An appraisal of techniques and equipment for cutting force measurement[*]

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Abstract: Current research focussed on the assessment of metal machining process parameters and on the development of adaptive control, shows that machine performance, work-piece and tool material selections, tool life, quality of machined surfaces, the geometry of cutting tool edges, and cutting conditions are closely related to the cutting forces. This information is of great interest to cutting tool manufactures and users alike. Over the years there have been significant developments and improvements in the equipment used to monitor such forces. In 1930 mechanical gauges were replaced by resistance strain gauges, and some 30 years later compact air gauge dynamometers were invented. Since this time intensive research has continued being directed towards developing new approaches to cutting force measurement. The Kistler Company, well-known manufacturer of acceleration and piezoelectrical dynamometers, has worked in this field for more than three decades, and developed very sensitive devices. While leading manufacturing research laboratories are often equipped with this technology, classical electrical strain gauges and other dynamometers of individual designs are still commonly used in industry. The present paper presents data obtained using different techniques of force measurement in metal machining processes. In particular, areas of uncertainties, illustrated through results concerning the turning process, are analysed, leading to an appraisal of the current status of these measurements and their significance.

Key words: Cutting force measurement, Frequency analysis, Piezocrystals, Strain gauges, Error sources
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INTRODUCTION

Metal machining processes are characterised mainly by quick changes in quantified elements. Individual changes do not occur in isolation and they influence each other. The analysis of these changes require study of the complicated complete systems in their real situations. The study of cutting processes such as turning and facing, from dynamic aspects, is very important. The trend towards the measurement of cutting forces in machining leads to many theoretical and practical problems. Theoretical problems associate mainly with the choice of a suitable technique to measure, and the statistical methods to ana-

lyse the components of cutting force to be determined in realtime. Practical problems involve the errors and uncertainties relating to the measurement system used.

A typical relationship between cutting force components acting on the cutting tool in a 3D single point cut is defined by Eq.(1):

$$F_R = \sqrt{F_x^2 + F_y^2 + F_z^2}. \tag{1}$$

Researchers familiar with this field know that it is not possible to measure directly the cutting forces and their amplitudes at their real origin. The measuring device selected for experiments should be independent of forces and associated movements at the point of application, so that the components of a general force vector can be measured as a reaction of

the cutting edge in a defined plane distant from the cutting edge.

It is generally known that the accuracy of cutting force measurement is closely dependent on the quality and sensitivity of the measurement device used. There are also effects of interactive factors associated with the static stiffness of joints in the machine-tool-workpiece systems. In order to obtain true measurements, it should be critically considered if the data, obtained within the limitations of the measuring and evaluating technique used, is repeatable and accurate.

According to the UK BS5233 standard—Glossary of Terms used in Metrology, terms of metrology, used in this text, are defined as:

(1) Error of measurement: any departure from an accepted standard due to imperfection in any part of the measurement system.

(2) Accuracy: the closeness of readings to an accepted standard.

(3) Precision: the repeatability of individual readings about their real value.

(4) Repeatability: the closeness between a number of measurements made at the same time.

(5) Reliability: confidence in a measurement affected by uncontrollable random factors.

(6) Reproductibility: the closeness of measurements of the same quantity obtained at different times.

(7) Scatter: the deviation from a real value of precise reading.

Pople (1980) wrote that good accuracy requires good repeatability, but good repeatability does not necessarily ensure good accuracy. It is, therefore, possible to have, for example, 2% repeatable system with accuracy of about 50%. He also stated that errors and uncertainties in strain measurement can never be less than ±1% when tests are carried out under the best test conditions by an expert, while for inexperienced operator the uncertainties may range ±5%. However, for unstable test conditions the uncertainties can vary in the range ±7% for expert and ±15% for unexperienced person. The author also mentioned that in extreme conditions errors can reach value of ±30% and more due to failure to control some of the main errors sources.

Herman (1961) stated that an economical procedure for calibration was to make repeated calibra-

tions at one or two scale points of typical instruments of varying accuracies with different observation on different days and at different locations, using the best standard that was available.

