STABILITY IN MODULATED TOOL PATH TURNING

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ABSTRACT

In this paper an experimental machining platform that provides in-process metrology during tube turning (orthogonal cutting) is used to determine cutting stability. The experimental machining platform provides in-process metrology for cutting force, tool vibration, feed motion, and chip formation for continuous feed and modulated tool path (MTP) turning. MTP is a tool path strategy that creates discontinuous chips by superimposing tool oscillations in the tool feed direction on the normal feed rate to repeatedly interrupt the cutting process. The tests were performed using AISI 1020 cold-drawn tube workpieces. The chip width was varied by conducting tests using different tube wall thicknesses to control machining stability. To determine cutting stability the system dynamics were measured using impact testing, the Fast Fourier Transform (FFT) was used to analyze the frequency content of machining signals, and once per revolution sampling (OPRS) of time domain signals was implemented.

INTRODUCTION

A major issue in conventional turning, boring, and threading operations is the generation of long continuous chips. In conventional turning techniques, the cutting edge engages the workpiece and it remains in contact at a user specified feed rate until the cut is completed. The result is continuous chips, which can wrap around the chuck and tool requiring manual removal. The buildup of continuous chips around the chuck and tool produces several unwanted results: increased machine downtime, degraded surface finish, tool damage, and increased risk to operator safety. Conventional methods to create discontinuous chips include: specialized rake face tool geometries (chip breakers) and high pressure coolant aimed at the rake face-chip interface. An alternative is modulated tool path (MTP), which was developed to repetitively break chips and manage chip length [1-6]. MTP breaks chips by intentionally creating an interrupted cut through a superposition of tool oscillations in the feed direction. Prior MTP efforts have demonstrated its effectiveness for controlling broken chip length in both turning [1-5] and threading [6].

In this paper, an experimental platform is described that provides machining stability control and metrology during tube turning (which approximates orthogonal cutting conditions) for cutting force, tool vibration motion, feed motion, spindle speed, and chip formation during constant feed and MTP turning. The experimental platform was devolved to explore unstable cutting (chatter) in MTP by measuring the relevant process signals. Unstable cutting, or chatter, is described as a self-excited vibration [8] that produces tool vibration near a natural frequency. The disadvantages of chatter include poor surface quality, scrapped parts, increased waste, increased tool wear, and, in severe cases, possible tool breakage.

To identify unstable cutting conditions, three steps were completed: 1) impact testing was conducted to identify the system dynamics; 2) the frequency content of the machining signals was analyzed to identify content near the dominant natural frequency; 3) once per revolution sampling (OPRS) was used to identify asynchronous vibrations.

MTP DESCRIPTION

MTP is a customized tool path strategy that produces discontinuous chips by superimposing tool oscillations in the tool feed direction to create an interrupted cutting operation. There are two user-defined MTP parameters: 1) the tool oscillations per spindle revolution, OPR; and 2) the oscillation amplitude relative to the global feed per revolution, RAF.

$$OPR = \frac{60 \cdot f}{\Omega} \qquad (1)$$

$$RAF = \frac{A}{f_r} \qquad (2)$$

In Eqs. 1 and 2, f denotes the tool oscillation frequency (Hz) in the feed direction, Ω is the spindle speed (rpm), A is the tool oscillation amplitude, and f_r is the global feed per revolution for a traditional, constant feed turning operation [7].

