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Real-time Investigation of Induced Vibration for Optimizing Surface Roughness in Turning Process with Modified System

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Abstract: In the turning operation, vibration is a vital characteristic to blemish effect which spoils the surface finish of the machined part. It is essential to diminish the induced vibration during metal cutting process. Hence, the selection of cutting parameters during the machining process are carried out through proper planning and by standard procedures. In this work, the experiment is conducted to determine the effect of induced tool vibration on the surface finish of machined part in the turning of Al6063. The cutting parameters are selected as cutting speed, feed rate and depth of cut, whereas the other parameters are kept as constant. The experimental design of L27 orthogonal array is developed by taguchi method for three process parameters and three levels. The experiments resulted that there is a significant role of induced vibration in affecting the surface roughness of work piece and it proportional to cutting tool acceleration. In addition, it is prominent that the exerted force during the machining process is one of the dominating factors in affecting the quality of final product. Therefore, the static and dynamic cutting forces is measured by dynamometer which has been tailored for the CNC turning operation. The static and dynamic behaviour are analysed from the modified dynamometer which has been attached during the real-time machining. The numerical values measured from dynamometer can be stored in a computer by data acquisition system for further vibration analysis. From the experimental investigation the measurement of surface roughness and dynamic behaviour of modified dynamometer during the turning operation were identified for optimized surface finish.
Keywords: Induced Vibration, Response Surface Methodology, Dynamometer, Strain gauge

I. INTRODUCTION

Vibration is a vague phenomenon which may not be evaded during the machining process. The self-excited chatter vibrations are more harmful than free and forced vibrations to fine surface finishing of the machined part. The chatter vibration induces at one of the natural modes of cutting system. Under this condition, the dynamic cutting force is produced at a frequency close to one of the natural modes. This dynamic force causes to excite the system additionally. The system becomes unstable, if the amplitude of chatter vibration is continued to be exist in the system. It is found from the chatter research that the depth of cut is the most influencing parameter in affecting the stability of the system. It is necessary to stabilize the system during machining process for achieving the high surface finish of the machined components. Hence, it is well-known that the monitoring the cutting force in turning operation is very crucial. A turning dynamometer is one of the devices which capable to measure static and dynamic forces. However, the cutting forces have the immediate and direct influence on the heat generation, tool characteristics. It hints to the incorrect results through theoretical calculations due to its various unknown factors. It is necessary to perform experiments using dynamometer to determine the static and dynamic cutting forces induced during the metal cutting process. The previous researchers have contributed in the factors involved in the turning process and its optimization as follows; (Süleym N et al., 2011) focuses on the effect of tool geometry on the surface characteristics of the machine part in the turning process of steel. They concluded that nose radius is most influencing factor on the surface roughness obtained by AISI 1040 steel. (Vladimir A et al., 2013) evaluated the process parameters affecting the surface roughness and natural frequency in turning of AA2024 under dry condition. (Tarngaet Y.S et al,. 2000) controlled the chatter vibrations in turning operation by using tuned vibration absorber. It is found that the tuned vibration absorber is able to control the frequency response function of the cutting tool which in turn to improve cutting stability in turning operations. (Kayhan M et al., 2009) investigated the tool life under vibratory cutting conditions. (Krishankant et al., 2012) studied an optimization of process parameters using taguchi method for maximizing material removal rate in the process of turning of EN24 steel. (Budak E et al., 2007) modelled to study the stability of turning and boring processes. It is shown that the imprecise process geometry leads to very high errors in stability. (Siddhpura M et al., 2013) investigated the occurrence of regenerative chatter

