Tool Failure Detection Based on Statistical Analysis of Metal Cutting Acoustic Emission Signals

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Abstract—The analysis of Acoustic Emission (AE) signal generated from metal cutting processes has often approached statistically. This is due to the stochastic nature of the emission signal as a result of factors effecting the signal from its generation through transmission and sensing. Different techniques are applied in this manner, each of which is suitable for certain processes. In metal cutting where the emission generated by the deformation process is rather continuous, an appropriate method for analysing the AE signal based on the root mean square (RMS) of the signal is often used and is suitable for use with the conventional signal processing systems. The aim of this paper is to set a strategy in tool failure detection in turning processes via the statistic analysis of the AE generated from the cutting zone. The strategy is based on the investigation of the distribution moments of the AE signal at predetermined sampling. The skews and kurtosis of these distributions are the key elements in the detection. A normal (Gaussian) distribution has first been suggested then this was eliminated due to insufficiency. The so called Beta distribution was then considered, this has been used with an assumed β density function and has given promising results with regard to chipping and tool breakage detection.

Keywords—AE signal, skew, kurtosis, tool failure

I. INTRODUCTION

ON-LINE detection of cutting tool failure which includes cracking, chipping and fracture of the tool during machining, plays an important role in the improvement of un-manned machining and automation of manufacturing processes. The acoustic emission (AE) measurement has been so far applied to such studies and proved successes to certain extent. However, there still remains much unknown about the basic properties of the AE signals detected from the cutting process for better use and reliable application of the technique in practice.

Acoustic emission can be defined as "the elastic stress wave generated as a result of the rapid release of strain energy within a solid material in association with the deformation and/or the fracture of material" [1].

The analysis of AE signal generated from metal cutting processes has often approached statistically. This is due to the stochastic nature of the emission signal as a result of factors affecting the signal from its generation through transmission and sensing [2]. Different techniques are applied in this manner, each of which is suitable for certain process(s). In metal cutting where the emission generated by the deformation process contains both the continuous and burst type of the AE signal, an appropriate method for analysing the AE signal based on the root mean square (RMS) of the signal is often used and it is suitable for use with the conventional signal processing systems.

Employment of the RMS value to monitor the cutting process is adequate since the source and sensor position are not changed because the level of the DC equivalent or the mean RMS amplitude is sensitive to both source and sink locations [4].

Various other techniques are common in use in analysing AE data such as count and count rate which is a measure of burst type AE events obtained by counting the number of times the AE signal exceeds a threshold voltage, spectral analysis, amplitude distribution analysis, etc. In defiance of vast research works employed it is still not possible to identify source mechanism directly from most of these techniques. This is due to various reasons. The most significant is the damping effect of the medium, transducer response and waveguide resonance [4].

Statistical analysis based on the distribution moments of the measured acoustic emission signal associated with metal deformation, cracking and fracture has been used as a mean of understanding the current status of these materials and predicting their likely condition thereafter. Kannatey-Asibu and Dornfeld [5] have suggested another use of the distribution moments. They found that the skew and kurtosis of an assumed ß distribution for the RMS level of AE generated during progressive tool flank wear were sensitive to the degree of wear. β functions have been first introduced by Whitehouse [6] in the characteristic analysis of surface typology with satisfactory results, then have been used in the study of tool wear by the analysis of metal cutting acoustic emission [7] .

The demodulated AE signal represented in the RMS value, is the source of forthcoming analysis implemented in this work for tool failure detection

II. DISTRIBUTION MOMENTS

The shape of the distribution can be much more illuminating from the point of view of detecting process changes than the calculated average value of the distribution. The nth central moment, i.e. the nth moment of a random variable X about the mean $\bar{x}$ is defined as:

$$\bar{x}_n = E[(X - \bar{x})^n] \qquad (1)$$

where n=0,1,2,... It follows that $\bar{x}_0 = 1$, $\bar{x}_1 = 0$, $\bar{x}_2 = \sigma^2$, i.e. the second central moment or second moment about the mean is the variance.

