Mechanism and Machine Theory 91 (2015) 269–288

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Sommerfeld effect characterization in rotors with non-ideal drive from ideal drive response and power balance ☆

M. Karthikeyan, Alfa Bisoi, A.K. Samantaray *, R. Bhattacharyya

Department of Mechanical Engineering, Indian Institute of Technology, 721302 Kharagpur, India

ARTICLE INFO

Keywords:
Sommerfeld effect
Non-ideal drive
Rotor dynamics
Finite element model
Bond graph

ABSTRACT

Rotor dynamic systems are often analyzed with ideal drive assumption. However, all drives are essentially non-ideal, i.e., they can only provide a limited amount of power. One basic fact often ignored in rotor dynamics studies is that the drive dynamics has complex coupling with the dynamics of the driven system. Increase in drive power input near resonance may contribute to increasing the transverse vibrations rather than increasing the rotor spin, which is referred to as the Sommerfeld effect. In this article, we generate the rotor response with finite element (FE) model by assuming an ideal drive. Thereafter, the rotor system's response with ideal drive is used in a power balance equation to theoretically predict the amplitude and speed characteristics of the same rotor system when it is driven through a non-ideal drive. The integrated system with drive-rotor interaction is modeled in bond graph (BG) form and the transient analysis from the BG model is used to validate the theoretical results. The results are important from the point of actuator sizing for rotor dynamic systems.

1. Introduction

Sommerfeld effect [1,2] is observed in eccentric rotor dynamic systems when the input power is increased to bring the shaft speed near a critical speed. When the input power is increased further to increase the shaft speed, the extra input power ends up in exciting the lateral flexural vibrations (rotor whirl) and the shaft speed does not increase appreciably at critical speed zone. This continues till the power input is increased sufficiently, whereupon the rotor spin speed suddenly jumps to much higher value and the transverse vibration amplitude reduces appreciably. Similar phenomenon is observed during coast down operation, where near the critical speed the rotor spin speed jumps from a higher value to a lower value and the flexural amplitude jumps from smaller values to larger values. One interesting property of Sommerfeld effect is that certain rotor speeds near the critical speeds can never be achieved both during coasting up and down [3–8]. Sommerfeld effect leads to large synchronous whirl amplitudes for considerable duration during passage through resonance [9–11]. Previous work in this field obtained closed form solution for Sommerfeld effect in symmetric rotor systems driven by non-ideal source [10,12] and source interactions at stability threshold [13,14]. These consider Sommerfeld effect at the first critical speed and neglect the gyroscopic coupling. In this paper, we present a semi-numerical solution for Sommerfeld effect at higher critical speeds in any general rotor dynamic system with gyroscopic coupling and rotating material damping.

☆ An abridged version of this article was presented in the 1st International and 16th National Conference on Machines and Mechanisms (iNaCoMM 2013), Dec 18–20, 2013, IIT Roorkee, India, held under the aegis of Association for Machines and Mechanisms (AMM), and the International Federation for the Promotion of Mechanism and Machine Science (IFToMM). This article was recommended by three anonymous reviewers and the conference committee for publication in a special issue dedicated to the said conference in the official IFToMM research journal "Mechanism and Machine Theory".

* Corresponding author. Tel.: +91 3222 282998.
E-mail address: samantaray@mech.iitkgp.ernet.in (A.K. Samantaray).

http://dx.doi.org/10.1016/j.mechmachtheory.2015.04.016

Sommerfeld effect characterization through purely numerical studies is extremely time consuming and requires a great deal of effort due to stiff governing equations. In our approach, we simulate the FE model of the corresponding rotor dynamic system with ideal drive to generate its steady-state response characteristics. The steady-state synchronous whirl amplitudes of transverse and rotary whirls are obtained for various rotor speeds. Use of the response characteristics obtained from the FE simulations of the rotor system with ideal drive in the power balance equation for the non-ideal drive yields predictions of the rotor spin speed(s) and amplitude(s) for given power supply in the non-ideal system. We then use a bond graph model of the rotor along with its non-ideal drive to perform transient analysis of the system. The transient analysis with quasi-static power variation in the non-ideal drive is used to determine the threshold power requirement for passage through resonance.