vibrations in facing and turning processes. It is evident that the effect of chatter vibrations on the sensor signals drastically increased as the amplitudes of these signals increased. (Khaider B et al., 2010) experimented hard turning with CBN tool of AISI 52100 bearing steel, hardened at 64 HRC. It is found that feed rate and cutting speed are most influencing factors in affecting surface roughness. Also, thrust force is found to be highest of cutting force components and it is be contingent with work piece hardness, negative rake angle and tool wear evolution. In addition, the depth of cut displays most influencing on cutting force. (Suleyman Y et al., 2006) developed a turning dynamometer to acquire the signals of cutting forces and it is processed using a data acquisition system. (Nishant S et al., 2006) developed a strain gauge-based dynamometer to measure the cutting force during metal removing operation which is performed by lathe machine tool. The cutting force signals were captured, amplified, conditioned, converted to digital signals and read by a microprocessor. (Tulio H et al., 2012) have designed, constructed and tested a strain gauge dynamometer to measure the three components of the turning force. The results show that the turning force decrease slightly as cutting speed is increasing and increase linearly with feed rate and depth of cut. (Ergun A et al., 2013) designed one-piece dynamometer to minimize the residues and to acquire the reliable cutting force components.
The work is mainly focussed on the sources that affect the surface roughness of the workpiece. Vibration is mainly created due to the interaction between tool and workpiece system. So, the CNC turning operation is to be conducted for the workpieces by varying some of the selected parameters. Then the relationships between surface roughness and acceleration are investigated. The cutting tool dynamometer is to be designed for the same CNC turning operation for measuring various forces that acts during the operation.

II. MATERIALS AND METHODS

The independent variables shown in Table 1 are considered in this investigation for the CNC turning operation are, depth of cut, cutting speed and feed rate.

TABLE I
Process Parameters And Its Level

Sl. No	Factor Design	Notation	Symbol	Unit	Levels		
					Low	Medium	High
1	Cutting speed	F1	N	rpm	260	380	500
2	Feed rate	F2	F	mm /rev	0.1	0.2	0.3
3	Depth of cut	F3	T	mm	1	1.5	2

Other variables that are considered to be constant are such as,

1) Workpiece overhang =55mm
2) Tool overhang =25 mm

The lathe that has been used for conducting the experimental investigation of the turning operation is MTAB FLEXTURN CNC lathe.

A. Machining Materials

In the present study, AA 6063 aluminium alloy is used as the workpiece for the turning operation. AA 6063 has the good mechanical properties and is heat treatable and weldable. It is similar to the material of aluminium alloy HE9.

B. Experimental Setup

The experimental setup of the vibration measurement during the CNC turning operation is shown in Fig.1. The magnetic mount is placed over the tool which is connected with accelerometer which is shown in Fig. 2.

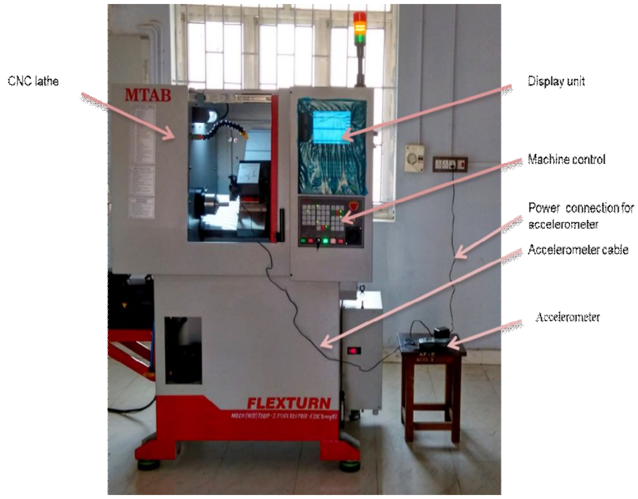

Fig. 1. Experimental setup in the CNC lathe

The accelerometer is connected to the power and the magnetic mount is placed over the turning tool. The CNC programming is given for the turning operation for which each sequence of the operation is conducted. This gives the specific function of control over the tool and workpiece system. The readings are measured for each of the turning operation from the display of the accelerometer.

