Development of Compliant Vibration Isolation Damper and Its Performance Analysis in Turning Operation

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The major setback faced by any of the production industry was maintaining the surface quality and dimensional accuracy of parts manufactured. Higher productivity is expected from industrial point of view, but resulting in poor surface texture. This work aims at addressing this problem by developing a suitable damping system for increased production with high precision products. In conventional method, dampers used is assembled of many parts, whereas the innovation in this paper is that the damper structure is monolithic in nature. Hence, manufacture time and cost of new innovative compliant damper is reduced. The work addressed the problem of damping by the use of compliant mechanism developed through building blocks of planar compliant mechanisms synthesis. Finite element analysis (FEA) was carried out in deciding the final form of the damping system. The proposed design was created by following fused deposition modelling (FDM 3D printing technique) using acrylonitrile butadiene styrene (ABS) material. Based on the results obtained from the experiments, the damping system has an impact on the surface quality of the product. The cutting force produced between the cutting edge and work surface could be improved by providing continuous contact (i.e., higher tool stability). The tool stability could be improved by using the compliant damping design and 3D printing technology for developing the complex designs into real products. The major limitation of the proposed work is the complexity in analysing compliant models with all the boundary conditions prevailing in the real time environment. The major influencing boundary conditions could be applied in neglecting insignificant factors. This work is a novel approach for developing a compliant mechanism-based damper that could restrict the effects of chatter in machining operation. The building blocks-based design was produced using 3D printing of the ABS material. Turning of aluminium was analysed for surface improvement by the tool stability improvement. Results revealed the impact of the ABS compliant damper. On an average, surface roughness of the products was reduced by 27.61%.

1. Introduction

The term vibration in machining also referred as chatter has been defined as an important factor in deciding the surface finish quality of products [1, 2]. An interest in analysing the dynamic behaviour of turning operation with respect to material removal using a finite element approach gave an insight towards the process. Vibration responses were
identified to be a major indicator of stability in components positioned inside or placed over a dynamic object [3]. The chaotic phenomenon arising in dynamic components were studied in relation to the hinges and supports provided along the system. The positive contributions of flexible connection are evaluated upon the loss of kinematic constraints between the clearance joint parts. The vibration isolation is a vital process in the precision manufacturing process [4]. The decoupling controller was developed for executing the mentioned problem in maintaining precise tolerance of machined components. The stability lobe diagram can be used in the analysis of robust dynamic behaviour of machine tools with respect to chip formation [1, 2]. A large amount of vibrations occurs in heavy duty turning operation and thereby it attracts reduction of such a phenomenon [5].

The component of assembling cell phone vibration motor has been a very complex operation, which was easily carried out using a compliant microgripper [6]. Based on the topology optimization procedure, the dimensions of hinges were chosen with further optimization through the ANFIS algorithm. The prediction of force exerted was within acceptable limits of 4%. A flexure based zero stiffness beam type positioning stage was proposed in order to deliver a constant torque output [7]. Parametric optimization was carried out using Ansys FEA technique and topology optimization with principal structural variables as length, width, thickness, and orientation for constant force shaft. The constant force embodiment on objects being held was a major crisis in the area of gripping. A constant force
mechanism was developed with the aid of compliant [8]. Proposed compliant gripping reduced the holding principal stress encountered within an allowable range [9]. A statically balanced compliant mechanism (SBCM) is proposed, dynamically modeled, and experimentally demonstrated to design ultralow wide bandwidth vibrational energy harvesters, which can provide a practical structural solution for harvesting energy from a range of vibrational scenarios (e.g., ocean waves, human motions, and bridge vibrations) with ultralow wide bandwidth frequencies and weak accelerations [10]. A polylactic acid polymer prototype is 3D printed and the frequency response of input force to transmitted force is experimentally measured showing a large 41 Hz band gap with a center frequency also around 72 Hz [11]. The prototype of the met material beam is fabricated by additive manufacturing, and the experimental investigation is conducted to verify the formation mechanism of the band gaps, which shows very low-frequency band gaps [12]. The design objectives in deciding overall topological parameters for a compliant suiting the applications demanding both flexibility and stiffness was presented as “design for required deflection beam” principle [10].

The response surface methodology is one of the renowned approaches for determining the relationship between process parameters and output parameters in any given problem. It represents the relationship in a simple 3D surface model [11–14]. Optimum results of the given problem can be easily identified along with the relationship analysis through the ANOVA technique. Traditionally, several algorithms based on nature were followed for selecting or identifying the optimized process parameters. Genetic algorithm, particle swarm optimization, and ants colony algorithm, were few examples. The newer approaches try to improve the prediction efficiency by integrating a traditional approach with other modern methodologies [11–14]. The RSM was used to develop a model for predicting required dependent variable from the independent variables. An attempt was made to clearly reduce the energy consumption of motor by selecting proper operating conditions during the turning operation.

