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CORRELATION ANALYSIS BETWEEN COMPONENTS OF FORCE AND VIBRATION IN TURNING OF 11SMN30 STEEL

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Abstract. *Workability of material is defined as the ease of operating on it. 11SMn30 is widely used material in automobile manufacturing industries. Cutting forces have been shown to be the most effective measure for understanding metal machining processes. The forces which helps in performing machining operation also affects the cutting tool, in terms of deformation, bend, wear, which leads to the vibration in the machining system, This article aims to study the correlation between feed, components of cutting forces and components of vibration in turning of 11SMn30 steel grade using dynamometer and MPU6050 sensor.*

Keywords: *turning operation; cutting forces & vibrations; correlation; analysis of variance.*

1. Introduction

Automation in manufacturing industries is rapidly growing, enhancing the efficiency, leading towards the reduced labour costs and with automation adoption of Artificial Intelligence is on the rise as industries recognises the benefits of in predictive maintenance and operational efficiency which helps industries in economic growth and provide low cost solutions in the market. In addition the companies are prioritizing the sustainable practices by focusing on use of material. Material selection one of the key variable in manufacturing industry, which frequently causes uncertainties regarding its workability. Workability of material is defined as the ease of operating on it. 11SMn30 is widely used material in automobile manufacturing industries. Joy. B. et al . [1], Varghese. L. et al. [2], quoted 11SMn30 is free cutting steel for bulk applications for joining elements in mechanical engineering and automotive components. Manganese and sulphide exist as globules in the microstructure which aid machining these act as discontinuities in the sites to form broken chips as a results there is need to investigate the workability of 11SMn30 steel grade. Sharma V. et al. [3] highlighted that to produce automotive parts like shafts, turning operation is more economical, turning is the most commonly used machining process in the manufacturing industries to produce shaft from hard material. For turning operation to be efficient selection of cutting parameters is highly recommended by the researchers. Machining parameters like feed, cutting forces & vibrations induced from the interaction of workpiece and tool, because they directly influence the quality of product, production time, tool wear, which overall determines financial aspect of the manufacturing industries and has an impact on the environment. For successful implementation of turning study of cutting forces is critically important because cutting forces correlate strongly with cutting performance such as surface accuracy, tool wear, tool breakage, cutting temperature. The cutting force is one of the most significant characteristic variable to monitor the cutting operations, since its variation is directly proportional to the cutting conditions. Cutting forces have been shown to be the most effective measure for understanding metal machining processes. I.N. Tansel et al., Rashid Ali Laghari et al., Ulvi Şeker et al. [11, 12, 13] mentioned that a significant amount of this research has been focused on measuring and predicting cutting forces during milling. That is because understanding the cutting forces is critical because they have a direct impact on heat generation, tool wear, machined surface quality, and shape precision. They are also used to design machine tools, cutting tools, and fixtures. The forces which helps in performing machining operation also affects the cutting tool, in terms of deformation, bend, wear, which leads to the vibration in the machining system [7]. Abdullah Aslan [8], investigated variations in cutting forces and vibration have a direct impact on flank wear. Yong Wu [9] mentioned one of the most frequently accepted reasons for machine tool chatter is surface regeneration theory, the machined surface becomes wavy as a result of relative vibrations between the tool and the workpiece as a result, delay effects emerge in metal cutting operation models because the cutting force is controlled by the chip thickness, which is dependent on both the present tool position and the delayed position from the preceding cut, in result, the delay-differential equations are employed to describe machine tool vibrations, and regenerative machine tool chatter can be viewed as the manifestation of self-excited oscillations in a time-delay system. Zerti et al. [10], applied the Taguchi approach to reduce cutting forces and other machinability parameters. Turning experiments were carried out on AISI D3 steel using CC650 grade ceramic inserts without coolant. Haibo X. and Zhanjiang W. [11], [12] investigated how EVC factors such as vibration frequency, amplitude, and cutting speed affect cutting forces. The feed force is responsible for the cutting in machining operation therefore the feed rate influences the cutting forces which results in vibration. U. Şeker et al. [5], investigated that increasing feed rate, increases cutting forces in turning operations, while cutting force decreases with increasing speed. K. Kotaiah et al. [13], studied feed has a marked effect on stability in turning due to force variation. Rashid Ali Laghari et al. [6] studied that higher depth of cut, followed by feed rate, increases the cutting force, while higher cutting speed reduces it. Kagde and Deshmukh [14], studied optimization and effect of cutting parameters on numerous performance variables (work piece surface roughness, spindle load) obtained during turning operations. Experiments were conducted using a CNMG 090308 PF carbide insert as a tool and HCHC steel as the workpiece material. The results highlights that spindle speed and feed rate were the most important parameters for numerous cutting performance metrics. Shunmugesh. K. [15]. results suggest that the key factor influencing surface roughness is depth of cut, followed by cutting speed and feed. Sharma V. et al. and Al-Ahmari [3], [16], studied the machinability of turning operations using input parameters such as cutting speed, feed, depth of cut, and nose radius, and response parameters such as cutting forces and surface roughness. Dong Y. [17] study demonstrate that cutting conditions such as cutting speed, feed rate, depth of cut, tool geometry, and material qualities of both the tool and the workpiece, have a considerable impact on the surface quality of machined parts. Monitoring quality indicators such as tool wear, surface integrity, cutting power, and vibration, among others, contributes to consistent development for best results. Monitoring process parameters improves productivity and increases tool life. To make these parameters more efficient, additional investigations on cutting forces and vibration components are critical for complete understanding. Not only should the significance of their weight be understood, but so should their correlation with one another, several studies on cutting forces and vibrations is undertaken, however study of the components and their relationship with machining parameters is still lacking.

