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Control of Machining in Manufacturing of Parts for Automobile and Aerospace Engineering

by D. St. Rose
Advisor: G. Zhang

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Desmond St. Rose
Faculty Advisor: Dr. Guangming Zhang

Abstract

Machining during the manufacturing of parts for aircraft engines or automobile cams and crank shafts requires precision control of the tool path. This precision control has become essential for quality assurance and productivity improvement. This research focuses on the development of an instrumented transducer to measure the cutting force in an on-line fashion. Design of a strain gage layout is presented to minimize the cross-talks. Calibration based on the transformation matrix method establishes the mapping function between the three cutting force components and the measured voltage signals. A strategy to use this instrumented dynamometer for on-line monitoring of the machining process is discussed.

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INTRODUCTION

Machining during the manufacturing of parts for aircraft engines or automobile cam and crank shafts requires precise control. The quality of machined parts for engineering applications has received great attention during the past ten years because reliability and durability of the product are directly influenced. Controlling the surface characteristics of machined parts is essential in quality control environments. The factors which degrade the surface quality during machining are the roughness of the surface finish due to tool vibration, tool geometry, and machining parameters. By controlling tool vibration, the quality of parts being produced can be greatly improved. Vibration can be controlled by effectively measuring the cutting force acting on the cutting tool during machining. The cutting tool is used to machine parts, and during machining the cutting force is generated on the tip of the cutting tool (see figure 1). The cutting force can be considered a combination of three components: the feed force, the tangential force and the radial force. By designing a tool holder dynamometer using strain gages, the cutting force can be measured and in turn used to study and correct deficiencies in the cutting process.

The basic uses of a dynamometer are to study the machining processes, which is the removal of material from a rotating workpiece (see figure1), and used for measuring the cutting force over the range of light to medium depths of cut. The dynamometer should be sensitive to small changes in the cutting force, yet rigid enough to prevent the occurrence of chatter vibration. Dynamometers have to be rigid to ensure that the cutting force does not deflect the cutting tool enough to significantly alter the cutting angles[1]. There are different types of dynamometers, such as the boring dynamometer and the instrumented transducers dynamometer.

