Acoustic Emission Transferability using Transfer Function

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Abstract

This paper presents an acoustic emission transferability method in applications of valve leakage rate detection and tool wear monitoring. The method aims to transfer the information between AE inspection systems using different types of sensor and position by relationship which was called a transfer function. The spectrum density function/AErms spectra of both wide band (WD) and resonance (R15 and R30) AE sensors were studied. The results demonstrate a very good similarity transfer function in various conditions. Three sets of cutting condition of tool wear monitoring in machining tests were conducted. A tool shank of type SDJCL 1616H 11 and carbide tool inserts of type CG 4035 DCMT 11 T3 04-UF (Sandvik Coromant) were used. Two AE sensors were mounted on the tool-holder: a WD sensor (PAC) at the end of the tool-holder and an R30 sensor (PAC) on the side. For valve leakage rate detection, artificial leaks from incomplete closure of ball valve are used to simulate the leakage. The tests were conduced by varying inlet pressure from 1 to 5 bars in three valve sizes of 1, 2 and 3 inches respectively. The AE signals detected at the two sensors (WD and R15) were analyzed in real-time using a Hewlett Packard HP 89410A. Transfer functions of two AE sensors are calculated and represented by the ratio of frequency responses of the two sensors. This is particularly useful since the information obtained from one sensor may be converted into another without having to repeat the experiments. With the proposed acoustic transferability, it will be possible to make comparison between results obtained from different set-ups.

Keywords: Acoustic emission, transfer function, tool wear monitoring, valve leakage rate.

1. Introduction

Acoustic emission (AE) is the generation of stress waves created by the release of strain energy as a result of the material yielding under stress. Previous tool wear monitoring research has shown a direct correspondence between the energy or the root mean square value of the AE signal (AErms) and the different stages of tool wear[1,2]. The energy and AErms refer to the respective energy and root-mean-square value of the voltage output from the AE sensor. Models were proposed[1] to describe the influence on the AErms of process variables in machining such as the feed rate, depth of cut and cutting velocity in single-point machining. For the valve leakage measurement using AE, it has been investigated on establishing the relationship between AE parameters and leakage rate of valve[3-5]. The characteristic of AE leak signals was also explained.

However, the both applications of the obtained relationships are limited to systems using the same set of equipment and wave propagation part. Changes in set up of the system for example types of sensor and signal conditioners require costly reinvestigation. Varying of coupling between sensor and test piece (tool shank or value) or place of mounting AE sensor was also affected the relationship. Therefore, the main contribution in this paper is an attempt to make the information obtained from one AE inspection system transferable to another.

Similar work has been active in the field during the last decade, for example, to find AE artificial sources to calibrate AE systems[6,7] and an attempt to make information transferred from one to other systems in tool wear monitoring[2,9]. In this paper, the proposed method makes use of constant "frequency response function" and validates the results by a set of experiments.

2. Theories

2.1 Comparison of shapes and sizes of AE spectra

An n-point RMS discrete AE-spectrum can be thought of as a vector u defining a point in the n-dimensional vector space. By analogy with vectors in the three-dimensional space, the length squared of u is the inner product of u with itself. Thus, the length of u can be computed from

$$|u| = \sqrt{u.u} = \sqrt{\sum_{k=1}^{n} u_k^2} \tag{1}$$

where $|u|$ = the length of an n-point RMS discrete spectrum

u_k = a point in the n-dimension vector space

This length $|u|$ gives the overall AErms of the AE signal.

The vector u can be normalised by dividing its elements by the length of the vector. Thus a normalised vector, denoted by $\bar{u}$, can be computed from

$$\bar{u} = u/|u|$$

Given two normalised vectors, $\bar{u}$ and $\bar{v}$, in the n-dimensional space, the included angle θ between them is related to the inner product of $\bar{u}$ and $\bar{v}$ as

$$\cos\theta = \bar{u}.\bar{v}\,. \tag{2}$$

$\cos\theta$ is named the similarity coefficient. When it is one the two unit vectors $\bar{u}$ and $\bar{v}$ point in the same direction. Which means that the two corresponding spectra have the same shape differing by a scale factor. When the similarity coefficient is zero, the two vectors $\bar{u}$ and $\bar{v}$ are orthogonal to each other, which suggests that the two corresponding spectra have nothing in common, or maximum dissimilarity.