This article aims to study the correlation between feed, components of cutting forces and components of vibration in turning of 11SMn30 steel grade using dynamometer and MPU6050 sensor. To check the significance of the regression model, analysis of variance (ANOVA) was used.

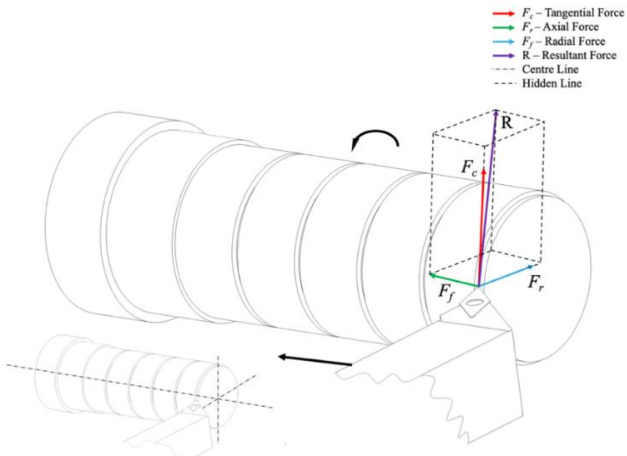

Figure 1. Components of cutting force in turning operation

2. Material and Methods

The workpiece shaft used to conduct the experiment is 11SMn30 grade steel, non-alloy quality, and not suitable for heat treatment, according to EN 10277-3 [18] . The chemical composition and mechanical properties of the workpiece material are shown in Table 1.

Table 1. Chemical composition in weight% and Mechanical properties of steel 11SMn30 (1.0715)

C	Si	Mn	P	S
max 0.14	max 0.05	0.9 – 1.3	max 0.11	0.27 – 0.33
Nominal thickness (mm)	R_m – Tensile strength (MPa) (+C)	$R_{p0.2}$ 0.2% proof strength (MPa) (+C)	Min. elongation at fracture (%) (+C)	
40 – 63	400 – 650	305	9	

The workpiece was parted in 5 equal parts as shown in Fig. 2. It is to understand the relation between feed, components of cutting forces and vibration with varied feed in all the surfaces as mentioned in Table 2. [19]. Other machining parameters like depth of cut was kept 1 mm, spindle speed was 2000 rpm, for all the machining passes. Using these parameters, cutting forces and vibration data was recorded.