EXPERIMENTAL SETUP

The testbed for the experiments was a Haas TL-1 computer numerically-controlled (CNC) lathe (8.9 kW, 2000 rpm spindle). Tubular workpieces were machined from AISI 1020 cold-drawn steel. The outside diameter of the workpieces was 72 mm and the wall thickness was {1, 1.5, 2, and 2.5} mm. 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). Orthogonal tube turning was selected, so that the cutting speed, v_c, would not vary with a fixed spindle speed. Experiments were conducted at a cutting speed of 93.75 m/min 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 federate so that MTP could be compared to traditional turning. Stability of the cut was controlled by varying the tube wall thickness.
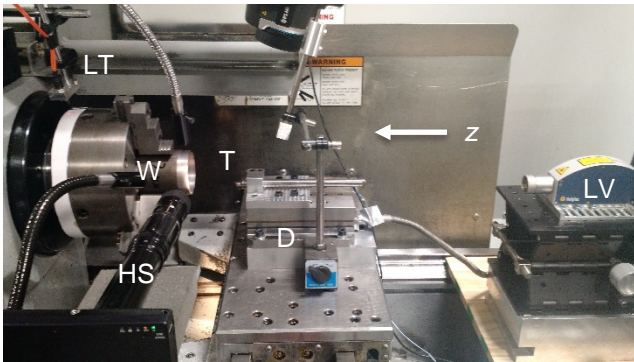

Figure 1. Photograph of orthogonal tube turning setup including: workpiece (W), tool (T), high speed camera, (HS), laser tachometer (LT), dynamometer (D), and laser vibrometer (LV).

Dynamic cutting forces were measured using a three-axis dynamometer (Kistler 9257B) mounted to the lathe's cross slide. A high speed camera (Fastec IL-3) with a maximum frame rate of 1250 frames/sec was mounted to a tripod which was fixed to the shop floor. A laser vibrometer (Polytec OFV-534/OFV-5000) was used to measure the feed direction motion (*z*). An accelerometer was fixed to the free end of the tool to measure the tool vibrations in the cutting direction. A laser tachometer was used to record a once per revolution trigger for OPRS signal analysis. A photograph of the setup is provided in Fig. 1 and additional views are provided in Fig. 2. The thrust

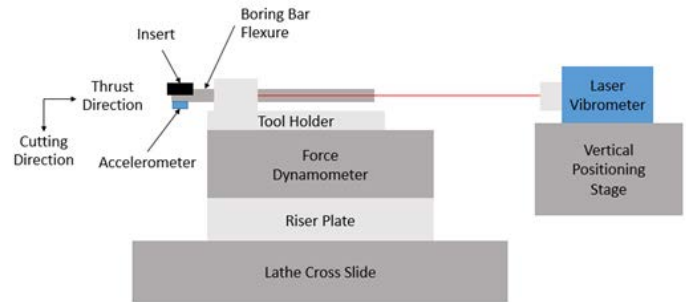direction is aligned with the spindle axis, while the cutting direction is tangent to the cut surface.

Figure 2. Side view of the experimental setup.

RESULTS

In this section, the experimental steps and results are described for: impact testing, frequency domain analysis, and time domain OPRS.

Impact Testing

The system dynamics must be identified to enable frequency domain analysis of the machining signals. To measure the system dynamics, impact testing was completed to identify the frequency response function (FRF). See Fig. 3, which shows the tool point FRF in the cutting direction (the thrust direction result was much stiffer and neglected).
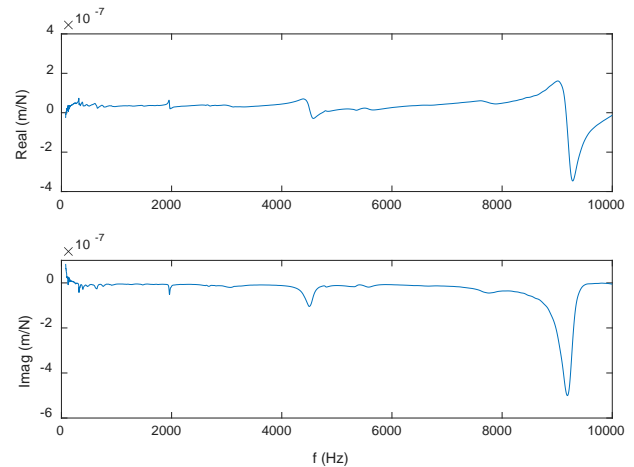

Figure 3. Tool point FRF.

