Analysis of Effect of Coating Materials on Dynamic Properties of Structure

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Abstract: - Damping in material or structure is main criteria to judge mechanical design. Lack of sufficient damping in structure induced abrupt noise and system may fails. There are different ways to damp the induced vibration like active and passive damping treatments. Active damping introduces the vibration of same amplitude which caused it but in opposite direction. Passive treatment includes external layer of different materials on parent materials so called as coating. In this report the work of passive damping is done for alloy steel and aluminum structure with hard chrome, graphite and PVC and Natural, Synthetic and Butyl rubber respectively.

Index Term: - Damping, Active, Passive, Frequency, FEA

1. Introduction

1.1 Noise and vibration control is a major concern in several industries such as aeronautics and automobiles. The reduction of noise and vibrations is a major requirement for performance, sound quality, and customer satisfaction. Passive damping technology [1,2] using visco-elastic materials are classically used to control vibration.

1.2 The fundamental work in this field was pioneered by Ross, Kerwin and Ungar (RKU) [3], who used a three-layer model to predict damping in plates with constrained layer damping treatments. Kerwin [4] was the first to present a theoretical approach of damped thin structures with a constrained visco-elastic layer. He stated that the energy dissipation mechanism in the constrained core is attributable to its shear motion. He presented the first analysis of the simply supported sandwich beam using a complex modulus to represent the visco-elastic core.

1.3 Reuss and Hasin-shtrickman (H-S) theory relations young's modulus of composite section which then subsequently applied to section of switched beam for complex behavior. In the Reuss structure, two different phases are aligned perpendicular to the direction of the external load so that they experience the same stress. The generalized Reuss formula can be expressed as Eq.1[5]

$$\frac{1}{E^*} = \Sigma \frac{V_i}{E_i} \qquad \text{Eq.1}$$

the structure damping tanδ depend on the ratio of the coating and substrate's modulus E_c/E_s and the thickness fraction of the coating layer h_c, that is expressed as Eq.2

$$\tan\delta = f\,(E_c/E_s, h_c) \qquad \text{Eq.2}$$

Liming Yu, Yue Ma, Chungen Zhou, Huibin Xu [6] contributed for the optimum coating thickness and damping efficiency for the substrate materials $1Cr_{18}Ni_9T_i$stainless steel, $1Cr_{13}$stainless steel and the coatings layer NiCrAl metal and Al_2O_3 ceramic coating for thickness of substrate and coating layer 950-1000 µm respectively.

Since elastic modulus[E] measure the stiffness of the materials and tanδ the damping, the product of the two Etanδ is a useful figure of merit that combines damping and stiffness[6]. Materials that combine high damping and high stiffness are not common, for most of the existing materials for example, the product Etanδ of Al alloy, stainless steel and tungsten are 0.07GPa,0.2GPa, 0.4GPa, respectively[1-6].

It is obvious that the coating structure's modulus and damping capacity changes in the opposite direction while increasingh_c. But on the other hand, when the ratio E_c/E_s approaches zero, which means the stiffness difference between the coating layer and substrate is increasing, the modulus and the damping capacity of the coating structure will increase simultaneously [6].

The theoretical results based on the Reuss model and Hashin-Shtrickman equation show that for a coated beam structure, there exist an optimum thickness of the coating layer $h_c$that maximizes product Etanδ of the coating system obtain the maximum value provided that the damping capacity of the coating layer and the substrate are not equal.

1.4 Relation of Metal Coating and Resonating Frequency

Ashok Kumar Pandey, K P Venkatesh and Rudra Pratap shown that the metal coating increases the stiffness and the effective mass of composite structure and the residual stress increases or decreases the net stiffness if it a tensile or compressive type respectively. Author investigated both phenomenon by constructing the micro- cantilever beam which is made of 2 μm thickness poly-silicon material and is coated with 500 nm thickness of gold layer and found out its frequency response and for residual stress sffect, analytical model was prepared with MEMS gyroscope [8].

The standard of ASTM E-756(05) was used for preparation of test specimen using Oberst beam technique. It was found that FRF curve smoothening more, as effect of more damping present than un-damped beam. Poly Urethane, Butyl and Nitrile were found with damping factor ζ of 0.123,0.247 and 0.130 respectively.

1.5 Dynamics of Vibrations for Composite Beam

Voltera, E., Zachmanoglou, E. C modeled the un-damped model relation form theory of vibration and string equation which gives the mode shape and natural frequency of vibration analytically [11]. The same model was used for composite beam which gives the un-damped model behavior. It also been concluded that as addition of coating thickness changes the natural frequency of vibration.Vice-versa changes in natural frequency due to addition of mass of non-homogeneous material can be used to find the young's modulus of coating material.

2. DAMPING TREATMENT AND MATERIAL SELECTION

The material modeling for measurement of damping for visco-elastic material is achieved by two ways of providing the damping material on surface of substrate as free layer and constrained layer damping treatment.

2.1 Free Layer Damping Treatment

Oberst Beam Method (OBM) is the classical method for the characterization of damping materials based on a multilayer cantilever beam which consists of a base beam and one or two layers of other materials. The base beam is almost always made of a lightly damped material such as steel and aluminium. This method is useful in testing materials such as metals, enamels, ceramics, rubbers, plastics, reinforced epoxy matrices and woods. The mentioned multilayer cantilever beam is given in figure 4.1. The root of the beam is wedged into a heavy and stiff clamping system.

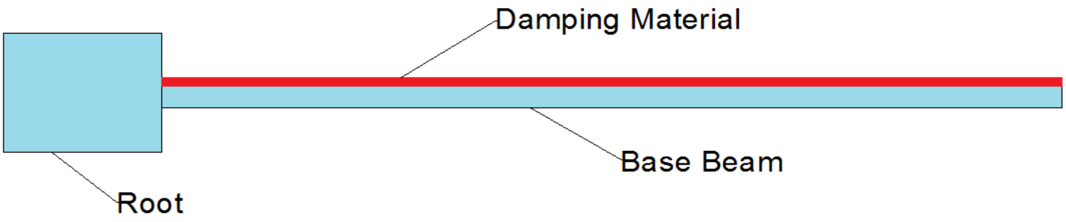


Fig.1: Free Layer Damping

2.2 Constrained Layer Damping Treatment

Constrained Layer Damping treatment is the surface treatment where the damping material is sandwiched between base and constraining layer as shown in figure 2. The Constrain Layer damping is more effective than the free layer damping since more energy is consumed and dissipated in the workdone by the shearing mode in the visco-elastic layer.

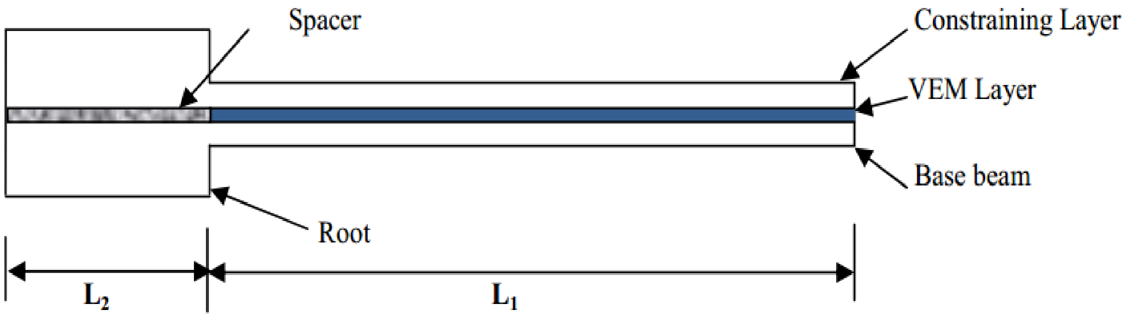


Fig.2: Constrained Layer Damping

To measure damping performance of VEM. Visco-Elastic Material, ASTM standard E-756-05 is widely used. As per ASTM standard E756-05, Structure dimensions are decided. Root sections above and below the section of beam are at least equal to thickness of beam section. Length, Width and Thickness are chosen as 400x50x5, which are the interest of large set of resonating frequency

Table 1: Parts of Beam

Part Name	**Thickness (mm)**
Base Beam	2
Constrained Layer	1
Constraining Layer	2

In this work experiment both specimens are analyzed and tested for damping accordingly as one for free layer and other for constrained layer damping treatment for Visco-elastic and elastic material coating respectively given in table 1.