2. Design and Development of Compliant Damper

The compliant mechanism however is widely used for conversion of movements without many linkages. An attempt to convert reciprocating movement into a closed elliptical movement was carried out [11]. The mechanism proposed was capable of withstanding large deflection without achieving the yield point condition by eliminating flexural joints in the system. Spatial beam constraint modelling of large flexural beams is difficult to design directly without any consideration for FEA [12]. The fluid-based microcompliant actuators paved a way for vibration isolation easily without any changes to the existing design [13]. The temperature-based modulus was analysed through experiments to validate the vibration isolation efficiency through fluid medium and provide insight ideas in the successful implementation. This work focuses on developing a compliant mechanism that could be used for vibration isolation in turning the operation of aluminium work piece [14]. This building block tool (as shown in Figure 1) is used in the development of compliant damper in this study for reduction in machine chatter and to improve the surface quality of the product.

The 3D printing technology was utilized for developing complex structured mechanism [7] in addition to the simpler designs that are time consuming if traditionally produced. The 3D printing of complaint microholders followed by the finite element analysis using Annoys was carried out [8]. The
FEA simulated results and analytical results revealed the performance gap bridging of such devices. The analysis through ADAMS and dynamic equations with respect to multiple degree of freedom resulted in successful isolation of vibration in all the modes [4]. The hexapod test rig offers six degree of freedom for any given payload. The designing for additive manufacturing itself is a tedious work [15]. The idea about the early designing of geometry suiting the fabrication facility has been presented. The additive manufacturing process has been around for almost a decade; however, selecting the correct parameters for developing a customized model needs to be explored [16–18]. Several factors like cooling rate, build speed, and fill density must be considered in arriving at the desired end product. Still some surface errors or deviation from the design are encountered. This can be avoided by the help of the FEA method towards additive manufacturing. Similar to the abovementioned technique, various parameters like laser intensity, power, layer thickness, hatch space, and base temperature play an important role in the completion of the product with respect to dimensional accuracy and surface texture [19]. The fused filament fabrication technique was used for the creation of compliant damper used in this study show in Figure 2. The initial studies on the damper design were made randomly. Based on the finite element, 1800 N is applied with the top surface of damper with a fixed boundary condition at the bottom face for different plastic damping materials. The model and structural analysis of the design arrived from the blocks (Figures 3 and 4) using ANSYS 15.0 [20], the best design in static with higher isolation efficiency was made from the ABS material having young modulus $-1.79$ GPA, yield strength $-29.6$–$48$ MPa, and density: $1.060$ g/cm$^3$. [14].

**Figure 4:** Developed compliant damper and its structural analysis report from ANSYS.
3. Experimental Setup

The experiments were conducted on the conventional lathe machine with CNMG 120408TK insert (as seen in Figure 5) with variation in operating parameters. Aluminium rods of dimension $\Phi 23\text{mm} \times 100\text{mm}$ are used for turning with end product diameter reduced to 20 mm with the same length. The cutting speed, feed, and cutting depth were chosen as input parameters along with the changes in dampers. The parameter and their level selection were done based on the specification given in the machinery by the manufacturers as shown in Table 1, following full factorial design of the experiments. The additional change in the system is the replacement of rubber dampers with plastic compliant dampers, placed on the bottom of the lathe leg. The sensor was placed at the one of the legs of the machine. The responses were measured using the UIL15 lathe tool dynamometer and VB-820IHA contact type vibrometer. Parameters like velocity ($v$), acceleration ($a$), displacement ($d$), and frequency ($f$) were observed using vibrometer, whereas surface roughness ($R_a$) was measured by pick up type (TR110) portable surface analyser in the work piece along the parallel axis direction.

4. Results and Discussion

The 27 experiments were conducted following full factorial design of experiments with three levels of variations in each parameter, with compliant damper and conventional rubber. The results are presented in the following sections.

4.1. Velocity, Acceleration, Frequency, and Displacement Measurements. The vibration responses velocity, acceleration, displacement, and frequency measured using the vibrometer is plotted in Figure 6. The velocity profile indicates almost equal performance at high-speed turning. At lower speed, the developed ABS compliant damper operates with less velocity than rubber. The acceleration and frequency profile clearly indicates higher magnitude while using the ABS compliant damper. Even with higher frequency, the displacement experienced by the proposed damper is negligible when compared with traditional rubber damping [2, 21–23].