2.2 Transferable between systems using constant frequency response

In this work, constant frequency response ratio in form of RMS spectrum is presented to make information transferable between systems using different AE and location. An RMS spectrum is simply the square root of the energy spectrum. It can be defined as

$$AErms = \sqrt{\frac{1}{T}\int_{t_0}^{t_0+T} v^2(t)dt} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} v^2(n)} \quad (3)$$

where v is the voltage signal from an AE sensor, t is the initial time, T the integration time of the signal, and N the number of discrete AE data within the interval T.

It also known as the spectral density function. In terms of the spectral density function, the transfer characteristics from input source to the output of the sensing instrument is governed by

$$G_y(f) = |H(f)|^2 \cdot G_x(f) \quad (4)$$

Where the spectral density functions of the input and output are $G_x(f)$ and $G_y(f)$, respectively and H(f) is the frequency response function describing the dynamic of the input signal transmitted through AE sensors. It should be noted that $G_x(f)$ denotes the AE produced at the source of the leakage by the escaping gas. Fig. 2 shows different signal propagation paths from a common input to two different sensors.

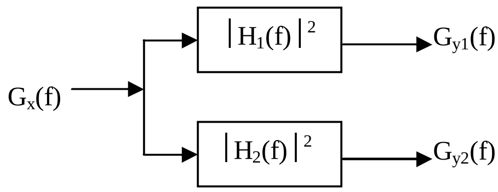

Figure 1. Different signal propagation paths with a common input

Since the same input $G_x(f)$ is used, their transfer equations can be written as

$$G_{y1}(f) = |H_1(f)|^2 \cdot G_x(f) \quad (5)$$

and

$$G_{y2}(f) = |H_2(f)|^2 \cdot G_x(f) \quad (6)$$

By dividing equation (5) by equation (6), we arrive at

$$G_{y1}/G_{y2} = |H_1|^2/|H_2|^2 \quad (7)$$

where G_{y1} is AE output of one AE sensor while G_{y2} is that of the other. According to equation (7), the ratio G_{y1}/G_{y2} of the AE spectra output represents the transfer function of both AE sensors.

2.3 Relationship between AErms and Valve Leakage Rate

For continuous AE signal from time and frequency domains, the most frequently used AE parameters are the average energy (AErms) that is the root mean square value of the AE signal. Since Acoustic Emission activity is attributed to rapid releases of energy in the material, the energy content of the acoustic emission signal is related to this energy release.

The relationship between AErms and valve leakage rate is selected as the subject to be transferred to another system in this work. From the previous research work[5], AErms exhibits the relationship with valve leakage rate. The experiment had been conducted using three sizes of ball valve of diameter 1, 2 and 3 inches and inlet pressure between 1-5 bars. An only AE sensor with resonant frequency of 150 kHz was selected to measure signal since its frequency response covered the frequency range of the leakage. That result was investigated and the relationship can be shown as the equation below

$$\log(Q) = 1.782\log(AErms) - 0.543\log(P) + 0.320\log(S) - 3.440$$

where Q is the leakage rate in ml/sec, P the inlet pressure in bars and S the valve size in inches. However, when a part of AE system (e.g. the type of AE sensor) was changed, the previously founded equation is not transferable.

3. Experimental Setup

3.1 Tool wear monitoring

A tool shank of type SDJCL 1616H 11 and carbide tool inserts of type CG 4035 DCMT 11 T3 04-UF (Sandvik Coromant) were used. The detail of the insert geometry was as follows: insert shape 55°, clearance angle 7°, rake angle 0°, cutting edge length 11 mm, thickness 3.97 mm and nose radius 0.4 mm.

Two AE sensors were mounted on the tool-holder: a WD sensor (PAC) at the end of the tool-holder and an R30 sensor (PAC) on the side as shown in Figure 2.

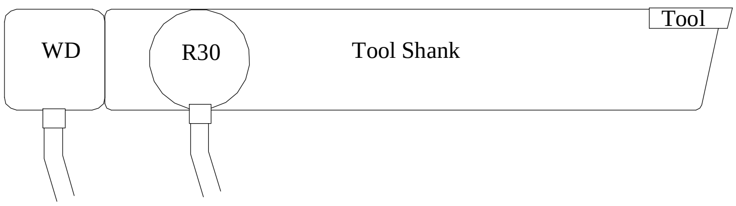

Figure 2. Two AE sensors (WD and R30) on the tool holder

Both signals were amplified by 34 dB at the pre-amplifiers fitted with a 100 kHz – 1 MHz band-pass filter. The AE signals detected at the two sensors were analysed in real-time using a Hewlett Packard HP 89410A Vector Signal Analyser to produce a 401-line AErms spectrum spanning 0 to 1 MHz averaged over 70 consecutive spectra.

