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Design Development and Testing of a Dynamometer for Drill Force Measurement

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Abstract: In this paper a strain gauge type drilling dynamometer is designed and constructed. The dynamometer was designed and constructed to measure the cutting forces in drilling. Elastic strain theory is used as the working principle. The dynamometer was calibrated to measure static forces produced while drilling. Four load cells each having two elastic beams is used to measure the force. Four strain gauges are present in each load cells. When we apply a force, elastic beams get deflected. This will induce a proportional distortion in the strain gauges. This distortion will result in change in resistance and thereby the voltage. Hence, by measuring this change in voltage, we can measure the cutting forces generated during metal cutting operations. The force measured will be displayed digitally. The proposed dynamometer has been calibrated using different mass of known value. Performance analysis of the designed and constructed two-dimensional strain gauge type dynamometer for drilling or allied process has been executed by measuring thrust force on the steel MS E250, heat treated HB = 160. Cutting tests has been conducted at different feed rates by using drill tools having different diameter. The cutting forces in the tests were compared to the results of the proposed empirical equations by Shaw and Oxford.

Keywords: Drilling Machine, Strain Gauge, Load Cell, Force, Force Calibration.

I. INTRODUCTION

Force measurement in metal cutting is an essential requirement as it is related to design of machine tool, tool design, power consumptions, vibrations, part accuracy, etc. It is the purpose of the measurement of cutting force to be able to understand the cutting mechanism such as the effects of cutting variables on the cutting force, the machinability of the work piece, the process of chip formation, chatter and tool wear. For over 100 years, metal-cutting researches attempting to understand the cutting behaviour better have investigated the cutting forces in metal cutting. It has been observed that the force values obtained by engineering calculations contain some errors compared to experimental measurements. Since the un deformed chip thickness and the direction of cutting speed vary at every moment, cutting process in milling is geometrically complex. Owing to such complexity, the cutting forces even in steady-state conditions is affected by many parameters and the variation of cutting force with time has a peculiar characteristic.

The accurate measurement of forces, however, has been a challenging task due to a number of reasons. With regards to micromachining specifically, the frequency bandwidth of commercially available force sensors is inadequate for the majority of micro-machining cutting-force frequency regimes due to the very high rotational speeds used for micro-milling processes. Also any force sensing system that is remote to the cutting tool has a limited frequency bandwidth caused by dynamics of the mechanical elements located between the cutting point and sensors (Albrecht, et al., 2005). In terms of conventional piezoelectric force sensors, a significant limitation is their inability to measure static forces. The quartz crystals of a piezoelectric force sensor generate an electrostatic charge only when force is applied to or removed from them. Even though the insulating electrical resistance of the sensor, cables and amplifier is quite large, the electrostatic charge will eventually leak to zero through the lowest resistance path, causing the signal drift. The inability to accurately measure the static component of forces often results in force measurements matching the expected forces in qualitative analysis of the machining processes, but not in the quantitative terms.

Force sensors for static and slower dynamic force measurements are based on strain gauges. They are used because of their ease of application, and comparatively low cost to piezo transducers. The most widely used characteristic that varies in proportion to strain is electrical resistance. Although capacitance and inductance-based strain gages have been constructed, these devices' sensitivity to vibration, their mounting requirements, and circuit complexity have limited their application. Based on the strain effect, rotating dynamometers mounted on main spindle and table force sensors placed between the workbench and work piece were both developed. Because of their few mounting constraint requirements, various types of rotating dynamometers have been proposed too. However, considering the difficulties in prolonging the power supply time of their wireless network modules and as well as enhancing the sensor bandwidth limited by the stiffness of the drilling spindle, table force sensors are mainly studied.

If a strain gauge is glued to a structure, any distortion of the structure will also cause a distortion of strain gauges. The gauge contains conducting material, and the distortion results in a change in its resistance. This distortion is proportional to changes in voltage. Hence, by measuring this change in voltage, we can measure the cutting forces generated during metal cutting operations. Due to complicated tool geometry and varying cutting conditions of metal cutting, the analytical cutting force calculations may not always give accurate results. Hence, experimental measurement of cutting forces is required. For this purpose, various kinds of

Dynamometers are designed, developed and tested to measure the cutting forces. The dependence of machining parameters like spindle speed, feed rate and depth of cut on cutting forces and the ability to control the quality and production cost by optimizing these parameters completely justify the need of Dynamometers to measure these forces.

