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Optimal spindle speed determination for vibration reduction during ball-end milling of flexible details

Krzysztof J. Kalinski, Marek A. Galewski *

Gdansk University of Technology, Faculty of Mechanical Engineering, G. Narutowicza 11/12, 80-233 Gdansk, Poland

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ABSTRACT

In the paper a method of optimal spindle speed determination for vibration reduction during ball-end milling of flexible details is proposed. In order to reduce vibration level, an original procedure of the spindle speed optimisation, based on the Liao–Young criterion [1], is suggested. As the result, an optimal, constant spindle speed value is determined. For this purpose, non-stationary computational model of machining process is defined. As a result of modelling, a hybrid system is described. This model consists of following subsystems, i.e. stationary model of one-side-supported flexible workpiece (modal subsystem), non-stationary discrete model of ball-end mill (structural subsystem) and conventional contact point between tool and workpiece (connective subsystem). The method requires identification of some natural frequencies of stationary modal subsystem. To determine them, appropriate modal experiments have to be performed on the machine tool, just before machining. Examples of vibration surveillance during cutting process on two high speed milling machines Mikron VCP 600 and Alcera Gambin 120CR are illustrated.

1. Introduction

In case of modern machining centres, ball-end milling of flexible details is observed frequently. In this case, dynamic phenomenon of considerable importance is tool–workpiece relative vibration. In certain conditions it may lead to a loss of stability and cause generation of self-excited chatter vibration. Additionally, vibrations in a machine tool system reduce the quality of the machined surface, increase tool wear and, in extreme cases, may lead to the destruction of a tool or a workpiece [2].

The regeneration phenomenon is recognised as the most important cause of chatter vibrations [3]. There are many different methods for reduction and surveillance of the chatter vibration, i.e. the use of cutting edge chamfers [4], using mechanical dampers [5] or smart materials [6], robust optimal control [7], active methods (i.e. active structural control [8], active holder [9], active damper [10]), cutting with variable spindle speed [11,12].

The method of chatter reduction by the spindle speed optimal-linear control [12] appeared to be successful for milling rigid workpieces. However results of further research have disclosed that milling flexible workpieces at variable spindle speed appears unsuccessful, from a point of view of vibration surveillance. Thus, the paper proposes different method of vibration reduction, which is based on matching the spindle speed to the optimal phase shift proposed by Liao and Young [1].

2. Cutting process dynamics

Dynamic analysis of a slender ball end milling process has been performed, based upon following assumptions [13]:

- The spindle, together with the tool fixed in the holder, and the table with the workpiece, are separated from the machine tool structure.
- Flexibility of the tool and flexibility of the workpiece are considered.
- Coupling elements (CEs) are applied for modelling the cutting process dynamics.
- An effect of first pass of the edge along cutting layer causes proportional feedback, and the effect of multiple passes causes delayed feedback additionally.

For instantaneous contact point between the chosen tool edge and the workpiece (idealised by CE no. l), proportional model of

* Corresponding author.
E-mail address: margalew@pg.gda.pl (M.A. Galewski).

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the cutting dynamics is included [13–16]. Based on this model, the cutting forces depend proportionally on instantaneous cutting layer thickness $h_l(t)$, and also on instantaneous depth of cutting $a_l(t)$; both of them vary in time. It is assumed that the resultant cutting force lies in the orthogonal plane. According to the direction of the action, we separate cutting force component F_{yl1} acting along nominal cutting velocity, cutting force component F_{yl2} acting along cutting layer thickness (Fig. 1). The third cutting force component F_{yl3} is neglected.

Thus, all the components of instantaneous cutting force can be described [13,14]:

$$F_{yl1}(t) = \begin{cases} k_{dl}a_l(t)h_l(t), & a_l(t) > 0 \wedge h_l(t) > 0, \\ 0, & a_l(t) \le 0 \vee h_l(t) \le 0, \end{cases} \tag{1}$$

$$F_{yl1}(t) = \begin{cases} \mu_l k_{dl}a_l(t)h_l(t), & a_l(t) > 0 \wedge h_l(t) > 0, \\ 0, & a_l(t) \le 0 \vee h_l(t) \le 0, \end{cases} \tag{2}$$