Three sets of machining tests were conducted and their conditions are detailed in the following:

- Machining Test Set 1: Variable feed rates from 0.05 mm/rev to 0.4 mm/rev in increments of 0.05 mm/rev. Cutting speed and depth of cut were constant at 120 m/min and 0.75 mm respectively.

- Machining Test Set 2: Variable speeds from 80 m/min to 150 m/min in increments of 10 m/min. Feed rate and depth of cut were constant at 0.2 mm/rev and 0.75 mm respectively.

- Machining Test Set 3: Variable depths of cut from 0.3 mm to 1.0 mm in increments of 0.1 mm. Cutting speed and feed rate were constant at 120 mm/min and 0.2 mm/rev respectively.

The material of the workpiece, measured 63.5 mm in diameter and 150 mm in length, was EN24T with 0.35-0.45 %carbon. All tests were conducted on a Traub lathe.

3.2 Valve leakage rate detection

A set of experiments was designed to investigate the transferability of the relationship obtained from a system using one type of transducer to another. Varying in operating conditions including leak size of valve and inlet pressure was also examined. The test system is set up as illustrated in Fig 3. In order to compare and establish the correlation between AE signals obtained from different AE sensors, PAC piezoelectric sensors of wide band (WD) and resonant (R15) types were mounted in each other vicinity at the down stream side of the valve to reduce variation due to spatial difference in the installed locations. The output signals of R15 and WD sensors are represented by $G_{y1}(f)$ and $G_{y2}(f)$, respectively. Since the application of appropriate couplant to minimize energy loss at the interface of workpiece and sensor is one of the most important factors in applying an AE measurement, couplant of the same type (from PAC) was employed in a standard procedure. Signals from both AE sensors were amplified with the same pre-amplifier set at the gain of 60 dB. A band pass filter with a pass band ranging from 100 kHz to 1200 kHz (from PAC) was used as a signals conditioner. The space between AE sensor and pre-amplifier was kept minimal to minimize signal loss in connecting cables. Output signals from the pre-amplifier were fed into a LOGAN 320 set at gain of 20 dB and were recorded by a real time signal analyzer HP 89410A (with a sampling rate of 10 MHz). The AE spectrum in the frequency span from 0 to 1 MHz was recorded using 401 sample points and was averaged for 500 times. Pencil lead breaks in accordance to ASTM Standards, to verify performance of AE sensor attachment is performed after the installation. An air compressor was used to generate the system pressure which was kept steady by a regulator. The valve leakage rate was determined from differential pressure of the known volume chamber. A high precision pressure gauge with resolution of 0.05 bar was used for monitoring the chamber's pressure.

In the experiments, artificial leaks from incomplete closure of ball valve are used to simulate the leakage. The tests were conduced by varying inlet pressure from 1 to 5 bars in three valve sizes of 1, 2 and 3 inches respectively. In each result, the curve of the ratio G_{y1}/G_{y2} was computed.

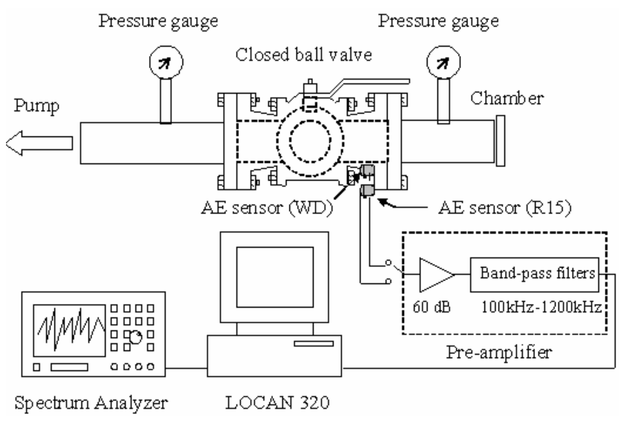

Figure 3. The schematic diagram of experiment set-up

4. Results and discussion

4.1 Tool wear monitoring

The ratios of G_{y1}/G_{y2} for the three sets of machining tests were first obtained and then the mean ratios for each set were calculated. The mean ratios for the three different machining conditions are shown in Figure 4.

