Numerical study of free vibration behaviour of filled tool holder using epoxy-granite

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Abstract. This paper presents a computer simulation focused on identifying the effect of cutting tool construction and damping material on its natural frequency. To this end, nine cutting tools with different cross-section of tool holder filled up with high damping material were presented. The free vibration analysis performed by ANSYS Workbench indicated that vibration amplitude decreases in cutting tools with epoxy-granite compared to that of conventional cutting tool. The relationship between the first and second natural frequencies with the length and diameter of the absorber chamber reveals that increase in diameter and length will reduce the natural frequency. Moreover, Multiple Regression Technique (MRT) was used to present a new equation for calculating the first natural frequency of filled tool holder via the dimensions of epoxy-granite cell. Next, various cases of filled tool holder were analysed based on Taguchi method. The results of the Taguchi sensitivity analysis showed the effect of length parameter (58%) on the natural frequency is more than the effect of diameter parameter (42%) on it. Moreover, it is also concluded that the natural frequency is more effectively reduced if the part between tool head and first tightening screw is filled with an increased volume of the absorbent.

Keywords: Computer simulation, cutting tool, damping, machining process, natural frequency, vibration.

1. Introduction
Chatter vibration has been one of the main challenges of modern machining processes (turning, boring, drilling, milling processes, and etc.) for years, which was firstly identified as a major limitation of machining productivity by Taylor [1]. The chatter vibration during the turning process causes excessive noise, machine tool breakage, undesirable surface finish, reduced tool life and productivity [2-4]. Therefore, researchers have been attracted to develop machining process models which are more accurate and reliable. Machine tool dynamics play an important role in the stability of the machining process. Vibration, as one of the main parameters in turning operation, directly affects tool life and workpiece quality. Factors causing vibration during machining process are associated with tool clamping, cutting insert, geometrical (length and diameter) and material characteristics of the toolholder, and cutting conditions [5, 6]. Actually, dynamic excitation of the machine happens when a cutting tool starts cutting on an undulated surface, causing vibrations which changes the chip thickness. As a result, dynamic cutting forces at a frequency close to one of the natural modes are created causing the further excitement of the system [7] and tool breakage [8]. An unstable vibration takes place when the depth of cut exceeds an allowable limit. This is a main obstacle in achieving maximum material removal rate. Additionally, the wavy machined surface is the result of the relative vibration between cutting tool and workpiece [9]. In fact, in a turning operation, free, forced, and self-excited vibrations take place due to a lack of dynamic stiffness/rigidity of the machine tool system (cutting tool, tool holder, workpiece, and machine tool) [7, 10].

There are different methods to avoid chatter during machining process such as changing the cutting conditions [11, 12], analysing the compliance between cutting tool and workpiece [13, 14], changing
the cutting tool’s geometry [15, 16], and applying the stability lobes diagram obtained by means of turning modelling [7, 17]. Active and passive damping control techniques are also used to eliminate undesirable vibrations during the machining process. Among these approaches, the passive method is quite effective and desirable due to its simplicity [18] and it can be implemented by increasing damping constant or by modifying the structure. Hence, one of the well-known methods to reduce vibration is improving damping properties of cutting tool, which is possible by using a material with high damping property. Daghini has improved the boring bar’s performance by implementing with viscoelastic polymer composites with high damping interface [19]. The proposed boring bar is compared to a geometrically equivalent conventional tool in terms of experimental modal analysis, the clamping technique, and capturing the operational dynamic parameters during machining test at different cutting parameters. Wang et al. have improved the machining stability by proposing a new-type nonlinear tuned mass damper [20]. The authors claimed that it could effectively suppress the magnitude of the real part of the frequency response function of the damped machining system. Ghorbani et al. have applied epoxy-granite as a composite material with high damping capability in the boring bars’ toolholder [21]. The authors stated that composite boring bars reduced vibration during machining process leading to a better surface roughness.