$$F_{yl3}(t) = 0, \tag{3}$$

where $a_l(t) = a_{pl}(t) - \Delta a_{pl}(t)$, $h_l(t) = h_{Dl}(t) - \Delta h_l(t) + \Delta h_l(t-\tau_l)$, $a_{pl}(t)$ is desired depth of cutting, $\Delta a_{pl}(t)$ is dynamic change in depth of cutting, $h_{Dl}(t)$ is desired cutting layer thickness; $h_{Dl}(t) \cong f_z \cos\varphi_l(t)$, $\Delta h_l(.)$ is dynamic change in cutting layer thickness, k_{dl} is average dynamic specific cutting pressure, μ_l is cutting force ratio (a quotient of forces F_{yl2} and F_{yl1}), τ_l is time-delay between the same position of CE no. l and of CE no. l–1, f_z is feed per edge, $\varphi_l(t)$ is instantaneous angular position of CE no. l.

This is convenient to present relationships (1)–(3), which describe cutting forces of CE no. l in case of proportional model, with the use of matrix notation. Hence appropriate vector of forces of CE no. l will have a form [13]

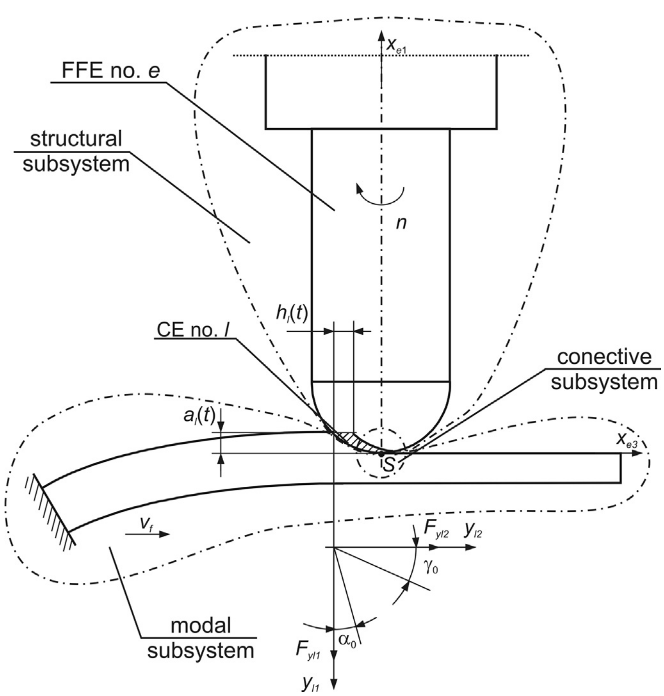

Fig. 1. Scheme of a slender ball end milling of one-side-supported flexible workpiece.

$$\underbrace{\begin{Bmatrix}F_{yl1}\\F_{yl2}\\F_{yl3}\end{Bmatrix}}_{\breve{\mathbf{F}}_l(t)} = \underbrace{\begin{bmatrix} k_{dl}a_{pl}(t)h_{Dl}(t)\\ \mu_l k_{dl}a_{pl}(t)h_{Dl}(t)\\ 0\end{bmatrix}}_{\breve{\mathbf{F}}_l^0(t)} - \left\{ \underbrace{\begin{bmatrix}0 & k_{dl}a_{pl}(t) & k_{dl}h_{Dl}(t)\\ 0 & \mu_l k_{dl}a_{pl}(t) & \mu_l k_{dl}h_{Dl}(t)\\ 0 & 0 & 0\end{bmatrix}}_{\breve{\mathbf{D}}_{Pl}(t)} - \underbrace{\begin{bmatrix}0 & k_{dl}\Delta a_{pl}(t) & 0\\ 0 & \mu_l k_{dl}\Delta a_{pl}(t) & 0\\ 0 & 0 & 0\end{bmatrix}}_{\breve{\mathbf{D}}_{Pl}^{(n)}(t)}\right\} \cdot \underbrace{\begin{Bmatrix}q_{zl}(t)\\ \Delta h_l(t)\\ \Delta a_{pl}(t)\end{Bmatrix}}_{\Delta\breve{\mathbf{w}}_l(t)} + \left\{ \underbrace{\begin{bmatrix}0 & k_{dl}a_{pl}(t) & 0\\ 0 & \mu_l k_{dl}a_{pl}(t) & 0\\ 0 & 0 & 0\end{bmatrix}}_{\breve{\mathbf{D}}_{Ol}(t)} - \underbrace{\begin{bmatrix}0 & k_{dl}\Delta a_{pl}(t) & 0\\ 0 & \mu_l k_{dl}\Delta a_{pl}(t) & 0\\ 0 & 0 & 0\end{bmatrix}}_{\breve{\mathbf{D}}_{Ol}^{(n)}(t)}\right\} \cdot \underbrace{\begin{Bmatrix}q_{zl}(t-\tau_l)\\ \Delta h_l(t-\tau_l)\\ \Delta a_{pl}(t-\tau_l)\end{Bmatrix}}_{\Delta\breve{\mathbf{w}}_l(t-\tau_l)}, \tag{4}$$

