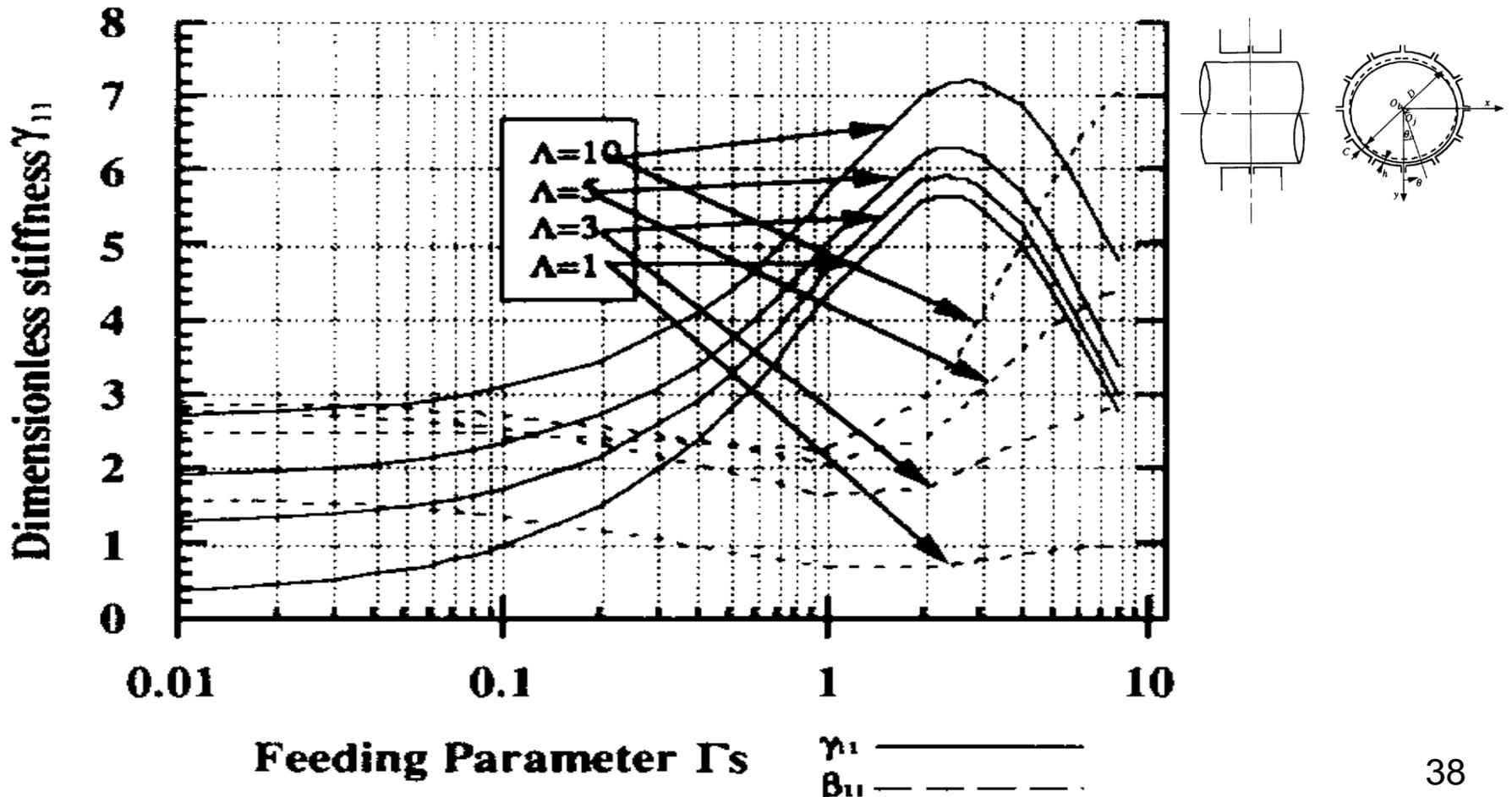
Comparison of static stiffness between dynamic stiffness coefficients





