Core Temperature Measurement in Subtractive Manufacturing Processes

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Abstract

Temperature variation is one of the most important factors that affect the dimensional accuracy and surface integrity of workpieces during machining processes. Several attempts have been made towards estimating machine tool and workpiece temperature. The techniques used generally depend on the type of material and the level of accuracy required. However, none of the existing techniques gives a true representation of the core temperature of the workpiece.

The speed of sound in any material depends on the temperature of the material. This dependence can be used to obtain the temperature of the material, provided that the speed of sound can be obtained. The speed of sound can be obtained using the length of the material and the ultrasonic time of travel through the material. The challenge however arises in developing a cost effective acquisition device that can resolve up to 0.5 °C variation with ± 1 °C accuracy. In order to achieve this goal, simulations were done in MATLAB using the k-wave toolbox to determine the required parameters needed for achieving the stated resolution and accuracy. Sensitivity analysis was conducted and the results show the output of simulation of two viable ultrasonic thermometry methods – the pulse-echo method and the continuous wave method. The results of this study will serve as the input for designing and developing an in-process temperature measurement system for subtractive manufacturing processes.

1 Introduction

The primary goal of any manufacturing process is to deliver products that consistently meet specifications. Two of such specifications are the dimensional accuracy and surface integrity of the product. The quality of the product is indicated by its adherence to these specifications. Temperature variation influences both dimensional accuracy and surface integrity, hence, in order to produce high quality workpieces, temperature monitoring and compensation are essential.

Typical temperature variation during machining can reach 10 °C. For aluminium of say 200 mm length, this temperature variation will result in 50 µm expansion and 25 µm expansion in steel. Precision machining should produce workpieces of dimesional error less than 5 µm, this implies that workpiece temperature needs to be measured with accuracy of 1 °C and resolution of 0.5 °C.

Many attempts as well as approaches of measuring workpiece temperature have been described in literature[1]. However, none of the methods give the level of accuracy required in precision manufacturing. For example, infrared cameras provide temperature measurement with accuracy of ± 2 °C[2]. However, this value is only valid in ideal conditions as the accuracy will greatly reduce in harsh machining environments. Also, of all the methods previously used, none directly estimates the core temperature of the workpiece. This is because conventional sensors are usually placed on the surface of the workpiece.

In this paper, a novel method of measuring the core temperature of the workpiece is presented. Using ultrasonic waves, the dependence of sound speed on temperature is exploited to resolve up to 0.1 °C change in temperature.

With k-Wave MATLAB toolbox - an open source toolbox for time domain acoustic and ultrasound simulations, ultrasonic pulse-echo and two frequency continuous wave technique of the phase shift method were simulated. K-Wave gives a real-time A-scan of the medium during simulation and wave propagation plot [3].

2 Methodology

Pulse-echo method is the traditional means of ultrasonic measurement. In pulse-echo method, the principle of time-of-flight (tof) is used, an ultrasonic pulse is sent through a medium and the pulse is then reflected when it encounters a medium of different physical property[4]. The tof from the ultrasonic transmitter to the receiver and the length of the travel path is used to compute the ultrasonic velocity [5]. This relationship is given as:

$$c = \frac{d}{tof} \tag{1}$$

Where ***c*** is the ultrasonic velocity, ***d*** is the distance travelled and ***tof*** is the time of flight [6].

The phase-shift method on the other hand uses the difference in phase of steady-state frequency ultrasonic wave between transmitted and received signal [7]. For an ultrasonic wave of known frequency travelling through a known distance, the phase difference between the transmitted and recieved signal can be used to compute the ultrasonic velocity through the medium. The relationship between ultrasonic velocity and phase shift is given in the equation below:

$$L = \left(n + \frac{\varphi}{2\pi}\right)\frac{c}{f} \qquad (2)$$

Where $\boldsymbol{L}$ is the distance between the transmitter and receiver, $\boldsymbol{n}$ is the integer number of wave periods, $\boldsymbol{\varphi}$ is the phase shift, $\boldsymbol{f}$ is the ultasound frequency and $\boldsymbol{c}$ is the ultrasonic velocity through the medium [5].

