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An overview of data acquisition system for cutting force measuring and optimization in milling

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Abstract

This paper presents an approach, for the systematic design of condition monitoring system for machine tool and machining operations. The research is based on utilising the genetic optimization method for the on-line optimization of the cutting parameters and to design a program for the signal processing and for the detection of fault conditions for milling processes. Cutting parameters and the measured cutting forces are selected in this work as an application of the proposed approach.

Keywords: Optimization; Acquisition; Ball-end milling; Cutting process

1. Introduction

One of the most significant developments in the manufacturing environment is the increasing use of tool and process monitoring systems. Many different sensor types, coupled with signal processing technologies are now available, and many sophisticated signal and information processing techniques have been invented and presented in research papers. However, only a few have found their way to industrial application. The aim of this paper is to present the cutting force measurement system for the ball-end milling. The system is based on LabVIEW software, the data acquisition system and the measuring devices (sensors) for the cutting force measuring. The system collects the variables of the cutting process by means of sensors and makes transformation of those data into numerical values. Generally used measuring devices for cutting force measuring are piezoelectric dynamometer. Delivered signals are distorted due to their self-dynamic behaviour. Their dynamic characteristics are identified under normal machining operation. The proposed method is based on the interrupted cutting of a specially designed workpiece that provides a strong broadband excitation. The three components of the exciting force and the acceleration of the gravity centre of the dynamometer cover plate are measured simultaneously. The measured values are delivered to the computer program through the data acquisition system.

The data obtained from the acquisition system, are a basis for the optimization of the machining process—cutting parameters.

2. Cutting force measuring

The present world market competition has attracted the manufacturer's attention on automation of manufacturing systems for condition monitoring of machine tools and processes for the improving of the quality of products, eliminating inspection, and manufacturing productivity [1].

Successful condition monitoring system depends, to a vast extent, on the ability of the system to identify any abnormalities and respond, on-line, with an appropriate action. A condition monitoring system, as shown in Fig. 1 consists of sensors, signal processing stages, and decision-making systems to interpret the sensory information and to decide on the essential corrective action.

The ability of a condition monitoring system relies on two basic elements: first, the number and type of sensors used and second, the associated signal processing and simplification methods utilised to extract the necessary important

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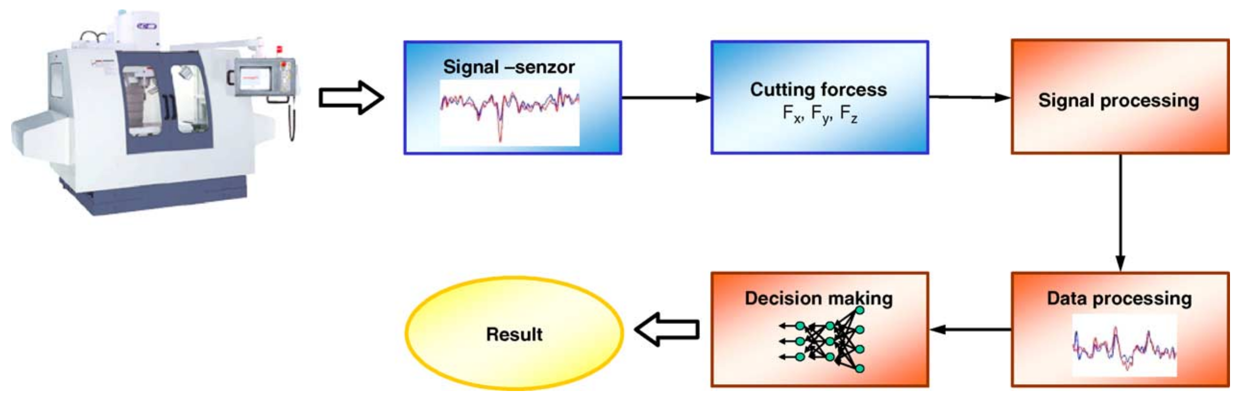

Fig. 1. Monitoring system.

information from machining signals. The first element involves expensive hardware, which influences the cost of the system, whereas the second element affects the efficiency and the speed of the system. The main issue here is to design a condition monitoring system with high efficiency, short development time, and with a reduced number of sensors. This basically includes the selection of sensors and associated signal processing methods which provide the minimum classification error of process faults.