Piezoelectric measuring devices, force transducers and dynamometers are among the most important developments in instrumentation for experimental stress analysis. Today they are used generally, for example, in metal machining processes, for acceleration measurements of dynamic forces, their components and amplitudes. A number of these techniques have been evolved mainly due to the efforts of the Kistler Company over the past 30 years. Before the piezoelectric principle was discovered, mechanical and electrical resistance strain gauges were commonly used to measure strains on actual test materials. It is interesting to recall the pioneering work of Kelvin who in 1856 discovered the principle on which electrical resistance strain gauges operate (Webb and Luxmoore, 1971).

The production of commercial strain gauges started about 1930 and still continues. From a wide range of manufacturers of the precision metal-foil strain gauges and special-purpose sensors the Micro-Measurements Division Company can be mentioned, and data relating to the products of this company can easily be found in catalogues (Catalogue 500 Part A-B—Strain gauges, 1994).

Currently there are not many published studies concerning performance evaluation and the sensitivity of systems used for cutting force measurement. For example, Evans and Morgan (1964) and Field (1967) investigated the problem associated with the sensitivity of the pneumatic gauging technique.

Field (1967) tested a compact dynamometer, apparently based on air gauge principles in longitudinal turning operations, at normal production conditions. The results showed that design and performance of dynamometers of this type were suitable for use under production conditions in restricted spaces and under a flood of cutting fluid. He concluded that the instrument had strictly linear calibrating characteristics which coincided during loading and unloading. However, it was also found that the air gauging system was rather slow in comparison with electrical systems. In a later paper Field used this equipment to investigate the dimensional changes in cutting tool as a result of cutting forces and temperature, but the

precision of the calibration was not mentioned.

Gibson and Kobler (1967) tested a three-component lathe dynamometer under static and dynamic load conditions. They found that a possible difficulty with the technique was that differences in response time of the three measuring bridges could cause spurious transients in the traces. A second possible difficulty was that differences in drift rate or changes of sensitivity among the measuring bridges could upset the balance points of the mixing circuits. In practice, these effects have not been reported to cause any problems.

Pople (1977) conducted a theoretical analysis of errors and uncertainties of electrical resistance strain gauges, and reported that errors in strain measurements made with metal foil gauges were inevitable owing to the nature of the materials and techniques employed. In some cases the magnitude and sign of errors could approximate to about 20% depending on the choice of materials selected.

Murty (1977) published a theoretical study on the precision of metal-cutting dynamometers. He adopted known statistical methods to determine the uncertainty in a function composed of several independent variables, and used them for comparison of analytical values and results obtained from calibration characteristics of various dynamometers. He recommended that for reliable determination of precision the number of calibrations should be between four and ten and the number of calibration points be 25.

Several authors have also reported the measurement of forces in metal cutting with dynamometers of different design, but not many of them have reported the performance accuracy of the dynamometers used.

Ohtani (1986) in cutting experiments reported a range for variation of cutting force components with the change in flank wear. However, they did not comment on the precision of the dynamometer employed in the experiment, nor did they specify the balance between individual signals of radial tangential and feed force emitted by the output circuits of their dynamometer.

Ravindra *et al*.(1993) used multiple regression analysis to investigate the relationship between cutting forces and tool wear in the turning process. Data obtained was reported without any mention of the uncertainty associated with measuring these forces.

Previous reports by Gautschi (1971) and Kail and Mahr (1995) discussed the sensitivity of Kistler equipment in some practical situations. However, consideration was given only to the theoretical analysis of errors and uncertainties relating to the measurement systems tested. These results confirmed that much research remained to be carried out. Thus, individual examples of studies, as published, do not illustrate the scope on a range of use of this very sensitive technique. For example, a work-material's machinability is closely dependent on the experimental set-up. Dynamic changes which are developed in the process while machining have to be studied as a whole in realtime. In particular it is critically important to ascertain if the technique used is sufficiently sensitive to indicate dynamic changes caused by nature and homogeneity of work-materials used.

