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Full Length Research Paper

High capacity three-component dynamometer design, construction and its calibration

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In this study, a three-component dynamometer design, construction and its calibration were carried out. The dynamometer system consisted of three 20 kN high capacity single point load cells, three isolated strain gauge input modules, a terminal board, an analogue-to-digital card and a software for recording and analyzing the data. The load cells were mounted in three different planes vertical to each other. These load cells were loaded up to 10 kN in various steps from unloaded condition. The output strains obtained as the results of the loads were recorded and these files were introduced to the software. The system records four data each of which consists of the average of 256 data block per second. By using the dynamometer, the forces occurring during clamping of workpiece and during cutting were monitored on the PC screen and their magnitudes were accurately transferred to the PC. Besides, the dynamometer was used on larger sized workpieces successfully.

Key words: Dynamometer, force measurement, calibration.

INTRODUCTION

Machining comprises of the principal operations in the manufacturing of mechanical parts. The most common machining processes are milling, turning, drilling and grinding. In these processes, the measurement of the cutting forces has important and extensive applications within industry and research alike. The estimation of cutting forces allows: supervising tool wear evolution; to predict machined workpiece surface quality; to establish material machinability data; to optimize cutting parameters and study phenomena such as chip formation or apparition of vibrations (Castro et al., 2006).

Knowledge of stresses is important in metal cutting applications as they are used in the design of machine tools, cutting tools and fixtures. Therefore, a considerable amount of investigations has been directed towards the prediction and measurement of cutting forces. The cutting forces generated during metal cutting have a direct influence on the generation of heat, and thus tool wear, quality of machined surface and accuracy of the workpiece. Due to the complex tool configurations/cutting conditions of metal cutting operations and some unknown factors and stresses, theoretical cutting force calculations failed to produce accurate results and therefore, experimental measurement of the cutting forces became unavoidable. For this purpose many dynamometers have been developed (Seker et al., 2002).

Independent of the machining operation type, methods for cutting force measurements can be divided into two general categories (Castro et al., 2006). In measurement systems of the first group, measurement of force was carried out through the analysis of current and voltage signals taken from the engine to which control system or the cutter is attached. As for the ones in the second group, measurement of force was made via converters (strain gages, load cells, dynamometers) placed on work piece or cutter.

In the first group, Kim and Kim (1996) presented an adaptive cutting force controller for the milling process, which can be attached to most commercial CNC machining centers in a practical way. The cutting forces of *x*, *y* and *z* axes are measured indirectly from the use of currents drawn by a.c. feed-drive servo motors. The

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pulsating milling forces can be measured indirectly within the bandwidth of the current feedback control loop of the feed-drive system. Kim et al. (1999) presented the indirect cutting force measurement method in contour NC milling processes using current signals of servo motors. A Kalman filter disturbance observer and an artificial neural network (ANN) system are suggested. The Kalman filter disturbance observer is implemented using the dynamic model of the feed drive servo system, and each of the external load torques to the *x* and *y*-axis servo motors of a horizontal machining centre is estimated. Jeong and Cho (2002) examined and analysed the unusual current behaviour between 45 and 60 Hz. The bandwidth of the current sensor was expanded to 130 Hz using an empirical approach. Stein and Wang (1990), Lee et al. (1995), Altintas (1992) examined the process of estimating the cutting force from AC servomotor and feed motor using the motor current to detect tool breakage.

In the secondary group, strain gauges are widely used in the tool holder or workpiece supports. Force signals are captured and processed using a computer through designed strain-gauge amplifiers and analogue-to-digital converter ADC. Oraby and Hayhurst (1990) propose a compact three-component tool-shank dynamometer. It is based on a design in which the load bearing section has its stiffness reduced by two holes symmetrically positioned about the centre-line, and connected by a narrow slit. Korkut designed and constructed a strain gauge based dynamometer (Korkut, 2003). The cutting force signals were captured and processed using a personal computer through operational amplifiers and analogue-to-digital converter. Yaldiz and Unsacar (2006), Yaldiz et al. (2007) designed and constructed a dynamometer that can measure static and dynamic cutting forces by using strain gauge and piezo-electric accelerometer. The orientation of octagonal rings and strain gauge locations were determined in order to maximise sensitivity and to minimise cross-sensitivity. The force and torque signals were captured and processed using proper data acquisition system. Karabay carried out the analysis of octagonal ring type transducers by considering some basic elastic theory of thin circular ring. Using those transducers, a drilling dynamometer was designed and constructed to measure drill cutting forces: thrust and torque. In the dynamometer, strain gagues mounting places were indicated clearly on the transducers by appreciating characteristics of the strains due to drill forces (Karabay, 2007). Santochi and Dini (1997) described the development of cutting tools using strain gages for the measurement of forces in turning operations. The output signal of the measurement bridge is amplified and sent to an external data acquisition system by infra-red transmission.

