Design and Development of a Three Component Milling Dynamometer

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Abstract. The cutting forces that are generated during metal cutting influence the work piece precision, tool wear, the nature of the machined surface, and heat generation. These cutting forces can be measured analytically however; precise outcomes may not be expected due to its included stresses, parameters of cutting, and the perplexing tool geometry. Henceforth the exploratory estimation of cutting forces is fundamental. For this reason, a milling dynamometer of three-segment is structured, created, and tried to gauge the three cutting forces which are produced during the operation of milling strain gauges can be utilized to quantify dynamic and static cutting forces through milling dynamometer. During the process of metal cutting, a dynamometer that is based on strain gauge is fit for estimating three-force segments. The dynamometer was designed based on the octagonal ring principle. The octagonal rings orientation and location of strain gauges have resolved to expand affectability and to limit cross- affectability.

1. Introduction

In mechanical components, metal evacuation possesses the most significant segment. For more than 100 years the generation of forces in the operation of metal cutting has been examined by the researches of the metal cutting domain. In metal cutting, force estimation is a fundamental prerequisite as it is identified with machine part configuration, part accuracy, vibrations, power consumptions, tool design. The motivation behind force estimation is to comprehend the cutting system, for example, the impacts of cutting factors on the cutting power, tool wear, chatter, and the procedure of chip development and the machinability of the work piece. It has been seen that the estimated forces by designing computations have a few mistakes contrasted with test estimations. Since the unreformed thickness of the chip and the course of cutting pace shift at each snapshot of cutting procedure in processing, so estimation of force is geometrically perplexing. Attributable to such multifaceted nature, the forces of cutting even in relentless state conditions is influenced by numerous parameters and the variety of cutting force with time has an unconventional quality. The requirement for estimation of all cutting force segment emerges from numerous components, however likely the most significant is the requirement for connection with the tool wear advancement. In the event that this can be acquired, it will be conceivable to accomplish tool wear checking in processing dependent on power variety. As it is, a decent indicator in tool wear detection is the other reason behind cutting force estimation.

Either by acquiring consumed power indirectly (or) from metal cutting dynamometer directly the estimation of cutting forces, which are generated in machining operations, can be done. Attributable to the intricacy of the procedure of the metal cutting, created forces hypothetical figuring when chip is expelling from a work piece should coordinate with the outcomes noted by methods for extremely
delicate electro-mechanic force estimating gadgets. In this manner, the exactness of the observational conditions used to gauge cutting forces ought to be affirmed by the trials. In order to calculate the frame rigidity and power requirement, the cutting forces are fundamental to machine tool manufactures. The tool ought to have adequate quality competent to expel chip from the work piece at the ideal amount in the design. It will be utilized to compute the intensity of the tool driver framework and furthermore cutting powers following up on the tool.

2. Force Measurements
Force estimation is communicated as the disfigurement on a material force as force units by methods for adjustment component, similar to an alignment ring. Elastic element deformation feature has been used for detecting force signals. When suitable material is retained in the flexible zone, all in all, the variety of disfigurement with force is direct. The twisting zone distortions can be detected by electrical transducers, optical, pneumatics, mechanical and so forth. As strain gauges are made small and fitting is simple which convert electrical signals from mechanical variations that are generally favoured in designing applications. The body strain is dependably caused by an inner impact (or) outer impact structural changes of the material, heat, moments, pressures and forces can cause the strain. On the off chance that specific conditions are satisfied the sum or the estimation of the affecting amount can be gotten from the strain esteem. So as to gauge strain, it is advantage form direct variety of obstruction with strain. The spring element which is formed properly in the transducer is called strain gauge which produces a reasonable connection between the deliberate amount and the strain on an appropriate spot on the component of the spring.

It is important to design and fabricate dynamometers with adequate precision, to quantify force at wanted exactness level. The cutting forces and tool wear indirect connection can determine the tool life to monitor conditions of tool. Cutting parameter selection ought to be founded on cutting forces. Scientific dimension has been gained by tool wear and surface roughness to the process of machining. Thus the design and assembling of the dynamometer are especially appropriate for dynamic burdens

2.1. Dynamometer design

2.1.1. Dynamometer design criterions
Due consideration of the following requirements for its appealing accuracy, operation and consistency of force estimates should be given during the structuration of the dynamometer.
1. Transducing device affectability
2. Unbending nature of part of dynamometer
3. Force estimation accuracy
4. Least cross sensitivity
5. Linearity of calculation
6. The frequency of the dynamometer is substantially greater than operating frequency
7. Minimum sliding component
8. Least environmental effect
9. Dynamometer compacting unit
10. Improved instrument design

The inflexibility and affectability are two contradicting yet these are fundamental necessities in dynamometer structure. What's more, the dynamometer structure should meet more prerequisites worried to the characteristic recurrence, wide recurrence reaction and little cross-affectability [1]. The ring components machined must be indistinguishable and symmetrical to forestall cross-affectability and they ought to have certain surface quality and high estimation resistance. Strain rings mechanical properties must be resolved tentatively. Dynamometer basically comprises of a significant ring component. The unbending nature, high common recurrence, consumption opposition, and high warmth conductivity components were thought about while choosing the ring materials. Additionally, distortion under the heap ought to fit in with that of strain measures.

