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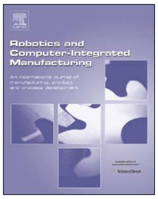

Tool condition monitoring in interrupted cutting with acceleration sensors

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ABSTRACT

Tool breakage is a serious issue in conditions with highly variable stress such as interrupted turning. The tool may fail suddenly though commonly tool failure is preceded by other symptoms such as chipping or fracture of tool edges and tool wear before the complete failure. These symptoms can be used to predict reliably complete tool failure. In the case of a complete failure, the surface integrity of the workpiece is commonly ruined causing waste, making the individual events one of the most expensive failures in small series and flexible manufacturing in addition to collisions. In earlier studies, tool wear has been monitored by force sensors. There are also methods for estimating cutting force with acceleration sensors. In this study, it is demonstrated that it is possible to estimate tool deflection, connected to main cutting force, with acceleration sensor and use this information for detecting the chipping and small fracture of the tool edge. The method presented in this study can be used as a predictor for complete tool failure and thus prevent waste.

1. Introduction

The manufacturing industry requires increased reliability from machining equipment. Intelligent machining using sensorial perception can fulfil this requirement [1,2]. Multiple sensors can be used for tool condition monitoring (TCM) as separate sensors or by applying sensor fusion [3]. To maintain high quality in automated and unmanned manufacturing, the tool integrity must be maintained and therefore, tool condition monitoring is required. Some studies suggest that 20% of cutting machine downtime is caused by tool failure [1]. Interviewed local industry contacts agree that tool breakage is an issue, especially in interrupted turning. The downtime caused by tool failure could be reduced by monitoring systems [1] though predicting it is especially difficult in interrupted cutting due to highly variable stress causing increased tool wear.

Tool wear has been demonstrated to be visible in several types of sensors, including acoustic emission [1,2,4,5], acceleration [1,2,5,6] and force sensors [1,2,5,7,8]. It has been shown that cutting force may be estimated with acceleration sensors [6,9,10]. Regardless of sensors, care must be taken to maintain that sensors within proper operating order and proper calibration. In the case of piezoelectric acceleration sensors, the conditioners do also affect the calibration and measurements.

In this article, a system able to classify tool condition is presented. The system detects or predicts catastrophic tool breakage by estimating tool displacement in interrupted turning, a particularly challenging case for tool condition monitoring due to variable stress. Past studies suggest that this is feasible [6,11], so in this study, the methods are experimentally verified based on the behaviour of the tool deflection during the machining process, and the resulting model is explained based on established theory of cutting forces.

2. Material and methods

2.1. Experimental design

Cutting experiments were recorded using an impeller cast of G-X 2 CrNiMoN 25 6 3 provided by an industrial partner. The workpiece had been subject to prior destructive testing. The thickness of the cut impeller blades was 5 mm, and the length of the blades was 82 mm. The blades were supported from both ends by a solid disk. 26 experiments were planned to be cut with a broken tool and 48 with an intact tool. More than one sample could be captured from a single experiment, resulting in 264 samples with a broken tool and 341 samples with an intact tool. The tools used were a Sandvik CNMG 120412-MR 2025 insert and a Sandvik PCLNL 2525M12 holder in a Doosan Puma 2500Y CNC lathe manufactured 07/2005 based on its identification plate.

The planned design of experiments included a full high-low design with centre points on feed rate and cutting speed. The high/low levels were 0.5 and 1.0 mm for depth of cut, 0.2, 0.3 and 0.4 mm/rev (millimeters pers revolution) for feed rate and 45, 54, and 63 m/min for cutting speed. Tests were conducted for with two levels of tool wear ("intact" and "broken") and repeated once. The intact tool was new at

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the beginning of the experiment. The broken tools were selected by visual inspection from a set of available worn tools and had minor chipping of the tool edges, allowing them still to function but making them already suspect to breaking. The experiments with 1.0 mm depth of cut, 0.4 mm/rev feed rate and 63 m/min cutting speed with a broken tool proved to be unfeasible for safety reasons and were omitted.

Tangential (main cutting force direction) acceleration was measured with a PCB Piezotronic 353B03, with a linear measurement range up to 500*g* (± 4905 m/s^2 pk) and nominal sensitivity of 10 mV/G within 0.7–11000 Hz (± 5%) according to the specifications. The sensor was coupled with a Kistler 5114 conditioner, and the analog/digital conversion was done with a National Instruments PCI-6251 data acquisition card using 20 kHz sampling frequency and 16-bit accuracy (−10 to +10 V). The rotational velocity was acquired from the CNC control. Sample length was computed to be two full revolutions of the spindle to equalise the number of blade hits seen in every sample. There are 16 blades in the impeller, so 32 hits should be visible in each captured sample. The recording of the signals, signal processing and classification was all done in Matlab.

