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ORIGINAL ARTICLE

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Development of an online machining process monitoring system: a case study of the broaching process

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Abstract This paper presents a new online machining process monitoring system based on the PXI hardware platform and the LabVIEW software platform. The whole system is composed of the following interconnected packages: sensing, triggering, data acquisition, characterisation, condition monitoring and feature extraction packages. Several signal processing methods, namely, cross-correlation, resample, short-time Fourier transform (STFT) and statistical process control, are developed to extract the features of tool malfunctions and construct the thresholds of malfunction-free zones. Experimental results show that the developed online process monitoring system is efficient for acquiring, analysing and presenting sensory signals simultaneously, while the developed signal processing techniques are effective for detecting tool wear and constructing thresholds for tool-malfunction-free zones. Additionally, a sensitivity analysis of the signals acquired from alternative sensors versus those collected from a dedicated platform dynamometer has been carried out. This enables the evaluation of the possibility to employ alternative sensing techniques in an industrial environment.

Keywords Process monitoring · Broaching · Feature extraction

1 Introduction

Competitiveness in the global market has stimulated aero-engine manufacturers to provide high-quality products by implementing advanced manufacturing techniques. Broaching is an effective process in the production of components with complex internal and external profiles to meet the increasing demands in high surface integrity and geometrical accuracy. It has been often employed to manufacture notorious difficult-to-cut, heat-resistant titanium and nickel base alloys. For instance, in the gas turbine power generation and aero-engine industries, broaching is conducted through a sequence of roughing, semi-finishing and finishing operations in a single stroke. The broaching tool malfunctions, i.e. tool wear, tool chipping and teeth breakage, will affect the finishing quality and can even scrap expensive components, such as engine discs. Although poor finishing quality due to tool malfunctions might be detected by time-consuming non-destructive inspection, the development of the online monitoring of tool malfunction has received more and more attention to reduce production losses and enhance efficiency, reliability and work-piece quality in manufacturing processes. The development of a general applicable online machining process monitoring system is one of the top research priorities within the engine industry and academia. Several significant advantages, such as maintaining machine tool reliability and in-process sensing product quality, are expected to be achieved by the implementation of online process monitoring systems.

The exclusive review of research activities in machining process monitoring can be found in [1, 2]. Although significant amounts of research efforts had been conducted in laboratory settings, the deployment of a machining process monitoring system on the shop floor is still problematic. The first obstacle is the fact that the available sensors still cannot fulfill the task of measuring the responses in a machining process with high accuracy, robustness and cost-effectiveness [1]. The cutting force is one of the most important characteristic variables in machining processes, due to its strong correlation with tool malfunctions, i.e. tool breakage, tool wear and tool chipping [3]. Although commercial dynamometers have been often employed for cutting force measurement with high accuracy, the implementation on the shop floor is restricted because of its high cost, negative impact on machining system rigidity, the requirement for a wiring

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harness and extra space for installation [4]. Recently, the study of indirectly measuring the cutting force through the feed/spindle motor current of a machining tool has received more and more attention due to the ease of installation and low cost [4–7]. However, this indirect measurement of the cutting forces is feasible only in a low frequency range up to about 60 Hz and is not sensitive and accurate enough to measure the cutting force in machining processes [4, 5]. As a result, for the purpose of ease of deployment in a production environment, alternative force sensors have to be validated to strike the balance between accuracy and cost. Another obstacle of current process monitoring systems is the lacking in the ability of automatic data acquisition and constructing thresholds for malfunction-free machining zones [8]. The currently available monitoring system on the market is rather a data logging system than a self-contained online monitoring system. By taking advantage of new achievements in data acquisition techniques, a new online machining process monitoring system is developed to acquire, present and construct thresholds in real time in this paper. Additionally, up to now, major research efforts of tool malfunction monitoring have been focussed on conventional machining processes, namely, turning [9], milling [10], drilling [11] and grinding [12]. An initial study into broaching tool condition monitoring through multiple sensors, namely, dynamometer, accelerometer, pressure sensor and acoustic emission sensor, have been reported [13]. The time and frequency domain approaches have been proposed to extract the features of tool malfunctions, i.e. worn tool, chipped teeth and weakened teeth. Continual efforts have been made to investigate the correlation between the sensory signals and surface anomalies, such as chatter marks, burr formulation, plucking, smearing and overheating [14]. However, to the authors' knowledge, no online broaching process monitoring technique has been developed to acquire, analyse and construct thresholds in a real-time manner. No research efforts have been conducted in broaching process monitoring using alternative force/strain sensors rather than platform dynamometers.

In this research work, an online machining tool malfunction monitoring system is developed and demonstrated by broaching experimental trials. Firstly, the software architecture and hardware configuration of the online monitoring system to acquire sensory signals is presented. Secondly, a novel statistical process control technique is introduced to specify the thresholds for "tool-malfunction-free" machining zones. Several signal processing techniques, namely, cross-correlation, resample and short-time Fourier transform (STFT) are developed to extract the features of broaching tool malfunctions. Finally, the correlation between the signals acquired from a platform dynamometer and miniature sensors is investigated. The possibility of using alternative sensing solutions (miniature piezoelectric strain/force sensors) to perform tool condition monitoring is discussed based on the critical analysis of the experimental results.

2 Characteristics of the online process monitoring system

2.1 Architecture design of the online process monitoring package

The architecture of the online process monitoring package has been designed to detect specified tool malfunctions for broaching processes according to industrial requirements. The whole system, which contains various interconnected packages, i.e. sensing, triggering, data acquisition, characterisation, statistical process monitoring and feature extraction packages, has been developed and validated in experimental trials and is considered for further industrial testing. The architecture of the online process monitoring system is shown in Fig. 1, while the details about each package will be introduced in the following sub-sections.

2.2 Sensing package

A wide range of sensors, i.e. platform dynamometers, miniature integrated force sensors, piezoelectric strain sensors and accelerometers, were employed to sense the

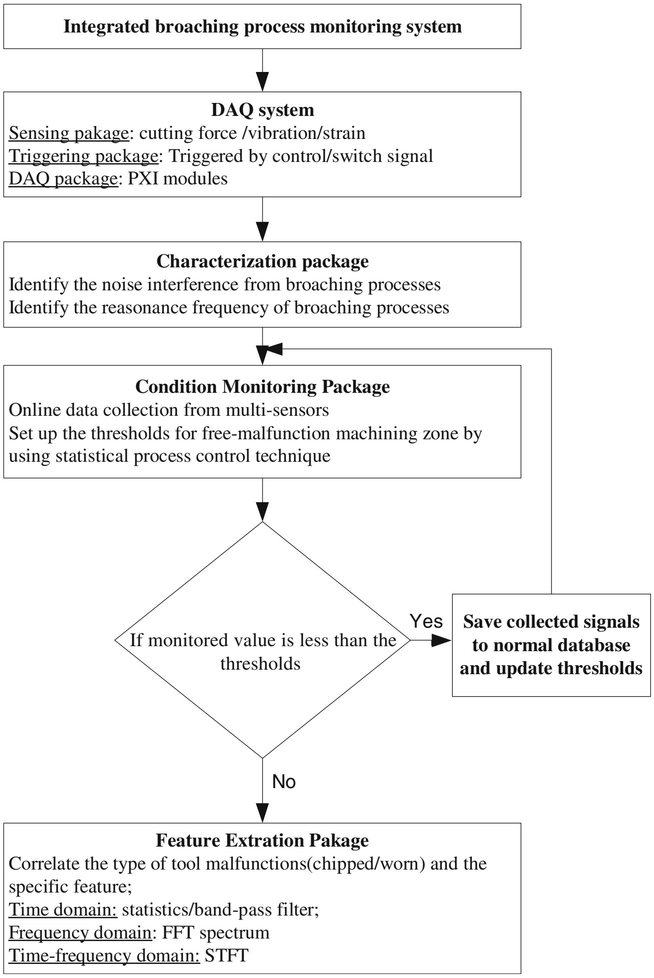


Fig. 1 Architecture of the online broaching process monitoring package

responses from broaching processes. The details of the employed sensors are listed as follows:

- Cutting forces:
  - 3-axis 9255B Kistler platform dynamometer operated with 3× 5011 Kistler charge amplifiers
  - 3-axis 9602 Kistler integrated force sensor
- Vibration:
  - 3-axis Kistler 8692C01M1 accelerometer operated with a 5134 Kistler coupler
- Strain sensors:
  - 9241CA3 Kistler transverse piezoelectric sensor operated with a 5011 Kistler charge amplifier
  - 9232A Kistler surface-mounted strain sensor operated with a 5011 Kistler charge amplifier

The platform dynamometer is the most accurate and dedicated sensor for measuring the cutting forces in experimental broaching trials. However, due to the cost and difficulty in mounting, the implementation of platform dynamometers is restricted to industrial environments. Consequently, some alternative sensors, namely, integrated force sensors, surface-mounted piezoelectric strain sensors and hole-mounted transverse piezoelectric sensors, have been employed to measure the broaching responses. The correlations between signals collected from the dynamometer and the alternative sensors have been investigated and the possibility of using alternative sensors instead of the platform dynamometer for industrial environments has been determined in experimental trials.

2.3 Triggering package

In comparison with the free sampling technique, the triggered sampling technique can acquire and align signals automatically and provide several benefits to the users. Firstly, it times the input signal relative to the trigger event, so that the user captures the signal only in the region of interest and conserves hardware memory requirements. Secondly, the utilisation of the triggering technique will make the whole sampling process fully automatic without the need for manual interference. This is especially desirable in an industrial environment. Additionally, the acquired signals are started and stopped at the exact same moment and can be compared and used to construct thresholds furthermore. In general, there are two different approaches to conduct triggering, namely, threshold-based analogue triggering and the control-signal-based digital triggering technique. An analogue trigger can be conducted by the specification of the level and slope of an analogue signal. In such a system, an analogue trigger circuit on the data acquisition board (DAQ) continuously monitors the analogue signal to determine whether it satisfies the trigger conditions. Once the trigger conditions are met, the analogue trigger circuit generates an internal trigger signal to initiate the acquisition. However, a digital start trigger is used to synchronise the starting or stopping of data acquisition with an external source. This external source may be an electrical switch, proximity probe or a control signal from the CNC control unit. In this research work, two switches have been mounted onto the broaching machine and are selected as the start and stop switches, respectively. The corresponding software has been developed to initiate acquiring data at the exact moment when the broaching ram reaches the position of the start switch and to stop acquiring data at the exact point when the ram reaches the position of the stop switch. Furthermore, the software program can be running in a re-triggerable way to continually acquire the signal at successive broaching strokes without manual interference.

2.4 Data acquisition package

In this work, PXI and LabVIEW have been selected as the platform of hardware and software to construct the data acquisition package, respectively. PXI (PCI eXtensions for Instrumentation) is a high-performance and low-cost deployment platform for measurement and automation systems. By adding rugged industrial packaging, plentiful slots for I/O and advanced timing and triggering capabilities, the PXI system has been extensively implemented in manufacturing, military and aerospace industries. The whole PXI-based DAQ system delivers a significant performance improvement over older architectures by combining the high-speed, industry-based PCI bus with modular chassis-based architecture. Furthermore, the advanced timing and synchronisation features of PXI provide a high level of integration between different modules. In general, PXI systems are comprised of three basic components: the chassis, the system controller and peripheral modules. The chassis provides the rugged and modular packaging for the system for industrial environments. Controller options include remote control from a standard desktop PC or a high-performance embedded control with either a Microsoft operating system or a real-time operating system. In this research work, National Instruments PXI modules, namely, a NI PXI-1031 chassis, a 3.0GHz Pentium 4 rack-mount PXI controller and a 16-Bit PXI-6251 with 16 analogue inputs and 24 digital I/Os, have been selected as the hardware platform to construct the DAQ package.

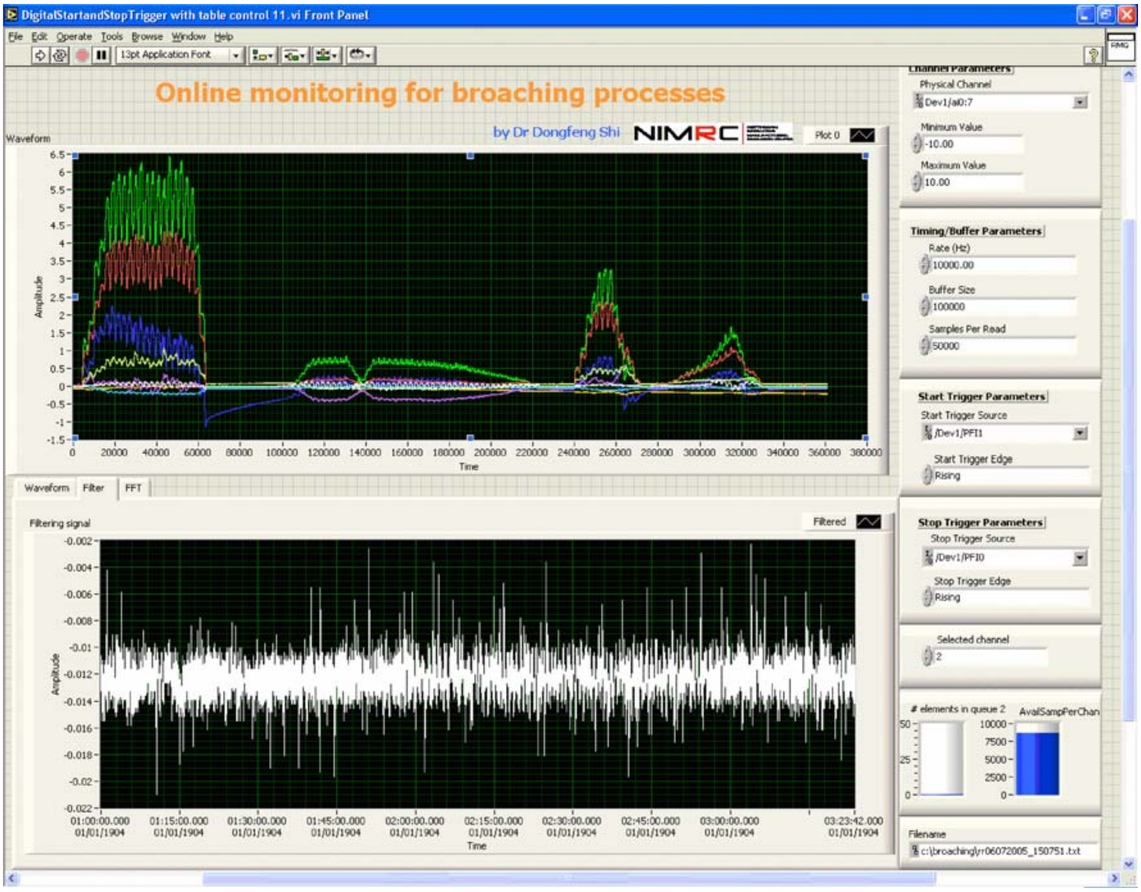
Naturally, LabVIEW has been selected as the software platform to develop the whole software package, due to its powerful performance in data acquisition, user interface design, data management and hardware connectivity. LabVIEW delivers a powerful graphical development environment for signal acquisition, measurement analysis and data presentation. A continuous re-triggerable DAQ system has been developed to acquire signals automatically by using a digital triggering technique. In a continuous acquisition, data is placed into a circular buffer by the DAQ hardware and the software removes previously acquired data from the buffer and processes it simultaneously. Furthermore, the developed DAQ system is able to acquire, analyse and present the data simultaneously, due to the utilisation of multi-thread programming techniques, i.e. queue techniques. The acquired data can be pushed into one queue initially and then assigned into a different thread to be processed. In this multi-threaded application, the data acquisition resides on a different, high-priority thread than the user interface in order to avoid losing data. The developed DAQ system can conduct fast Fourier transform (FFT), filtering and STFT in real time through the selection of different table controls, as shown in Fig. 2. STFT is an efficient signal processing tool to present the sensory signals in the joint time–frequency domain and details will be introduced further in Section 3.4. In order to reduce the manual interference required, the data can be automatically saved in one file and its name can be generated according to the date and time of sampling.