The current paper presents the results of a study concerned with the assessment of metal machining process parameters and the development of adaptive control. Experimental findings obtained from the turning process have been analysed to evaluate the precision of metal cutting dynamometers and their potentials for use in adaptive control.

EXPERIMENTAL DETAILS

Kistler three-component piezoelectric dynamometer Model 9265B, Model 9257B, and 4 electrical resistance strain gauges Type 125UN were selected, and tested statically and dynamically. The purposes of static testing of measuring systems were to determine: (1) the signal level which could be obtained, and (2) interaction in the output from the cutting force components. Dynamic testing was conducted to determine the influence of various interference factors from the surroundings on the accuracy of data obtained using different measuring techniques.

Before starting the cutting experiments both the dynamometer—Type 9265B and simple two-component cutting tool dynamometer equipped with strain gauges were calibrated, together with the evaluating technique selected, relating to a 5 cm overhang of the cutting tools. A dynamometer—Model 9257B was tested together with the original Kistler evaluating technique, so in this case no calibration was necessary,

and calibration sensitivity of F_x, F_y, F_z was used, as received, to set-up the transducer sensitivity of the charge amplifiers—Model 5011A.

The performance and sensitivity of the metal-machining dynamometers was tested in the turning processes. An HMT lathe with 20 kW power was employed to perform the machine tests. A number of round bars, Bohler Type K460 (0.95% C, 0.3% Si, 1.1% Mn, 0.5% Cr, 0.12% V and 0.55% W), 25 mm in diameter and 100 mm in the length, were machined with non-chamfered uncoated carbide inserts—Type P30-SM30 under standard cutting conditions—at cutting speeds of 60 m/min and 90 m/min, depths of cut of 0.5 mm and 1 mm, and a constant feed rate of 0.1 mm/rev.

Data concerning dynamic changes in the frequency characteristics of cutting forces, their amplitudes and magnitudes were recorded and evaluated by using three different techniques. In order to examine the limitations and efficiency of the proposed evaluating techniques, it was also necessary to use other different data collection systems.

Experimental details relating to these three different measuring systems are reported as follows:

(1) The sensitivity of the dynamometer—Model 9265B was 8.8 and 3.7 pC/N for the F_x, F_y and F_z, respectively. The natural frequency of the dynamometer approximated to 2 kHz, while its stiffness was 800, 800 and 200 N/μm for the x, y and z direction, respectively. The output signal from this dynamometer was transformed into a proportional voltage by a charge amplifier and carried to an evaluating device designed specially for the purpose of these measurements (Kazimir and Audy, 1990). For three transducers one parallel comparative A/D board was used and the data were analysed by PMD computer in a code.

(2) The natural frequency of the dynamometer—Model 9257B was about 3 kHz and its threshold was smaller than 0.01 N. The output from this dynamometer was carried by a connecting cable—Type 1687B5 to the multichannel charge amplifiers—Model 5011. Each transducer required one amplifier. Cutting forces and their amplitudes were monitored in realtime with sensitivities of −7.98 pC/N for F_x, 7.95 pC/N for F_y and 3.78 pC/N for F_z. After monitoring the data were analysed by using IBM computer—Model 486 equipped with Snap-Master

Programme.

(3) Four strain gauges—Type 125UN having a resistance of (120±0.3%) Ω, were attached to a simple tool holder Type hR171.11-1925 and used for recording dynamic changes in both F_z and F_x cutting force constituents. The tests were conducted so that the F_y constituent approximated to zero and as such could be ignored. The signals of F_z and F_x forces were transferred through a Wheatstone bridge to an IBM computer equipped with PCL-718A/D card. Data so obtained were analysed by using a Snap-Master.

In detail, computer software to analyse the data obtained from the experimental measurements was selected according to Nyquist's criterion. It was reasoned that for frequencies higher than 1 MHz, the sampling rate should be about 80 MHz (Subramanian *et al.*, 1993). All the tests were conducted so that the natural resonant frequencies of a particular dynamometer used could also be found.