2.2. Methods

The spring force F_s can be calculated as a multiplication of the displacement x with the spring constant k_s as shown in Eq. (1).

$$F_s = -k_s x \tag{1}$$

While in general the tool holder is considered a solid object, if small changes in displacement can be detected, it can alternatively be considered a very stiff spring. The stiffness of the tool holder is unknown and changes based on the exact way it is installed in the lathe, so estimating exact force is challenging. Additionally, the sensor is not installed on the tip of the tool holder, but slightly higher for practical reasons. Detecting the change in deflection is assumed to be sufficient for classifying tool condition. Integrating the accelerometer signal to calculate the displacement does have some problems with the transient shift phenomena, such as “zero shift” (changing sensor offset) as well as random noise, both of which need to be mitigated by signal processing methods.

The main cutting force F_c (also called tangential force) can be calculated as a function of width b and thickness h of removed layer and specific cutting resistance (or specific cutting force) k_c as shown in Eq. (2)

$$F_c = b\ h\ k_c \tag{2}$$

The width and thickness of the removed layer can be calculated based on cutting edge angle κ, depth of cut a_c and feed rate f_c as shown in Eqs. (3 and 4)

$$b = a_c / \sin\kappa \tag{3}$$

$$h = f_c \sin\kappa \tag{4}$$

If we assume these forces are equal (Eq. (5)) we may connect the deflection amount to some of the cutting parameters (Eq. (6)).

$$F_s = F_c \tag{5}$$

$$-k_s x = b\ h\ k_c = a_c f_c\ k_c \tag{6}$$

Therefore, it can be expected that the tool displacement x is a function of depth of cut a_c and feed rate f_c. In theory, the tool displacement can be calculated as the second integral of the acceleration signal. Since the tool stays still, the signals can be assumed to be zero-mean. In practice, calculating the tool displacement requires filtering out significant interference from the signal.

In this study, the impacts of the tool on the workpiece are detected, and the tool deflection is calculated. Based on the statistics of tool deflection behaviour, a model is generated to classify the tool condition.

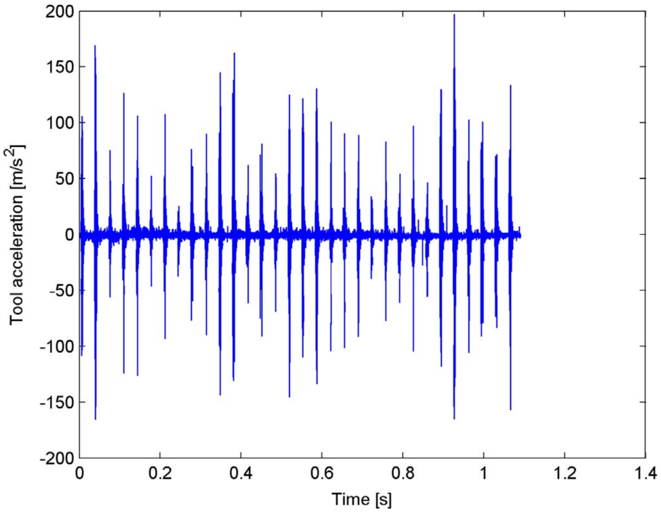

Fig. 1. Tangential acceleration signal captured from machining an impeller. a_c =0.5 mm, f_c =0.2 mm/rev and v_c =63 m/min, tool intact.

3. Calculation

The acceleration signal (Fig. 1) is used to approximate tool deflection, which is useful as a force estimate. The signal is numerically integrated to measure peak tool deflection during the contact to the workpiece. Tool deflection can be calibrated by assuming the tool position to be at zero deflection when the tool does not connect with the impeller blades.

The amount of interference or random noise in the sample can be estimated by measuring the amount of variation when the tool is not cutting the blades. In the recorded signals, the approximate level of interference is 10 m/s^2. Additionally, a periodic but irregular signal at 50 Hz is visible in the samples. Due to impact level when the tool is engaging a blade, some transient response (most likely zero shift) is expected.

As the first step, the approximate systematic error in measurement was estimated by selecting the parts of the signal where the tool does not contact the workpiece as defined by the long-duration low absolute value of the signal. These parts should be at zero and, therefore, the value can be used as an estimate of systematic error. Further elimination of random noise could be achieved by filtering the signal with a short, three-unit median filter. As a desirable property, median filters do conserve edges in the signal.

The tool velocity is calculated by numerically integrating the error corrected tool acceleration signal. The integration amplifies the effect of the transient effects as well as the variable offset caused by the 50 Hz interference, causing disastrous-looking distortion in the signal (Fig. 2). The trend can be removed by calculating the median of the signal at a long window, with window length approximately equal to the time between successive tool contacts. Effectively, the median filter is now filtering out the relatively brief tool impacts and outputting the zero level of the signal. By removing this trend from the signal, the variable trend is removed, returning the non-cutting parts of the signal to zero (Fig. 3). Due to the short duration of the impacts, despite apparently high acceleration values, the tool velocities are not very high.

Mathematically, we note that (Eq. (7))

$$v(t) = \int a(t)dt + C_1 \tag{7}$$

The measurement does have considerable interference, and in this case C_1 is not actually constant, but (Eq. (8))

$$v^*(t) = \int a(t)dt + C_1(t) \tag{8}$$