2.5 Characterisation package

The objective of the characterisation package is to evaluate the noise sources of manufacturing processes, i.e. DAQ board, sensors, driving chain, coolant and the environment. By conducting this package, the main noise source can be identified and the corresponding noise-cancelling task can be carried out by re-organising the wires to improve the signal-noise ratio of the sensory signals. Additionally, the resonant frequencies of machine tool components, i.e. ram, worktable, tool holder and support structures, can be identified by a modal testing technique. The corresponding package has been developed to identify the dominant resonance frequencies of machine tools by performing hammer testing. Once the manufacturing process is characterised, the amplitude variations of the resonance components can be monitored to detect the malfunction of processes, i.e. chatter or tool wear.

2.6 Condition monitoring package

The objective of this package is to automatically construct and update the thresholds of malfunction-free zones. The automatic alignment and statistical process monitoring techniques have been introduced to estimate and update the thresholds of malfunction-free zones. The details of the above two methods are introduced further in Section 3. If the monitored value exceeds the corresponding thresholds, the data is further analysed by the feature extraction package. Otherwise, the data is saved in the normal database and the corresponding threshold will be updated automatically.



DigitalStartandStopTrigger with table control 11.vi Front Panel

Online monitoring for broaching processes

by Dr Dongfeng Shi

Channel Parameters

Physical Channel: Dev1/ai0:7

Minimum Value: -10.00

Maximum Value: 10.00

Timing/Buffer Parameters

Rate (Hz): 10000.00

Buffer Size: 100000

Samples Per Read: 50000

Start Trigger Parameters

Start Trigger Source: /Dev1/PFI1

Start Trigger Edge: Rising

Stop Trigger Parameters

Stop Trigger Source: /Dev1/PFI0

Stop Trigger Edge: Rising

Selected channel: 2

Filename: c:\broaching\yr06072005_150751.txt

Fig. 2 Graphical user interface of the online broaching process monitoring package

2.7 Feature extraction package

The objective of this package is to extract the features of tool failures, i.e. tool wear, chipping, weakened tools and breakages. The extracted features should be sensitive to the tooling conditions and insensitive to the cutting parameters, workpiece materials and geometry. The resample technique has been firstly introduced to decompose the cutting force signal into static and dynamic components to enable the extraction of the features related to tool failures in the time domain. Secondly, the cutting force signal can be Fourier transformed into the frequency domain and the corresponding frequency domain features can be extracted. Thirdly, the STFT has been further introduced to extract the transient features of tool failures. The details of the cutting force decomposition and STFT are introduced in Section 3.

3 Signal processing techniques

3.1 Automatic alignment method

The objective of the automatic alignment method is to align free-sampled broaching signals from different trials to the same starting point. For the purpose of comparison among signals and construction of the alarming thresholds, the development of the automatic alignment method is crucial. There are two different approaches to achieve automatic alignment, namely, the hardware approach (switch triggering), as suggested in Section 2, and the software approach. Prior to the implementation of this online process monitoring system, plentiful sensory signals were acquired by free-sampling software. These sensory signals were not acquired at the exact moment and cannot be used to estimate thresholds without the alignment. Consequently, a cross-correlation approach has been investigated to align free-sampled signals. The cross-correlation function as illustrated in Eq. 1 provides a degree of correlation between two signals as a function of time shift l:

$$r_{ij}(l) = \frac{1}{N}\sum_{n=0}^{N-1} F_i(n) \cdot F_j(n+l) \tag{1}$$

where:

F_i	Cutting force of slot i
F_j	Cutting force of slot j
l	Time shift between two cutting forces
N	Number of sampling points

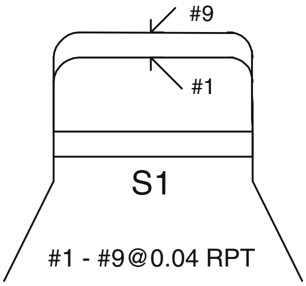


Fig. 4 Profiles of the first and last teeth of the short broaching tool

The cross-correlation is a measure of the linear synchronisation between two signals acquired from different trials. The time series of the cross-correlation associated with different time shifts l can be constructed according to Eq. 1. The time shift associated with the maximal value of the cross-correlation function corresponds to the real-time delay between two signals and can be obtained by:

$$d_{ij} = \arg\left(\max\left(r_{ij}(l)\right)\right) \tag{2}$$

Once the time delay d_{ij} is obtained, the cutting force signal F_j can be aligned against F_i.

3.2 Decomposition of the broaching forces

The pattern of the broaching signal is more complex than some other machining processes, due to the variation of the number and profile of teeth involved and the frequent teeth entrance or exit in broaching processes. The objective of the decomposition technique is to divide the cutting force into dynamic and static components to extract the cutting force patterns and enhance the signal-noise ratio by removing interference terms associated with teeth entrance or exit. Then, the static component indicates the consistent cutting force and the dynamic component corresponds to the dynamic cutting force introduced by teeth entrance or exit. Several techniques, i.e. band-pass filtering, wavelet package decomposition and resample, may be employed to decompose broaching forces. In this research work, for the purpose of the reduction of time-consumption in the decomposition, the resample technique is adopted. Additionally, by the utilisation of the resample technique, the broaching force signals can be further compressed to reduce the complexity and memory requirements in the construction of the alarming thresholds. In general, the