The others in the secondary group used load cells and dynamometer with data acquisition system for measuring the forces. Kang et al. (2005) suggested a cutting force measuring system composed of two piezo load cells placed between the moving table bracket and the nut flange of the ball screw in milling. Şeker et al. (2002), Günay et al. (2004) designed and produced a dynamometer for measuring the forces. Their experimental set-up comprised bending beam type load cells, a data acquisition system consisting of a signal conditioning module, an analogue-to-digital converter card, a personal computer and data acquisition software.

Hameed et al. (2004) presents a methodology by which the dynamometer can be replaced effectively by six instrumented locators with uniaxial piezo-electric force sensors in a fixturing setup.

The system was developed using the output from six uniaxial force sensors, which were positioned around the workpiece to suit the configuration of the workpiece. Chen and Chen (1999) developed an on-line and in-process based monitoring system to detect tool breakage via an accelerometer and successfully evaluated this system in an end milling operation. Toh (2004) apply the variance analysis using static and dynamic cutting forces in up milling and down milling. Cutting force measurements were carried out using a Kistler three component piezoelectric platform dynamometer type 9257A. This has a resonant frequency of 2.3 kHz in the *x*- and *y*-axes and 3.5 kHz in the *z*-axis. The dynamometer was connected to a series of charge amplifier Kistler type 5011A which, in turn, was connected to a four channel Gould 6000 series oscilloscope with a maximum sampling rate of 200 M samples.

Baro et al. (2005), Patel and Joshi (2006) used dynamometer platforms to measure cutting forces. The experimental set-up consisted of a Kistler three-component force measurement dynamometer platform, Kistler charge amplifier, a multi-channel force data acquisition and data storage system.

The individual analog signals were first amplified and conditioned by charge amplifier. After amplification and conditioning, the output signals were applied to a multiplexer. Further, they were converted into digital signals by the A/D converter sequentially. Isik (2007) also developed a system, where the cutting force data used in the analyses were gathered by a tool breakage detection system that detects the variations of the cutting forces measured by a three-dimensional force dynamometer. The experimental set up consists of a dynamometer, a pre-amplifier, an A/D converter, and a personal computer. The cutting force signals are sampled simultaneously in the range of 1–1000 Hz and output voltage is in 0–10 V range. Maximum 16 different values can be input into the software simultaneously.

This study aims at developing a three-component dynamometer design and its construction and calibration. Three strain gauge load cells (Tedea-Huntleigh, Model 1320) were mounted in three different planes perpendicular to each other. These load cells were loaded up to 10 kN in various steps from unloaded condition. The strain data obtained from these loads were recorded as

Figure 1. Clamping of the workpiece to the system.

a separate file and introduced to DasyLab software where necessary. The system records four data each of which consists of the average of 256 data block per second. The data obtained from the load cells were transferred to the PC via three isolated strain gauge input modules (Advantech-Adam 3016), a terminal board (Advantech-PCLD-8710), a data acquisition card (Advantech-PCI 1710 HG) and a software (DasyLab 7.0) for recording and analyzing the data.

METHODOLOGY

Dynamometer design

Three analogue load cells were used in this study to measure the forces in X, Y and Z directions independently. The load cells were strain gauge based and had a measuring capacity of 20 kN and measuring area of 1200 mm x 1200 mm. By effecting a connection between the dynamometer and the computer, the clamping and cutting forces acting on the load cells were transferred to the computer simultaneously. The load cells were mounted in there different planes (X, Y, Z) perpendicular to each other. By mounting the workpieces on these load cells, force measurements were carried out. Clamping of the workpiece can be effected in one point at three planes in order to constraint six degrees of freedom of the workpiece (Figure 1).

Table 1 shows the technical specification of the high capacity single point load cell while Figure 2 shows the load cells and wiring schematic diagram.

