



INDIRECT ASSESSMENT OF THE TOOL TIP TEMPERATURE USING KALMAN FILTER

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Abstract. *The cutting temperature is an important parameter in machining processes, having a direct influence on the tool wear, with effects such as plastic deformation of the tool and the quality of the workpiece. Due to its constant contact with the workpiece, the tool tip is inaccessible for temperature measurement using sensors such as a thermocouple. In turning, the most common way to determine the tool temperature is through the tool-workpiece thermocouple. This method is not highly accurate nor easy to be implemented. The main objective of this paper is to develop an algorithm based on Kalman filter to estimate the temperature at the tool tip, by combining a mathematical model made from a computer simulation and a temperature input on the insert of the tool. The Kalman filter consists in a statistical estimator used to combine data from sensors or mathematical models and remove noises and other uncertainties that may come from the sensors or the process itself. A routine written in MatLab was employed to process the data using the Kalman filter algorithm. As a result of this work, a state space description of the turning tool system was created, making it possible to use the Kalman filter algorithm to estimate the temperature of the tool tip with the input of a temperature measured at a lateral face of the insert. The temperature input was 93 °C and the temperature of the tool tip indirectly measured was 360 °C.*

Keywords: *temperature, simulation, tool tip, indirect measurements, Kalman filter*

1. INTRODUCTION

Manufacturing processes have been evolving quickly ever since the industrial revolution. Since then, different methods, tools and materials have been created and used (Esmailian *et al.*, 2016).

Machining processes is one of them. The definition of machining is the process of removing undesired material from a workpiece in order to obtain a final product of a desired specification (Youssef and El-Hofy, 2008). Some of the processes included in machining are turning, milling, boring and drilling.

The turning process consists on the longitudinal or transverse movement of the turning tool while the workpiece spins around its axis (Machado *et al.*, 2009). It can be used in a cylindrical manner, a conical manner, internal or external, and so on.

There are many different parameters that influence turning processes: cutting speed, tool wear and temperature (Machado and da Silva, 2004). Temperature is one of the most important, since it has direct impact on the quality of the workpiece and on tool wear.

The part of the tool that is affected the most is the tool tip, where the temperature reaches its highest value, due to the fact that it has constant contact with the workpiece. This constant contact makes the tool tip inaccessible to sensors such as thermocouples, which makes techniques like implanted thermocouples, tool-workpiece thermocouples and metallography testing be used in order to determine the temperature in the tool tip. Due to its inaccessibility, an indirect assessment of the tool tip temperature becomes essential for this problem.

In order to measure the temperature indirectly, a Kalman filter algorithm can be used to combine data from a temperature input, that could be seen as thermocouple located elsewhere on the body of the tool with easier access, and a mathematical model, making a reliable estimation of the temperature on the tool tip.

The Kalman filter is a tool used to estimate the state of a controllable process in discrete time by combining a prior estimate of the state with a given measurement and feeding it back to itself recursively to make a posterior estimation and keep repeating this process for the duration of the analysis of the system (Welch and Bishop, 2001).

To obtain the mathematical model that correlates the temperature measured on the body of the tool and the temperature on the tool tip, the COMSOL computer software was used.

The main objective of this work is to develop an algorithm capable of indirectly measure the temperature of the tool tip of a turning machine, by using the Kalman filter and a mathematical model created via computer software.

2. METHODOLOGY

The methodology consists of three parts: the development of the Kalman filter on Matlab, computer simulation on COMSOL and creation of the transfer function and the combination of the mathematical model with the Kalman filter.

2.1 Mathematical modeling of the Kalman filter on Matlab

The Kalman filter is a recursive mathematical method created by Rudolf E. Kalman, in 1960, to estimate real values of variables that may contain noises or disturbances on its signal. It can also be used to estimate different variables based on the measurement of just one parameter (Grewal and Andrews, 2008).

The general concept of the Kalman filter algorithm is to estimate the state of a variable or the state of a group of variables at a given time, measure the state of one or more variables and use this data to improve upon the last step estimation, creating a new estimate state for all the variables involved (Brunton and Kutz, 2017).

To use the Kalman filter, a set of equations are necessary to describe the dynamics of a controllable system. With these equations, a state space description of the system has to be made as an input of the filter.

