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Stability analysis of modulated tool path turning

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ABSTRACT

A new periodic sampling-based method for identifying the stability of modulated tool path turning (MTP) is presented. A metric is defined that provides a numerical value to indicate stability; it is nominally zero for forced vibration and large for self-excited vibration. Tests were performed using ASM 6061-T6 aluminum tubes with varying wall thicknesses to control stability, where MTP was applied to create discrete chips by superimposing sinusoidal oscillation in the feed direction. Results are compared for the new periodic sampling metric and the traditional frequency-domain approach, where the frequency spectrum is analyzed to identify the chatter frequency (should it exist).

1. Introduction

Unlike milling operations where the rotating tool constantly engages and disengages the workpiece to produce intermittent cutting conditions, conventional turning, boring, and threading operations typically exhibit continuous cutting. Once the cutting edge is engaged with the workpiece, it remains in contact at a specified feed rate until the cut concludes. This tends to produce a continuous chip that can wrap and collect near the cutting edge when machining ductile materials; see Fig. 1. The local buildup of this continuous chip can result in one or more of several undesirable outcomes including workpiece scratching, tool damage, machinist injury, and increased cycle time to clear the chip(s) from the tool/workpiece.

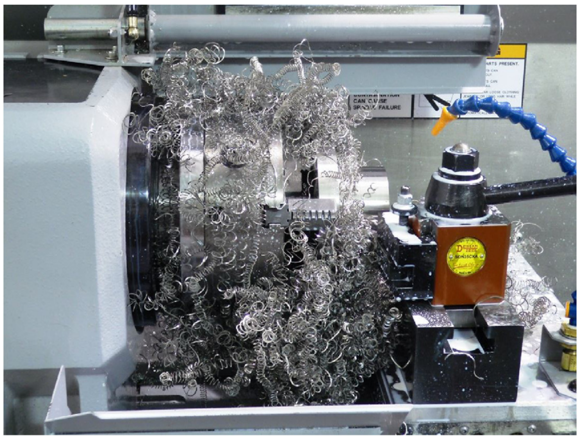

Fig. 1. Chip buildup observed in a turning operation.

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Existing chip management strategies include the use of specialized rake face geometries (i.e., chip breakers) and high pressure coolant directed at the rake face-chip interface to intentionally fracture the otherwise continuous chip. The performance of these strategies depends on the chip thickness, chip radius of curvature, and workpiece material [1], as well as the coolant pressure, direction, and location when high pressure coolant is applied.

An alternative approach to these techniques is modulated tool path (MTP) turning, where discrete chips are formed by repeatedly interrupting the continuous chip formation by using the machine axes to superimpose low frequency tool oscillations on the nominal tool feed motion. In this case, successful chip separation is based on the oscillation frequency relative to the spindle speed and the oscillation amplitude relative to the global feed per revolution.

Prior MTP efforts have demonstrated its effectiveness for controlling broken chip length in turning [2–5] and threading [6]. An experimental setup used to measure feed motion, force, temperature, and chip formation data using both constant feed and MTP cutting conditions was described [7,8]. Here, stability is reported for MTP turning with a flexible tool. The stability is established using: (1) the traditional frequency-domain analysis, where the frequency content of a process signal is analyzed to identify the chatter frequency magnitude (should it exist); and (2) a new periodic sampling approach, where the synchronicity of the sampled signal is evaluated numerically. The two methods are demonstrated using force, acceleration, and velocity data in a tube turning (orthogonal cutting) setup. Potential advantages of the new approach are: (1) a generic threshold for instability is defined in the absence of noise ($M > 0$); and (2) a smaller number of samples may be required to evaluate stability relative to the frequency spectrum analysis since a higher number of samples is not required to increase frequency resolution.

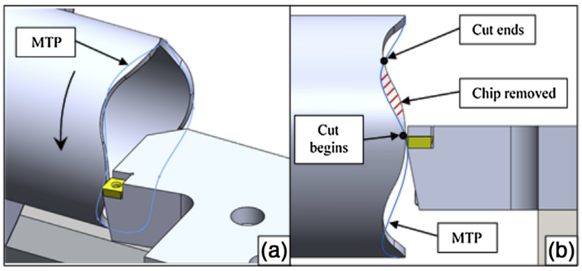

Fig. 2. (a) The tool feed motion is varied sinusoidally to produce a wavy surface in the feed direction. (b) By selecting appropriate *OPR* and *RAF* values, broken chips are periodically produced.

