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International Journal of Machine Tools & Manufacture 46 (2006) 978–987
INTERNATIONAL JOURNAL OF MACHINE TOOLS & MANUFACTURE DESIGN, RESEARCH AND APPLICATION
www.elsevier.com/locate/ijmactool

Development of the active balancing device for high-speed spindle system using influence coefficients

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Received 4 April 2005; accepted 28 July 2005
Available online 16 September 2005

Abstract

A high-speed spindle can be very sensitive to rotating mass unbalance which has harmful effect on many types of rotating machinery. Therefore, the balancing procedure is certainly needed to reduce vibration in all high-speed rotating systems. In this study, an active balancing program using influence coefficient method and an active balancing device of an electro-magnetic type with both simple and reliable structures were applied to the developed high-speed spindle system. A gain scheduling control using influence coefficients of the reference model was proved to be effective in balancing the spindle system although its characteristics were changed. The stability of reference influence coefficients was verified by experiments with frequency response functions. The active balancing experiment of the manufactured spindle system using an active balancing program and device was also performed efficiently during the operation. As a result, controlled unbalance responses after balancing work were below the vibration limit at all rotating speed ranges including critical speeds.

Keywords: Active balancing; Unbalance; Influence coefficient; High-speed spindle; Gain-scheduling control; Critical speed

1. Introduction

Recently, rotating machines such as machine tool's spindle or turbo-machine are getting intelligent and speedup to improve the machining efficiency and accuracy. One of the important considerations for speedup of spindles is vibration due to unbalance mass. The amount of vibration is proportional to square of rotating speed, and it may deliver damage on the rotating system or overall system passing the critical speed.

Therefore, balancing procedure at high-speed spindles is mandatory for reducing the vibration due to unbalance. To date, almost all of the balancing procedure has been the off-line balancing, which determines correction mass through the trial operation using various trial masses, and attaches or removes it while the spindle stops. Since the off-line balancing is done with the system stopped, it causes a great amount of loss in terms of time and cost. In order to reduce the loss and improve operation efficiency and accuracy, there are many ongoing research and development about on-line active balancing which is done with the rotating system run by moving the balancing rotor [1–5].

The balancing procedure for high-speed spindles requires the implementation and calculation of correction mass for active adaptation against the change of system characteristic. Active balancing using the reference influence coefficient of the reference model was proposed and new active balancing devices were developed [6–9]. This method provides effective active balancing control owing to require only one trial operation for the reference system.

In this study, we applied active balancing device and control technique developed at previous researches at high-speed spindle system of 20,000 rpm-grade machine tool. As the control method of the balancing device, the gain scheduling control algorithm utilizing referential influence coefficients was used for developing program. We performed experiments upon consecutive balancing with the operation speed changing without stopping spindle using the developed program. In addition, we performed experiments upon the determination of stability for several representative tools of machine tool in order to determine the stability of the influence coefficients on account of the change of tools of spindle system of machine tool.

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doi:10.1016/j.ijmachtools.2005.07.048