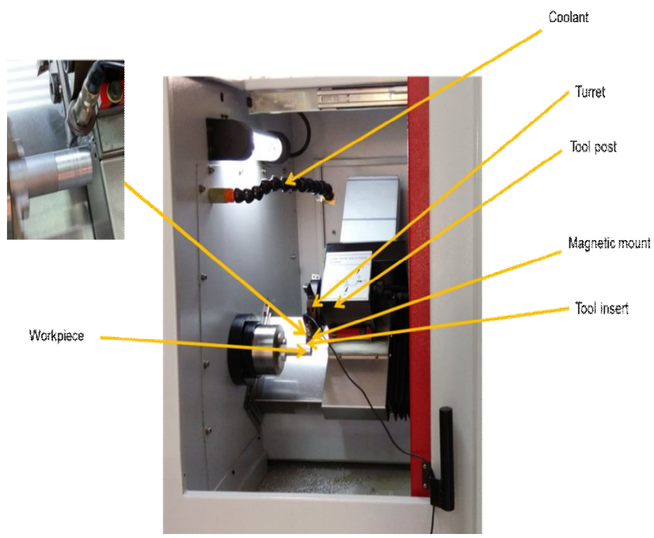

Fig. 2. Magnetic mount over the tool

The cutting tools insert SDSCR1212 11F3 is used for the CNC turning operation. The 911 vibration data collector is used for measuring the acceleration during the cutting. Three number of tool inserts were used to minimize the effect of tool wear.

C. Response Surface Methodology

Response Surface Methodology (RSM) is the statistical approach used to provide the mathematical relationship between process parameters and output responses. In this study, three process parameters are considered and each three levels. Totally 27 experiments are conducted by using Taguchi design of experiments from the Minitab 17 Statistical software. The Fig. 3 shows the workpieces after the turning operation.

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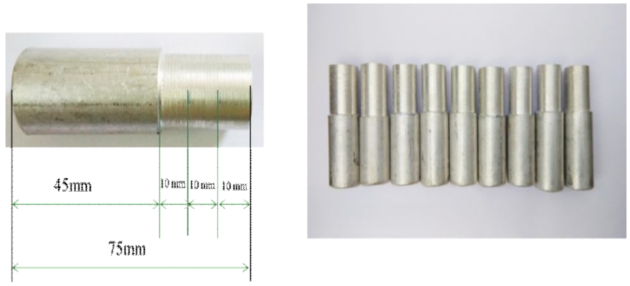

Fig. 3. Machined samples

III.DESIGN OF EXPERIMENTS

The design of experiments was conducted using Taguchi L27 orthogonal array and the responses such as acceleration and surface roughness are noted. Through RSM the regression equations are created using Minitab software from the 27 experiments were shown in Table 2.

TABLE II
Design Of Experiments

S. No	F1 (rpm)	F2 (mm/rev)	F3 (mm)	Acceleration (m/s^2)	Surface Roughness (µm)
1	260	0.1	1	0.063760	9.09
2	260	0.1	1.5	0.032372	3.06
3	260	0.1	2	0.042439	4.88
4	260	0.2	1	0.040465	4.42
5	260	0.2	1.5	0.033162	3.37
6	260	0.2	2	0.048361	6.04
7	260	0.3	1	0.049545	6.26
8	260	0.3	1.5	0.046387	5.16
9	260	0.3	2	0.055862	7.02
10	380	0.1	1	0.067113	9.35
11	380	0.1	1.5	0.045005	4.52
12	380	0.1	2	0.076588	11.18
13	380	0.2	1	0.049743	6.29
14	380	0.2	1.5	0.041649	4.34
15	380	0.2	2	0.061586	7.65
16	380	0.3	1	0.035925	3.55
17	380	0.3	1.5	0.058033	5.43
18	380	0.3	2	0.058231	5.63
19	500	0.1	1	0.058822	6.60
20	500	0.1	1.5	0.042834	4.48
21	500	0.1	2	0.065139	9.32
22	500	0.2	1	0.047571	4.77
23	500	0.2	1.5	0.029214	2.76
24	500	0.2	2	0.044413	4.50
25	500	0.3	1	0.052506	6.48
26	500	0.3	1.5	0.051322	8.60
27	500	0.3	2	0.041452	3.69

From the design of experiments the optimized surface roughness is obtained as, Ra=2.76 µm. In which the acceleration is measured as, A=0.029214 (m/s^2).

The other independent variables are such as,

1) Cutting speed, F1= 500 rpm
2) Feed rate, F2 = 0.2 mm/rev
3) Depth of cut, F3 =1.5 mm

A. Vibration Data Collector S911

The data that are collected from vibration data collector 911 are saved for particular parameters and then transformed into waveforms by using the MCME2.0H software in a computer system. The Figures 4,5,6,7 represent the waveforms at different points for a particular operation.