2.2. Evaluating octagonal ring dimensions
The sensitivity and rigidity are affected by the circular strain ring’s width b, radius r and thickness t parameters which controllable. As rings modulus of elasticity (E) and width b has no effect on the strain with respect to unit deflection. In order to setup rings securely, 30 mm b can be taken for the minimum to set up the rings securely.

Fig. 1(b) and (c) shows the circular ring deformation with respect to the main cutting force $F_c$ and thrust force effect $F_t$. Within the more flexible reaches of the ring material, for whatever period the load on A or B is fixed (Fig. 1(a), the deflection and load due to the principal cutting power should be regarded for the end objective of the ring structure for expansion of firmness ($F_c/\delta_c$) and affectability ($\varepsilon_t/F_c$).  

![Fig. 1. Circular strain ring deformation under (a) combined; (b) thrust $F_t$; and (c) main cutting $F_c$ forces.](image)

At maximum value of the concentration of stress, the strain checks ought to be put. The experiments showed high results for octagonal rings, where the inclined measurements are 45° from the vertical instead of 39.6° needed by circular ring theory. The strain per unit deflection can be communicated as

$$\frac{\varepsilon_t}{\delta_t/r} = \frac{1.09r}{1.8r} \approx 0.61 \frac{r}{r} = 0.224$$

Where $\varepsilon_t$ is the strain because of pushed power $F_t$ and $\delta_t$ is the deflection in the direction of radial. It is apparent that for most extreme affectability and unbending nature $\varepsilon_t/\delta_t$ ought to be as huge as could reasonably be expected [2]. This necessitates $r$ ought to be as little as could be allowed and t as enormous as would be prudent. Nevertheless, $r$ can be decreased distinctly to the point where it turns out to be too hard to even think about mounting inside gages precisely. In either of these lines, t should be large enough to be dependable with optimal affectability for a certain ring of r and b size. Ito et al. have performed finite element analysis for the flexible conduct of octagonal rings. They reported that when compared with the circular ring $t/r$ is not precisely or equals 0.05, the difference between the octagonal ring and circular ring is <10 per cent, with $t/r$ more prominent or comparable to 0.25. The octagonal ring is liberally tightened. To be reliable with this articulation, the ring sweep and ring thickness were taken as 20 and 8mm, individually. Consequently, the proportion of $t/r$ (8/20 = 0.4) gives the relating affectability to firmness proportion $\varepsilon_t(\delta_t/r)$ of the octagonal ring [3-4].

### 2.3. Dimensional verification of octagonal rings

The maximum expected force, 3500 N is expected when the rings are subjected in every direction. Unless the cross-sectional components of a bar that are curved are lighter than the centreline radius, they are considered to be a thin ring as seen in Fig.2. By accepting the measurements as thickness (t) = 8 mm, radius (r) = 20 mm and width (b) = 30 mm the flexible strains $\varepsilon_t$ and $\varepsilon_c$, because of powers $F_t$ and $F_c$ are determined by the theory of ring by utilizing the accompanying conditions:

Young’s modulus of EN8 steel E=210 GPa.

$$\varepsilon_t = \pm \frac{1.09F_t r}{Ebr^2} = \frac{1.09 \times 3500 \times 20}{210 \times 10^3 \times 30 \times 8^2} = 1.8923 \times 10^{-4}$$
\[ \varepsilon_c = \pm \frac{2.18 F_c r}{E b r^2} = \frac{2.18 \times 3500 \times 20}{210 \times 10^4 \times 30 \times b^2} = 3.784 \times 10^4 \]

Fig. 2. Schematic diagram of octagonal ring

The stresses on the rings resulting from thrusts and major forces of cutting may be estimated by inserting elastic pressure ratio values in equations (3) and (4) as follows.

\[ \sigma_t = E \varepsilon_t = 210 \times 10^3 \times 1.8923 \times 10^{-4} = 39.7 \text{ N/mm}^2 \quad (3) \]

\[ \sigma_c = E \varepsilon_c = 210 \times 10^3 \times 3.784 \times 10^{-4} = 79.46 \text{ N/mm}^2 \quad (4) \]

The ring material is made up of EN8 steel, its output strength is 465 N/mm\(^2\) (min), the stresses imposed on the rings are within the material safety limitations. In addition, the design and fabricated octagonal ring is as shown in Fig.3.