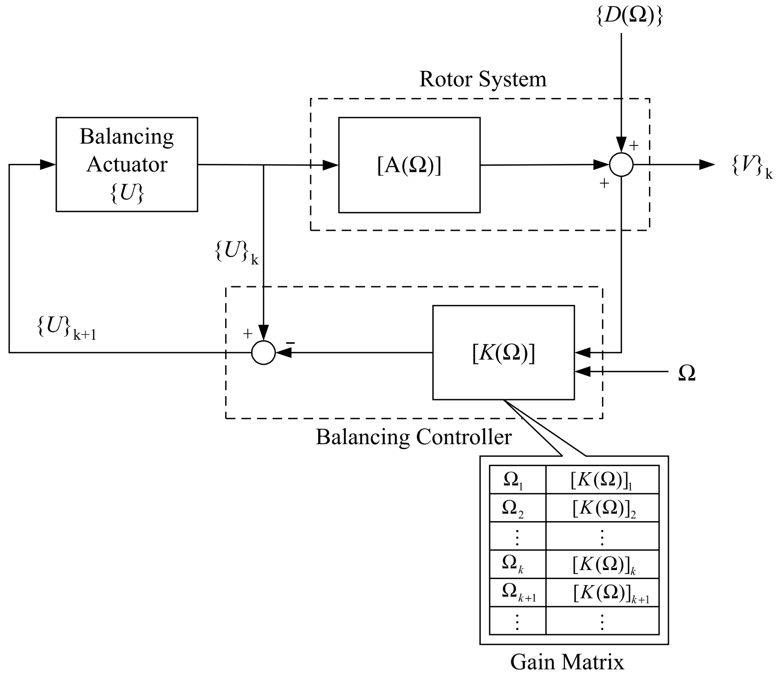

Fig. 1. Active balancing algorithm for accelerating rotor system using influence coefficient gain matrix.

2. Active balancing theory

2.1. Active balancing using influence coefficients

There are influence coefficient method, modal method and mixed method in the off-line balancing methods [10,11]. Among them, influence coefficient method is known as the most suitable active balancing method. The influence coefficients represent the change of system response about unbalance and indicate the dynamic characteristics of system, as functions of rotating speed. The unbalance vibration signal vector at kth control iteration is given by [12,13]

$$\{V\}_k = [A(\Omega)]\{U\}_k + \{D(\Omega)\} \tag{1}$$

where

$\{V\}_k$	unbalance vibration signal at kth iteration,
$[A(\Omega)]$	influence coefficient matrix at rotating speed Ω,
$\{U\}_k$	unbalance vector by balancing device at kth iteration,
$\{D(\Omega)\}$	vibration signal due to initial unbalance at rotating speed Ω.

Similarly, the unbalance response at $k+1$th control iteration is given by

$$\{V\}_{k+1} = [A(\Omega)]\{U\}_{k+1} + \{D(\Omega)\} \tag{2}$$

Subtracting Eq. (1) from Eq. (2) gives

$$\{V\}_{k+1} - \{V\}_k = [A(\Omega)]\{\{U\}_{k+1} - \{U\}_k\} \tag{3}$$

The key of balancing is to find correction mass vector $\{U\}_{k+1}$ that makes the response zero after control. Hence, the correction vector can be

$$\{U\}_{k+1} = \{U\}_k - [A(\Omega)]^{-1}\{V\}_k \tag{4}$$

Eq. (4) can be used only if the number of measurement plane equals to the number of balancing plane, that is, on the condition that the influence coefficient matrix is a square matrix, and the inverse matrix exists. If the number of measurement plane is larger than balancing plane, it becomes an optimization problem and correction vector should be found to minimize unbalance response. The cost function is defined by

$$J_{k+1} = \{V\}^{\mathrm{T}}_{k+1}\{V\}_{k+1} \tag{5}$$

The correction vector to minimize cost function can be obtained as

$$\begin{aligned}\{U\}_{k+1} &= \{U\}_k - ([A(\Omega)]^{\mathrm{T}}[A(\Omega)])^{-1}[A(\Omega)]^{\mathrm{T}}\{V\}_k \\ &= \{U\}_k - [K(\Omega)]\{V\}_k \end{aligned} \tag{6}$$

where $[K(\Omega)]$ is the control gain. With the influence coefficient of system, the correction mass that minimizes the vibration signal can be obtained from Eq. (6), when the current vibration signal and position of active balancing rotor are known. The matrix of influence coefficients at a rotating speed is obtained from the trial operation using the trial mass, and arbitrary trial mass can be obtained by operating the rotor. Each coefficient that composes influence coefficient matrix at the active balancing device can be obtained from Eq. (7)

$$a_{ij} = \frac{(V_i)_k - (V_i)_{k-1}}{(U_j)_k - (U_j)_{k-1}} \tag{7}$$