**Mancais radiais**

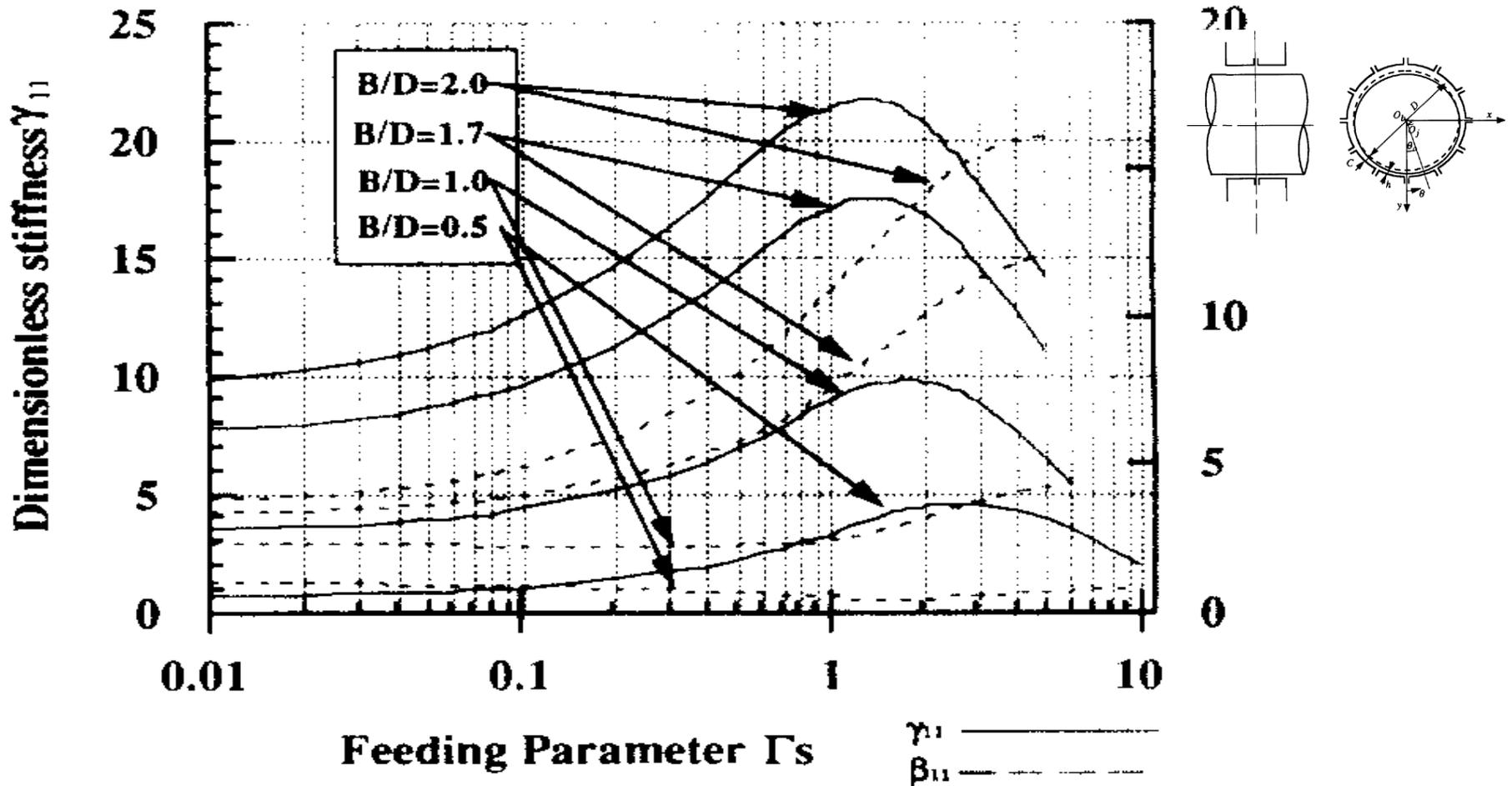
Feeding parameter versus stiffness and damping coefficients ( $P_s = 6$ )