3. FEM ANALYSIS AND VALIDATION OF MODEL

3.1 Un-damped Beam

FEM result is compared with experiment result and hence model is validated. FEM tool Ansys 15 with solid bricks 8-node-185 is used. The un-damped modal analysis by Block Lorenz Eigen value and mode extraction is preferred as less time consuming method[10]. The detail step by step procedure followed for this analysis is added in appendix. The subsequent figures and table gives Ansys-15 modeling and result.

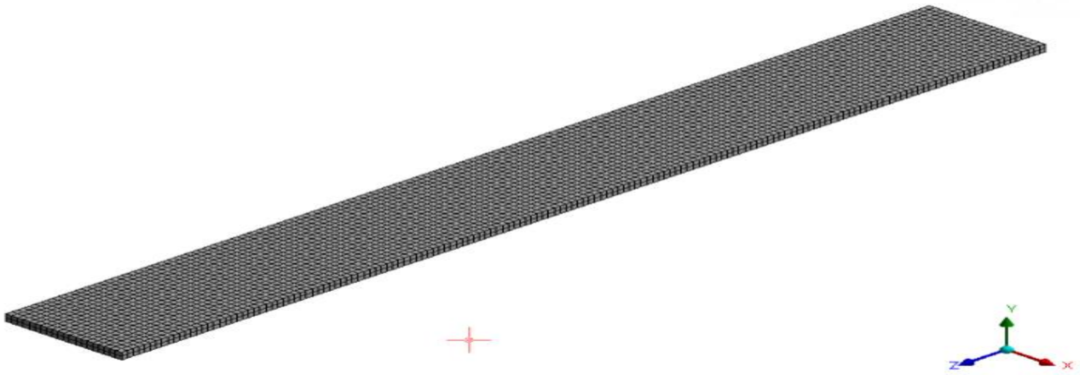


Fig. 3: FEM-Ansys Model for Undamped Al-Beam

By using mechanical prosperities of Al the first five modal frequencies are derived by FEM tool Ansys -04 and tabled below for comparison with those with analytical.

Table 2: FEM Modal Frequency

n	**1**	**2**	**3**	**4**	**5**
k_nL	1.875104	4.69409	7.854	10.9956	14.1372
k_n	4.68776	11.7352	19.6369	27.4889	35.3429
$f_n(FEM)$	163.34	255.71	387.16	457.37	896.79

3.2 Free Layer Coated Cantilever Beam

As case of free layer coating Alloy steel and Aluminium as substrate of dimension 400×50×**5**mm is chosen and varying coating layer from 1 mm to 3 mm of PVC and chromium as metallic coating are modelled and FEM result are plotted.

Table 3: FEM result for Modal Frequencies with coating thickness for free layer coating of hard chrome with alloy steel as a substrate and PVC with aluminium as a substrate

Alloy Steel 5 mm and Chrome Plating

Coating	Mode Shape	Frequency	Deflection
0	1	164.71	8.2846
	2	258.46	8.1475
	3	398.48	8.8952
	4	461.09	8.9475
	5	908.74	8.7925
1	1	167.09	8.4285
	2	258.97	8.9254
	3	405.06	8.4361
	4	467.79	8.7842
	5	916	8.6482
2	1	168.57	6.47253
	2	259.29	6.2233
	3	408.79	6.7583
	4	471.92	6.4802
	5	980.91	6.4863
3	1	170.04	6.7845
	2	259.61	6.2541
	3	412.48	6.4875
	4	632.88	6.7432
	5	1018.51	6.5287

Aluminium 5 mm PVC Coating

Coating	Mode Shape	Frequency
0	1	163.34
	2	255.71
	3	387.16
	4	457.37
	5	896.79
1	1	178.33
	2	247.27
	3	409.67
	4	508.68
	5	553.45
2	1	224.41
	2	243.45
	3	551.94
	4	587.33
	5	671.41
3	1	224.18
	2	272.72
	3	585.33
	4	604.52
	5	747.12

3.3 VEM Coated Cantilever Beam

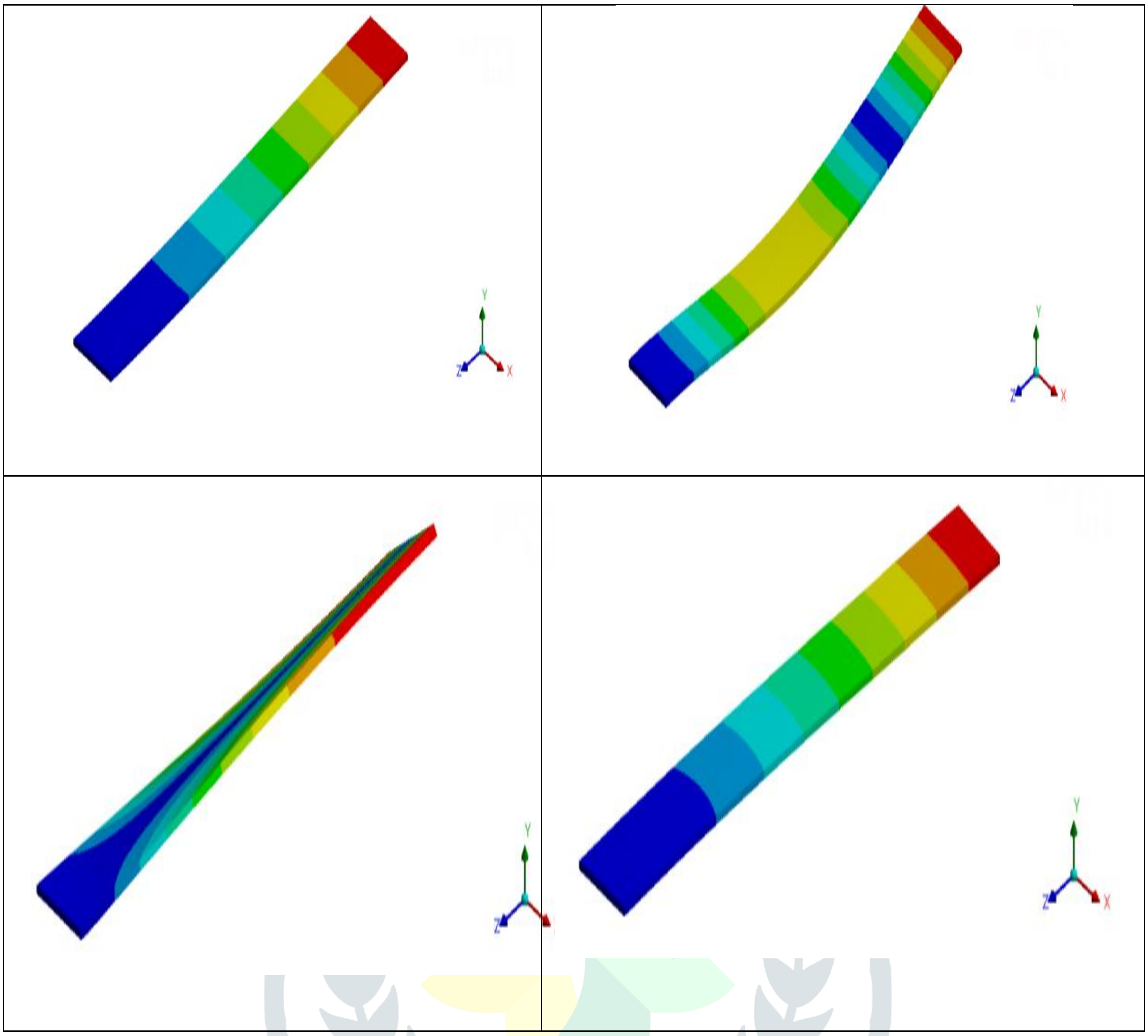
A Cantilever beam of VEM of Silicon 60A rubber, Natural rubber and Butyl rubber are modeled as shown in figure 4 and solved by FEM tool Ansys-15 with solid Bricks 8-node-185. Modal frequencies of first five mode and maximum deflection vector sum are listed in following table 4.

