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Investigation on Dynamic Analysis of VMC Bed using epoxy Composite

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Abstract: The current trend in the machine tools market is to produce machines capable of faster cutting speeds. The level of vibration in a machine tool has always influenced the accuracy, both dimensional and geometrical, of the product machined. Increasing structural stiffness could help in avoiding these problems. Alternate materials which could increase the structural stiffness while enhancing other characteristics including damping simultaneously should be used for machine tool structures. On the other hand, epoxy composite has exceptional damping characteristics. In this work, the bed of the Vertical Machining Center was considered for modifications to enhance both its stiffness and damping characteristics. Finite element analysis (FEA) was also carried out for standard dimensions of hybrid samples of different steel face thicknesses. Static and modal analysis were carried out for the hybrid samples. From the results of the analysis the optimum thickness of the steel face for the bed is determined as 1.5 mm. The bed of Vertical Machining Center (VMC) was modeled using Pro/E and the finite element analysis of the bed was carried out. Static and modal analyses of the bed were carried out using ANSYS. The hybrid samples containing epoxy concrete core and steel face were fabricated. From the experimental results the damping factor of hybrid samples is calculated as 0.45 which is higher than the damping factor of cast iron (damping factor = 0.2)

Keywords: Machine tool, damping, epoxy composite and modal analysis

Nomenclature:

F = Thrust force

k= work piece material Constant

S = feed rate

x_1 = Amplitude of first peak in the graph

x_2 = Amplitude of successive peak in the graph

δ = logarithmic decrement

ζ = Damping factor

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1 Introduction: The high transfer speed as well as the high cutting speed of machine tools is important for the productivity improvement. Faster cutting speeds can not only ensure faster cutting rates but also promise lesser cutting forces both of which can in turn bring about a whole lot of other benefits like reduction in time cycle, costs, fatigue and failures as well as increased machine usage rates, improvements in product quality, precision and accuracy. Faster cutting speeds can be facilitated only by structures which have high stiffness and good damping characteristics [1]. The machine life has been found to be inversely proportional to the levels of vibration that the machine is subjected to. Not only is the worker affected by the high levels of vibration prevalent in the working conditions leading to fatigue and finally to lower productivity **[2],** but also tool life gets severely shortened thereby greatly increasing the cost associated with it and also severely jeopardizes the accuracy of the component manufactured and damages the parts of the machine Increasing structural stiffness could help in avoiding such problems. Though materials that can show positive features in majority of the aspects are preferred, such materials still remain indescribable **[3].** This makes it necessary to combine the materials in appropriate ways to form composite structures that can optimize the improvements **[4].** This was the motivation behind the idea to go in for a composite model involving steel and polymer composite. Steel has good strength and stiffness properties but scores low when it comes to satisfying damping requirements **[5]**. On the other hand epoxy composite, though suffers from low strength, has exceptional damping characteristics. This makes it ideal to combine these materials in an appropriate manner.

Since the bed in machine tool plays a critical role in ensuring the precision and accuracy in components and is one of the most vital machine tool structures that also tends to absorb the vibrations resulting from the cutting operation **[6],** the bed of Vertical Machining Center was considered for redesigning to enhance both its stiffness and damping characteristics. Hence recognizing the multi-pronged benefits that a stiffer bed can reap, we decided to analyze the bed for possible material changes that could increase stiffness, reduce weight, improve damping characteristics and isolate natural frequency form the operating range **[7]**. Despite rapid strides having been made in recent times in the field of materials used for machine tool structures, most of the materials when used individually offer only unbalanced benefits. From the literature, it is observed that, many studies were done to find out the suitability of composite materials in replacing the conventional materials **[8]**. However, a few or no studies were found to compare the deformation of composite materials. A study of materials based on constant deformation will provide a better comparison of size, weight, damping properties etc., for the machine tool structure manufactured using alternative material suggested for it. In this study, epoxy composite, and cast iron structure exhibiting constant displacement were modeled analytically and tested numerically **[9]**. A rectangular beam has been selected for to simulate the machine tool component as bed. The deformation was calculated analytically. The test specimens of size were manufactured and their characteristics were studied conducting modal analysis for the samples **[10]**.