## Mancais radiais

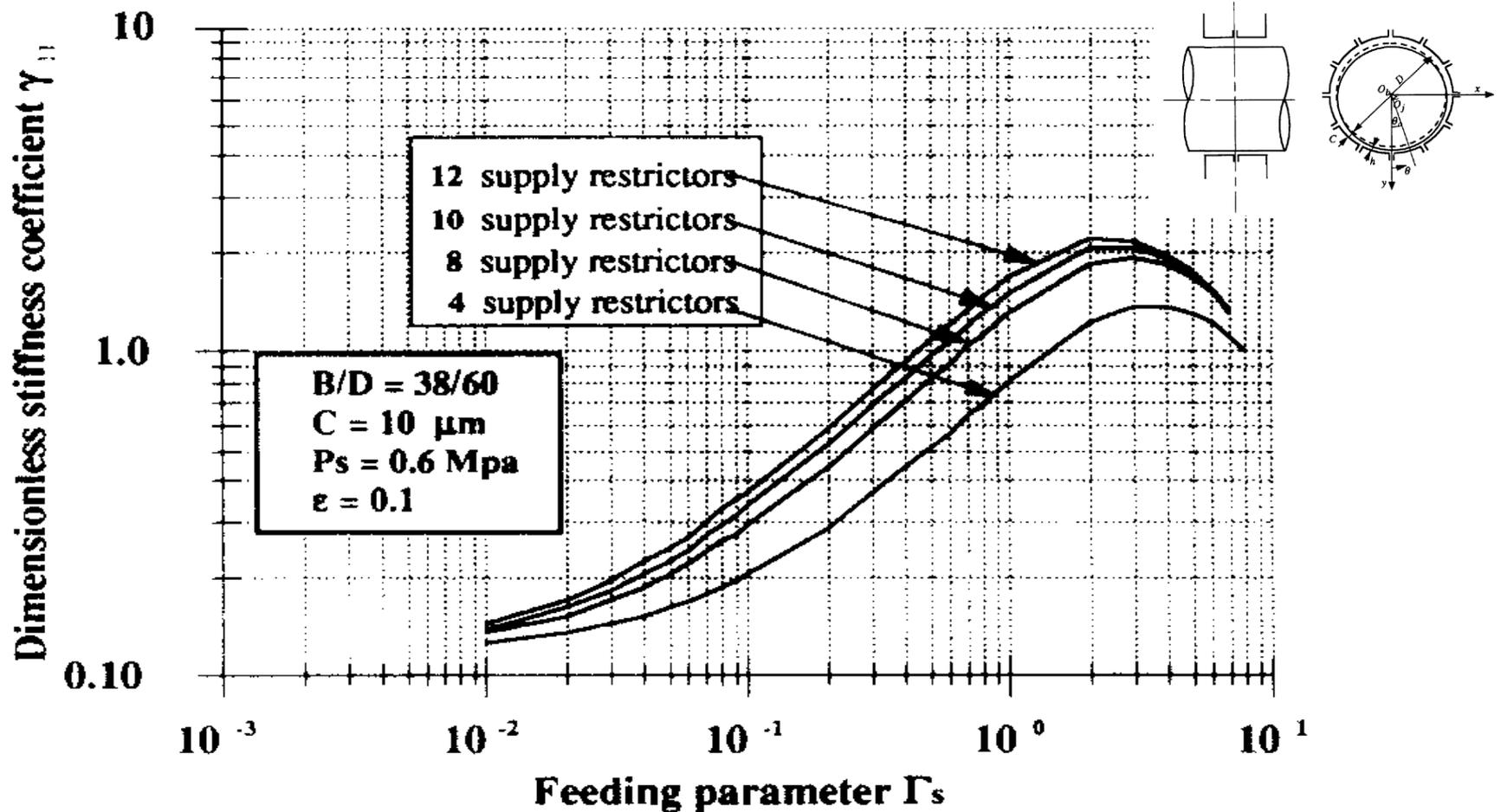
*Influence of B/D ratio*





## Mancais radiais