Fig.4: VEM coated Constrained Layer FEM-Ansys Model

Table 4: FEM Model Solution For VEM coated Constrained Layer Model

	Material		
Mode	Al- 1mm Natural rubber	Al- 2mm Natural rubber	Al- 3mm Natural rubber
1	150.84	167.62	181.24
2	232.07	227.76	228.74
3	245.72	236.9	228.98
4	371.64	389.43	405.94
5	641.96	644.92	654.98
	Material		
Mode	**Al- 1mm Butyl rubber**	**Al- 2mm Butyl rubber**	**Al- 3mm Butyl rubber**
1	209.29	202.67	232.17
2	249.87	179.43	254.9
3	298.93	365.89	363.4
4	338.25	379.48	382.32
5	352.58	393.56	406.89
	Material		
Mode	**Al- 1mm Silicone rubber**	**Al- 2mm Silicone rubber**	**Al- 3mm Silicone rubber**
1	150.74	167.48	181.09
2	231.64	227.43	228.5
3	245.93	237.88	229.49
4	371.7	388.81	405.33
5	403.52	423.37	653.83

3.4 First Four Mode Shapes for Natural rubber Coated Al FEM Model Solution



4. PREPARATION OF TEST SPECIMEN AND DAMPING MEASUREMENT

As discussed, there are two damping treatment used here namely free layer and constrained layer treatment. Hard Chrome and Synthetic Rubber by Plastic-Dip manufacturer with Structural Steel-335 as substrate for free layer treatment and Silicone60A, Vinyl (PVC) and Butyl rubber with aluminum as constrained layer damping treatments are designed according ASTM-576(15) and manufactured at local manufactured.

The specimens so prepared are shown below in figure 5 photographed at the time of test and are subjected to the dynamic vibration test.

Fig.5: Specimens-01, 02, 03 and 04 - 20 µm, 40µm, 70µm and 100 µm Chrome Plated

For the preparation of Specimen, 1, 2 and 3mm PVC sheet are stacks between the Aluminum strips and then are adhered along the surface of Aluminum by SR990 Fevicol commercially used for the preparation of PVC coated tanks which are used where they are susceptible to chemical and corrosion attack. After applying uniform pressure on sandwiched PVC beam, it is heated to transition temperature about 45-50°c in induction furnace so as get uniform bonding. The finished specimen in shown in figure 6.

Fig.6: 1mm, 2mm and 3mm PVC coated Free layer Specimens.

Fig.7: 3mm Butyl Rubber coated Constrained layer Specimen

Fig.8: 3mm Natural Rubber coated Constrained layer Specimen

5. EXPERIMENTATION AND RESULTS

The experimentation consists of exciting the cantilever specimen by instantaneous hammer impact and dynamic response is measured by accelerometer and input to the FFT analyser which displayed at computer end.

5.1 Instrumentation and setup

In order to measure the natural frequency of vibration and time domain as well as frequency domain signals namely decay and FFT of different specimen the following instruments were used as shown in figure 10. Experiments are carried for every individual specimen by using DEW-Soft Data Acquisition System. Test setup consists of FFT analyzer with three I/O terminals, Impact Hammer with tip sensitivity of 2.44 m V/n and vibration accelerometer of sensitivity of 6.44Mv/G

1. Accelerometer 2. Impact hammer 3. FFT Analyzer 4. Dew-Soft Software 5. Computer Terminal for Display

Fig 9: FFT Analyzer and Data Acquisition System for Impulse-Hammer Test

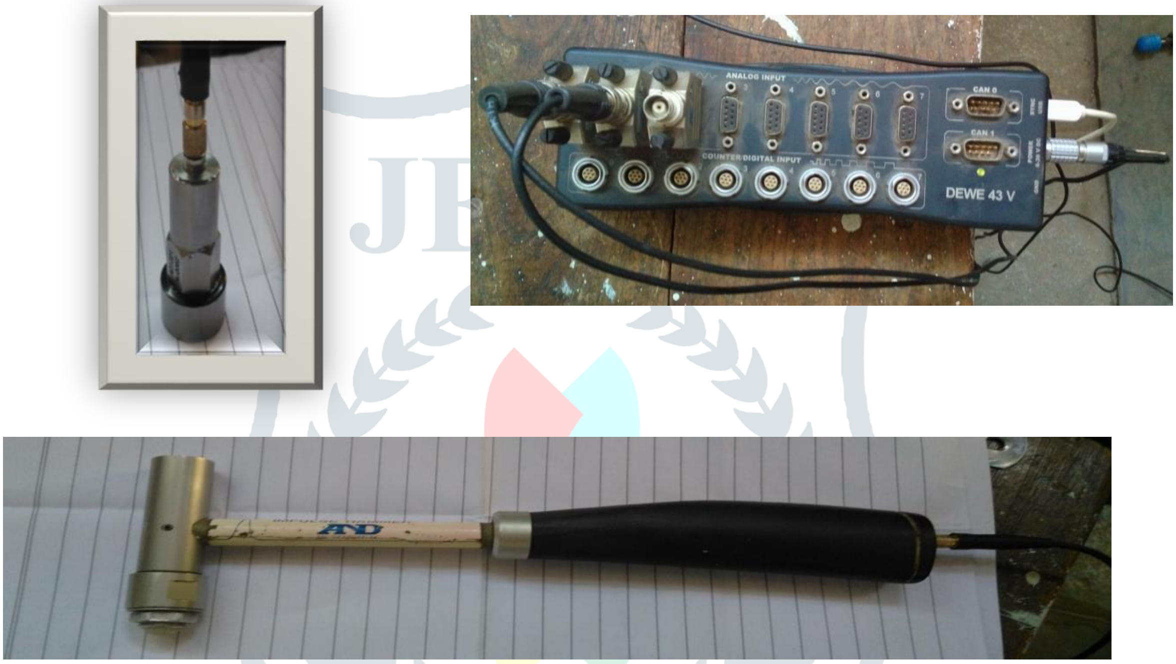


Fig 10: Vibration Accelerometer, FFT Analyzer and Impact Hammer Resp.

With approximately zero noise condition, the impulse hammer when impacted at particular node with continuous signal recording with Dew-soft Data Acquisition system the response in frequency and time domain of typical specimen is shown in figure 11

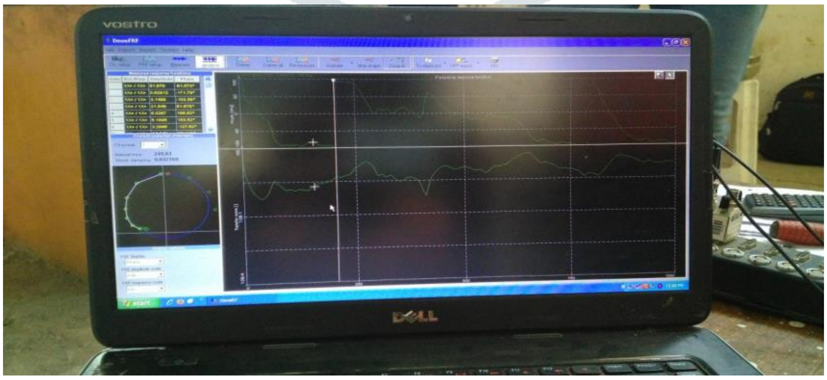


Fig 11: Typical FRF from DEW-Soft-7

5.2 Modal Frequency

Here are experimental results of prepared coated beam tested by DEW-Soft FRF-07 Data Acquisitions System for measurement of FRF is presented. The table 5 lists the modal frequency of tested specimens.

