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Review

On the modelling of the dynamic characteristics of aerostatic bearing films: From stability analysis to active compensation

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ABSTRACT

Determination of the static characteristics of air bearings constitutes the necessary first phase in a design problem, which determines general feasibility. In order to realize a successful application, a good knowledge and assessment of the dynamic behaviour is needed to complement the previous step. In a conventional, passive bearing application, dynamically stable behaviour should be ensured by overcoming the occurrence of self-excited vibrations; the so-called "pneumatic hammering". In active bearing applications, on the other hand, the dynamic bearing force, induced by actuation of the gap geometry or supply pressure, provides for a means of enhancing bearing static and dynamic performance, when integrated in a mechatronics system context.

This paper presents on the one hand an overview of the methods used to model the dynamic characteristics of aerostatic films, deducing that the method of harmonic perturbation is often sufficient in providing a good estimate of the dynamic stiffness. This is confirmed by comparing theoretical results with dynamic response experiments. On the other hand, the general problem of active dynamic compensation is outlined and an application example is provided to show the high levels of performance achievable by employing this method.

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1. Introduction

Air bearings offer important advantages over conventional bearings, which emanate from their low friction/high speed capabilities combined with their high accuracy and long life [1]. That is why aerostatic bearings are widely used in precision systems. Those advantages of air bearings cannot however always be realised to the full owing to some limitations, in particular, their low specific stiffness and their liability to develop negative damping, which may lead to pneumatic hammering, in certain working conditions. The question is how to overcome these limitations, or even turn them to advantages.

The necessary first step in bearing design is the prediction of the static characteristics: this provides the general domain of feasibility of a bearing application, especially in regard to load carrying capacity, or mean bearing pressure. Such a domain is bounded by the minimum allowable film thickness and the maximum allowable pressure. Knowledge of the dynamic behaviour of the air film is, however, needed to complete or modify this picture. This may lead to either limiting or extending the domain of feasibility, depending on whether the application be that of a passive or an active bearing, respectively.

In the first of these two instances, air bearings are prone to a type of self-excited vibration known as "pneumatic hammer", whose likelihood seems to increase the more one tries to enhance the static characteristics [1]. In other words, dynamic stability represents an additional limit-line for bearing design optimisation. However, in understanding the problem of dynamic stability, we hope not only to be able to predict its likelihood, in order to avoid it, but eventually also to be able to overcome it by modifying either bearing or supporting structure or both.

In the second instance, the air film characteristics depend on such design parameters as feed pressure and film geometry, which, although usually taken to be fixed, can be dynamically varied by applying suitable actuators. In this way, the dynamic characteristics can be modified by means of *active compensation*. This possibility, which is encouraged by recent developments in actuator/sensor/controls technology and the advances made in the mechatronics methodology, should lead to an extension of the range of application of air bearings.

A third aspect pertaining to dynamic behaviour is the use of a fluid film as a "squeeze" film bearing, damper, or both. Here, the fluid flow in the film is caused solely by the reciprocating motion of the bearing surfaces so as to generate a damping force, or even a net load carrying force when the oscillation amplitude is sufficiently large (owing to the non-linear behaviour of the air film).

The key to utilising all these aspects and possibilities is a good fundamental understanding of the dynamic behaviour of air bearing films. This is the main subject of this paper. Although there has been much work on the dynamic stability of air bearings [2], no systematic treatments of the dynamic characteristics are available.

This paper will review the questions of mathematical modelling of the dynamics of an aerostatic film and the subsequent use of those models (i) for dynamic stability analysis of systems incorporating aerostatic bearings and (ii) for the design of actively compensated bearings. The analyses are based on the consideration of a nominally flat, circular, centrally fed air bearing pad such would lead to easy formulation of the problem without loss of generality. The treatment could be easily extended to bearings of other forms and configurations.

In the following section, the problem is briefly outlined. Thereafter, a mathematical formulation is sketched together with the form of the results. Applications to the problem of dynamic stability and to actively compensated bearings are then discussed.

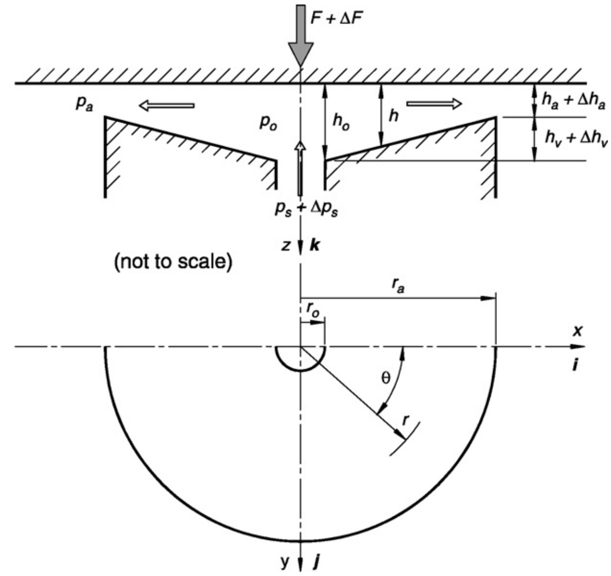

Fig. 1. Aerostatic bearing configuration.

2. Background

A schematic of an aerostatic bearing pad is depicted in Fig. 1. Air at an absolute pressure p_s is fed through the central hole, of radius r_o, entering the gap at a pressure p_o,[1] whence it flows in a viscous manner with mass flow rate $\dot{m}$ to atmosphere, pressure p_a, at the outer boundary of the bearing. The gap is assumed to have an axisymmetric form with an arbitrary height function $h(r)$. In particular, however, we will consider only the case of a linear gap variation so that the gap form is characterised by a single parameter h_v, termed the "conicity" of the bearing. This is usually of the same order of magnitude as the nominal gap height h_a (measured at the outer edge). It may be regarded as a special case of shallow grooves or recesses, which could be treated in a similar way. The bearing supports a force F which, in the static case, is equal in magnitude to the integral of the film pressure over the area.

The static characteristics of the bearing, i.e. the bearing force (or load capacity) F, the stiffness $k = -\partial F/\partial h_a$ and the flow rate $\dot{m}$ (for a given bearing size r_a) are obtained as

$$\{F, k, \dot{m}\} = f(p_s, h_a, h_v, r_o, r_a) \quad (1)$$

through the solution of the Reynolds equation in the viscous flow part of the film together with the feed and entrance flow problems (see Refs. [2–4]). In these references, reliable models have been developed that can accurately predict the static behaviour of this bearing type.

With the help of these models, the static performance may be optimised. The objective can be, for instance, to maximise the bearing force or stiffness for a given flow rate over a certain gap height range.

A word about the static characteristics of bearings with convergent gap geometry may be in order here. Both theory and experiment [1] have shown that such type of bearing geometry yields higher load capacity and better stiffness characteristics, especially

[1] This is in fact an expedient (fictitious) pressure value obtained by extrapolating the downstream viscous pressure profile back to gap entrance. In reality, there will be a pressure depression/recovery period immediately downstream of the feedhole. For details about this, see Ref. [2–4].