Modified Approach for Cutting Force Measurement for Face in Milling

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Abstract

In modern manufacturing processes, there is an ever increasing demand for higher productivity. The continuous demand for higher productivity and product quality asks for better understanding and control of machining processes by reducing machining time with the increase of cutting force and material removal rate. The variation in cutting force results in deflection in the tool and workpiece and which intern deteriorates geometrical accuracy. One of the methods of improving productivity and quality lies in fact, to develop monitoring system which can control and maintain the cutting force at a prescribed level by adjusting cutting parameters using adaptive control technique.

The cutting force is one of the important characteristic variables to be monitored in the cutting processes.

This research paper consists of an indirect cutting force estimator during face milling process. Cutting forces and torque models are derived from cutting geometry in face milling process. The relationship between feed motor current and cutting forces has been developed from the proposed force models. Cutting forces are measured indirectly by sensing the currents of feed drive servomotors through the Fanuc SERVOGUIDE software. The instantaneous current data captured through the software is utilized for determining the instantaneous torque developed by the feed motor and instantaneous cutting forces have been estimated by using force and torque models. Practical issues calculating cutting force using motor current on a commercial machining center is also carried out.

The experimental methodology involved estimation of torque consumption by the motor, first during idle movement and second during actual machining of the component. The machining of the components using standard cutting condition has been carried out and the cutting force estimated using the above method were validated by comparing the cutting force data derived from an accurate dynamometer for similar cutting condition. Practical experimental results are found to be in agreement with the estimated value to an accuracy of ± 10%. This proves indirect measurement is quite reasonable and economical and it has an important application value with high compatibility and stability.

Keywords: Cutting force, Feed motor, face milling, tool dynamometer

1. Introduction

In CNC Machines it is important to monitor an abrupt malfunction during machining, such as overload on the cutting tool, tool breakage, machine tool chatter, work surface finish etc .hence it makes important to control the condition of the cutting forces, for which the tool dynamometers used in most industrial machines to provide the most accurate measurement of cutting forces. It is known that cutting process is well identified from cutting force signals measured by a tool dynamometer. However, the use of a tool dynamometer in industrial environments is not desirable due to many disadvantages such as heavier and reduces the rigidity of work piece clamping against as suggested, rigid mounting practice adopted in industrial requirement makes them less durable, less flexible, and expensive[1]. Many researches have been carried out to monitor and diagnose the malfunctions during machining. Cutting force signals, AE signals, and acceleration signals have been used to monitor the cutting process [1-6].

The DC feed drive was used as a cutting force sensor and motor current can be used to measure the cutting force [5, 6]. Motor current is proportional to the output torque of the motor and therefore the cutting force. Thus, current measurement sensor can be used to monitor the cutting process in a manner similar to a tool dynamometer.

Face milling process includes rough machining and finishing. During rough machining overload on the tool can lead to tool fracture or machine tool chatter, and damage the workpiece and machine tool itself. Therefore, feedrate is usually set to a low level than increase in spindle speed to avoid the overload. Sometimes, operators manually decrease the feedrate under severe cutting condition and increase it under light cutting condition. Hence, it is necessary to detect the overload on the tool and to regulate the cutting force at a constant level during machining in order to increase productivity [2, 3].

In face milling operation surface finish and dimensional accuracy are important factors. In addition, one should choose right tool and cutting parameters for the job. The success of the face milling operation can be measured in many ways. One of the easiest methods is computation of the static and dynamic force. Variable spindle speed computation is the other method used to determine the quality of face milling process.

In this research work, cutting force was measured indirectly from feed motor current of X Y and Z axes of Vertical machining centers. Spindle motor current is independent of the feed and of the cutting direction. In Addition the use of feed motor current for monitoring multi-axis machining is difficult because of different phase lags of each axis. [7] After the cutting force was measured from the feed motor current, it was validated using dynamometer for various control parameters.

2. Literature Review

Machining process is dynamic, nonlinear, random and strong coupling. The cutting force mainly varies with these factors, including work piece materials, cutter materials, cutter geometric shapes, cutting angle, cutting speed, cutting depth, cutting fluids, feed at which work piece advances, type of chip and so on. Therefore the accurate measurement of cutting force has been a difficult problem in the manufacturing industry for a long time.