A three component table drilling force sensor with strain gauges is proposed in the present study. Elastic strain theory is used as the working principle. Four load cells are arranged in 90degree to each other in a frame. Each load cell having four strain gauges is used to measure the thrust force in drilling. The proposed dynamometer has been calibrated using different mass of known value. Performance analysis of the designed and constructed two-dimensional strain gauge type dynamometer for drilling or allied process has been executed by measuring thrust force on the steel MS E250, heat treated HB = 160. The cutting forces in the tests were compared to the results of the proposed empirical equations by Shaw and Oxford.

II.COMPONENTS AND DESCRIPTION

The components that are used in the manufacturing of **STRAIN GAUGE DYNAMOMETER** are as follows,

1. Frame
2. Circular plate
3. Load cell
4. Battery
5. Microcontroller
6. Connecting wires

A. Frame

This is made of mild steel material. The whole parts are mounted on this frame structure with the suitable arrangement. Boring of bearing sizes and open bores done in one setting so as to align the bearings properly while assembling. Provisions are made to cover the bearings with grease.

B. Circular Plate

Mild steel has a high resistance to breakage. **Mild steel**, as opposed to higher carbon **steels**, is quite malleable, even when cold. This means it has high tensile and impact strength. Higher carbon **steels** usually shatter or crack under stress, while **mild steel** bends or deforms.

C. Load Cell

A **load cell** is a type of transducer, specifically a *force* transducer. It converts a force such as tension, compression, pressure, or torque into an electrical signal that can be measured and standardized. As the force applied to the load cell increases, the electrical signal changes proportionally. The most common types of load cell used are hydraulic, pneumatic, and strain gauge.

D. Strain Gauge Load Cell

Strain gauge load cells are the kind most often found in industrial settings. It is ideal as it is highly accurate, versatile, and cost-effective. Structurally, a load cell has a metal body to which strain gauges have been secured. The body is usually made of aluminium, alloy steel, or stainless steel which makes it very sturdy but also minimally elastic. This elasticity gives rise to the term "spring element", referring to the body of the load cell. When force is exerted on the load cell, the spring element is slightly deformed, and unless overloaded, always returns to its original shape. As the spring element deforms, the strain gauges also change shape. The resulting alteration to the resistance in the strain gauges can be measured as voltage. The change in voltage is proportional to the amount of force applied to the cell, thus the amount of force can be calculated from the load cell's output.

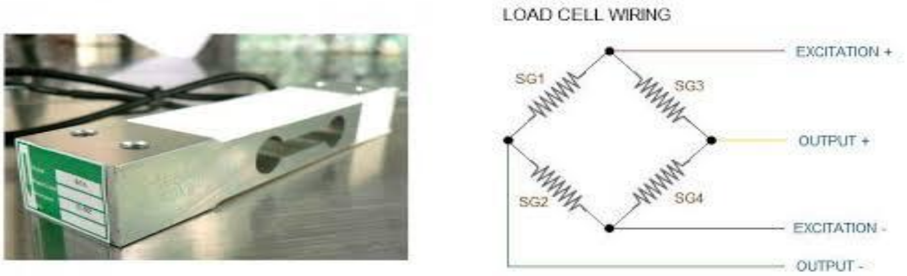

FIG.1. Strain Gauge

A strain gauge is constructed of very fine wire, or foil, set up in a grid pattern and attached to a flexible backing. When the shape of the strain gauge is altered, a change in its electrical resistance occurs. The wire or foil in the strain gauge is arranged in a way that, when force is applied in one direction, a linear change in resistance results. Tension force stretches a strain gauge, causing it to get thinner and longer, resulting in an increase in resistance. Compression force does the opposite. The strain gauge compresses, becomes thicker and shorter, and resistance decreases. The strain gauge is attached to a flexible backing enabling it to be easily applied to a load cell, mirroring the minute changes to be measured. Since the change in resistance measured by a single strain gauge is extremely small, it is difficult to accurately measure changes. Increasing the number of strain gauges applied collectively magnifies these small changes into something more measurable. A set of 4 strain gauges set in a specific circuit is called Wheatstone bridge.