5.2.1 Free Layer Damping Specimen

Alloy Steel-Chrome-1

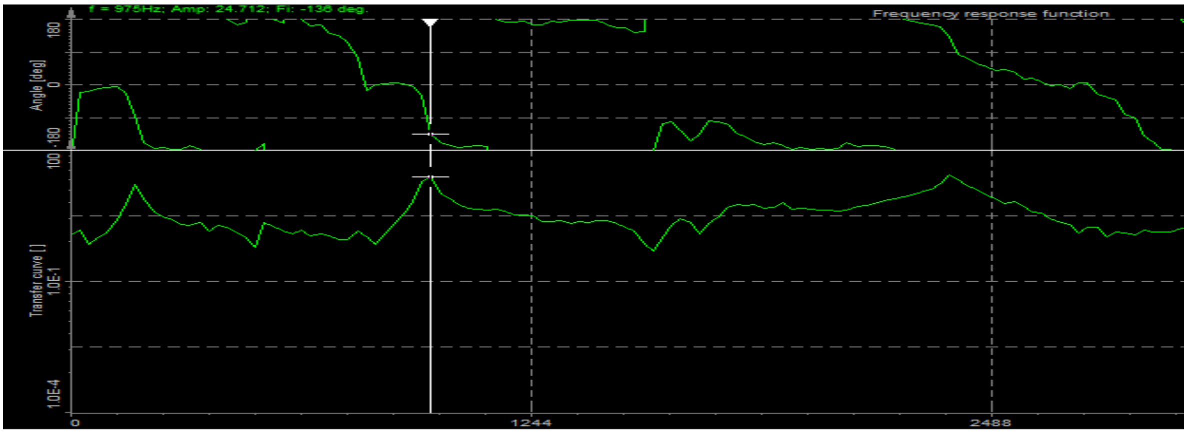


Fig 12: FRF for Alloy Steel-Chrome- 20micron

Alloy Steel-Chrome-2

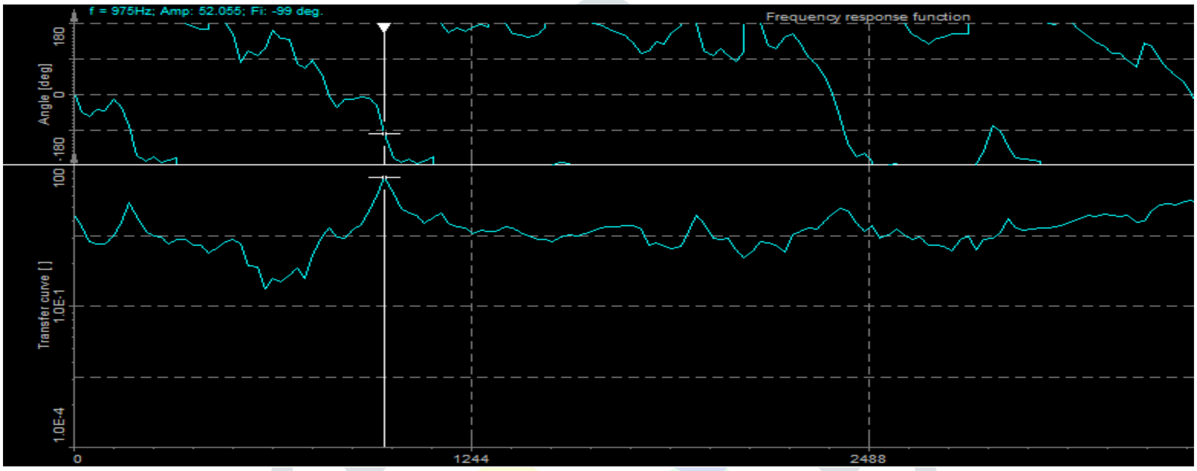


Fig 13: FRF for Alloy Steel-Chrome- 40micron

Alloy Steel-Chrome-3

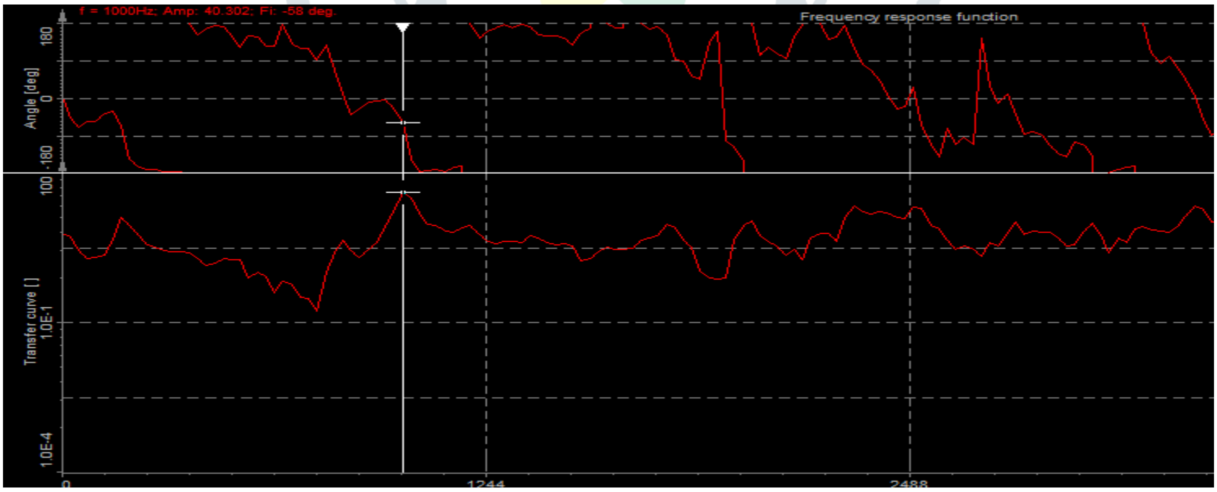


Fig 14: FRF for Alloy Steel-Chrome- 70micron

Alloy Steel-Chrome-4

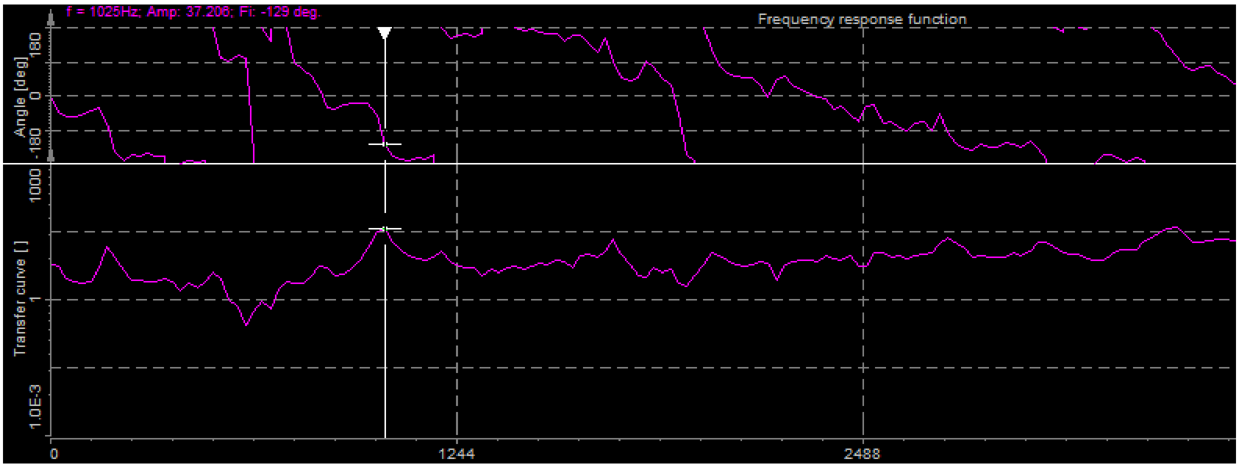


Fig 15: FRF for Alloy Steel-Chrome- 100micron

Aluminium- PVC- 1

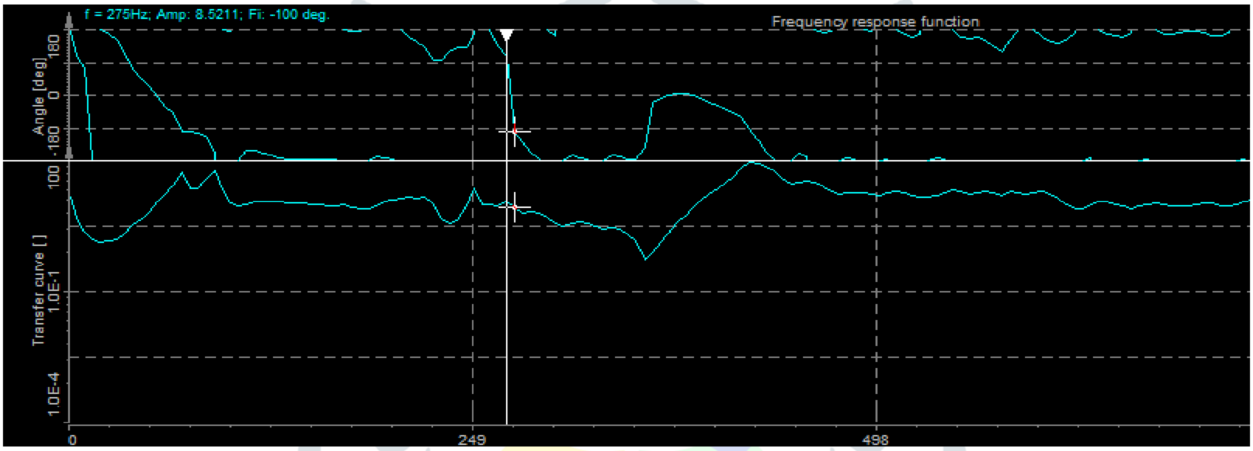


