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Effects of bearing clearance on the chatter stability of milling process

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ABSTRACT

In the present study, the influences of the bearing clearance, which is a common fault for machines, to the chatter stability of milling process are examined by using numerical simulation method. The results reveal that the presence of bearing clearance could make the milling process easier to enter the status of chatter instability and can shift the chatter frequency. In addition, the spectra analysis to vibration signals obtained under the instable milling processes show that the presence of bearing clearance could introduce more frequency components to the vibration responses but, however, under both the stable and instable milling processes, the generated frequency components will not violate the ideal spectra structures of the vibration responses of the milling process, which are usually characterized by the tooth passing frequency and its associated higher harmonics for the stable milling process and by the complex coupling of the tooth passing frequency and the chatter frequency for the instable milling process. This implies that, even under the case with bearing clearance fault, the stability of the milling process can still be determined by viewing the frequency spectra of the vibration responses. Moreover, the phenomena of the chatter frequency shift and the generation of more components provide potential ways to detect the bearing clearance in machines.

1. Introduction

Chatter is a problem of instability occurring in the metal cutting process [1], which is associated with forced and/or self-excited oscillations and usually characterized by violent vibration, loud sound and poor quality of surface finish. Chatter can cause a life reduction to the tool and affect the productivity by interfering with the normal functioning of the machine process. The problem has been widely investigated by manufacturing community and has been a popular topic for academic and industrial research. The pioneering chatter instability models were the regeneration theory proposed by Trusty and Polacek [2], and Tobias and Fiswick [3] almost at the same period but independent of each other, which now is referred to by almost every researcher investigating the chatter instability. The regeneration theory has been further developed by many researchers to make it applicable for different metal cutting scenarios including turning and boring [4], drilling [5], milling [6] and grinding [7] operations. Altintas and Weck [8] have contributed a comprehensive review to the fundamental modelling of chatter vibrations and the associated chatter stability lobes for the four metal cutting and grinding processes. Efforts have also been made to improve the prediction accuracy of the chatter stability by taking into account various factors which are probably encountered in practice, for example the influence of structural interfaces on the dynamic stiffness of the machine [9], the mode-coupling effect [10], the feed speed variation [11] and the effect of noise excitation [12]. In

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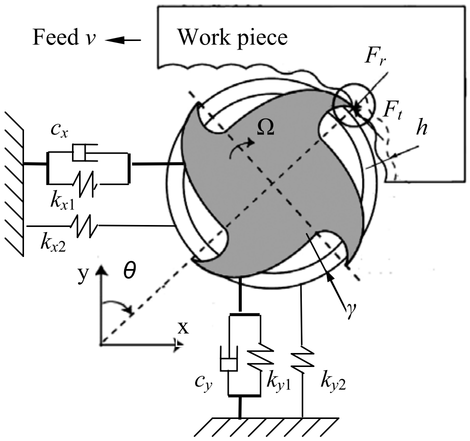

Fig. 1. The model of milling process with bearing clearance.

addition, particular attentions have been paid to the vibration response of machine tool because monitoring the vibration frequencies during machining is an efficient way for identifying machine tool chatter and distinguishing between different types of instabilities [13]. During the stable cutting process, the vibration signals are usually dominated by the tooth passing frequency, and although the higher harmonics may appear in the vibration signals, the motion would still be period-one type [14]. In contrast, during the chatter instable cutting, the machine tool can behave with quasi-period motion [14] or even with chaotic motion [15], and the vibration signals contain multiple frequencies, which usually are dominated by both the tooth passing frequency and the chatter frequency [14]. The spectra structures of the vibration are well defined, and therefore the stable and instable cutting cases can clearly be distinguished based on the spectra. However, sometimes the nice structure of the chatter frequencies can be influenced or destroyed by several other effects in practice, for example the runout [16–18] where the geometric axis of the milling cutter differs from the rotation axis. The bearing clearance is a common fault for the machines, which can lead the machine to complex nonlinear behaviours like quasi-period motion and chaotic motion [19–22]. The appearance of bearing clearance fault could considerably deteriorate the performance of machines, and therefore it is of significance to investigate the effects of the bearing clearance to the cutting process and to inspect the spectra structures of the vibration signals in order to accumulate information for the machine condition assessment purpose and also for identifying the machine tool chatter under the bearing clearance case.

In this paper, based on a 2-DOF of milling process model, the effects of the bearing clearance to the cutting process are analyzed by comparing the stability lobe diagrams and the corresponding response spectra for the milling models with and without bearing clearance. The theoretical stability lobe for the milling model without bearing is also calculated using the method proposed by Opitz [23]. The frequency components that arise due to bearing clearance are clearly identified. This provides useful information to determine if the bearing clearance and chatter are present.

2. Model of milling process

The 2-DOF model of a workpiece-tool system with bearing clearance is illustrated in Fig. 1. The feed direction and spindle rotation are shown for an up-milling operation. The tool is represented by an equivalent two-degree-of-freedom spring–mass-damper system, and the workpiece is assumed to be rigid, and the effect of the bearing clearance is modelled using the discontinuous stiffness model which has been discussed in [20,22]. The 2-DOF oscillator with bearing clearance is excited by the cutting force, and the governing equation can be written in the following equation.

$$\left.\begin{aligned} m_x\ddot{x} + c_x\dot{x} + k_{x1}x + \delta(D-\gamma)k_{x2}(D-\gamma)\cos(\varphi) = F_x(t) \\ m_y\ddot{y} + c_y\dot{y} + k_{y1}y + \delta(D-\gamma)k_{y2}(D-\gamma)\sin(\varphi) = F_y(t) \end{aligned}\right\} \tag{1}$$

where x and y are the displacement of the cutter-head in X- and Y-directions respectively, and $D = \sqrt{x^2+y^2}$, $\cos(\varphi) = x/D$, $\sin(\varphi) = y/D$, and γ is the radial clearance of the bearing, and $\delta(\bullet)$ is a switch function with $\delta(\Delta) = 1$ if $\Delta \geq 0$ and $\delta(\Delta) = 0$ for others. $F_x(t)$ and $F_y(t)$ are the cutting force at time t in X- and Y-directions. The system described by Eq. (1) is a typical nonlinear dynamic system with discontinuous stiffness characteristics.

For the cutting process study, one key problem is about the modelling of the cutting force. Assuming that the number of teeth in the cutter-head is N and the spindle speed is Ω, the tooth passing period τ is equal to

$$\tau = \frac{1}{N\Omega}. \tag{2}$$

Referring to Fig. 1, the ith tooth is acted upon by an orthogonal force, $F_r(i, t)$ which is the feed force in the radial direction, and $F_t(i, t)$ which is the tangential cutting component in the direction of cutting speed. Usually, the force is taken