1) F1=500RPM
2) F2=0.1(mm/rev)
3) F3=1.5(mm)
4) A=0.042834 m/s2 Peak; V=0.02 mm/s RMS; D=2.17 µm Pk-Pk; Ra=4.48 µm

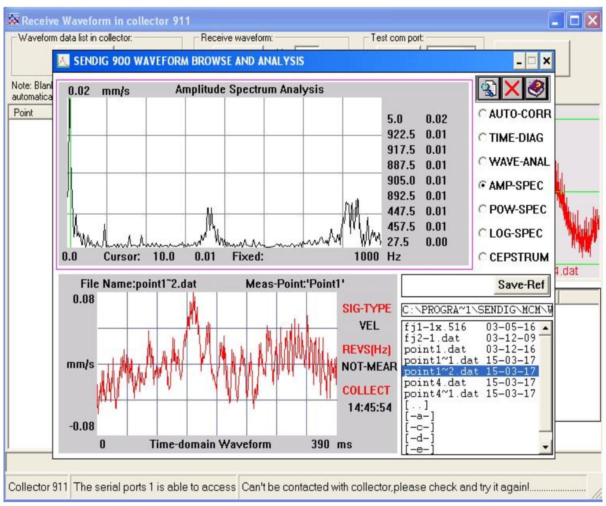

Fig. 4. Point 1

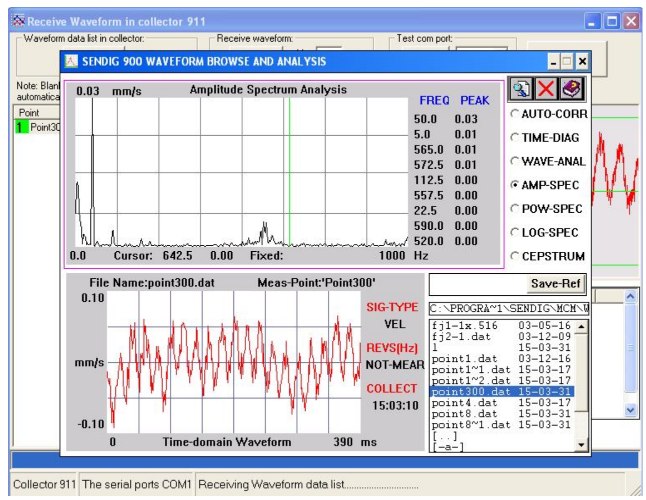

Fig. 5. Point 8

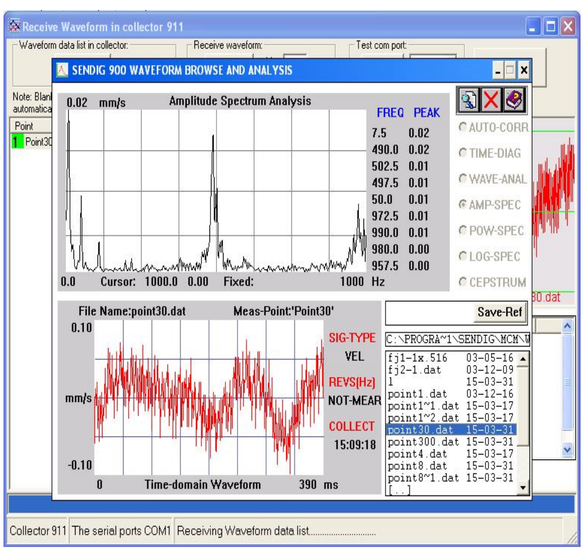

Fig. 6. Point 30

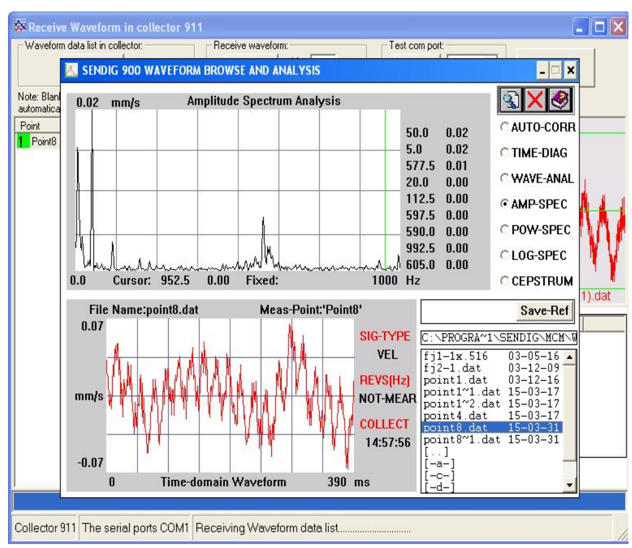

Fig. 7. Point 300

Through these waveforms, the vibrational frequencies and their respective displacements over the different points are determined. The time-domain waveform gives their particulars in the velocity form.

B. Regression Equation

Through the responses, regression equations are created using the Minitab software.