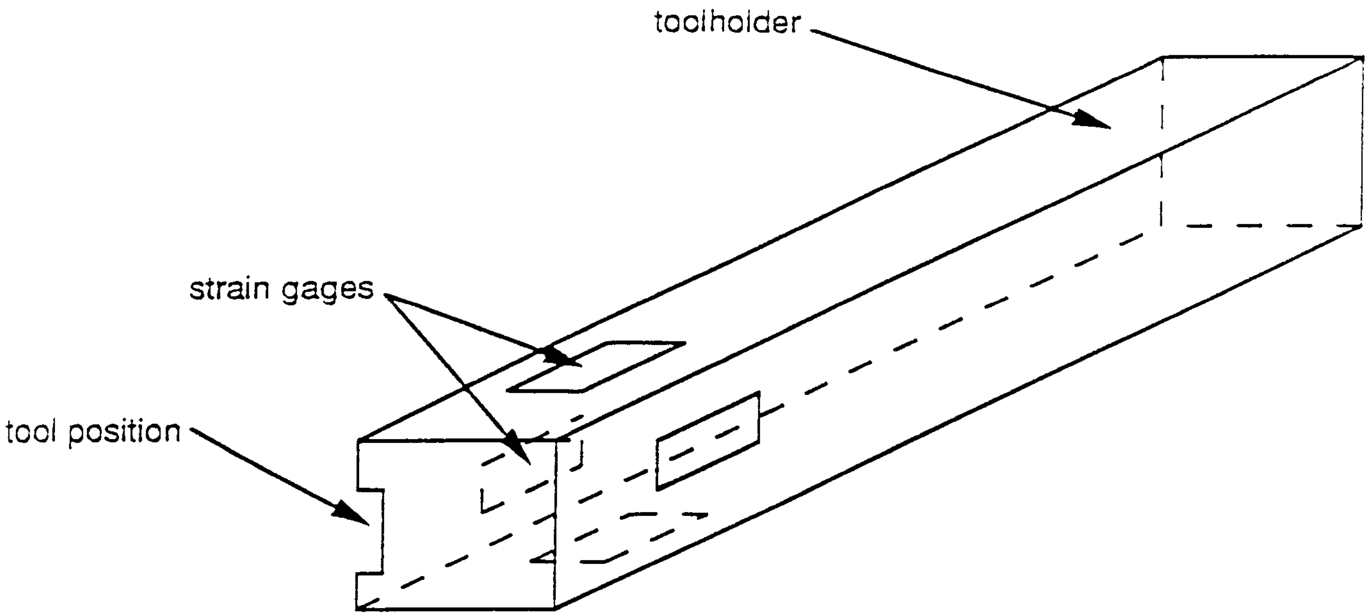

Figure 2. Strain Gage Layout on Toolholder

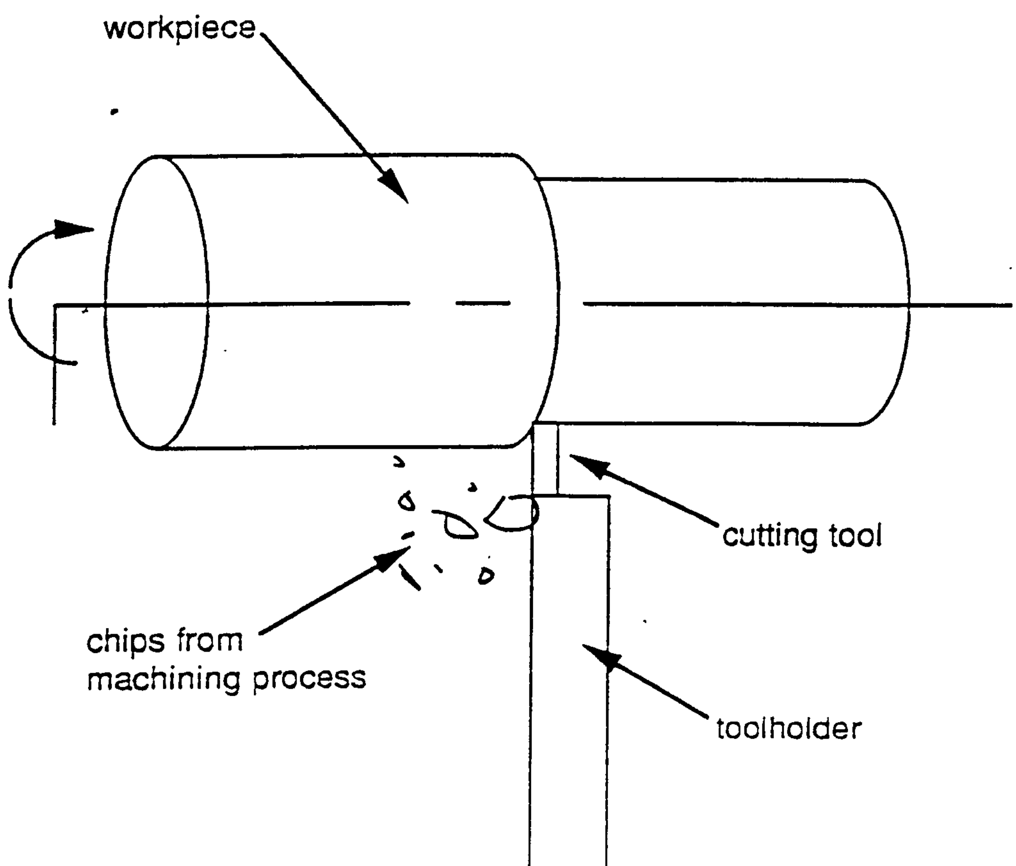

Figure 1. Machining Process

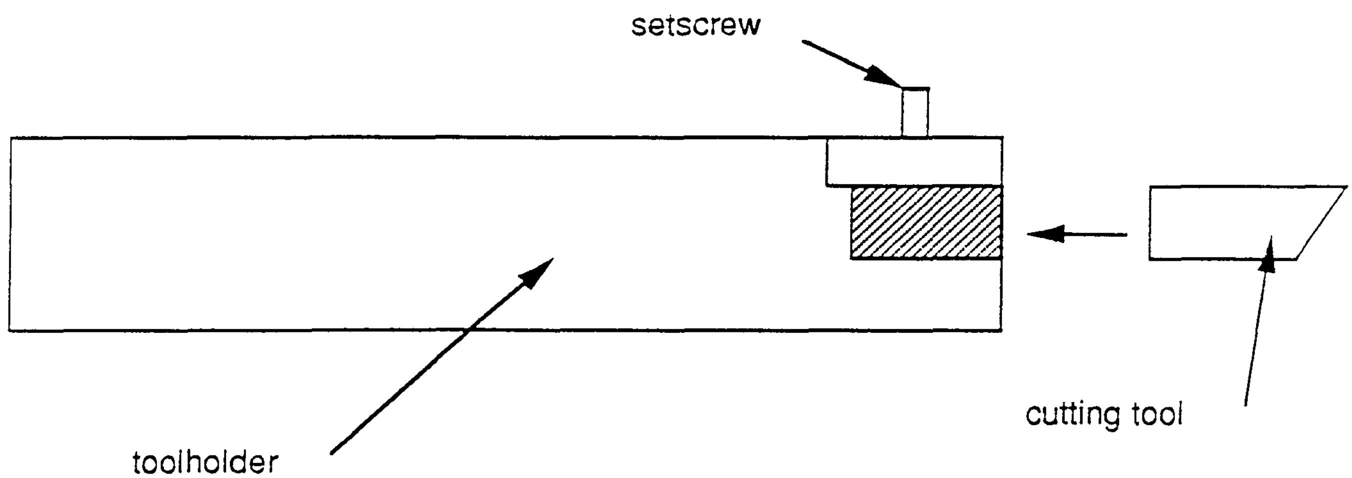

Figure 3. Cutting tool placed into toolholder

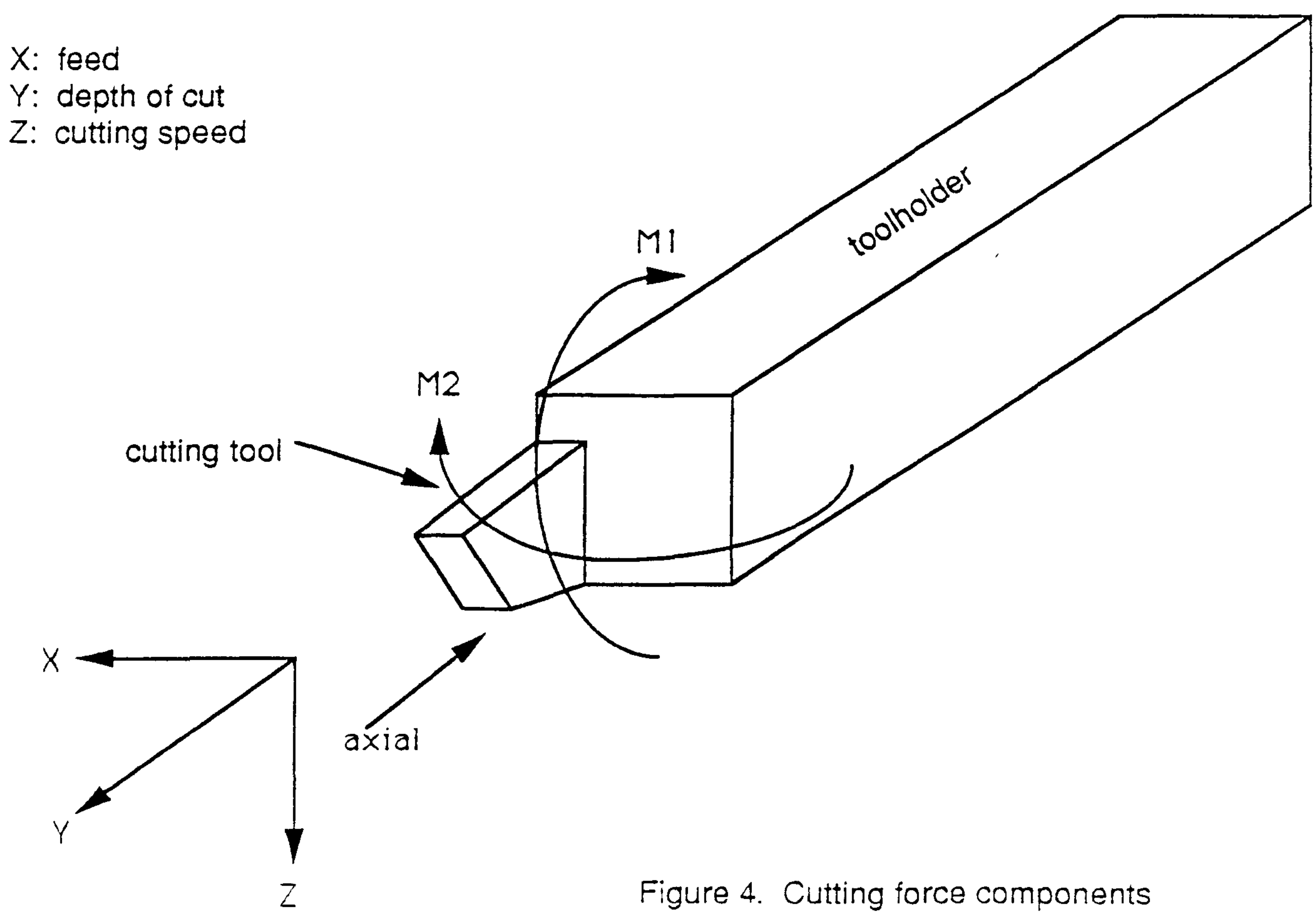

Figure 4. Cutting force components

The instrumented transducers will be designed to measure the cutting force, and at the same time they must be sensitive to the applied forces. The cutting force is measured by mounting four foil strain gages symmetrically around the dynamometer. The sensitivity of the strain gages allows the strains created by the cutting force to be accurately measured (see figure 2). Usually a dynamometer is attached on a machine tool, and the cutting tool is fixed on the dynamometer or tool holder (see figure 3).

The strain produced on the tool holder or dynamometer from the cutting force at the tip of the cutting tool is detected by the strain gages. The strain gages are connected to a wheatstone circuit, which detects the change in resistance of the gages due to the strain, and gives the reading in voltage. This voltage is amplified by the bridge amplifier subsystems, so the data can be input in to the computer for calculating the components of the cutting force. The calculated force components obtained are multiplied by a matrix conversion factor to determine the cutting force. Once the cutting force is measured, vibration can be minimized so parts can be machined to exact tolerances resulting in smooth surfaces.