At present the traditional measurement of cutting force can be classified into two groups. One of them uses experience formulae [8-9]. There are usually versatile experience formulae corresponding to different machining. The experience formulae are simple and convenient to be used hence they are widely used in manufacturing. But there are many factors, such as work piece materials, cutter materials, cutter geometric shapes and other factors, to which are not given enough consideration in these experience formulae, so the result from this method is imprecise and can only be used as reference.

In the other method, force measuring sensors and control signal has been used to measure the forces induced during the cutting. The accuracy of force sensor mainly depends upon accuracy of the sensor and the testing methodology applied to measure the forces. There are different types of force measuring sensors, especially the resistance strain measure system and the piezoelectric crystal measurement, which are commonly used in testing cutting forces [10]. The resistance strain measure system is also divided into two types, static and dynamic measurement. They differ mainly in the core element. The cutting force is typically random and changes with the machining time and cutting conditions, thus we can only adopt the

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dynamic resistance strain measurement to measure the cutting force.

The dynamic resistance strain measurement is quite common to measure the cutting force [5]. In the machining, the strain area and magnitude are varied with the different cutting edge and direction. According to this, the strain element should be differently placed. Currently, the dynamic resistance strain measurement is successfully used to measure the cutting force of milling, grinding and lathe operations. A sketch of measurement of cutting force using dynamometer in milling is shown in figure 1.When testing the cutting force of the milling machines in face milling processing, it is difficult to fix the sensor on the cutter hence it is fixed on the work piece. In the process, because of the shape and size of workpiece keeps changing, the stress distribution caused by the cutting force is changing over time. Therefore, it is difficult to attain the value of cutting force simply by measuring the response in milling process. And the resistance strain measure system has lower precision to measure the cutting force. In the control system, the controller sends the current signal to the servo driver, where this signal gets amplified to drive the servo motor at a specified feed rate. A tacho generator generates a signal according to the feed of the table. This signal is sent back to the machine control unit(MCU) for comparison between the actual feed of the servo motor and the desired feed, if there is an any error, which is corrected by MCU and adjusted feed rate signal send to the servo driver. The comparison of the dynamometer measured cutting force and the indirect method of measuring the current signal of the controller has been done by Tae young Kim (1995) and Na Wang, Xiangbo Ze, Changsheng Ai, Yumei Ji (2006). Several current measuring sensors have been developed to measure the current consumed during the process. A system controlled current signal was used, which is sent to driver during the cutting. The drives then amplify this signal according to the servo motor requirements. For communication purpose SERVOGUIDE diagnostic software which is developed by the FANUC was used.

1.1 Mathematical model to measure the current in the control system

The linear transfer function between the variation of the feed rate command V_c and the variation of the actual feed rate V_d for the x-axis feed-drive system is identified as

$$\frac{V_c}{V_a} = \frac{\omega_c}{\omega_a} = \frac{K_1\, K_{it}\, K_t\, e^{-st}}{J_e L_a\, S^3 + J_e\left(R_a + KHK_{Ip}\right)S^2 + K_t\left(K_p\, K_{ip} + K_b\right)S + K_i K_t K_{ip}}$$

As shown in the figure 2, the motor drive torque T_m is exerted in accelerating the equivalent feed-drive inertia J_e, and in overcoming the disturbance torque T_d. The disturbance torque T_d consists of the friction torque in the drive T_f and the cutting torque T_c reflected on the motor shaft [2, 4, and 7]

Therefore Mechanical equation for torque is,

$$T_m = J_e \frac{d\Omega}{dt} + T_d \qquad (1.1)$$

where, T_d = sign (Ω) $T_f + T_c$ (1.2)

Electrical equation for torque is

$$T_m = K_t\, I \qquad (1.3)$$

3. Methodology of cutting force estimation

3.1 The Servo Drive System of the CNC Machine Tool

The servomotor is widely used in NC machine tools, processing centers, industrial robots, printing machinery and other high-performance electromechanical equipments, because of the characteristics of good control performance, simple structure, smooth low-speed operation and high precision positioning. A servomechanism is a closed-loop control system in which the mechanism position or motion will be precisely controlled. Hence in the NC machine tool, the servomechanism is usually adopted to feed. Figure 3, shows the arrangement of a servomechanism of NC machine tools wherein servomotor generates electromagnetic torque T_m and drives precision ball screw assembly which serves to transform rotary motion into linear motion to move the workbench. Thus, the machining process can be approximately divided into three sequential processes: the formation of cutting force, the transfer of cutting force and the conversion from mechanism to electricity. The cutting force is exactly the head parameter and the servo current is exactly the end parameter of three sequential processes. When the servomotor works in the stable state, the electromagnetic torque of the servomotor should be equal with the load torque which consists of

