ACOUSTIC EMISSION AS TOOL WEAR MONITORING

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Original scientific paper

This paper describes a fast Fourier transformation and its application to monitoring tool wear. It describes the transformation of the collected signal during cutting from the time domain to the frequency. The introduction describes the discrete Fourier transform, DFT deficiency observed in a large number of samples. Therefore, its use in this case is fast Fourier transform. As an example, an indirect method for monitoring tool wear is shown, based on the measurement values of process variables (acoustic emission) and the relationship between tool wear and these values. Tool wear monitoring is a difficult task because many machining processes are non-linear time-variant systems, which makes them difficult to model and the signals obtained from sensors are dependent on a number of other factors, such as machining conditions.

Keywords: acoustic emission, FFT, tool wear, tool wear monitoring

Praćenje trošenja alata pomoću akustične emisije

Izvorni znanstveni članak

U radu je opisana brza Fouriova transformacija te njena primjena na praćenje trošenja alata. Opisana je transformacija prikupljenog signala tijekom rezanja iz vremenske domene u frekvencijsku. U uvodu je opisana diskretna Fouriova transformacija, nedostatak DFT se primjećuje kod većeg broja uzoraka. Stoga svoju primjenu u ovim slučajevima nalazi brza Fouriova transformacija. Kao primjer opisana je indirektna metoda za praćenje stanja alata koja se temelji na mjerenju vrijednosti procesnih varijabli (akustična emisija), na koje utječe vrijednost istrošenja alata.Praćenje trošenja alata je težak zadatak, jer mnogi obradni procesi su nelinearni vremenski promjenljivi sustavi, te se kao takvi ne mogu modelirati i ti signali dobiveni iz senzora ovise o nizu drugih čimbenika, kao što su uvjeti strojne obrade.

Ključne riječi: akustična emisija, FFT, praćenje trošenja, trošenje alata

1 Introduction

Tool wear is an important feature for monitoring in machining processes, because the quality of the surface roughness, dimensional accuracy and cut, the amount of energy needed to remove the metal directly depend on the degree of tool wear. Included here are two mechanisms of tool wear, flank wear and cratering. Every system for monitoring tools must be able to recognize one or both of the wear mechanisms [1]. The first section of the paper shows discrete Fourier transformation and its disadvantages (time of calculating) for using in the sound signal processing. This paper describes mathematical model of fast Fourier transformation. It shows how, with help, fast Fourier transformation transformed signal from time domain to frequency domain. The most suitable way for monitoring tool wear is through frequency of acoustic emission. As an example, the sound signals were analysed which were obtained from the milling process for tool wear monitoring. Based on the knowledge accumulated from conventional cutting tool condition monitoring research, indirect sensing technologies, such as power, cutting force, vibration, and acoustic emission signals are candidates for detecting tool conditions [2, 3, 4]. However, installing a contact sensor on the system of machine tools or production lines is usually a significant challenge for engineers. An experienced worker on the machine can determine the condition of the tool according to the sound generated by the cutting process. Thus, sound signals have attracted attention in the development of tool wear monitoring [5, 6]. The noncontact microphone feature provides a solution to the challenge of installing contact sensors on the structure of the machine. Unlike other signals, such as vibration, acoustic emission, cutting force and spindle current, sound signals collected during metal cutting have not been extensively investigated for failure monitoring tool (Fig. 1).The sound signals obtained from the microphone were first collected and transformed to a frequency domain using FFT [7]. Novelty in this work is potentiality automatisation and optimization of any conventional or nonconventional cutting process with using sound signals.
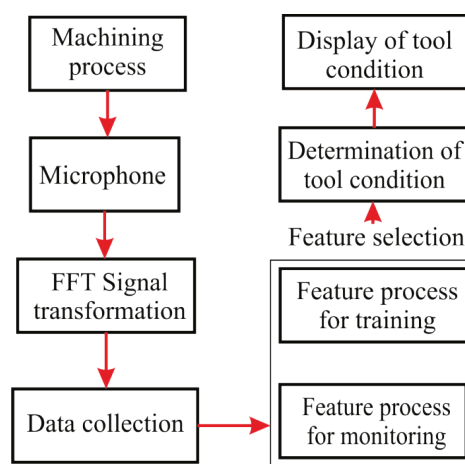

Figure 1 Schematic of tool condition monitoring

2 DFT (Discrete Fourier Transformation)

When computing spectra on a computer, it is not possible to carry out the integrals involved in the continuous time of Fourier transform. Instead, a related transform called the discrete Fourier transform is used [8].