The work described in this paper suggests cutting tools with a modified construction of toolholder filled up with a composite material possessing high damping capability (epoxy-granite). The numerical study using ANSYS Workbench presents several sample simulations of the toolholder vibrations. As a result, the natural frequencies are suppressed using modified cutting tools with epoxy-granite.

2. Finite element simulation

2.1. Geometric model of cutting tool

The tool cutting including main body, the cutting insert, the shim, and the clamping screw was modelled and with a precise dimension assembled into three-dimensional in Design Modeler 16.1 (Figure 1).

| Table 1. Characteristics of the cylindrical chamber hollowed out from the cross-section of the main cutting tool |
|---|---|---|---|---|---|---|---|---|---|---|
| Case No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Diameter (mm) | 150 | 150 | 150 | 100 | 100 | 100 | 50 | 50 | 50 | 50 |
| Height (mm) | 20 | 20 | 15 | 10 | 10 | 10 | 100 | 100 | 100 | 100 |
| Situation | One-third end of cutting tool | Two-third end of cutting tool | Whole main body of cutting tool | Primary cutting tool |
Also, in order to investigate the effect of vibration absorbent material (epoxy-granite) on the natural frequency of the cutting tool, cylinders with three radii and three different heights were emptied from a square cross-section and were filled up with Epoxy-Granite. The various cases used in this study (different geometrical parameters) for filling the cutting tool with the adsorbent material are given in table 1. Moreover, an overview of the ninth mode is shown in figure 2.

2.2. Materials
In this study, different materials, including AISI 5140, TiC, and epoxy-granite were used for cutting tool body, cutting insert, and filler absorbent material in the main tool body, respectively. The mechanical properties of the materials are reported in table 2.

Table 2. The mechanical properties of the materials used in this study

| Material                   | AISI 5140 [16] | TiC [16] | Epoxy-Granite [22] |
|----------------------------|----------------|----------|-------------------|
| Density (Kg/m³)            | 7700           | 4940     | 2500              |
| Elastic modulus (GPa)      | 190            | 450      | 350               |
| Poisson’s ratio            | 0.3            | 0.19     | 0.25              |
| Tensile strength (N/m²)    | 570            | 258      | 15                |
| Yield strength (N/m²)      | 293            | -        | -                 |
| Thermal expansion coefficient (1/K) | 15             | -        | 12                |
| Thermal conductivity (W/m.K) | 44.8           | 21       | 1.8               |
| Specific heat (J/kg.K)     | 452            | 563      | -                 |
| Material damping ratio     | -              | -        | 0.6               |

2.3. Meshing
The Hex Dominant method with tetrahedral element priority was used to make a meshing process. The side lengths of the elements are assumed to be equal to 1 mm with a change of less than 10% of the longitudinal value. It is clear that by having a uniform mesh, the most accurate FE response can be obtained in comparison with the reality. In this regard, figure 3 shows an overview of the finite element model of the cutting tool.

Figure 3. Finite element model of cutting tool.

2.4. Boundary conditions
According to the actual conditions at the time of turning operations, the underside of the tool is completely fixed (three translational (X, Y, and Z) and three rotational (RX, RY, and RZ) movement). The upper surface of the clamping tool is also fixed by two screws (the circular cross-sectional area specified in figure 1).

2.5. Mesh convergence
In order to reduce computational costs, including analysis time and the characteristics of the solvent system used (CPU, RAM, and HARD DISK), it is necessary to optimize the number of elements in the FE model to speed up the solution time and obtain an accurate and acceptable respond [23]. In order to
determine the correctness of the response the mesh sensitivity analysis was carried out considering the first three natural frequencies. The details of this evaluation are reported in table 3.