The state space description necessary for the Kalman filter is defined by Eq. (1) and Eq. (2).

$$\dot{x} = [A]x + [B]u + wd \quad (1)$$

$$y = [C]x + wn \quad (2)$$

where \dot{x} is the filter output, $[A]$, $[B]$ and $[C]$ are parameter matrices, u is the input, y is the measured variable, x is the state variable, wd is a disturbance related to the state of the system and wn is the disturbance from the sensor used to measure the variable y . As long as the pair of matrices $[A]$ and $[C]$ are observable, it is possible to fully estimate the state of a system (Brunton and Kutz, 2017). Observability of matrices are not under the scope of this paper.

By taking the graph of the temperature distribution along the tool in the computer simulation, it is possible to create a transfer function relating the temperature of the tool tip and the body of the tool. Then, the transfer function can be shaped in the state space description aforementioned and, therefore, be used in the Kalman filter.

The Kalman filter algorithm takes into consideration possible disturbances related to the process and the measured values used as inputs. Since a mathematical model created via a computer simulation is used and the input is constant throughout the process, there is no disturbance in this particular case. So, in order for the Kalman filter to work properly, a negligible disturbance was intentionally put into the system.

All of the inputs necessary to the Kalman filter algorithm are: state space description matrices ($[A]$, $[B]$ and $[C]$), the input u (in this case, the temperature measured at the body of the tool) and the disturbances wd and wn . The Kalman filter algorithm was developed on Matlab.

2.2 Computer simulation on COMSOL and creation of the transfer function

To represent the dynamic behaviour of the temperature in a certain structure, a second-order differential equation is necessary and sufficient (Jacquot, 1994). Since there are no trivial equations capable of defining the transient temperature distribution along a turning tool and the geometry of the tool tip is complicated, a computer simulation was made to estimate the temperature distribution with time.

Figure 1 shows a simplified model of the turning tool and the workpiece on COMSOL. The insert is highlighted in blue.

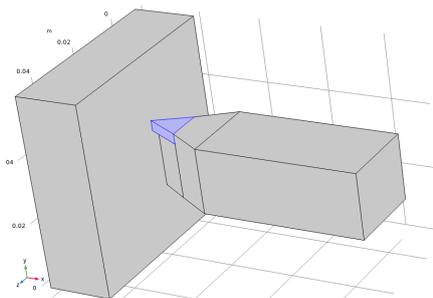


Figure 1. 3D view of the simplified drawing.

Since the goal is to measure the temperature at the tool tip, the chip flow direction and the workpiece size itself are

irrelevant at this point. The triangular insert is touching the workpiece with the tool tip, at the point that is going to be measured.

COMSOL Multiphysics is a computer software capable of simulating many types of physical situations. One of them is the heat transfer in solids.

This software takes into consideration the material of the pieces involved, their geometry, initial conditions such as room temperature and the temperature of a section of the tool, for instance, and all the necessary thermal related coefficients (conductivity, convection coefficient, etc).

Before the generation of the mesh elements, initial conditions had to be implemented and materials had to be chosen. The room temperature was set at 20 °C. The tool tip temperature was set to be 360 °C, which is an average value of the temperature reached between different cutting forces and feeding (Maranhão *et al.*, 2016). The workpiece used on Maranhão's work was the AISI D2 hardened steel, which was the one chosen for the simulation. The turning tool insert chosen was triangular shaped and made of CBN (cubic boron nitride) with a length of 11 mm and thickness of 3.175 mm, and the turning tool holder material chosen was a stainless steel 304, since it is a very common material used in turning tool holders. The COMSOL material library possesses the necessary coefficient and values to run the simulation.

The point chosen to measure the temperature of the body of the tool was in the middle of the tool insert, in one of its lateral faces. Since the geometry of the insert is symmetrical, which lateral face is irrelevant.

To generate an adequate mesh, it is necessary to reach an optimal number of mesh elements. The mesh analysis made is shown on Table 1.

Table 1. Mesh elements analysis.

Number of Elements	Temperature of the Measured Point
265	177.53 °C
450	153.16 °C
1050	119.22 °C
1800	100.77 °C
4500	94.24 °C
8000	92.33 °C
9000	93.29 °C
10000	92.95 °C

Since the temperature measured at the insert was no longer having significant change with the refinement of the mesh, the number of elements chosen was 10000. Then, the mesh elements were created, as shown on Fig. 2.