For a continuous variable the nth central moment can be defined as:

$$\bar{x}_n = \int_{-\infty}^{\infty} (x - \bar{x})^n f(x)dx \qquad (2)$$

Other parameters related to the characteristics of the distribution X are the skew S and Kurtosis K. The skew is the normalised third order central moment given by:

$$S = \frac{1}{\sigma^3} \int_{-\infty}^{\infty} (x - \bar{x})^3 f(x)dx \qquad (3)$$

and the kurtosis is the normalised fourth order central moment given by:

$$K = \frac{1}{\sigma^4} \int_{-\infty}^{\infty} (x - \bar{x})^4 f(x)dx \qquad (4)$$

The first attempts of this work for acoustic emission signal analysis, was based on consideration of the distribution moments to obtain values of the third order (skew) and fourth order (kurtosis) central moments of the demodulated AE signal through the so called normal distribution (Gaussian distribution). The density function of this distribution is given by:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\bar{x})^2/2\sigma^2} \qquad -\infty < x < \infty \qquad (5)$$

where $\bar{x}$ and σ are the mean and the standard deviation. Referring to equations 3 and 4, the skew and kurtosis can thus be obtained respectively as:

$$S = \frac{1}{\sigma^3} \int_{-\infty}^{\infty} (x - \bar{x})^3 . \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\bar{x})^2/2\sigma^2} \qquad (6)$$

$$K = \frac{1}{\sigma^4} \int_{-\infty}^{\infty} (x - \bar{x})^4 . \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\bar{x})^2/2\sigma^2} \qquad (7)$$

The results obtained from though were not satisfactory, therefore another mean of tool failure detection has been investigated. The so called Beta distribution was contemplated. This was used in this study with an assumed β density function

The β function $\beta(r,s)$ is given by:

$$\beta(r,s) = \int_0^1 x^{r-1}(1-x)^{s-1} dx \qquad (8)$$

where r and s are parameters of the β distribution . On grounds of this distribution, the skew S_B and kurtosis K_B of the β distribution can be calculated as [8]:

$$S_B = \frac{2(s-r)}{r+s+2}(\frac{r+s+1}{rs})^{1/2} \qquad (9)$$

$$K_B = \frac{6\{(r-s)^2(r+s+1) - rs(r+s+2)\}}{rs(r+s+2)(r+s+3)} \qquad (10)$$

and the parameters r and s can be expressed in terms of $\bar{x}^2$ and σ^2 as follows:

$$r = \frac{\bar{x}}{\sigma^2}(\bar{x} - \bar{x}^2 - \sigma^2) \qquad (11)$$

$$s = \frac{1-\bar{x}}{\sigma^2}(\bar{x} - \bar{x}^2 - \sigma^2) \qquad (12)$$

Therefore knowing the mean $\bar{x}$ and variance σ^2 of a distribution, the parameters r and s can be obtained and thus the values of the skew S_B and kurtosis K_B are calculated. The sensitivity of these variables to tool condition is the key element of this work.

III. EXPERIMENTAL CONDITION

Experiments for tool condition monitoring were carried out on WAFUM turning machine type TUD 50. Two different types of inserts have been used to conduct the tests, they are SNUN 120408-S30S and TNMG 160408-NT25. The work material was bars of steel 45 (with 2 cm wide longitudinal groove along the bar). Other test variables and conditions are presented in Table 1, while the set-up of the experimental apparatus is shown in Fig. 1.

TABLE I
EXPERIMENTAL CUTTING CONDITIONS

Variable	from	to
Cutting speed (m/min.)	120	310
Feed rate (mm/rev.)	0.24	0.84
Depth of cut (mm)	2.5	4.0
Workpiece diameter (mm)	100	158

To evaluate and confirm tool failure detection by the AE technique, an assistant strategy has been used, which is an algorithm developed in Warsaw University of Technology based on tool failure detection through on-line measurement of cutting forces [PC-1, Fig. 1] [9]

