Development of a surface acoustic wave sensor based smart cutting tool with application to the fly-cutting process

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Abstract

An essential aspect in the control of metal cutting processes is the monitoring and control of cutting forces particularly in-process. A successful cutting operation is judged on the quality of the machined surface, which is inherently linked to the condition of the cutting tool. During the cutting operation, wear and breakage of cutting inserts can increase cutting forces and vibrations of the machining system, resulting in poor surface finish and loss of dimensional accuracy of the machined workpiece. Therefore, it is critical to measure the cutting force changes in-process with a high accuracy. This paper presents the development of a novel smart cutting tool based on a surface acoustic wave (SAW) sensor applied to a fly-cutting application. Moreover, wireless transmission technology has been incorporated into the proposed SAW-based smart cutting tool in order to collect the cutting force signal. Cutting trials using both the proposed SAW-based smart cutting tool and a Kistler dynamometer were carried out to demonstrate the ability of the system to measure the cutting force in real-time.

1 Introduction

To achieve the in-process monitoring and control capabilities in machining, it is necessary to develop and test an innovative cutting tool with an embedded sensing element, in order to collect data or information from the tool-workpiece interface during machining. In metal cutting it is essential to measure cutting force with high precision, because any change in the measurement during cutting will have a direct effect on the machining outcome [1 and 2]. Previously published results have shown that a piezoelectric ceramic sensor embedded between the cutting insert and the spacer is capable of measuring the cutting force with high accuracy in a real machining environment [3] and this configuration has been successfully applied as a standalone force measurement system to replace the dynamometer in adaptive smart machining applications. However, both the wire connected to the piezoelectric ceramic and the BNC cable connected to the charge amplifier, need to be fully protected in this design, as the wires can sustain damage by swarf and by flying chips. It is important, therefore, to exploit the capabilities of wireless data transmission adopted to overcome the above mentioned limitation in the smart cutting tool design. This paper presents the innovative development of an SAW based smart cutting tool for measuring the cutting force in real-time. The design, modelling and analysis of the smart cutting tool is described in details and further supported with experimental trials with the application to fly-cutting.

2 Design principle of the smart cutting tool and its experimental testing

2.1 Surface acoustic waves embedded within the smart cutting tool

Surface acoustic waves are ultrasonic waves propagating along the surface of solids; the transmission and reception principle is based on piezoelectric transducers. SAW sensors often consist of hundreds of electrodes, namely inter-digital transducers (IDTs) as shown in Figure 1, fabricated comb-shapes on the top surface of piezoelectric substrate material, for example quartz or lithium-niobate. The function of IDT is to convert electrical energy into mechanical energy, and vice versa, for generating and detecting the SAW. When the IDTs are directly connected to an antenna, the SAW can be excited remotely by electromagnetic waves. Moreover, the significant advantage of the SAW system is that it can be operated in a very low power consumption mode. It is, therefore, possible to construct passive, wireless, remotely operable SAW devices [4].

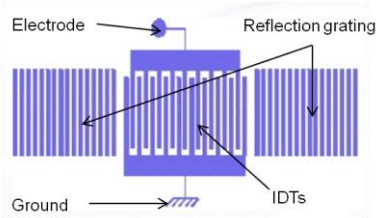

Figure 1: Schematic of the surface acoustic wave strain sensor structure applied to the fly cutting tool

2.2 Tooling and testing configuration: hardware and software

Figure 2 shows the force-based smart fly-cutting tool instrumented with the surface acoustic wave sensor (SAW). The SAW sensor is mounted on the flat surface adjacent to the fix-end, where the maximum strain will occur during the fly-cutting process. The antenna is firmly bolted to the fly-cutter cylinder-head, close to the center of rotation in order to reduce centrifugal force, as shown in Figure 2. The sensor system interrogator is composed of a transmission part and a receiver part, as shown in Figure 8(a). The interrogation unit sends an interrogation signal (a pulse) to the SAW strain sensors, where a surface acoustic wave is generated and propagates from the IDT. The interrogation unit is then switched into “listening mode’’ to receive the signal, sent back from the SAW sensors, which contains the information of the measured physical phenomenon [4 and 5]. The maximum sampling rate of the SAW sensors is 150 Hz (also known as data sampling frequency between the interrogation unit and the SAW strain sensors), and the interrogation distance is about 30 cm between the antenna and the interrogator.