In the tool point FRF there are multiple modes. The most flexible mode represents the bending mode of the boring bar. The bending mode has a natural frequency of 9191 Hz. This mode's natural frequency establishes the chatter frequency during unstable machining. Frequency content near the natural frequency indicates that chatter is occurring.

Fast Fourier Transform (FFT) Analysis
The FFT approach converts the time domain machining signals to the frequency domain so that the frequency content can be analyzed. Content in the frequency domain near the natural frequency indicates that the cut is unstable. This process was applied to the force and the acceleration signals in the cutting direction.
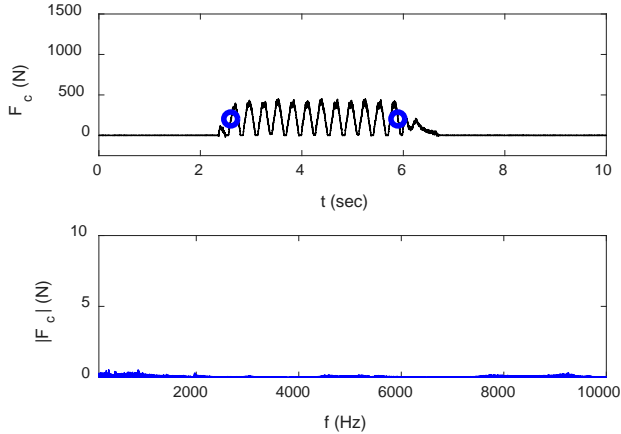

Figure 4. Time and frequency domain plots for the cutting direction force, F_c, with a chip width of 1 mm. (Top) Time domain cutting direction force component. (Bottom) Frequency content of the cutting force.

The time domain plot for the 1 mm chip width cutting direction force, F_c, is shown in Fig. 4 (top panel). The FFT is shown in the bottom panel. The circles on the time domain plot represent the range for the FFT calculation.
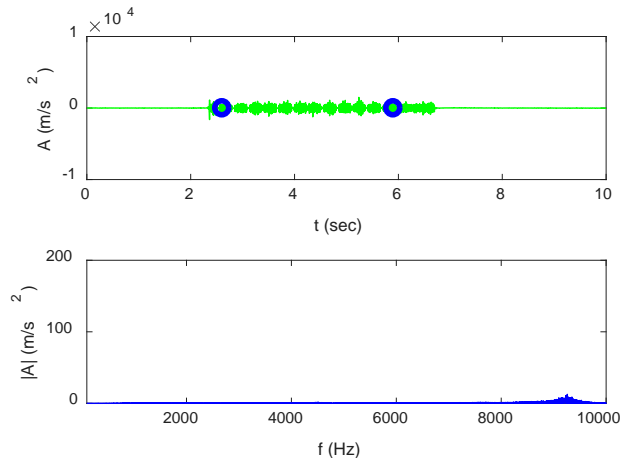

Figure 5. Time and frequency domain plots for accelerometer response, A, in the cutting direction with a chip width of 1 mm.

Figure 5 displays the accelerometer results for a 1 mm wall thickness. Similar to Fig. 4, there is no appreciable content near the natural frequency. This indicates that the cut was stable.
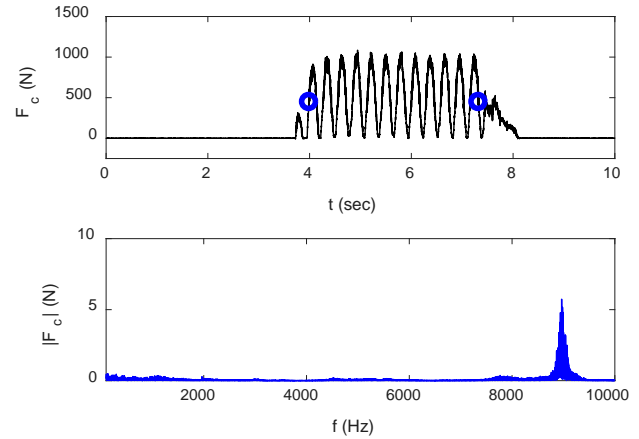

Figure 6. Time and frequency domain plots for the cutting direction force, F_c, with a chip width of 2.5 mm.