The Discrete Fourier Transform (DFT) is the equivalent to the continuous Fourier Transform for signals known only at N instants separated by sample times T (i.e. a finite sequence of data). If $f(t)$ is the continuous signal which is the source of the data, then N samples are denoted $f[0], f[1], f[2],..., f[k],..., f[N-1]$.

The Fourier Transform of the original signal $f(t)$ would be:

$$F(i\omega) = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}\,dt.$$

We could regard each sample $f[k]$ as an *impulse* having an area $f[k]$. Then, since the integrand exists only at the sample points:

$$F(i\omega) = \int_{0}^{(N-1)T} f(t)e^{-i\omega t}\,dt = f[0]e^{-i0} + f[1]e^{-i\omega T} + \dots$$

$$\dots + f[k]e^{-i\omega kT} + \dots + f[N-1]e^{-i\omega(N-1)T} \quad (1)$$

$$\text{i.e. } F(i\omega) = \sum_{k=0}^{k=N-1} f[k]e^{-i\omega kT}.$$

We could, in principle, evaluate this for any ω, but with only N data points to start with, only N final outputs will be significant. The continuous Fourier transform could be evaluated over a finite interval (usually the fundamental period T_0) rather than from $-\infty$ to $+\infty$ if the wave form was *periodic*. Similarly, since there are only a finite number of input data points, the DFT treats the data as if it was periodic (i.e. $f(N)$ to $f(2N-1)$ which is the same as $f(0)$ to $f(N-1)$) [9].

Since the operation treats the data as if it was periodic, we evaluate the DFT equation for the fundamental frequency (one cycle per sequence $\frac{1}{NT}$ Hz, $\frac{2\pi}{NT}$ rad/s) and its harmonics, not forgetting the d.c. component (or average) at $\omega = 0$, i.e. set $\omega = 0$, $\frac{2\pi}{NT}$, $\frac{2\pi}{NT}*2, \dots, \frac{2\pi}{NT}*n, \dots, \frac{2\pi}{NT}*(N-1)$ or, in general

$$F[n] = \sum_{k=0}^{k=N-1} f[k]e^{-i\frac{2\pi}{N}kn}, \quad (n = 0, \dots, N-1), \quad (2)$$

$F(n)$ is the Discrete Fourier Transform of the sequence $f(k)$.

We may write this equation in matrix form as:

$$\begin{pmatrix} F[0] \\ F[1] \\ F[2] \\ \vdots \\ F[N-1] \end{pmatrix} =$$

$$= \begin{pmatrix} 1 & 1 & 1 & 1 & \cdots & 1 \\ 1 & W & W^2 & W^3 & \cdots & W^{N-1} \\ 1 & W^2 & W^4 & W^6 & \cdots & W^{N-2} \\ 1 & W^3 & W^6 & W^9 & \cdots & W^{N-3} \\ \vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ 1 & W^{N-1} & W^{N-2} & W^{N-3} & \cdots & W \end{pmatrix} * \begin{pmatrix} f[0] \\ f[1] \\ f[2] \\ \vdots \\ f[N-1] \end{pmatrix},$$

where $W = e^{-i\frac{2\pi}{N}}$. This matrix equation requires N^2 complex multiplication and addition. Therefore is valid $t_{DFT} \propto N^2$.

For large N ($N > 50$), the computation time and memory required are significant.

It can generally be assumed that each computational process whose complexity increases with the potency of N is not suitable for applications especially for relatively large N. Moreover, due to the large number of multiplications and additions, it can be calculated with a relatively large error or noise rounding.

Fourier transform has a number of valid mathematical properties, many of which have a physical interpretation that is practical [10]. Some of them are:

- Linearity: The sum of Fourier transform function is the sum of each Fourier transform, Fourier transform of product functions with constant is Fourier transform of function multiplied by a constant.
- Movement in space or time: if the signal $f(x)$ is late (either spatially or temporally, depending on the interpretation of the variable x) for value $f[0]$, Fourier transform of such a "shift" function is equal to the Fourier transform starting function multiplied with a factor exp $(-i\omega x_0)$.
- Symmetry: if Fourier transform (FT) is understood as the starting function and calculated its Fourier transform (i.e. Fourier transform of the Fourier transform), it is obtained that the starting function is calculated in the opposite variable (variable with the minus sign) and multiplied by the appropriate constant (for the upper form of formulas that factor is 2π).
- Fourier transform (FT) derivation: if Fourier transform is known Fourier transform, Fourier transform of its derivative is Fourier transform multiplied with a factor $i\omega$.
- Product $\leftrightarrow$ convolution: Fourier transform (FT) of product is function of the convolution of their Fourier transforms and vice versa - Fourier transform convolution of functions is the product of their Fourier transforms.