| FEM No. | 1  | 2  | 3  | 4  | 5  |
|---------|----|----|----|----|----|
| Element size (mm) | 1 | 1.5 | 2 | 3 | 4 |
| Number of elements | 167524 | 63130 | 30757 | 11252 | 7652 |
| First-natural frequency (Hz) | 2482.9 | 2520.1 | 2532.3 | 2531.8 | 2540.9 |
| Second-natural frequency (Hz) | 2778.9 | 2844.2 | 2849.4 | 2855.3 | 2862.9 |
| Third-natural frequency (Hz) | 7942.4 | 8018.1 | 8024.8 | 8036.5 | 8057.7 |
| First-natural frequency difference in comparison with finest mesh (%) | 1.50 | 1.65 | 1.97 | 2.34 |
| Second-natural frequency difference in comparison with finest mesh (%) | 2.35 | 2.54 | 2.75 | 3.02 |
| Third-natural frequency difference in comparison with finest mesh (%) | 0.95 | 1.04 | 1.18 | 1.45 |
| Mean difference (%) | 1.1 | 1.74 | 1.97 | 2.27 |
| Running time (min) | 137 | 58 | 16 | 2 | 0.9 |

As can be seen from the results presented in Table 3, it is possible to reduce the solving time about 68.5 times by considering a maximum of 2% error in response to the results of the finite element analysis. Also, the industrial experience of engineers indicates that the time to reach a response against a response error (about 10%) is much more important. Hence, a finite element model with 11152 elements was used for future analysis in this study.

3. Statistical analysis

3.1. Multiple regression technique (MRT)
In general, the relationship between a group of independent variables and a dependent response can be studied using this technique [24]. In other words, this technique is used to estimate the response in terms of different changes of multiple inputs in the shortest possible time. In the present research, the various cases reported in table 1 (10 runs) were used.

3.2. Design of experiments
Taguchi approach is one of the most well-known algorithms of DOE that results in the minimum number of required tests to investigate the effects of input parameters on output [25]. In this study, two geometrical parameters including diameter (D) and length (L) of epoxy-granite cell were considered as input variables. Also, three levels were assumed for each of them. The first natural frequency of the system was considered as an output. To perform Taguchi sensitivity analysis, the smaller is better viewpoint is considered for the first natural frequency of cutting tool. Also, the L9 orthogonal matrix with the characteristics of 3² was used.

4. Results and discussion

4.1. Finite element analysis
Modal analysis was performed by considering the boundary conditions described above. The values of six natural frequencies and mode shapes of the primary lathe tool (without epoxy-granite) are shown in
It is evident that the modifications of the mode shapes are related to the tool head and one third of the beginning of the main body.

According to the data extracted from modal analysis for different cases (Table 4), it is clear that the first three cases (No. 1-3) had no effect on the natural frequency values of the system. However, the next three cases (No. 4-6) resulted in a slight and negligible changes in the values of the first and second natural frequencies. In other words, using the six first filled tool has no affected to reduce natural frequency. Because the underside of the clamping tool and the second pre-bolt portion as well as the part between the two tightening bolts on the top side of the clamping tool make the mode shapes of the ending section of the tool remain constant and without motion. Moreover, it is also observed that the last three cases, which relate to the filling of the part between the head and the first screw in the tool by the epoxy-granite adsorbent, have resulted in a significant decrease in the natural frequency values. So that, using the structure intended for the ninth case can reduce the system's first and second frequencies by at least 10%. The damping capacity of cutting tool is related to the vibration energy consumption by cutting tool and epoxy-granite associated with the amount of amplitude [26]. Actually, the damping capability of cutting tool results from the fact that vibration waves pass through the mediums metal and epoxy-granite leading to a vibration suppression, their partial reflection and change of their direction, which suppress vibration, stabilize the cutting tool position, and improves the surface quality [22]. The effect of two geometrical parameters of the cylindrical chamber (the volume of the vibrating absorbent material in the main body of the tool), including the diameter and height on the natural frequency of the system was investigated. Figure 5 and figure 6 illustrate the comparison of the effect of the diameter and height parameters for the different cases, respectively.

Since the first natural frequencies have more importance in system failures such as damage, resonance, etc., this section deals only with the first two natural frequencies of the system. The results obtained from finite element analysis of different cases of filling of the tool body by the epoxy-granite vibration absorber are presented in Table 4.