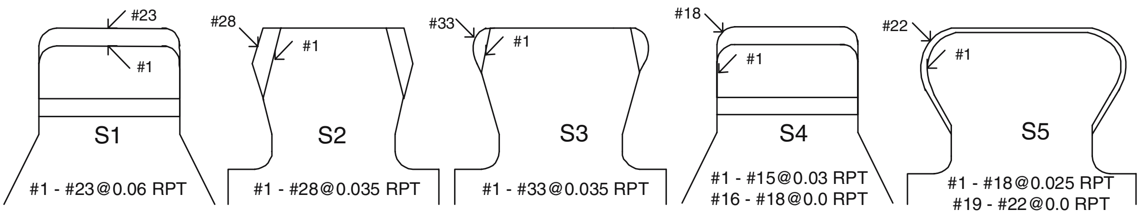
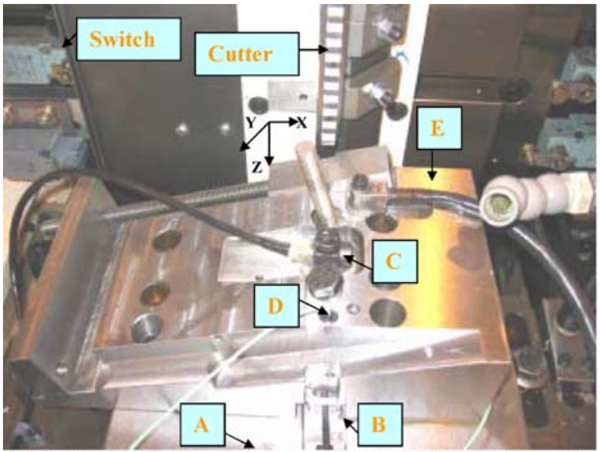


Fig. 3 Profiles of the first and last teeth of the five-segment broaching tool



A 3-axis Kistler 9255B platform dynamometer
B 3-axis Kistler 9602 integrated force sensor
C 3-axis Kistler 8692C01 accelerometer
D Kistler 9241C transverse strain sensor
E Kistler 9232A surfaced mounted strain sensor

Fig. 5 Platform and configuration of the sensors in the experimental trials

resample technique is an efficient approach to reconstruct the signal by either raising or lowering the sampling rate by an arbitrary factor. The process of lowering the sampling rate of a signal has been called decimation; similarly, the process of raising the sampling rate of a signal has been called interpolation. Decimation is normally conducted by the combination of band-pass filtering and sub-sampling and more details can be found in [15]. In order to extract the static component of the broaching force, the resample frequency is specified as slightly lower than the broaching teeth passing frequency, which can be estimated by:

$$f_p = \frac{v_c}{p} \tag{3}$$

where:

f_{p} Broaching teeth passing frequency
v_c Broaching speed
p Pitch of the broaching tool

After the decomposition of the cutting forces, the static component corresponding to the consistent cutting force and the dynamic component associated with the fluctuations of the cutting force introduced by teeth entrance or exit can be obtained.

3.3 Statistical process control (SPC) to construct the thresholds of the cutting forces

The construction of alarm thresholds for tool-malfunction-free machining has been investigated by using statistical process monitoring techniques. Several broaching force signals are acquired in normal cutting conditions and are further pre-processed by the automatic alignment and resample techniques. The statistical moments of the static cutting forces are used to construct the alarming thresholds. The average and standard deviation series of static broaching forces can be estimated by:

$$\overline{F}(t) = \frac{1}{K}\sum_{k=1}^{K} F_k(t) \tag{4}$$

$$\sigma^2(t) = \frac{1}{K-1}\sum_{k=1}^{K}\left(F_k(t) - \overline{F}(t)\right)^2 \tag{5}$$

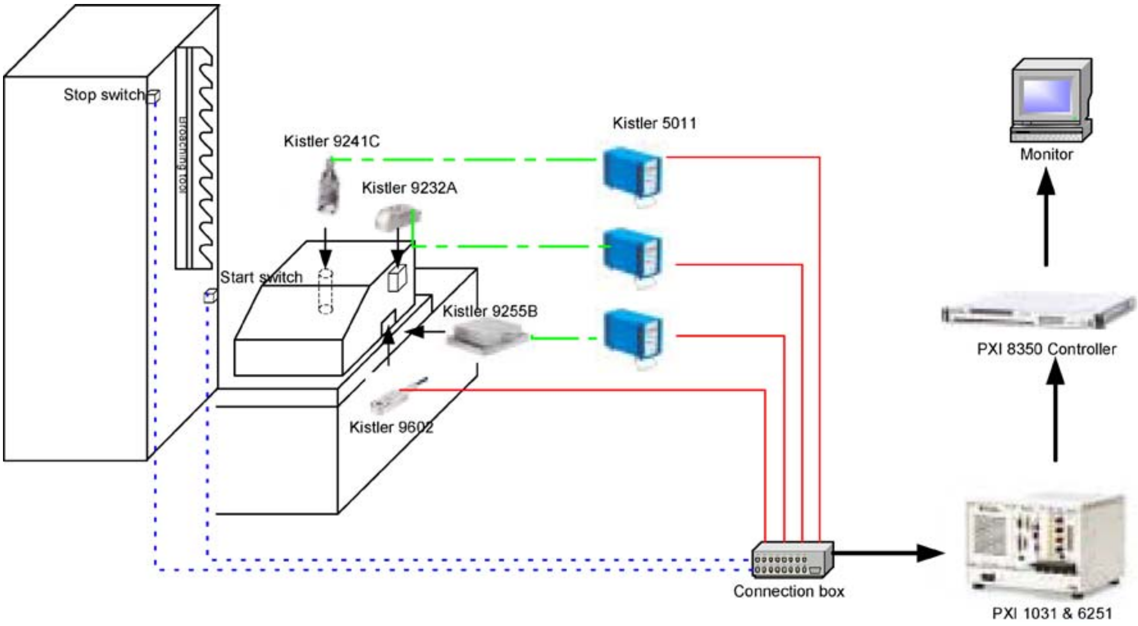
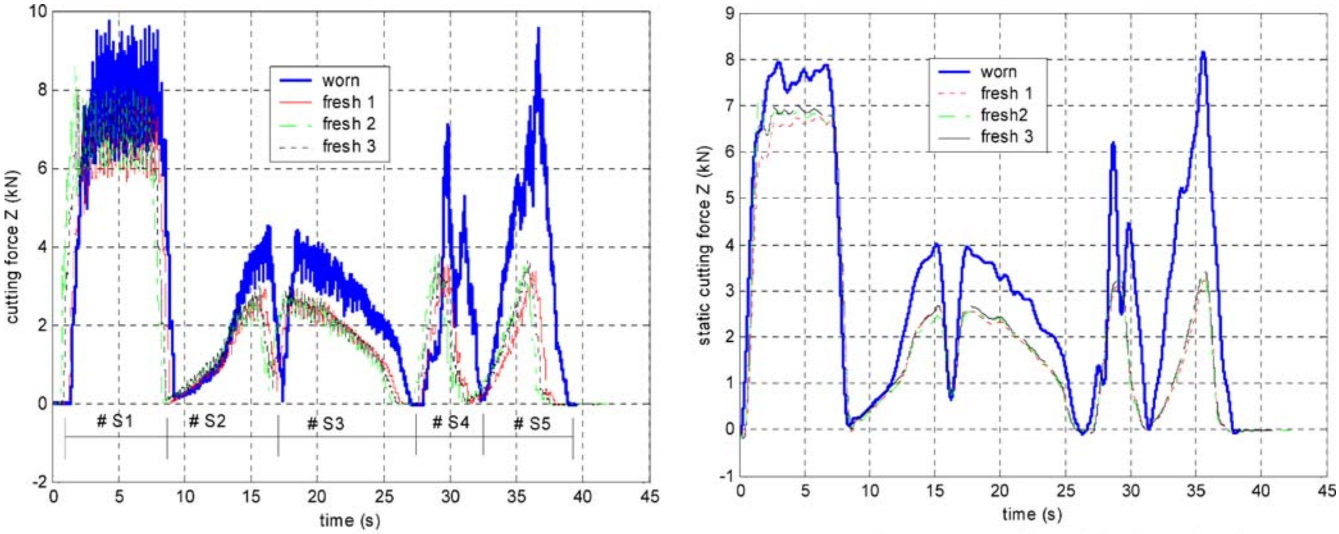
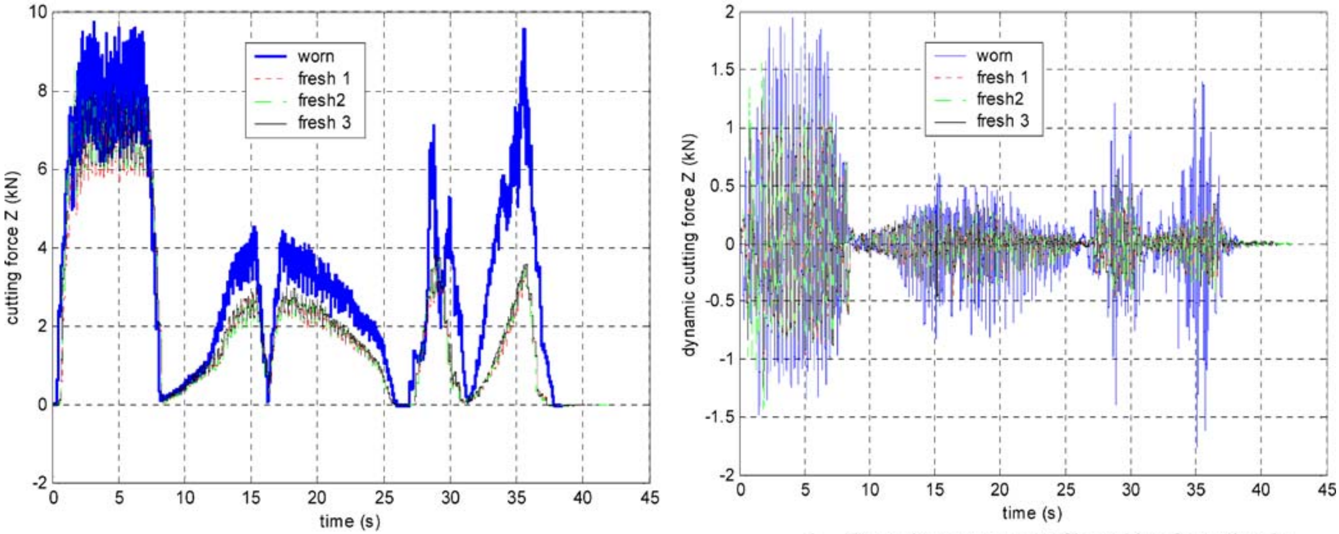