3 Fast discrete Fourier transformation

A sequence $f(k)$ of samples is divided into two groups of $N/2$ samples. The division is based on even and odd numbers indices and the making of the first part of $f[0]$, $f[2]$, $f[4]$, and the second part consist of $f[1]$, $f[3]$, and $f[5]$, (Fig. 2).

For this purpose we denote $y_k = f[2k]$ and $z_k = f[2k+1]$, $k = 0, 1, 2, \dots, N-1$.

$$\begin{cases} y_k = f[2k] \\ z_k = f[2k+1] \end{cases}, k = 0, 1, 2, \dots, N-1. \quad (3)$$

DFT for the new sequences (y_k) and (z_k) of the $N/2$ samples is given by the following (2):

$$B_m = \sum_{k=0}^{k=\frac{N}{2}-1} y_k W_{\frac{N}{2}}^{mk}, \; C_m = \sum_{k=0}^{k=\frac{N}{2}-1} z_k W_{\frac{N}{2}}^{mk}, \; m = 0,1,2,...,\frac{N}{2}-1, \; (4)$$

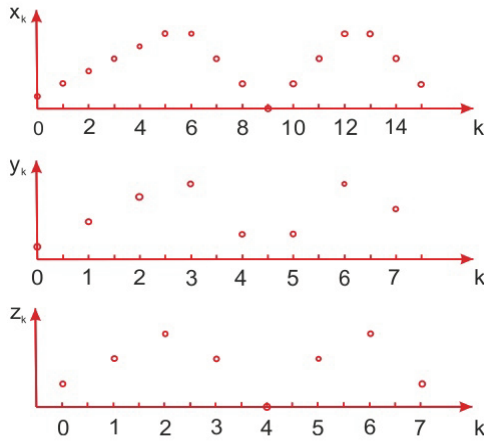where $W_{\frac{N}{2}}^{mk} = \mathrm{e}^{-i\frac{2\pi}{N}}$.

Figure 2 Original sequence x_k and subsequence y_k and z_k

It is necessary to find the relation connecting factors A_m with B_m and C_m coefficients. In order to do this note

$$A_m = \sum_{k=0}^{k=\frac{N}{2}-1} \left(y_k W_{\frac{N}{2}}^{mk} + z_k W_{\frac{N}{2}}^{m(2k+1)} \right), \; m = 0,1,2,...,\frac{N}{2}-1,$$

or

$$A_m = \sum_{k=0}^{k=\frac{N}{2}-1} y_k W_{\frac{N}{2}}^{mk} + W_N^m \sum_{k=0}^{k=\frac{N}{2}-1} z_k W_{\frac{N}{2}}^{mk}, \; m = 0,1,2,...,\frac{N}{2}-1, \quad (5)$$

where A_m is a discrete Fourier transformation of sequence $f[k]$. The Eq. (5) with the Eq. (4) becomes:

$$A_m = B_m + W_N^m C_m, \; 0 \le m \le \frac{N}{2}. \tag{6}$$

For $m > \dfrac{N}{2}$, Fourier coefficients B_m and C_m are repeated symmetrically. Replacing m with the (6) gives:

$$A_{m+\frac{N}{2}} = B_m + W_N^m C_m = B_m - W_N^m C_m. \tag{7}$$

Because it applies:

$$W_N^{\frac{N}{2}} = \mathrm{e}^{-i\frac{2\pi}{N}\frac{N}{2}} = -1.$$

From Eqs. (6) and (7) follows:

$$\begin{aligned} A_m &= B_m + W_N^m C_m, \; 0 \le M \le \frac{N}{2}, \\ A_{m+\frac{N}{2}} &= B_m - W_N^m C_m, \; 0 \le M \le \frac{N}{2}. \end{aligned} \tag{8}$$

The Eq. (8) says that the N Fourier coefficients of the time sequences $f[n]$ ($n = 0, 1,..., N-1$) can be obtained via $N/2$ Fourier coefficients obtained over two DFT with $N/2$ samples (Fig. 3).
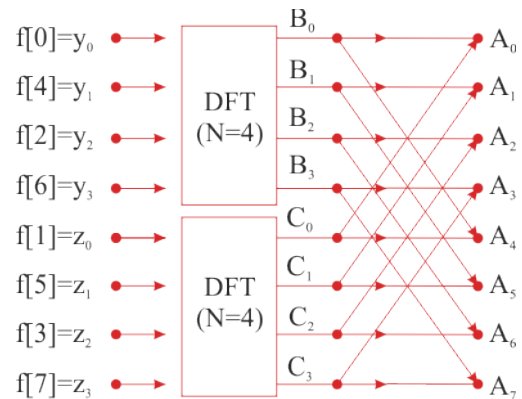