**Figure 4.** The first six natural frequencies and mode shapes of primary cutting tool.

From figure 5, when the cylinder length is limited to one-third and even two-thirds of the end of the tool, increasing the diameter does not affect the natural frequency values. However, it is clearly evident that in the model where the epoxy-granite adsorbent is filled completely (L=150 mm), the natural frequency values decrease sharply with increasing diameter. Also, the reduction of both the first and second natural frequencies of the system has the same trend with respect to the diameter. Figure 5 shows
that the natural frequency of the lathe tool decreases with increasing the diameter and the filling length of the cylindrical chamber. However, this change is evident when the maximum diameter (D=20 mm) is considered. This means that the natural frequency is reduced if we fill the part between the top of the tool and the first tightening screw by increasing the volume of the adsorbent. But this linear relationship is not true for other parts of the tool.

Table 4. FE results of the free vibrator of the tool with the absorbent Material

| Case No. | First natural frequency (Hz) | Second natural frequency (Hz) | The 1th frequency reduction compared to the primary cutting tool (%) | The 2th frequency reduction compared to the primary cutting tool (%) |
|----------|-----------------------------|-------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| 1        | 2533.4                      | 2858.1                        | 0                                                           | 0                                                           |
| 2        | 2532.8                      | 2855.3                        | 0                                                           | 0                                                           |
| 3        | 2533.0                      | 2857.1                        | 0                                                           | 0                                                           |
| 4        | 2526.5                      | 2857.6                        | 0.21                                                        | 0                                                           |
| 5        | 2514.0                      | 2850.9                        | 0.70                                                        | 0.15                                                        |
| 6        | 2485.2                      | 2838.2                        | 1.84                                                        | 0.60                                                        |
| 7        | 2506.8                      | 2823.7                        | 0.99                                                        | 1.11                                                        |
| 8        | 2443.3                      | 2745.5                        | 3.50                                                        | 3.85                                                        |

Figure 5. Influence of cylindrical chamber diameter filled with epoxy-granite on the first and second frequencies of the tool.

Figure 6. Influence of cylindrical chamber height filled with epoxy-granite on the first and second frequencies of the tool.

4.2. Linear multiple regression results

The linear relationship between the geometrical parameters of epoxy-granite cell (diameter (D) and length (L)) and the first natural frequency of filled tool holder with epoxy-granite was presented by applying a multiple regression technique (Equation 1). To measure the error rate of the proposed relationship in comparison with the results of finite element simulations, the comparative diagrams are depicted in figure 7.
\[ \text{Natural frequency} = 2531.8 - 2.1D + 1.75L + 0.36D^2 - 0.0149L^2 \] (1)

The results showed that the maximum and the mean difference between FE results and MRT for predicting the first natural frequency of filled tool holder is less than 12.4% and 4.5%, respectively. However, this technique can predict the natural frequency of primary cutting tool (without the use of the absorber material) with complete accuracy as shown in figure 7.

![Figure 7. The comparative diagrams between the results of multiple regression method and FE results.](image)

4.3. Results of Taguchi analysis
The influence ranking of geometrical parameters of the epoxy - granite cell has shown that the length parameter has the greatest effect on the natural frequency with 58% followed by diameters with 42%.

5. Conclusions
The implementation of epoxy-granite as a damping material in the structure of cutting tool by changing the cross-section at different locations resulted in reduction of magnitude of unwanted deleterious vibrations. When the epoxy-granite is filled between the tool head and the first screw in the tool, it reduces the system's first and second natural frequencies by at least 10%. This suggests that the damping material significantly increases the energy dissipation inside the structure material, making the cutting tool into a passive damper. This model could be useful for cantilever type cutting tools, when the high quality of machining surface is needed by decreasing the vibrations amplitudes. In addition to the above, the most important findings of this research are summarized:
1. A new equation is presented to calculate the first natural frequency of the filled tool holder by epoxy-granite in terms of cell length and diameter. The mean accuracy of this equation is less than 4.5% compared to the finite element result, but it is much faster to solve.
2. The results of the Taguchi approach revealed that the effect of cell length of absorber material is far greater than the effect of cell diameter of absorber material with the aim of the natural frequency reduction.

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