Fig.16: FRF For Aluminum-PVC-1mm

Aluminium- PVC- 2

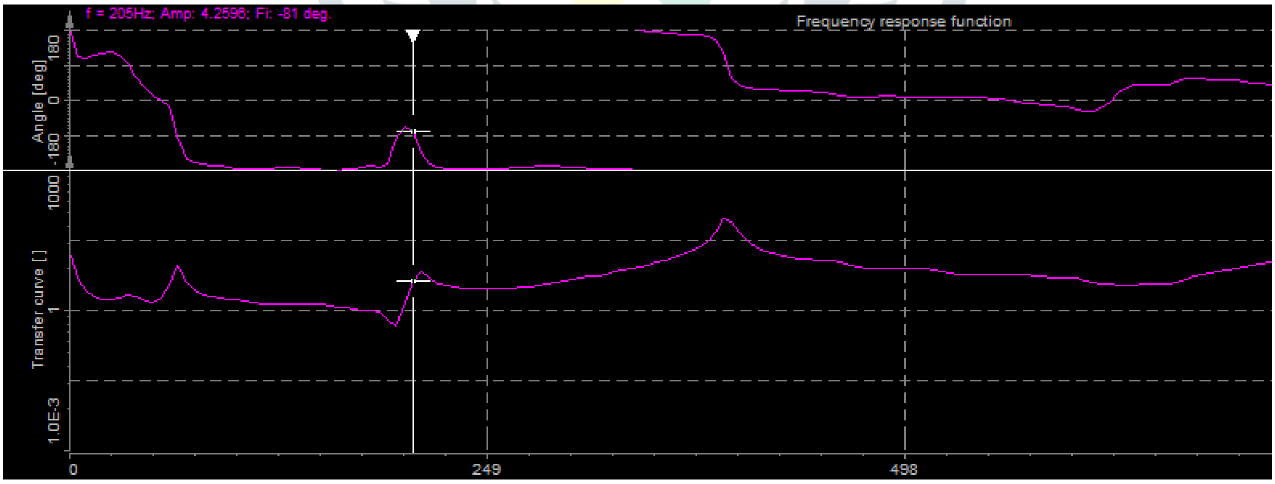


Fig.17: FRF For Aluminum-PVC-2mm

Aluminium- PVC- 3

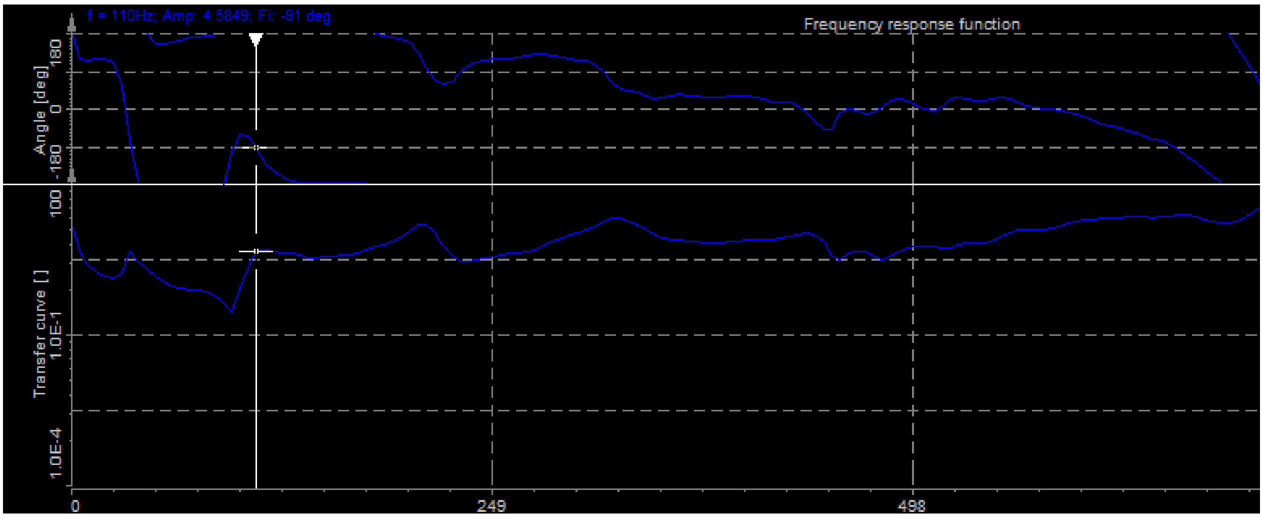


Fig.18: FRF For Aluminum-PVC-3mm

5.2.2 Constrained Layer Damping Specimen

Aluminium-Natural Specimen-1

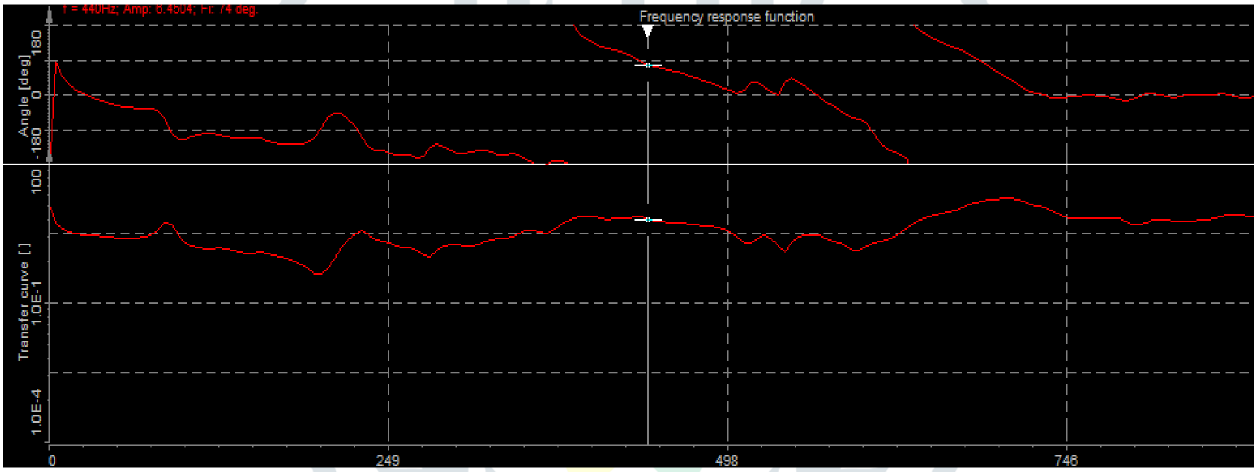


Fig.19: FRF For Aluminium-Natural-1mm Rubber with Circle fit structural Damping

Aluminium-Natural Specimen-2

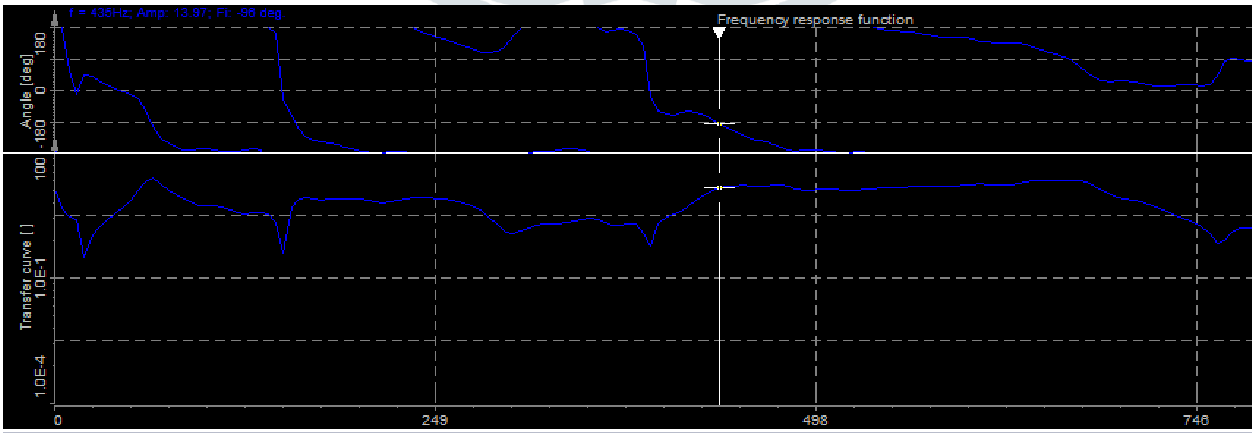


Fig.20 FRF For Aluminium-Natural-2mm Rubber with Circle fit structural Damping