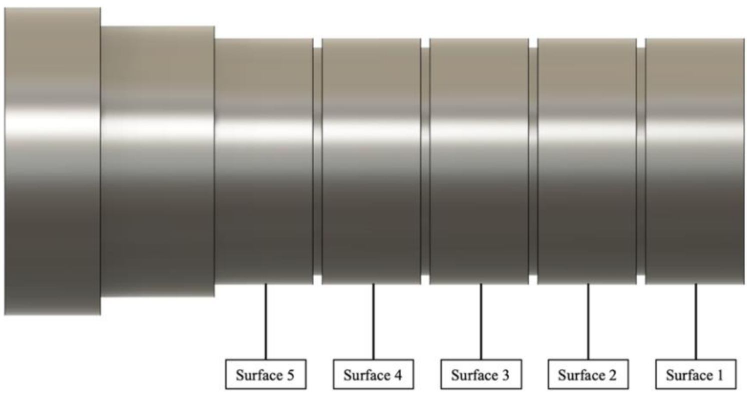

Figure 2. Partition of surfaces for the experiment.

The machining operation was repeated two times to collect more data on cutting forces and vibration, resulting in good correlation accuracy. The diameter of the workpiece specimen was 42 mm before machining, and it was reduced to 40 mm in first machining pass, after final pass it is 38 mm as shown in Fig. 3.

Table 2. Machining Parameters according to surface partition.

Surface No.	5	4	3	2	1
Feed (f_z) mm/r	0.3	0.25	0.2	0.15	0.1
Depth of Cut (a_p) mm	1	1	1	1	1
Spindle Speed RPM	2000	2000	2000	2000	2000

The specimen was divided into 5 equal parts of 16 mm length, each partitioned by a 1.5 mm groove, to test the vibrational signals and cutting forces at different feed rates and to draw the relationship between feed, cutting forces and vibration, Fig. 3. represents the final machined part to analyse the corelation between feed, cutting forces, and vibration.

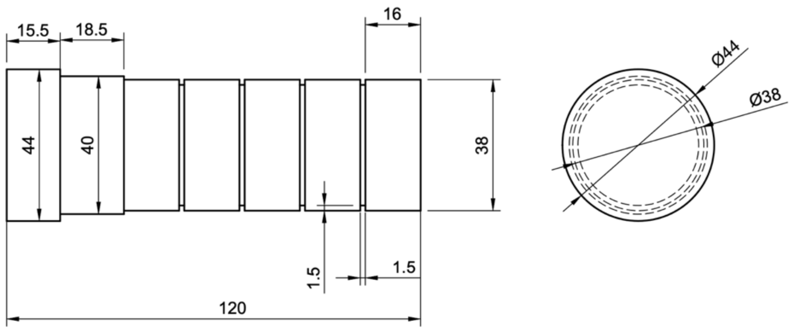

Figure 3. Drawing final machined part.

The tool used was the SVHBR2020K11 Walter Turn shank tool with screw clamping (S), as shown in Fig. 4. This tool has positive basic form insert and is appropriate for small-diameter shafts or low cutting pressures. The tool and insert specification for the VCGX style, used for the cutting operation, are listed in Table 3, [20].