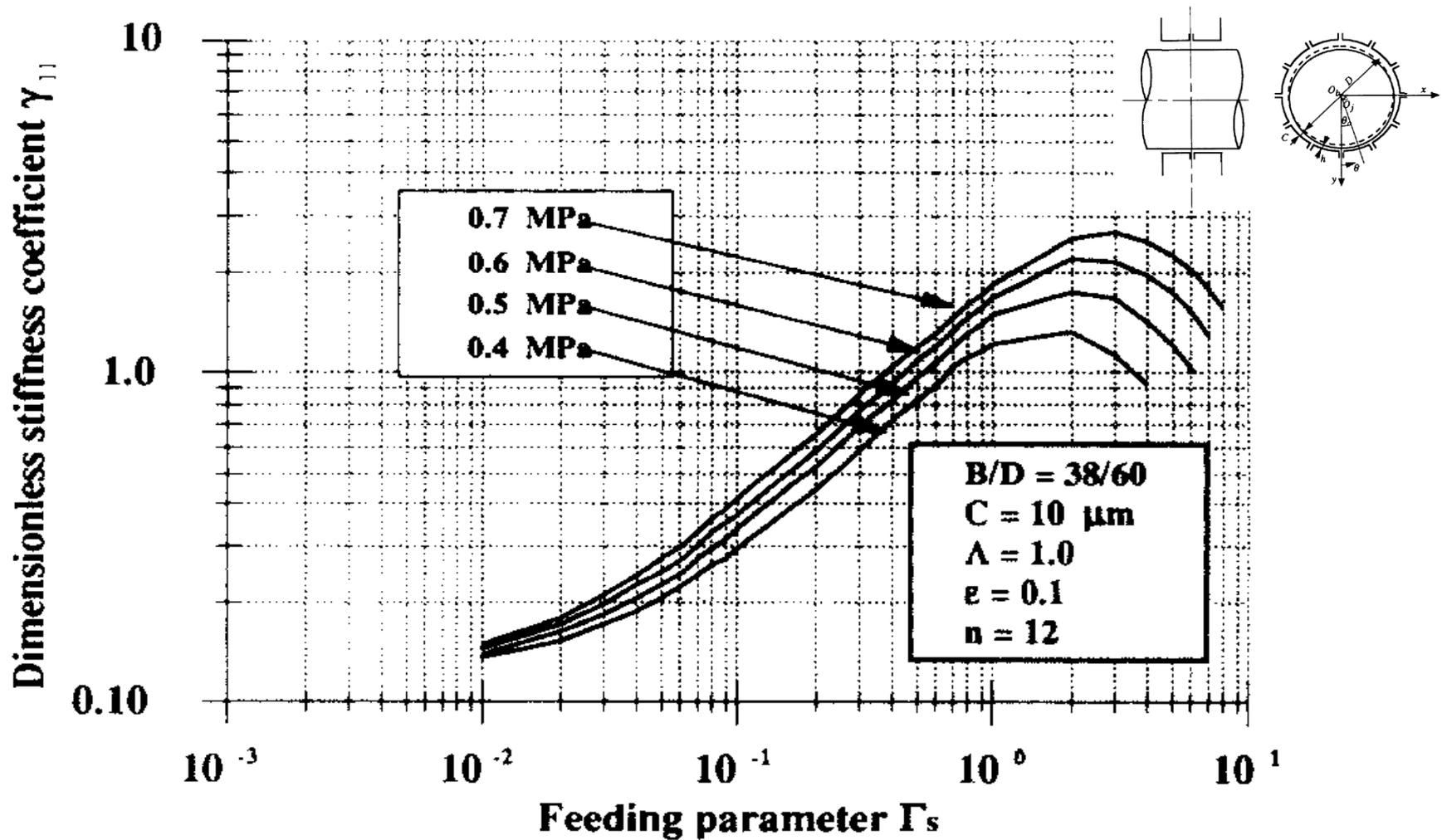
*Influence of number of supply restrictors ( $\Lambda=1$ ,  $P_s=6$ )*