RESULTS

Stress and deflection analysis of the cutting tools tested

The theoretical analysis of stress and deflection was carried out for two different tool holders—Type hR171.11-1925 and Type MTJNR2525M16M1. Both these holders were loaded by static forces (60 N and 1400 N) applied in the vertical direction. Stress and deflection were calculated with the aim of showing the influence of the cross section and overhang of cutting tools on the dynamic variables (cutting forces and their amplitudes) acting on the cutting tool during machining processes. The calculations showed clearly that 51.8% increase in stress and 62% increase in deflection were expected due to 28% difference between two cross-section areas of both these cutting tools. It was also found that the stress and deflection of any cutting tool increased with the reduction of the cross-section area of the tool holder selected and with the increase of the overhang length used. The sensitivity of electrical strain gauges clearly depended closely on the resistance of sensors selected, and their position on the tool holder.

Analysis of problems associated with the static calibration

Possible error sources caused by the design of a

dynamometer calibrating device were studied using two different calibrating systems. Static testing of a simple two-component machining dynamometer, equipped with strain gauges was made for the 5 cm tool overhang situation. The known loads simulating the feed and tangential forces were then applied to the tool point through two perpendicular arms situated in z and x directions, and the associated changes in resistance were measured by a Wheatstone bridge. Both the maximum sensitivity and the temperature compensation of the full W-bridge were secured by employing four active gauges in uniaxial stress field—two aligned with maximum principal strain vector, two 'Poison gauges'. The strain gauge bridge was equipped with special circuits to separate certain types of loading and to compensate for the effect of temperature gradient generated in the body of the tool holder tested while machining.

Fig.1 exhibits the typical chart records (F_z (N) and electrical output (V)) obtained from the static calibration of the tool. The unfiltered part in this diagram shows variations in the voltage supply which is a difficult factor to control in instrument performance. The effect of such unwanted signals was limited by using filters as evident from Fig.1b.
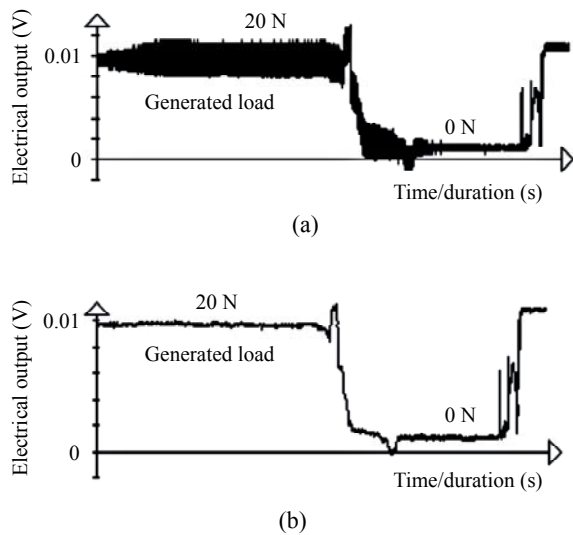

Fig.1 Calibration records of F_z force constituent applied in the vertical position. (a) Unfiltered part; (b) Filtered part

Fig.2 exhibits the effect of cross sensitivity which developed due to both a design modification of the calibrating system used to calibrate the cutting

tool dynamometer, and the errors in the position of strain gauges fixed on the tool holder.
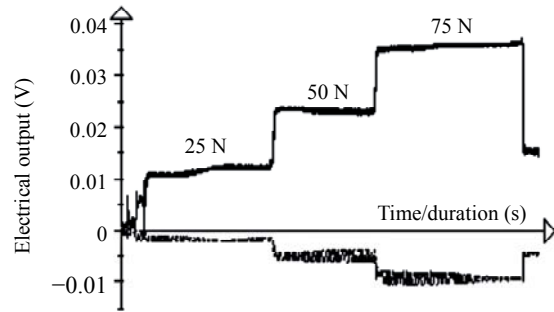

