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Lumped parameters models of rectangular pneumatic pads: Static analysis

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ABSTRACT

A lumped parameters model of a rectangular pneumatic pad is developed and static analysis is performed. The model can be implemented more quickly than a distributed parameters model and is equally accurate. The influence of geometric parameters is discussed to help the reader in the design of pneumatic pads. Analysis is carried out in dimensionless form to obtain results of general validity.

1. Introduction

Gas bearings are widely used in precision engineering because of their low friction, oil-free operation and freedom from wear. Accordingly, more and more linear guideways for measuring machines and precision positioning systems are provided with these components. Their design is important in ensuring that the machine meets requirements for load capacity, stiffness, air flow consumption and time response.

Analytical models of flow can be used only for a few simple bearing geometries [1–7]. With the advent of computerized methods, distributed parameters (DP) models made it possible to simulate the pressure distribution under the bearings more realistically, in particular for complex geometries. Finite difference methods [8–12] and finite element methods [13–17] have been shown to be capable of calculating bearings of any geometry. A multiphysics finite element model can also be used to consider the interaction between the air flow dynamics and the bearing's structural flexibility, as for example in [18]. Recently, computational fluid dynamics (CFD) was used jointly with experimental activities to improve the description of the flow field near the supply holes [19–23]. In [24,25], by contrast, semi-analytical methods were employed to determine orifice discharge coefficients, which were then used in analytical formulations.

However, DP models can require considerably longer solution times and it is more difficult to identify the dominant factors that influence pad characteristics. With Lumped Parameters (LP) models, only a few values of pressure in the gap are sufficient to calculate the bearing's characteristics. Though LP models yield less accurate results than DP models, they are faster and simpler to implement in the design process and in optimization. Nevertheless, few papers have addressed simplified LP models.

A circular porous thrust bearing is studied using an LP model in [26]. In paper [27], a circular thrust bearing with multiple pocketed orifices was modeled with a simplified calculation method that was found to be faster than DP methods. An integral gas bearing is analyzed in paper [28] with an LP model, providing information about the most appropriate configuration. Paper [29] analyzes rectangular pads with a supply recess. Analysis makes use of simplifying assumptions and an empirical formula which relates the recess pressure to the supply pressure. In paper [30], a lumped model is used to study the behavior of a pneumatic journal bearing.

As far as the authors know, rectangular pads have been investigated in only a few experimental studies [31,32] and in analytical analyses dealing with simplified geometries [33]. The present paper introduces a lumped parameters model that is a practical and sufficiently accurate tool for designing and optimizing rectangular pads with multiple holes. This model is the evolution of a previous model described in papers [34,35]. A rectangular pad shape is considered with different aspect ratios, supply pressures and number and diameter of supply holes. Static results are discussed in dimensionless form. The results of the LP model are compared with those of the DP model and their accuracy is estimated.

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Nomenclature

α	dimensionless distance from pad edge
β	pad aspect ratio
γ	dimensionless distance between supply holes
μ	gas viscosity
$\bar{d}_s$	supply hole diameter
b	critical pressure ratio
c_d	supply hole discharge coefficient
d_s	dimensionless supply hole diameter
h	air gap
h_{ref}	reference air gap (=10 μm)
k	pad stiffness
$\bar{k}$	dimensionless pad stiffness
k_T	temperature coefficient, $k_T = \sqrt{\frac{T_0}{T}}$
l	distance from pad edge
p	pressure
p_a	ambient pressure
p_c	supply hole downstream pressure
p_0	mean pressure in supply rectangle
p_s	supply pressure
ρ_0	air density in normal conditions (p_0 = 100 kPa and T_0 = 293.5 K)
w	distance between supply holes
C	conductance of the supply hole
F	pad load capacity
$\bar{F}$	dimensionless load capacity
Φ	pressure ratio coefficient
G	gas mass flow rate
$\bar{G}$	dimensionless gas mass flow rate
H	dimensionless air gap
L_x, L_y	length of pad sides
N_x, N_y	number of supply holes along x, y directions
P	dimensionless pressure
R	gas constant, in calculations =287 J/(kg K)
Re	Reynolds number
T	absolute temperature, in calculations =293 K
Ψ	coefficient of isentropic expansion, in calculations $\psi = \frac{0.685}{\sqrt{R \cdot T}}$
X, Y	dimensionless axes