1) $A = 0.0852 + 0.000476\,F1 - 0.327\,F2 - 0.1371\,F3 - 0.000001\,F1*F1 + 0.839\,F2*F2 + 0.0443\,F3*F3 - 0.000241\,F1*F2 - 0.000001\,F1*F3 + 0.0385\,F2*F3$
2) $Ra = 17.9 + 0.0471\,F1 - 55.0\,F2 - 22.5\,F3 - 0.000059\,F1*F1 + 144.6\,F2*F2 + 7.40\,F3*F3 - 0.0211\,F1*F2 + 0.0021\,F1*F3 - 0.5\,F2*F3$

The predicted surface roughness for the regression at optimized level is obtained as, Ra=3.699µm. The residual plots for acceleration and surface roughness are shown in Fig. 8 and 9.

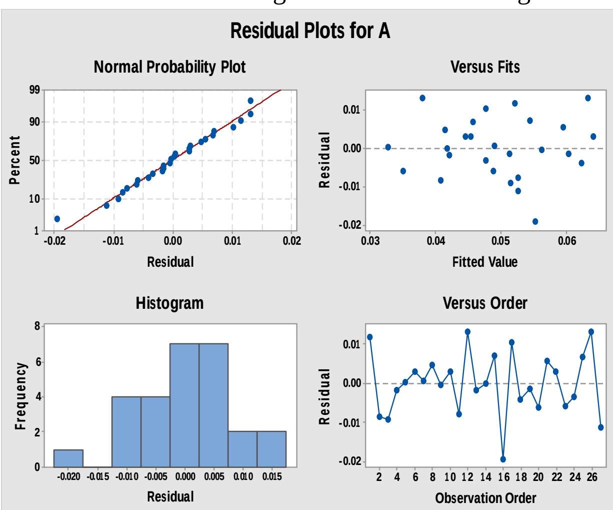

Fig. 8. Residual Plots for Acceleration

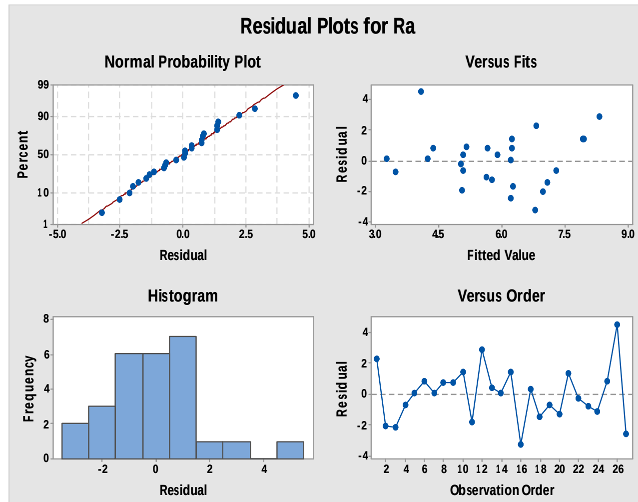

Fig. 9. Residual Plots for surface roughness

The regression equation that is generated from the Minitab software is used for optimizing the surface roughness and for optimizing the variables.