2 Material: The epoxy composite is composed of aggregates bound with polymer matrix which is usually epoxy or unsaturated polyester. The epoxy resin is used as the matrix material and unsaturated polyester resin was employed as a binding material, were purchased from Kovai Seenu fabrics, Coimbatore. Epoxy is less expensive and suitable for large structure such as machine tool bed due to its diverse curing rate. The properties of cast iron and epoxy are given in table 1

Table (1): Properties of cast iron and epoxy resin

Material	Density (ρ), kg / m^3	Modulus of Elasticity (E), GPa	Poisson ratio, (ν)
Cast iron	7200	110	0.3
Epoxy resin	1.17	3.5	0.25

The epoxy composite samples of standard sizes were fabricated for conducting compression tests. According to ASTM standard C580, the specimen sizes for conducting compression test on epoxy composite should be ø150mm x 300mm. The epoxy composite specimen was manufactured using the following composition. The coarse (gravel material size 2 – 5mm) to fine (material size less than 0.5mm) aggregate material ratio was taken as 88% by weight, 12% by weight of epoxy resin (Araldite LY 556) including 2% by weight of resin mixture as hardener (ARADUR HY 951) has been used as the matrix material. The test specimen was cured for 24hours at room temperature. The standardized weight fractions of the constituents were used to have lesser void spaces and better degree of compaction in the epoxy concrete samples after curing[4]. The moulds used for epoxy concrete samples are PVC pipes of 150mm internal diameter and 300mm length.

2.1 Experimental setup: The epoxy composite samples of required size has been manufactured as two pieces and fixed into the test setup. The natural frequency of the model was determined experimentally using the following components such as Labview software, Impact Hammer test (ASTM C215-91 Test) using the piezoelectric accelerometer and the impact hammer, BNC cables and connecting wires.The Experimental setup for the Modal Analysis of the epoxy concrete sample is shown in Figure 1 .

Figure (1): Experimental setup for dynamic analysis

A hybrid structure consists of steel outer face and epoxy concrete inner core. Dimensions of the hybrid samples are 500mm x 100mm x 15mm. Steel frame for outer face of the hybrid sample is fabricated using welding. Subsequently polymer concrete mixture is prepared with standard weight fractions of its constituents. Polymer concrete mixture is filled inside the steel outer face and rammed for better compaction. Accelerometer position on the hybrid sample is shown in Figure (2).

Figure (2): Accelerometer position on the hybrid sample

3. Results And Discussion : The different methods to validate the model, the natural frequency based evaluation method was adopted. The natural frequency of the VMC bed was found experimentally through the impact hammer test (ASTM C215-91test). The following equipment are used in experimental setup. They are, 4374 Miniature Piezoelectric Charge, Accelerometer, NI PXI 1042 Impact Hammer and BNC cables. The Sensors and accessories were used during the test.

3.1 Numerical Analysis : The beam structures were modeled numerically using ANSYS 10 software. The Stiffness of the hybrid structure largely depends on the thickness of the steel plate. Hence, appropriate thickness of steel outer frame for the hybrid bed of the machine tool has to be determined. Optimization of steel face thickness has based on Static analysis of the samples, Modal analysis of the samples and optimization of the steel face thickness from the results. For the static analysis of the samples, a standard sample of dimension 1000mm x 100mm x 100mm. the load of 100 N was applied on it. The same sample is used for modal analysis[5]. Static analysis was carried out for hybrid samples of steel plate thicknesses 0.6mm, 1mm, 2mm, 3mm and 4mm. the deformation of 2mm plate is shown in Figure(3).

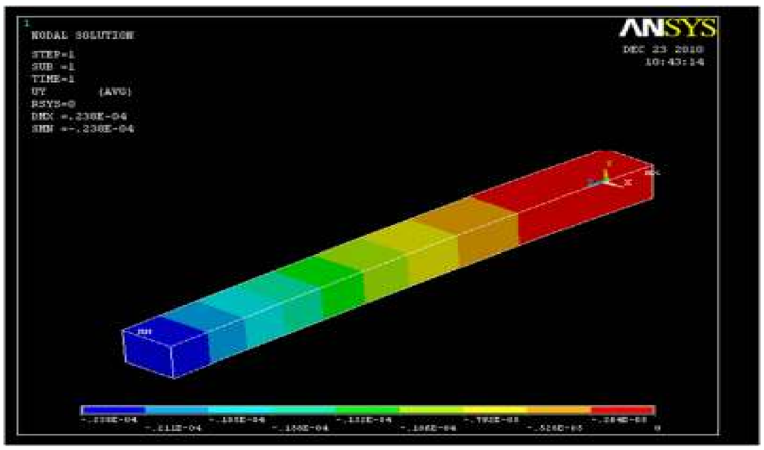


Figure (3): Deformation of 2mm plate

The steel face thickness was optimized. The values of deformation and natural frequency were compared. The comparison results are shown in Figure (4).