Fig. 6 Schematic diagram of the broaching process monitoring system



a Original broaching force signals

c Static components of broaching force signals



b Aligned broaching force signals

d Dynamic components of broaching force signals

Fig. 7a–d Broaching force signals with different tool conditions. **a** Original broaching force signals. **b** Aligned broaching force signals. **c** Static components of broaching force signals. **d** Dynamic components of broaching force signals

where:

$F_k(t)$	kth cutting force signal
$\overline{F}(t)$	Average of cutting force signals in normal cutting conditions
$\sigma_F(t)$	Standard deviation of cutting force signals in normal cutting conditions
$F_{\mathrm{alarm}}(t)$	Estimated threshold of cutting force

Furthermore, the upper and lower thresholds of the broaching cutting forces can be determined by:

$$F_{alarm}(t) = \overline{F}(t) \pm \alpha\sigma_F(t) \tag{6}$$

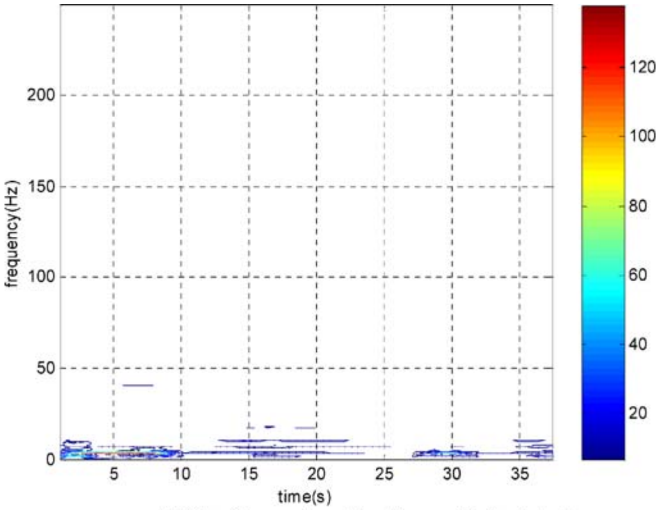
where α is a confidence coefficient.

At any given time t, there will be a 99.74% probability that the broaching force signal is within the threshold band with α=3. For the purpose of online updating the thresholds, the averages and standard deviations can be calculated recursively. Applying Eq. 4 for the first k−1 and k data and subtracting one from the other, we can get:

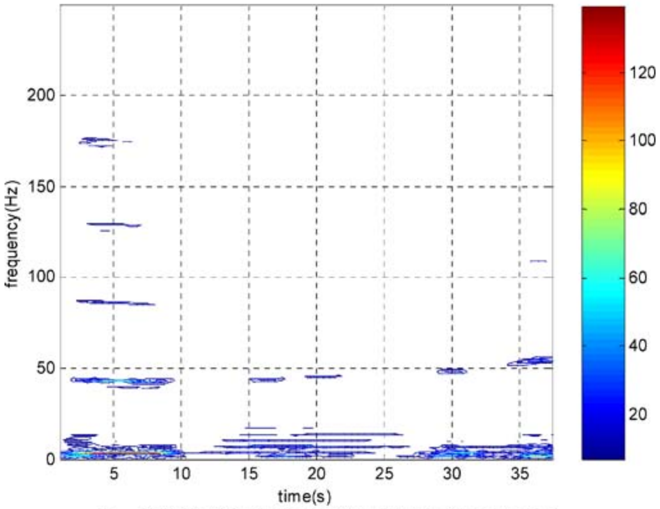
$$K\overline{F}_K(t) = (K-1)\overline{F}_{K-1}(t) + F_K(t) \tag{7}$$

Additionally, by applying Eq. 5 for the first k−1 and k data, the following equations can be obtained:

$$\begin{aligned}(K-1)\sigma_K^2(t) \\ = F_1^2(t) + F_2^2(t) + \ldots + F_K^2(t) - K\overline{F}_K^2(t)\end{aligned} \tag{8}$$



a STFT of dynamic cutting force with fresh tools



b STFT of dynamic cutting force with worn tool

Fig. 8a, b Short-time Fourier transform (STFT) of dynamic forces with different tool conditions. **a** STFT of the dynamic cutting force with a fresh tool. **b** STFT of the dynamic cutting force with a worn tool

$$(K-2)\sigma_{K-1}^2(t) = F_1^2(t) + F_2^2(t) + \ldots + F_{K-1}^2(t) - (K-1)\overline{F}_{K-1}^2(t) \tag{9}$$

By subtracting these two equations, Eq. 10 can be obtained:

$$(K-1)\sigma_K^2(t) = (K-2)\sigma_{K-1}^2(t) + (K-1)\overline{F}_{K-1}(t)^2 + F_K(t)^2 - K\overline{F}_K(t)^2 \tag{10}$$

By substituting Eq. 7 into Eq. 10, then:

$$(K-1)\sigma_K^2(t) = (K-2)\sigma_{K-1}^2(t) + K\big/(K-1)\left(F_K(t) - \overline{F}_K(t)^2\right) \tag{11}$$

The average and standard deviation can be estimated recursively by using Eqs. 7 and 11 with initial values $\overline{F}_1(t) = F_1(t)$ and $\sigma_1^2(t) = 0$. The recursive algorithm can improve the efficiency of the construction of thresholds significantly.