Fig.2 Unfiltered record of the F_z cutting force obtained from the static calibration of a tool holder equipped with strain gauges

The graphs in Fig.2 also indicate that simple two-component dynamometers equipped with strain gauges, while calibrated may indicate wrongly the presence of tangential force (F_z) when only feed force (F_x) is applied and vice versa. The explanation of this problem is shown in Fig.3. Error sources which occurred during the static calibration of a single cutting tip are associated with both the design changes in the mechanical part of the calibrating system and variations in the angular deviation from the perpendicular direction in which the load is applied on the testing point of a cutting tool.
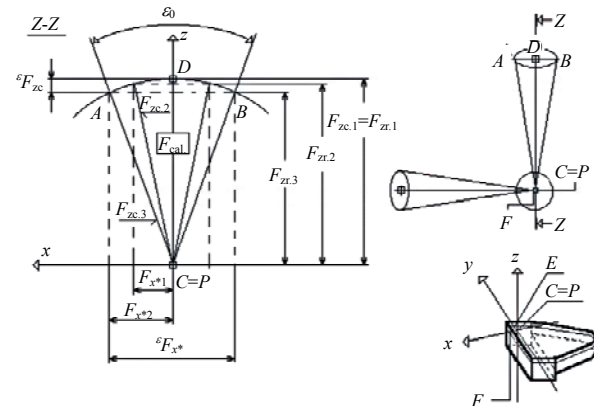

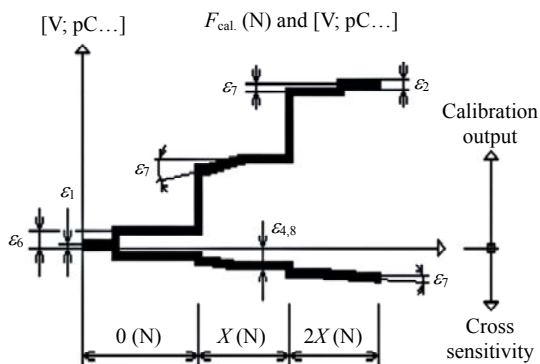**Fig.3 Errors in the static calibration of a cutting tool system**

Table 1 shows the real values of a calibration force (F_z) relating to the deviation in the angle load applied in the vertical direction. These calculations demonstrate clearly that the accuracy of the calibration is reduced markedly with any small variations in

Table 1 Errors and accuracy in the static calibration of cutting tool dynamometers as influenced by deviations in the angle of applied load

δ (x dir.)	F_x (N)	F_z (N)	ε in F_x (%)	ε in F_z (%)	Accur. F_z (%)
0	0	200	0	0	100
0.2	39.70	196.1	19.87	1.99	98.1
0.4	77.88	184.2	38.94	7.89	92.2

the angle of the applied load.

Typical potential errors which occurred during static calibration of the cutting force dynamometers are exhibited in Fig.4 showing obviously that error sources include mainly variations due to zero drift (ε_1), voltage supply (ε_2), temperature and thermal zero shift (ε_3), cross sensitivity (ε_4), sensitivity among W.B (ε_5), interference signals from surroundings (ε_6), toughness of calibration device (ε_7), non-linearity associated with the bridge configuration (ε_8), deviation in the angle of applied load (ε_9). There are also inaccuracies due to hysteresis, calibration linearity, zero drift and sensitivity changes.