Figure 6 displays the time domain plot for the 2.5 mm chip width cutting direction force, F_c, in the top panel. The lower panel shows the frequency content. A peak is present near 9000 Hz, indicating unstable cutting conditions.
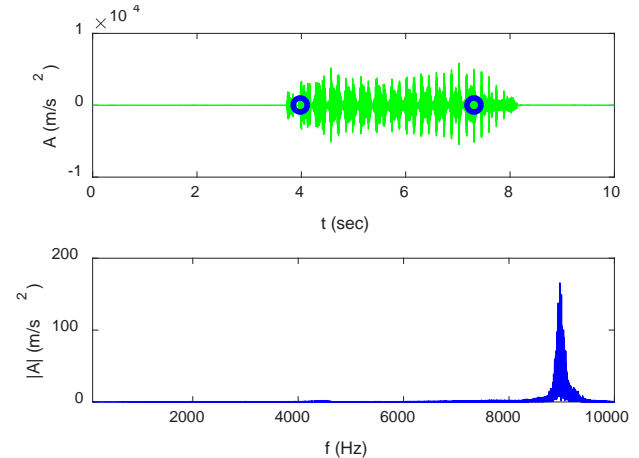

Figure 7. Time and frequency domain plots for accelerometer response, A, in the cutting direction with a chip width of 2.5 mm.

Figure 7 shows the time domain accelerometer results in the cutting direction in the top panel. The FFT of the signal is shown in the bottom panel. Both Figs. 6 and 7 show a peak in the force spectrum near 9000 Hz, which matches the bending mode of the cutting tool (Fig. 3). This indicates the presence of self-excited vibration.

OPRS Analysis

Using the laser tachometer to capture a once per revolution time stamp, the cutting force and acceleration signals were sampled to analyze stability. Sampled points that exhibit a low variance from a mean value are indicative of a stable cut. Conversely, if the variance of the sampled points is large, the cutting operation is unstable. The OPRS method was applied to complement the FFT method. OPRS was applied to the cutting direction force and acceleration signals, similar to the FFT method.
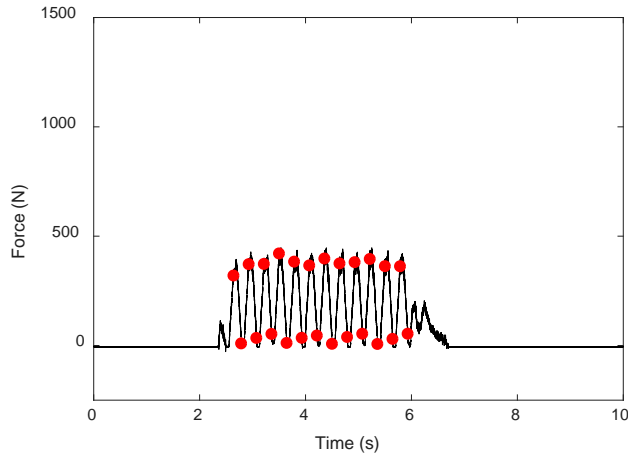

Figure 8. OPRS of the force signal in the cutting direction with a chip width of 1 mm.