Aluminium-Natural Specimen-3

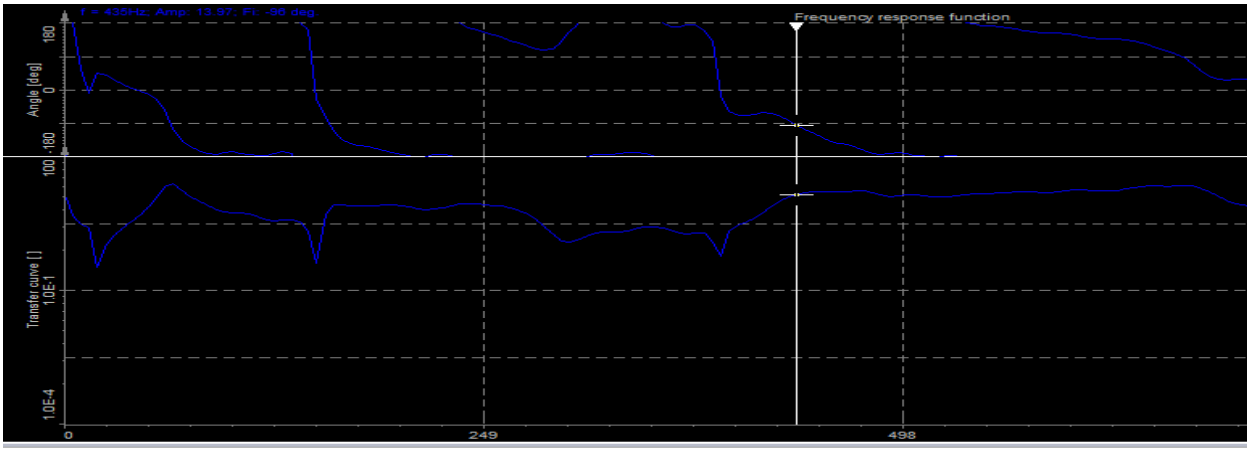


Fig.21: FRF For Aluminium-Natural-3mm Rubber with Circle fit structural Damping

Aluminium-Butyl Specimen-1

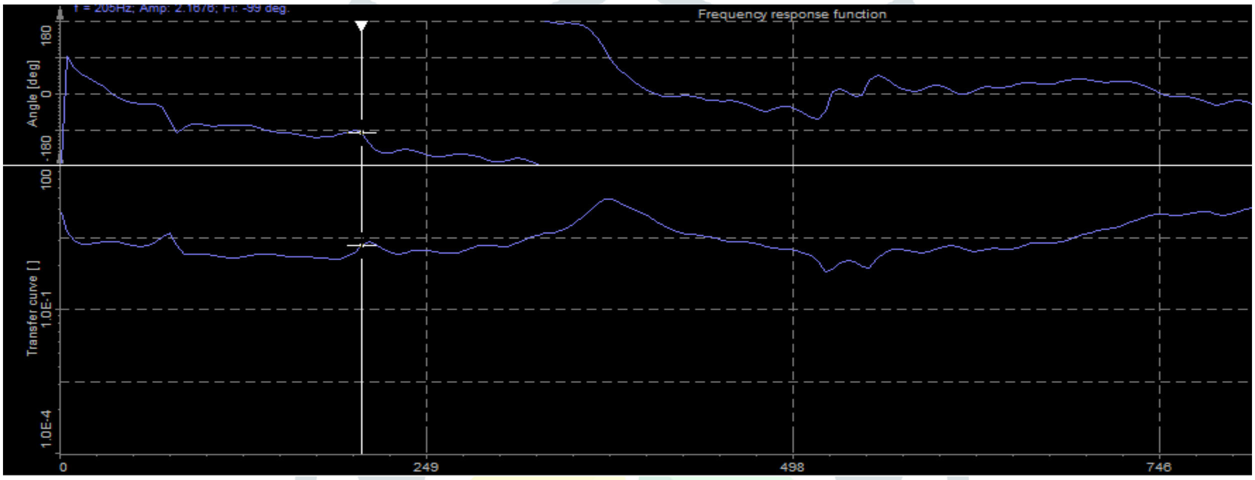


Fig.22: FRF For Aluminium-Butyl Rubber -1mm with Circle fit structural Damping

Aluminium-Butyl Specimen-2

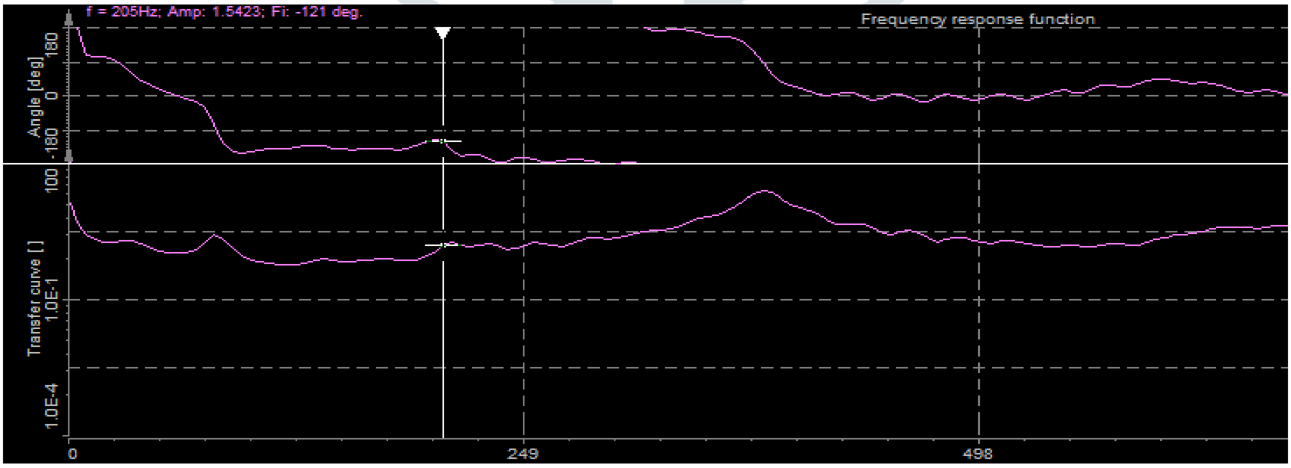


Fig.23: FRF For Aluminium-Butyl Rubber -2mm with Circle fit structural Damping

Aluminium-Butyl Specimen-3

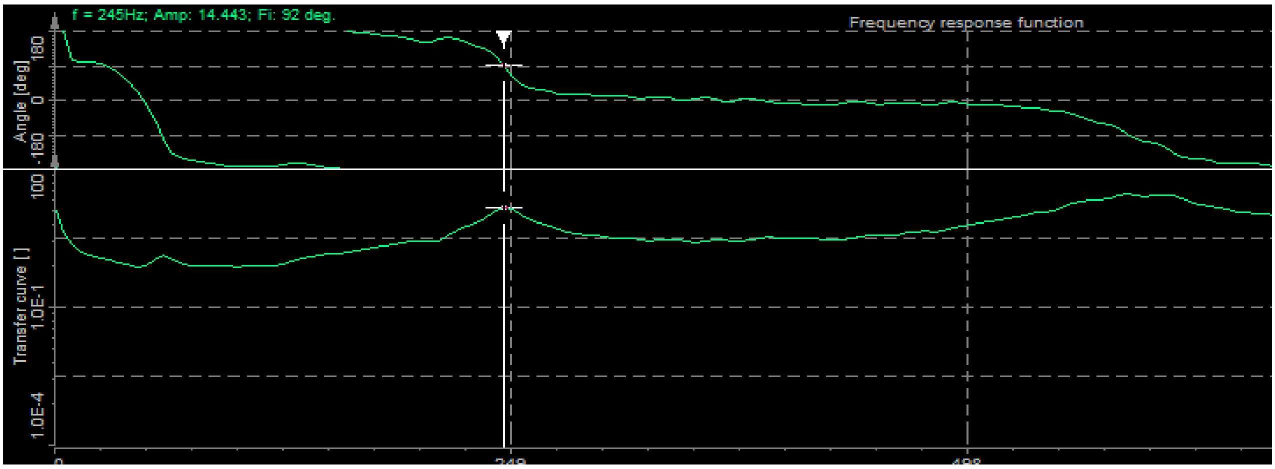