Table 3. Tool & Insert Specification

Des.	Shank height	Shank width	Functional width	Functional length	Max Projection length	Orth. Rake angle	Inclination angle
Symbol	$h = h_1$	b	f	l_1	l_4	γ	λs
Value	20 mm	20 mm	25 mm	125 mm	19 mm	0 °	0 °
Insert Style	Insert Shape		Clearance Angle		Size	Corner Radius (Re)	
VCGX	35° Diamond		7° Positive		0.25	0.016	
Insert Material	Work Material		Machining Application		Insert Coating	Insert Thickness (S)	
Carbide	High Temp+Cast Iron+Non-Ferrous		Roughing & Finishing		Uncoated	0.125	

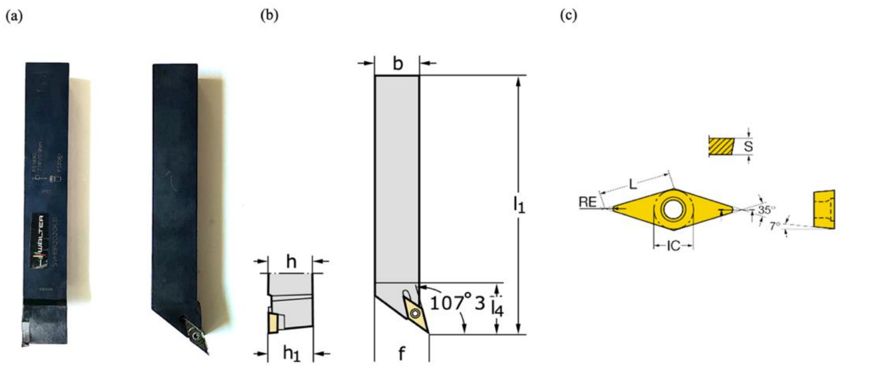

Figure 4. (a) Tool (b) Tool Specification (c) Insert specification [20]

The cylindrical turning operation was conducted in a dry condition using the Optimum Opti Turn S600 CNC machine Fig. 5(a). The vibrational data was collected by connecting the MPU6050 sensor to the tool, as seen in Fig. 5(c). MPU6050 sensor, the comprehensive 6-axis motion tracking device which integrates a 3-axis gyroscope, 3-axis accelerometer, and digital motion processor with ESP32 microcontroller comprised of two 240MHz cores [36, 37], each housing a Tensilica

Xtensa 32-bit LX6 microprocessor were used to measure the vibrational signal during each machining pass. The microcontroller was used to upload the code, and an SD card module connected to the microcontroller was used to gather the data. Sensor was attached to the tool with the help of a clip, the electronic setup was attached with the help of a screw to the tool holder in CNC machine, in case of movement of tool the electronic setup will also move to keep the connection secure between sensor and microcontroller, the microcontroller was attached to monitor to provide the power supply and also to visualise real time output vibration signals.

Fig. 5(b), depicts the electronic configuration. The orientation of sensor with respected to tool is shown in Fig. 5(c).

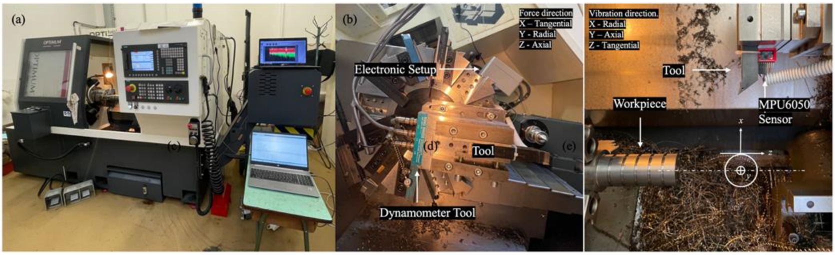

Figure 5. Experimental Setup (a) CNC Machine, (b) Dynamometer Setup, (c) Accelerometer Setup.