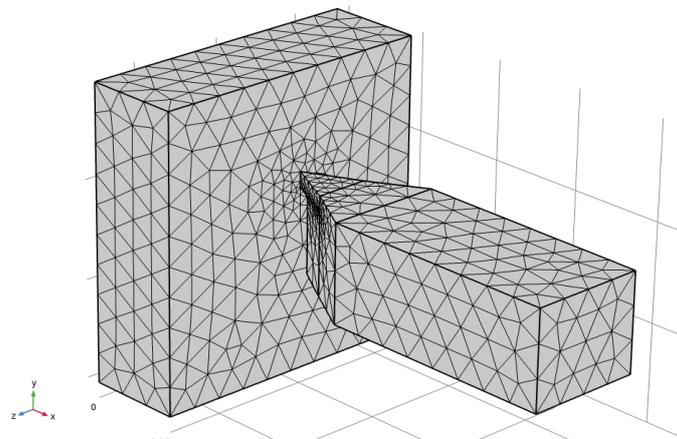


Figure 2. Mesh elements.

After the simulation, temperature distribution graphs were drawn. By selecting the tool tip point and the point in the middle of the insert, it is possible to draw a graph of the temperature over time regarding this desired points.

Using a Matlab toolbox called System Identification, with the data points gathered from the COMSOL simulation, a second-order transfer function relating the temperature on the tool tip and the temperature on the body of the tool was estimated.

2.3 Combination of the mathematical model with the Kalman filter

After the simulation and the estimation of the second-order transfer function, all of the inputs for the Kalman filter can be gathered.

By using inverse Laplace transform and algebraic manipulation, it is possible to transform the transfer function in a state space description. Therefore, the matrices [A], [B], and [C] necessary for the filter are found.

The temperature measured at the insert is the input u for the Kalman filter. It can be found in the graph that shows the distribution of the temperature over time on the measured point.

With the inputs gathered and put into the Kalman filter algorithm, the response of the estimator is the distribution of temperature on the tool tip, without actually giving to the filter temperature used on the simulation. Therefore, in a future experiment with a real turning machine, the Kalman filter will be able to determine the temperature of the tool tip based only on the temperature of the measured point on the insert.

3. RESULTS

The distribution of the temperature along the tool is shown in Fig. 3.

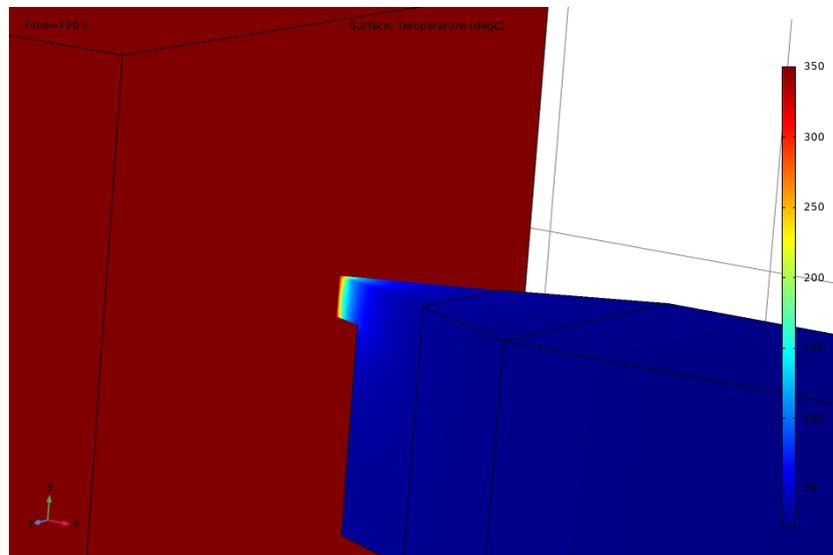


Figure 3. Temperature distribution along the tool.

Figure 4 shows the temperature behaviour on the tool tip and the temperature behaviour on the measured point on the insert.