The three components of the cutting force F_c, F_p and F_f were measured by a three component piezoelectric dynamometer, type Kistler 9263, to which the tool shank was attached. The dynamometer force ranges are: $F_f = F_p = 1000$ N and $F_c = 2000$ N. The three charge outputs of the dynamometer were directly converted into proportional voltage signals using charge amplifiers type Kistler 5001. Output signals from the charge amplifiers were then fed to an analogue-digital converter {installed in PC-1} for processing. A sampling frequency of 2 kHz was used and 30 seconds of data measurements can be registered for each test.
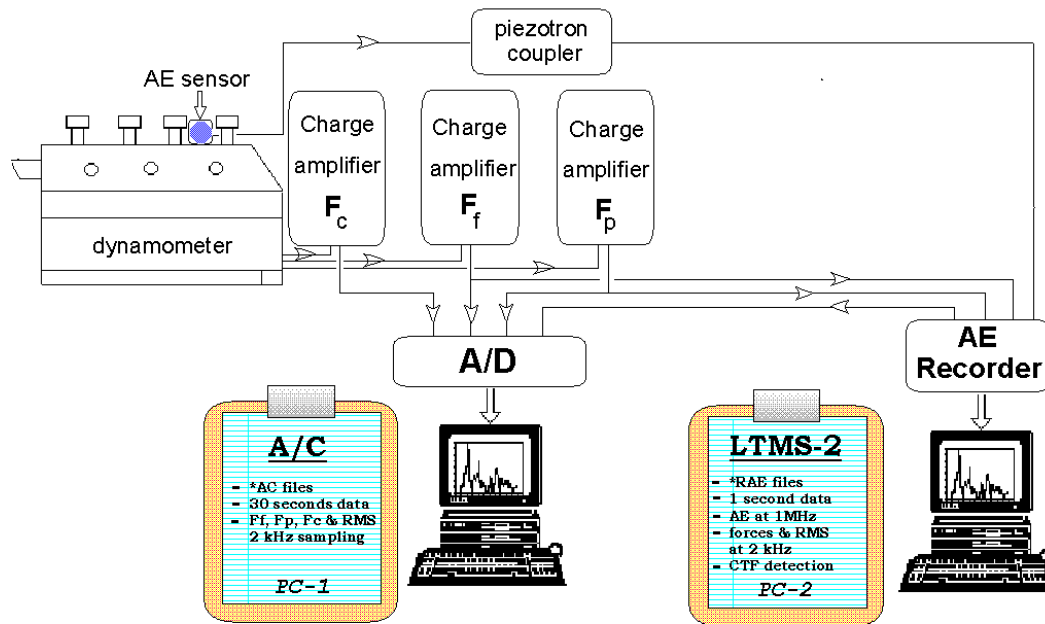
Fig. 1 Tool failure monitoring apparatus set-up

A broadband AE transducer (sensor), type Kistler 8152A1 was mounted on the dynamometer for simultaneous AE signal detection. The sensor was secured in place by means of a magnetic clamp. A thin layer of a coupling media (oil) was applied on the base surfaces of both the AE sensor and the tool shank to reduce signal attenuation. The detected signals were then pre-amplified and filtered by means of a piezotron coupler type Kistler 5125A. This coupler enables also an assessment of the root mean square (RMS) value of the AE signal. The output signal from the piezotron coupler together with the measured force components were then fed to a laboratory tool monitoring system (LTMS-2). Data is recorded in an acoustic emission recorder for further signal processing. For the AE signal processing a sampling frequency of 1 MHz was used.

By this system an original acoustic emission signal is obtained together with the RMS of the signal, and since the sampling frequency is 1 MHz, the resulting measurement time is ~ 1 second. The sampling time is variable depending on the sampling frequency used. The maximum sampling frequency that can be used by this system is 4 MHz with a resulting sampling time of 0.25 second.

From the original AE signals obtained from the LTMS-2, data of demodulated signals can be obtained. Demodulated signal represents a 1/500 of the original AE signal thus enables reading a full 1 second of measured data in one time (screen) if this signal was squeezed 4 times.

The original AE signal and the RMS assessed from the piezotron coupler together with two components of the cutting force F_f and F_p were traced via a catastrophic tool failure detector in the LMST 2. The third component of the cutting

force F_c was excluded because it has been found that it is less sensitive to tool deterioration. In the case of catastrophic tool failure the last one second (or the sampling time) of the measured data at the moment of CTF is recorded in the AE recorder, it is divided in two parts 3/4 second proceeds the CTF whereas the second part (1/4 second) comes after the CTF. This facilitates reading the changes in the measured parameters before and after the CTF. Outstanding cases on which interesting results have occurred were then saved in the computer for further processing. They are classified as follows:-

- CTF detection, any case on which the alarm system has been activated.