Figure 3 DFT of $N = 8$ samples expressed through two DFT of $N/2$ samples

In the same way, dividing sequence y_k and z_k in two parts, the DFT of each of these sequences can be counted by two DFT of N/4 samples. Figure 4 shows an example of how the DFT of 8 samples is calculated by four DFT in two samples.
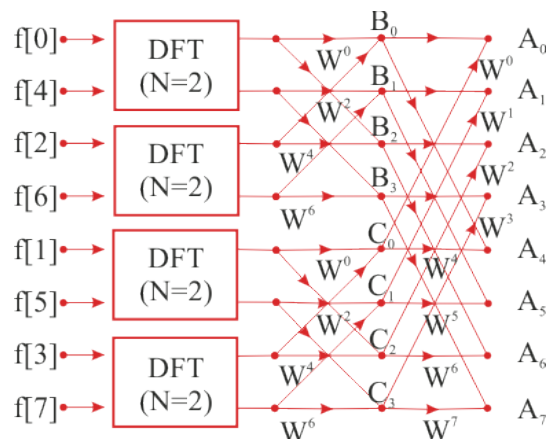

Figure 4 DFT of $N = 8$ samples expressed by four DFT of $N/4$ samples

The above method of sharing is applied repeatedly until we finally get the DFT of N times by only one sample where the course DFT single sample equals to the sample. For example, $N = 8$ files in Fig. 5 shows a flowchart of computing in all N Fourier coefficients.

Obviously, the procedure of computing is valid only under the condition

$$N = 2^M, M = 1, 2, 3,...$$

Thus, the number of samples of the time sequence $f(k)$ should have a value of

$$N = 2, 4, 8, 128, 256, 512, 4096.$$

However, it is possible, with certain modifications, to use described FFT algorithm for any N (i.e. $N \ne 2^M$).
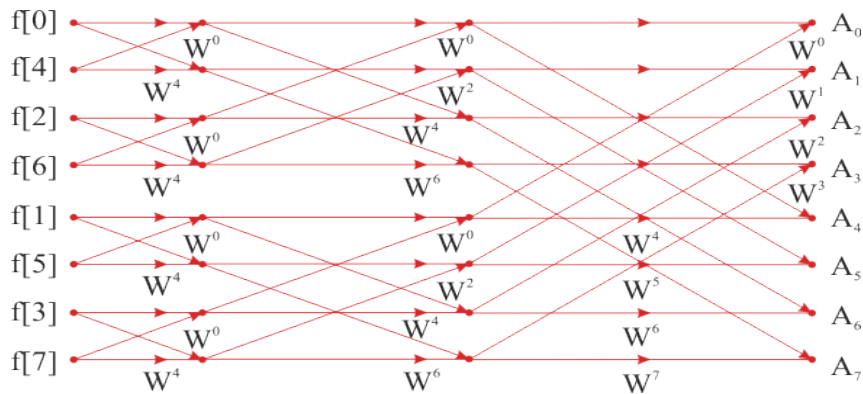
Figure 5 Flowchart FFT procedure for $N = 8$

From the flowchart in Fig. 5 we can follow the necessary refurbishment sequence of input samples. However, refurbishment sequence of input samples is usually unacceptable especially for signal processing in real time. The problem sequence of input samples can be solved by converting the diagram in Fig. 5 in the form shown in Fig. 6. If the sequence denotes binary code (Fig. 6) it can be easily seen that this is mirrored by random bits.
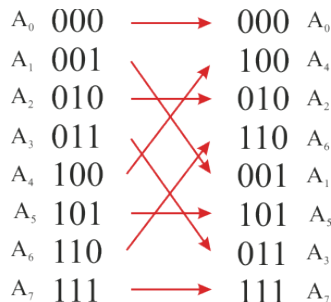

Figure 6 Refurbishment order of Fourier coefficients with $N=8$

The refurbishment of the sequence of Fourier coefficients is usually an integral part of FFT routines that are normally used in a variety of software packages (e.g., Matlab, Mathematica, Statistica, Labview) [11].