Fig.4 Error sources associated with the static calibration of metal-cutting dynamometers

Static testing of a piezoelectric dynamometer Kistler—Type 9265B was made by using a DOCM-1 calibre. Loads simulating feed, tangential and radial forces were applied to the tool point through the screws situated in three perpendicular directions x, y and z in the calibrating construction. The calibration, made for 5 cm of tool overhang, was necessary, because of the use of a different evaluating technique than that recommended by the Kistler Company. Preliminary static testing of this dynamometer was made using a press machine, with the aim to find the maximum signal level which could be obtained from
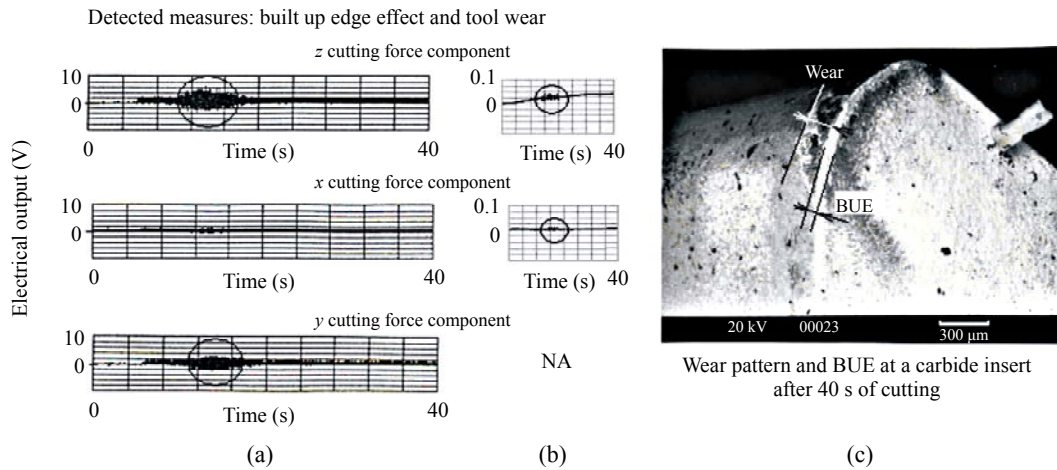
the feed, cut and radial forces. In both cases, the chart records (F_x, F_y, F_z) were obtained in code. The step between individual codes (AA, A1~A99) depended closely on the sensitivity of the measuring range selected for the evaluating technique used. Major errors developed in the system proved to be caused by the inaccuracies due to variations in voltage supply, zero drift, hysteresis and cross sensitivity. However, their value was so small that they could be ignored.

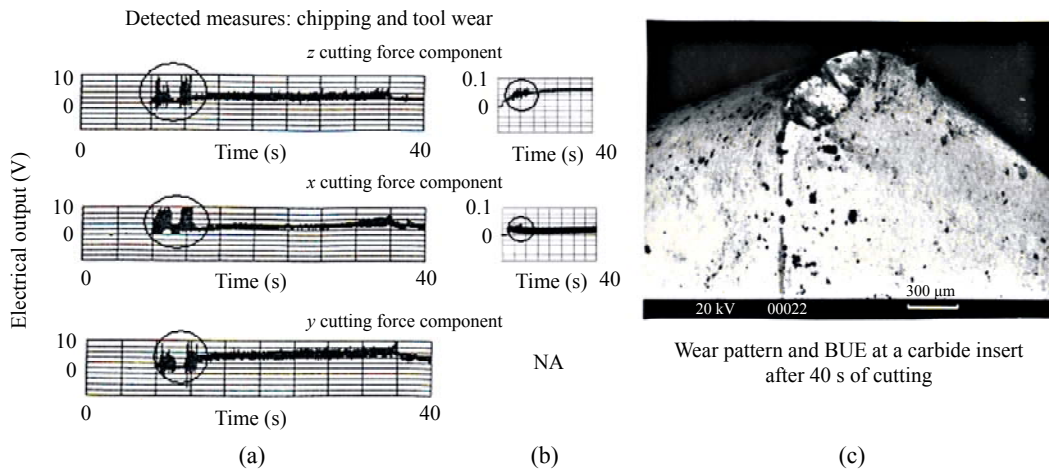**Analysis of problems associated with the dynamic testing of the measuring systems used**

All three systems, described in Section 2, were finally tested in the turning process under normal production conditions. Some examples are shown in the following Figs.5 and 6.