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the friction torque T_f, the additional friction torques T_p and the cutting torque T_c. Hence there is a balance equation of the servo system as,

$$T_m = T_f + T_c + T_p \quad (2.1)$$

$$T_p = F_p \frac{p}{2\pi\eta}$$

$$T_f = F_f \frac{p}{2\pi\eta}$$

$$T_c = F_c \frac{p}{2\pi\eta}$$

Using the terms T_f, T_c and T_p in equation (4) and solving for F_c, we have,

$$F_c = ([T_m - T_f - T_p] \times 2 \times \pi \times \eta)/p \quad (2.2)$$

Equation (2.2) is the mathematical model to determine F_c from T_f, T_c and T_p. Obviously, the corresponding relations exist between the electromagnetic torque and the cutting force. When the cutting force increases, the electromagnetic torque of the servomotor also increases.

According to the control theory of the electromagnetic torque of the motor, the current of the servomotor will also augment. Hence a relation can be established between the current and the milling force. Therefore, the indirect measurement of the cutting force is feasible through testing.

3.2 The Characteristics of the Drive Motor

In the CNC machine, permanent magnet synchronous motor (PMSM) is widely used to drive the machine tool. Here it is used to analyze the characteristics of the servomotor. Next we use the vector conversion technology to illustrate the relation between the testing current and the electromagnetic torque of the PMSM. This technology is used to analyze the motor current in the rule of forming the same rotary magnetic field. According to this, the three phase electrical current of the servomotor can be equalized to two-phase electrical current to establish the d-q coordinate system. Thus we can control the servomotor just like controlling the DC motor through the vector conversion control. Three-phase stator currents of the PMSM generate the rotary magnetic field, but the permanent magnetism poles of the rotor generate sinusoid magnetic field which is located on the rotor. So the rotor magnetic potential is attracted to rotate by the stator magnetic potential.

In the coordinate rotation system, we take the rotor magnetic field as axis d, thus the three-phase stator currents of the PMSM and i_u, i_v, i_w can be decoupled as shown in Figure 3. In the d-q coordinate system, the three-phase alternating current can be expressed below equation.

$$i_u = I \cos\theta$$

$$i_v = I \cos\frac{(\theta+2\pi)}{3}$$

$$i_w = I \cos\frac{(\theta-2\pi)}{3}$$

and, $i_u + iv + i_w = 0$ (2.2)

When the gas magnetic field of the motor is distributed as sine wave, λ_m is constant $i_u = I \cos\theta$

$$i_v = I \cos\frac{(\theta+2\pi)}{3}$$

$$i_w = I \cos\frac{(\theta-2\pi)}{3}$$

and, $i_u + i_v + i_w = 0$ (2.2)

Through the vector conversion, the two-phase electrical current on the d-q coordinate system can be expressed as follows.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta+\frac{2\pi}{3}\right) & \cos\left(\theta-\frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta+\frac{2\pi}{3}\right) & \sin\left(\theta-\frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} \quad (2.3)$$

Apparently, the current i_d and λ_q can be calculated using either two phase current of the servomotor or stator current in actual control. The common form of the above equation of the electromagnetism torque of the PMSM is,

$$T_m = \frac{3}{2} P \left[\lambda m \; ip + id \; iq\left(L_d - L_q\right)\right] \quad (2.4)$$

Generally it is adopted as $i_d = 0$ on the basis of principle of the maximum of the ratio of the torque and current equation above, then the electromagnetism torque can be simplified as,

$$T_m = \frac{3}{2} P \left[\lambda_m \; i_q\right] \quad (2.5)$$

When the gas magnetic field of the motor is distributed as sine wave, λ_m is constant, so Tm is proportional to the armature current i_q. Therefore, the current measurement of the PMSM can reflect the variety of the electromagnetic torque of the motor. Each motor has its own torque constant. Then equation (8) can be simplified further as,

$T_m = T_t.i_q$ (2.6)

3.3 Data Acquisition System and Milling Tool Dynamometer

Milling tool dynamometer is a recent development in the electronic field of measurement which helps the tool designer to have an accurate knowledge of the different forces involved in machining operation.