2. Sommerfeld effect characterization from ideal drive response

2.1. System description and modelling assumptions

A uniform continuous shaft carrying a rigid rotor, as shown in Fig. 1, is considered here with simply supported ends or ideal bearings. The rotor is driven by a DC motor which is a non-ideal drive. The shaft has uniform circular cross section and it has no unbalance. An eccentric rotor disk is mounted with its plane perpendicular to the shaft axis. The shaft has internal damping, bearing spin damping and external transverse and rotary damping act on the rotor disk. The aerodynamics damping on spin can be accounted with bearing spin damping. The right bearing allows free sliding and thus there is no axial load on the shaft. It is assumed that deflections are small and usual Euler-Bernoulli beam theory assumptions are valid.

There is no bending torsion coupling due to geometric effects in a shaft with symmetric cross-section. For small deflections, the disk spinning axis can be assumed to be the same as the bearing axis and disc wobbling is insignificant. We attempt to predict the steady-state rotor spin speed and vibration amplitudes during coasting up and down operations for any given motor supply voltage (or power), and the exact motor power requirement during the passage through critical speeds for actuator sizing purpose. At steady-state operation, the rotor has no angular acceleration. Also, just before passage through resonance, the rotor speed almost gets stuck at the critical speed and the angular acceleration of the rotor disk is small. For studying the afore-stated two aspects only, it is not required to make a computationally stiff and resource intensive transient analysis of the system behavior with complete dynamics included in the system model. Therefore, the torsional vibration of the shaft is neglected in this study. This is also valid for quasi-static rotor spin-up studies reported herein. For large angular acceleration immediately after passage through resonance, the transient response obtained without considering torsional vibration is incorrect; only the steady-state vibration amplitudes obtained after the rotor angular speed reaches a constant value (no angular acceleration) are correct.

2.2. Modal analysis through finite element model

Simulation based modal analysis and stability domain determination is a very inefficient method. To determine critical speeds through simulation, frequency spectra of transient responses at different rotor speeds need to be visually inspected in order to locate the rotor speed at which a natural frequency becomes equal to the rotor speed. This becomes very difficult due to the fact that the forward and backward whirl natural frequencies of a gyroscopic system split and change with the rotor speed. Likewise, it is extremely difficult to determine the exact stability threshold through manual inspection of the transient responses. Eigenvalue analysis is the most efficient approach for these purposes. However, none of the available commercial bond graph software support eigenvalue analysis tool. Therefore, FEA software is used to here to study the critical speeds and stability thresholds through eigenvalue analysis. The continuous shaft-rotor system is discretized into a finite degrees-of-freedom system and modeled using FE software ANSYS. The shaft is modeled using BEAM188 element and the rigid disk is modeled using MASS21 element. The external translational and rotational dampers are both modeled using a MATRIX27 element which contributes a damping matrix to the node to which the disk is attached. The coefficients of the damping matrix are the translational and rotational damping coefficients. The internal damping coefficient is specified using the BETAD command. The rotating internal damping, which in the stationary reference frame contributes to the system's stiffness (introduces circulatory forces) and damping matrices, is modeled using the 'damping effect' option in CORIOLIS command. The stationary reference frame is selected using the 'reference frame' option in CORIOLIS command. The gyroscopic couples and their associated damping forces are also modeled using the 'Coriolis effect' option in the CORIOLIS command. The gyroscopic damping matrices are generated for BEAM188 element and MASS21 element. The unbalance forces on the disk due to its eccentricity

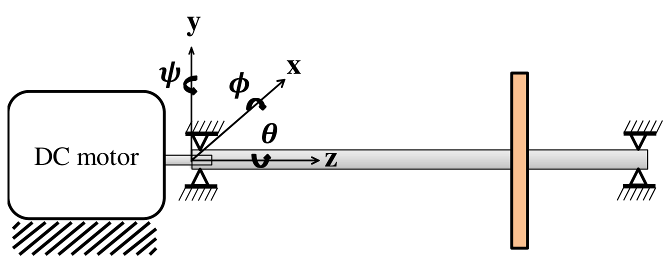

Fig. 1. Continuous shaft with a non-central eccentric rotor driven by a DC motor.