Several condition monitoring strategies have been proposed and evaluated during the last 20 years [2–5]. However, until now there is no such a universal systematic and general approach for condition monitoring design and evaluation, and the need is still there for a systematic and general approach in designing such systems, particularly in a complex process such as end milling. The condition monitoring research in general is based on evaluation of process monitoring methods and pattern recognition techniques to identify specific conditions of a process or to identify abnormalities from normal conditions. However, such techniques are based, most of the time, on trail and error basis where machining signals are obtained and processed to look for a specific feature which indicates the condition on focus.

Different attempts have been found in literature to aid designing of monitoring systems [6,7]. The mentioned references describe a methodology of designing a monitoring system by choosing the best configuration of sensors and signal processing methods using scatter matrix method and feed forward back propagation neural networks. The problem with such techniques that they are time consuming since they need long repetitive iterations to reach the required minimum error and in some cases the iterations might be divergent. Such techniques also require full factorial experimental work in order to evaluate the capability of the system. For a complex process, such as end milling, there is still a need for a new method to design the experimental work in order to evaluate the features particularly since the machining signals change significantly according to the machining parameters.

The new developed approach of automating the design methodology of condition monitoring systems using genetic algorithms and features extraction of sensory signals to select the most appropriate sensor and its associated signal processing methods in order to reduce cost and development time. For each sensory signal obtained, an attempt is made to extract sensitive sensory characteristic features that can be related to cutter conditions using wide range of signal analysis and simplification techniques.

The purpose of this paper is to presents the system for the cutting force measuring in milling. The force generated during machining process is an important parameter, which reflects the machining conditions. The most frequent approach taken to milling process monitoring is to attach sensors to the machine and then monitor the signals obtained from these sensors.

With a cutting force acquisition system, the cutting process can be monitored easily. The data acquisition system frequently commences with experiments using a table force dynamometer which quantifies the actual force exerted on the milling tool during the cutting process.

Using different cutting tools and different cutting conditions, the tool which generates the smaller force is expected to be the more effective in cutting. With this system, different tools of different mechanical properties can be tried out on the same workpiece, enabling a suitable cutting tool to be chosen. The objectives of this paper are to design a system for the cutting forces measuring in milling.

The results show that the methodology outlined in this paper can be used to reduce the cost and complexity of the condition monitoring system and the number of sensors required for fault identification of milling cutters without compromising the system's ability to detect cutter faults. The approach, however, can be used for other operations and faults with minimal modification.

3. Tool condition monitoring sensors

The sensor is a key element of any tool/process monitoring system. Although numerous different sensor types have been invented and applied in laboratories, only a few are now in commercial use. A different sensors applied by different suppliers are presented in Fig. 2.