The cutting force components were measured using a three-component piezoelectric dynamometer, from Kistler Corporation 9257-A, Fig. 8(a) and 8(b). The dynamometer's output was amplified using a charge meter Kistler Corporation Model 5015A for three force components i.e., Fx, Fy, Fz, has been connected to National Instruments Compact DAQ-9171 four-channel data acquisition unit (USB), The amplified signals from the charge amplifier are supplied into the data acquisition system, where they are transformed to digital output, which is then transferred to the computer. This setup allowed for the installation of a dynamometer between the tool holder of the CNC lathe and the tool without interacting with other parts. The three cutting force components were measured, as seen in Fig. 5(b). Tool, dynamometer and sensor position is defined in Fig. 5(b) and 5(c) respectively, monitor allows to validate the data during the process to avoid any error it is recommended to visualise the real time data. This configuration allowed the experiment to be conducted cleanly and without errors. Two boxes were fabricated using machining and 3D printing processes as shown in Fig. 5(b), and an outer wire casing was used to protect wires. These casings served as a shield to protect electronic setup from chips generated during the machining process.

3. Results

The results represents the calculated data of Force RMS (F RMS) for each components, for tangential cutting force (F RMS T), Radial cutting force (F RMS R) and axial cutting force (F RMS A), In Table 4. RMS calculation of force components is presented, it can be seen that active forces are the tangential and axial force as mentioned in article [23], the force RMS value measured for the tangential are much higher than radial and axial, and in comparison the significance of radial forces are much lower which is understandable because radial direction the tool is stationary and do not apply the force downwards. The results also presents the calculated values of vibration RMS for each components, Vibration RMS in tangential (Vb RMS T), Vibration RMS in Radial (Vb RMS R) and Vibration RMS in Axial (Vb RMS A), It can be concluded from Table 4. That tangential vibration RMS values is much higher in compared to radial and axial vibration.

Table 4. Forces RMS and Vibrations RMS data.

Individual							
Ex. No.	Feed Rate	F RMS T	F RMS R	F RMS A	Vb RMS T	Vb RMS R	Vb RMS A
EX1S1	0.1	216.63	2.3	111.34	9.09	5.23	1.51
EX1S2	0.15	315.01	3.26	161.4	9.09	5.24	1.67
EX1S3	0.2	395.4	5.16	181.98	9.14	5.25	1.49
EX1S4	0.25	473.69	7.46	191.19	9.28	5.32	1.78
EX1S5	0.3	532.61	10.91	183.74	9.43	5.31	1.75
EX2S1	0.1	206.59	4.39	114.63	9.08	5.22	1.47
EX2S2	0.15	303.55	6.7	164.73	9.12	5.24	1.48
EX2S3	0.2	366.82	11.71	178.89	9.1	5.25	1.41
EX2S4	0.25	425.64	19.03	182.08	9.3	5.31	1.79
EX2S5	0.3	Tool Break	Tool Break	Tool Break	Tool Break	Tool Break	Tool Break

The active vibration considered is tangential and radial because it has much greater impact than the axial. It is understandable, because tool is moving in axial direction, so the vibration values can be ignored in axial direction. In terms of force the axial force is much higher in comparison to radial because of the contact between workpiece and tool. Table 5. represents the correlation between individual directional forces and vibration, it can be concluded that feed has high influence on tangential and axial force which is considered as active force and weak correlation with radial forces. In terms of vibration feed has strong correlation on tangential and radial and weak correlation on axial. tangential and radial vibration are considered as active vibration.

Table 5. Correlation Analysis Feed, Forces RMS & Vibrations RMS.

	Feed Rate	F RMS T	F RMS R	F RMS A	Vb RMS T	Vb RMS R	Vb RMS A
Feed Rate	1	.989**	.693*	.864**	.899**	.918**	.681*
Force RMS Tangential	.989**	1	0.59	.890**	.871**	.900**	.674*
Force RMS Radial	.693*	0.59	1	0.581	0.607	.672*	0.446
Force RMS Axial	.864**	.890**	0.581	1	0.593	.731*	0.477
Vibration RMS Tangential	.899**	.871**	0.607	0.593	1	.914**	.794*
Vibration RMS Radial	.918**	.900**	.672*	.731*	.914**	1	.850**
Vibration RMS Axial	.681*	.674*	0.446	0.477	.794*	.850**	1
** Correlation is significant at the 0.01 level (2-tailed).							
* Correlation is significant at the 0.05 level (2-tailed).							