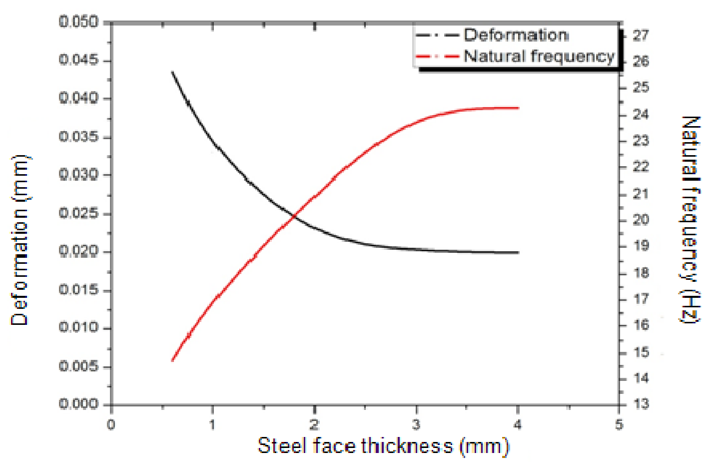
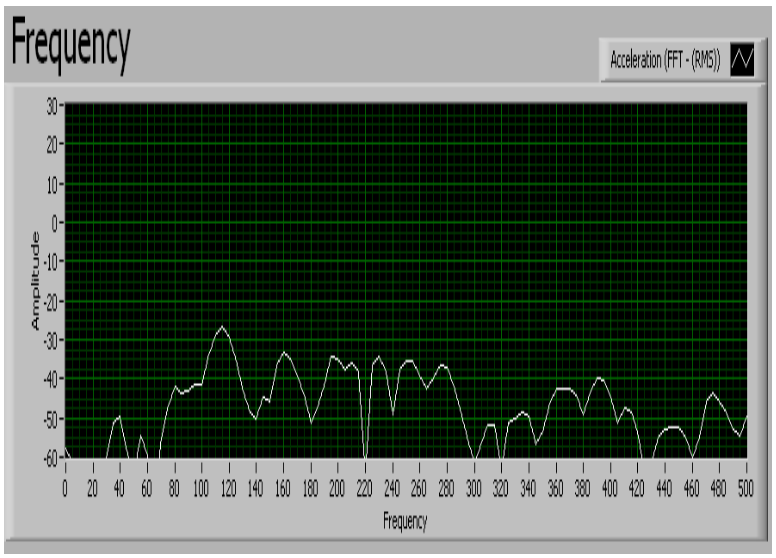


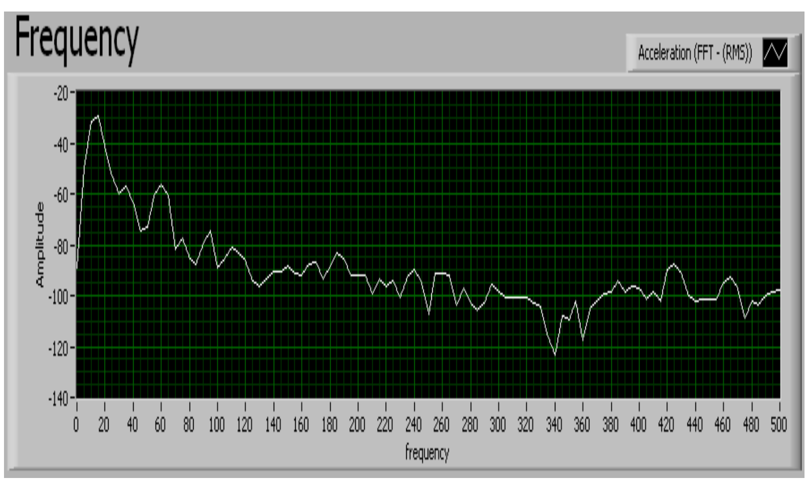
Figure (4): Steel face thickness vs deformation and natural frequency of hybrid samples of different plate thicknesses

The optimum thickness of steel face for having minimum deformation and maximum natural frequency had been determined as 1.5 mm. Figure (4) explains, the results of deformation and natural frequency, it is inferred that, as the thickness of the steel plate increases, deformation decreases and natural frequency increases. Hence to have less deformation and higher natural frequency a steel face thickness of 1.5 mm should be used in the bed.