PROCEDURE AND METHOD

A dynamometer is an instrumented transducer that provides information relating to the cutting force produced during machining. The cutting force generated on the cutting tool during machining can be treated as a spatial vector, which is conventionally decomposed into its three components (figure 4 and figure.5). The cutting force component along the feed direction, F_x, is called the feed force component. The cutting force component along the cutting speed direction, F_z is called the tangential force component. The cutting force component along the radial direction, F_y, is called the radial force component[2].

The purpose of the dynamometer is to determine the force components. The technical issues involved in determining the force components are:

(1) strain gage layout
(2) bridge amplifier subsystem
(3) cutting force measurement
(4) calibration

1.0 Strain gage layout:

When a cutting force acts on the cutting tool, for instance in the F_z direction, bending moments are created around the X-axis and Y-axis. The bending moments produce strain on the dynamometer (see figure 4). M1 and M2 are the moments around the X-axis and Y-axis, respectively. Four strain gages are mounted symmetrically on the surfaces of the toolholder (see figure 2) to convert information on the cutting force components into measurable voltage outputs. The type of strain gages that are used to measure the cutting force is a foil or printed type strain gage. The foil gage consists of very thin foil cemented to a lacquer sheet . The foil is printed with the strain gage configuration and then placed in an acid wash for five minutes. This removes the metal foil except where it has been protected by the printed design of the gage configuration[3] (see figure 12). The printed design is then placed on a backing foil. The backing foil of the strain gage provides a means for handling the foil pattern during installation, and also provides electrical insulation between the metal foil and the test object. The principal component which determines the operating characteristics of a strain gage is the strain-sensitive alloy used in the foil grid[4]. The strain gages that are used to determine the cutting force are constructed with constantan alloys which have an adequately high strain sensitivity or gage factor. The basic principles for designing the strain gage layout are: (1) Each bridge output is sensitive mainly to one specific force component, and (2) The gage layout itself is temperature compensated. For the layout of the strain gages, the first thing to do is clean the four surfaces of the dynamometer with light sand paper. Next, apply a solvent degreaser and wipe clean in one direction only. After degreasing, layout the lines to install the strain gages and reclean with the surface conditioner. The strain gages are then installed on the dynamometer with cellophane tape and an adhesive bonding. When the bonding is dry remove the cellophane tape.

1.1 Wheatstone Bridge and Circuit:

The strain gages will be connected in a half bridge wheatstone connection (figure 6) in order to detect the change in resistance of the gages when subjected to a strain corresponding to the applied force in the F_z direction. Since the force components that will be measured with the dynamometer are the F_x and the F_z components, only two wheatstone half bridge connections are needed. For the applied force in the F_z direction, the top gage is the active gage (tension) and the bottom gage is the compensation gage (compression) (see figure 2). The wheatstone

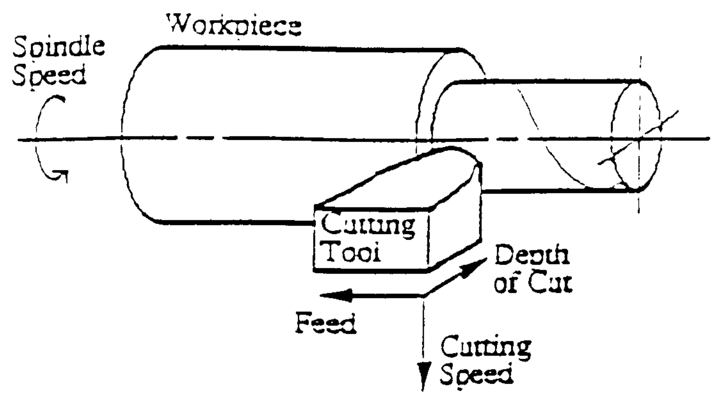

Figure 5. Cutting force detail

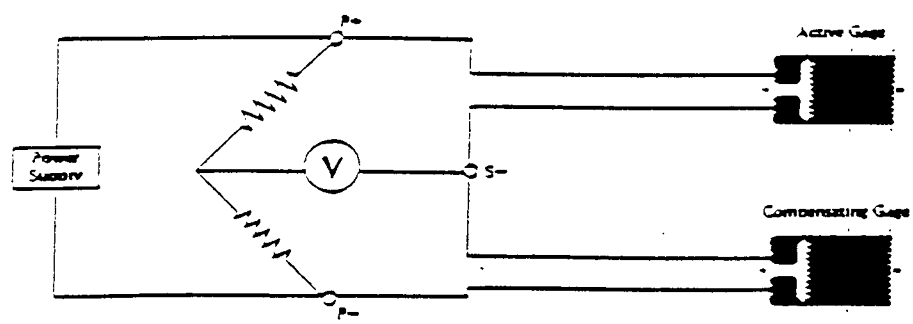

Figure 6. Wheatstone bridge connection

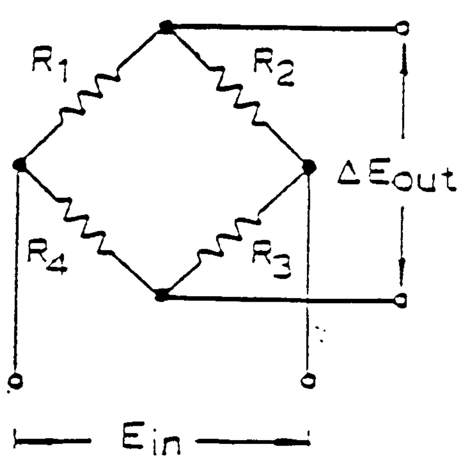

Figure 7. Wheatstone bridge circuit

bridge circuit determines the change in resistance within the strain gages when subjected to an active force component, and initially balanced the bridge status before the cutting force is applied (see figure 7). The bridge is initially balanced when R1xR3 = R2xR4. The output voltage, Eout, can be calculated after the cutting force is applied. This voltage output is due to the resistance change of ΔR1, ΔR2, ΔR3, and ΔR4, where ΔR is the reading obtained due to the unbalance of the strain gages once a force is applied.

The temperature effect in each gage cancel out since they are the same in each leg, and the resistance changes in adjacent legs of the bridge circuit are self-nullifying. In order to overcome the difficulty encountered by the possibility of temperature changes, a dummy resistor is installed in the arm of the bridge adjacent to the strain gage that will be measuring the detected strain. According to the strain gage layout on the dynamometer, the wheatstone bridge produce output sensitive mainly to the force components F_z and F_x[2].

1.2. Wire Connections:

A strain gage has two solder tabs for making proper leadwire connections. The wires are connected to the solder tabs by soldering, and should be long enough so connections can be made to the bridge amplifier circuit after the dynamometer is installed in to the machine tool.

2. Bridge Amplifier Subsystem:

The voltage outputs from the wheatstone bridge are small analog signals, which cannot be stored and directly used for data manipulation on a digital computer· This analog signal must be converted into digital signal to be stored on a digital computer.

Since the voltage outputs from the bridge are usually in the order of 10 millivolts, amplifier circuits are needed to magnify the bridge voltage outputs to a level suitable for the data acquisition system[1]. The bridge amplifier subsystem is an inverting amp that magnifies the voltage output from the wheatstone bridge corresponding to an applied force (figure 8). Since there are two wheatstone half bridge circuits connection on the dynamometer, two bridge amplifier circuits are needed in the design of this dynamometer. According to figure 8, the four bridge circuit (which is the first circuit) is used to measured the voltage output from the radial force component. The resistors that are label D1 and D2 are the dummy resistors. These resistors and the strain gages have the same resistance of 120 ohms. The magnified voltage outputs from the bridge amplifier circuits are then transferred to the digitizer. The digitizer converts the magnified analog signals from the bridge amplifier circuits to digital signals that can be stored into the computer for data manipulation (see figure 9). The gain of each amplifier is equal to the ratio of Rf/Rin, which means that the output voltage,V_{out}, of the different amplifier is equal to ΔE_{out} x (Rf/Rin). The excitation voltage E_{in}, the dummy resistors, and the different amplifiers are assembled as the bridge amplifier subsystems[2].