E. *Microcontroller Unit*

A microprocessor consists of a powerful **CPU** tightly coupled with memory (RAM, ROM or EPROM), various I/O features such as serial port(s), parallel port(s), Timer/Counter(s), Interrupt controller, Data Acquisition inter-faces Analog to Digital Converter (ADC), Digital to Analog Converter (DAC), everything integrated onto a single silicon chip.It does not mean that any micro controller should have above said features on-chip. Depending on the need and area of application for which it is designed, the on-chip features present in it may or may not include all the individual sections said above. Any micro computer system requires memory to store a sequence of instructions making up a program, parallel port or serial port for communicating with an external system, timer/counter for control purposes like generating time delays, baud rate for the serial port, apart from the controlling unit called the Central Processing Unit.

III. WORKING PRINCIPLE

- The dynamometer consists of a frame, circular plate, load cell & microcontroller.
- The frame is made up of rectangular channel on which the whole setup is mounted.
- The load cell is placed on to the frame at an angle 45degree to each other on the four sides of the rectangular channel which is used for measuring the mechanical load applied on the load cell.
- Four strain gauges are present on each load cell. They are mounted at both end of the load cells. When a force applied a pair of load cell will be under tension and the other pair will be under compression.
- From each load cell, there will be two excitation channel and two output channels.
- The 4 load cells on the all directions tends to gives the output from each of the directions and it will be shown in the display.
- The load cells & circuit is powered by a 12V, 2Amps battery.

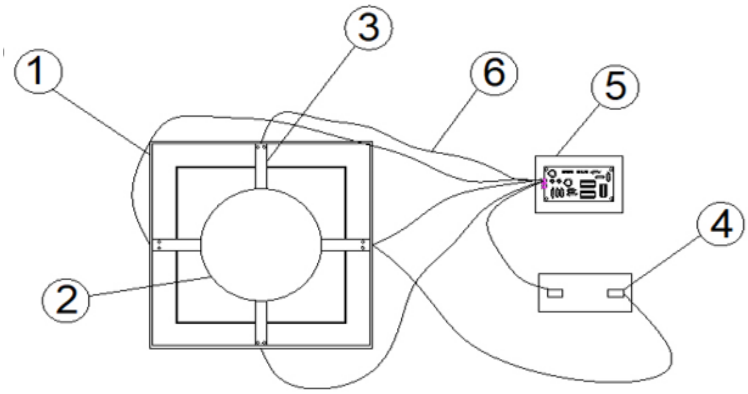

FIG. 2. 2D Drawing of dynamometer

From the above figure (fig. 2), the components are;

1. Frame
2. Circular plate
3. Load cell
4. Battery
5. Micro controller
6. Connecting wires

Consider the case of a beam rigidly fixed at the ends A and B as shown in figure. Let the end A be supported on a rigid base and the other end B capable of deflection without rotating at the supports.

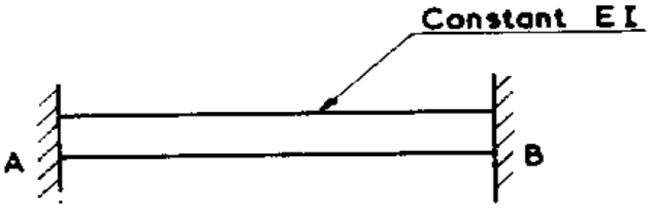

FIG. 3. Elastic beam supported at two ends (load cell) [11].

Force at A = Force at B = $\frac{12\delta_B E I_Z}{l}$ …….(1)

Where,

δ_B- Deflection of the beam at point B, m

E - Modulus of elasticity, MPa

I_Z - Moment of inertia of the beam about z axis, Nm^2

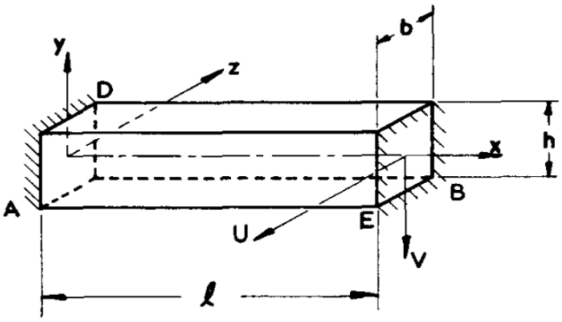

FIG. 4. Forces acting on elastic beam or load cell [11].