Figure 8 contains the time domain force signal in the cutting direction. The once per revolution samples are shown by the dots. Two alternate repeating solutions are observed because the MTP OPR value of 0.5 indicates that one full tool oscillation occurs every two spindle revolutions.
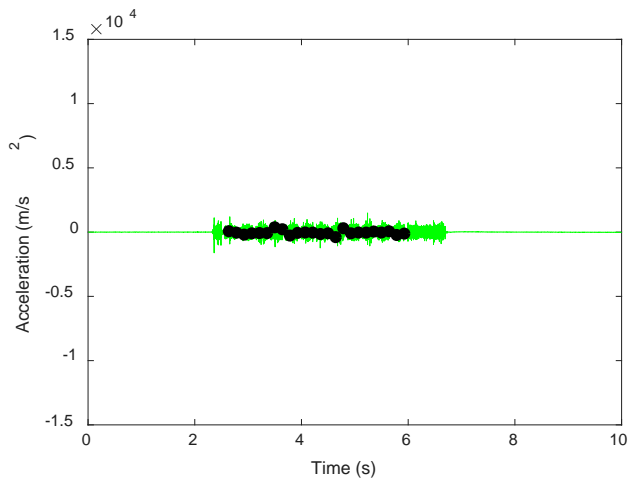

Figure 9. OPRS of the acceleration signal in the cutting direction with a chip width of 1 mm.

The acceleration signal in the cutting direction is shown in Fig. 9 with the once per revolution samples shown by the dots. Figures 8 and 9 both exhibit repeating behavior, indicating a stable cut. These results reinforce the stable cut conclusion obtained from Figs. 4 and 5.
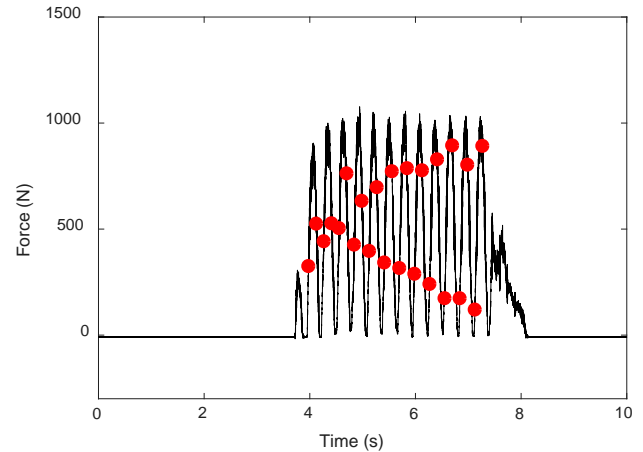

Figure 10. OPRS of the force signal in the cutting direction with a chip width of 2.5 mm.

The time domain force signal in the cutting direction, F_c, with overlaid once per revolution samples for a 2.5 mm chip width is displayed in Fig. 10.
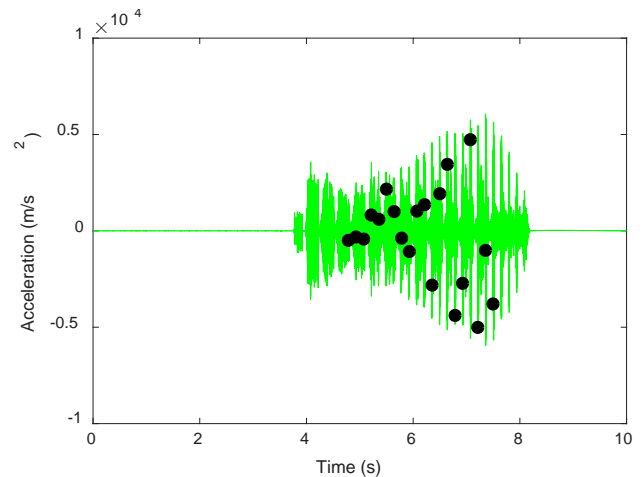

Figure 11. OPRS of the acceleration signal in the cutting direction with a chip width of 2.5 mm.

Figure 11 displays the acceleration signal with overlaid once per revolution samples. In both Figs. 10 and 11 the samples deviate substantially indicating that the motion is asynchronous with spindle rotation and that the cut is unstable. This agrees with the results shows in Figs. 6 and 7.