These are the equations that govern the voltage output from the strain gages:

$$E_{out} = \frac{-E_{in}(1+\upsilon)F_x S_g}{2E_c A} \qquad (1)$$

$$E_{outz} = \frac{E_{in}}{4}(2*\frac{F_z L_1 H}{EI})S_g \qquad (2)$$

$$E_{outy} = \frac{E_{in}}{4}(2*\frac{F_y L_1 H}{EI} - 2*\frac{F_x L_3 H}{EI})S_g \qquad (3)$$

A = cross-sectional area of toolholder

E_c = compressive modulus of elasticity of the toolholder

EI = elastic rigidity of the toolholder

Lx = distance of toolpoint to gage X

H = distance of gage from neutral axis

u = Poisson's ratio of the toolholder

Sg = Gage Factor of the strain gage

3.0 Cutting Force Measurement:

Once the cutting tool makes contact with the material to be cut during machining, the strain on the transducer, which is been produced by the cutting force, can be used to measure the two cutting force components during machining. The strain is detected by the wheatstone bridge circuit and gives the output in voltage. A quantitative relation between the voltage outputs from the computer and the applied force must be established. This relationship is needed to determine the correct force acting on the cutting tool during machining that corresponds to the voltage outputs. The voltage outputs from the computer are obtained in terms of the applied force (equation 6). The mathematical relation between the voltage outputs and the applied force is defined as the transfer function (see equation 4). Since there are two wheatstone bridges from the dynamometer, the transfer function should be in a matrix form (see equation 5). After testing the dynamometer with different applied forces that vary in magnitude, and after recording the voltage outputs from the computer, the force can be determined by using equation 7, where $[Tr]^{-1}$ is the influence matrix or the inverse of the transfer function.

$$Tr = \frac{Output}{Input} = \frac{V_{out}}{F} \tag{4}$$

$$[V_i] = [Tr]\,[F_i] \qquad i = x,y,z \tag{5}$$

$$[Tr] = \begin{vmatrix} \frac{\Delta V_x}{\Delta F_x} & \frac{\Delta V_x}{\Delta F_y} & \frac{\Delta V_x}{\Delta F_z} \\ \frac{\Delta V_y}{\Delta F_x} & \frac{\Delta V_y}{\Delta F_y} & \frac{\Delta V_y}{\Delta F_z} \\ \frac{\Delta V_z}{\Delta F_x} & \frac{\Delta V_z}{\Delta F_y} & \frac{\Delta V_z}{\Delta F_z} \end{vmatrix} \tag{6}$$

$$[F_i] = [Tr]^{-1}\,[V_i] \tag{7}$$

By using equation 8, the strain on the strain gage can be computed. Equations 2 to 4 are used to determine the voltage outputs from the bridge for each component. The voltage outputs are then substitute into equation 7 to determine the force on the cutting tool.

$$\varepsilon_{1,3} = -\frac{F_x}{E_cA} \pm \frac{F_xL_3H}{EI} \pm \frac{F_yL_2H}{EI} \pm \frac{F_zL_2H}{EI} \tag{8 a}$$

$$\varepsilon_{2,4} = \upsilon \left(-\frac{F_x}{E_cA} \pm \frac{F_xL_3H}{EI} \pm \frac{F_yL_2H}{EI} \pm \frac{F_zL_2H}{EI} \right) \tag{8 b}$$

$$\frac{\Delta R_1}{R_1} = \left(-\frac{F_x}{EcA} + \frac{F_xL_3H}{EI} + \frac{F_yL_2H}{EI} + \frac{F_zL_2H}{EI} \right) S_g \tag{8 c}$$

where, υ = Poisson's ratio of the bar material

A=cross-sectional area of the dynamometer

E_C = compressive modulus of elasticity of the dynamometer

EI = elastic rigidity of the cutting material

L_2 = distance of the tool point and the gage location in the radial direction

L_3 = distance of the tool point and the gage location in the radial direction

H = distance of the gage location away from the neutral axis in the cross-section of the boring bar

4.0 Calibration:

Calibration of the strain gage dynamometer is necessary in order to validate the acquired experimental data. The basis of the calibration process can be seen in Figure 10. The applied load generates a mechanical strain within the toolholder. This strain is then detected by the strain gages as internal resistance which produces an output voltage via the wheatstone bridge. The operational amplifier magnifies the output voltage from the wheatstone bridge to a level suitable for data acquisition. For accurate output, loads are applied as close as possible to the cutting tip of the cutting tool. Calibration of the dynamometer is done for all of the applied loads in the different directions, such as the cutting speed and the tangential directions.

With the dynamometer installed into the toolholder and clamped and the strain gages wires connected to the bridge amplifier circuit, measurements were taken for the different applied loads. The measurements were recorded in terms of voltage to the corresponding force component (See table 1).

Force in Tangential Direction (Fz)

Weight(kg)	$\mu\varepsilon_1$	$\mu\varepsilon_2$	μV_1	μV_2
0.000	0.0	0.0	0.0	0.0
0.355	3.0	0.0	0.8	0.0
4.895	31.0	2.0	12.0	2.4
9.435	58.0	4.0	24.0	4.8
13.975	84.0	5.0	34.4	7.2
17.153	102.0	6.0	42.4	9.6
20.331	120.0	7.0	48.8	10.4
23.509	138.0	8.0	56.0	11.2

Force in Normal Direction (Fx)

Weight(kg)	$\mu\varepsilon_1$	$\mu\varepsilon_2$	μV_1	μV_2
0.000	0.0	0.0	0.0	0.0
0.170	0.0	2.0	0.0	4.0
4.170	0.5	27.0	0.0	47.2
9.250	1.0	57.0	0.0	96.0
13.790	1.5	85.0	0.0	117.0
16.968	2.0	103.0	0.0	174.0
20.146	2.5	121.0	0.8	205.0
23.324	3.0	139.0	0.8	236.0

