Tool wear monitoring based on non-monotonic signal feature

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Abstract Most of tool condition monitoring (TCM) strategies are founded on the assumption that the monitored diagnostic signal feature is increasing, the monotonic function of the tool wear, but this is not always the case. The paper presents the TCM strategy based on non-monotonic signal features. A used up portion of the tool life (\(\Delta T = t/T\)) was used as the tool condition indicator. It is much more informative than the direct value of a sensor signal or any signal feature, and more practical than tool wear measures (VB, KT) which are not usually measured at the factory floor conditions.

Keywords: cutting, tool wear monitoring

1. INTRODUCTION

Application of tool condition monitoring systems is an important factor of improvement of product quality and reduction of production costs. Although a number of such systems is available on the market and numerous are successfully applied in factory floor conditions, they still are not very often used. This is because they are still not reliable enough and not enough user friendly [10].

The existing tool condition monitoring systems, both laboratory and commercially available, are based on the measurements of physical phenomena which are correlated with the tool wear, and thus can be exploited as the tool wear symptoms. Most often used quantities in commercial TCM systems are cutting force components and force related quantities like power, acoustic emission (AE) and vibration [7, 8, 9]. A review of earlier developments can be found in [5]. The monitoring strategies used in these systems make use of monotonous increment of some signal feature accompanying the tool wear progress. The most often used signal measure (SF) is average value of the signal, but also maximum signal value and other signal features also can be used.

Figure 1 presents a typical strategy of tool wear monitoring. Learning of the system consist in machining the first workpiece with a new, sharp tool. The obtained value of the signal feature \(SF_0\) (here it is the area under the signal vs. time curve) is automatically normalized, that is regarded as 100%. Then the threshold level of the signal feature (\(SF_T\)), or the so called wear limit, is calculated as admissible increase in the signal feature value in percentage terms:

\[
SF_T = SF_0 \left(1 + \frac{dSF_T}{100}\right)
\]

where \(dSF_T\) – limit factor, admissible relative increase in the signal feature value:

\[
dSF_T = \frac{SF_T - SF_0}{SF_0} \times 100\%
\]

Fig. 1. Tool wear monitoring strategy used in most of TCM systems [1]. 1: area signal learned =100%, 2: larger area signal (e.g. through worn tools), 3: learnt area (bar diagram), 4: pre-alarm limit (e.g. 130%), wear limit (e.g. 150%), 5: pre-alarm (area exceeds wear limit), 6: wear alarm (area exceeds wear limit).
While monitoring, after each cycle, the system displays the value of the selected signal feature in a digital or graphic form (Fig. 2). When the feature reaches the threshold level, the tool life is assumed to have come to its end (tool failure). Sometimes two limits can be set – a warning limit (e.g. 130%) and the proper one (e.g. 150%). The admissible increase in the dSF \textsubscript{T} measure in percentage terms can be preset by the manufacturer, but its final and conclusive value must be determined by the operator. System tuning consists in correcting the dSF \textsubscript{T} value. The operator has to make some additional computations according to formula (1) and (2), which is a rather inconvenient and unclear procedure which requires some expertise. There are no reasons why the operator should not be relieved of dealing with signal values by making the system tuning easier by means of simplifying the communication between the system and the operator.

![Fig. 2. Examples of information on signal feature values presented to the user [4].](image)

Necessary condition for signal feature applicability for tool condition monitoring is a correlation of the feature with the tool wear. Commercial systems make use of only those measures which are positive, monotonous and increasing. This eliminates a lot of signal features which do not fulfill these conditions, although they are quite well correlated with the tool wear.

The project undertaken at the Warsaw University of Technology aims at changing this. The system should require the user to input only simple and essential information, and instead of quoting signal values, the system should be able to indicate tool wear in percentage terms. The system’s learning process should be easy, requiring no direct definition of threshold or factor values. The tuning of these values should be equally straightforward. Moreover, the system strategy should make it possible to use the signal feature, regardless their sign, direction of changes and – if possible - also their monotonicity. This paper presents the basic principles of such strategy.

### 2. USED-UP PORTION OF TOOL LIFE AS THE INDEX OF TOOL WEAR

Although every machine tool operator knows what the cutting force or the motor power is, in practice he/she does not use these quantities and has no intuitive sense of their values and changeability. As far as the tool condition is concerned, the natural categories would rather include “sharp”, “partially worn” or “worn out” (failed). Such tool wear measures as VB or KT are seldom used in factory floor conditions. Let us then introduce the concept of the *used up portion of tool life* (\( \Delta T \)), defined as the ratio of the cutting time as performed so far to the overall tool life span: \( \Delta T = \frac{t}{T} \).