FFT and OPRS Comparison

For each test, the magnitude of the chatter frequency and the variance of the once per revolution samples were recorded. This was completed for both the MTP and constant feedrate tests. The FFT magnitudes and OPRS variances, σ^2, were then plotted against the associated chip width to give a global view of the change in stability as chip width was increased.
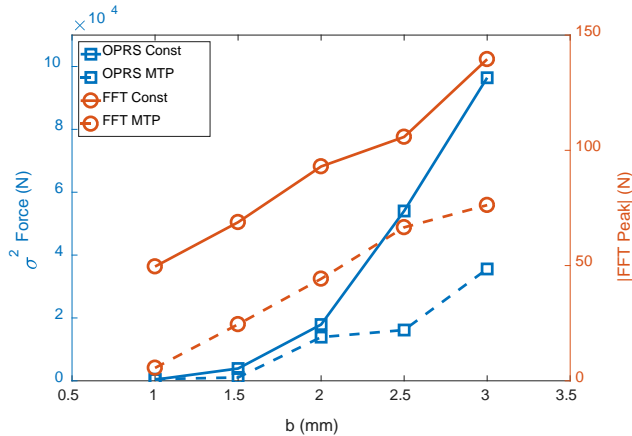

Figure 12. Force OPRS variance and FFT magnitude of both MTP and constant feedrate as chip width is varied.

The results for the force signal OPRS variance and FFT magnitude are presented in Fig. 12. The blue line with square markers denotes that the data set was obtained through the OPRS method, while the orange line with circular markers denotes the FFT method. A solid line indicates that the cut used a constant feedrate and a dotted line indicates that an MTP cut.
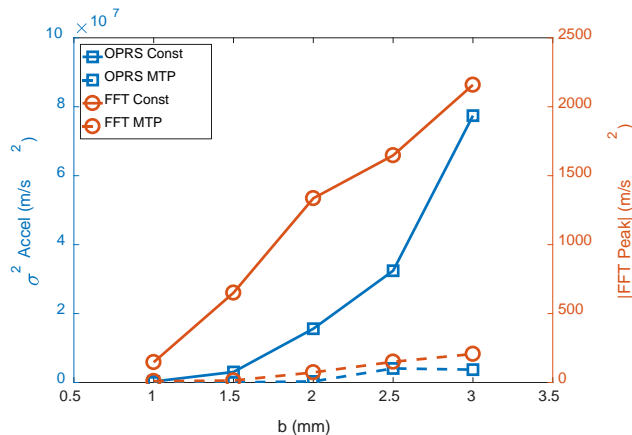

Figure 13. Acceleration OPRS variance and FFT magnitude of both MTP and constant feed rate as chip width is varied.

Figure 13 displays the OPRS variance and FFT magnitude for the acceleration signals. Both Figs. 12 and 13 show an upwards trend in both the FFT magnitude and OPRS variance indicating with the increase in chip width. This identifies the transition from stable to unstable cutting conditions.

CONCLUSIONS

This paper provided machining stability analysis for MTP and constant feed cutting conditions in tube turning. Stability was identified by analyzing the frequency content and synchronicity of the machining signals. The synchronicity was evaluated using a once per revolution sampling (OPRS) strategy. MTP provided a tool path strategy to create discontinuous chips by superimposing tool oscillations in the tool feed direction and repeatedly interrupting the cutting process. Results were presented for turning of AISI 1020 cold-drawn steel tubes. The system dynamics were obtained through impact testing and used to identify the chatter frequency as the bending mode of the flexible tool. The FFT was used to analyze the frequency content as a metric to determine machining stability. The OPRS technique was applied to provide an alternative stability identification metric. Both stability metrics were applied to a range of chip widths for both MTP and continuous feedrate cutting tests. Future work will including modeling and predicting cutting forces and tool vibration using time domain simulation of the MTP and continuous cutting tests.

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