Flowchart from the FFT follows that an intact budget is allocated in $M = \mathrm{lb}N$ steps. It is also obvious that once the sample was taken and calculated intermediate, it is no longer required in order to proceed, and it can give way to the new calculated values. Thus, in one place in memory, which is stored at the beginning of a complex value of the sample, it is replaced by M values throughout the FFT accounts to the end of the stored value of the complex Fourier coefficients. Obviously, the FFT algorithm takes only N complex of computer memory. It can, therefore, be concluded that the FFT computation time is proportional to $N*\mathrm{lb}N$ and then applies:

$$t_{FFT} \propto N * \mathrm{lb}\, N. \tag{9}$$

4   Numerical and empirical example

As an example, a milling process is used, with the help of cutting sound monitored tool wear; in Fig. 7a can be seen cutting signal with new (sharp) tool. Then, microphone records time domain signal, amplitude of time signal does not have deviations from the required value. The vibrations that occur during the cutting of the tool are small. That means that the other measuring will be compared with this first measuring. As tool wear increases, also increase vibrations on the cutting tool and deviations on the time signal are more significant. In the last Fig. 7c, where the tool wear is significant (max tool wear), there is a big impact on the amplitude of time domain signal.
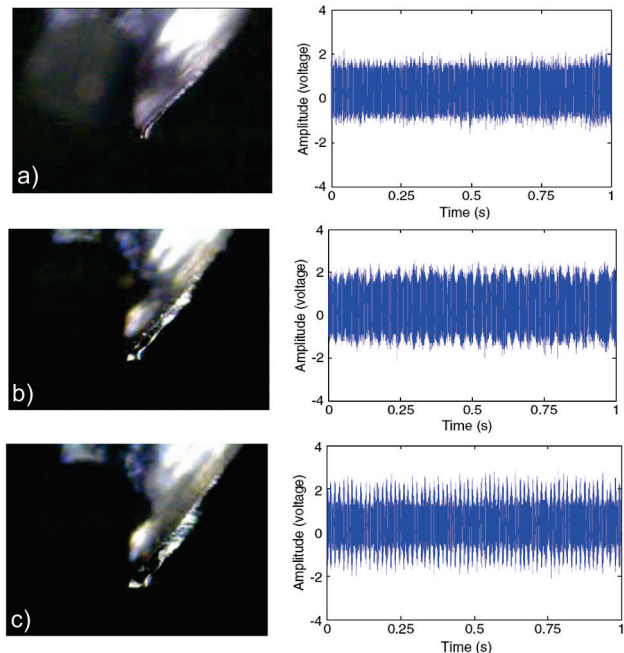

Figure 7 Tool wear level and corresponding time domain signal for tool condition: a) sharp tool, b) fourth cutting pass (VB= 0,026 mm), c) fifth cutting pass (VB= 0,038 mm) [7]

What is observed from this Fig. 7 is that there is nothing in automatic terms of online monitoring process, and can only be said that by using a worn tool, wear has impact on vibrations of the tool. This signal must be transferred to frequency domain signal by using Fast Fourier Transformation.

After we recorded the audio signal in the time domain by using the FFT we transferred to the frequency domain. The sound frequencies did not exceed 20 kHz, which is the limit of what a human ear can hear. The signal of cutting with a worn tool was compared with the signal of cutting with a sharp tool. Therefore, we noticed that the frequency value in recorded sound changed with the increase of the tool wear that was observed, and thus, frequency was transferred to the higher frequency area. [12, 13]. It also increases the amplitude of the signal. In

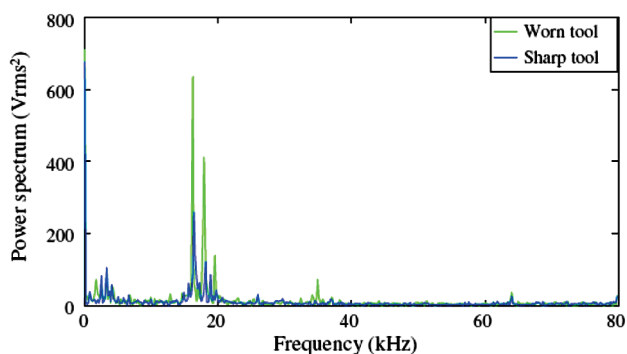this way, we can conclude that there has been the wear of the cutting tool.

Figure 8 Frequency domain signal change for the increase of tool wear
(tool wear *VB* = 0,038 mm)

5   Conclusion

The transmitted sound has demonstrated its feasibility as a tool condition monitoring method first as a qualitative assessment for a conventional machining operations done by machinists, and has evolved then into an increasingly active area of research. The sound signals obtained from a microphone were analysed for tool wear monitoring. To analyse the signal feature in the frequency domain, features higher than 20 kHz, which is the upper limit of frequency range for human hearing, provided a better approach to distinguish a worn tool from a sharp tool than features lower than 20 kHz. Therefore, it can be concluded that with the increase of tool wear, amplitude of frequency signal has a significant increase, frequency peak also increases in higher frequency zone, but not so much.

6   References

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