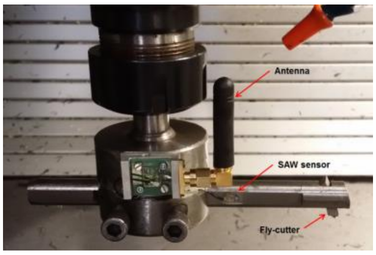

Figure 2: Fly-cutting tool instrumented with the surface acoustic wave sensor and antenna

A customized user-interface has been developed in LabVIEW, shown in Figure 3. In order to read the signal output of the SAW sensor through a RS232 LabVIEW connection several communication protocols, such as input/output connection channel (COM5), baud rate (57600), data bits (8) and buffer size (4096), need to be defined. The output communication protocol displayed in read string block includes frequency, received power, emitted power and measurement variance, to indicate the working condition of the SAW strain sensor. The two output frequencies of the SAW strain sensors are also displayed in Figure 3 [6].

VISA resource name: COM5
baud rate: 57600
Input buffer size: 4096
data bits: 8
End write with termination character? ●
parity: None
End read on termination character? ●
stop bits: 1.0
flow control: None
termination char (0xA = '\n' = LF): DA
XON Character: 11
XOFF Character: 13
timeout (ms): 10000

string to write: *IDN?

bytes to read: 711
actual bytes read: 711

read string:

```
9 03133 010 00354 85328 103
002 432597649 03018 008 01094 433387905
03138 010 00045 85328 103
002 432595601 02997 008 00058 433388785
03103 010 00145 85328 103
002 432595553 03033 008 00041 433388705
03113 010 00259 85328 103
002 432595617 03018 008 01104 433388993
03116 010 00001 85328 103
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Figure 3: Analytics-oriented user interface developed in LabVIEW illustrating the output frequency reading of the SAW sensors

2.3 Corresponding cutting force transduction theory

The basic working principle of the proposed SAW-based smart cutting tool can be described mathematically by the following equations. The relationship between this force and the frequency changes are explained by using Equation (1) and (2) based on the elastic theory of cantilever beam deflection. Equations (3) and (4) describe the piezoelectric performance of the SAW sensor. The strain shifts one natural frequency of the SAW away from its original one, so the relationship between the cutting force and the frequency difference can be established, as demonstrated in Figure 4. An FEA simulation has been carried out to investigate a variety of proposed structures, set with accurate boundary conditions, in order to gain a better understanding of the SAW strain performance when used as a machining force sensor.

$$\varepsilon = -\frac{h}{2}\frac{F(L-x)}{IE} \qquad (1)$$

$$\Delta f = 2S_G \cdot \varepsilon \qquad (2)$$

Substituting equation (2) in to (1) is to derive the relationship between the cutting force and the natural frequency change of the SAW strain sensor as below,

$$F = -\frac{\Delta f \cdot I \cdot E}{S_G\ (L-x)}$$

Where F is the cutting force, ε is the strain induced by the cutting force, h is the thickness, b is the width and L is the length of the tool shank respectively, Δf is the natural frequency change of the SAW strain sensor, S_G is the gauge factor of the SAW, x is the distance between the SAW and the fixed end, E is the Young's modulus of the tool shank and I is the second moment of area.

$$\{T\} = [C^E]\{S\} + [e]\{E\} \qquad (3)$$

$$\{D\} = [e]^t\{S\} + [\varepsilon^s]\{E\} \qquad (4)$$