The piezoelectric accelerometer which was fixed using bee wax transmitted signals, picked up when the surrounding region was excited by hitting with the impact hammer, through BNC cables to the Ni-PXI 1042 Q which acquires data and processes it as directed by the program used. The impact hammer was also connected to NI-PXI 1042 Q in a similar way. The miniature piezoelectric charged accelerometer had a sensitivity of 9.88 mV/g. The LabVIEW software was used to develop the program. The test was performed in the exciting the bed with the hammer and by running the program simultaneously. Modal analysis is conducted to verify the damping ratio of both the bed materials. The frequency response curves obtained using Lab VIEW program for the cast iron bed and epoxy concrete bed are shown in Figure. 5(a) and (b) respectively.



(a)



(b)

Figure (5): Frequency response spectrum: (a) cast iron and (b) hybrid structure.

The peaks in the above figure correspond to the consecutive modes of natural frequency of the bed. The peaks of natural frequency increasing with decreasing in the above figures. These values of natural frequencies obtained using experimental method are used to validate the values of natural frequencies obtained using Finite Element Analysis. The 3D model was imported and latter attached for Finite Element Analysis purpose in ANSYS. From the comparison, it is evident that the values of natural frequencies obtained experimentally and analytically are good. The CAD model of the bed is validated using experimental results. The Lab view software was used to develop the program. The peaks in the above figure correspond to the consecutive modes of natural frequency of the hybrid sample.

The Comparison of stiffness of cast iron and hybrid bed was carried out using the following analyses, static analysis of the cast iron and hybrid beds and modal analysis of the cast iron and hybrid beds. The comparison result of natural frequency of cast iron bed and epoxy concrete bed is given in Figure (6).

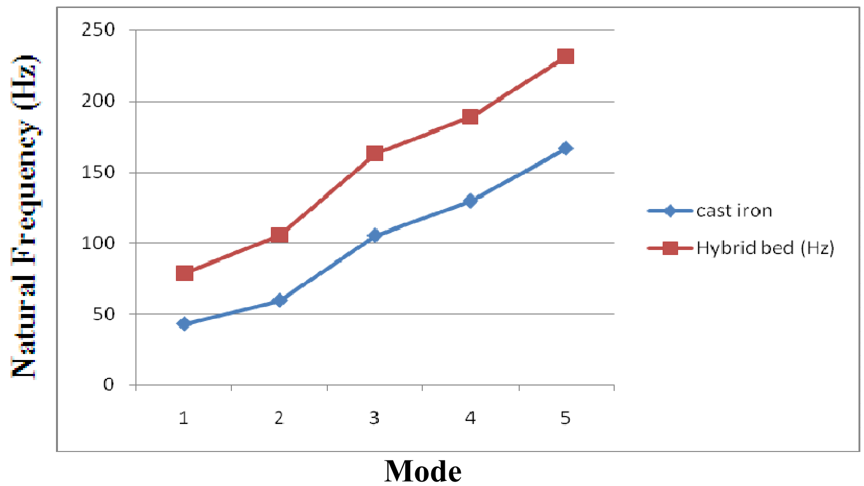


Figure (6): Natural frequencies of cast iron bed and Hybrid bed

Figure (6) explains, the natural frequency of cast iron bed increases also increase the hybrid bed. From the comparison shown in Table 2, it is evident that the values of natural frequencies of hybrid bed were higher than the cast iron bed. The deformation of the hybrid bed under given loading condition was also lesser than the cast iron bed. The deformation of the modified bed was reduced by 38%. Harmonic response analysis is a technique used to determine the stead-state response of a linear structure to loads that vary sinusoidal with time. Harmonic response analysis gives the ability to predict the sustained dynamic behavior of the structures which enables the designer to verify whether or not the designs will successfully overcome resonance, fatigue, and other harmful effects of forced vibrations.