4.2. Cutting Force Measurement. The maximum amount of material removal occurs while the cutting tool and work piece are orthogonal in position. The relative motion between the tool cutting edges and work material surface would cause self-excitation [21]. The stability analysis of the tool can be easily carried out using the surface analysis of the chip formed, chatter produced, and cutting force exerted. The least amount of displacement experienced by the machine tool is helpful in improving the continuous contact with the work piece during the turning operation [1, 2, 24].
Figure 6: Vibration parameter responses for each experimental run—(a) velocity, (b) acceleration, (c) frequency, and (d) displacement.

Figure 7: Comparison of the average cutting force with the rubber and ABS compliant damper.

Figure 8: Comparison of surface roughness with the rubber and ABS compliant damper.
This increases the tool stability by reducing the tool movement [5, 25]. The average cutting force is higher during all the runs while running with a proposed compliant damper as seen in Figure 7. The ability and nature of the compliant to withstand higher vibration without much deflection owing to the singular elemental structure without mechanical joints. The cutting force sustained by 3.05% on an average while using the 3D printed ABS damper in the system [26, 27].

### 4.3. Surface Roughness Measurement

The surface roughness is an important parameter in deciding the quality and dimensional stability of the product developed by machining [18, 21, 24, 28]. The integration of the compliant mechanism concept into the vibration reduction and damping system provides a boon to the industries. Higher amount of finish in product can be easily achieved with reduction in surface roughness, thereby reduces the deviation in dimension and nucleation of crack formation. The surface roughness measured at each run with both the dampers in position is plotted in Figure 8. An average of 27.61% surface roughness has been reduced by using the 3D printing technology and compliant mechanism in damping.

#### 4.4. Interaction between Speed, Feed, Cutting Depth, and Damping Material

Based on the above results and analysis, it is evident that the introduction of 3D printing technology and compliant damping mechanism has greatly influenced the product quality. The interaction effects of various machining parameters over the damper are presented in Figures 9 and 10. Based on these results, it could be concluded that speed has significant effects on the cutting force exerted with reference to the damper. The proposed model provides higher cutting force at low speed itself. In contrary, the conventional rubber damping provided higher force only at high speeds. The feed had a negligible effect and cutting depth improves force proportionally.

Similarly, the interaction for surface roughness was also plotted showing a distinct improvement in the result for all parameters with reference to the damping system. All three
parameters speed, feed, and cutting depth had reduced the surface roughness in all their levels when coupled with 3D printed compliant dampers. The same could be evidenced from Figure 8.

5. Conclusion

The main objective of this work was to design and develop a compliant damper for improving the surface quality of machined parts by reducing the effects of chatter. The designing of the compliant damper was carried out using building blocks of the planar synthesis method. Then, the finite element analysis was carried out for deciding the final structure capable of withstanding maximum deflection. The final design was 3D printed using the additive manufacturing technology with the ABS material. The machining was carried out according to the plan and responses were noted during each run. The velocity profile expressed similar pattern for both the dampers. The values of velocity during turning of aluminium work piece with the rubber and ABS compliant damper have observed. The initial runs at lower feed rate of 0.6 mm/min show almost equal velocity values for both the dampers. The ABS damper reduced the velocity at lower feed rate of 0.6 mm/min and increased the same at higher feed rates of 0.9 mm/min and 1.2 mm/min. The average value for all damping seems to be equal to 1 mm/min. Also, the average value was improved from 2.0 mm/min to 2.4 mm/min while using the ABS compliant damper. This could be caused due to the material characteristic of polymers capable of immediately dissipating the absorbed energy. The acceleration and frequency were high with the proposed damper model. The displacement however was very much smaller compared to the rubber damper. It is clear that the displacement is reduced by using the ABS compliant damper instead of the rubber damper. The maximum value of 65 0.55 mm was observed with rubber damping. This value was reduced by incorporating the ABS compliant damper to 0.51 mm which is 8.18% lesser than the former value. At high-speed machining condition, the displacement is greatly reduced. The average reduction in displacement was over the range of 4.63%. Cutting force exerted on the work piece was higher at a lower speed level and...
increased by 3.05% with the ABS compliant damper. The surface roughness greatly reduced by 27.61% with the ABS damper. The maximum value of 2.8 \mu m was reduced to 1.5 \mu m with the presence of compliant dampers. The interaction of process parameters and damping material was studied for cutting force and surface roughness. The significant effects on cutting force were observed only for speed, whereas all three chosen parameters had significant impact on surface roughness with compliant damping.

**Data Availability**

The data are available on request from the corresponding author.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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