Design and development of a Strain Gauge based Dynamometer for measurement of cutting force on a Lathe

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Abstract

Knowledge of stress is important in metal cutting applications as they are used in the design of machine tools, cutting tools and fixtures. 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 the experimental measurement became indispensable. For these purposes, dynamometers were developed. In these dynamometers, cutting force measurement is mainly based on elastic deformation of materials.

In this study a strain gauge based dynamometer capable of measuring cutting force component during metal cutting operation on a lathe has been designed and constructed. In order to read (and save) the cutting force data automatically, the necessary data acquisition system was designed and developed with the necessary hardware and software devised and connected to it. Cutting force signals were captured, amplified, conditioned, converted to digital signals and read by a microprocessor. The corresponding force readings thus obtained after a series of tests and calculations are displayed on a standard LCD.

Keywords

Dynamometer, Lathe, Strain Gauge, Microprocessor, LCD

Introduction

Metal cutting is one of the most important manufacturing processes used widely in number of industries such as automobiles, aerospace and household items. Basic geometries of machine tools may be similar but they have to be designed and constructed according to the purpose they serve, for effective usage. In the present industrial area where quality control is being very important, optimum design of machine parts depends upon right determination of direction, types and strength of forces they are subjected to. In cases, where calculation cannot be done accurately for determination of forces, the experimental or online measurements have given true results. For this reasons, dynamometers have been developed in the past. Also, since cutting forces is an important criterion on tool condition monitoring they are taken as reference to decide output parameters such as tool wear, surface roughness and tool life and in turn used for feedback and adaptive control in many cases.

The present study focuses on the design and development of a strain gauge based dynamometer for measuring cutting force on a lathe. The voltage signals analog in nature are amplified, converted into digital format and corresponding force values displayed on a LCD. This is done with the help of an ATmega8 microcontroller.

The Lathe Machine

Over decades lathe has been at the centre stage among all the metal cutting machines and will remain their in the future too. The purpose of a lathe is to rotate a part against a tool whose position it controls. It is useful for fabricating parts and/or features that have a circular cross section. The spindle is the part of the lathe that rotates. Various work holding attachments such as three jaw chucks, collets, and centers can be held in the spindle. The spindle is driven by an electric motor through a system of belt drives and/or gear trains. Spindle speed is controlled by varying the geometry of the drive train. The tailstock can be used to support the end of the work piece with a center, or to hold tools for drilling, reaming, threading, or cutting tapers. It can be adjusted in position along the ways to accommodate different length work pieces. The ram can be fed along the axis of rotation with the tailstock hand wheel. The carriage controls and supports the cutting too. In industry lathe has been used for wide range of metal cutting operations like turning, facing, parting, drilling and boring operations.

The lathe has been continually modified over the years so as to meet the current demand of the industry which is increasingly moving towards automation. The advent of CNC lathes has sparked a new revolution in the industry. The industry is continuously trying to improve the lathe so as to get better products at less cost and with no rejections. To achieve this, a lot of research work is done to identify the optimum conditions for metal cutting. Some CNC machines are also provided with the 'adaptive control system' which modifies the system parameters online according to the feedback so as to get the optimum machining quality.

Since the force exerted to do the machining plays a central role in determining the quality of final product it becomes
imperative to understand the effect of force on lathe and hence it is necessary to devise an instrument that is capable of measuring the forces on lathe. This also requires understanding the nature of forces acting on the lathe so as to decide the type of instrument that will effectively measure these forces.

The Analysis and Measurement of Cutting forces on a lathe

Lathe is one of the most basic machines used in tool rooms, workshops all around the world. It uses machine tools that perform turning operations in which unwanted material is removed from a work piece rotated against a cutting tool. The rotating horizontal spindle to which the work holding device is attached is usually power driven at speeds that can be varied.

At any time during cutting operation on a lathe, the tool is subjected to the following forces as shown in the figure

![Figure 1: Cutting forces on a Lathe](image)

The cutting force, Fc, supplies the energy required for the cutting operation. Usually the cutting force is measured in a 3 dimensional cut i.e. both the minor and minor cutting edges such as in the case of turning of a bar.

The thrust force, Ft, also called feed force, acts longitudinally in the feed direction.