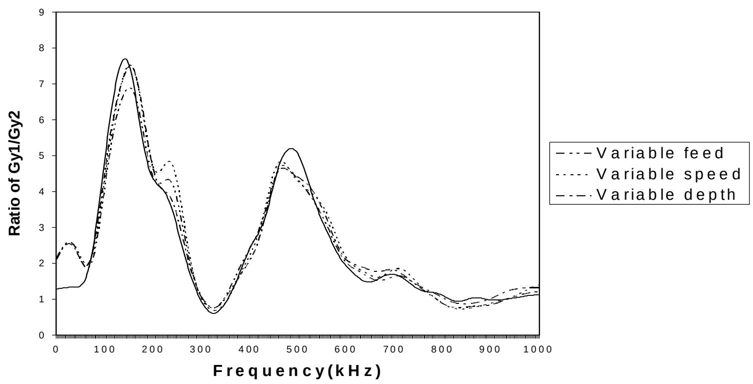

Figure 4. The ratios of G_{y1}/G_{y2} for the three sets of machining tests.

It can be observed that these curves match each other very closely. These results may arise from two possibilities. The first hypothesis might be that both $H_1(f)$ and $H_2(f)$ were not affected by cutting conditions or that both $H_1(f)$ and $H_2(f)$ were equally affected. The implication is that the frequency response functions $H_1(f)$ and $H_2(f)$ in equations (5) and (6) are insensitive to the input states, whether they be caused by changing machining conditions.

The similarity coefficient was calculated using equation 2.Their coefficient for the cutting conditions of roughing, semi-roughing and finishing, are 0.75, 0.87 and 0.60 respectively.

4.2 Valve leakage rate detection

The tests were conduced by varying inlet pressure from 1 to 5 bars in three valve sizes of 1, 2 and 3 inches respectively. In each result, the curve of the ratio G_{y1}/G_{y2} in various leak size was computed. The curve of the ratio in each value size is similar. It was shown slight difference in the size of value at 3 inch. The example of ratios for various leak sizes of valve 2 inch are shown in Figure 5.

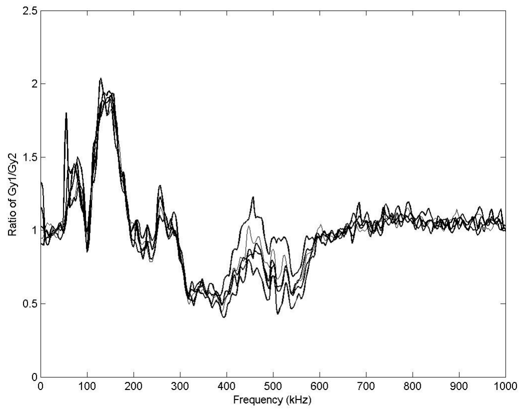

Figure 5. The ratios of Gy1/Gy2 for various leak sizes of valve 2 inch.

From equation (7), the ratio of the frequency response function, corresponding to different sensors remain the same at any leak sizes and pressures. Agree with the tool wear condition monitoring, the implication is that the frequency response functions $H_1(f)$ and $H_2(f)$ in equations (5) and (6) are insensitive to the input states, whether they be caused by changing of pressure and values sizes.

The similarity was computed. The similarity coefficient in each condition was shown in Table 1.

Table 1 similarity coefficient of the curve of the ratio at various inlet pressure levels and valve sizes.

Valve Sizes	Inlet Pressures	similarity coefficient
1 inch	1 bar	0.87
	3 bar	0.59
2 inch	1 bar	0.78
	3 bar	0.67
3 inch	1 bar	0.68
	3 bar	0.94

5. Conclusions

Correlation of AE signals from two AE systems for valve leakage rate detection application and tool wear monitoring were studied by monitoring AErms outputs of two AE sensors for various conditions. Transfer functions of two AE sensors are calculated and represented by the ratio of frequency responses of the two sensors.

This means that we can obtain the transfer function of another sensor from that of previously examined transducer. This is particularly useful since the information obtained from one sensor may be converted into another without having to repeat the experiments.

With the propose method, it will be possible to make comparison between results obtained from different set-ups. The benefit is to building up knowledge base on various AE applications.

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