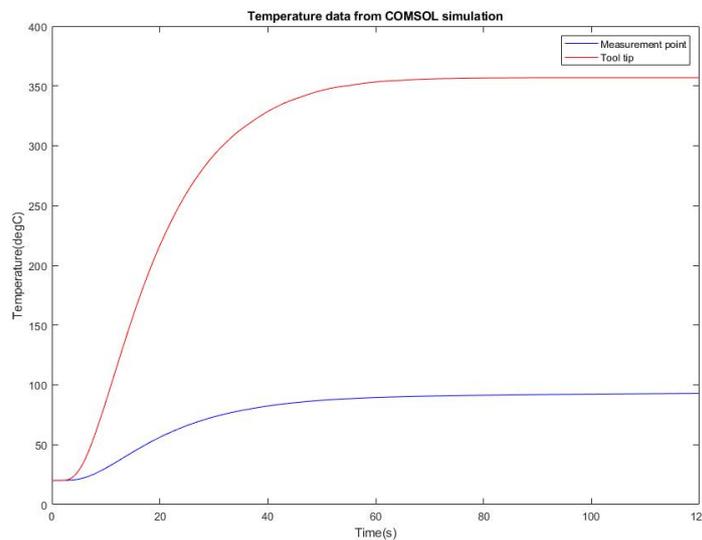


Figure 4. Temperature behaviour on tool tip and on measured point.

The temperature of the point analysed on the insert of the tool was 93 °C after the system stabilized. Therefore, that is the value of the temperature needed to be input on the Kalman filter.

By using data from the graph on Fig. 4, a transfer function was created on Matlab using the toolbox System Identification to describe the tool tip temperature behaviour. Figure 5 shows the simulated data gather from COMSOL and the associated transfer function created by the aforementioned toolbox.

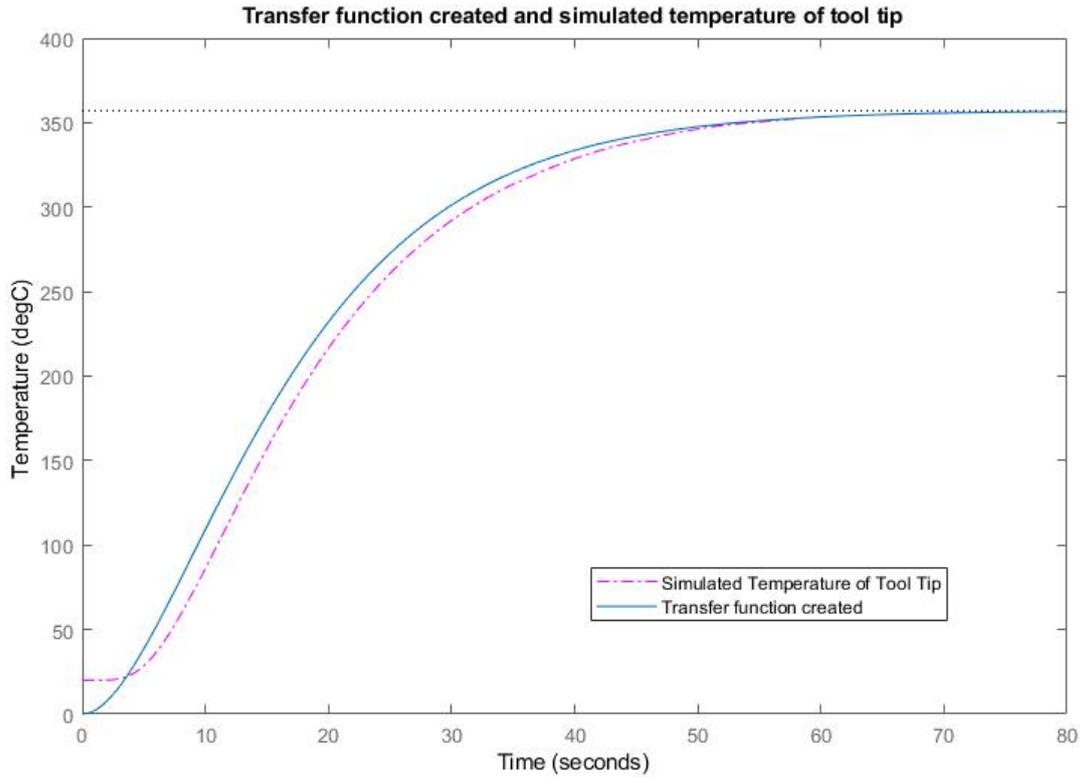


Figure 5. Simulated temperature and transfer function.