Fig.24 FRF For Aluminium-Butyl Rubber -3mm with Circle fit structural Damping

Aluminium-Silicone rubber Specimen-1

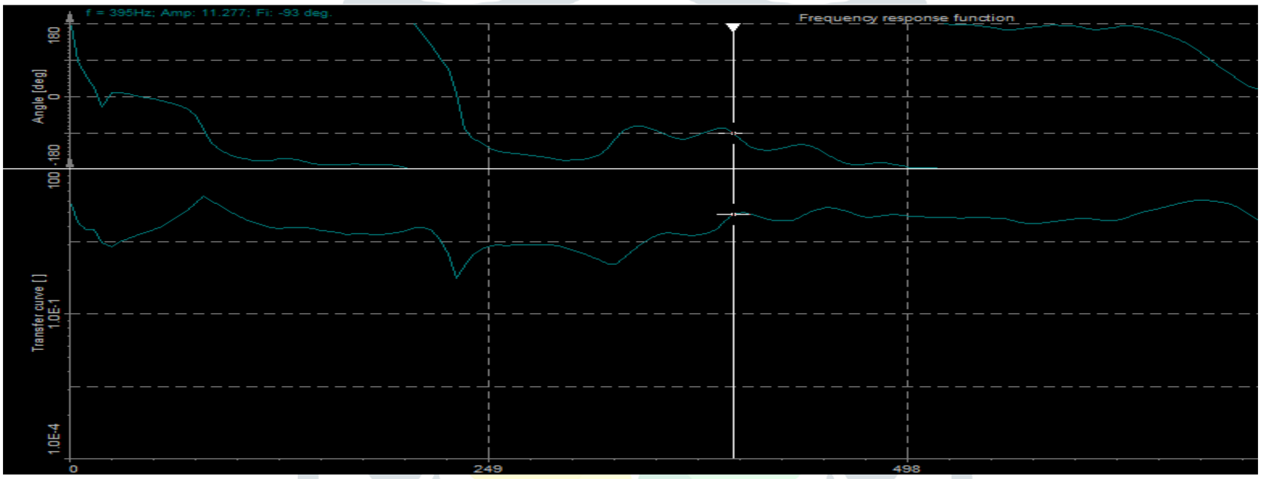


Fig.25: FRF For Aluminium-Silicone Rubber -1mm with Circle fit structural Damping

Aluminium-Silicone rubber Specimen-2

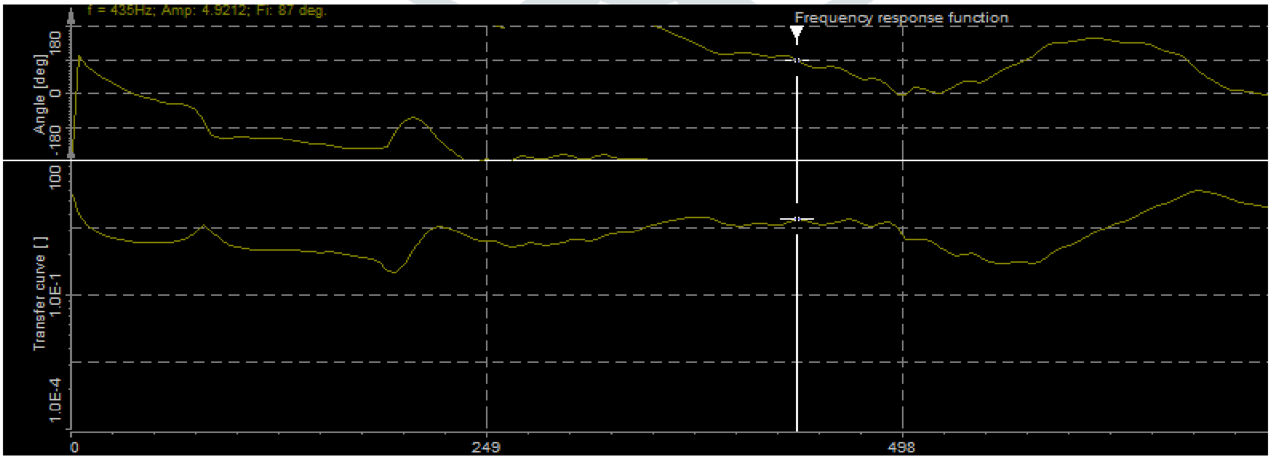


Fig.26: FRF For Aluminium-Silicone Rubber -2mm with Circle fit structural Damping

Aluminium-Silicone rubber Specimen-3

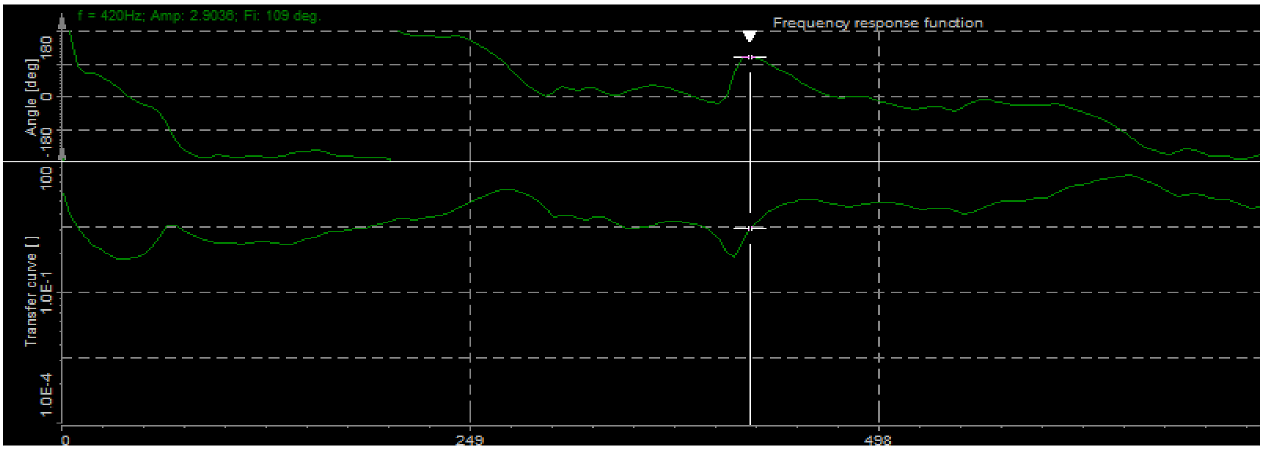


Fig.27: FRF For Aluminium-Silicone Rubber -3mm with Circle fit structural Damping