As it was already said, the user is informed about initial (SF\textsubscript{0}), current (SF) and threshold (SF\textsubscript{T}) values of the signal feature (see Fig. 2). These values are not interesting for the operator for the values sake. Comparing them, he/she tries to evaluate the quantity which is interesting: used up portion of the tool life as:

\[
\Delta T = \frac{t}{T} = \frac{SF - SF_0}{SF_T - SF_0}
\]

that is e.g. for data in Fig. 2:

\[
\Delta T = \frac{300 - 250}{400 - 250} = 0.33
\]

Of course the formula (3) is in terms of SF linear, which is not always the case. Therefore, a special procedure must be developed to make use of not linear, and not monotonic signal features.
3. STRATEGY OF TOOL WEAR MONITORING SYSTEM

3.1. Learning of the system

Learning of the TCM system begins with the first operation (work piece) machined with a new, sharp tool. During this operation, the system measures available signals, their maximum and minimum values, number of cuts and respective tools. In this and in the following operations, the system calculates selected signal feature and stores it in an array SF<sub>Op</sub> – values of SF assigned to the operation number. Machining is carried out until after performing a subsequent operation, the operator recognizes the end of the tool life, by means of criteria independent from the monitoring system, used before its installation, such as deterioration of surface quality or machining accuracy. It should be pointed out that there is no need for the operator to enter any numerical values. Let us also note that it is not necessary to determine the tool wear, i.e. to measure the direct tool wear indices like VB, KT, etc.

After completing the first tool life, the system transforms the array SF<sub>Op</sub> into the array SF<sub>ΔT</sub> (Fig. 3). Firstly the array SF<sub>Op</sub> is smoothed (low pass filtered) to eliminate random changes of the signal feature. Then to each operation number, the used up portion of the tool life is assigned according to the formula:

\[ \Delta T = \frac{n}{N} \]  

where:  
\( n \) – operation number,  
\( N \) – total number of operations to the tool failure

Finally, the array having number of elements equal to the number of operations is transformed into 20-elements array consisting of SF values corresponding to the used up portions of the tool life, every 5% of \( \Delta T \), according to the formula:

\[ ST_{ΔT}[i] = (SF_{c} = SF_{Op}[\text{ceil}(x)] - SF_{Op}[\text{floor}(x)])*\frac{x - \text{floor}(x)}{\text{floor}(x)} + SF_{Op}[\text{floor}(x)] \]  

where:  
\( x = \frac{i*N}{20} \)  
i – index of the array SF<sub>ΔT</sub> corresponding to the used up portion of the tool life \( \Delta T=5*i ; i = 0:20 \)  
\( \text{floor}(x) \): largest integer \( \leq x \)  
\( \text{ceil}(x) \): smallest integer \( \geq x \)

Then the array is extrapolated to \( \Delta T=150\% \) meaning 10 elements are added according to the formula:

\[ SF_{ΔT}[i] = (SF_{ΔT}[20] - SF_{ΔT}[19])*(i-20) + SF_{ΔT}[20]; \quad i = 21:30 \]  

Fig. 3. Transformation of the array SF<sub>Op</sub> into the array SF<sub>ΔT</sub>.

3.2. Tool wear monitoring

During machining with the subsequent tools, the TCM system measures the signals, and after each operation, it calculates the signal feature value – just like during learning described above. This time however, the system evaluates used up portion of the tool life by searching for the value of SF, closest to the one obtained in the last operation, in the SF<sub>ΔT</sub> array. (Fig 4a).

It may happen that the SF value corresponds to a value of used up portion of the tool life lower than that reached in the previous operation. Such system indication would be disorienting for the operator. Therefore, it was assumed
that the search starts from the $\Delta T$ value obtained last time, which means that used up portion of the tool life presented to the operator cannot decrease (Fig. 4b).

Fig. 4. Evaluation of used up portion of the tool life using measured value of the signal feature SF and array SF$\Delta T$.

Sometimes it happens that the SF value affected by some disturbances corresponds to very high increase of the tool wear. To remedy such mistake, the search is limited to six elements of the SF$\Delta T$ array, that is to 30% of the tool life. This means that in the case of accelerated tool wear, the system allows to perform three operations before it signalizes the tool failure. This procedure has also another purpose – it enables, at least to some extent, to utilize the signal features which are not monotonic versus used up portion of the tool life, as it is presented in Fig. 4d. In the example shown here, the signal feature value corresponds to $\Delta T=70\%$ and $\Delta T=90\%$. Restriction of the array search to 30% of $\Delta T$ results in indication of $\Delta T=70\%$.

Fig. 4. Evaluation of used up portion of the tool life using measured value of the signal feature SF and array SF$\Delta T$. 
It may also happen that because of some distraction, the SF value ceases its typical changes and remains in the value range denoting absence of the tool wear. To force rising indications anyway (the tool cannot stop wear), it was decided that the system indication cannot be lower than 70% of that resulting from the previous experience, calculated accordingly to the formula:

$$\Delta T \geq 70^{\circ}/n/NB \quad (7)$$

where: $n$ – number of just finished operation 
$NB$ – number of operations in the previous tool life.