The optimized values that are obtained such as,

Cutting speed, F1=483.149 rpm

Feed rate, F2= 0.231 mm/rev

Depth of cut, F3= 1.453 mm

IV. EXPERIMENTAL INVESTIGATION

In this investigation, three cutting force components dynamometer is used to measure the cutting force occurred during turning operation in CNC lathe. AISI 4140 steel is considered as the ring material.

A. Determination of Octagonal Rings

The thickness t, radius r, and width of the circular strain ring b are the three basic controllable parameters that affect the rigidity and sensitivity. Since there is no effect of ring width b and modulus of elasticity (E) on the strain per unit deflection, b_{min} can be taken as 10 mm to set up the rings securely. The deformation of circular ring under the effect of thrust force Ft and main cutting force Fc separately is shown in Fig.10.

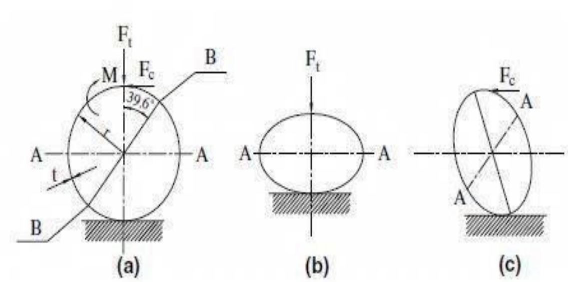

Fig. 10. Deformation under: (a) combined, (b) Thrust Ft, (c) Cutting Fc forces

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As long as strain on A and B where the strain gauges are going to be fixed are within the elastic limits of the ring material, the strain and deflection due to the main cutting force should be considered for the purpose of the ring design for maximization of sensitivity (ε_c/F_c) and stiffness (F_c/δ_c). The strain gauges should be placed where the stress concentration has maximum value. The experiments have shown that good results are obtained for octagonal rings when the inclined gauges are at points 45^0 from the vertical instead of 39.6^0 required by the circular ring theory.
The strain per unit deflection can be expressed as,

$$\frac{\varepsilon_t}{\delta_t/r}=\frac{1.09t}{1.8r}\cong 0.61\frac{t}{r}$$

Where,
δ_t is the deflection in a radial direction
ε_t is the strain due to thrust force F_t.
It is clear that for maximum sensitivity and rigidity ε_t/δ_t should be as large as possible. This requires that 'r' should be as small as possible and 't' as large as possible. But small 'r' brings some difficulties in mounting the internal strain gauges accurately. Therefore, for a given size of 'r' and 'b', 't' should be large enough to be consistent with the desired sensitivity. The difference in displacement of circular ring and octagonal ring is less than 10% if t/r equals 0.25 or greater.
In order to be consistent with this expression, the ring thickness and ring radius were taken as 1.4mm and 3mm, respectively. The fig.11 shows the thickness (t), radius (r) and width (b) of the dynamometer.

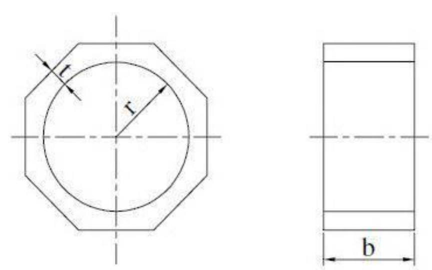

Fig. 11. Octagonal dynamometer ring dimensions

B. *Confirmation of Octagonal Rings*

The maximum expected force, which the rings may face in each direction, is assumed as 1200 N. If the cross-sectional dimensions of a curved bar are smaller than the radius of the centre line, it is considered to be thin ring. Taking into account of the dimensions, t=1.4mm, r=3mm, b=10mm, elastic strains ε_t and ε_c due to forces Ft and Fc are calculated according to ring theory by using the following equations,

TABLE III
Stress Analysis

Type	Elastic strain		Stress N/mm^2		Natural frequency (Hz)
	ε_τ	ε_c	σ_τ	σ_c	
Theoretical	9.533×10^{-4}	1.9067×10^{-3}	200.2	400.4	612.75
Analytical	9.44×10^{-4}	2.389×10^{-3}	192.9	383.7	652.072

As AISI 4140 steel was used for manufacturing the ring and its yield strength is 550–900 N/mm^2, the calculated stress values (and) occurring on the rings are within Safety limits for this material.