Table 1: Calibration Voltages and Applied Weights

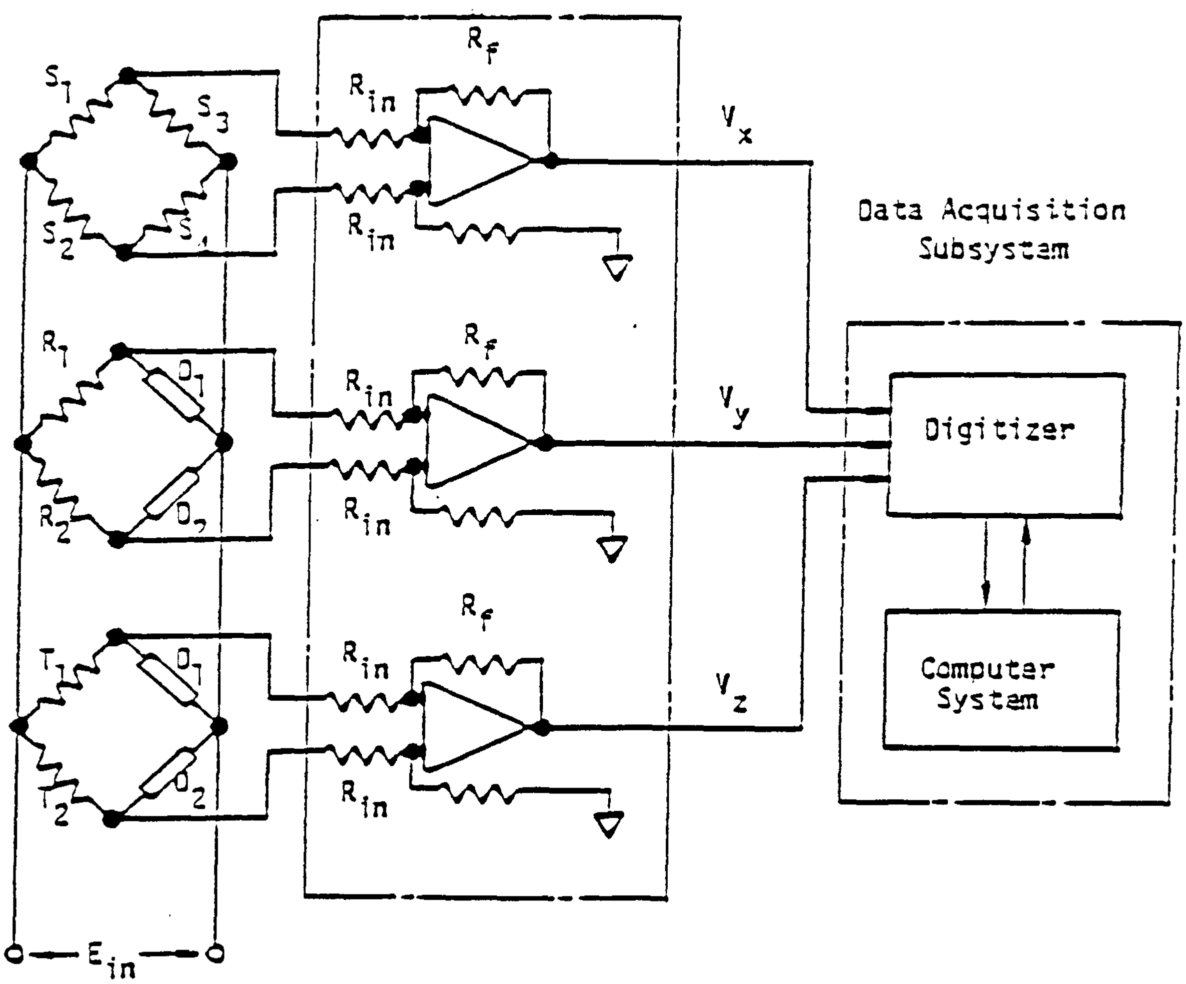

Figure 8. Bridge amplifier circuit

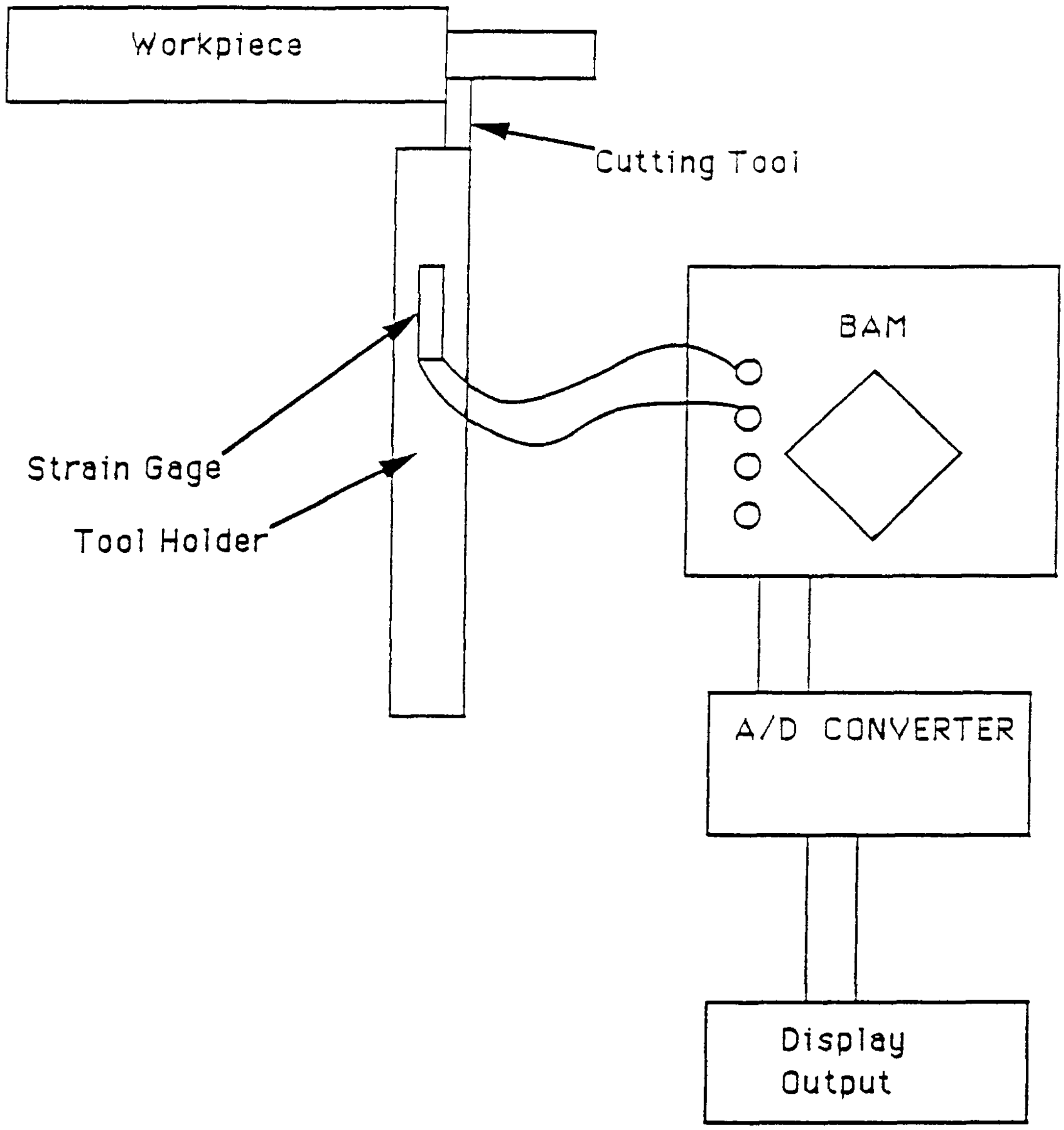

Figure 9. Basic methodology

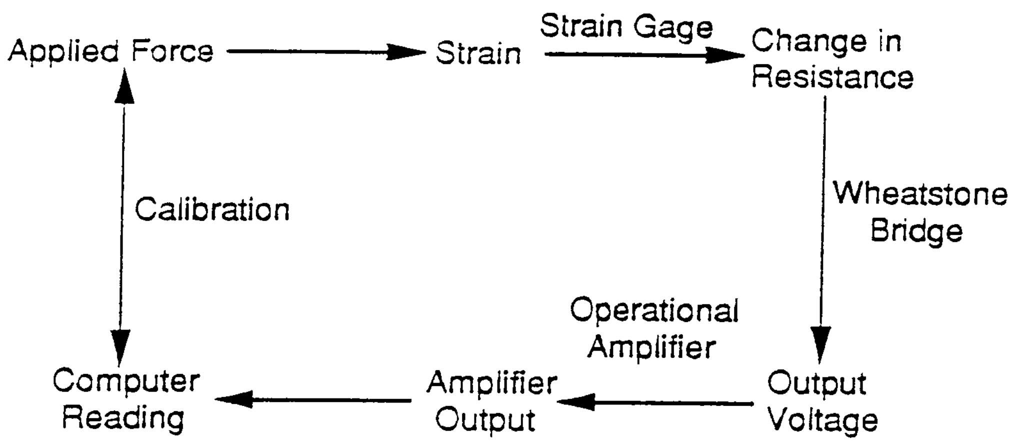

Figure 10. Basis for calibration

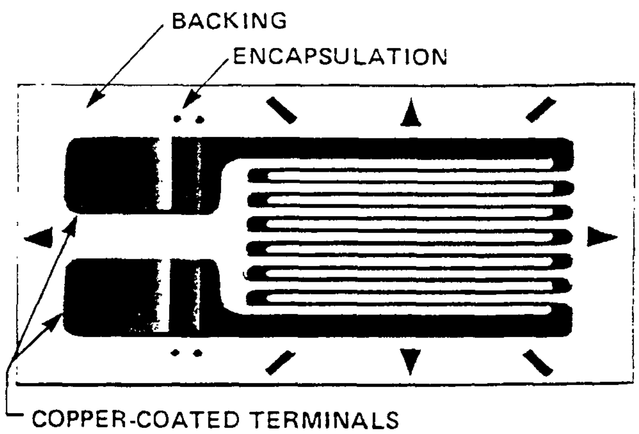

Figure 11. Strain Gage

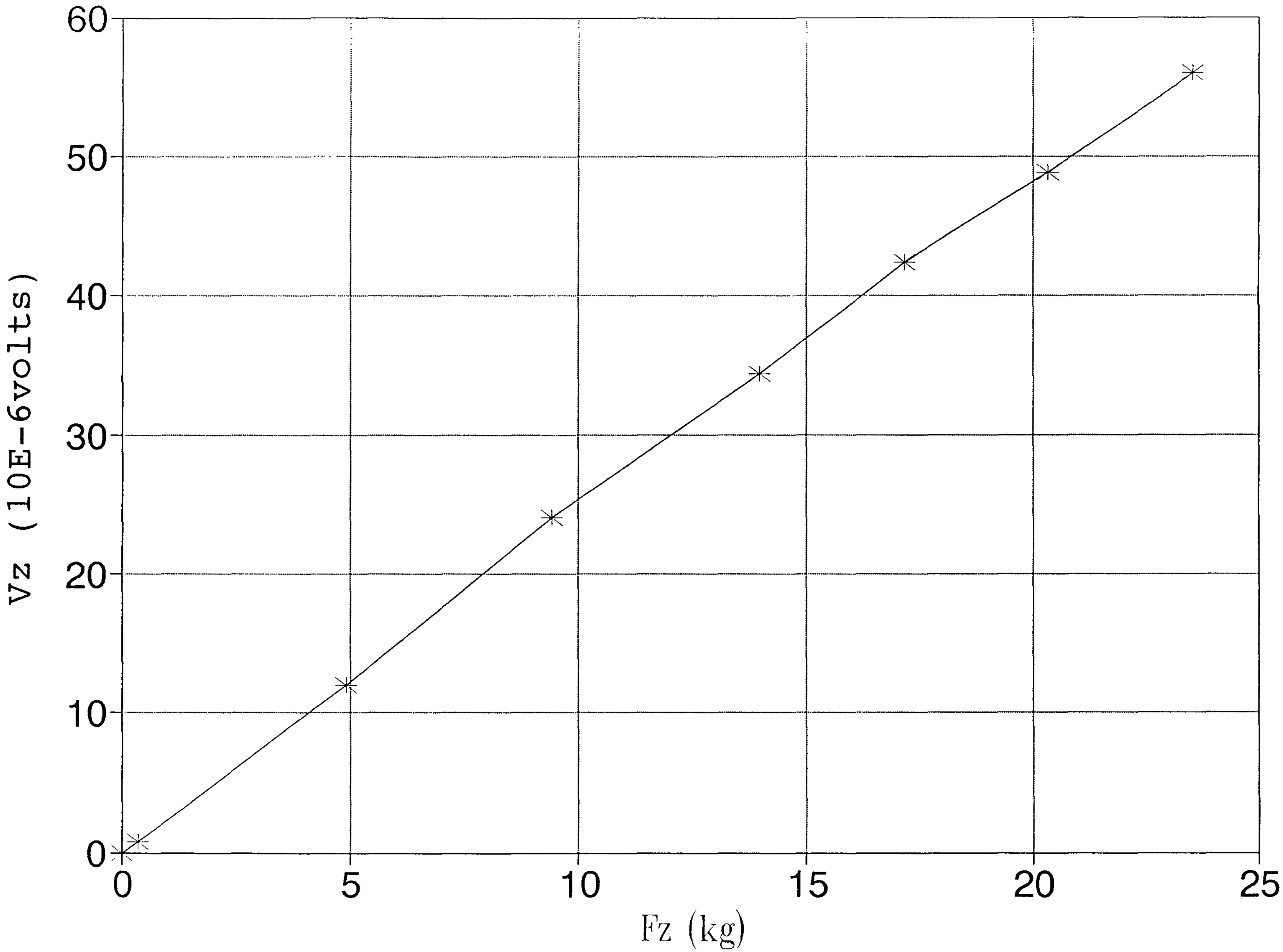

Figure 12. Graph of Vz vs Fz

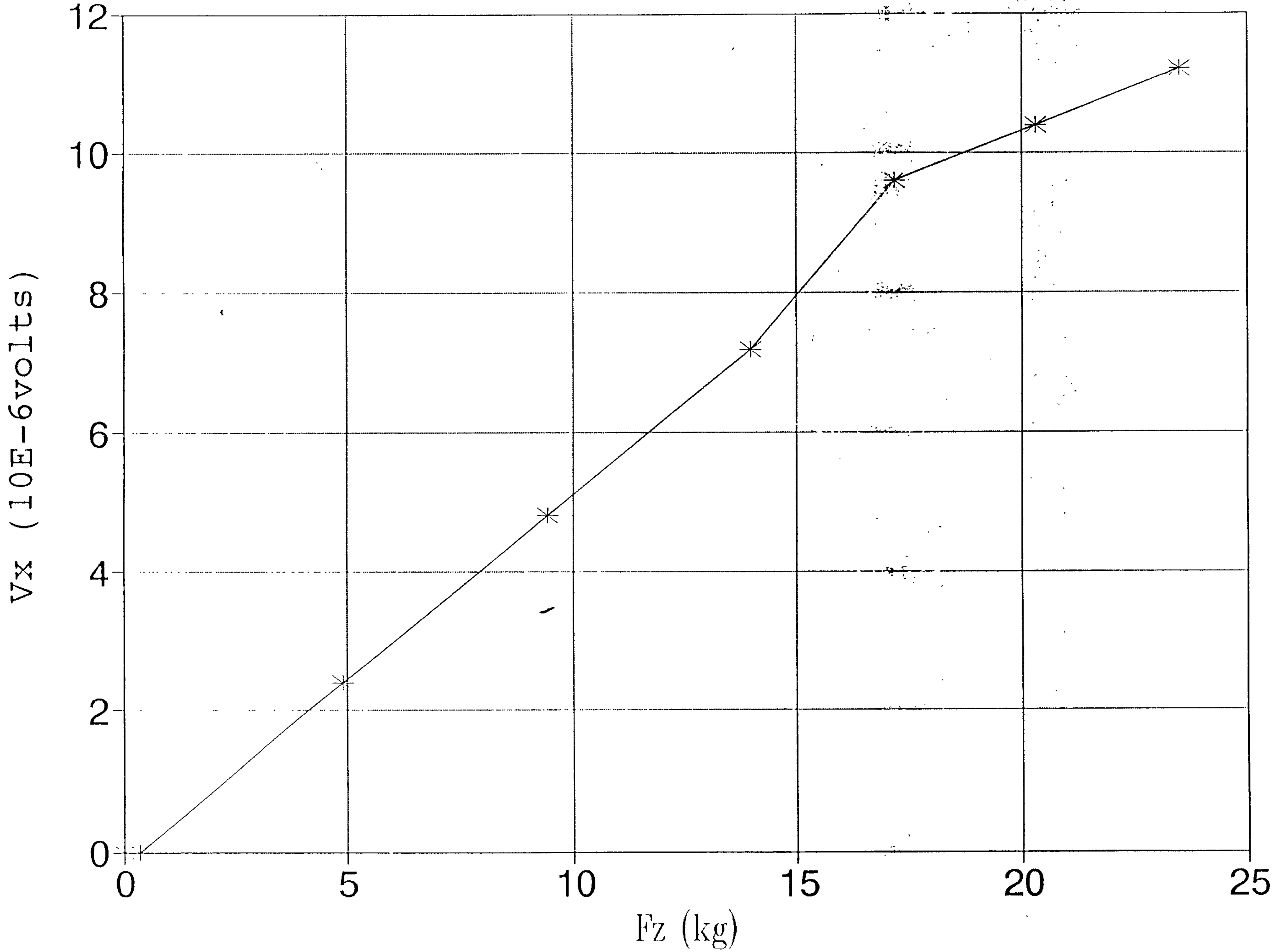

Figure 13. Graph of V_x vs F_z

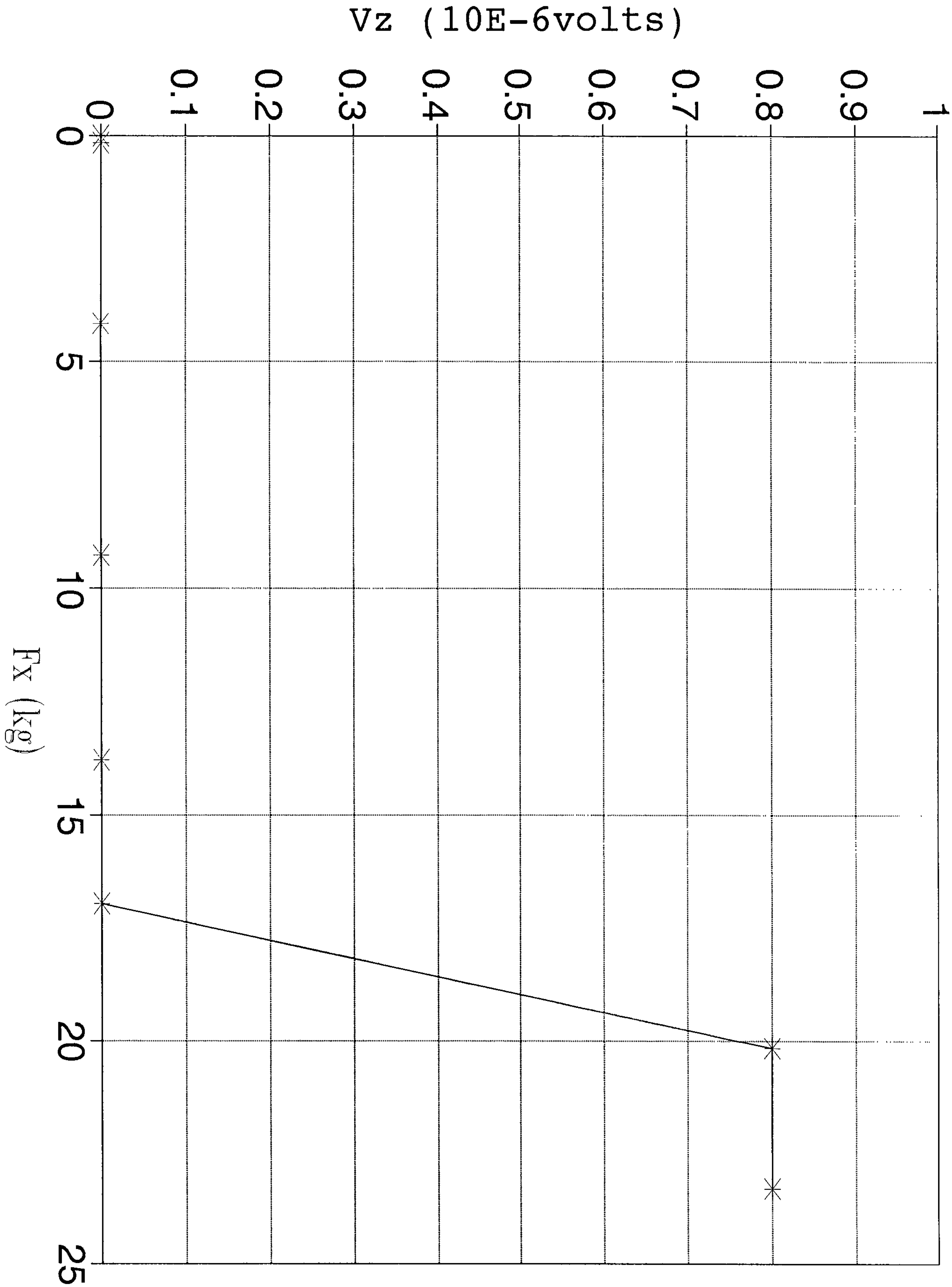

Figure 14. Graph of Vz vs Fx

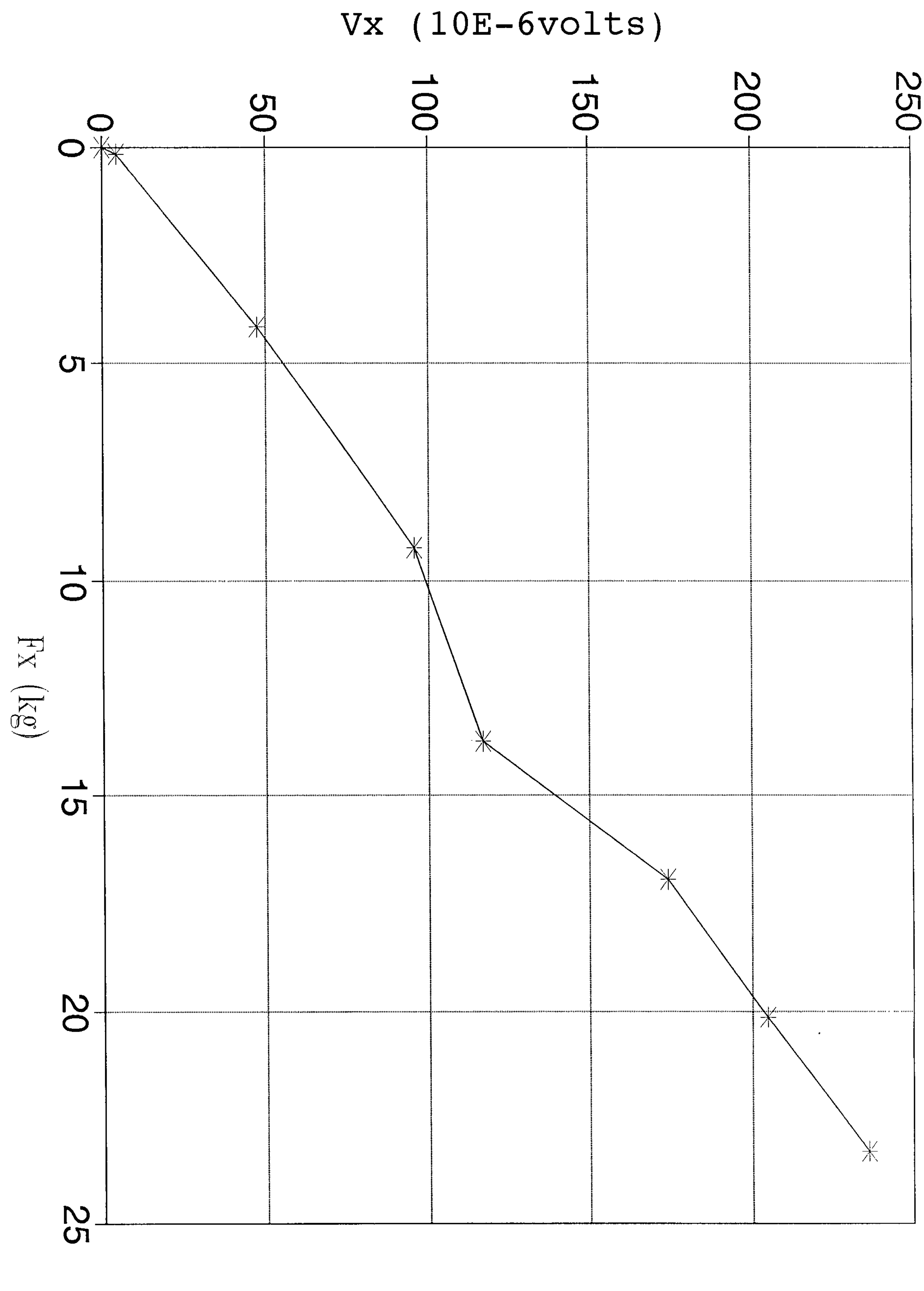

Figure 15. Graph of Vx vs Fx

The transfer function matrix was determined by taking the slope of the four graphs. Using equation 6, T_{11} represent the slope from the the graph of V_z vs F_z, T_{12} represent the slope from the graph of V_x vs F_z, T_{21} represent the slope of the graph V_z vs F_x, and T_{22} is the slope of the graph V_x vs F_x (See figure 12 to 15).

$$[Tr] = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} 2.402 & 0.5072 \\ 0.030 & 9.939 \end{bmatrix} \qquad (6)$$

The inverse of the transfer function matrix or the influence matrix $[Tr]^{-1}$ was calculated to be:

$$[Tr]^{-1} = \frac{1}{23.85}\begin{bmatrix} +9.939 & -0.5072 \\ -0.030 & +2.402 \end{bmatrix} = \begin{bmatrix} +0.4166 & -0.0213 \\ -0.0013 & =0.1007 \end{bmatrix}$$

where 1/23.85 is the determinant of the matrix. $[Tr]^{-1}$ was then substituted into equation 7 to determine the cutting forces that correspond with the voltage reading.

$$\begin{bmatrix} F_z \\ F_x \end{bmatrix} = \begin{bmatrix} +0.4166 & -0.0213 \\ -0.0013 & +0.1007 \end{bmatrix} \begin{bmatrix} V_z \\ V_x \end{bmatrix} \qquad (7)$$

$$F_z = 0.4166V_z - 0.0213V_x$$