Table (2): Comparison of analytical natural frequencies of cast iron bed and hybrid bed

Mode	Cast iron (Hz)	Hybrid bed (Hz)	Improvement in natural frequency (%)
1	43.025	78.562	81.29
2	59.688	105.352	77.64
3	105.520	162.840	54.28
4	129.841	188.405	45.74
5	166.909	231.152	40.48

3.2 Modal Analysis Of Vmc Bed : The 3D model of VMC bed was created by using Pro/E wildfire 4.0. The 3Dimensional model of vertical machining Centre bed is shown in Figure (7)

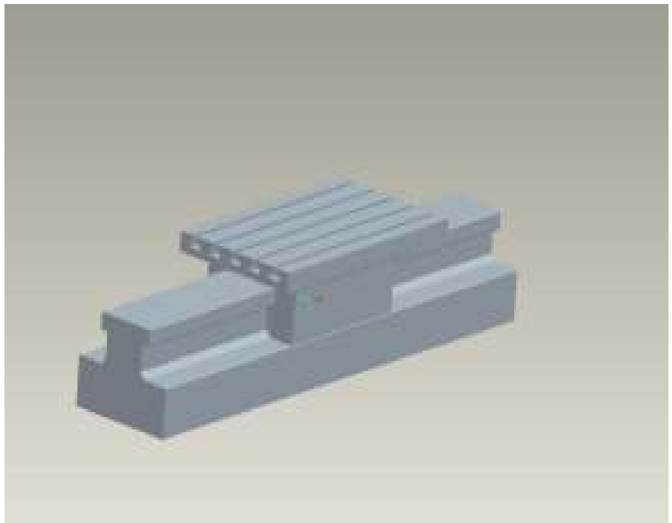


Figure (7): 3D model of VMC bed

The 3D CAD model was imported and later attached for Finite Element Analysis (FEA) purpose in ANSYS. The meshed model of VMC bed is given in Figure (8).

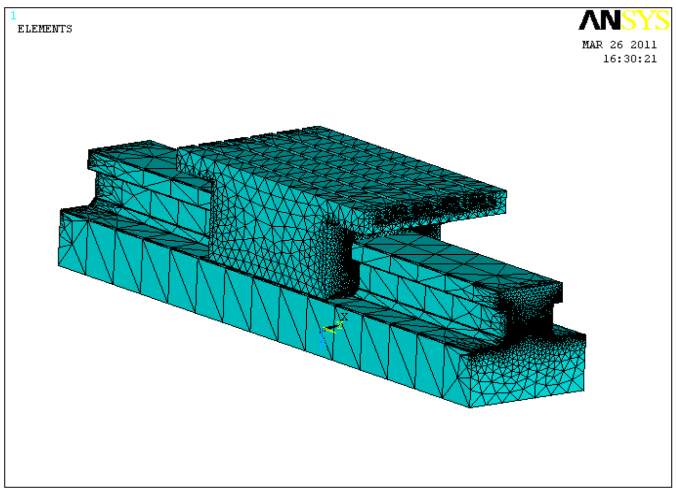


Figure (8): Meshed model of VMC bed

The idea is to calculate the structure's response at several frequencies and obtain a group of some response quantity (usually displacements) versus frequency. Peak responses of displacements are then identified on the graph at the peak frequencies. Harmonic analysis for drilling operation on the VMC bed was carried out. Using equation (1) the Cutting force was calculated.

Thrust force, F $= 1.16 \times k_1 \times d\,(100 \times s)^{0.85}$ ---------------- (1)

Where,

k_1 = work piece material Constant
= 1.07 for Mild Steel

S = feed rate
= 0.3 mm/rev,

d = hole diameter
= 20mm

Using the above relation cutting force was calculated as 4470 N and this load is applied as a harmonically with a frequency range of 0 – 100 Hz .Harmonic analysis results for cast iron and hybrid bed are given in Figure (9) and Figure (10) respectively.