A modification of the phase-shift method which considerably improves both the range and resolution of measurement is the *two frequency continouos wave method (TFcw)*, which uses two frequencies for speed of sound computation. The TFcw equation is given as:

$$c = \frac{2\pi L\Delta f}{\Delta\varphi} \qquad (3)$$

Where $\boldsymbol{c}$ is the ultrasonic velocity, $\boldsymbol{L}$ is the length of travel, $\boldsymbol{\Delta f}$ is the difference between the two frequencies $(f_1 - f_2)$ and $\boldsymbol{\Delta\varphi}$ is the difference of the phase shifts given as [7]:

$$\Delta\varphi = \varphi_1 - \varphi_2, \qquad if\ \varphi_1 > \varphi_2,$$
$$\Delta\varphi = \varphi_1 + 2\pi - \varphi_2, \quad if\ \varphi_1 < \varphi_2$$

2.1 Procedure

Three simulations were performed in MATLAB R2017b using the k-Wave toolbox. The first simulation was set up to resolve 0.1 °C change in temperature with *tof* of ultrasonic wave. Steel was chosen as the medium of propagation with a nominal length 200 mm. The k-wave grid (Nx) was defined to be 6.561e+03 grids, the spacing (dx) was defined to be 1.2e-04. The ultrasonic wave parameters were set up to achieve sensitivity of 0.1 °C. The sensor position for the simulation is given in figure 1 below:

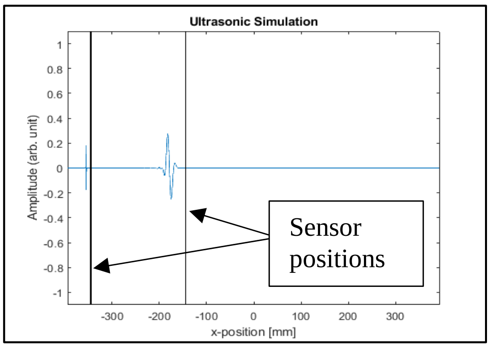

Figure 1: A-scan image of simulation

The ultrasonic velocity used is based on temperature-velocity relationship given by Ihara et al [8]. This is given as:

$$v(T) = -0.636T + 5917.6 \quad (4)$$

where ***v(T)*** is the temperature dependent ultrasonic velocity and ***T*** is the temperature.

The simulation was run over the range of 25 °C to 25.5 °C to observe if the corresponding change in time of flight can be reliably measured. The peak detection technique was used to record the time the ultrasonic pulse strikes the sensor at both the transmitting position and the receiving position.

The second simulation was carried out to observe the individual effect of change in ultrasonic velocity and change in material dimension (expansion) on *tof*. This was done in order to verify if the *tof* can be reliably estimated from the change in velocity alone or from expansion alone or by combining both. The ultrasonic velocity was varied using equation 4, while material expansion was varied using the equation 5 given below:

$$\Delta L = \alpha_L \Delta T L \quad (5)$$

where ΔL is change in length, α_L is linear coefficient of thermal expansion, ΔT is change in temperature and L is the original length.

The third simulation was done using the TFcw method, the aim of the simulation was to obtain the frequency pair which can consistently sense 0.1 °C change in temperature.

3 Results and Discussion

With 1.2 MHz frequency tone burst and sampling frequency of 10 GHz, sensitivity of 0.1 °C was achieved. The recorded tone burst at 25 °C and the *tof* for the whole range of simulation are given in figure 2 and table 1 respectively.

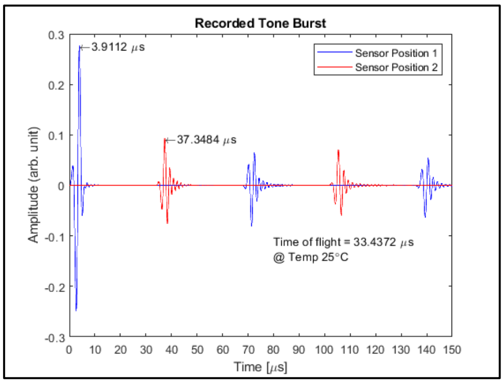

Figure 2: Recorded tone burst

Table 1: Time of flight variation with temperature

Temperature (°C)	Velocity (m/s)	Time of flight (μs)
25.0	5901.7	33.4372
25.1	5901.6364	33.4376
25.2	5901.5728	33.438
25.3	5901.5092	33.4384
25.4	5901.4456	33.4388
25.5	5901.382	33.4392

As seen from the choice of parameters, there is need to sample at frequency of at least 10 GHz to sense a change in time of flight caused by 0.1 °C change in temperature.
The simulation for expansion and ultrasonic speed was done over the temperature range of 0 to 200 °C. Over this range, the relationship between velocity and temperature is almost linear [8]. The result of this simulation is given in figure 3.

