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# Analysis and experimental study on a novel gas foil bearing with nested compression springs

Kai Feng[a], Wanhui Liu[a,*], Rui Yu[a], Zhiming Zhang[b]

[a] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China
[b] The Clean Energy Automotive Engineering Center, School of Automotive Studies, Tongji University, Shanghai 201804, China

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## ABSTRACT

This paper presents a theoretical analysis and experimental study on a novel nested compression spring gas foil bearing (NSFB), which uses a layer of springs as elastic support structure. The stiffness and damping of the support structure can be easily controlled by adjusting the spring number and diameter. Reducing the stiffness of the springs at both ends of the NSFB significantly improves bearing load capacity. The direct stiffness and damping coefficients of NSFB with 39 and 47 springs are much larger than those of NSFB with 31 springs. Experiments were conducted to investigate the start-stop characteristic, the stiffness and damping performance of NSFB. As the spring number increased from 31 to 47, both the linear stiffness and loss factor increased.

## 1. Introduction

As the technical improvement in the field of turbomachinery, the rotating equipment develops toward miniaturization, compactness and simplification. However, particular operating parameters, especially power output, should be ensured. Thus, increasing the rotational speed is a feasible method. As the speed increases, the traditional bearings may fail because of some problems like unstable, serious wear, excess heat generation, and oil degradation. Gas foil bearing (GFB) technology is an effective solution to these problems since its proposal in the mid-20th century because of its frictionless and oil-free support for the rotor in turbomachinery. GFBs have distinct advantages over ball bearings or oil-lubricated bearings, such as high operating speed, compact structure, high efficiency, and be able to work in extreme temperature condition. Generally, GFBs are assembled by a bearing sleeve, a layer of elastic support structure and a top foil [1]. The elastic support structure provides stiffness and damping for the bearing. The eccentricity ratio of the rotor supported on GFBs may be larger than 1 because of the elastic support structure, which indicates their high capability to accommodate large rotor excursion and the misalignment. Compared with rigid gas bearings, GFBs have higher load capacity and superior damping performance [2]. All of these advantages indicate that GFBs are suitable in high-speed turbomachinery and can improve the performance and efficiency of these machines significantly. GFBs have been successfully used in air cycle machines(ACMs), air compressors, and micro gas turbines [3–5]. Moreover, efforts have been exerted to apply GFBs in oil-free turbochargers, high-speed motors and high-speed compressors for fuel cell vehicles [3,6–8].

However, low load capacity and inadequate damping still hinder the development of GFB. To overcome these shortcomings and improve the performance of GFB, various GFB types have been proposed [6,9–15], each with its own set of advantages. Bump-type GFBs not only have high load capacity, but also exhibit specific damping performance. Advanced bump-type GFBs have load capacities up to five times those of simple designed GFBs [16]. A hybrid air foil bearing with external pressurization has been proposed to improve load capacity and reduce friction during start/stops. Kim et al. [15,17–22] has conducted large amount of significant theoretical and experimental studies on the hybrid air foil bearings, which includes static and dynamic performance prediction, parameter studies, force coefficients identification, imbalance responses and stability characteristic analysis, start-stop characteristics, and thermal behavior analysis. This type of GFB has excellent cooling performance, which is critical for high-speed and heavy-loaded gas bearings. Metal mesh GFBs exhibit significantly improved damping performance because of the numerous friction pairs in the metal mesh layer which dissipate large amounts of energy from rotor vibration [23]. Multi wound GFBs are easier to fabricate and assemble than ordinary GFBs, and its performance can be controlled by accommodating the density and distribution pattern of the projections [24]. Among all types of GFBs, bump-type GFB is the most successful and most widely used, and it has been developed from the first generation to the third generation [25,26]. Although the bump-type GFB has been studied by many researchers because of its high load capacity, it is difficult to fabricate, especially for the third generation

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[*] Corresponding author.
*E-mail addresses:* jkai.feng@gmail.com (K. Feng), duozhu@yeah.net (W. Liu), cheliang302@163.com (R. Yu), zhangzm@tongji.edu.cn (Z. Zhang).

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## Nomenclature

| | |
|---|---|
| $A_i$ | a coefficient relative to the spring coil |
| $a$ | spring radius (m) |
| $b_i$ | equivalent viscous damping |
| $C$ | nominal clearance (m) |
| $C_{xx}$, $C_{xy}$, $C_{yx}$, $C_{yy}$ | dynamic damping coefficients (N s/m) |
| $D_2$ | spring intermediate diameter (m) |
| $d$ | spring wire diameter (m) |
| $E_I$ | bending rigidity (N m$^2$) |
| $[F]$ | force matrix |
| $f_i$ | dry friction at one contact point between adjacent springs (N) |
| $G$ | spring shear modulus |
| $G_J$ | torsional rigidity (N m$^2$) |
| $h$ | film thickness (m) |
| $[K_f]$ | global stiffness matrix |
| $K_L$ | linear stiffness (N/m) |
| $[K_s]$ | stiffness matrix of the elastic foundation |
| $[K_t]$ | stiffness matrix of the top foil |
| $K_{xx}$, $K_{xy}$, $K_{yx}$, $K_{yy}$ | dynamic stiffness coefficients (N/m) |
| $k_1$ | vertical stiffness of one-fourth of the spring coil (N/m) |
| $\mu$ | air viscosity (Pa s) |
| $\mu_f$ | sliding friction coefficient |
| $\delta$ | foil displacement (m) |
| $[\delta]$ | global foil displacement matrix |
| $\upsilon$ | bearing excitation frequency (Hz) |
| $\omega$ | angular velocity of rotor (rad/s) |
| $\Upsilon$ | frequency ratio |
| $k_i$ | stiffness of one spring coil (N/m) |
| $p$ | gas pressure (Pa) |
| $p_a$ | atmospheric pressure (Pa) |
| $p_s$ | spring pitch (m) |
| $R$ | bearing radius (m) |
| $r$ | displacement amplitude (m) |
| $S$ | area of hysteresis loop (N m) |
| $T_i$ | force acting on one spring coil from the top foil (N) |
| $t$ | time (s) |
| $\Delta U$ | amplitude of excitation (m) |
| $u_i$ | vertical displacement of one spring coil (m) |
| $v$ | spring coil excitation frequency (Hz) |
| $\Delta W_{ci}$ | energy dissipation caused by Coulomb damping (N m) |
| $\Delta W_{vi}$ | energy dissipation caused by viscous damping (N m) |
| $z$ | axial coordinate |
| $\Delta z_i$ | axial preload (m) |