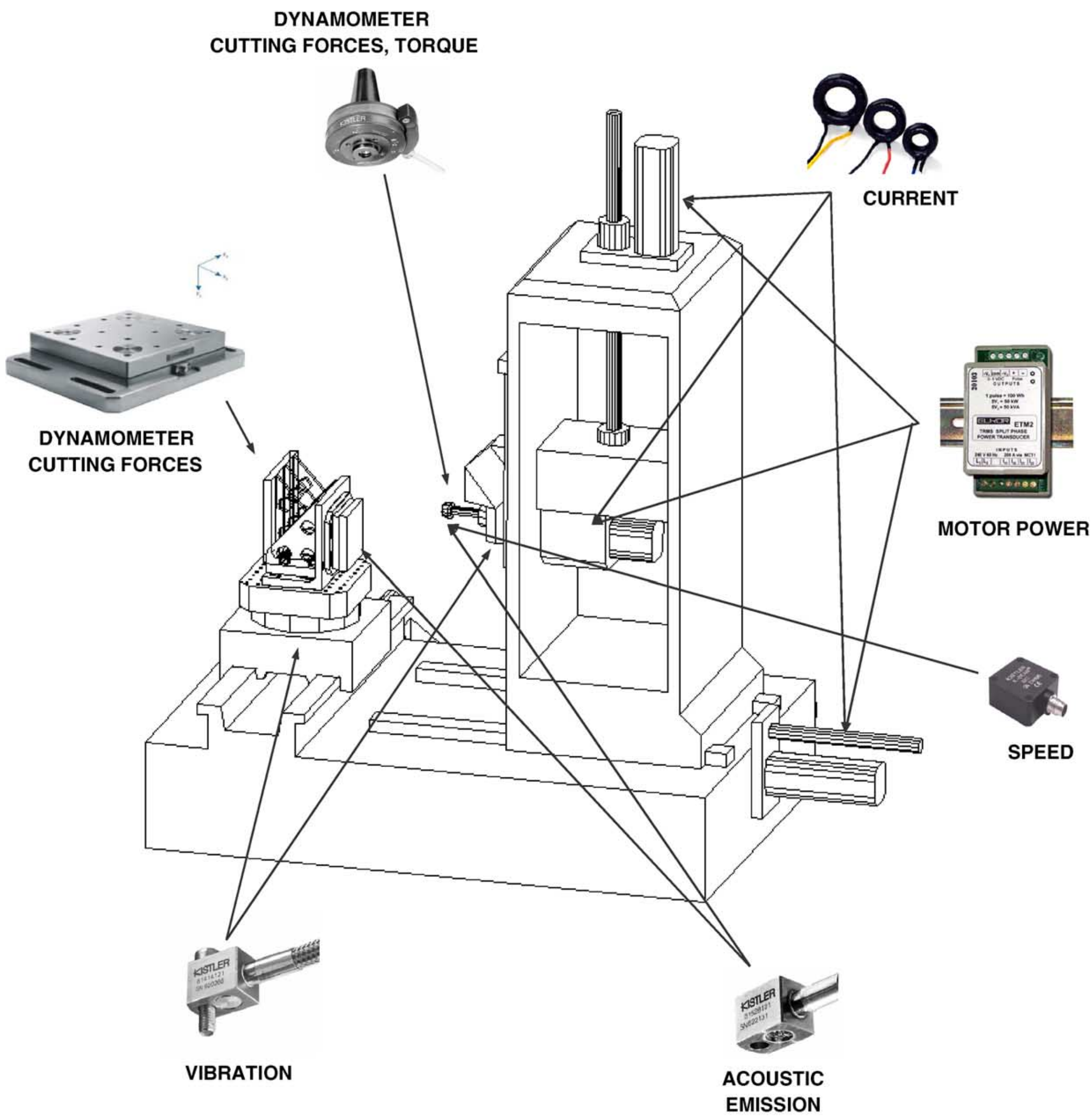

Fig. 2. Sensors for monitoring systems.

A wide variety of sensors have been utilised to monitor most machine tool related failure modes. These ranges from specific problems such as collision monitoring and thermal drift compensation, to fault identification within machine tool functions such as the hydraulic and lubrication systems. The monitoring of cutting tools has included approaches to tool identification, tool wear monitoring, tool breakage and tool life. Most practical approaches to cutting tool condition monitoring have been developed utilising indirect measurements of tool performance rather than by directly measuring tool properties. Within most environments indirect signal measurement is easier to achieve than direct measurements. Significant continuity exists between the sensors used for tool monitoring during a variety of machining operations. Fig. 2 identifies the approaches most commonly used sensors.

It is assumed that cutting force is approximately proportional to the cross sectional area of the metal removed and that during normal operation the volume of metal removed during one tool rotation is constant. Monitoring cutting force can then provide an indication of the amount of material removed. This leads to the assumption that the metal removed by a broken tooth is less than normal and hence the cutting force declines. It then follows that the sharp tooth following a broken tooth removes a larger volume of material than normal and that the cutting force reflects this extra work.

The invalidation of any one of these assumptions would cause a breakdown in the methodologies developed. Work has shown that these assumptions can be justified, and that data analysis based upon them can lead to accurate tool monitoring. Most of these techniques have normally placed additional sensors on the machine.

4. Force sensors

Force sensors are required for a basic understanding of the response of a system. For example, cutting forces generated by a machining process can be monitored to detect a tool failure or to diagnose the causes of this failure in controlling the process parameters, and in evaluating the quality of the surface produced. Force sensors are used to monitor impact forces in the manufacturing process. Robotic handling and assembly tasks are controlled by detecting the forces generated at the end effector. Direct measurement of forces is useful in controlling many mechanical systems.

Some types of force sensors are based on measuring a deflection caused by the force. Relatively high deflections (typically, several micrometers) would be necessary for this technique to be feasible. The excellent elastic properties of helical springs make it possible to apply them successfully as force sensors that transform the load to be measured into a deflection. The relation between force and deflection in the elastic region is demonstrated by Hooke's law. Force sensors that employ strain gage elements or piezoelectric (quartz) crystals with built-in microelectronics are common. Both impulsive forces and slowly varying forces can be monitored using these sensors.