Where {T} is the stress vector and {S} is the strain vector (both with six elements each: x, y, z, xy, yz, xz), {D} is the electric displacement vector and {E} is the electric field vector (both with three elements each: x, y, z), [CE] is the stiffness matrix evaluated at constant electric field (i.e. short circuit), [e] is the piezoelectric matrix relating stress to electric field, [e]t is the piezoelectric matrix relating stress to electric field (transposed) and [ε^S] is the dielectric matrix evaluated at constant strain i.e. mechanically clamped.

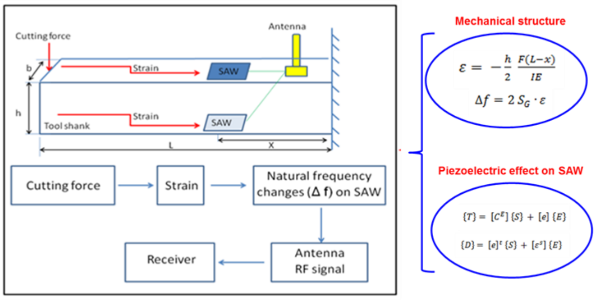


Figure 4: Schematic and flowing chart demonstrating the principle of using SAW sensors to detect cutting force in machining

When a cutting force is applied on the tool tip during machining, the effect of the physical parameter strain can be induced in the tool shank and then sensed by the SAW sensor. Instrumentation with acoustic waves is based on measuring variations of the acoustic propagation velocity of the wave, or wave attenuation. These variations imply changes in wave properties (such as frequency for resonators) which can be translated into the corresponding change of the physical parameter measured. Any applied strain changes the resonant frequency of the SAW strain sensors, which can then be used to correlate to the corresponding change of the physical parameter measured.

2.4 ANSYS based FEA simulation on the SAW sensor

The SAW strain sensor substrate is made of quartz with an STX cut and the electrodes are made of Al. Rayleigh waves can be generated using quartz-STX with a velocity of 3158 m/s, moreover, the energy of the Rayleigh wave is confined close to the surface and dies out within two or three wavelengths in depth from the surface. The resonant frequency of the SAW is chosen to be 433 MHz. Based on the resonant frequency (fr) and the velocity (V), the elastic wavelength (λ) can be determined by

$$\lambda = V/fr = (3158\ \text{m/s})/(433\ \text{MHz}) = 7.29\ \mu\text{m}$$

The distance between successive ITD electrodes P is 3.645 µm, which is half of the elastic wavelength. The geometries of the SAW structure used in the simulation are listed in Table 2.

Table 2: Geometries of the SAW substrate and IDT

Components	Geometry (µm)
Substrate thickness	15
Periodicity of electrode	7.29
Width of electrode	1
Al electrode thickness	0.2

In order to simulate the SAW strain sensor, the boundary conditions for the FEA simulation, Figure 4, need to be defined accurately, as well as the material properties for both the piezoelectric substrate and the Al electrodes. There are three matrices required to be inputted into the FEA simulation, these are the stiffness matrix, the piezoelectric matrix, and the permittivity matrix. Young's modulus, Poisson's ratio and density are also needed for the Al electrodes. The modal analysis has been studied to detect the modal frequencies and the corresponding mode shapes, in order to choose the proper propagation wave mode travelling along the substrate. The simulation can also be used as the starting point for further harmonic analysis to find the corresponding dynamic response in the frequency components of interest. The modal analysis was performed to show several mode shapes and modal frequencies. The 8th mode shape and its corresponding modal frequency of 465 MHz were found to be the preferred propagation wave mode, as shown in Figure 5, because the wave only propagates near the surface and maximally penetrates about 1.2 λ below the surface, which agrees with the theory of Rayleigh waves.

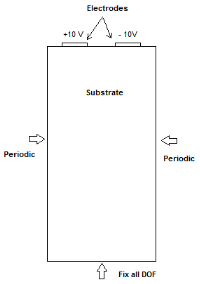
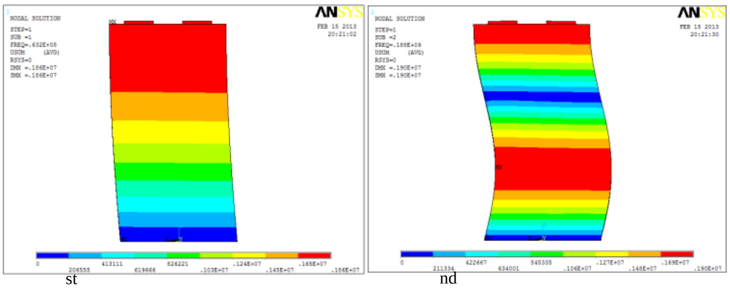


Figure 4: Boundary conditions defined propagation for the FEA simulation.

3 Experimental testing trials and analysis