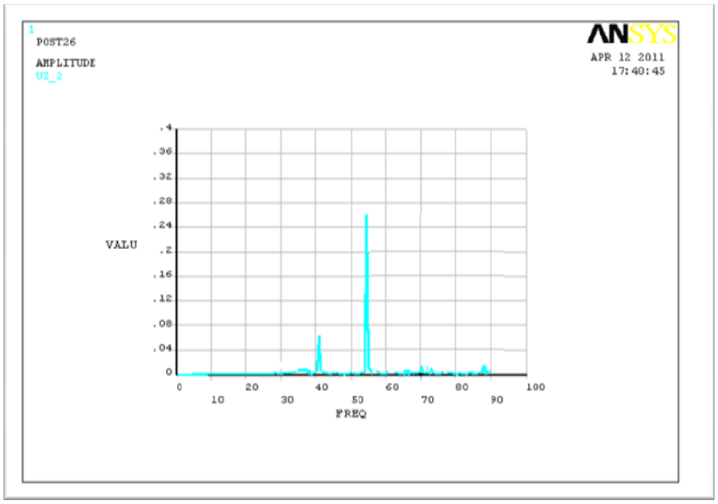


Figure (9): Displacement vs frequency for CI bed under harmonic loading conditions

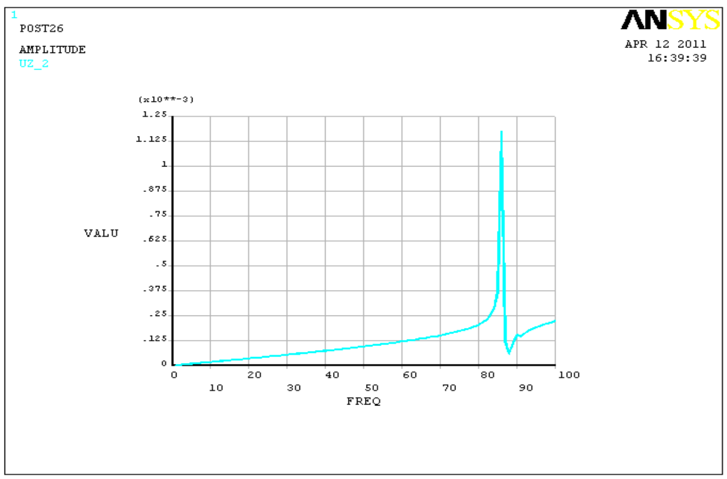


Figure (10): Displacement vs frequency for hybrid bed under harmonic loading conditions

From figure (9) and (10) explains, under the given loading conditions, cast iron bed has the displacements of 0.06 mm and 0.26 mm at the frequencies of 42 and 56 Hz respectively. The Hybrid bed has a displacement of 1.15 x 10^{-3} mm at a frequency of 88 Hz. The harmonic analysis results are given in Figure 11.

