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DYNAMICAL SIMULATION OF A CNC TURNING CENTER (SURVEY PAPER)

AL-ZGOUL MOHAMMAD – ATTILA SZILÁGYI

University of Miskolc, Department of Machine Tools
3515 Miskolc-Egyetemváros
mohammadzgoul90@gmail.com

Abstract: This paper shows the most common rotor systems which can be used to analyse a CNC turning center. Starting with the simplest rotor system representation (single-degree-of-freedom) up to analysing multi-degree-of-freedom and infinite-degree-of-freedom rotor systems using the TMM (Transfer Matrix Method) when it comes to cases like multi desk rotors and Jeffcott-rotors.

Keywords: *rotor systems, turning center, Transfer Matrix Method*

1. Introduction

These days, dynamical simulation of machine-tools is essential and very important. The reason for this is to maximise these machines' accuracy and productivity [1]. The main goals behind performing dynamical analysis in most cases are to monitor, analyze and reduce mechanical vibrations in machine-tools [2]. In general, and most commonly, the model which is simulated by CAD 3D modelling and modal analysis is verified by a mathematical model [3]. The dynamical analysis and simulation of a CNC turning center have special focus on describing the dynamical behaviour of the spindle and the impact of each part connected to the spindle itself [4]. Special rotor-models have been set up during recent years in order to conduct more detailed dynamical investigations which result in a much clearer overview of the nonlinear behaviour of this especially important part of a turning-center. In the following sections, the most frequently applied dynamical models of the main spindle of a turning-center are overviewed.

2. Rotor models

Rotor models have a noticeable history of development, mainly due to the interaction between the theory and the practice [5]. The wide array of rotor models provides the researcher or engineer the flexibility to pick out the most suitable model for analysis or research and development.

2.1. Single-DOF rotor model

The simplest representation of a rotor system can be modelled as a single-degree-of-freedom system *(Figure 1)*. The whole rotor is treated as a single mass. This mass takes one of the following forms: a point mass, a rigid disc or a long rigid shaft. The two supports are assumed to be flexible and that is why each support (bearing) is assumed to have a stiffness of a specific value which leads to having an overall effective stiffness for the summation of the stiffnesses of the supports. The main disadvantage of this model is that it only deals with the translatory transverse motion of the rotor along one axis and it does not deal with the rotational motion and the translatory motion of the rotor [6].

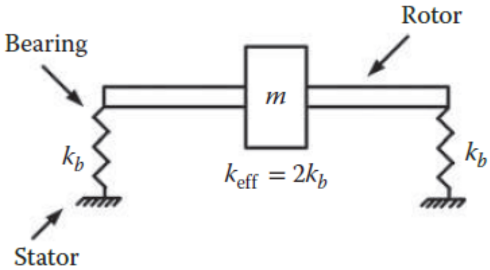

Figure 1
A SDOF rotor system

2.2. Jeffcott rotor model

The single-DOF rotor model can only show the oscillation in one transverse direction. This is one of this model's primary limitations. It is more accurate to have a model that can describe the orbital motion of the rotor in two transverse directions. This model is the typical Jeffcott rotor. It consists of a flexible, massless, simply supported shaft with a thin disc installed in the middle of it *(Figure 2)*. There is an eccentricity of *e* between the disc center of rotation, C, and its center of gravity, G. The shaft spins at a speed of $\boldsymbol{\omega}$. The whirl frequency is represented by $\boldsymbol{\nu}$. For this case, the synchronous whirl is assumed (i.e. v = w). The sense of rotation of the shaft spin and the whirling are the same forming what is known as a forward synchronous motion [7]**.**

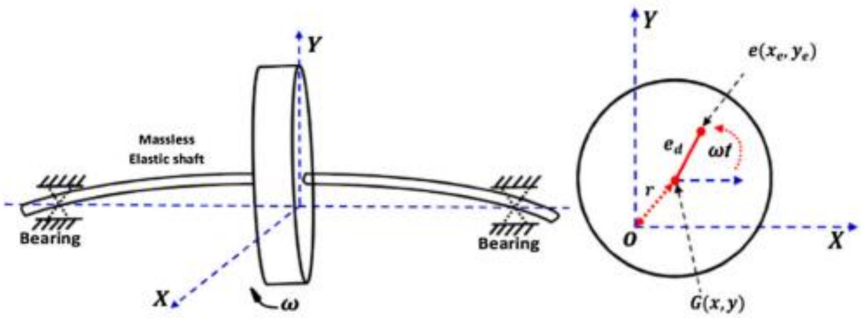

Figure 2
Jeffcott rotor system [8]

2.3. A two-disc tortional rotor system with a stepped shaft

The previous models consider only the transverse vibrations of rotor-systems. Meanwhile, the torsional vibration of rotor-systems is another very important kind of vibration that must also be taken into consideration. The following system best represents the case of torsional vibrations. This system consists of a stepped shaft with two large discs at the ends. It is assumed here that the shaft has a negligible polar mass moment of inertia compared to the large discs. In this approach, the actual shaft will be replaced by a uniform diameter equivalent shaft. The equivalent shaft diameter should meet the smallest diameter of the real shaft and must have the same torsional stiffness as the real shaft. *Figure 3* illustrates the case [9] [10].