3.4 Short-time Fourier transform

The broaching process is a typical non-stationary machining process due to the frequent teeth entrance and exit. The ordinary FFT spectrum can evaluate only an average spectrum over a definite time period, while fully losing the non-stationary characteristics of the broaching force signal. The STFT is a joint time–frequency analysis method that extends the FFT to process non-stationary signals [16]. The STFT is given by:

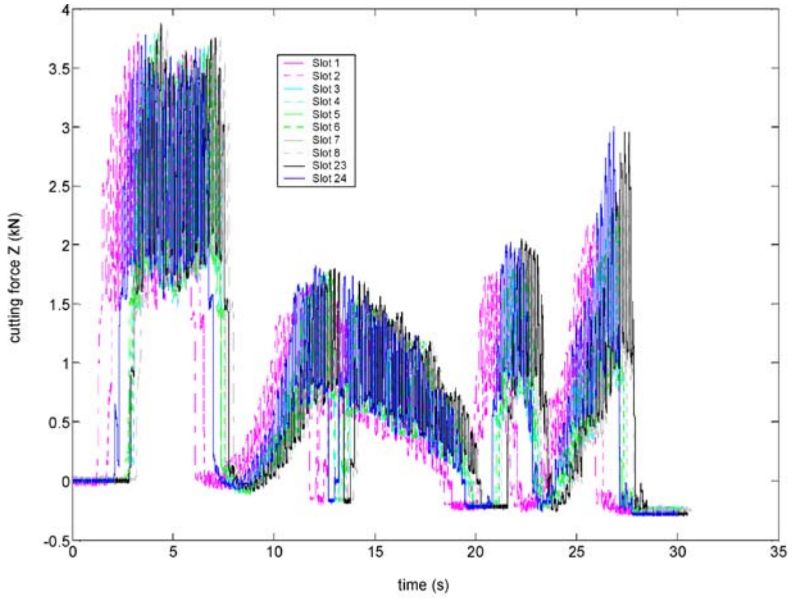
$$STFT(\tau,\ \omega) = \int_{\tau-t_l}^{\tau+t_l} F(t)\gamma(t-\tau)e^{-j\omega t}dt \tag{12}$$

where:

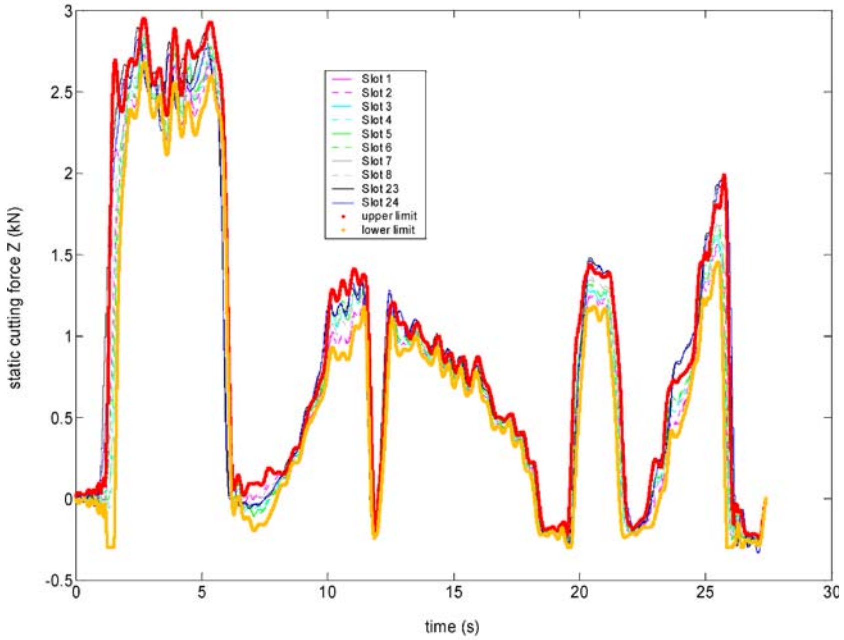
$F(t)$	Cutting force signal
τ	Time instance at which the signal is Fourier transformed
$\gamma(t)$	Sliding window function
t_l	Length of overlap between two adjacent sliding windows

The function $\gamma(t)$ usually has a short period duration and, thereby, is named the sliding window function. Gaussian, Hanning or Hamming window functions can be selected to calculate the STFT. The STFT is a regular inner product and reflects the similarity between a signal $x(t)$ and the elementary function $\gamma(t)exp(j\omega t)$. The STFT can express the non-stationary signal in the joint time–frequency domain and can be used to analyse the variation of the frequency distribution with time. In this research work, the STFT is used to characterise the broaching process by detecting the resonance frequencies.

Fig. 9a, b Cutting force signals acquired in successive slot broaching. **a** Original broaching force signals. **b** Static broaching force signals and the construction of thresholds