Of the available force measuring techniques, a general subgroup can be defined as that of load cells. Load cells are comprised generally of a rigid outer structure, some medium that is used for measuring the applied force, and the measuring gage. Load cells are used for sensing large, static or slowly varying forces with little deflection and are a relatively accurate means of sensing forces. Typical accuracies are of the order of 0.1% of the full-scale readings. Various strategies can be employed for measuring forces that are strongly dependent on the design of the load cell. The hydraulic load cell employs a very stiff outer structure with an internal cavity filled with a fluid. Application of a load increases the oil pressure, which can be read off an accurate gage.

Other sensing techniques can be utilized to monitor forces, such as piezoelectric transducers for quicker response of varying loads, pneumatic methods, strain gages, etc. The proper sensing technique needs special consideration based on the conditions required for monitoring.

For force measurements, the direct piezoelectric effect is utilized. The direct longitudinal effect measures compressive force; the direct shear effect measures shear force in one direction. For example, if a disk of crystalline quartz (SiO_2) cut normally to the crystallographic *x*-axis is loaded by a compression force, it will yield an electric charge, nominally 2.26 pC/N. If a disk of crystalline quartz is cut normally to the crystallographic *y*-axis, it will yield an electric charge (4.52 pC/N) if loaded by a shear force in one specific direction. Forces applied in the other directions will not generate any output.

A charge amplifier is used to convert the charge yielded by a quartz crystal element into a proportional voltage. The range of a charge amplifier with respect to its conversion factor is determined by a feedback capacitor. Adjustment to mechanical units is obtained by additional operational amplifiers with variable gain.

5. System for the cutting force measurement

The system for the cutting force measurement presents the data acquisition system, LabVIEW software, and the results measured cutting forces. The data acquisition system used in this experimental model consists of dynamometer, fixture module, hardware and software module as shown in Fig. 3.

A significant amount of research has been based around the measurement of cutting forces [1–6]. Force measurements are commonly taken using a table mounted dynamometer during machining. These dynamometers measure the cutting force in three mutually perpendicular directions notationally the *X*-, *Y*- and *Z*-axis. The dynamometer is clamped between the workpiece and the table or pallet.

The dynamometer system is composed of a dynamometer (Kister Model 9255), a multi-channel charge amplifier (Kister Model 5001) and their connecting cable. When the tool is cutting the workpiece, the force will be applied to the dynamometer through the tool. The piezoelectric quartz in the dynamometer will be strained and an electric charge will be generated. The electric charge is then transmitted to the multi-channel charge amplifier through the connecting cable. The charge is then amplified using the multi-channel charge amplifier. In the multi-channel charge amplifier, different parameters can be adjusted so that the required resolution can be achieved.

Essentially, at the output of the amplifier, the voltage will correspond to the force depending on the parameters set in the charge amplifier. The interface hardware module consists of a connecting plan block, analogue signal conditioning modules and a 16 channel A/D interface board (PC-MIO-16E-4). In the A/D board, the analogue signal will be transformed into a digital signal so that the LabVIEW software is able to read and receive the data. The voltages will then be converted into forces in *X*-, *Y*- and *Z*-directions using the LabVIEW program. The LabVIEW data acquisition module is based on a PC computer, and is a general-purpose programming system with an extensive library of functions and subroutines for any programming task. It also contains an application specific library for data acquisition, serial instrument control, data analysis, data presentation, and data storage. A graphical