$$F_x = -0.0013V_z + 0.1007V_x$$

DISCUSSION

As material is removed during the machining process, a cutting force is generated on the cutting tool. The cutting force, which is broken down in two components, is considered to be a spatial vector with both magnitude and direction. The two force components, the feed and tangential components, will be measured by the strain gages installed on the four surfaces of the dynamometer.

A satisfactory production-oriented dynamometer must be such that it does not interfere with the normal operation of the machine tool[5]. There should be little interaction between the two components measuring systems and the strain gages. At the same time a dynamometer should be flexible to prevent phase shift in readings during uneven cuts[1]. The dynamometer used in this research project is an instrumented transducer dynamometer. This particular design was created because the dynamometers commercially available do not fit the requirements that are necessary to measure the on-line cutting force.

Electrical resistance strain gages, when correctly affixed, will provide good linearity. When randomly placed on the toolholder, strain gages would provide enough information to determine the force component. The reading from the strain gages that correspond with the strain from the applied loads in either of the component direction will be used in equation 8 to the determine the cutting force. The strain gages have a gage factor ,Sg, between 2 and 3. Since the deflections in the X and the Z direction are relatively large, the gage factor used must be high enough to accurately obtain a correct result for the strain. Before using the cutting tool and the dynamometer on the machine tool, the