The dynamometer comprises of the sensing element bonded with strain gauges dealt with the provision to fix the tool and clamp rigidly. When the work piece is being machined the forces associated are displayed on the indicator. The dynamometer manufactured by Syscon Instruments Pvt. Ltd (one part in 2000 resolution) is used to find the cutting forces.

3.4Servoguide

SERVOGUIDE software from FANUC system is used for monitoring and performance check of the CNC machine. It has facilities for communication between the CNC machines to personal computer. This software is developed by a FANUC company for motor tuning, program upload and download (both application and operating), feed and speed commands, measurements of power consumed by the spindle motor, torque and current drawn by the each axis servomotor and spindle motor etc. The current drawn by the each axis is collected. This current is nothing but the current required to move the table move at specified feed rate, overcome friction, electrical and mechanical disturbances. In “with cutting method” tool is engaged with the material by a specified depth of cut and current drawn by the servo motor is collected. This current includes the current required to remove the material and also current required to move the table, overcome from friction, electrical and mechanical disturbance. This current multiplied by the torque constant gives the cutting force required to cut the material. The current drawn by the servo motor was collected through the SERVOGUIDE software.

3.5Macine Tool

Machine tool used in this work is Vertical machining centers (model: Agni BFW, BMV 45 T20, manufactured by Bharath Fritz Werner Ltd). BT 40/A70 /RD 25 SEENU Precision Shank, Insert Type face milling cutter of 50mm Diameter with 5 inserts. The total clamping area is of $0.450 \times 0.9 m^2$. Spindle 5.5/7.5KW conti./30min. rating with Fanuc CNC systems. Power of Permanent magnet motors used for x and y direction feed drives and a squirrel-cage induction motor is used for the spindle drive. The spindle motor and the feed motor currents were measured by current SERVOGUIDE and the cutting force was measured by a tool dynamometer. Measured data were stored in the computer through AD2200 AD converter. The relationship between the spindle motor current and the cutting force was obtained from the stored data.

4. Results and Discussion

4.1 The mathematical model of the cutting force and the current of the servomotor

When the feed servo motor of the machining tool is in the stable state, from (1.3) (2.1) and (2.6), we can obtain the equation for cutting forces (3.1) as follows,

$T_m = T_t \quad iq \quad = \quad T_f + T_c + T_p = K_t I$

$T_c = (K_t I) - T_f - T_p$ (3.1)

Thus, there is a linear relationship between the cutting force and servo electrical currents and other parameters such as torque coefficient, preload torque, and frictional torque, efficiency of the ball screw and pitch of the ball screw. As the cutting force increases, the current also increases, and vice versa. By measuring the spindle power and current of the feed motor indirect measurement of the cutting force can be achieved using the equation (3.1) in Face milling operation in NC systems. In actual control, the current signals respond slower than the cutting force. When cutting force is zero, the current value is not zero mainly because current signals are also subject to the effects of resistance along the way. Clearly, there is a lag in servo motor currents. The current (which can reflect the changes of the cutting force) can be extracted to investigate the changes of cutting force after dealing with the motor currents in some methods such as intelligent adaptive control.

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Figure 4 represent the variation in torque with feed motor current for two different directions of feed (X and Y). As seen from the figures, torque exhibits a linear dependence on feed motor current. It can also be observed that the idle current of the servo motor is not 0A at 0 load. This proves that the indirect measurement of the cutting force is feasible through the current or the power of the feed motor.

The purpose of this work is to estimate the cutting force using the measured motor current. The current consumed (I_o) by the feed drive system in idle cutting is -0.0007v + 0.3476 which varies with feed speed v. The remaining current ($\Delta I = I - I_o$), called the cutting current, depends on the feed speed due to the additional friction caused by the cutting load and damping of the feed drive affect feed speed v .It is essential to understand the relationship of the cutting force with the cutting current and spindle speed.

To compare the estimated results and actual ones, cutting tests were carried out on the CNC milling center Agni BFW, BMV 45 T20. A Syscon 960042R cutting force dynamometer was used to obtain the force patterns and the magnitude of the actual force, which was compared with estimated one obtained from equation (3.1). The cutting force patterns obtained from the dynamometer as shown in figure 8 to14 for various combination of cutting parameters. The measured value Verses theoretical values are plotted in figure 5 for cutting forces along X and Y axis respectively. The error between the actual and the estimated force under all experimental cutting conditions are is within 10-15%, table 1 and table 2 which validates the accuracy and feasibility of the suggested approach.