- False CTF detection, alarm was activated but no significant tool failure has occurred.

- CTF was not detected by the algorithm but tool breakage has been observed by the operator.

- CTF was not detected by the algorithm neither by the operator but a significant change in force values has been distinguished while viewing recorded result.

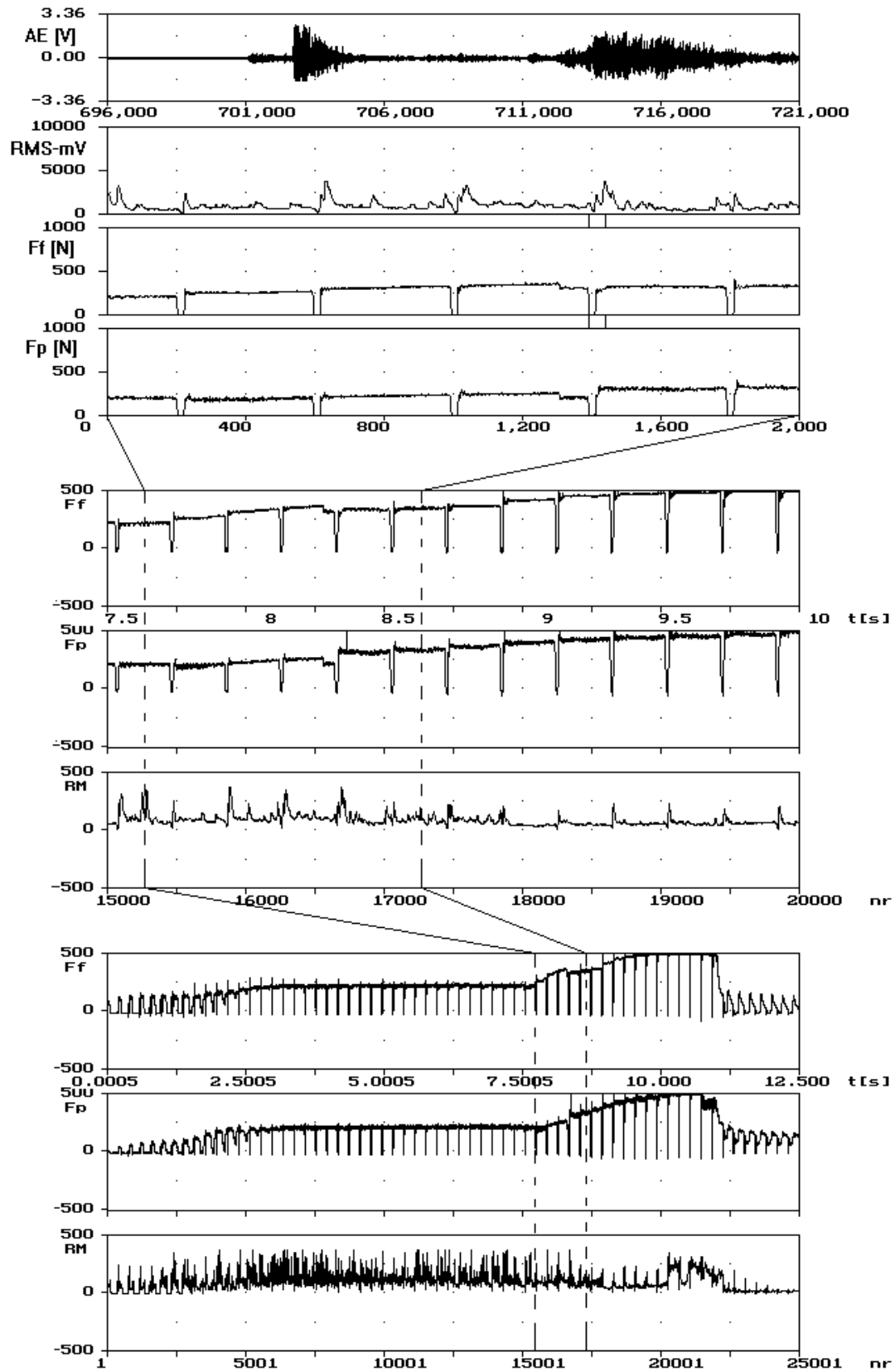- Accidental cutting conditions such as chip jamming to the tool, ... etc.