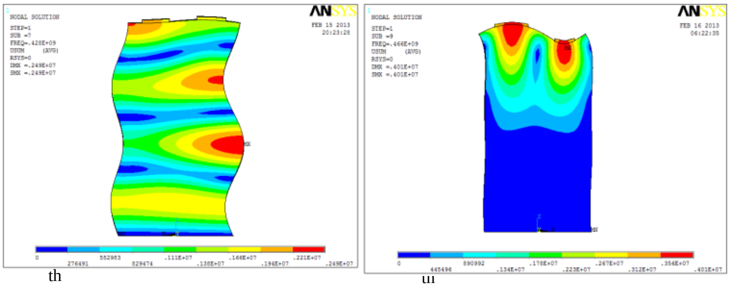
3.1 Smart cutting tool calibration

To some extent, static force components can be used to investigate cutting process performance and cutting tool condition. In order to use the SAW-based smart cutting tool device for force measurement in real machining, calibration was carried out to find the correlation factor between strain and force. Moreover, there is a need to detect the dynamic response of the smart cutting tool because it can strongly influence the workpiece surface finish. The proposed experimental setup, as shown in Figure 6(a), includes the impact hammer, accelerometer, sensor power supply and NI data acquisition card (DAQ). Figure 6(b) shows that the dynamic response of the proposed smart cutting tool is 425 Hz. The results of the dynamic response indicate that the spindle rotation speed cannot be operated close to 425 Hz in order to prevent resonating the smart cutting tool. Such resonance could lead to damage to the SAW strain sensors due to excessive strain and as well as possible chattering during the machining process.



1st mode shape – 63.2 MHz

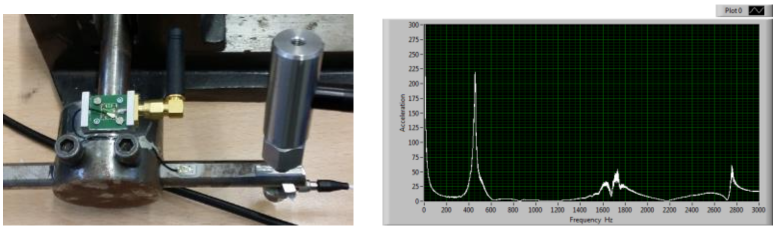
2nd mode shape – 188



7th mode shape – 428 MHz

8th mode shape – 465

Figure 5: Modal shape of SAW at the different excitation frequencies



(a)

(b)

Figure 6: (a) Experimental setups – Kistler impact hammer, accelerometer and the proposed smart cutting tool (b) Dynamic response of the proposed smart cutting tool is 425 Hz based on the hammer testing technique

3.2 Strain effect

For the conventional fly-cutting process, a fly-cutter is a rotating component and a workpiece is firmly clamped to the working surface of a CNC machine. In its normal cutting condition, a vibration signal will be captured by the SAW sensor due to the strain occurring on the fly-cutter induced by a rotation speed, which might influence on the SAW sensor performance and interrogation transmission between the transceiver and receiver. Figure 7 shows the signal output from the smart cutting tool when the fly-cutter switched from a stationary to a rotating speed of 800 rpm and then back to the stationary again. It can be observed that the signal has a low amplitude fluctuation in the stationary condition and then it has a relatively high amplitude fluctuation when it is in the rotating condition. The preliminary testing result suggests that the proposed smart cutting tool is even sensitive to detect a signal output between the stationary and the rotary conditions.

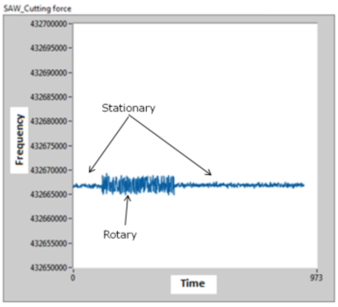


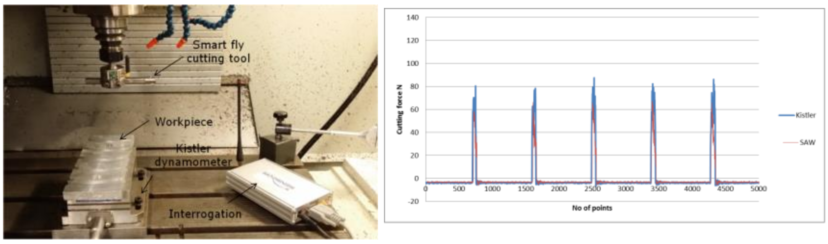
Figure 7: Strain effect on the proposed smart fly-cutting tool in dynamic condition

3.3 Temperature effect

Previous research [3] on a piezoelectric ceramic based smart cutting tool found that the signal output contained not only the machining force measurement but a component due to the change in temperature caused by the pyroelectric effect of piezoelectric material. As a result, further signal processing was required in order to extract useful signals correlated to the machining force only [6]. The proposed SAW-based smart cutting tool in this fly-cutting application employs quartz with an STX cut. The ST cut (Y-rotated 42.75°) of quartz with X-propagation direction has been the classical temperature stable crystal orientation widely used for the development of SAW devices when temperature stability is a primary concern. The characteristic feature of this direction were developed to ensure first order zero temperature coefficients