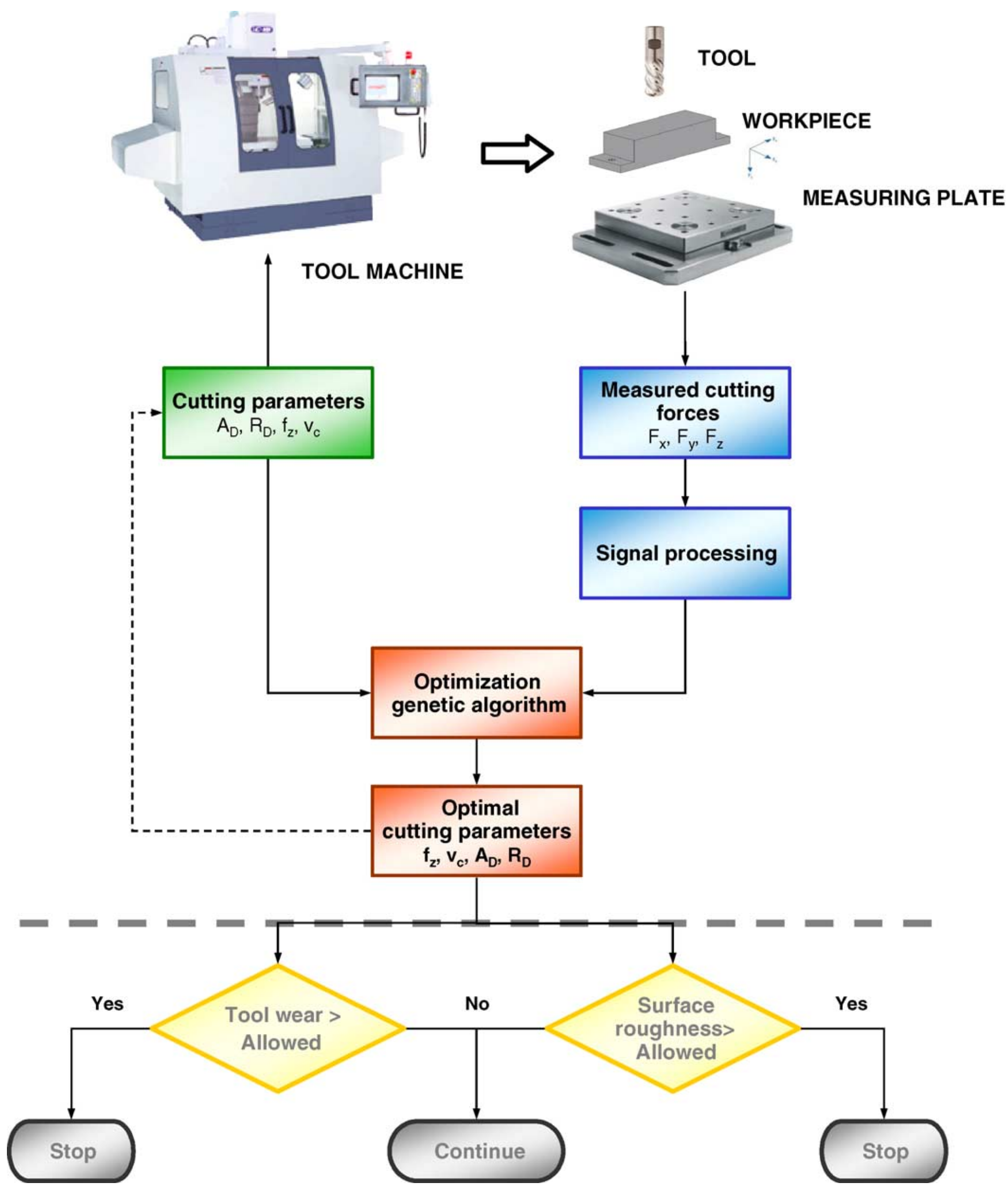

Fig. 3. System for the cutting force measurement.

representation of the data acquisition program is shown in Fig. 4.

6. Signal analysis

The kind of signal analysis methods used is of some importance. Sometimes it looks as if some researchers think that if the measured signal is acceptable then it would be possible with a clever diagnostic tool to solve everything. Unfortunately this is not the case. The diagnosis always needs to be based on reliable and meaningful information and this is where signal analysis can help by providing effective features as a basis for diagnosis.

The role of signal analysis could be described as a tool which tries to pick up the meaningful information out of the mass of information. In many cases the dilemma is that the more sophisticated methods need a lot of raw signals and it takes time to collect this raw material and it also takes time to perform the calculations. Consequently, many of the most sophisticated methods are not suitable, e.g. for tool breakage monitoring. In addition, the results with a sophisticated analysis function are influenced by the cutting process, i.e. workpiece material, type of tool, feeding and cutting speed which makes the diagnosis more demanding. On the other hand, very simplistic methods are fast to use and often not that sensitive to changes in cutting conditions.