When the beam is subjected to a bending force V in any cross section B which is at a distance of x from the center of the beam as shown in the figure, maximum tensile stress occur at section B is given as,

$\sigma_{max} = \frac{6Vx}{bh^2}$ ……..(2)

Where,

σ_{max} – maximum stress at B, N/m^2

V- force acting at a section B, N

x- distance between the section at which the force is acting and the center of the beam, m

h- height of the section, m

b- breadth of the section, m

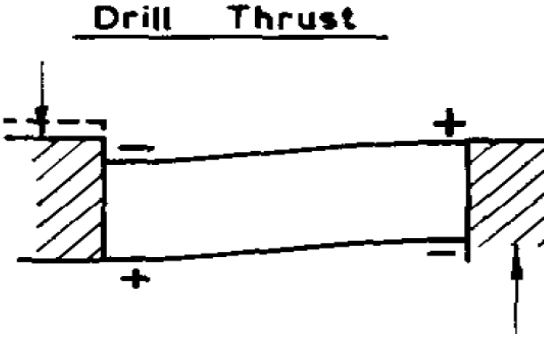

FIG. 5. Effect of thrust force on elastic beam or load cell [11].

A. Electrical Circuit and Instrumentation

The accuracy of the measurements obtained from the dynamometer depends upon the design of the electrical circuit and the choice of the instrument, DC supply being used for the bridges. The electrical circuit was designed to satisfy the following requirements:

(1) Indication and control of current in each bridge.
(2) Independent sensitivity control for each bridge.
(3) Independent balancing of each bridge.
(4) Measurement of output of each bridge separately.

The power to the bridges was supplied by means of accumulators. The sensitivity control for each bridge was obtained by selecting suitable carbon resistors. Complete electrical screening and earthing of the whole system were of great importance in order to eliminate any noise in the signal.

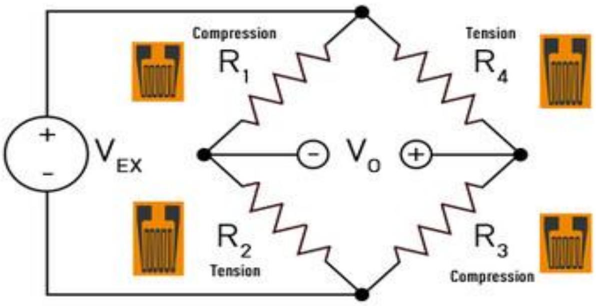

FIG. 6. Strain gauge circuit.

IV. CALIBRATION OF DYNAMOMETER

The dynamometer is calibrated using different known mass. Mass under almost every terrestrial circumstances, is the measure of matter in an object. Measuring force takes additional factors into account; air density, material density and gravity. It’s the effect of gravity which can produce significant errors when comparing mass and force measurements. Gravity is not constant over the surface of the earth. The most extreme difference is 0.53% between the poles and the equator. A force measuring device calibrated in one location using mass weights then deployed somewhere else will produce different strains on the physical element. The resulting errors can be significant. Corrections for the difference in force and mass measurements is possible. When a device is adjusted for force measurements, the device will measure force without additional error for gravity correction, air density correction and so on needed.

$$\text{FORCE} = \frac{M\times g}{g\times(1-\frac{d}{D})} \quad \text{……..} \quad (3)$$

Where; M: mass of the object
g: acceleration due to gravity
d: air density
D: material density

For materials having high density, the value of the term $(1\text{-}\frac{d}{D})$ will always be less than one. So by neglecting the values of air density and material density, the value of the force will be approximately equal to

$$\text{FORCE} = \text{MASS}\times \mathit{LOCAL\ GRAVITY} \quad \text{…….(4)}$$

This method completely ignores air density and material density which carries more error and risk. This is the method most calibrators use. The proposed dynamometer is calibrated by using mass of 1kg, 2kg, 3kg, 4kg and 5kg. The values are then recorded and a graphical relation is plotted.

