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Experimental verification of a dynamic model of a tube roll in terms of subcritical superharmonic vibrations

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ABSTRACT

The non-idealities in a rotor-bearing system may cause undesirable subcritical superharmonic resonances that occur when the rotating speed of the rotor is a fraction of the natural frequency of the system. These resonances arise partly from the non-idealities of the rotor and partly from the non-idealities of the bearings. The superharmonic vibrations of complex rotor-bearing systems can be studied accurately by combining a detailed rotor and bearing model with a multibody simulation approach. The complex rotor-bearing system under investigation is a tube roll of a paper machine supported by a hard-bearing-type balancing machine. Resonances affect the quality of end product and therefore have to be studied in detail. Non-idealities of the rotor-bearing system are measured from the existing structure and the parameters of the real structure are emulated as accurately as possible in the simulation model. The simulation model is verified using the results from experimental modal analysis and the measurement results for the subcritical superharmonic response of the roll. The analogy between the simulation and experimental results of the studied system is substantial.

1. Introduction

A complete rotating machine (Fig. 1) consists of several components from a rotating rotor shaft to a supporting structure. Further, it can contain a coupled drive shaft system and other components, such as motors and gearboxes. Traditionally, single components of the drive train are analyzed separately. However, all of these components affect the overall performance of the machine and all of the interactions between individual components have to be taken into account in the analysis. Manufacturing tolerances cause a number of non-idealities in the rotor system. Common non-idealities are, for example, the uneven mass or stiffness distribution of the rotor and the waviness of the bearing rings. Such non-idealities are harmful since they can cause superharmonic resonances in the rotor system. Superharmonic resonances are sometimes referred to as subcritical resonances, as they occur at the subcritical rotational speed. In some applications, such as in paper machines, subcritical resonances are of practical significance because they may be within the operating speed range and can influence the quality of the final product. In order to study the superharmonic responses of the rotor system, the impulses caused by the bearings and non-idealities of the rotor must be taken simultaneously into consideration.

Traditionally, rotordynamics concentrates on simple rotor-bearing systems. The purpose is to calculate the critical rotational speeds and the stability in the rotational speed range of the machine as well as study the steady state responses due to unbalancing excitations [1,2]. The simplest systems are usually analyzed by using a Jeffcott rotor model. Some typical characteristics needed in the analysis of rotordynamics such as gyroscopic effects, internal damping, and the dependence of critical speeds on the rotational frequency, can be taken into account when using the model of the Jeffcott rotor as presented in [3]. Still, for more complex analysis, a more accurate method is needed, such as the transfer matrix method (TMM) or the finite element method (FEM). The transfer matrix method was proposed for analyzing vibrations of beams by Myklestad [4] and later

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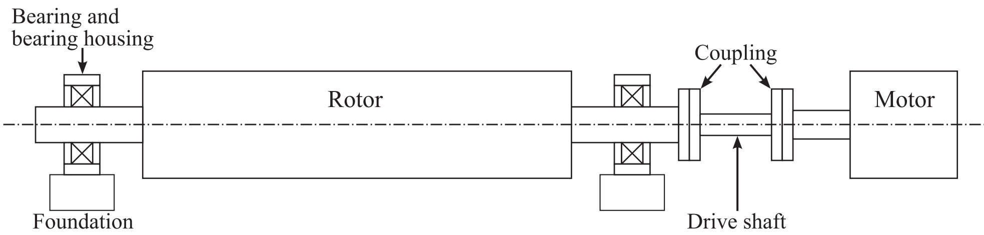

Fig. 1. Components of a rotating machine.

extended for rotor vibrations by Prohl [5]. Recently it has been used, for example, to analyze coupled lateral and torsional vibration of the rotating system as presented by Hsieh et al. [6]. Using the finite element formulation, rotary inertia, gyroscopic moments, the shear deformation of the shaft and the asymmetry of the rotor and the bearings can be straightforwardly taken into account [7,8]. Steady state responses are usually solved in a frequency domain, which requires the linearization of the nonlinear bearing components. For transient analysis, the finite element equations of motion are solved directly or by employing modal synthesis methods [9,10] that can be used to decrease the degrees of freedom of the system.