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V. RESULTS AND DISCUSSION

The static and dynamic analyses in the CNC turning machine were conducted for the octagonal rings which were verified with the theoretical values. They are shown in the following Figures 14, 15 and 16.

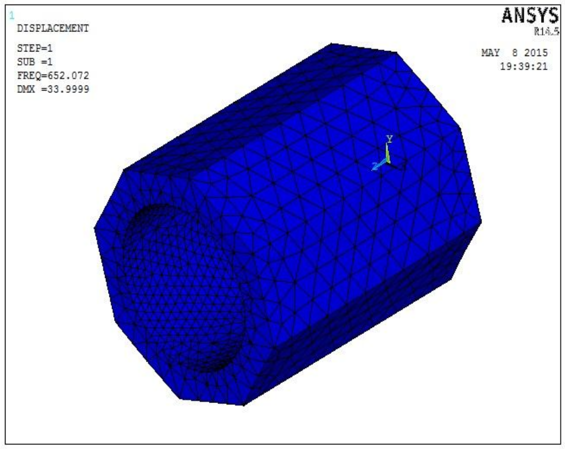

Fig. 12. Strain along thrust

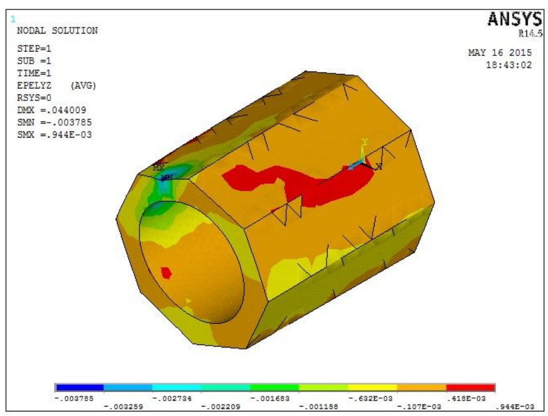

Fig. 13. Stress along thrust

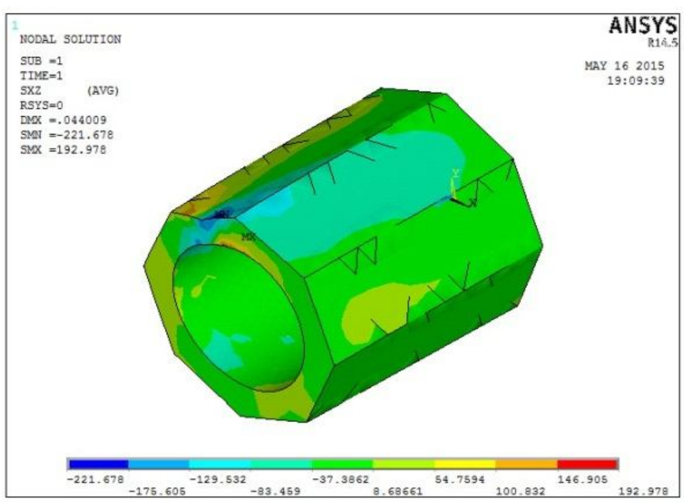

Fig. 14. Mode shape of the octagonal ring

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A. Orientation of Strain Gauges and Rings

The proper selection of the points where the strain gauges are mounted is essential for achieving high accuracy in the Wheatstone bridge circuits. The orientation of the strain gauges on the rings and the position of the rings on the dynamometer were shown in the Fig. 15,