The displacements of the load cells on which the workpiece is mounted due to the forces generated during clamping and cutting are measured. The displacements of the load cells create electrical voltage and this electrical voltage is transferred to the PC through voltage amplifier and data acquisition card.

The experimental system is shown schematically in Figure 3. As can be seen from Figure 3, one of the load cells is mounted to the machine tool table while the other two are mounted at two different planes perpendicular to the table. The load cells were mounted parallel to the planes. The workpieces are also mounted on the load cells and machining is then performed.

Since the analogue signals received from the load cells were low, the amplifiers were needed. Three amplifiers (Advantech-Adam 3016) were used to amplify analogue signals received from three channels; and supply voltage, input/output signals and deviation values for the desired measurement range were adjusted. The analogue input of the load cell which constituted the base of the system was force (N) while the analogue output was strain (V).

Channel number order adjustment of the signals whose strain levels were regulated using the amplifier was provided using a PCLD-8710 threaded terminal board and the signals were sent to analogue to digital converter card. In order to facilitate reading and analysing the signals obtained from the load cell on the PC, a multi functional analogue to digital I/O card PCI 1710 HG was used.

Analogue (A)-digital (D) conversion, digital-analogue conversion, digital input, digital output and counting are some of the measuring and control functions of this card. Programmable sampling number of the card is 30 MHz and working temperature range is between 0 and 50°C.

DasyLab Rel. 7.0 software was used for data analysis. The data

Table 1. Technical specifications of the load cell.

Parameter		Value		Unıt
Rated capacity-R.C. (Emax)		2000		kg
NTEP/OIML Accuracy class	NTEP	Non-Approved	C3	
Maximum no. of intervals (n)	3000 single	1000	3000*	
Y = Emax/Vmin	1000	3333	10000	Maximum available
Rated output-R.O.		2.0		mV/V
Rated output tolerance		0.2		±mV/V
Zero balance		0.2		+mV/V
Zero Return, 30 min.	0.0330	0.0300	0.0170	±% of applied load
Total Error	0.0200	0.0500	0.0200	±% of rated output
Temperature effect on zero	0.0040	0.0100	0.0023	±% of rated output/°C
Temperature effect on output	0.0010	0.0030	0.0010	±% of applied load/°C
Eccentric loading error	0.0033	0.0025	0.0017	±% of rated load/cm
Temperature range, compensated		-10 to +40		°C
Temperature range, safe		-30 to +70		°C
Maximum safe central overload		150		% of R.C.
Ultimate central overload		300		% of R.C.
Excitation, recommended		10		Vdc or Vac rms
Excitation, maximum		15		Vdc or Vac rms
Input impedance		415±15		Ohms
Output impedance		350±3		Ohms
Insulation resistance		>2000		Mega-Ohms
Cable length		5		m
Cable type		6wire, braided, Polyurethane, dual floating screen		Standard
Construction		Plated (Anodized) aluminum		
Environmental protection		IP66		
Recommended torque		165.0		N*m

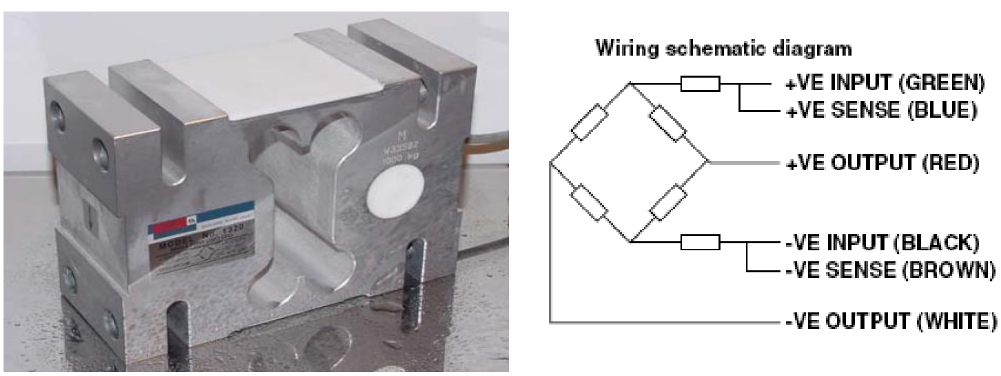

Figure 2. The load cell and its wiring schematic diagram.

reading and recording circuit in this software is given in Figure 4. The icons necessary for constructing the circuit were selected from menu and placed on the screen and lines are formed between these icons. The circuit was designed in a way that the data acquisition from the three channels is carried out simultaneously.