Table 1. Dynamometer calibration

Mass added to dynamometer, (kg)	Theoretically calculated value of force, F = M x g , (N)	Dynamometer reading (kg)
1	9.8	2
2	19.6	3
3	29.4	4
4	39.2	4
5	49	5

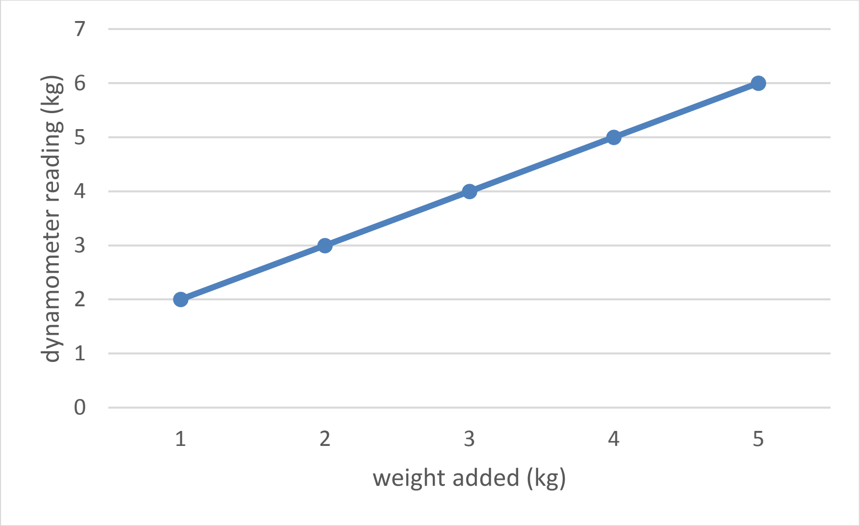

FIG. 7. Graphical plot of dynamometer calibration

From the above graphical plot (fig. 7), we can see a linear relationship between the dynamometer reading and mass added. The dynamometer shows reading almost equal to the actual reading. In-order to get the force value, we have to multiply the dynamometer reading and the value of acceleration due to gravity.

V. RESULTS AND DISCUSSION

Performance analysis of the designed and constructed two-dimensional strain gauge type dynamometer for drilling or allied process has been executed by measuring thrust force on the steel MS E250, heat treated HB = 160 using the dynamometer. The cutting forces in the tests were compared to the results of the proposed empirical equations by Shaw and Oxford. They derived those equations by measuring the cutting forces on the test material SAE 3245, HB = 196–207. In our experiments, forces exerted by drill tools of diameter 8mm,10mm and 12mm to the work piece with feeds 0.1mm/rev, 0.15mm/rev, 0.2mm/rev and 0.25mm/rev were measured during machining. In the tests, metal cutting was performed without using any cutting-fluid. Derived empirical equations for drill thrust and torque and also equations from similar works performed by Shaw and Oxford have been presented in Eqn. (5).

$T_v = 8.17\ H_B f^{0.8} d^{0.8} + 2.54 x 10^{-2} H_B d^2$ ……..(5)

Thrust forces for different drill diameters of 8mm, 10mm, and 12mm obtained from the dynamometer is compared graphically with those obtained through theoretical calculations. The comparison is given below.Force value from dynamometer can be obtained by multiplying dynamometer reading and acceleration due to gravity (here we taken acceleration due to gravity g= $9.8 m/s^2$).

Force value from dynamometer reading = dynamometer reading× g, N ……(6)

Table 2. Value of thrust force for drill tool diameter of 8mm

Feed (mm/rev)	Dynamometer reading (kg)	Force value obtained from dynamometer (N)	Force value obtained from theoretical calculations (N)
0.1	120	1176	1350
0.15	158	1548	1780
0.2	210	2058	2165
0.25	282	2764	2540

Table 3. Value of thrust force for drill tool diameter of 10mm

Feed (mm/rev)	Dynamometer reading (kg)	Force value obtained from dynamometer (N)	Force value obtained from theoretical calculations (N)
0.1	192	1882	1714
0.15	238	2332	2215
0.2	262	2568	2685
0.25	310	3038	3130