5. Conclusion

A modified method of a cutting force estimator with motor currents is proposed for face milling machines. Cutting forces are measured indirectly from the observed currents of feed drive servomotors through the mathematical estimator. The validity of the developed estimator has been verified on a vertical machining center through the experiments

1. The prediction accuracy from the modified approach of the cutting forces values in this research work are about 90%.
2. Simple and inexpensive way of measuring cutting force proposed in the research work can be implemented in cutting process monitoring such as tool breakage or wear, the machining error and defective workpieces in milling with greater expediency.
3. Feed motor current was used to measure the cutting force indirectly; electric torque was shown to be proportional to the actual mechanical torque. The effectiveness of current monitoring has been evaluated as a measure of the feed cutting force of the feed drive system.
4. The cutting forces obtained from the dynamometer is almost equal to the forces calculated using motor currents, it is indicating that dynamometer can be avoided.

This method is, in principle, capable of the development of adaptive control system to a wide range of cutting conditions, workpiece and tool material. Experimental results have shown that this modified approach of measuring cutting force is effective, simple low cost and industry applicable.

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Table 1.Correlation between the calculated and measured cutting force exerted along X-Axis

S. No:	Speed (RPM)	Feed Rate (mm/min)	DOC (mm)	Cutting Current (A)	Cutting Force Calculated (N)	Cutting Force Measured(N)	Error (%)
1	300	120	0.1	0.7	225.4463	245.25	8.074
2	325	130	0.1	0.71	230.7811	245.25	5.899
3	350	140	0.1	0.82	289.4638	294.3	1.643
4	350	210	0.1	0.45	92.07644	98.1	6.140
5	350	52.5	0.1	0.9	332.1422	323.73	-2.59
6	375	160	0.1	0.99	380.1553	392.4	3.120
7	400	170	0.1	1.01	390.8249	402.21	2.830
8	450	67.5	0.1	0.45	92.07644	98.1	6.140
9	478	52.5	0.1	0.67	209.4419	215.82	2.955
10	450	180	0.15	0.89	326.8074	362.97	9.962
11	300	195	0.15	0.91	337.477	353.16	4.440
12	325	210	0.15	0.9	332.1422	343.35	3.264
13	350	87.5	0.15	0.83	294.7986	284.49	-3.62

14	350	280	0.15	0.57	156.094	166.77	6.401
15	350	225	0.15	1.18	481.5164	470.88	-2.25
16	375	240	0.15	0.92	342.8117	353.16	2.930

Table 2.Correlation between the calculated and measured cutting force exerted along Y-Axis

S. No:	Speed (RPM)	Feed Rate (mm/min)	DOC (mm)	Cutting Current (A)	Cutting Force Calculated (N)	Cutting Force Measured(N)	Error (%)
1	300	120	0.1	0.7	225.4463	245.25	8.074
2	325	130	0.1	0.71	230.7811	245.25	5.899
3	350	140	0.1	0.82	289.4638	294.3	1.643
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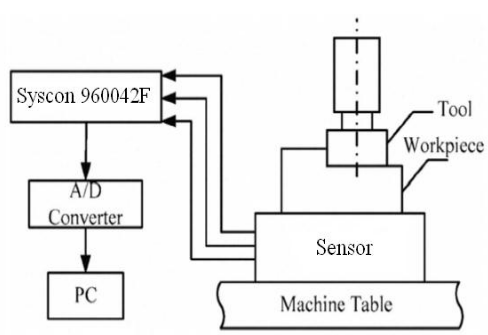

Figure 1. The block diagram of the Cutting force measurement using dynamometer

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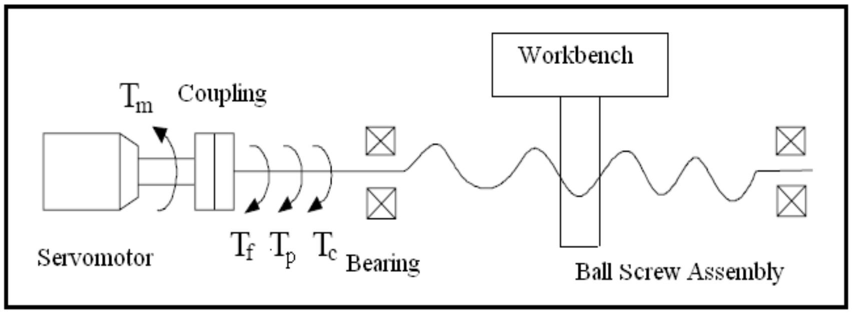