a Original broaching force signals

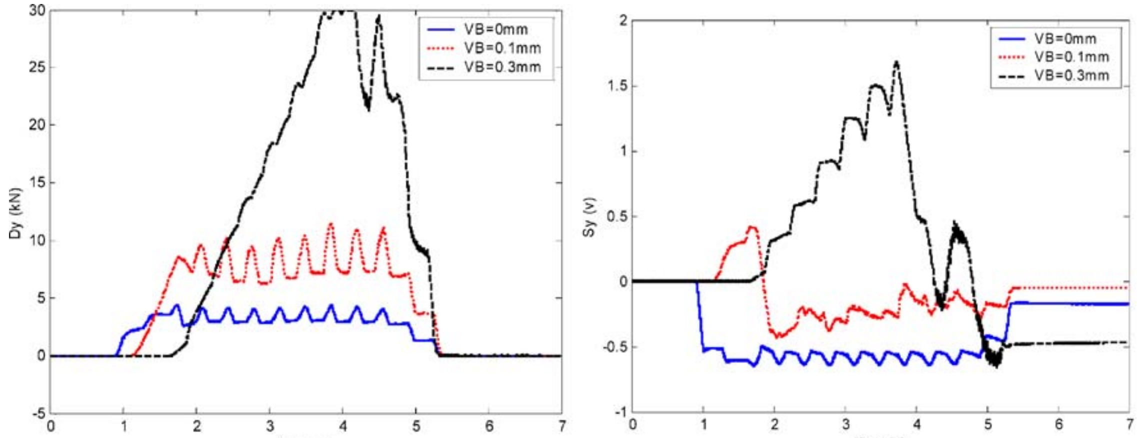


b Static broaching force signals and construction of thresholds

4 Results and discussions

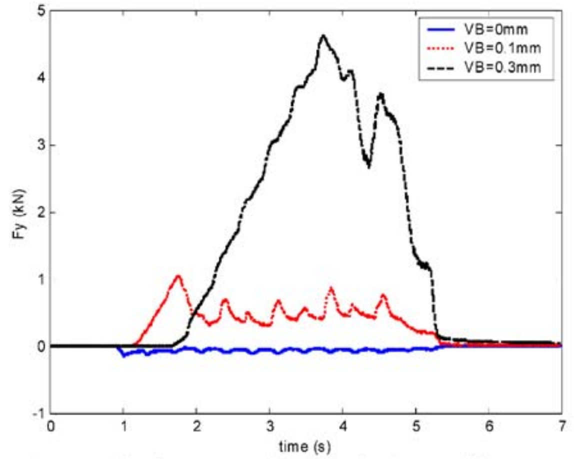
4.1 Experimental setup

A Cincinnati vertical broaching machine has been employed with two different sets of tools to produce slots. The first set of tools comprised five segments with different profiles to broach tilt dovetail slots in rectangular blocks. Figure 3 shows the profiles of the first and the last tooth of each tool segment (S1–S5) and the parameters of the tool, i.e. the rise per tooth (RPT) in mm, which is the indication of the cutting teeth (RPT≠0) or the finishing teeth (RPT=0). Due to the limitations of the broaching stroke (1,375 mm), the initial rectangular slots were milled in the testing bars preliminary to the broaching tests. In one broaching stoke, the successive cutting of the segments S1–S5 results in the production of the final dovetail profile. A constant tool pitch (*p*=8 mm) and tool edge preparation (clearance angle 1° and rake angle 13°) with different tooling conditions were employed to conduct broaching trials. The second set of tools is to broach tilt slots in rectangular blocks of Inconel 718 and the technical parameters can be found in Fig. 4. Several short tools (*p*=10 mm) with different tool malfunctions have been used to conduct broaching trials to validate the alternative sensors against platform dynamometers. A special platform



a Broaching forces at Y axis measured by dynamometer

c Broaching strains at Y axis measured by transverse strain sensor

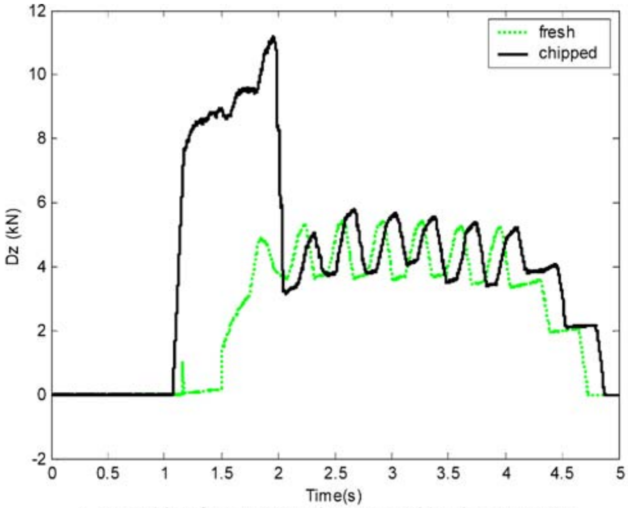


b Broaching forces at Y axis measured by integrated force sensor

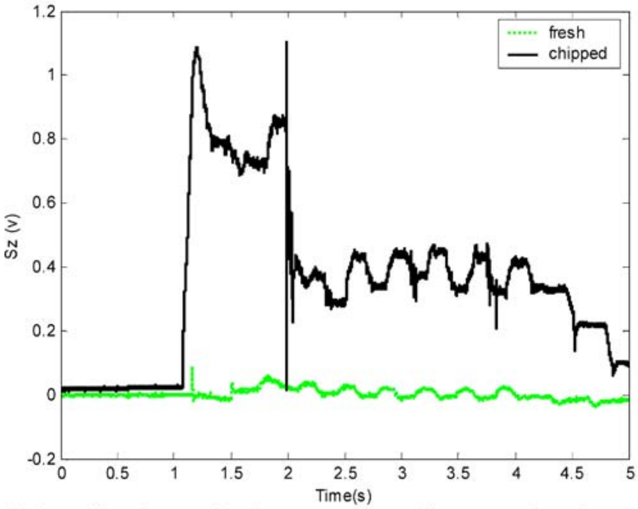
Fig. 10a–c Tool wear detection using a platform dynamometer and alternative sensors. **a** Broaching forces at the *Y* axis measured by the dynamometer. **b** Broaching forces at the *Y* axis measured by the integrated force sensor. **c** Broaching strains at the *Y* axis measured by the transverse strain sensor

Table 1 Performance evaluation of various sensors

	Dynamometer	Integrated force sensor	Surface-mounted strain sensor	Transverse strain sensor
Accuracy	Very high	High	High	Fair
Cost	Very high	High	Low	High
Mounting	Difficult Needs extra space	Needs preload Needs slot to mount	No preload M6 screw	Need preload Φ10 hole
Range	−10–40 kN (Dz) −20–20 kN (Dx, Dy)	−5–5 kN (Fz) −2.5–2.5 kN (Fx, Fy)	−600–600 mε	−300–200 mε
Size and weight	360×300×95mm 52 kg	57×25×10 mm 30 g	40×17×17 mm 50 g	40×Φ10 38 g
Sensitivity	X, Y: 8 pC/N Z: 3.7 pC/N	X, Y: 2 mv/N Z: 1 mv/N	80 pC/mε	15 pC/mε
Tool wear detection	Very high	High	High	High
Tool chipping	Very high	high	High	Fair
Note	Difficult to implement in industrial environment	Integrated charge amplifier	Easy mounting High sensitivity	Low sensitivity



a Broaching forces at Z axis measured by dynamometer



b Broaching forces at Z axis measured by surface mounted strain sensor

Fig. 11a, b Tool chipping detection using the platform dynamometer and alternative sensors. **a** Broaching forces at the *Z* axis measured by the dynamometer. **b** Broaching forces at the *Z* axis measured by the surface-mounted strain sensor

was designed to hold the workpiece at a tilt angle of 15° and to mount several sensors as shown in Fig. 5. The integrated force sensor produces an amplified, low-cost impedance force-proportional voltage signal which can be directly acquired by the DAQ system without the need of a charge amplifier. In order to accommodate the integrated force sensor, a pocket of 16-mm height, 30-mm width and 30-mm length was produced in the bottom of the platform. The integrated force sensor was then installed and preloaded to 25 kN by an adjustable wedge. The transverse strain sensor is shaped as a cylindrical pin and its head is sensitive to the transversal force. An integrated clamping tool was used to preload the sensor in the borehole (Φ10H8) within the platform to measure the compressive force in the *Y* direction. In comparison with the well-known wire strain gauge, the surface-mounted strain sensor is made by a piezoelectric element with high sensitivity, large overload resistance and unlimited life, even under fluctuating loads. The surface-mounted strain sensor is acceleration-compensated and capable of producing an electric charge proportional to the cutting force. The sensor was screwed to the platform and aligned in the *Z* direction by using one fastening screw. Two electrical switches mounted in the broaching machine were specified as the start and stop switches, respectively, and a corresponding circuit with a 5-V power supplier was connected to the trigger channels of the PXI system. The whole broaching process monitoring system is shown schematically in Fig. 6.