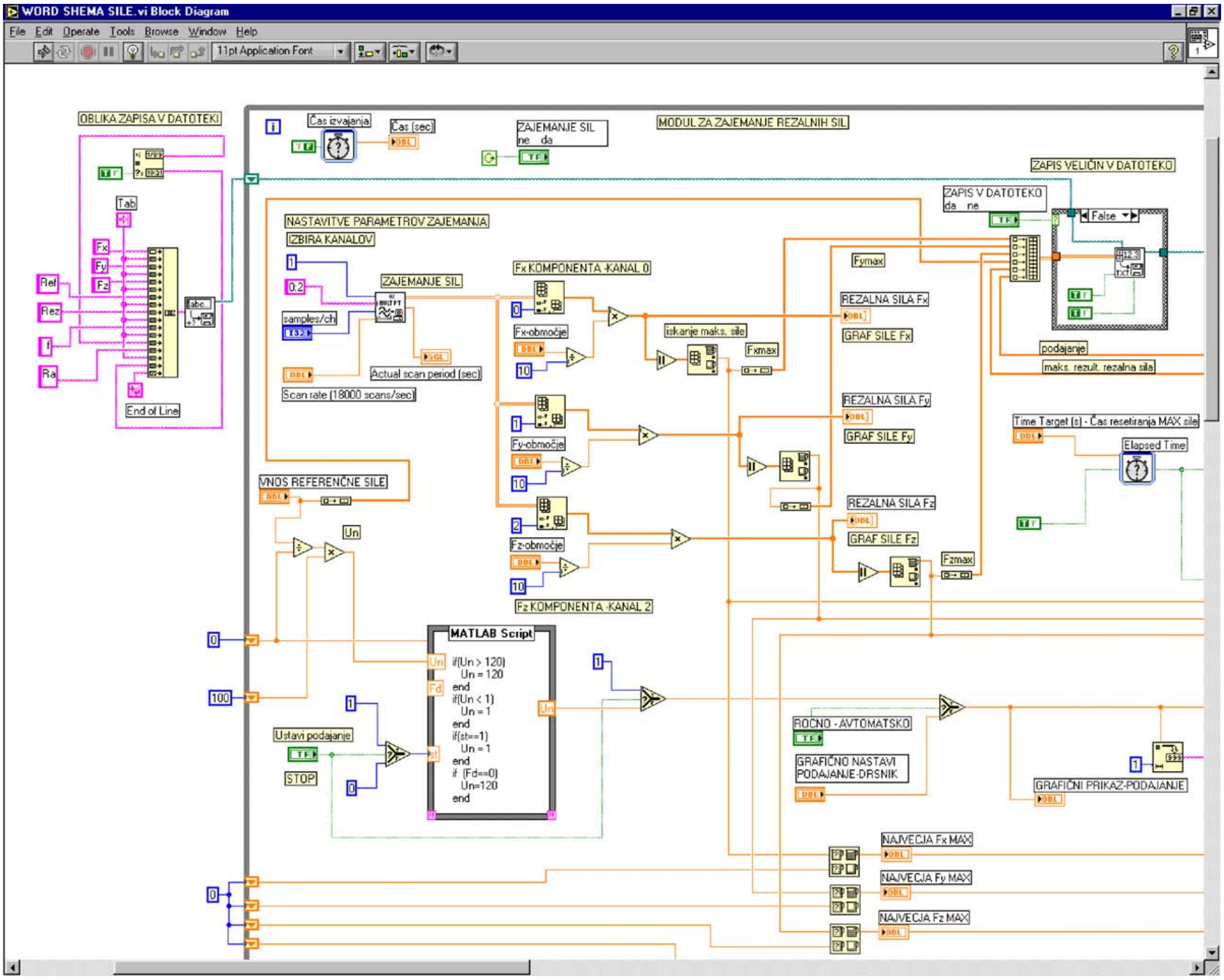

Fig. 4. Graphical representation of the data acquisition program.

7. Cutting forces in ball-end milling

The ball-end milling is used for machining the freely shaped surfaces such as dies, moulds, turbines, propellers, and for the aircraft structural elements [8].

The existing knowledge about the cutting forces gives support in planning of the process, in selecting of suitable cutting conditions for reduction of excessive wear, deformation and breakage of the tool.

7.1. Analysis of results in case of ball-end milling

An extensive number of experiments have been performed on a milling machine for testing the system for the cutting force measurement in milling.