Recorded traces relating to the cutting force components, obtained from the actual machining tests, were compared. The similarity of these records in fact indicated good repeatability of measurements. Variations in the individual charts which developed due to limitations of measuring systems were calculated and examined. It was found that the accuracy of a single two-component dynamometer was markedly limited due to interactive factors from surroundings. The uncontrolled increase in the errors and uncertainties developed as a result of high cross sensitivity between the strain gauges used. From this example, it also became evident that variations in strength and deflection calculations of single two-component metal-cutting dynamometer depended very closely on the gauge position.

Error categories relating to strain measurement reduced the level of recorded strain by approximately 35% due to gauge misalignment, gauge mislocation, and unwanted signals of bending effects. There was also a self-heating effect and thermal shock which were not eliminated completely by strain gauges. By using the Kistler technique it was possible to eliminate most of these errors.

Detected measures: built up edge effect and tool wear

(a)   (b)   (c)

Wear pattern and BUE at a carbide insert
after 40 s of cutting

Fig.5 The dynamic cutting force components recorded by using a Kistler three-component piezoelec-tric dynamometer—Type 9257B (a), and those recorded with a simple two-component machining dynamometer equipped with strain gauges (b), from a hardened and tempered steel bar machined with a carbide insert at a depth of cut of 1 mm, a feed rate of 0.1 mm/rev and a cutting speed of 60 m/min (c). The scale of measurements (0 to 10 V), for piezocrystals, is equal to (0 to 1500 N) for F_x, F_y, F_z cutting force components, while the scale (0 to 0.1 V) for strain gauges is equal to (0 to 350 N) and (0 to 225 N) for F_z and F_x force components, respectively

Detected measures: chipping and tool wear

(a)   (b)   (c)

Wear pattern and BUE at a carbide insert
after 40 s of cutting

Fig.6 The dynamic cutting force components recorded by using a Kistler three-component piezo-electric dynamometer—Type 9257B (a), and those recorded with a simple two-component machining dynamometer equipped with strain gauges (b), from a quenched steel bar machined with a carbide insert at a depth of cut of 0.5 mm, a feed rate of 0.1 mm/rev and a cutting speed of 90 m/min (c). The scale of measurements (0 to 10 V), for piezocrystals, is equal to (0 to 1500 N) for F_x, F_y, F_z cutting force components, while the scale (0 to 0.1 V) for strain gauges is equal to (0 to 350 N) and (0 to 225 N) for F_z and F_x force components, respectively

Classification of error sources in the measuring and evaluating systems used in the metal cutting environment

Table 2 condenses the major error sources and uncertainties which developed in the measurement of the magnitudes and amplitudes of cutting forces.

These errors can be conveniently divided into three main categories relating to the measuring system used, the evaluating technique selected and the experimental conditions adjusted. The increase in the uncertainty level of the testing equipment selected and examined, is shown through effects of the potential

Table 2 Errors sources relating to the three measuring and evaluating systems (A, B, C) tested in the static and dynamic conditions

	Measuring system and its parts		Error sources ε	
			Static tests	Dynamic tests
A	Dynamometer	Strain gauges 125UN	$\varepsilon_1, \varepsilon_2, \varepsilon_4$	$\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4, \varepsilon_{11}$
	Wheatstone bridge	Resistors	$\varepsilon_5, \varepsilon_8$	$\varepsilon_6, \varepsilon_8, \varepsilon_{10}$
	Evaluating technique	IBM computer	*	ε_{14}
	Program	Snap-Master	*	*
	Lathe	HMT	−	ε_{12}
	Calibration device	Arms	$\varepsilon_7, \varepsilon_9$	−
B	Dynamometer	Kistler (9265A1)	*	*
	Evaluating technique	PMD computer	ε_{14}	ε_{15}
	Program	Machine code	ε_{13}	$\varepsilon_{13}, \varepsilon_{14}$
	Lathe	SUI50	−	*
	Calibration device	Bridge	*	−
C	Dynamometer	Kistler (9257B)	*	*
	Evaluating technique	IBM computer	*	*
	Program	Snap-Master	*	*
	Lathe	HMT	−	ε_{12}
	Calibration device	Kistler Manual	−	−