The radial force, Fr, is in the radial direction and tends to push the tool away from the work piece.

Ft and Fr are difficult to calculate because of the many factors involved in the cutting process. They are determined experimentally. These forces are important in the design of machine tools as well as in the deflection of tools for precision machining operations.

Knowledge of the forces and power involved in cutting operations is important for the following reasons:

- Power requirements have to be determined so that a motor of suitable capacity can be installed in the machine tool.

- Data on forces are necessary for the proper design of machine tools for cutting operations that avoid excessive distortion of the machine elements and maintain desired tolerances for the machined part.

- Whether the work piece can withstand the cutting forces without excessive distortion has to be determined in advance.

Cutting is a complicated process wherein the performance depends upon a number of cutting and tooling conditions. To conduct a successful cutting, generally speaking, not only must the tool material be harder than the work material but it must also be able to maintain its hardness at elevated temperatures.

The Cutting Tools

A wide variety of cutting tools are used on lathe depending on the type of operation and the material. Despite of the large variety of cutting tools they have certain common features which facilitate the standard design of dynamometer for all kind of tools that are mounted on the tool post of the carriage.

Though the present work is focused to determine force on a single tool, the concept can be applied and the instrumentation devised can be used to develop a standard instrument that can be used to accommodate variety of tools.

The Design of Dynamometer

Criteria for selection of strain gauge

When force is applied to a structure, the length of the structure change. Strain is the ratio of this change in dimension to the original, and strain gauges are used to measure it. If a strain gauge is glued to the structure, any distortion to the structure will also cause a distortion of the strain gauge. The gauge contains conducting material and the distortion therefore results in a change in its resistance. By measuring this change in resistance we can measure the strain. Strain gauges are frequently used in mechanical engineering research and development to measure the stresses generated by machinery. Aircraft component testing is one area of application wherein tiny strain-gauge strips are glued to structural members, linkages, and any other critical component of an airframe to
measure stress. Most strain gauges are smaller than a postage stamp, and they look something like this:

![Strain Gauge Diagram](image)

The following items are important to understanding Strain Gauge applications:

**Gauge Factor:** An SG specification always indicates the correct relation through statement of a gauge factor (GF), which is defined as

\[
GF = \frac{\Delta R/R}{\text{Strain}}
\]

where \( \Delta R/R \) = fractional change in gauge resistance because of strain

\( \text{Strain} = \Delta L/L \) = fractional change in length

For metal gauges, this number is always close to 2. For some special alloys and carbon gauges, the GF may be as large as 10.

**Construction:** Strain gauges are used in two forms, wire and foil. The basic characteristics of each type are the same in terms of resistance change for a given strain. The design of the SG itself is such as to make it very long in order to give a large enough nominal resistance (to be practical) and to make the gauge of sufficiently fine wire or foil so as not to resist strain effects. Finally, often the gauge sensitivity is made unidirectional, that is, it responds to strain in only one direction. These gauges are usually mounted on a paper backing that is bonded (using epoxy) to the element whose strain is to be measured. The nominal SG resistances (no strain) available are typically 60, 120, 240, 350, 500, and 1000 W. The most common value available is 350 W.

Based on the above criterions, we finally selected a strain gauge with Gauge Factor=2, Resistance= 350 ohms and Gauge Length=5 mm.

**Wheatstone Bridge Formation**

The resistance of a strain gauge may change only a fraction of a percent for the full force range of the gauge, given the limitations imposed by the elastic limits of the gauge material and of the test specimen. Forces high enough to induce greater resistance changes would permanently deform the test specimen and/or the gauge conductors themselves, thus ruining the gauge as a measurement device. Thus, in order to use the strain gauge as a practical instrument, we must measure extremely small changes in resistance with high accuracy.

Such demanding precision calls for a bridge measurement circuit. The change in resistance is measured through a Wheatstone bridge arrangement (figure 3). This has 4 arms, arranged in a square. Each arm contains either a resistor of known resistance, or a strain gauge. For our circuit, we have used 4 strain gauges of 350 ohms each.

![Wheatstone Bridge Circuit](image)

**Realization of setup**

The strain gauges were mounted on the tool as schematically displayed in figure 4. The strain gauge was pasted using a standard procedure in (1).

