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Stability and vibration characteristics of a rotor-gas foil bearings system with high-static-low-dynamic-stiffness supports

Yongpeng Gu *, Yanhui Ma, Gexue Ren

School of Aerospace Engineering, Tsinghua University, Beijing 100084, China

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A B S T R A C T

Supporting gas bearings with proper flexible supports can improve the stability performance of a rotor-bearings system. Many researchers had successfully applied O-rings to stabilize the high-speed rotor mounted on the rigid surface gas bearings. However, no systematic investigation on dynamic characteristics of gas foil bearing with flexible supports is available so far. Furthermore, how the support properties affect the unbalance and shock vibration characteristics has not been fully investigated yet. There may well be this case that a trade-off between stability, unbalance and shock vibration reduction performances exists. So this research aims to synthetically study the effects of support stiffness and damping on dynamic characteristics of the rotor-gas foil bearing system, i.e., stability, unbalance and shock vibration characteristics. In addition, high-static-low-dynamic stiffness (HSLDS) type springs are used as flexible supports to improve the dynamic performances of the system. Parameter studies of support stiffness and damping on dynamic performances provide guidance for the design of HSLDS. Simulation results demonstrated the effectiveness of the application of well-designed HSLDS.

1. Introduction

Gas bearings are increasingly popular in advanced high-speed rotating machinery [1,2]. They have specific advantages in comparison to traditional rolling-element and oil bearings, such as fewer components, oil-free, low frictional losses and wide temperature operation ranges. However, with the limited damping capacity of gas bearing, the major problem that encountered in high-speed condition is the self-excited whirl instability [2–4]. Besides, vibrations excited by the unbalance mass and the shock response from base movements are also concerns. In another word, the stability and vibration problems together limit gas bearings to extent to such extreme high-speed applications.

Continuous efforts had been carried out to improve the stability of the high-speed rotor-gas bearing system. Approaches to enhance the stability can be classified into two categories [3], respectively, measures within the gas film or outside. The former mainly optimizes the geometric configurations of bearing to achieve better stiffness and damping characteristics of the gas film. And the latter introduces additional damping outside the film to improve the dynamic stability of system by supporting the bearing with flexible elements, such as rubber O-rings [5]. As a special case, the foil structures of the gas foil

* Corresponding author.
E-mail address: wmguyp@gmail.com (Y. Gu).

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bearing (GFB) both take measures within and outside the gas film, i.e., they change the film geometry by deformations of top foil under the pressure of gas film and introduce external damping which are generated by frictions due to relative motions of the foil structures.

In 1965, Lund [6] first investigated journal bearings with flexible supports and showed that the flexible support with proper parameters can improve stability of the rotor-bearings system. Since then, many researchers [3,5,7–15] have investigated on the use of flexible support to improve stability of gas bearings through theoretical and experimental methods. The most used flexible support element is rubber O-ring. Several researchers [5,9,13,16] had measured the stiffness and damping characteristics of rubber O-ring and studied how these properties influences the stability of rotor system. In Ref. [5], Powell et al. studied the pressurized air bearing with rubber O-rings and made a conclusion that this is a simple and effective way of stabilization. Theoretical and experimental results by Kazimierski et al. [8] indicated that rubber O-rings increase the threshold speed of rotor system. A second stable region was theoretically found at particular values of stiffness and damping in Ref. [7,10,11,15]. There is an optimal dynamic stiffness that maximizes the threshold speed. In the last decade, Belforte et al. [12,13], Waumans et al. [3] and Miyanaga et al. [14,16] applied O-rings to stabilize the high-speed rotor mounted on the rigid surface gas bearings. All of them achieved higher threshold speeds than the fixed bearing bushing, demonstrating the effectiveness.

However, all above studies focused on rigid surface gas bearings, investigations of GFB with flexible support are not available in the published literatures so far, though GFB has been widely used. Foil structures of GFB and flexible elements that support the bushing can each play a specific role in improvements of dynamics performances. On one hand, gas foil bearings mounted on flexible support would further enhance the stability on the base of foil bearings. On the other hand, the flexible support can act as an isolator that reduce the vibration due to mass unbalance or shock excitation.

Furthermore, how the support properties affect the unbalance and shock vibration characteristics has not been fully investigated yet. Recently, the nonlinear isolators, especially those with high-static-low-dynamic-stiffness (HSLDS) characteristic [17], are popular in vibration control of rotor-bearings systems [18–20]. The HSLDS type spring can give consideration to both the static displacement and vibration isolation. Carrella et al. [19] analysed a simple rotor model with HSLDS mounts. They showed that the HSLDS spring is more effective than the linear spring in comparing the system unbalance response. Abbasi et al. [18] presented an optimum design method of HSLDS for the vibration control of the rotor-oil film journal bearings system.

Based on these backgrounds, this research aims to synthetically study stability, unbalance and shock vibration characteristics of a rotor-GFBs system with HSLDS supports. To theoretically predict the system dynamic characteristics, efficient and accurate nonlinear dynamic simulation of this rotor-GFBs system with nonlinear support is needed. Recently, Pham and Bonello [21,22] presented an efficient computation method of the rotor-GFBs system by solving all of the state variables of system simultaneously, hence larger step size is allowed in simulations. Larsen et al. [23] got solutions of the mathematical model based on this strategy, and obtained a good correlation between experimental and theoretical results with correct estimation of stiffness and loss factor of foil structures. The simulation of the rotor system in this research is based on these previous works, so a set of coupled system of ODEs is established and solved.

The rest of this paper is organized as follows. In Section 2, the analytical model of a symmetric rotor-GFBs system with HSLDS supports is presented. Section 3 introduces numerical methods of time domain simulation and stability analysis of the rotor system. In Section 4, results and discussions on stability, unbalance and shock vibrations characteristics are given. Effectiveness of the use of HSLDS to improve dynamic performance of system are also presented in Section 4.

2. Analytical model

The symmetric rigid rotor-GFBs system shown in Fig. 1 is used as the model of this research, in which the bearing bushings are not fixed but supported by suspensions. The unbalance mass is located on the center disk only. The rotational speed of the rotor is denoted as Ω. The mass of the rotor is $2m_s$, so the static load in x direction per bearing is m_sg. The

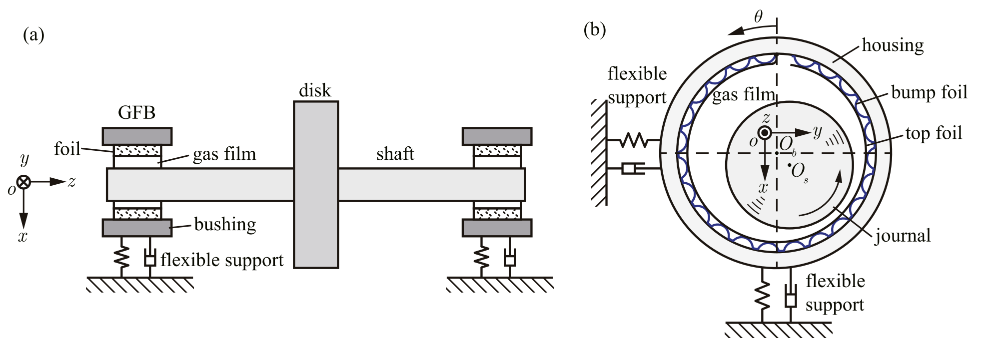

Fig. 1. Symmetric rigid rotor-GFBs system with flexible supports. (a) rotor-GFBs system; (b) configuration of GFB.