Table 4. Value of thrust force for drill tool diameter of 12mm

Feed (mm/rev)	Dynamometer reading (kg)	Force value obtained from dynamometer (N)	Force value obtained from theoretical calculations (N)
0.1	228	2234	2100
0.15	282	2764	2680
0.2	318	3116	3220
0.25	365	3577	3730

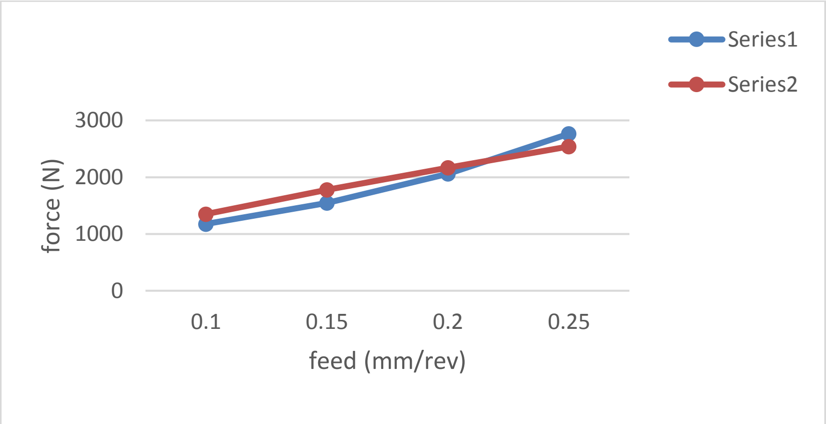

FIG. 8. Comparison of the observed and calculated drill thrust force for drill diameter 8 mm.

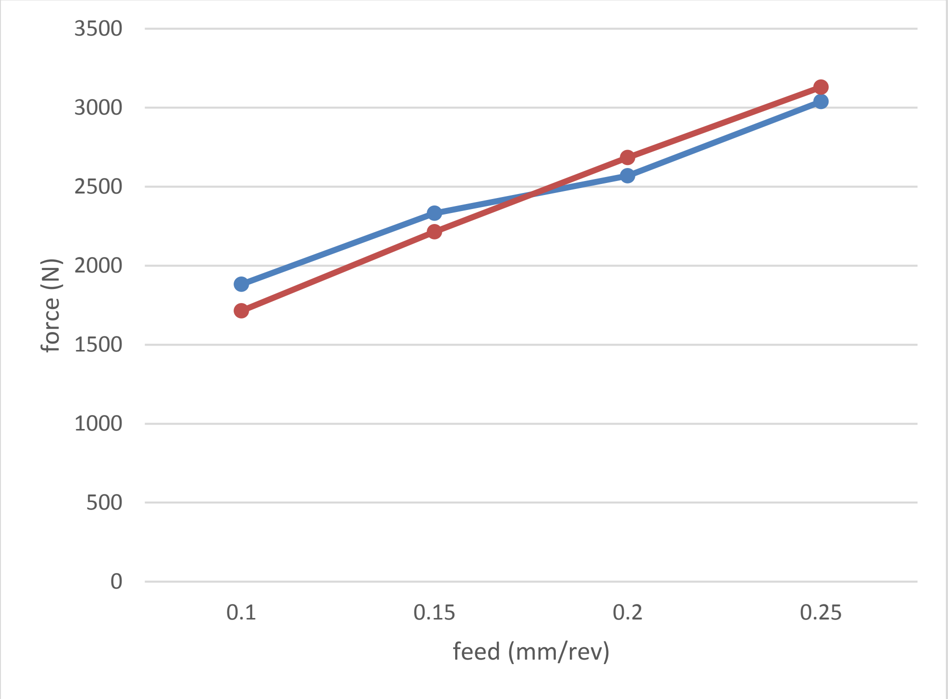

FIG. 9. Comparison of the observed and calculated drill thrust forces for drill diameter 10mm.