The forces in three directions, resultant force, force curves and test duration during clamping and cutting can be monitored instantly on the PC with the use of the created circuit (Figure 5).

The system records four data each of which consists of the average of 256 data block per second during the tests. So, a total of 4 x 256 data is processed per second. The number of data obtained from the system can be changed.

Calibration of the dynamometer

In the calibration of the dynamometer system, the load cells mounted to the system were loaded up to 10 kN in various steps

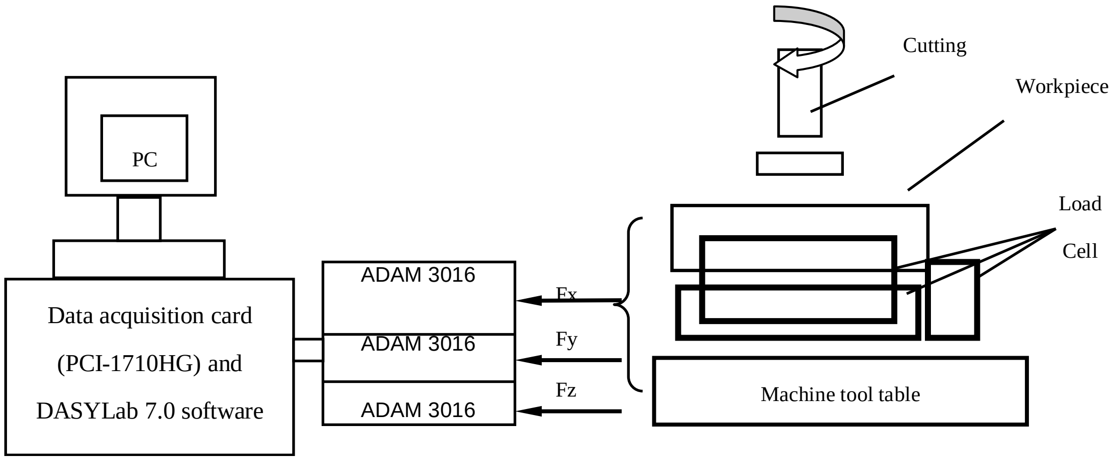

Figure 3. Schematic representation of the experimental set-up.