Fig. 2 Correlation of data obtained from PC- 2 to those obtained from PC-1

Data for the tests which satisfy the above mentioned cases were saved in both computers for the purpose of further analysis. Measured data in PC-2, which represents information of 1 second of cutting, were correlated to those obtained from PC-1 which gives some 30 seconds cutting data. This enables thorough analysis of the case. An example is shown in Fig. 2.

VI. EXPERIMENTAL RESULTS

The analysis of the AE measured data is essentially based on the calculated RMS value of the demodulated signal. The RMS of the signal is used to obtain S_B and K_B as per equations 9 and 10 at predetermined sizes of β distributions.

The number of data points taken in each distribution has been set to the minimum possible so that minute changes in tool condition can be detected. However, it is suggested that the number of data points per distribution is set to contain the measured AE data from one full revolution of the workpiece, see Fig. 3. This is particularly important when working with bars of non-continuous surface of cut like those used in this work. Such arrangement is appropriate as it includes in each distribution the acoustic emission generated from the tool engagement and disengagement with the workpiece due to the disturbance (groove) made in the part. The impact on the workpiece due to tool engagement is accompanied with acoustic emission signals of relatively high amplitude which necessitates taking that into consideration and including it in each single distribution. Furthermore, as the signal originated from a tool failure occurs in a very short time, this calls for a minimum data points/distribution in order to obtain optimum results. Therefore the number of data points taken in each distribution is a function of the rotational cutting speed and the sampling frequency of the demodulated AE signal.

In the example shown in Fig. 3, the data points in each distribution, according to the above mentioned ordering, is found to be 400 points/distribution which represents 0.2 seconds of measured cutting time in accordance with the sampling frequency of 2000 Hz. The peaks represent AE of tool engagement in each revolution because of the groove in the workpiece.
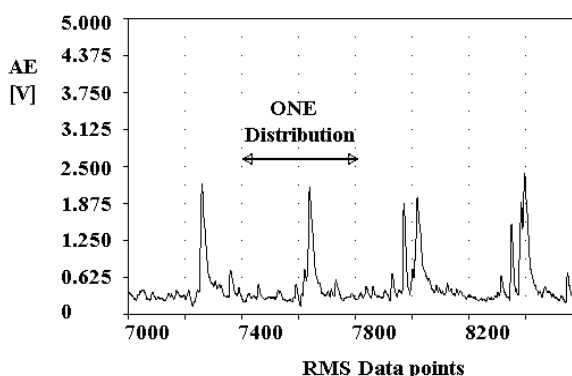

Fig. 3 Arrangement of number of data points taken in each distribution in the case of interrupted cutting

To reveal more information from the AE measured data, a compound distribution analysis in an overlapping mode is fulfilled. This exposes more data for analysis acts as a mean of data filtering. A step is to be initiated together with the size of the distribution, see Fig. 4. Thus the degree of data reprocessing is determined in accord, i.e. the lower the step/distribution ratio the more data being reprocessed.
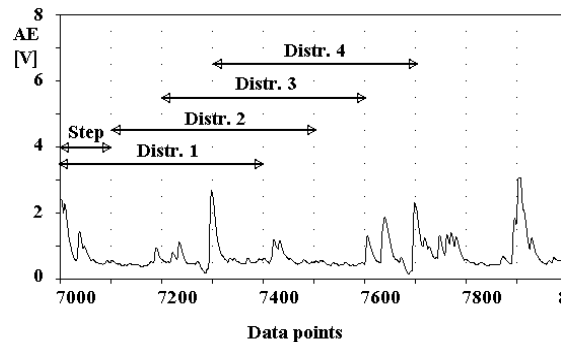

Fig. 4 Overlapping distributions

The first attempts of CTF detection by means of assessing the skewness and kurtosis of distribution moments is carried out by assuming a normal distribution (Gaussian distribution) which has a density function given in equation 5. Thus obtaining the coefficient of skewness S and the coefficient of kurtosis K as in equations 6, 7. Working with the normal distribution has been suggested because of the simplicity of the calculating equations which do not need lots of calculations and consequently can offer much faster data processing. However this has been eliminated because of insufficiency.