The transfer function $G(S)$ of the analyzed system is given by Eq. 3.

$$G(S) = \frac{0.04785}{s^2 + 0.2252s + 0.01246} \quad (3)$$

The average error of the transfer function when compared to the simulated data was given by the System Identification toolbox and was 1.04%.

With the transfer function in hand, the state space description of the problem was created. The parameters A, B and C are shown in Eq. 4, Eq. 5 and Eq. 6 respectively.

$$A = [0, 1; -0.01246, -0.2252] \quad (4)$$

$$B = [0; 0.04785] \quad (5)$$

$$C = [1, 0] \quad (6)$$

By using this description and the temperature input of 93 °C on the body of the tool, the Kalman filter indirectly measured the temperature on the tool tip, as shown in Fig. 6.

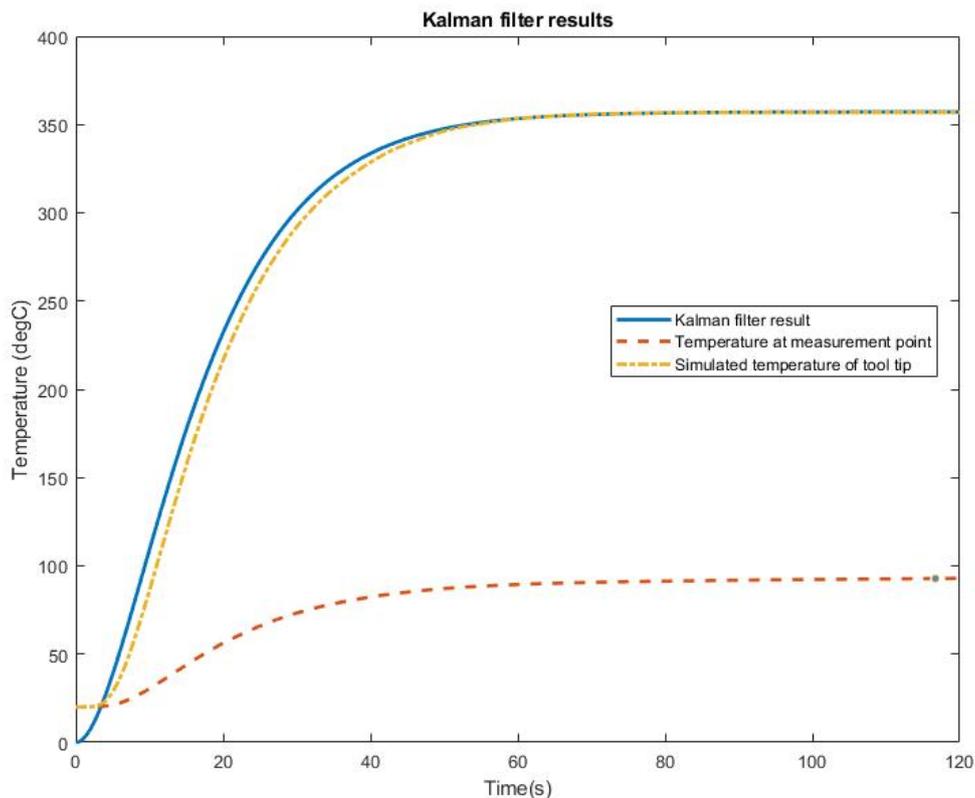


Figure 6. Kalman filter response of the temperature on the tool tip.

It can be seen that the temperature given by the Kalman filter for the tool tip at steady state is approximately 360 °C after the input of the temperature on the body of the tool of 93 °C, as it should be according to the computer simulation.

4. CONCLUSION AND REMARKS

This paper presented a method to indirectly measure the temperature of a turning tooltip based on a computer simulated mathematical model. The model created on the COMSOL Multiphysics software represented the behaviour of the temperature of the tool. The Kalman filter was used to predict the temperature of the tool tip using the input of a temperature measured at the face of the insert of the turning tool.

This method could be applied in a real turning process as a future research.

5. ACKNOWLEDGEMENTS

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