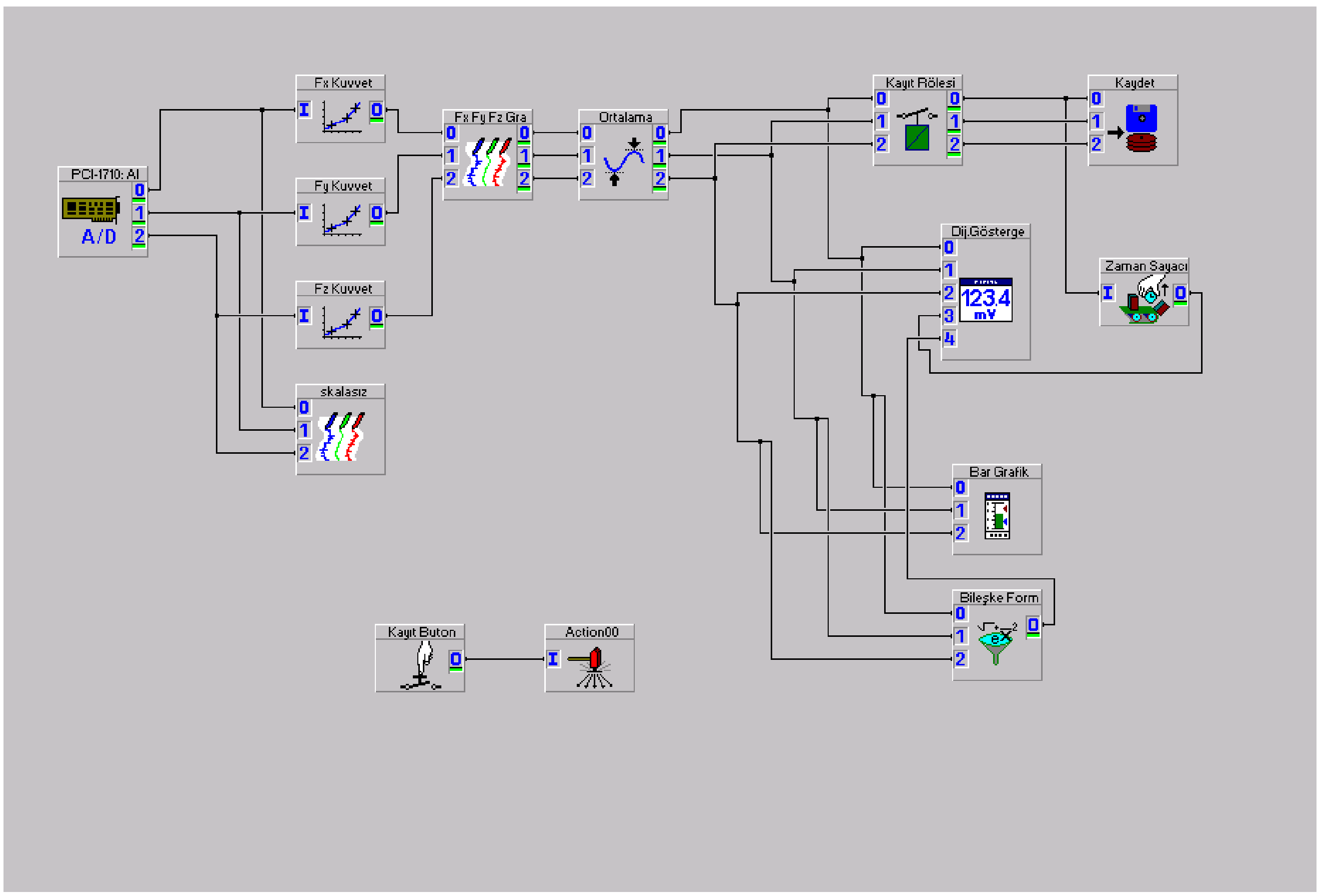

Figure 4. Experimental data reading and recording circuit.

from unloaded condition. The strain data which was obtained from the load cells and which was corresponding to the applied loads was recorded through the data acquisition system as a separate file for each load cell (Figure 6).

The calibration data was obtained by averaging the results of three loading and unloading. Figures 7, 8 and 9 give the calibration curves and their first order equations and regression coefficients.

The linear calibration curves of the load cells indicate soundness and accuracy of the force data obtained from the system.