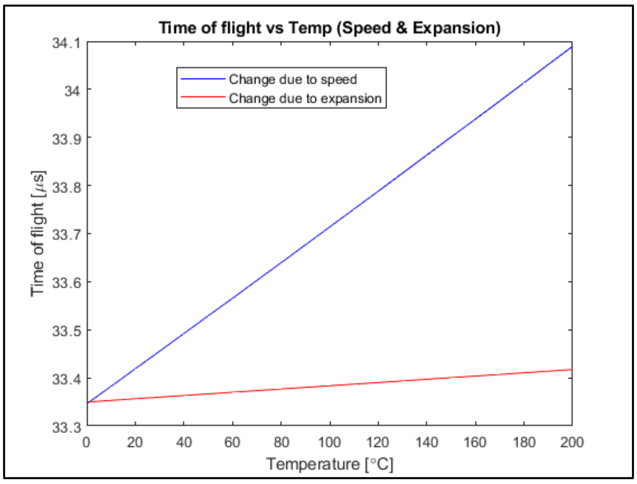

Figure 3: Effect of change in speed and expansion on tof

Figure 3 shows that the time of flight varied largely due to change in velocity and the variation due to expansion is smaller. The *tof* can be reliably estimated by considering ultrasonic velocity while compensating for expansion.

The third simulation used the TFcw technique for the estimation of ultrasonic velocity. With the knowledge of ultrasonic velocity, the medium temperature can be estimated. Firstly, relatively low frequencies of 0.6 MHz and 0.5 MHz were used to estimate ultrasonic velocity through phase shift. Secondly, the frequency pair of 10 MHz and 0.5 MHz were used to improve the sensitivity of the simulation for 0.1 °C change in temperature. The results for both simulations are given in the figure 4, figure 5 and table 2 respectively.

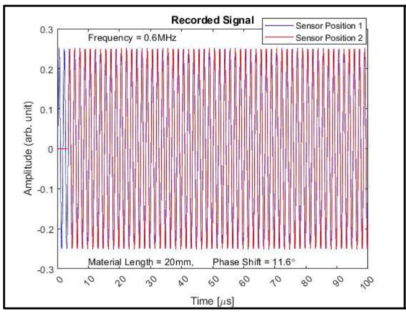

Figure 5: 11.6° phase shift at 0.6 MHz

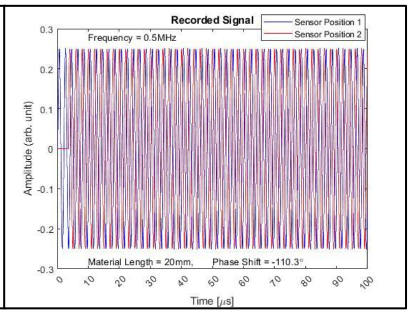

Figure 4: -110.3° phase shift at 0.5 MHz

Using equation 3, c was calculated to be 5906 m/s.

Table 2: TFcw sensitivity

Temp (°C)	φ_1(°) (Phase shift @ 10 MHz)	φ_2(°) (Phase shift @ 0.5 MHz)	$\Delta\varphi$(°) (φ1 - φ2)
20	-46.7	-110.3	63.6
20.1	-46.6	-110.3	63.8
20.2	-46.4	-110.3	63.9
20.3	-46.3	-110.3	64
20.4	-46.2	-110.3	64.1
20.5	-46	-110.3	64.3
20.6	-45.9	-110.3	64.4
20.7	-45.8	-110.3	64.5
20.8	-45.6	-110.3	64.6
20.9	-45.5	-110.3	64.8
21	-45.4	-110.3	64.9

From table 2, over the range of 1 °C and step of 0.1 °C, there was no change in phase shift with 0.5 MHz signal but the low frequency signal compensates for its low sensitivity with a higher measurement range. However, the 10 MHz signal is sensitive to 0.1 °C change in temperature but its range of measurement is shorter. To overcome phase ambiguity, introducing a third frequency will help achieve measurement of the required range and provide good sensitivity for precision temperature measurement.

From the simulations, *tof* method requires a very high sampling frequency to achieve high sensitivity required in precision temperature measurement. There are commercial pulser/receivers used in ultrasonic non-destructive testing with very high sampling frequencies. Another option is the continuous wave method. With signals of different frequencies and corresponding phase shift measurement, material temperature can be estimated.

4 Conclusion

This paper proposes a novel method for the measurement of core temperature during subtractive machining processes. Two main methods were presented, the pulse-echo method and the continuous wave method. The continuous wave method offers a way of obtaining high sensitivity without the corresponding high cost that is obtainable with the pulse-echo method.
A simulation was done to estimate the individual effect of expansion and change in ultrasonic velocity due to change in temperature on the time of flight. It was found that time of flight can be reliably estimated based on the ultrasonic velocity. This finding provides a foundation on which future experiments will be conducted.
Further work is planned which includes using the obtained parameters to design acquisition electronics and ultrasonic transducer to be used for in-process temperature measurement during subtractive manufacturing.

5 Acknowledgement

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