The critical speeds and the stability regions have to be taken into account in the early design phase of rotating machines. In addition, the superharmonic and the subharmonic vibrations of the rotor systems should be taken into consideration, as well. Non-idealities of the rotor are studied and, for example, the twice-running-speed response in horizontally mounted asymmetric rotors is well known [2,11,12]. Instead, the non-idealities of the bearings are more rarely studied because the nonlinear bearings are more complicated to analyze when using the finite element method or transfer matrix method. Bearing ellipticity is included in the analysis by Childs [13] and it can be noted that the twice-running-speed response arises from the ellipticity of bearings. Ehrich [14] studied a rotor that operates eccentrically within the bearing clearance and in local contact with the stator and concluded that an excited rotor system in subcritical speed will respond by bouncing at its natural frequency. Ehrich referred to this phenomenon as subcritical superharmonic response, which is related to the more studied supercritical subharmonic response [15,16]. In order to study the superharmonic vibrations caused by the non-idealities of the bearings, a nonlinear transient analysis must be employed.

A large number of formulations have been developed for the dynamic analysis of mechanical systems [17,18]. In general, a multibody system consists of a number of bodies which are connected with each other by constraints, such as springs, dampers and joints. The dynamics of a multibody system can be analyzed computationally by taking into account the bodies of the system, interactions between them and external forces. By using the multibody simulation approach, large relative translational and rotational displacements can be described. Multibody system dynamics offers an effective approach to analyze all types of mechanical systems including robotics, biomechanics and rotating systems among all other more traditional mechanical systems. Usually, multibody systems are assumed to have rigid bodies, which is an acceptable assumption in most engineering problems. However, in some cases, the rigid approach is not accurate enough, and the deformations of the bodies have to be taken into consideration, as well, in order to improve the accuracy of the numerical solution. The magnitude of the deformation has to be taken into account when determining the formulation used in analysis.

In flexible multibody simulation, rotating shaft problems were applied by Brown and Shabana [19]. In the multibody simulation approach, numerical methods are used to solve the nonlinear equations of motion with respect to time and the results can be post-processed in the frequency domain. The mechanical model of the system is modeled in the form of discrete bodies which can be coupled by constraint equations and forces. The forces can be nonlinear functions of system parameters, and therefore, the bearings can be described as force elements between the shaft and the supporting structure. It has to be noted that the coupling terms between rigid reference motion and deformation play an important role particularly in lightweight and high speed applications [20,21].

This study introduces a simulation approach that can be used to study the superharmonic vibrations of rotor-bearing systems. As shown in this study, the superharmonic vibrations of complex rotor-bearing systems can be studied accurately by combining detailed rotor and bearing models. Simulated results are compared to measured results obtained from the existing roller test rig and verified based on the measured results by using particular optimizing algorithms found in literature. A sensitivity analysis is performed in order to study the effect of different input parameters on the twice-running-speed superharmonic response. Results are shown in an amplitude chart in which the simulated cases can easily be compared with the measured ones. Waterfall diagrams of the measured responses and simulated responses of a particular optimized case are shown.

2. Rotordynamics in flexible multibody dynamics

Traditional research into rotordynamics is concerned mainly with the stability and natural frequencies of the rotor system. As demonstrated by Brown and Shabana [19], the equations of motion in traditional rotordynamics are usually derived using simplifying assumptions which also limit the use of these equations in more general cases. For example, bearing clearance, bearing ring waviness or bearing defects cannot be taken into account in a straightforward manner. Flexible multibody simulation provides a more general approach to rotordynamics, and the limitations mentioned above related to the bearing non-idealities