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On the experimental prediction of the stability threshold speed caused by rotating damping

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ABSTRACT

An ever increasing demand for lighter rotating machinery and higher operating speeds results in a raised probability of instabilities. Rotating damping is one of the reasons, instability occurs. Rotating damping, or rotor internal damping, is the damping related to all rotating parts while non-rotating damping appearing in the non-rotating parts. The present study describes a rotating setup, designed to investigate rotating damping experimentally. An efficient experimental procedure is presented to predict the stability threshold of a rotating machine. The setup consists of a long thin shaft with a disk in the middle and clamped boundary conditions. The goal is to extract the system poles as a function of the rotating speed. The real parts of these poles are used to construct the decay rate plot, which is an indication for the stability. The efficiency of the experimental procedure relies on the model chosen for the rotating shaft. It is shown that the shaft behavior can be approximated by a single degree of freedom model that incorporates a speed dependent damping. As such low measurement effort and only one randomly chosen measurement location are needed to construct the decay rate plot. As an excitation, an automated impact hammer is used and the response is measured by eddy current probes. The proposed method yields a reliable prediction of the stability threshold speed which is validated through measurements.

1. Introduction

Stability in rotordynamics has been an important topic for more than a century. Ever since De Laval showed experimentally that it is possible to operate rotors above the first critical speed [1], i.e. the rotor's lowest eigenfrequency, manufacturers experienced heavy vibrations above this speed. In 1924, Newkirk [2] designed an experimental test on a rotor and discovered among other things that these vibrations are not related to unbalance and that the precession speed, or the frequency of these vibrations, is independent of the operating speed. In fact, these vibrations emerge from a small disturbance. Increased damping in the foundation increases the speed at which this phenomenon occurs. In addition, Kimball [3] concluded that this effect originates from internal friction in the rotor causing a follower force which leads to instability. Although undesired, this stability problem can be dealt with by increasing the non-rotating damping, for instance in the bearings, and operating below the stability threshold speed. It appears that the stability threshold speed is highly dependent on the ratio between external (non-rotating) and internal (rotating) damping [4]. Nowadays rotating damping is becoming a

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more potential source of instability [5]. High performance is needed for lighter structures at high operating speeds. Under these conditions, even standard super-critically operated industrial turbines become sensitive to instability. Also, when long driveshafts consist of materials that are more dissipative compared to metallic materials, instabilities occur more frequently [6,7]. Besides experimental observations of these unwanted vibrations, the prediction of the exact stability threshold speed is of major importance. Such a prediction allows manufacturers to operate safely at high speeds. In the last decennia, finite element models are prominent in the calculation of the stability threshold speed. Zorzi and Nelson [8] introduced rotor internal damping into a finite element formulation. More recent work is done by Forrai [4,9] where it is shown that within this mathematical formulation, its operation above the stability threshold always leads to instability. However, the modeling of rotating damping suffers from the same problem as any kind of energy dissipation model. A damping model has to incorporate all physical phenomena that yield energy dissipation. Therefore, damping is difficult to model accurately, as opposed to mass or stiffness. The literature on the modeling of damping is extensive and a clear overview of the basics is given by Inman [10]. Mostly, damping is included as a linear term resulting in a linear model. Viscous and hysteretic damping is popular way to include damping into a linear model. Whereas viscous damping lacks physical relevance, hysteretic damping is a more feasible approach. Ehrich [11] and many others [12,5,13] use elastic hysteresis to explain instability and the follower force. Genta [14] gives clear insight into the implementation of hysteretic damping in the rotordynamic model. In previous work, the authors provided an overview on the sensitivity of the stability threshold speed resulting from the choice between viscous and hysteretic damping [15].

Damping models are only relevant if they are validated through experiments. Some basic methods are combined by Ewins in [16]. Advanced methods that include identification of the entire damping matrix are provided by Lancaster [17], and in more recent work by Adhikari and others [18–22]. Some of these methods assume viscous damping, others allow more general damping models, but they often require numerous accurate measurements. When stability of rotors is concerned, damping matrix identification techniques are promising in simulation [23] but difficult to apply in practice. This is mainly due to unavoidable measurement errors and incomplete data [24]. Besides the difficulties in damping measurements, experimental analysis of rotating systems is not straightforward. Both gyroscopic effect and rotating damping cause asymmetric coupling of the system and speed dependency. This implies that regular modal analysis techniques become insufficient. Decoupling of the system matrices is only possible by knowing the left and right eigenvectors, which is difficult to obtain experimentally [25,26]. Even though rotating damping is already known as a destabilizing effect for almost a century, and literature provides theoretical models to study this phenomenon, there is not much information on how to validate these models. Kandil [5] provided in 2004 an overview of the theoretical background. Jafri [27] focused, in 2007, on the potential of shrink fits as an internal damping component and witnessed an actual breakdown during experimentation. At the same time, Chatelet [7] elaborated on the shaft material, and in particular materials that are more dissipative than metallic materials. More recently, Chouksey [28] investigated the influence of rotating damping on the frequency responses. A recurring difficulty in these experimental contributions is the measurement procedure. The procedures generally require numerous measurements which are difficult to obtain in practice. However, because rotating damping instability is caused by one single pole, it should be possible to propose a simplified procedure that can be used in industrial applications. In this paper, an experimental setup is presented which is dedicated to gain insight into the effect of rotating damping on the stability threshold speed. The approximation that is done, is based upon the dominant behavior of the first forward mode and the similarity between energy dissipation caused by the asymmetric coupling and energy dissipation caused by regular damping. Subsequently, an efficient procedure is described to predict the stability threshold speed. The measurement effort is kept low because only one measurement location is needed. An experimental validation proofs that this procedure leads to an accurate prediction of the stability threshold speed. In Section 2, the dimensioning of the rotating damping setup is discussed. The justification for the single degree of freedom approach is described in Section 3. Consequently, the results are presented in Section 4. Section 5 provides the discussion of the predicted stability threshold speed.

2. The rotating damping setup

A schematic representation of the rotating damping setup is shown in Fig. 1 and a picture in Fig. 2 and the corresponding properties are listed in Table 1. An experiment is designed where the rotating damping is isolated from all other disturbances such as nonrotating damping, unbalance and external forces that originate from the motor or the foundation. The

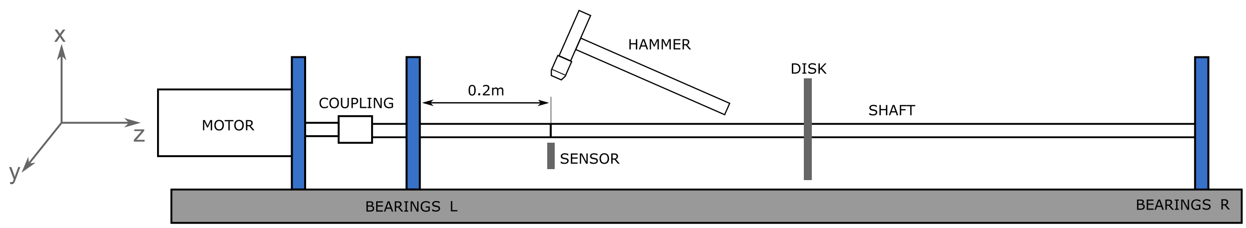

Fig. 1. Schematic representation of the rotating damping setup.