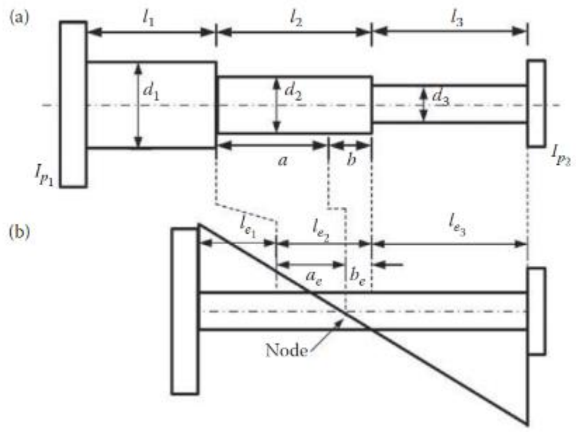

Figure 3
Two discs with (a) a stepped shaft and (b) an equivalent uniform shaft [11]

3. Transfer matrix methods

The previous rotor models are considered simple models. In real-life practice, more complicated models are to be analysed (multi-disc-rotor-system). Due to the large number of degrees of freedom, analysing such models, depending on the previous models, is a very complicated task. Here, the TMM is an adequate method of analysing such systems; it deals with a rotor system in a systematic way regardless the complexity of the system. In other words, the number of discs and their distribution over the shaft of a system do not complicate the case. In this method, the number of equations to be solved simultaneously, which forms the size of the system, generally depends on the dimensions of the state variable vector and does not depend on the number of stations. Practically, the TMM is suitable for long slender systems as in the case of rotating shafts [12].

A typical multidisc rotor system is shown in *Figure 4* and *Figure 5*. It is supported on frictionless supports and the z-axis is taken as the longitudinal axis whose discs have an angular displacement about, ϕz. The discs are considered as thin and rigid and locate at a point and the shaft is treated as flexible and massless. N is the number of discs and 0 to (n + 1) represents the station number. Then the system has the total number of stations as (n + 2).

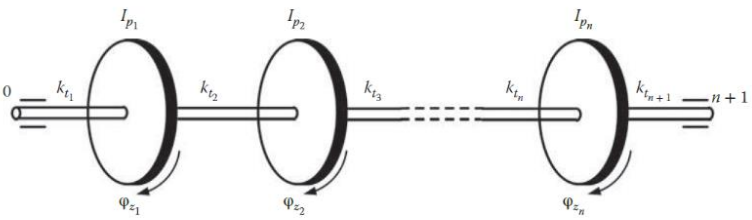

Figure 4
A multidisc rotor system [13]

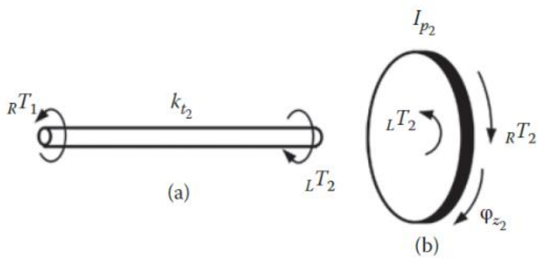

Figure 5
(a) A free body diagram of shaft section 2, (b) A free body diagram of disc 2

The so-called "point matrix" deals with the state variables at both ends of a thin disc. This is done to determine a state vector on the right-hand side relative to the state vector on the left-hand side. What the point matrix does is relates a state vector left of a disc to a state vector right of the disc. The so-called field matrix deals with the relationship between state variables at two ends of a shaft segment. Therefore, the role of the field matrix is to relate a state vector that is at the left end of a shaft segment to the right end of the shaft segment. Finally, the overall system transfer matrix relates the state vector at the far left to the state vector at the far right of the shaft. The overall transfer matrix elements are a function of the torsional natural frequency of the rotor system and they are a function of the excitation frequency for the case when the external toque is present [14] [15]. Below is an example on a matrix-system of a turning center spindle system. The total number of stations of the system is 3.

$$_L\{S\}_1 = [F]_1[P]_1\{S\}_0 = [U]_1\{S\}_0 \tag{1}$$

$$_L\{S\}_2 = [F]_2\,{}_R\{S\}_1 = [U]_2\{S\}_1 \tag{2}$$

$$\begin{Bmatrix} 0 \\ \varphi \\ M \\ S \end{Bmatrix}_{1}^{L} = \begin{bmatrix} u_{11} & u_{12} & u_{13} & u_{14} \\ u_{21} & u_{22} & u_{23} & u_{24} \\ u_{31} & u_{32} & u_{33} & u_{34} \\ u_{41} & u_{42} & u_{43} & u_{44} \end{bmatrix}_1 \begin{Bmatrix} -y \\ \varphi \\ 0 \\ 0 \end{Bmatrix}_0 \tag{3}$$

$$[U]_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & -m\omega_{nf}^2 I_d & 1 & 0 \\ m\omega_{nf}^2 & 0 & 0 & 1 \end{bmatrix}_1 = \begin{bmatrix} 1+\frac{1}{6}m\omega_{nf}^2\alpha l^2 & l-\frac{1}{5}I_d\omega_{nf}^2\alpha l & \frac{1}{5}\alpha l & \frac{1}{6}\alpha l^2 \\ \frac{1}{5}m\omega_{nf}^2\alpha l & 1-I_d\omega_{nf}^2\alpha & \alpha & \frac{1}{5}\alpha l \\ m\omega_{nf}^2 l & -I_d\omega_{nf}^2 & 1 & l \\ m\omega_{nf}^2 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

4. CONCLUSION

Among the various methods and models of analysing rotor systems, each presents advantages and disadvantages. Analysing simple systems with the dynamic approach is in some occasions faster when a high degree of accuracy is not required. On the other hand, for more complicated systems (multi-degree-of-freedom systems), the TMM is a better option due to its ability to deal, in a relative manner, with a greater number of DOF's with less complicated calculations.

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