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Tuning the vibration of a rotor with shape memory alloy metal rubber supports

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ABSTRACT

The paper describes a novel smart rotor support damper with variable stiffness made with a new multifunctional material – the shape memory alloy metal rubber (SMA-MR). SMA-MR gives high load bearing capability (yield limit up to 100 MPa and stiffness exceeding 1e8 N/m), high damping (loss factor between 0.15 and 0.3) and variable stiffness (variation of 2.6 times between martensite and austenite phases). The SMA-MR has been used to replace a squeeze film damper and combined with an elastic support. The mechanical performance of the smart support damper has been investigated at room and high temperatures on a rotor test rig. The vibration tuning capabilities of the SMA-MR damper have been evaluated through FEM simulations and experimental tests. The study shows the feasibility of using the SMA-MR material for potential applications of active vibration control at different temperatures in rotordynamics systems.

1. Introduction

In high speed rotating machinery the flexible rotor may work above the critical speed. Special rotor supports with tailored stiffness are designed to keep the critical speed far from the operational conditions. However, the critical speed of the rotor cannot be changed, since the stiffness of the support is constant. If the operational conditions change the rotor may pass through the critical speed, which can cause undesired large amplitude vibrations especially in rotors with significant mass imbalance. The critical speed can be however adjusted to avoid the variable working speed, if the stiffness of the support could be changed.

There are currently several techniques to achieve active vibration control in rotor systems. Examples of these approaches are electromagnetic bearings, variable squeeze film dampers (SFD) and shape memory alloy (SMA) elastic supports. The electromagnetic bearing was first applied in rotor vibrations control in 1974 [1], and has been studied extensively because of its characteristics (no contact friction, oil-free, sealing-free, variable support stiffness and damping [2–5]). Electromagnetic bearings do however have some disadvantages, like the lack of large load bearing capability [6–8]. The control system used for electromagnetic bearings is large and heavy, which is acceptable for ground gas-turbines, but not for aeroengines. Another device used in active vibrations control for rotors is the variable squeeze film damper (SFD), which is based on the

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traditional SFD design. Unfortunately, the mechanical characteristics of a SFD may deviate significantly from the ones predicted at design level, and the eccentricity ratio at the local rotor journal may be large. The rotor response can therefore increase, leading to nonlinear phenomena like the bistable jump up [9]. The support stiffness and damping of variable SFDs can be controlled by changing the structure of the film geometry [10,11] and oil characteristics [12,13]. However, a variable SFD is controlled using hydraulics hardware, which tends to be large in size and heavy for aeroengine applications. Moreover, the application of SFDs is restricted to oil-free turbomachinery. Another candidate device for rotor active vibrations control technologies is the shape memory alloy (SMA) elastic support. SMA is theoretically very interesting, because it would be possible to control both stiffness and damping performance through material phase transformations induced either by temperature or mechanical loading, which makes it quite popular in active vibration control area [14–18]. However, the current state of the art on the use of SMA materials for rotor vibrations control is mainly confined to theoretical and numerical simulations [19,20] and the corresponding experimental research is quite rare [21].

Metal rubber (MR) is a type of tangled metallic mesh manufactured via a process of wire-drawing, weaving and compression molding [22,23]. The term metal rubber arises from the similarity between the properties of MR and those of an elastomeric rubber, although some authors prefer to use the terms “entangled metallic wire material” [24] or “metal wire mesh” [25]. It is commercially available in a variety of applications such as sealing, filtering and vibration absorbers, because of its characteristics of elasticity, damping, reliability and adaptation to the operational environment. Childs first applied MR as a rotordynamic damper in parallel with an elastic support in cryogenic fuel turbopumps in 1978 [26] and then Okayasu [27], Ertas [28] and Ma [29] did similar work. Other researchers have studied the nonlinear stiffness, damping coefficients and worked on the improvement of the MR mechanical performance [22,23,30]. Recently, MR elements have been also developed as support dampers for rotors in oil-free bearings, such as the gas foil ones [31–33]. Erats et al. manufactured for the first time MR using Nitinol (the most popular shape memory alloy), and investigated the effects of vibration amplitude and frequency on the stiffness and damping coefficients of SMA-MR devices [34]. Nitinol MR shows a strong shape memory property and temperature dependent material characteristics [35,36], but must undergo a process of special heat treatment during manufacturing [37]. Ma et al. designed a novel smart rotor support with SMA-MR and tested its dynamic properties for variable temperatures and amplitudes [38]. However, previous works mainly focused on the mechanical performance of SMA-MR dampers [39] without involving rotor tests, and no attempt has been made to evaluate the potential of the smart damper as a platform for active rotor vibrations control applications. The work presented in this paper aims at understanding the feasibility of using SMA-MR damper devices with variable stiffness using temperature as a control parameter, with a series of tests carried out on a custom rotor rig.

2. Description of the SMA-MR support

Fig. 1 shows the components and the structure of the smart support with the SMA-MR elements. The squirrel cage steel structure provides the constant stiffness for the support, while the SMA-MR elements (Fig. 2) contribute to the variable part of the stiffness and generate the main mechanical energy dissipation through the material structural damping and dry friction that can be controlled through thermal loading. The eight SMA-MR elements are axially fixed by the end housing and assembled at an equal circumferential space of 4 mm in slots located on the outer and inner rings. The dimensions of the smart support are shown in Fig. 2 and the parameters of the SMA-MR elements are listed in Table 1.

The manufacturing of the SMA-MR elements can be summarized as follows (Fig. 3). The shape memory alloy wire has been initially encircled into a tight helix by distorting and twisting the wire. The helix obtained has been then tensioned at both ends (wire drawing) to provide an initial pre-tension. The drawn wire is then weaved in a crisscross pattern to obtain a rough porous base material. Finally, the rough samples are placed into a specially designed mold and formed in a device by applying a compressive force ranging between 20 kN and 60 kN for at least 1 min. The compression loading is tailored to provide a specific relative density for the specimens. As for SMA-MR the last step is to experience a heat setting process fixed in the special mold for 15 min at 500 °C [39]. The transformation temperature of Ti–50.3%Ni shape memory alloy coil was obtained by differential scanning calorimetry (DSC – Setaram Instrumentation, labSys Evo) thermal analysis as shown in Fig. 4.

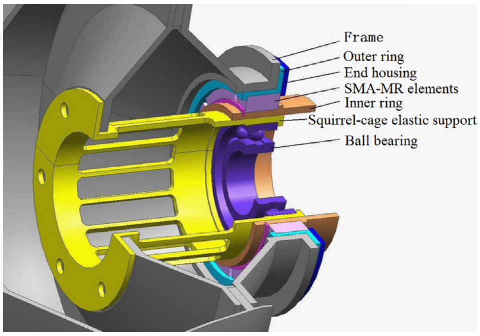

Fig. 1. UG model of the SMA-MR smart support.