The instantaneous cutting force signals in three orthogonal directions were measured by a table mounted piezoelectric dynamometer (Kister Model 9255). These signals were amplified (Kistler Model 5001), digitized (PC-MIO-16E-4) and stored in computer. The measured data was processed with the computer program made by LabWIEV. The experiments were run on the NC milling machine (type HELLER BEA1) and performed on material Ck 45 and Ck 45 (XM) with improved machining properties. The ball-end milling cutter with interchangeable cutting inserts of type R216-16B20-040 with two cutting edges, of 16 mm diameter and 10° helix angle was used for machining of the material. The cutting inserts R216–1603 M-M with 12° rake angle were selected. The cutting insert material is P30–50 coated with TiC/TiN, designated GC 4040 in P10–P20 coated with TiC/TiN, designated GC 1025. The coolant RENUS FFM was used for cooling.

The tests were performed in different cutting modes, feed rates, and cutting speeds. The measured cutting forces are presented in Fig. 5.

The experimental cutting parameters and cutting forces are summarized in Table 1, as well as the cutting forces predicted by the genetic program.

7.2. Future developments

The continuing development of efficient manufacturing systems requires a greater degree of process optimisation.

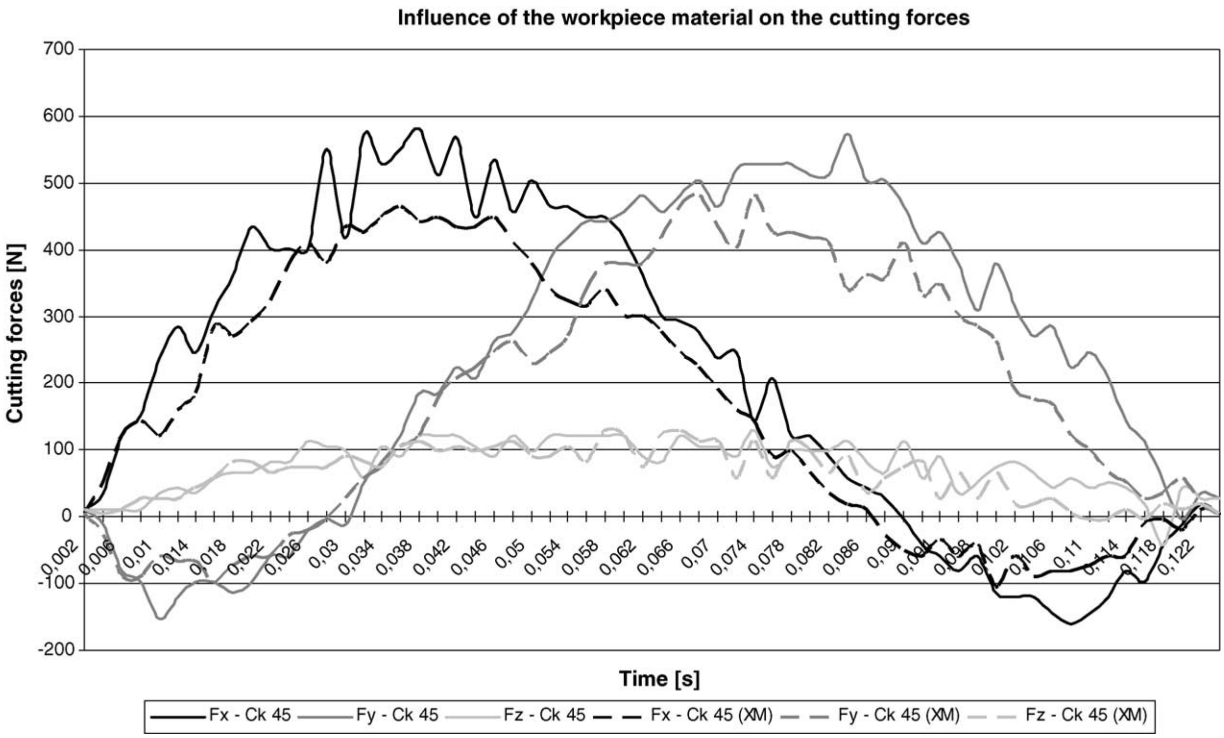

Fig. 5. Comparison of the cutting forces between material Ck 45 and material Ck 45 (XM). Ball-end milling tool R216-16B20-040, cutting insert R216-1603 M-M, cutting width $R_D = 2$ mm, cutting depth $A_D = 2$ mm, feeding $f_z = 0.05$ mm/tooth and cutting speed $V_c = 50$ m/min.