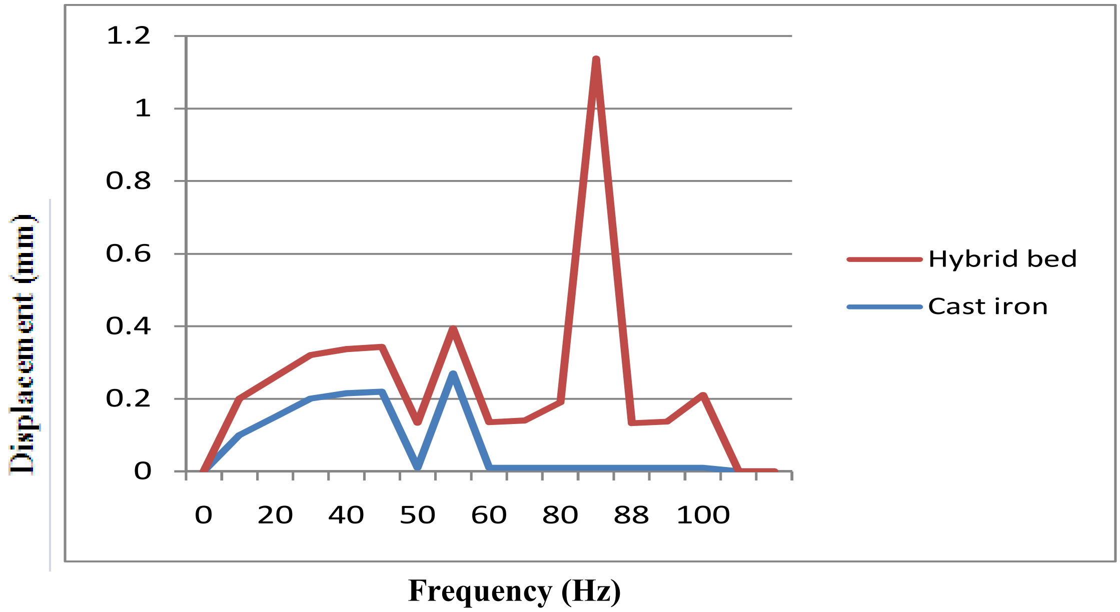


Figure (11): Harmonic analysis result of cast iron and hybrid bed

Figure (11) explains, the values of resonance displacement of hybrid bed are lower than the cast iron bed under given loading conditions. It is evident from the results that under dynamic loading conditions the hybrid bed has better dynamic stiffness than cast iron bed. The deformation of the hybrid bed under given loading condition is lesser than the cast iron bed by 99.55%. The same experiment is used to determine the damping factor of the hybrid samples. The sample is excited using a hammer. The displacement versus time curve is plotted and the logarithmic decrement value is obtained from the amplitude of two consecutive peaks from the results of the experiment are given in Figure (12).

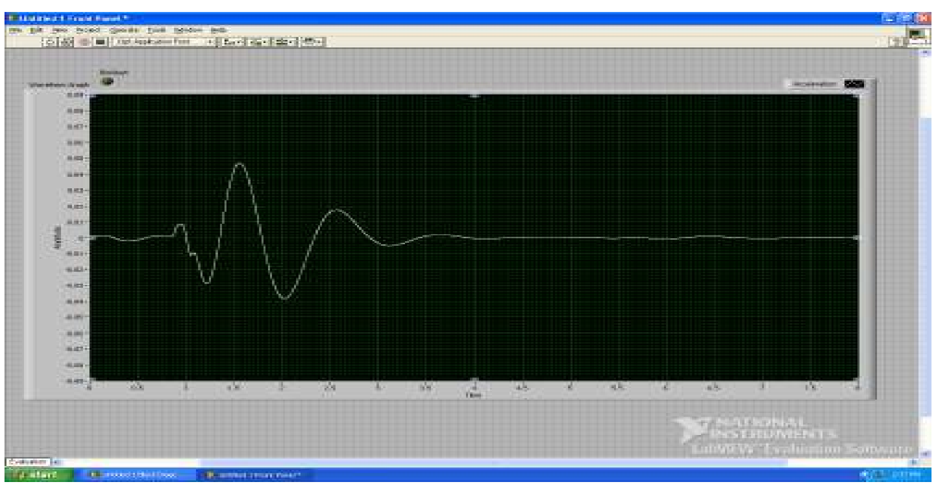


Figure (12): Screen shot of logarithmic decrement for hybrid sample

Figure (12) explains, the displacement of the sample reduces logarithmically. The vibrations damp out with time. The theoretical calculation for finding the damping factor was carried out. Equations (2) and (3) are used to determine the damping factor.

$$\delta = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}} \qquad \text{--------------------- (2)}$$

.
$$\delta = \ln \left(\frac{x1}{x2}\right) \quad \text{-------------------- (3)}$$

where, x_1 = Amplitude of first peak in the graph
x_2 = Amplitude of successive peak in the graph
δ = logarithmic decrement
ζ = Damping factor

Using the above relations the value of damping factor calculated for the hybrid specimens is 0.445%. The value of damping factor of cast iron is 0.2% but the value of damping factor for hybrid sample is calculated as 0.445%. Therefore it is evident that damping capacity of hybrid structure is higher than cast iron.

4. Conclusion: A hybrid structure containing steel outer face and epoxy composite core has been proposed as the material for the machine tool bed. Structural stiffness of this new bed had increased by around 40%. In addition, the poor damping characteristics of steel were counteracted by the presence of epoxy composite cores which have been claimed to have the best damping characteristics amongst the materials used for manufacturing beds. The experimental results have shown that the damping factor of hybrid structure is higher than the damping factor of cast iron. Damping factor of steel and epoxy composite hybrid structure was calculated as 0.45% which is higher than the damping factor of cast iron i.e. 0.2%. A modal analysis conducted on the modified bed also revealed an increase in the natural frequency of the bed, a desirable development that in effect tends to isolate the natural frequency further from the operating frequency.

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