Implementing the statistical analysis based on the calculated distribution parameters obtained from the β function has given more satisfactory results and revealed more detailed information contained in the acoustic emission signal associated with the catastrophic tool failure. Skew and kurtosis together with the parameters of an assumed density function of the Beta distribution were strictly used in this study and have been considered the main appliance of the catastrophic tool failure detection. The values obtained for S_B and K_B for each distribution were plotted versus the corresponding distributions in each test. The distributions were then expressed in the time of cut in seconds.

The method proposed for catastrophic tool failure detection based on the skew and kurtosis is established as follows:

Two variables are subject to monitoring, the skew S_B and the kurtosis K_B. As any one of the variables exceeds a predetermined threshold level, in other words, if the value of a variable at a certain distribution is more than the value of the preceding point with a certain pre-set increment; the other variable is subject to checking at this particular point. A case of catastrophic tool failure will be registered if both variables were reacted positively at the same point

The skew S_B was often found to be the most sensitive to the catastrophic tool failure followed by the kurtosis K_B in the second rank.

A case of catastrophic tool failure was detected when turning 132 mm diameter S 45 steel bar with a TNMG 160408 NT 25 tool at cutting speed of 124 m/min , feed rate of 0.54 mm/rev. and 4 mm depth of cut, see Fig. 5. At 24.75 seconds of cutting a major tool failure is detected by the cutting force algorithm followed by a dramatic rise in the values of the skew and kurtosis. This failure was proceeded with a minor failure at 24.4 second but hasn't been detected by the cutting forces. An apparent rise in the value of the skew associated drops in value of the kurtosis is shown. These fluctuant values of the skew and kurtosis are an indication of an unstable cutting at this particular moment of cutting resulted from the tool failure. This indicates that tool failure detection via AE skew and kurtosis can be more promising.

It has been mentioned earlier that when working with the distribution moments, better results can be obtained if the distributions have been arranged in an overlapping order with a predetermined step to be set-up in prior to signal analysis, see Fig 4, this is advantageous as by this way some hidden information in the AE signal can be exposed for analysis. Such information could not be unveiled if a sequential non-overlapping way of signal analysis is implemented. As for example, let us consider the test accomplished when turning S 45 steel bar with TNMG 160408 S30S tool at 132 m/min speed, 0.42 mm/rev. feed and 4.0 mm depth of cut, see Fig. 6. A minor tool failure has been detected in this test when overlapping distributions were employed. However the failure was not possible to be detected when non overlapping distributions were implemented see Fig. 6a. The kurtosis have shown a little rise in value at the moment of CTF, however this has not been confirmed by the skew. When overlapping procedure was considered, with the same distribution size, at a step of 100, see Fig. 6b, it was possible at this time to detect the CTF by both S_B and K_B. The CTF was detected more decisively when a lower step is taken, see Fig. 6c. This makes working with overlapping distributions more promising as it points out to the minor tool failures which are not likely to be detected if the ordinary sequential way of distribution analysis is used

V. CONCLUSIONS

The acoustic emission measurement was applied to in-process detection of the catastrophic tool failure. The detection was embedded on the statistical analysis of the metal cutting acoustic emission based on monitoring the skew and kurtosis of assumed density functions of both the Normal distribution and the Beta distribution. The main task has been to detect the catastrophic failure of the cutting tool, however minor fracture and chipping of the cutting tool were also investigated. The following remarks are concluded:

- The ordinary measures used in the analysis of acoustic emission signals generated from the cutting zone such as the mean value or the standard deviation of the RMS of the AE signal did not often give a clear indication of tool failure.

- The skew and kurtosis calculated from the Normal distribution did not show good correlation with the catastrophic tool failure when turning with any of the cutting tools which makes information obtained from this distribution inadequate for the CTF detection.