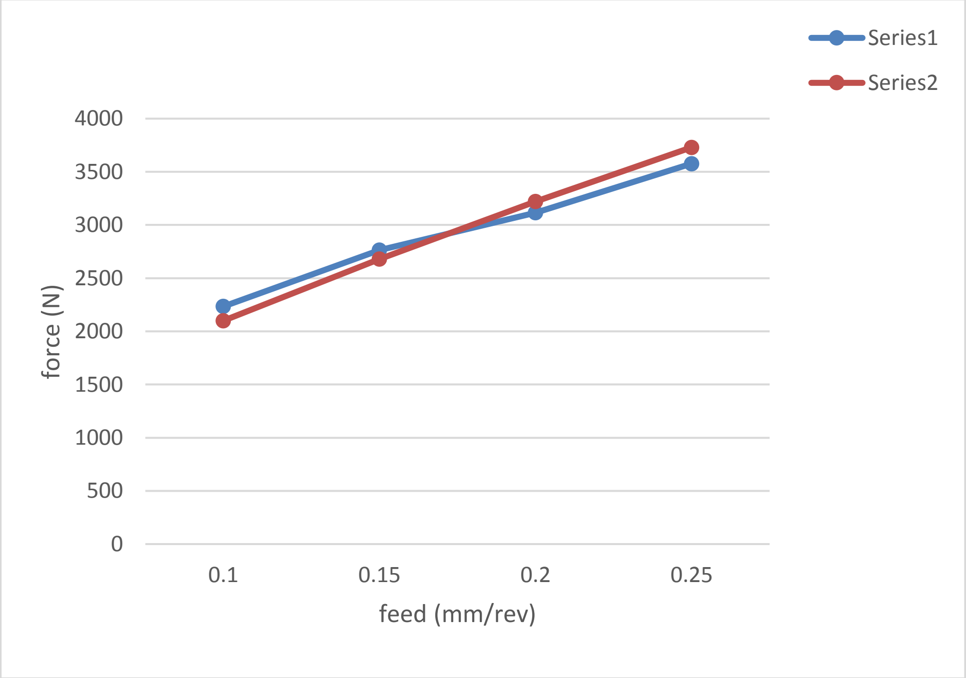

FIG. 10. Comparison of the observed and calculated drill thrust forces for drill diameter 12mm.

From the above figures series1 represents the value of drill thrust forces obtained for various drill tool diameters using the proposed dynamometer and series2 represents the value of drill thrust forces obtained for various drill tool diameters from the theoretical calculations using the empirical equations of Oxford and Shaw. Error of the drill dynamometer value from the theoretical value may be due to the error occurred from the calibration process. Because the dynamometer is calibrated by using different mass. By using Ring force gauges for calibration of the dynamometer, the errors will be minimised.

VI. CONCLUSION AND FUTURE WORK

A dynamometer with four load cells each having two elastic beams is designed and constructed. The designed and constructed dynamometer has been used to calculate the force values obtained by drilling mild steel, MS E250, with different drill tool diameters of 8mm, 10mm and 12mm. The experiments are conducted at various feed rates of 0.1mm/rev, 0.15mm/rev, 0.2mm/rev and 0.25mm/rev. The results obtained from the cutting tests has been compared with the empirical equations of Shaw and Oxford.

The difference between the observed and calculated values in these tests could be due to the fact that in the constants found by Shaw and Oxford, SAE 3245 was used, whereas the work piece material used in the present tests was SAE 1020. As well the proposed drill dynamometer was calibrated using different mass by neglecting the air density and material density. Mass calibration will produce more error in a force measuring system. Therefore, these expected small differences can be neglected in this comparison. Consequently, the dynamometer can be used efficiently for measurements of the machining forces for drilling or allied processes.

We can extend the project to calculate three component of forces such as radial force, thrust force and the force acting opposite to speed. For that we have to calibrate the dynamometer for all the component of force. We can also measure the force values under dynamic conditions by calibrating the dynamometer under dynamic conditions using vibration generators. The proposed dynamometer can also be used to measure torque produced during machining. The dynamometer can be coupled to a computer and we can generate graphical relationships between different parameters used at the machining time. By suitably insulating the system, we can use it to measure forces when using cutting fluids while drilling. The proposed dynamometer can also be used to measure cutting forces in milling operations. The sensitivity and capacity of the system can be increased by making suitable changes in hardware and software. By using load cells having high capacity we can increase the capacity of the system.

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