The one streak sign in table "*", Suggests correlation is significant at the 0.05 level (2-tailed). This indicates a moderately strong piece of evidence that the observed correlation is not due to chance. There's a 95% chance that a real relationship exists between the variables. tangential force also shows strong relationship with tangential and radial vibration and comparatively weak relationship with axial, which can be understood by the above results of active vibration and active force. radial force shows weak relationship with vibration because it has very low value in compared with the other directional forces. There is a strong correlation between force components and vibration components which suggests that with change in value of force will influence the as well vibration induced. The analysis of force and vibration components as well as the correlation between the variables explains the influence of variables on one another, which can be used to overlook the variables with the less effect on the machining process.

4. Conclusions

The introduced approach can be used to understand the machinability of material and relationship between cutting forces and vibration, and several findings can be drawn from this study.

Individual forces and vibration data allows us to understand the impact and dependency of one variable on others. Tangential values in forces and vibration calculations are much higher compared to radial and axial values, which implies that tangential direction has significant impact on both forces and vibration.

The direction of active forces and active vibration differs, active force is the sum of tangential and axial, whereas active vibration considers the sum of tangential and radial direction.

Correlation analysis results.

Feed Rate shows strong correlation with F RMS tangential and F RMS axial with 98.9% and 86.4% correlation respectively, also with the Vibration RMS Tangential and Vibration RMS Radial with 89.9% and 91.8% correlation.

Components of forces also show the strong correlation with components of vibration which suggests that the with change in value of cutting force value influences the vibration, which can be used to predict the vibration in tool.

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АНАЛІЗ КОРЕЛЯЦІЇ МІЖ СКЛАДОВИМИ СИЛИ І ВІБРАЦІЇ ПРИ ТОКАРНІЙ ОБРОБЦІ СТАЛІ 11SMN30

Анотація. *Технологічність матеріалу визначається як зручність його обробки. Сталь марки 11SMn30 є широко використовуваним матеріалом в автомобілебудуванні. Відомо, що зусилля різання є найбільш ефективним показником для розуміння процесів обробки металу. Для успішної реалізації токарної обробки вивчення сил різання є критично важливим, оскільки сили різання сильно корелюють з такими показниками різання, як точність поверхні, знос інструменту, поломка інструменту, температура різання. Сила різання є однією з найбільш значущих характеристичних змінних для контролю за операціями різання, оскільки її зміна прямо пропорційна умовам різання. Сили, які допомагають при виконанні операції механічної обробки, впливають і на ріжучий інструмент, в плані деформації, вигину, зносу, що призводить до вібрації в системі обробки, Компоненти сили різання у цьому дослідженні були виміряні за допомогою трикомпонентного п'єзоелектричного динамометра фірми Kistler Corporation 9257-A. Вихідний сигнал динамометра був посилений за допомогою підсилювача Kistler Corporation моделі 5015A для трьох силових складових, а саме, Fx, Fy, Fz, був підключений до чотириканального блоку збору даних (USB) National Instruments CompactDAQ-9171, Посилені сигнали від підсилювача надходять в систему збору даних, де перетворюються на цифровий вихід, який потім передається на* *комп'ютер. Ця установка дозволила встановити динамометр між тримачем інструменту токарного верстата з ЧПУ та інструментом без взаємодії з іншими деталями. Було виміряно три складові сили різання. Положення інструменту, динамометра і датчика визначено відповідно, монітор дозволяє перевіряти дані в процесі для уникнення будь-яких помилок, рекомендується візуалізувати дані в реальному часі. Така конфігурація дозволила провести експеримент чисто і без помилок. Дана стаття має на меті вивчити взаємозв'язок між подачею, складовими сил різання і складовими вібрації в токарній обробці сталі марки 11SMn30 з використанням динамометра і MPU6050 датчика.*

Ключові слова: *операція токарної обробки; сили різання та вібрації; кореляція; дисперсний аналіз.*