*Insignificant data; ε_1: zero drift; ε_2: voltage supply; ε_3: temperature and thermal zero shift; ε_4: cross sensitivity; ε_5: sensitivity among Wheatstone bridge; ε_6: interfere signal from surroundings; ε_7: toughness of calibration device; ε_8: non-linearity in Wheatstone bridge; ε_9: deviation in the angle of applied calibration force; ε_{10}: differences in response time of the measuring bridge; ε_{11}: small sensitivity to the dynamic variables associated with the cutting forces; ε_{12}: design changes and the reduction in machine-tool flexibility; ε_{13}: limitation in the detectible range; ε_{14}: delay in the realtime measurement due to a number of A/D boards used; ε_{15}: slow speed of a computer used

errors accumulated in the system. As evident from Table 2, the precision in the measurement of dynamic variables depended closely on the accuracy of measurement device and evaluating technique used. Results obtained from this study showed that accurate frequency analysis has to be used to identify and characterise the dynamic variables of machining processes in relation to the experimental set-up.

DISCUSSION

The similarity of the records obtained from the dynamic testing of two-component strain gauge dynamometer indicated good repeatability of measurements. However, the results showed that relatively high variation in the accuracy of horizontal and vertical force components developed due to large effect of cross sensitivity, zero drift, and variations in voltage supply and temperatures. Another difficulty was that differences caused by changes of the sensitivity among the measuring bridges changed the balance points of the circuits. In practice, the measuring bridges were not stable and caused a number of problems.

The static tests applied on the Kistler dynamometer—Model 9265A1 showed that the evaluating system (B) was able to minimise the effect of cross sensitivity between three force components, so the accuracy of the system was limited only by the readability of a code system and adjusting the zero drift. The high resistance of the system, against the interference signals from the surroundings, was secured mainly by a special amplifier mounted at the output of the dynamometer. Repeatability of measurements, over a short interval, within the limit corresponding to the discrimination between force components and long term stability of the system was good. Interaction errors in reading between two calibration charts approximated to 0.2%. A possible difficulty with the evaluating technique, equipped with one A/D board for three force components, was that differences in the elaborating of three signals increased continuously (about 3 μs for each signal) with the time of measurement. In practice, these effects may be a problem when relating to the dynamic control of machining processes by a computer in realtime.

Data relating to the Kistler—Model 9257B measuring and evaluating technique showed that

variations in the linearity of calibration graphs did not exceed ±0.35%. A possible difficulty with this technique was expected because of the transfer of relatively small signal from the dynamometer to the amplifier. However, results showed that when a Kistler measurement system was tested in practical applications the signal carried by a Kistler cable to the charge amplifier was not influenced by the signal interference from the surroundings, so that the information relating to small changes in the tool condition could be obtained and evaluated.

CONCLUSION

The main conclusions to be drawn from this study may be summarised as:

(1) A simple two-component metal machining dynamometer equipped with strain gauges has been shown to be capable of discriminating only between two forces (F_x and F_z). Its flexibility and accuracy was limited because of the radial cutting force component (F_y) which cannot be measured and evaluated. Repeatability over a short interval was within the standard limits required for cutting tests. Interaction errors between two calibration charts for the same cutting conditions did not exceed 1%. However, the long term stability of the system was not good. The possibility of using this simple dynamometer to determine dynamic variables associated with cutting forces was markedly limited because of its low accuracy and sensitivity. In the extreme test conditions cumulative errors increased up to about ±35% due to failure to control some of main errors developed in the system, for example, due to temperature effects on the strain gauges.

(2) The use of three-component piezoelectric dynamometer Kistler equipped with a measuring and evaluating system from the same company made it possible to solve these problems.

(3) Each cutting force dynamometer must be calibrated for any change in the overhang of a cutting tool. It is recommended that this calibration is made in a bridge calibrating system instead of a calibrating system equipped with perpendicular arms.

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