3. Dynamometer Construction

3.1. Strain gauge orientation on the ring elements

The thrust force \(F_t\) is balanced by the dynamometer rings (A-D) as shown in Fig 3. Force \(F_t\) affects the strain gauges 3, 4, 7, 8, 11, 12, 15 and 16. The 3, 7, 11 and 15 strain controls are tractable stresses and 4, 8, 12 and 16 strains are compressive. The feed force \(F_f\) is reinforced by the dynamometer rings A and C as shown in Fig. 4. Strain controls should be installed on the exterior A and C surface of the rings at an elevation angle of 45° to measure feed force \(F_f\). The strain measurements 1, 2, 5 and 6 are impacted by the feeder force \(F_f\), as shown in Fig.4. These stress measurements include 1 and 5, whereas 2 and 6 are subject to compressive stress [5].

B and D rings as shown in Fig 3 support the essential cutting force \(F_c\). For strain inspections for measuring the basic cutting force \(F_c\) with a trend point of 45° on the vertical plane, B and D rings are fitted. The strain controls 9, 10, 13 and 14 as shown in figure 3 are impacted by the basic cutting power \(F_c\). In Fig.5 the modelled mounting dynamometer is illustrated.
3.1.1. Strain gauges mounting on rings

The ring surfaces were on the ground for easier stress measurement application. Absolutely 16 strain controls were installed on four octagonal rings. Two strain checks on the outside of each ring at 45° edges have been mounted equally, with two further strain checks one being inside and the other outside of the ring, which are also vertically placed, see Fig. 6.

For steel specimens and static or dynamic stacking, the proposed strain measurement F Arrangement 6/350 was applied. For a period of time a constant zero setting and exciting voltage should be chosen with care in order to achieve minimal vitality dissemination.

Fig. 4. Schematic illustrating the placement and orientation of the strain gauges of the octagonal rings

Fig. 5. Modelled Dynamometer

Fig. 6. Bridge connections for $F_r$, $F_x$, and $F_c$ [1]

Fig. 7. Developed dynamometer with bridge connections
3.2. Dynamometer’s dynamic properties

The frequency of vibration of the machine tool must be determined for the measurement of the cutting force by the natural frequency of the dynamometer put on it. Higher the natural frequency of vibration the more desirable it is [6]. Frequency of vibration and machine tool’s speed of the spindle are relative to each other. It is desirable that the natural frequency is 4 times of the machine tool’s frequency of vibration. A small mass with ring elements as supports is considered as a dynamometer for analytical analysis as depicted in Fig. 8.

In order to obtain the natural frequency of the dynamometer, the ring constant is needed. Equation (5) shows the value of rigidity for a lower-thick circular ring:

\[ K_t = \frac{F_t}{\delta_t} = \frac{Eh^3}{1.8r^3} \quad (5) \]

\[ = \frac{210 \times 10^3 \times 30 \times 8^3}{1.8 \times 20^3} = 224000 \text{ N/mm} \]

The ring constant of the dynamometer was found to be \( K_t = 224000 \text{ N/mm} \) to replace the relevant numbers in the preceding equation.

From the connection can be inferred the frequency of the natural vibration of the dynamometer believed to be a small group of ring components acting as supports (6)

\[ f_d = \frac{1}{2\pi} \sqrt{K/m} \quad (6) \]

\[ = \frac{1}{2\pi} \sqrt{224000 \times \frac{1000}{15.8}} = 599.56 \text{ rev/s} \]

Where,
\( K \) is ring constant of dynamometer (N/mm);
\( m \) is dynamometer mass (kg) and
\( f_d \) is natural frequency of dynamometer (rev./s).

The ring weight is 0.3066 kg. The natural frequency of the dynamometer is computed as \( f_d = 599.56 \text{ rev/s} \) by replacing these numbers in Eq.(6). For the feasibility of the above requirement as considered above, \( f_d \geq 4f_m \), the maximum speed of spindle we can allow is 2000 rpm [7].

\[ f_m = \frac{n}{60} = \frac{1800}{60} = 30 \text{ rev./s} \]

Therefore \( f_d \geq 4f_m \) [5],

\[ 599.56 \text{ rev/s} \geq 4 \times 30 \text{ rev/s} \]

\[ 599.56 \text{ rev/s} \geq 120 \text{ rev/s} \]

Hence our requirement has been fulfilled and the developed dynamometer can be seen in Fig.9.

