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Nonlinear behaviour of the regenerative chatter in turning process with a worn tool: Forced oscillation and stability analysis

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ABSTRACT

Self-excited and forced vibrations are important topics in machining processes because their occurrence results in poor surface finish, increase in tool wear and reduction of material removal rate. In this paper, turning process is modeled as a single degree of freedom (SDOF) dynamic system including quadratic and cubic structural nonlinearities. The effect of tool flank wear, as a contact force between the workpiece and tool, is addressed vigorously. Multiple scale method is used to find the solution of the nonlinear delay-differential equation including regenerative chatter, forced excitation and tool wear. During the stability analysis, it is shown that width of cut can be considered as the bifurcation parameter of the system. Finding frequency-response function, behaviour of the system under primary, sub-harmonic and super-harmonic resonances is explained. Specifically, under sub-harmonic and super-harmonic resonances, turning process shows interesting behaviour. The existence of jump phenomenon and its relationship with the machining parameters and structural nonlinearity is discussed in each resonance cases. Finally, stability of the steady state motion is investigated in terms of tool wear length, width of cut and spindle speed. Results are compared for two distinct cases: system with fresh and worn tools.

1. Introduction

Tool life, surface quality and productivity, as some features of machining processes, are adversely affected by the forced and self-excited vibrations. Forced vibration may be arisen from the unbalance of rotating members, servo instability, or using a multi-tooth cutter. Resonance condition is occurred when the cutting tool oscillates close to the natural frequency of the system. Self-excited vibration or chatter is initiated by imperfections in the cutting material, and is remained by the periodic driving force created from the oscillating thickness of the chip [1]. Two mechanisms known as regeneration and mode coupling are the major reasons for machine-tool chatter [2].

Regenerative chatter occurs when cuts overlap and the cut produced at time t leaves small waves in the material that are regenerated during each subsequent pass of the tool (as shown in Fig. 1). This phenomenon causes the chip thickness variation and consequently cutting force variation and increase in vibration amplitude of the cutting tool. Mode coupling is produced by relative vibration between tool and workpiece that occur simultaneously in two different directions in the plane of cut. Mode coupling usually occurs when there is no interaction between the vibration of the system and undulated surface of the workpiece. In this case, the tool traces out an elliptic path that varies the depth of cut in such a way as to bolster the coupled modes of vibrations (as shown in Fig. 1). Regenerative chatter is found to be the most detrimental phenomenon in most machining processes.

Interesting physical phenomena including saturation, jumps, sub-harmonic and super-harmonic resonances, self-excited oscillations, modes interaction and chaos occur in structures in the presence of nonlinearities. Due to the limitations of linear

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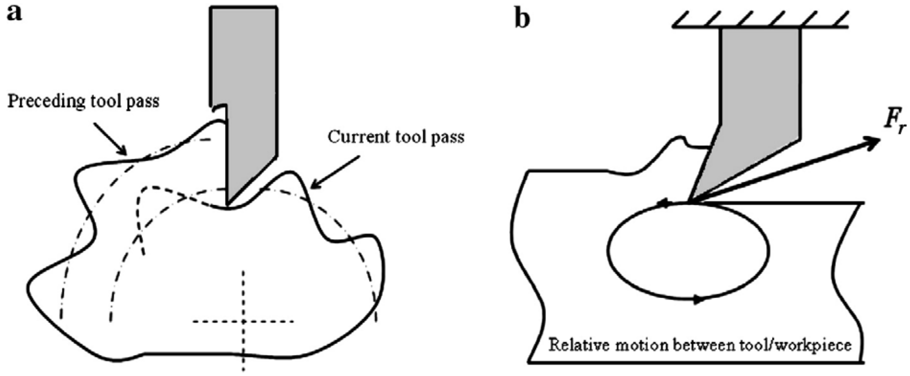

Fig. 1. Instability caused by a) regeneration b) mode coupling.

governing of physical systems, these phenomena cannot be predicted by linear models. Several nonlinear models of turning process have been presented. The first nonlinear models of turning process included material nonlinearity [3], a combination of material and structural nonlinearities [4], and high order nonlinear terms in cutting force [5,6]. Also, nonlinear frictional models including the effect of cutting velocity on friction coefficient [7,8] and models with two degrees of freedom [9,10] have been developed for turning process. Moreover, the effect of delay time on turning process with structural and cutting force nonlinearities has been studied [11,12]. Nonlinear viscoelastic models [13] and models with hysteresis effect arisen from the relation between cutting force and chip thickness [14], have been investigated. Tool-workpiece geometry [8,15] and separation of tool and workpiece [16] are other sources of nonlinearity.

Frictional properties of the tool-workpiece interaction affect the dynamic cutting force characteristics and consequently have a great influence on the stability problem. The complex nature of tool wear is regarded as a major obstacle in achieving of manufacturing automation. Many efforts have been done to find a correlation between machining parameters and tool wear [17]. To have a thorough understanding of the nonlinear behaviour of turning process, tool wear must be included in the previous investigations. Due to the high sensitivity of force signals to the status of machining process, measuring the amplitude of cutting forces is an indirect technique to detect the extent of the tool wear [18].

In this paper, a nonlinear SDOF dynamic model of the turning process is considered. This model includes the time delay and structural nonlinearities arisen from regenerative chatter and hardening stiffness, respectively. The effect of tool flank wear is modeled as a contact force between the workpiece and tool. Multiple scale method via an algorithm in MATLAB is used to find the free and forced nonlinear response of the system. From the stability point of view, it is found that width of cut plays as the bifurcation parameter of the system.

Characteristics of primary, sub-harmonic and super-harmonic resonances and jump phenomena for both fresh and worn tools are discussed. Implicit interaction between amplitude of vibration, frequency detuning parameter, amplitude of excitation, and other machining parameters is explained through the frequency-response equation. Interesting results are obtained under sub-harmonic and super-harmonic resonance situations. Finding singular points of the problem, stability of the steady state motion is investigated in terms of tool wear length, width of cut and spindle rotational speed. Finally, the analogue simulated block diagram of the system is developed by which the effects of other excitations such as step, ramp, etc. can be studied too.

2. Nonlinear dynamic model of the turning process with a worn tool

In orthogonal turning operation, cutting tool is directed perpendicular to the cylindrical workpiece spinning along its longitudinal axis (the spindle), shaving a thin piece of material (chip) as the spindle turns. It is common to use a single degree of freedom system to model the turning process in the orthogonal mode [19] (e.g. in plunge cutting of thin disks with a straight edge tool as shown in Fig. 2). In this model, spring and damping constants are considered for the stiffness of the machine structure. Oscillating mass represents the inertia of the tool and vibrating portions of the machine tool.

Considering cutting force proportional to the chip area, and structural nonlinearity in the form of stiffness with quadratic and cubic terms, the equation of regenerative chatter (arisen from variable component of cutting force) in the feed direction is written as:

$$m\ddot{x} + c\dot{x} + \sum_{i=1}^{3} k_i x^i = k_c w_c \phi(x) \tag{1}$$

where k_c is cutting coefficient, w_c is width of cut and $\phi(x)$ is the variation of chip thickness in the direction normal to the cutting edge and is given as [1]:

$$\phi(x) = [h_0 + x(t-T) - x(t)],\ T = 60/N \tag{2}$$