4.2 Broaching trials with the five-segment tool

Initially, the five-segment tool was employed to conduct the broaching trials and the broaching force signals measured by the platform dynamometer have been acquired by the PXI system. The rectangular block with thickness 26.5 mm was used to conduct broaching trials with cutting speed 1.8 m/min. The teeth passing frequency can be obtained as 3.75 Hz according to Eq. 3. Four sets of free-sampled broaching force signals with different tooling conditions, namely, fresh tool and worn tool, are shown in Fig. 7a–d. The tool was uniformly worn and the average VB is less than 0.2 mm. It can be seen that the broaching force signals have various patterns due to the difference in the teeth profile at every segment. The broaching force associated with the first segment is higher than some other segments, since the maximum amount of material is removed by first segment. In addition, the broaching forces have changed with the variation of the number of teeth involving cutting at each segment, as shown in Fig. 7a. In each segment, it can be seen that the broaching force starts from zero and increases with the number of teeth involved in broaching. The maximum number of teeth to broach the workpiece simultaneously is four and the cutting force reaches the maximum value in this situation. Then, the broaching force decreases successively with the last few teeth leaving the cutting zone. However, the start points of each broaching force signal are different, due to the use of free-sampling software. The time delays between signals can be estimated and then aligned by the cross-correlation approach, as illustrated in Fig. 7b. The aligned broaching force signals can be further decomposed into static and dynamic components by the resample technique, as shown in Fig. 7c,d, respectively. It is rather easy to detect tool-wear-related cutting force variation from the static component than the original broaching force, since interference terms generated by tool entrance or exit are removed. At each segment, the broaching force associated with a worn tool is much higher than a fresh tool, as illustrated in Fig. 7c. Furthermore, the dynamic component is used to detect transient events, such as tool chipping and chattering. The STFT of dynamic cutting forces with different tooling conditions can be obtained by Eq. 12 and is shown in Fig. 8a,b, respectively. The teeth passing frequency (3.75 Hz) and its harmonics, which are less than 40 Hz, can be found in both figures. One dominant frequency (44 Hz) and its harmonic components appeared if the tool was worn, as shown in Fig. 8b. This can be explained as the resonance frequency component being excited due to the cutting force increase with the worn tool. This dominant frequency was identified as one of the resonance frequencies associated with the ram system according to the results of further modal testing.

In order to demonstrate the performance of the signal processing techniques, further broaching trials have been conducted by using the same broaching tool. The Inconel 718 bar with thickness 10 mm has been employed to conduct the broaching trial with cutting speed 2.4 m/min. Twenty-four tilt dovetail slots have been broached with an initially fresh tool. The selective broaching force signals are presented in Fig. 9a. It can be seen that the broaching force decreased compared with the previous trial, since only two teeth cut the workpiece simultaneously. After implementation of the cross-correlation algorithm, these broaching signals can be further aligned. Then, the resample technique has been employed to extract the static broaching force, as shown in Fig. 9b. It is obvious that the static cutting forces increased with the proceeding of the broaching stroke, especially in the fourth and fifth segment. Furthermore, the thresholds of the malfunction-free zone can be constructed according to Eq. 6 by using the first eight broaching force signals. In this case, the broaching force associated with the 23rd and 24th slots exceeded the upper limit in the fourth and fifth segments. The statistical process monitoring technique has been proved to be rather sensitive for constructing the threshold.

4.3 New miniature sensors validation in machining processes

Several broaching trials have been conducted to investigate the correlation between signals acquired from platform dynamometers and alternative miniature sensors. The developed online monitoring software with a digital trigger technique has been validated as well. The graphical user interface of the online process monitoring software has been developed by using a multi-thread technique, as shown in Fig. 2. The channel parameters, sampling frequency, buffer size and start/stop triggering parameters can be configured by the user. The overall signals acquired by the PXI system is shown in the top plot and the instantaneous waveform, online filtering and FFT spectrum can be selected by the user to be shown in the bottom plot. Additionally, the acquired data can be saved to the hard disc with automatically generated filenames according to the time and date of sampling. Due to the utilisation of the start trigger technique, signals can be acquired at the exact starting point without the use of an alignment algorithm.

In order to evaluate the performance of new miniature sensors to detect the tool malfunctions, several broaching trials have been conducted using short broaching tools with different tooling conditions, namely, tool wear and tool chipping. The rectangular blocks with thickness 20 mm of Ti-6-4 alloy have been broached at a speed of 1.8 m/min. Firstly, the broaching signals with different tool wear were measured by several sensors and the sensory signals associated with the pushing force in the *Y* direction is shown as in Fig. 10a–c. It can be seen that the signals measured by the new miniature sensors follow the same pattern as the pushing force sensed by the platform dynamometer. Since the tool wear was generated artificially, only the first few teeth had contact with the workpiece without cutting and leaving extra material for the last few teeth to cut. Consequently, the amplitude of the sensory signals decreased slightly at the first few teeth and increased significantly at last the few teeth. The experimental results show that the new miniature sensors, i.e. the integrated force sensor and the transverse strain sensor, are sensitive enough to detect tool wear.

Secondly, another set of short broaching tools was artificially chipped at the clearance face in the fourth tooth by electrical discharge machining (EDM). This chipped tool was used to conduct further broaching trials to evaluate the sensitivity of alternative sensors to detect the tool chipping. Since the tool chipping had an influence on the effective contact length between the tooth and the workpiece, the variation of the broaching force in the *Z* direction would be more significant than the pushing force in the *Y* direction, as shown in Fig. 11a,b. It can be seen that the sensory signals measured by the platform dynamometer and the surface-mounted strain sensor both have a dominant peak when the chipped tooth started cutting at around 2 s. Additionally, the signal measured by the surface-mounted strain sensor correlates with the signal measured by the platform dynamometer very well. The experimental results show that the surface-mounted strain sensor is sensitive enough to detect tool chipping.

5 Conclusions

An online machining process monitoring system based on the PXI and LabVIEW platforms has been developed and validated in the broaching experimental trials presented in this paper. The major contributions of this work can be summarised as follows:

1. A digital trigger package based on electrical switches has been designed to start/stop data acquisition at the exact moments of a machining process.
2. An online data acquisition package based on a multi-thread programming technique (queue technique) has been developed to acquire, analyse and present sensory signals simultaneously.
3. Several signal processing methods, namely, cross-correlation, resample, short-time Fourier transform (STFT) and statistical process control, have been proposed to extract the features of tool malfunctions and construct thresholds of malfunction-free zones.
4. It has been proved that the sensory signal measured by alternative sensors, namely, surfaced-mounted strain sensors, transverse strain sensors and integrated force sensors, correlate with the dynamometer signal very

well and is sensitive enough to detect tool wear and tool chipping. The detailed evaluation results of the sensors employed in this research work are tabulated in Table 1.

The proposed online process monitoring methodology can be applied to some other processes, i.e. turning and milling, without any difficulties. Indeed, the developed system has been conducting thin-wall milling trials for aero-engine casing and hard turning trials for compressor discs. The effectiveness of the proposed signal process techniques and alternative sensors has been validated in experimental milling and turning trials. The results obtained from turning and milling trials look promising and will be reported in a separate paper. The developed online process monitoring system is currently considered for conducting industrial trials on the shop floor. The multivariate statistical process control technique and artificial intelligent technique will be further introduced to enhance the performance of the whole system.

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