- Skew and kurtosis of an assumed β distribution for the RMS acoustic emission signal were found to exhibit good sensitivity to the catastrophic tool failure. Results obtained from the majority of the conducted tests have shown good correlation of the skew and kurtosis to the CTF which makes them reliable measures of the CTF monitoring.

- The precision of tool failure detection was found to be a function of the size of both the distribution (number of AE data points in the distribution) and the step taken when overlapping distribution mode was considered. The lower the step/distribution rate value the more precise results are expected. Furthermore, it was found that implementing overlapping distributions technique reveals hidden information in the AE signal which can expose more data points for investigation and consequently could lead to tool failure detection.

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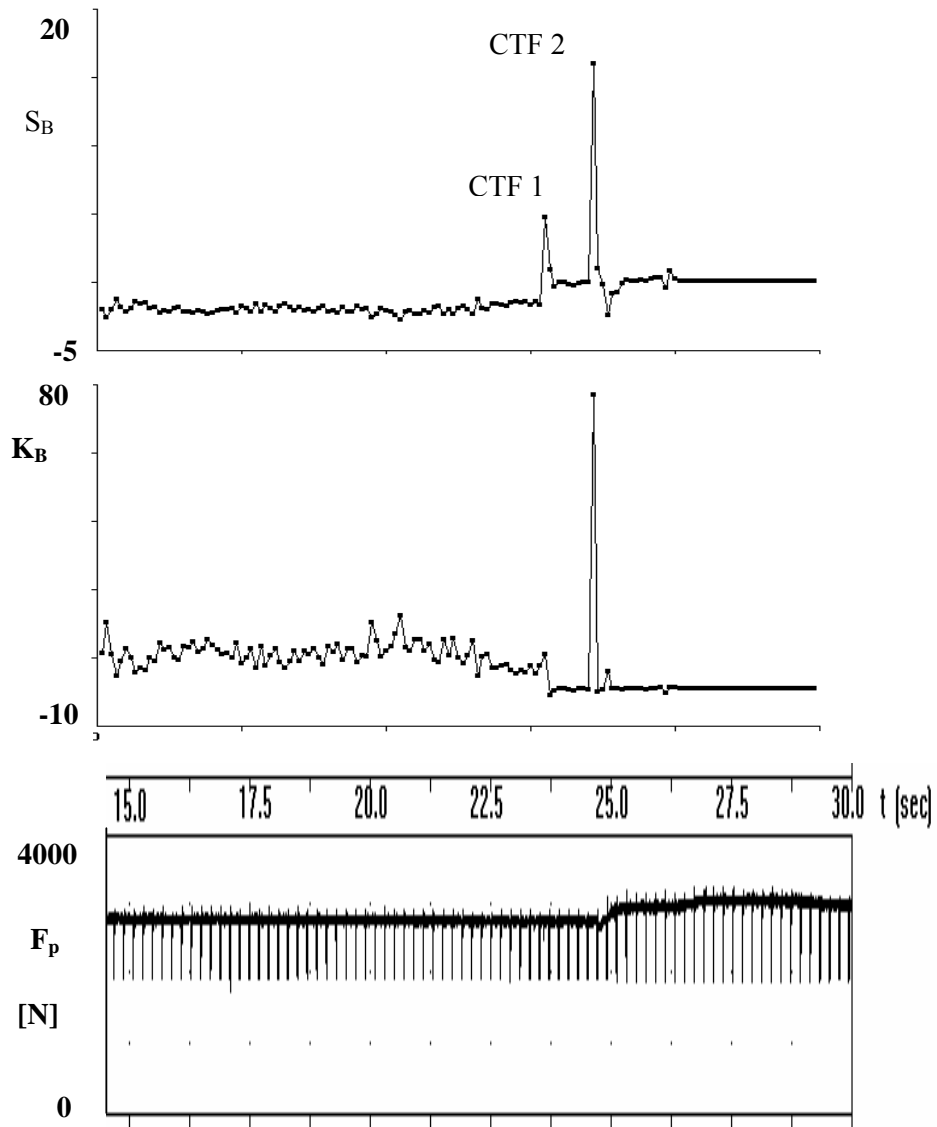
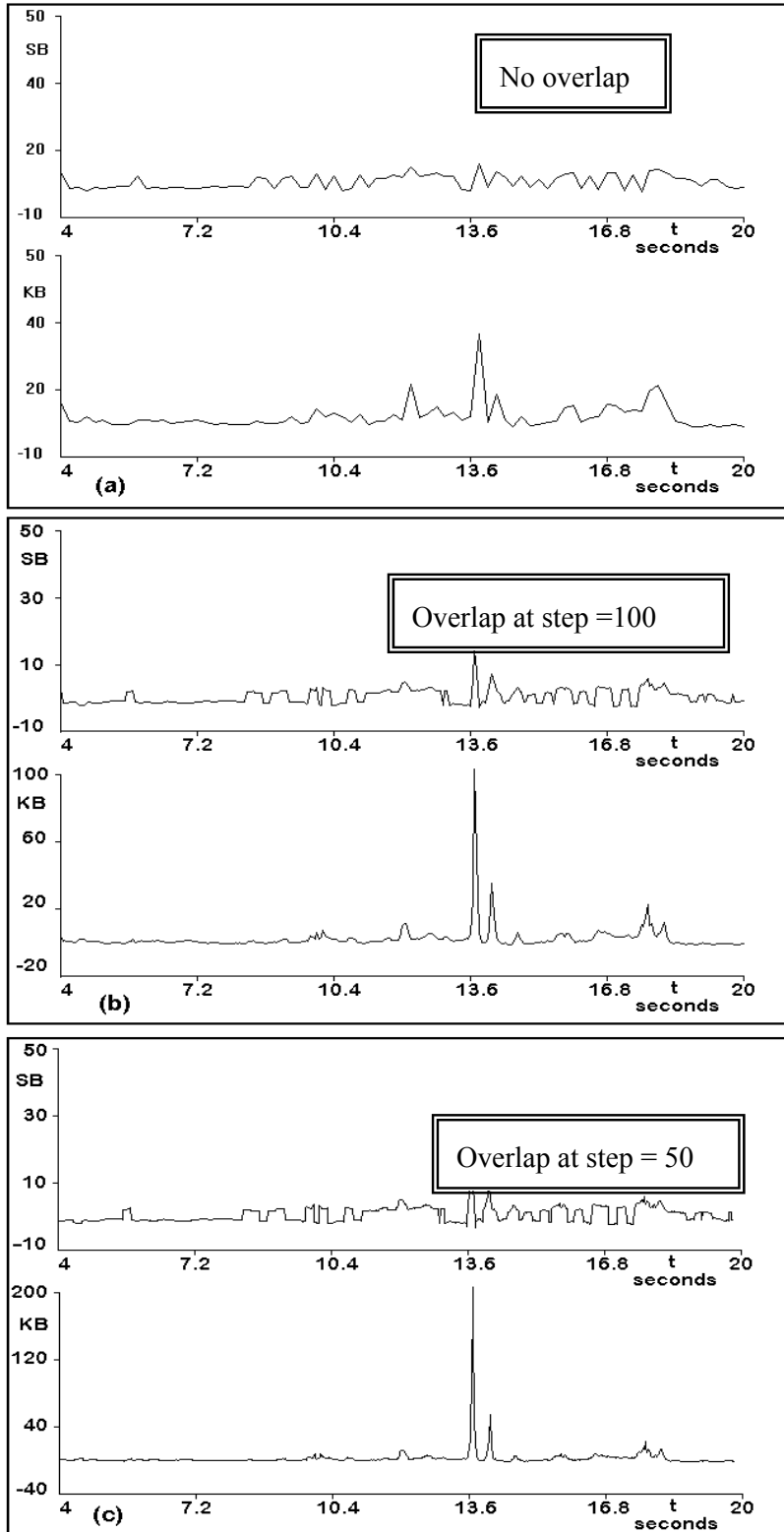Fig.5 The behaviour of the skew and kurtosis at CTF detection

Fig. 6 Tendency of revealing more information when using overlapping distributions