Tool wear and tool breakage problems constantly disrupt these processes. On-line tool condition monitoring strategies utilising multi-signal inputs to monitor and diagnose tool condition are being researched and should be encouraged.

The use of artificial intelligence, in particular neural networks, seems to be the way forward in the handling of both a multi-signal and a multi-model strategy. The earlier research into cutting process monitoring is still valid but now many of the methods can be combined into one comprehensive strategy. To do so it is important that established researchers who are familiar with the nature of the cutting process and those who operate within the area of intelligent systems engineering come together and meet with industrial machine tool users

Table 1
The comparison of the experimental and optimized cutting forces in ball-end milling

No.	R_D (mm)	A_D (mm)	f_{zb} (mm/tooth)	V_c (min^{-1})	Experiment			Optimization		
					F_X (N)	F_Y (N)	F_Z (N)	F_X (N)	F_Y (N)	F_Z (N)
1	8	8	0.025	500	141.32	570.99	333.18	141.64	590.62	348.84
2	8	8	0.2	500	97.66	1518.29	816.21	87.43	1568.90	856.95
3	8	8	0.1	370	63.70	1087.73	589.54	56.16	1123.95	618.98
4	8	8	0.2	250	124.29	1740.66	901.76	112.79	1798.84	946.96
5	8	4	0.2	500	−128.49	553.41	162.32	−138.31	570.44	171.38
6	8	4	0.025	250	−21.33	328.34	204.71	−24.61	338.69	213.83
7	8	2	0.025	500	10.66	15.34	−0.26	10.85	15.94	−0.27
8	8	2	0.1	370	−116.57	285.94	216.41	−122.60	293.96	225.46
9	8	2	0.025	250	−39.80	154.44	125.10	−42.24	158.96	130.18
10	8	2	0.2	250	−228.92	407.43	288.47	−239.72	418.30	300.94
11	4	8	0.025	500	8.68	451.39	301.22	5.33	463.73	311.42
12	4	8	0.2	500	−325.53	1056.86	545.13	−342.82	1086.57	563.90
13	4	8	0.2	250	−374.13	1079.65	547.31	−392.94	1110.08	566.19
14	4	4	0.2	500	−89.63	175.79	57.44	−94.66	181.81	61.28
15	4	4	0.1	370	−82.04	129.57	60.88	−86.26	133.81	64.56
16	4	2	0.025	500	4.17	8.07	0.43	4.25	8.41	0.47
17	4	2	0.2	500	−9.38	26.55	12.50	−9.94	27.46	13.15
18	4	2	0.1	370	−5.87	23.43	13.67	−6.25	24.24	14.34

Ball-end milling cutter R216-16B20-040, cutting insert R216-1603 M-M GC 4040, material Ck 45.

and manufacturers to develop a strategy for the advancement in this area.

Overall there seems to be the possibility that the next generation of monitoring tools can be engineered to fit into the control strategies used in the design of advanced machine tools. As such, truly intelligent monitoring systems will be capable of working with the machine to continuously optimise the cutting process. In this area the most promising approaches would seem to be those which will utilise, and indeed share, the signals used to control the elements of the machine tool as the basis of process monitoring. Work in this field is continuing to provide more reliable, robust and responsive tool condition monitoring systems which are needed in modern manufacturing systems. They are much needed, and must be developed if truly automated manufacturing is to develop further.

8. Conclusion

The increase in awareness regarding the need to optimise manufacturing process efficiency has led to a great deal of research aimed at machine tool condition monitoring. This paper also considers the application of condition monitoring techniques to the detection of cutting tool wear and breakage during the milling process. Established approaches to the problem are considered and their application to the next generation of monitoring systems is discussed. A many approaches are identified as being key to the industrial application of operational tool monitoring systems.

Multiple sensor systems, which use a wide range of sensors with an increasing level of intelligence, are seen as providing long-term benefits, particularly in the field of tool wear monitoring. Such systems are being developed by a number of researchers in this area. The second approach integrates the control signals used by the machine controller into a process monitoring system which is capable of detecting tool breakage.

Initial findings mainly under laboratory conditions; indicate that these approaches can be of major benefit. It is finally argued that a combination of these approaches will ultimately lead to robust systems which can operate in an industrial environment.

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