### *Greek alphabet*

| | |
|---|---|
| $\varepsilon$ | rotor eccentricity |
| $\theta$ | circumferential coordinate |
| $\theta_1$ | location of friction force acting on the left side of the spring (rad) |
| $\Lambda$ | bearing number |
| $\gamma$ | loss factor |

### *Subscripture*

| | |
|---|---|
| $i$ | spring coil sequent number |
| $x$, $y$ | $x$-, $y$- axes |

bump-type GFB. Moreover, the manufacture cost is high. Song and Kim [14] proposed a simple compression spring foil bearing that installs a series of springs to the bearing sleeve as the elastic support structure. Springs are widely used in many types of equipment because it is not only cheap but also easy to obtain. Moreover, the stiffness of the supported structure can be easily controlled by using springs with different diameters. The feasibility of the compression spring foil bearing has been demonstrated and its load capacity is comparative with that of the bump-type GFB. Feng et al. [27] proposed an advanced compression spring GFB by nesting the underlying springs. The nested compression spring GFB is shown in Fig. 1. The advantages of this bearing design is distinctly. Firstly, a high structure stiffness can be achieved by increasing the spring numbers because the springs are nested with one another. The high spring density reduces the top foil sagging between adjacent springs, thus improving ultimate load capacity. Secondly, the damping of NSFB is improved simultaneously as the spring number increases because of the dry friction between two adjacent springs. This means the NSFB can easily achieve high structure stiffness and high damping characteristic simultaneously, which is difficult for the bump-type GFB because the contact area between bump foil and sleeve is reduced by increasing bump numbers. Moreover, the structure characterization is tunable by selecting different springs with vary wire diameters and pitches. The pull–push and dynamic load tests were conducted to identify the structural stiffness and damping of the NSFB. The comparison between the NSFB and bump-type GFB showed that former has a larger loss factor, indicating superior damping performance. Moreover, an analytical model of the elastic support structure, which considered the effects of dry friction between adjacent springs, was proposed in Ref. [27].

The elastic support structure and self-generated hydrodynamic gas film constitute a series system when the GFB operates at high speed [28]. Thus, the GFB performance is determined not only by the elastic support structure but also by the gas film. Ref. [16] reported that reliable performance prediction is one of the three major obstacles to the widespread application of GFB. Accurate prediction models can enhance our understanding of GFB, to help us avoid tedious experimental exploration. Feng and Kaneko [29] proposed a link-spring analytical model for bump-type GFB, which considered the effects of bump stiffness, interaction forces, friction forces, and local deflection of the top foil. The authors analyzed the static performance, dynamic coefficients, thermohydrodynamic features, and nonlinear dynamic behavior of bump-type GFB based on this theoretical model [29–32]. Xu, Liu and Zhang et al. [33–36] built prediction models of bump-type journal and thrust GFBs, which adopted modified top foil model and considering the Coulomb friction in the foil structure, to improve the prediction accuracy. San Andrés et al. [37] introduced the prediction model of metal mesh GFB, which combined the finite element model of the top foil, the Reynolds equation and the stiffness model of the metal

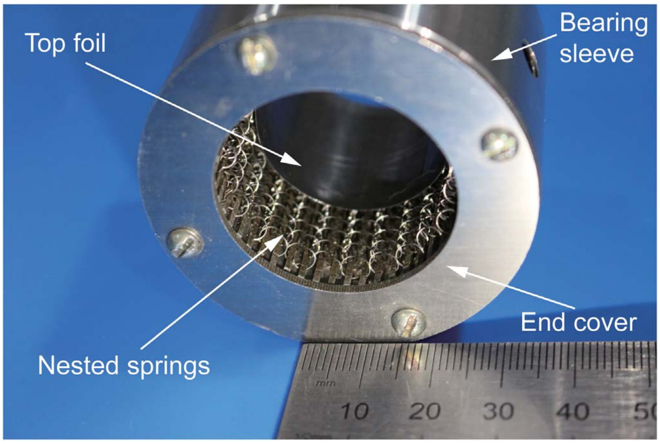

**Fig. 1.** Photograph of prototype nested compression spring gas foil bearing.