Figure 2. The block diagram of a servomechanism of the CNC machine tools

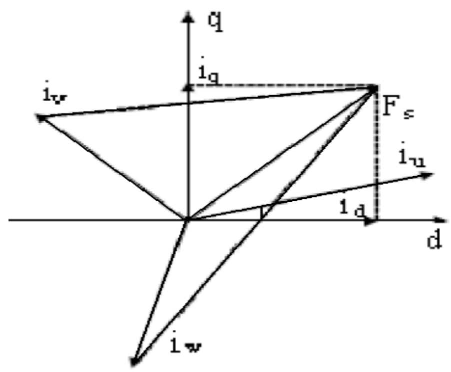

Figure 3. The vector conversion technology

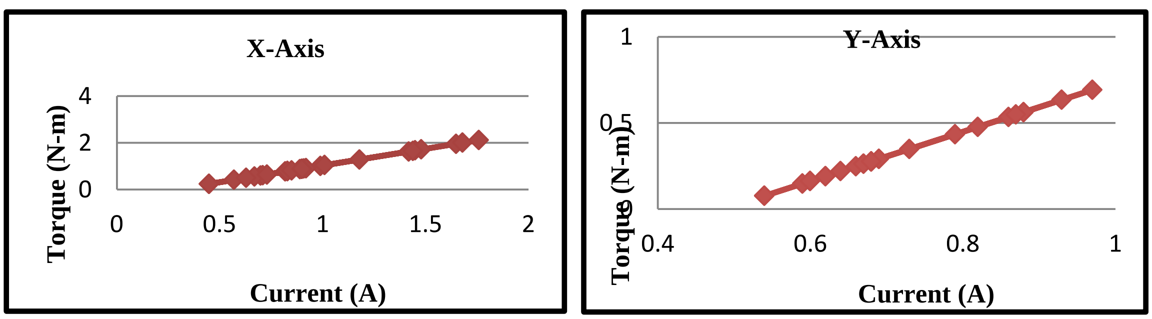

Figure 4. Current drawn by the X and Y axis feed motor Vs Torque (N-m)

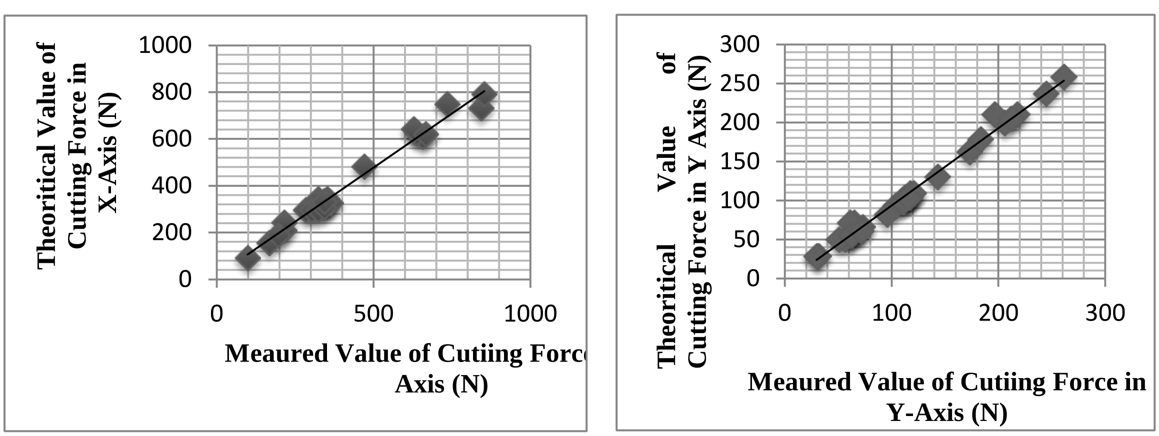

Figure 5: Measured value Vs Theoretical value of cutting forces along X and Y-Axis