2. Interrupted cutting

An exaggerated depiction of an MTP turning operation is displayed in Fig. 2. The broken chip length is dependent on two, user-defined MTP parameters: (1) the tool oscillation frequency relative to the spindle speed, or Oscillations Per Revolution (*OPR*); and (2) the oscillation amplitude relative to the global feed per revolution, or the Ratio of the Amplitude to the Feed rate (*RAF*). The MTP parameters are defined as:

$$OPR = \frac{f}{\Omega} \tag{1}$$

$$RAF = \frac{A}{f_r} \tag{2}$$

where f is the tool oscillation frequency in the feed direction, Ω is the spindle speed, A is the tool oscillation amplitude, and f_r is the global feed per revolution for a traditional, constant feed turning operation. The time-dependent feed motion of the tool relative to the work, z_f, is then described using these two parameters.

$$z_f = (\Omega f_r)t + (RAF)f_r \sin(\Omega(OPR)t) \tag{3}$$

3. Stability analysis

In interrupted cutting operations, two types of system response may exist. These are forced vibrations and self-excited vibrations (chatter). In forced vibrations, the response occurs at the excitation frequency [9]. In milling, this is the tooth passing frequency, which is defined by the product of the spindle speed and number of teeth on the rotating cutter. The tooth passing frequency describes the number of cutting edge contacts with the work per unit time. For example, the tooth passing frequency for a spindle speed of 6000 rpm using a four tooth endmill is 6000(4)/60 = 400 Hz. In MTP, the excitation frequency is the product of the spindle speed and *OPR*. For a 600 rpm spindle speed and an *OPR* of 0.5, the excitation frequency is 600(0.5)/60 = 5 Hz. The limit on this excitation frequency is the bandwidth for the computer numerically-controlled (CNC) lathe's axis control.

In self-excited vibration, on the other hand, the periodic forcing function is modulated by some physical mechanism into oscillation near the system's natural frequency that corresponds to the most flexible mode [10]. For machining operations, this physical mechanism is the feedback provided by the overcutting of the previous surface in the current pass. This yields a time delay because the current chip thickness depends on the commanded chip thickness, the current tool vibration state, and the tool's vibration state when leaving the previous surface.

Because the response frequencies differ between forced and self-excited vibrations, periodic sampling of machining signals at the forcing frequency enables stable (forced) and unstable (self-excited) behavior to be distinguished. When sampled at the forcing frequency, forced vibrations repeat. For self-excited vibration, the sampled points do not repeat because both the forcing frequency and the chatter frequency are present.

4. Stability metric

The variation in the periodically sampled points due to self-excited vibration enables a numerical value to be assigned that indicates stable or unstable behavior. The proposed new MTP stability metric is:

$$M = \frac{\sum_{i=2}^{N} |x_s(i) - x_s(i-1)|}{N}, \tag{4}$$

where x_s is a vector of periodically sampled x values and N is the length of the x_s vector. The x values can be any process signal, including displacement, velocity, or acceleration of the tool or workpiece; cutting force; or sound [11]. With this stability metric, the absolute value of the differences in successive sampled points is summed and then normalized. For stable cuts (forced vibration), the sampled points repeat, so the M value is close to zero. For unstable cuts, however, $M > 0$ [12,13].

5. Experimental setup

The testbed for the turning experiments was a Haas TL-1 CNC lathe (8.9 kW, 2000 rpm spindle). Tubular workpieces were machined from ASM 6061-T6 aluminum. The outside diameter of the workpieces was 72 mm and the wall thicknesses were {1, 1.5, and 2} mm, corresponding to stable, marginally stable, and unstable conditions for this setup. Concentricity and cylindricity of the outside and inside diameters with the rotational axis of the lathe spindle was assured by performing a finishing cut prior to conducting the experiments. Type C, 80° parallelogram carbide inserts with a zero rake angle, 7° relief angle, and a flat rake face were used (ANSI catalog number CCMW3252, Kennametal part number 3757916). Tube turning was selected so that the cutting speed would not vary with a fixed spindle speed [14]. Experiments were conducted at a cutting speed of 206 m/min (911 rpm) with a nominal feed rate of 0.102 mm/rev. The commanded *OPR* and *RAF* values for all tests were 0.5 and 0.8, respectively. The tests were then repeated using a constant feed rate so that MTP performance could be compared to traditional turning. Stability of the cut was controlled by varying the tube wall thickness (i.e., the chip width).

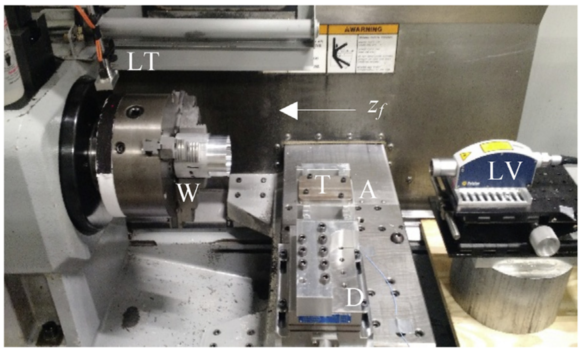

Fig. 3. Photograph of tube turning setup including: workpiece (W), dynamometer (D), flexure-based cutting tool (T), laser tachometer (LT), accelerometer (A), and laser vibrometer (LV).

Dynamic cutting forces were measured using a three-axis dynamometer (Kistler 9257B) mounted to the cross slide. A notch-type flexure was mounted to the top of the three-axis dynamometer [15]. This flexure carried the carbide insert and acted as the cutting tool. This configuration provided a flexible response in the sensitive direction (z_f). A laser vibrometer (Polytec OFV-534/OFV-5000) was used to measure the feed (z_f) direction velocity of the cutting tool. An accelerometer was fixed to the free end of the tool to measure the tool acceleration in the thrust direction. A laser tachometer was used to determine the actual spindle speed for periodic sampling at the MTP forcing frequency. A photograph of

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