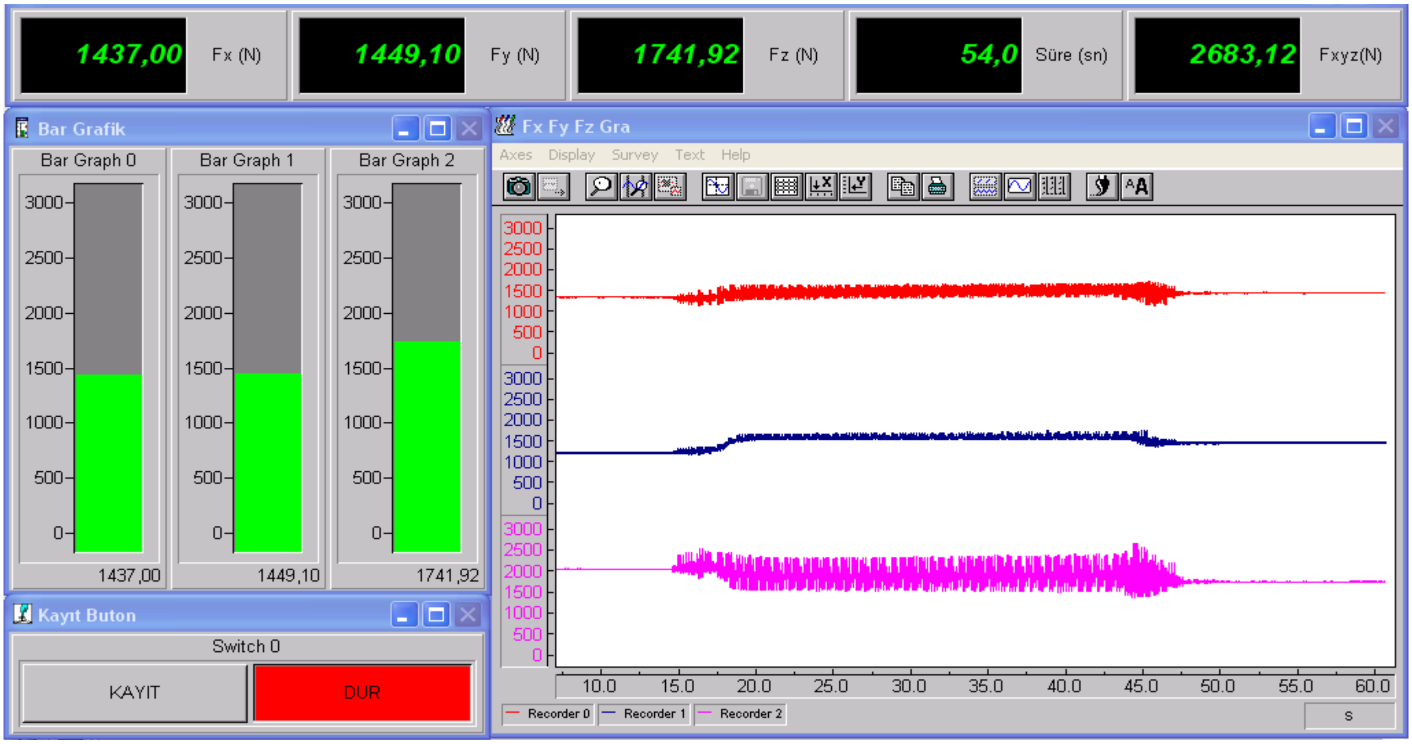

Figure 5. Test screen.

Figure 6. The loads applied to the load cells.

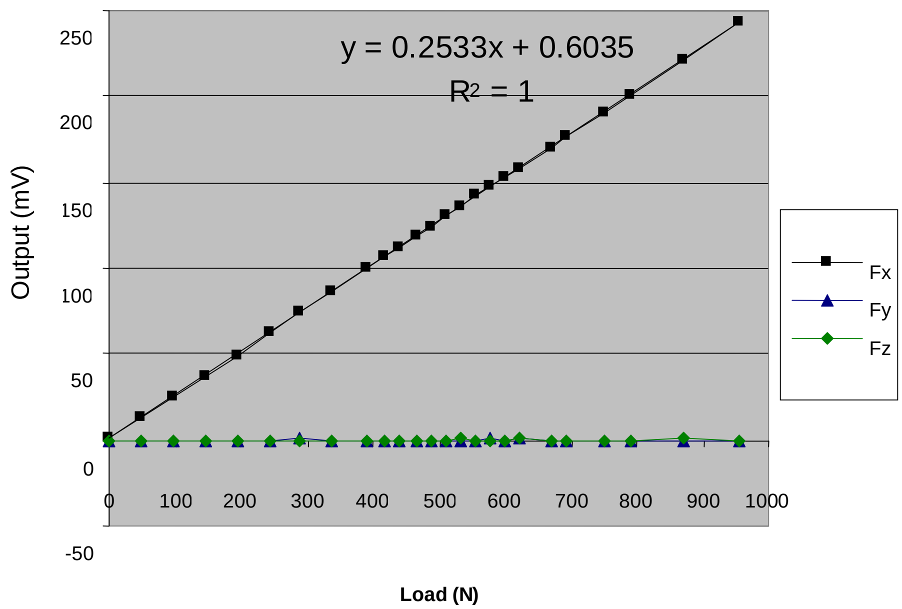

Figure 7. The dynamometer calibration curve in Fx direction.