strain gages must be tested statically. This is done by placing the toolholder in a vice. The jaw of the vice must be position close to the strain gages. Various weights of different magnitudes are applied to the tip of the cutting tool in the Fz and Fx directions. For every weight applied to the tip of the cutting tool, a reading in strain is obtained. With the equations for strain and voltage output, the cutting force can be determined statically. Once the cutting force is determined, tool vibration can be minimized in control machining.

CONCLUSION

The ever increasing competition on the market place is forcing U.S. industry to seriously evaluate the manufacturing of their products. Quality of machined surfaces has received great attention during the past ten years because reliability and durability of the product are directly influenced. Due to the rapid growth of the computer technology, several adaptive control systems in manufacturing have been proposed. These adaptive control systems for machine tools have shown a tremendous potential for improving productivity in manufacturing[2]. The instrumented transducer dynamometer was designed for on-line monitoring to provide information related to the cutting force produced during machining. Most dynamometers are primarily suited to research activity and do not have the operational flexibility or low cost required for use in a general purpose machining environment[5]. Also, dynamometers available do not have the rigidity necessary to effectively measure the cutting force and give acceptable results. From an analytical aspect, a dynamometer maps the force being measured to a voltage signal which can be recorded. To establish a relation between the voltage signal and the applied force on the cutting tool, the dynamometer must be calibrated. By applying a known force to the dynamometer and by recording the voltage signal, we can identify the corresponding relation between the applied force and the voltage signal through the transformation matrix (see equation 6). The main factor which degrades surface quality during machining is tool vibration which is caused by the cutting force generated during machining. The cutting force is a spatial vector and direct measurement of the cutting force is impossible. However, it is feasible to measure its three components, the feed force component, the tangential force component, and the radial force component. The three cutting force components generate strains in the cutting tool. From the strain measurements, the cutting force components can be calculated.

There are some alternative ways to measure the cutting force, such as the laser interference method, the ultrasonic method, and the radiation method. Of all the methods mentioned, the strain gage method is very low cost and can be acceptable in the manufacturing industries. This method can be used to integrate the analytical and computational techniques of control engineering and machining science , which is the current focus on developing an on-line monitoring strategy that determines tool path error during machining.

RECOMMENDATION

I recommend that this research project should be continued with a more in - depth research. By controlling the machine process during the manufacturing of parts for automobile and aerospace application, we may be able to minimize the number of defective parts that are being sold to the consumer.

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