or using the abbreviated notation:

$$\breve{\mathbf{F}}_l(t) = \breve{\mathbf{F}}_l^0(t) - \left(\breve{\mathbf{D}}_{Pl}(t) - \breve{\mathbf{D}}_{Pl}^{(n)}(t)\right)\Delta\breve{\mathbf{w}}_l(t) + \left(\breve{\mathbf{D}}_{Ol}(t) - \breve{\mathbf{D}}_{Ol}^{(n)}(t)\right)\cdot\Delta\breve{\mathbf{w}}_l(t-\tau_l), \tag{5}$$

where $\breve{\mathbf{F}}_l(t)$ is vector of cutting forces of CE no. l, $\breve{\mathbf{F}}_l^0(t)$ is vector of cutting forces of CE no. l, resulted from cutting geometry and kinematics, $\breve{\mathbf{D}}_{Pl}(t)$ is matrix of linear proportional feedback interactions, $\breve{\mathbf{D}}_{Pl}^{(n)}(t)$ is matrix of nonlinear proportional feedback interactions, $\breve{\mathbf{D}}_{Ol}(t)$ is matrix of linear time-delayed feedback interactions, $\breve{\mathbf{D}}_{Ol}^{(n)}(t)$ is matrix of nonlinear time-delayed feedback interactions, $\Delta\breve{\mathbf{w}}_l(t)$ is vector of deflections of CE no. l at instant of time t, $\Delta\breve{\mathbf{w}}_l(t-\tau_l)$ is vector of deflections of CE no. l at instant of time $t-\tau_l$, $q_{zl}(t)$ is relative displacement of edge and workpiece along direction y_{l1} at instant of time t, $q_{zl}(t-\tau_l)$ is relative displacement of edge and workpiece along direction y_{l1} at instant of time $t-\tau_l$.

Vector (5) can also be described in six-dimensional space, i.e.:

$$\mathbf{F}_l(t) = \mathbf{F}_l^0(t) - \left(\mathbf{D}_{Pl}(t) - \mathbf{D}_{Pl}^{(n)}(t)\right)\Delta\mathbf{w}_l(t) + \left(\mathbf{D}_{Ol}(t) - \mathbf{D}_{Ol}^{(n)}(t)\right)\cdot\Delta\mathbf{w}_l(t-\tau_l), \tag{6}$$

where:

$$\mathbf{F}_l(t) = col\left(\breve{\mathbf{F}}_l(t),\ \mathbf{0}_{3\times1}\right), \tag{7}$$

$$\Delta\mathbf{w}_l(.) = col(\Delta\breve{\mathbf{w}}_l(.),\ \mathbf{0}_{3\times1}), \tag{8}$$

$$\mathbf{F}_l^0(t) = col\left(\breve{\mathbf{F}}_l^0(t),\ \mathbf{0}_{3\times1}\right), \tag{9}$$

$$\mathbf{D}_{Pl}(t) = \begin{bmatrix}\breve{\mathbf{D}}_{Pl}(t) & \mathbf{0}\\ \mathbf{0} & \mathbf{0}\end{bmatrix}_{6\times6}, \tag{10}$$

$$\mathbf{D}_{Pl}^{(n)}(t) = \begin{bmatrix}\breve{\mathbf{D}}_{Pl}^{(n)}(t) & \mathbf{0}\\ \mathbf{0} & \mathbf{0}\end{bmatrix}_{6\times6}, \tag{11}$$

$$\mathbf{D}_{Ol}(t) = \begin{bmatrix}\breve{\mathbf{D}}_{Ol}(t) & \mathbf{0}\\ \mathbf{0} & \mathbf{0}\end{bmatrix}_{6\times6}, \tag{12}$$