## Mancais radiais

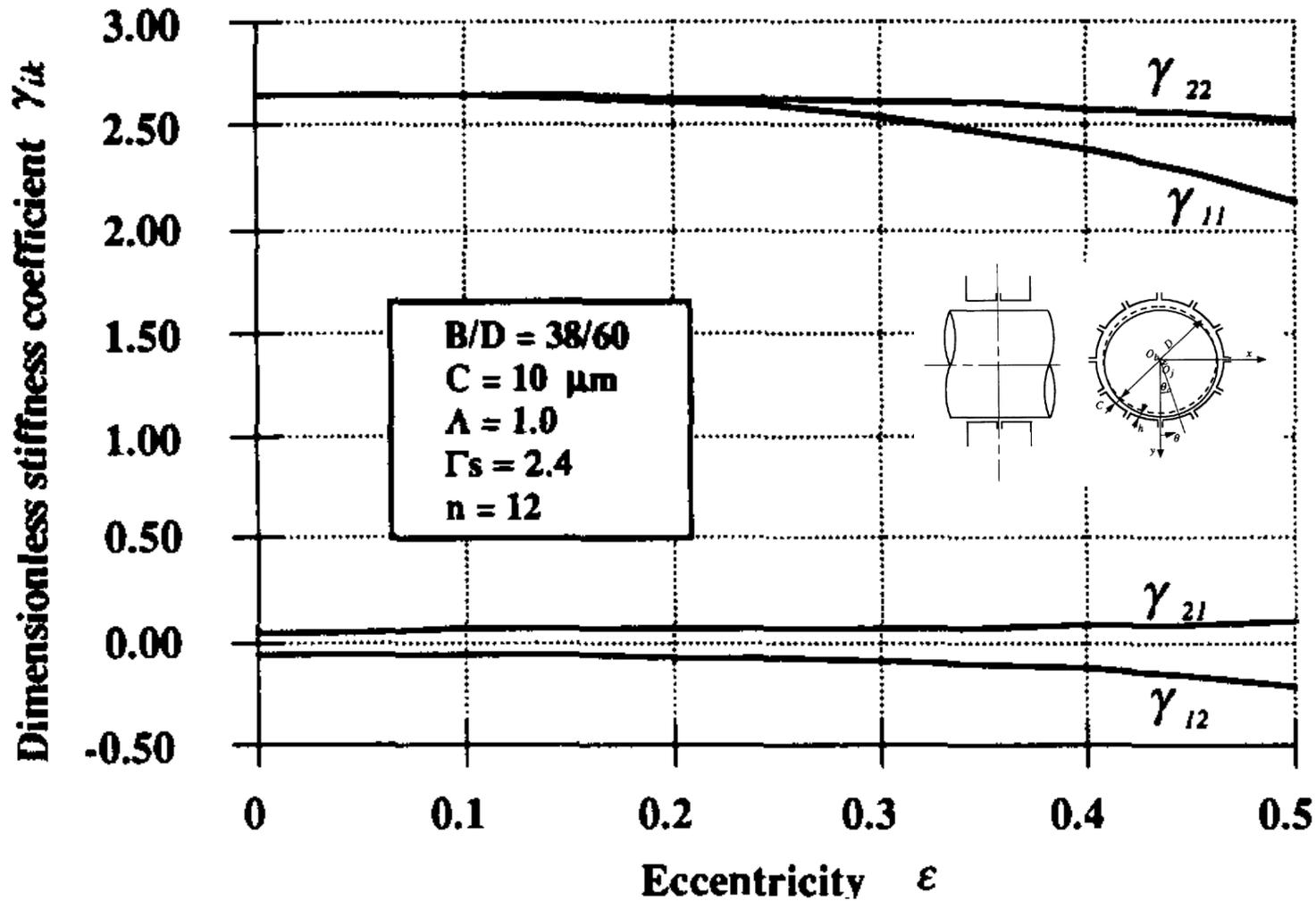
*Influence of supply pressure ( $\Lambda=1, n=12$ )c*