![Strain Gauge on Tool](image)

**Figure 2: Bonded strain gauge**

**Figure 3: Full bridge strain gauge circuit**

**Figure 4: This structure shows how four gauges can be used to measure beam bending. Two respond to bending and two are for temperature compensation**
Signal Conditioning

Excitation
Strain gauges require voltage excitation to generate a voltage representing strain. This voltage source should be constant and at a level recommended by the strain gauge manufacturer. While there is no standard voltage level that is recognized industry wide, excitation voltage levels of around between 3 and 10 V are common. While a higher excitation voltage generates a proportionately higher output voltage, the higher voltage can also cause larger errors because of self-heating. Keeping these factors in mind we prepared a circuit to give excitation voltage of 6V DC to the bridge.

Bridge Completion
For full-bridge strain gauges, the entire Wheatstone bridge is provided with the strain gauge. Our instrumentation provides the excitation outputs and measurement inputs.

Amplification
Strain gauges typically provide small signal levels. It is therefore important to have accurate instrumentation to amplify the signal before it is digitized by a DAQ device. The output of strain gauges and bridges is relatively small. In practice, most strain gauge bridges and strain-based transducers give output less than 10mV/V (10 mV of output per volt of excitation voltage). With 10V excitation, the output signal will be 100 mV. Therefore, strain gauge signal conditioners usually include amplifiers to boost the signal level to increase measurement resolution and improve signal-to-noise ratios.

Offset Voltage
When a bridge is installed, it is very unlikely that the bridge will output exactly zero volts when no strain is applied. Slight variations in resistance among the bridge arms and lead resistance will generate some nonzero initial offset voltage. Offset nulling can be performed by either hardware or software.

Shunt Calibration
The normal procedure to verify the output of a strain gauge measurement system relative to some predetermined mechanical input or strain is called shunt calibration. Shunt calibration involves simulating the input of strain by changing the resistance of an arm in the bridge by some known amount. This is accomplished by shunting, or connecting, a large resistor of known value across one arm of the bridge, creating a known DR. The output of the bridge can then be measured and compared to the expected voltage value. The results are used to correct span errors in the entire measurement path, or to simply verify general operation to gain confidence in the setup.

Data Acquisition and Display

Once the voltage readings from the strain gauge were obtained, conditioned and amplified to a gain of 600, they are still in analogue form as voltage. These analog signals need to be digitalized i.e. converted to digital signals. This can be done using an A-to-D converter. However, there is a need for calibrating the data thus obtained in the form of corresponding force measurements. Software control is required for doing the same. Thus, a microcomputer is required as well. Thereafter we need to display the readings on a display device.

These multiple tasks can instead be accomplished by the use of a single microcontroller. We have used Atmel’s AVR ATmega8 microcontroller for the same. The ATmega8 microcontroller has an in built 8-channel ADC with 10 bit accuracy and a facility for ADC noise reduction, programmable serial USART for interface with the computer and 4 ports of 8 bits each for input/output and for handling display devices.

The output signals of the amplifier serve as ADC input to the microcontroller. Then, with the help of pre-programmed instructions transferred to it by the USART, it converts them into corresponding force readings* and reads them out to a display unit connected to one of its ports. The display unit is a standard LCD HD44780 which can display 2 lines of 16 characters each.
Thus, the instantaneous (averaged over a period of 1 sec.) force readings are displayed on the LCD.

*Force readings established from voltage readings after proper calibration

**Conclusion**

The strain gauge based dynamometer for measuring cutting forces on lathe was successfully developed. The system was complemented with required signal conditioning and data acquisition system so as to directly display the force reading on the LCD screen.

The past development in metal cutting technologies and the longing for further improvement have increased the importance of measurement of cutting forces at the design of machine tools and cutting tools, fixtures, selection of cutting parameters for optimum operation performance. The dependence of cutting conditions (like speed, feed and depth of cut) on force and ability to control the quality and production cost by optimizing these parameters completely justify the development of dynamometer to measure the cutting force.

**Acknowledgements**

The authors express sincere gratitude to Mr. D.V. Gadre, Asst. Prof., Electronics Dept., NSIT, New Delhi and Mr. Pradeep Khanna, Head, Central Workshop, NSIT for their invaluable guidance, criticism, support and encouragement throughout this project work.

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