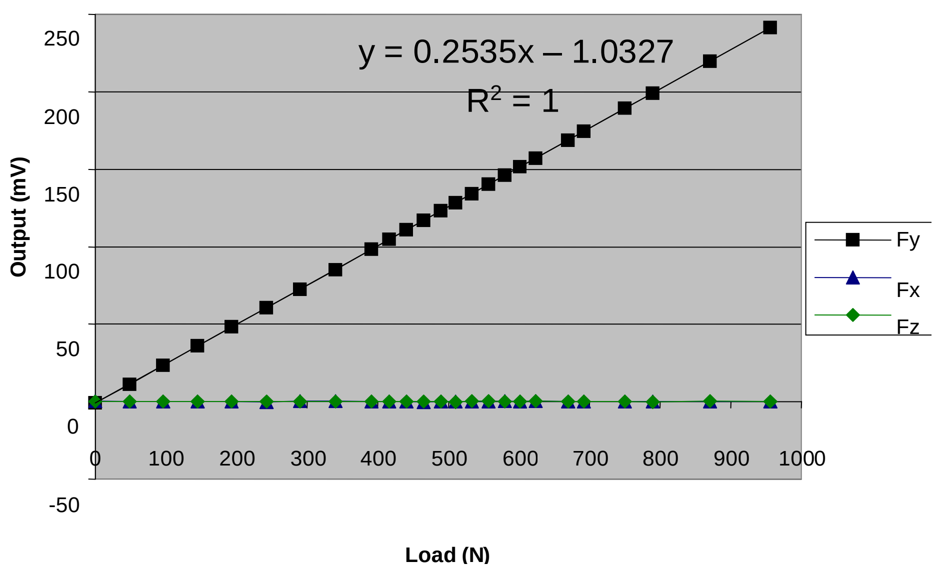

Figure 8. The dynamometer calibration curve in Fy direction.

In the X, Y and Z directions of the dynamometer, three different loads were applied for the performance tests. Percentage inaccuracy of the data obtained from the system due to the applied loads were found to be 0.03–0.12. The performance test results are given in Table 2.

RESULTS

The following results can be drawn from the present study:

1. The dynamometer enables accurate measurement of both the cutting and clamping forces.
2. During data acquisition, four data is obtained per second by taking the average of 256 data block. So, a total of 4 x 256 data is processed per second. In addition, the number of data obtained and recorded per second can be changed by the user.
3. As the capacity of the load cells are high (20 kN), the

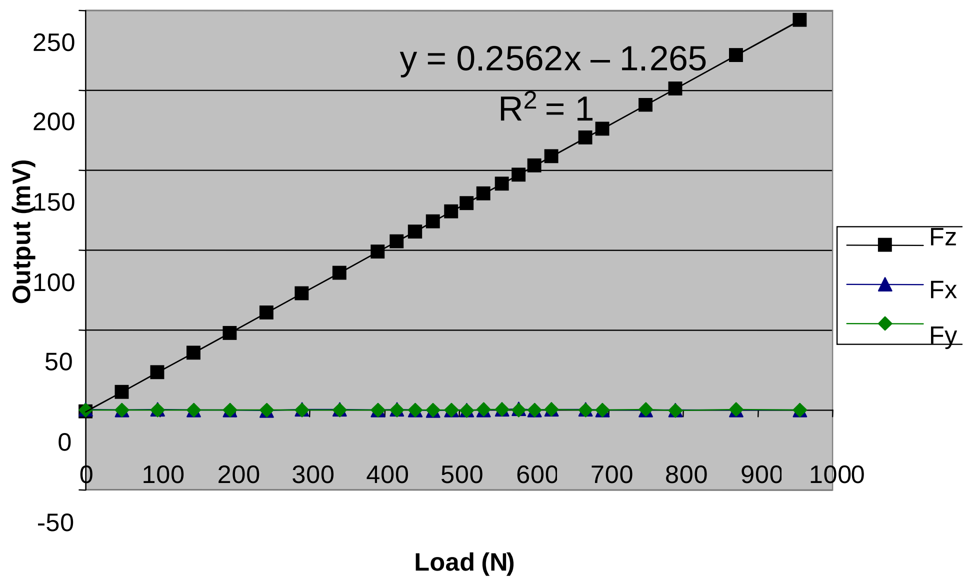

Figure 9. The dynamometer calibration curve in Fz direction.

Table 2. The results of tests performed on the dynamometer.

Axes	Load (N)	Output (N)	Output error (%)
	10	9.90	0.1
X	500	503.85	0.07
	1000	1004.20	0.04
	10	10.12	0.12
Y	500	502.95	0.06
	1000	1003.40	0.03
	10	10.10	0.1
Z	500	502.70	0.05
	1000	1002.80	0.03

system can be used for light and heavy cutting conditions.

4. As the load cell measuring is 1200 x 1200 mm, tests on larger sized workpieces can also be carried out.

5. It is possible to see the forces developed during workpiece clamping and cutting, cutting time and resultant force instantly on the PC.

6. Clamping of the workpiece can be effected in one point at three planes in order to constraint six degrees of freedom of the workpiece.

7. The workpiece can be clamped by a single clamp at one point 45º on X, Y and Z planes or by using more then one clamp.

8. The designed and constructed dynamometer is quite cost effective when compared to commercial dynamometers.

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