The value of used up portion of tool life calculated this way is displayed by the system after each operation. When the $\Delta T$ exceeds 100%, the system generates an alarm signal which can be used by the machine tool control system to automatically replace the failed tool or simply to inform the operator about the tool failure. The operator can judge that the tool failed earlier or later than indicated by the system by pressing a key. When he/she regards the tool as being dull, making use of the system indication or not, the array $SF_{Op}$ is transformed into $SF_{AT}$, like during the learning process. However, during monitoring the new contents of the table $SF_{AT}$ is calculated using just the obtained results $SF_{AT\text{current}}$ and the previous contents of the array $SF_{AT\text{prev}}$:

$$SF_{AT} = 0.25 \, SF_{AT\text{current}} + 0.75 \, SF_{AT\text{prev}} \quad (8)$$

This is how the system gathers experience, and singular untypical the signal feature courses have less influence at its performance.

3. RESULTS OF EXPERIMENTS

The experiments have been performed on the turning center VENUS 450 equipped with an industrial cutting force sensor (Kistler 9601A31) installed under the turret. The workpieces were steel C 45 bars, 160 mm diameter, machined in subsequent cuts with the depth of cut $ap=1.5$ (13 cuts) and $ap = 2$ mm (9 cuts), feed $f = 0.1$ mm/rev and cutting speed $v_c = 150$ m/min, down to 85 mm diameter. More details on experimental procedure is given in [3].

Fig. 5 presents the average value of the feed force signal obtained in three selected tool lives. It can be seen that this signal feature (and many others, not presented here) is non monotonic function of the used up portion of the tool life (tool wear). Here, this is caused rather by the sensor installation then by the real character of the feed force, but as it may happen in industry floor condition, it should be taken into account. Tool wear estimation is based on reverse function, where the value of the signal feature determines the tool wear estimation. As the non-monotonic functions are not reversible, all TCM systems using such strategies must fail if the signal feature appears to be non-monotonic.

Fig. 5. The average value of the feed force versus number of operation in three selected tool lives.

The first tool life (T0) out of three tool lives presented in Fig. 5 was used for presentation of learning of the system, while two others for showing the system functioning while monitoring.

Figure 6a presents transformation of ten elements array $SF_{Op}$ into filtered array $SF_{Op\text{filt}}$, and then into twenty elements array $SF_{AT}$. The latter is used for $\Delta T$ evaluation in the next tool life. It can be seen that the $SF_{AT}$ array fits to the $SF_{Op\text{filt}}$ array.

Fig. 6b presents such transformation after the end of the second tool life. Here smoothing of the $SF_{Op}$ array is visible even more clearly, and resulting $SF_{Op\text{filt}}$ array only partly (25%) affects the $SF_{AT}$ array used for the tool wear estimation. A similar performance can be seen after the third tool life (Fig. 6c).
Figure 6d presents the resultant $SF_{\Delta T}$ array contents after all three tool lives.

Fig. 6. Transformation of the $SF_{Op}$ array into the $SF_{\Delta T}$ array after the 1st (a), 2nd (b) and 3rd (c) tool life, and the resultant $SF_{\Delta T}$ array contents after these tool lives (d).
During the first tool life, the system only gathers information without the tool condition estimation, whereas during the subsequent tool lives, after each operation it indicates the used up portion of the tool life. In figure 7 these system indications are presented versus the actual (exact) values of the ΔT for two (T1 and T2) tool lives. Of course, if the indications were exact they would go along straight line $\Delta T_{\text{eval}} = \Delta T$ marked in Fig. 7 with a dotted line. It can be seen that evaluations of the used up portion of the tool life are quite exact. Here however, three tool lives out of the carried out nine were selected, having in mind convenience of presentation of the developed strategy.

![Fig. 7. The system evaluation of used up portion of the tool life ($\Delta T_{\text{eval}}$) versus actual (exact) values of the $\Delta T$ in selected tool lives.](image)

All average values of the feed force signals were presented in Fig. 8a, and used up portion of the tool life evaluation based on these values is presented in Fig. 8b. It can be seen that in some tool lives the selected signal feature had untypical values, which resulted in increasing of the $\Delta T$ estimation error. Thus, although the proposed strategy enables taking advantage of decreasing, negative or even non-monotonic signal features, random disturbances of the SF result in not very precise evaluation of the used up portion of the tool life. This is consistent with a generally accepted opinion that a reliable tool condition monitoring, based on the one signal feature, is not possible. The strategy using many signal features was presented in [2, 3].

![Fig. 8. The average value of the feed force versus number of operation (a) and the system evaluation of $\Delta T_{\text{eval}}$ in all tests (b).](image)
CONCLUSIONS

1. Used up portion of the tool life (\(\Delta T=t/T\)) is a convenient indicator of a tool condition, much more informative than the direct value of a sensor signal or any signal feature, and more practical than tool wear measures (VB, KT) which are not usually measured at the factory floor conditions.

2. The assumption about monotonic, increasing character of signal feature (SF) dependence on the tool wear, being the foundation of most TCM strategies, excludes many useful features. The difficulties related to reversing the non-monotonic functions SF(\(\Delta T\)) could be overcome by transforming them into array and limited range search of SF value closest to the measured one. Such transformation also makes it easy to use the signal features which are non-linear, decreasing or negative.

REFERENCES