of frequency (TCF1) for surface acoustic waves (SAW) device characteristics near room temperature used in application of strain measurement. Moreover, the SAW sensor is mounted a reasonable distance away from the heat source generated in the preliminary cutting zone. Both of them provide a significant advantage for the proposed smart cutting tool to be insensitive to the temperature fluctuation. So if temperature fluctuations do occur, it will make no contribution to the signal output from the SAW sensor, significantly increasing the robustness and the accuracy of the proposed SAW-based smart cutting tool.

4 Results and further discussion

Cutting trials were carried out with depth of cut 0.2mm, constant feed-rate of 100mm/min, and spindle speed of 800 rpm. Using these cutting conditions, the corresponding cutting forces were measured by both the Kistler dynamometer and the SAW-based smart cutting tool, as shown in Figure 8(a). The Al workpiece (width 100mm, length 200mm) was mounted onto the Kistler dynamometer in order to measure the cutting force. The interrogation unit was located at a distance of 300mm away from the antenna of the SAW-based smart cutting tool to provide good RF link in data transmission as discussed in section 2.2. Figure 8(b) shows a general agreement with the cutting force measurement between the Kistler dynamometer and the SAW-based smart cutting tool. The spikes represent the tool cutting the Al workpiece once within each spindle rotation. Both measurement devices captured the rising and falling edge accurately, representing the tool engagement and disengagement with the Al workpiece. There is always an amount of metal swarf in a real machining environment which might affect the RF link between the SAW sensors and interrogator, however, the SAW sensors performance even under these conditions was quite impressive.



(a) (b)

Figure 8: (a) Experimental setup including smart fly-cutting tool, workpiece, Kistler dynamometer and interrogator; (b) Comparison between Kistler dynamometer and SAW-based smart cutting tool on cutting force measurement in fly-cutting

5 Conclusion

A novel smart cutting tool has been developed based on an SAW technology and used to measure cutting force in a fly-cutting application. The SAW, mounted onto the tool shank, provides in simple configuration and ‘plug and produce’ format, without weakening the overall tool stiffness, whilst measuring the main cutting force during machining. FEA simulation has calculated the natural frequency of the detection system and corresponding mode shape in modal analysis, and the dynamic response through harmonic analysis fully demonstrating the working principle of the SAW detection system. The results of FEA simulation and experiment can be summarised as follows:

(1) An FEA simulation was developed to estimate the dynamic response, the modal frequency, and the corresponding mode shape of the SAW sensor.
(2) Experimental prototype of the smart cutting tool, based on the SAW sensor, was designed and manufactured. Calibration was achieved in both static and dynamic modes.
(3) Experiment has shown that the proposed smart cutting tool can sensitively provide a signal output when the fly-cutter is switch from the stationary to the idling condition as shown in Figure 7.
(4) The experimental result as shown in Figure 8 demonstrates the SAW-based smart cutting tool is capable of measuring the dynamic cutting force in real time for a fly-cutting application.

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