![Fig. 8. FBD of Dynamometer](image-url)
4. Experimental Setup

1) Machine equipment - Universal Milling Machine.
2) Dynamometer - A3-component force analog type dynamometer is designed which can measure cutting forces while carrying out the milling operations. The measurement of the schematic cutting force is shown in Fig. 10, able to measure feed force (F_f), thrust strength (F_t) and the crucial cutting force (F_c) that arises in friction operations. The strain gauges are positioned to support the dynamometer on the 4 elastic octagonal rings. These strain gauges with necessary connections would ensure the measurement of Wheatstone bridges.
3) Data Offline logger and realtime cutting force data information is read and documented manually during metal cutting. Due to the very high stiffness required for dynamometer and the Wheatstone bridge output being so less, digital multimeter converts the amplified analog signals coming from the strain gauges of the dynamometer to digital signals to meet the requirements. Retrieving of stored data is possible when there is a need for analysis.
4) Performed slot milling operation with varying spindle speed, depth of cut and feed.
5. Calibration of Dynamometer
Calibration should be done after the design and construction of the dynamometer. The objective of the calibration is to estimate the elastic deflection of the ring component in relation to the voltage of output at static charge. Loads of 250N, 500N, 750N and 1000N were applied soon after the dynamometer was positioned vertically on the table of Universal Testing Machine for calibration as shown in Fig. 11. Similarly, the strain was recorded after the application of each load.

![Dynamometer calibration on Universal Testing Machine](image)

Three directions are calibrated and the average voltage of millivolt is considered for each direction. Calibration curves for each direction were constructed to translate the output data into cutting force values. For vertical, horizontal and axial forces, the resulting calibration curves are shown in Fig. 12, 13 and 14. All measurements were three times repeated and the results obtained were fairly near. In order to check consistency. Minor oscillations were seen when the loading impact on the other force components in one direction was studied and small changes were noticed. The loading impact on the other force components may thus be neglected in one direction. When the calibration was completed before machines were tested, the dynamometer ran idle for 5 minutes with all the connections needed to measure dynamometer consistency.

![Calibration of $F_c$](image)
6. Results and Discussion
The developed dynamometer is a three-force analogue component type that can measure trimming forces during framing. Schematic illustration of the measuring cutting force system, allowing to measure feed force, thrust force and primary cutting force during milling activities. This strain gauge based dynamometer for measuring cutting forces on milling was successfully developed. The system was complemented with required signal conditioning and multimeter so as to directly display the force reading on the screen. It has high stiffness which increases the sensitivity. And also it possesses high natural frequency. Main advancement is, it is developed for milling but with small modification we can measure the forces generated during the grinding and turning operations. Developed dynamometer is cheap and one can easily manufactured when compared with the other digital milling dynamometers and use for academic purpose and easily carry from one place to another.
Table 1: Experimental values of force measurement on universal milling machine

| Spindle Speed RPM | Feed Rate | DOC div | $F_t$ Vm | $F_r$ Vm | $F_c$ Vm |
|------------------|-----------|---------|----------|----------|----------|
| 45               | 31.5      | 2       | -0.1     | 0.1      | 0.1      |
| 90               | 100       | 4       | 0.2      | 0.1      | 0.3      |
| 90               | 125       | 4       | 0.2      | 0.1      | 3.4      |
| 90               | 125       | 5       | 0.3      | 0.2      | 6.8      |
| 180              | 160       | 5       | 0.4      | 0.2      | 21.7     |
| 180              | 200       | 5       | 0.5      | 0.2      | 35.1     |
| 180              | 250       | 5       | 0.8      | 0.2      | 44.8     |
| 355              | 250       | 5       | 0.2      | 0.0      | 57.9     |
| 355              | 500       | 5       | 0.2      | 0.0      | 67.5     |
| 560              | 63        | 2       | 0.2      | 0.0      | 72.2     |

7. Conclusions
In the current study, development and design of a dynamometer (strain-gauge) is done. It is designed and connected to a suitable data system. The main advantage of the dynamometer is that it can take and store values of 3 axis components during the milling operation at the same time. The maximum design force up to which the present dynamometer can accurately measure values is 3500N. The positions of strain-gauges and octagonal rings are specified in such a way that it is possible to get maximum obtainable rigidity and cross-sensitivity as a minimum if considered while deforming. The dynamometer was physically calibrated to establish its accuracy. Curves of calibration (static type) for $F_t$, $F_r$ and $F_c$ forces show that the dynamometer has great linearity and very less cross-sensitivity errors. Best possible values are obtained in the milling process for the measurement of cutting forces. Subsequently, the obtained data for cutting forces are laid out for evaluation. The favourable rigidity obtained is satisfied by the dynamometer’s natural frequency. The results which were obtained using this dynamometer for machining processes with various parameters of cutting shows that this is highly reliable for the measurement of cutting forces not only for the milling operations but can also be favourable for processes like grinding, shaping and turning.

8. References

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