**Mancais radiais**

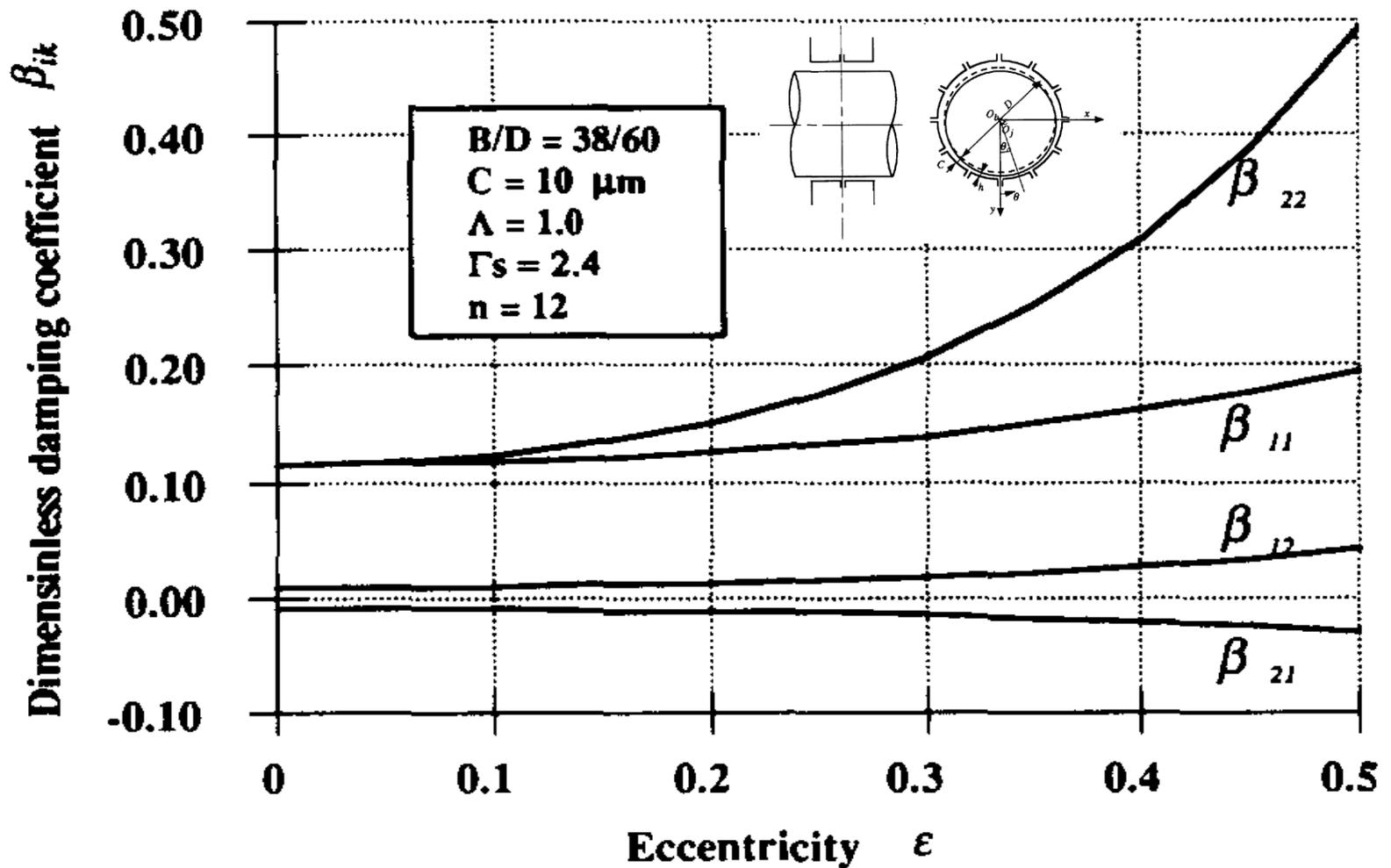
*Stiffness coefficients versus eccentricity ( $\Lambda=1$ )*





## Mancais radiais

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





## Mancais radiais





## 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**