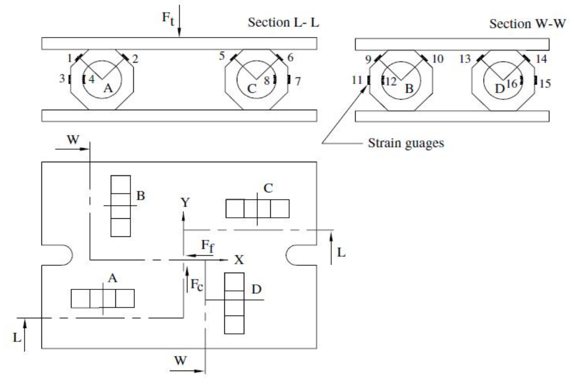

Fig. 15. Strain gauges and ring orientations

The thrust force F_t are supported by A, B, C and D rings of the dynamometer as shown in Fig. 15. The strain gauges 3, 4, 7, 8, 11, 12, 15 and 16 are affected by the thrust force F_t. Among these strain gauges, 3, 7, 11 and 15 are subject to tensile stress while 4, 8, 12 and 16 are subject to compressive stress. The feed force Ff is supported by A and C rings of the dynamometer. The strain gauges to measure the feed force F_f should be mounted on the outer surfaces of A and C rings with 450 inclination angles. The strain gauges 1, 2, 5 and 6 are affected by the feed force F_f.

Among these strain gauges, 1 and 5 are subject to tensile stress while 2 and 6 are subject to compressive stress. The main cutting force F_c is supported by B and D rings as seen in Fig. 15. The strain gauges for measuring the main cutting force F_c are mounted on rings B and D with 450 inclination angles with respect to the vertical plane. As shown in figure, the strain gauges 9, 10, 13 and 14 are affected by the main cutting force F_c.

B. Mounting of Strain Gauges on the Rings

The rings of dynamometer could be manufactured at CNC machine tools by using AISI 4140 steel. The surfaces of the rings should be ground for better strain gauge application. Totally 16, strain gauges were mounted on four octagonal rings. Two strain gauges were mounted horizontally on to outsides of each ring at 450 angles. Two more strain gauges, one inside and the other outside were also mounted vertically. LY11 6/120 type strain gauges recommended for steel specimens and for static or dynamic loading were utilised. To achieve low energy dissipation and hence a stable zero setting for a long time, excitation voltage must be selected carefully. The range of excitation voltage for a thick steel mounting surface may be obtained from the relation,

$$V_{in} = \sqrt{RP'_g A_g}$$

Where,

R is the gauge resistance in ohms,

P'g is the power density in the gauge grid (between 2 and 5 kW/m^2), and

Ag is the active grid area (6 · 2.8 for HBM for LY11 6/120).

For convenience, an excitation voltage of 10 V (calculated between 8 and 12.7 V) can be employed. The rings of dynamometer were mounted between two plates by using (Ø4 mm) pins and M5 screws. Pins were used in order to prevent the motion of plates due to clearance, which may cause the cross-sensitivity during measurements. The dimensions of plates were 22×22×1.4 mm. plates were covered with 1 mm thick transparent plastic material in order to prevent the strain gauges from hot chips and from cutting fluid during turning.

C. Results from the Analysis

Through the static and modal analysis works carried out in the Ansys software, the following results are obtained. The stress and strain value give the results of dynamometer under the loading condition. The total deformation is less than the allowable deformation. Hence it is safer to operate. The natural frequency of the dynamometer is higher than that of the excitation frequency of the machine tool. Hence it is safer to operate with the maximum spindle speed.

VI. CONCLUSION

The following conclusion made from this experimental investigation of induced vibration shows that, In the CNC turning operation, the induced vibration and surface roughness of the tool workpiece system is induced by random disturbances, and their effects are investigated on a sample surface.

A. The surface roughness of work piece is directly proportional to the cutting tool acceleration. The effect interacts with the variables such as cutting speed, feed rate and depth of cut.

B. The regression equation is generated using RSM for the cutting tool acceleration and surface roughness of the workpiece. The optimization is conducted for the regression equation, where the optimized parameters are obtained for the surface roughness.

C. The modified dynamometer provides a strain gauge-based dynamometer which has been modified for the CNC turning tool. The dimensions of the octagonal rings are verified by theoretically and analytically. It can measure static and dynamic cutting forces by using strain gauges. The orientation of the octagonal rings and strain gauge locations has been determined to maximize the sensitivity and to minimize cross-sensitivity.

D. The dynamometer is capable of measuring force up to 1200N and the sensitivity of the system is ±5 N. The cutting force signals can be captured and transformed into the numerical values and can be stored in computer by data acquisition system consisting of necessary hardware and software systems. The dynamometer has been analyzed using the Ansys software and the stress, strain and deformation values are obtained through that. The modal analysis gives mode shapes and the natural frequencies of the designed dynamometer.

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