2. Pad geometry

Rectangular pads with sides L_x and L_y are considered. Pad geometry is shown in Fig. 1. Multiple supply holes are positioned on the sides of a supply rectangle at distance l from the edges of the pad. This distance is the same along x and y directions. The holes are equi-spaced at a distance w, which is also assumed to be equal along the two directions. The hole diameter is d_s. The following dimensionless parameters completely define pad geometry and supply hole position:

$$\alpha = \frac{l}{L_x}$$
$$\beta = \frac{L_y}{L_x} \tag{1}$$
$$\gamma = \frac{w}{l}$$

α is the dimensionless parameter that indicates the distance of the supply holes from the edges of the pad. β is the aspect ratio of the pad and γ is the ratio of the distance between the holes referred to the distance from the edges. L_x is assumed to be greater than L_y, so $0<\beta<1$? Coefficient α is defined in the range $0<\alpha<\beta/2$? Case $\alpha = 0$ is not realistic, as the supply hole would be in correspondence of the pad edge. Case $\alpha = \beta/2$ is not realistic too as two rows of holes would coincide in only one row positioned at the center axis of the pad. Given these three parameters, the number of holes N_x and N_y along the x and y directions is defined by formulas (2):

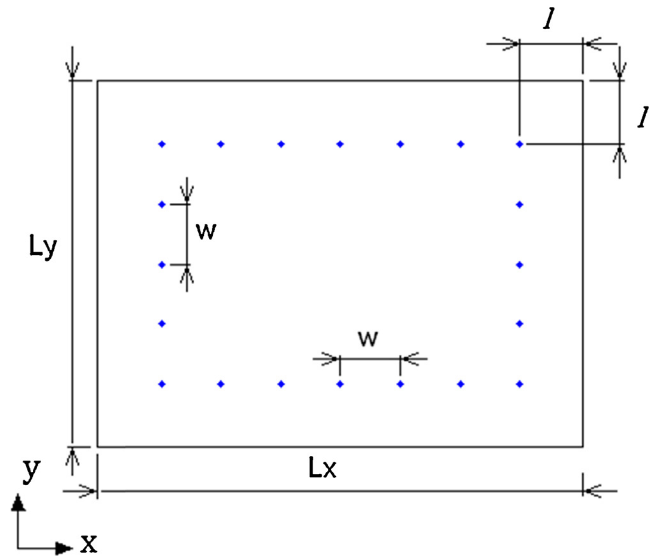

Fig. 1. Sketch of the pad geometry under investigation.

$$N_x = \frac{1-2\alpha}{\gamma\alpha} + 1$$
$$N_y = \frac{\beta-2\alpha}{\gamma\alpha} + 1 \tag{2}$$

The total number of supply holes is $2N_x + 2N_y - 4$. The minimum number of supply holes in this model is 4.

3. Distributed parameters model

The dimensionless form of the Reynolds equation for gas-lubricated bearings in steady conditions (3) is solved for the pads under investigation,

$$\frac{\partial}{\partial X}\left(PH^3\frac{\partial P}{\partial X}\right) + \frac{\partial}{\partial Y}\left(PH^3\frac{\partial P}{\partial Y}\right) = 0 \tag{3}$$

where $X = x/L_x$, $Y = y/L_x$, $H = h/h_{ref}$, $P = p/p_a$. h_{ref} is the reference air gap, assumed equal to 10 μm.

A flow term at the input orifices is added to Eq. (3). Pad input flow is the sum of the contributions of each supply hole. It can be easily approximated by an ellipse in the subsonic regime using ISO 6358 formula [40].

$$G = Ck_T\rho_0 p_s\sqrt{1-\Phi^2} \tag{4}$$

where C is the conductance of each supply hole, ρ_0 is the air density in normal conditions (p_0 = 100 kPa and T_0 = 293.5 K), Φ is a coefficient that depends on the pressure ratio across the supply hole and $k_T = \sqrt{\frac{T_0}{T}}$ a temperature ratio coefficient. The expression of the conductance is

$$C = \pi\frac{d_s^2}{4}\frac{\Psi c_d}{\rho_0}$$

where, considering isentropic expansion, see [40], we have

$$\Psi = \frac{0.685}{\sqrt{R \cdot T}}$$