Table 5: Damped Modal Frequencies of test Specimens FRF values

h_c	1	2	3	Material
Modal Frequency (ω_d) FRF value	440	435	435	Al-Natural rubber
	205	205	245	Al-Butyl rubber
	395	435	420	Al-Silicone rubber
	975	1000	1025	Alloy Steel- Chrome
	275	205	110	Al-Pvc

5.3 Frequency Domin Damping Estimation by Circle Fit Method

Natural Rubber 1, 2, 3

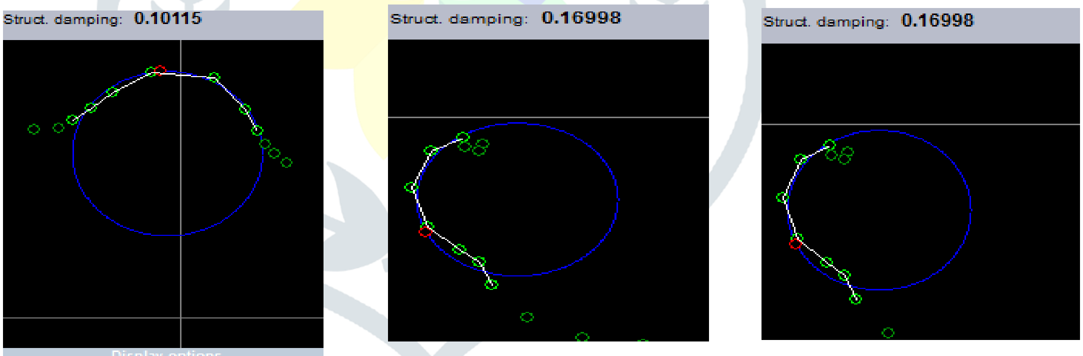


Fig. 28: Circle-Fits for Natural Rubber-01, 02 and 03 specimen

Butyl Rubber 1, 2, 3

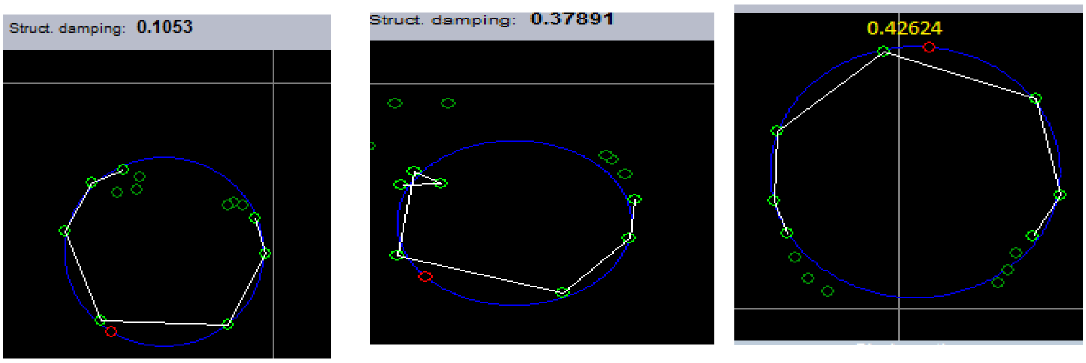


Fig. 29: Circle-Fits for Butyl Rubber-01, 02 and 03 specimen

Silicone rubber 1, 2, 3

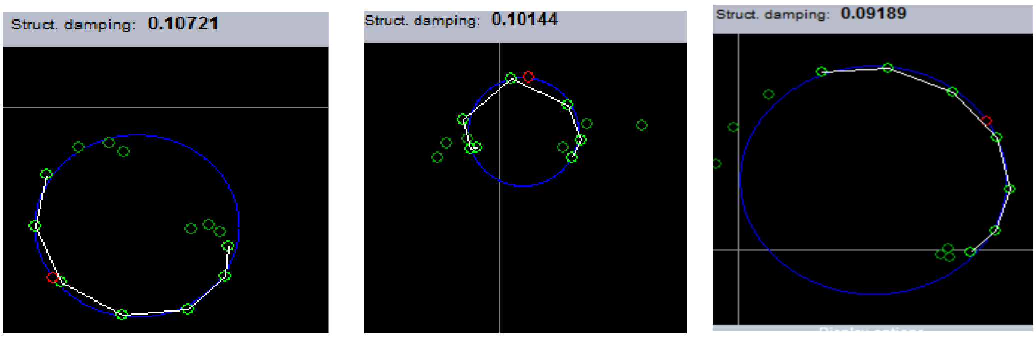


Fig. 30: Circle-Fits for Silicone Rubber-01, 02 and 03 specimen

Chrome 1, 2, 3

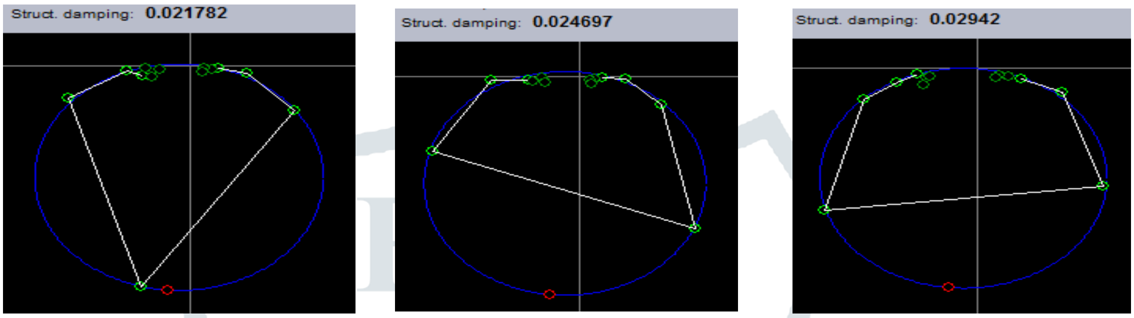


Fig. 31: Circle-Fits for Chrome-01, 02 and 03 specimen

PVC 1, 2, 3

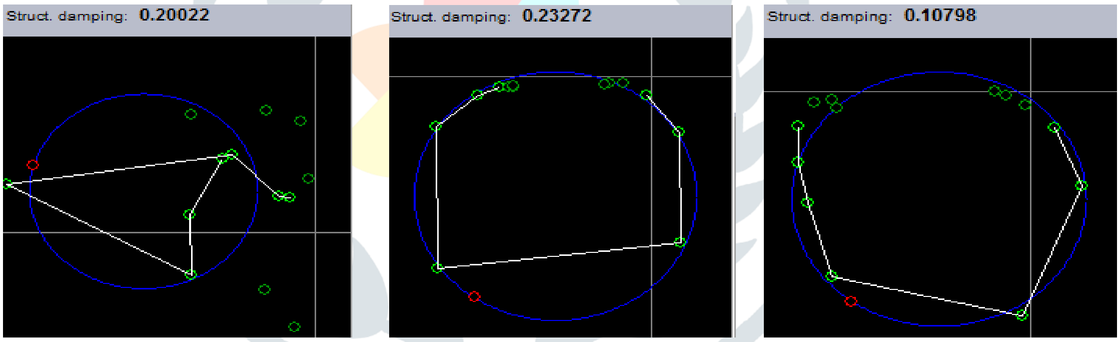


Fig. 32: Circle-Fits for PVC-01, 02 and 03 specimen

Table 6: Damping ratio(ζ) by Circle Method

Coating thickness (h_c)	**1**	**2**	**3**	**Material**
Damping ratio(ζ) by Circle Method	0.10115	0.16998	0.16998	Al-Natural rubber
	0.1053	0.37891	0.42624	Al-Butyl rubber
	0.10721	0.10144	0.11567	Al-Silicone rubber
	0.021782	0.024697	0.02942	Alloy Steel- Chrome
	0.20022	0.23272	0.10798	Al-Pvc

6. CONCLUSION

The performance of different VEM on vibration response amplitude is presented. It is observed that the damping factor of symmetric sandwitch CLD beam with all VEM is found to increase as compare to un damped beam.

From this experimentation found that natural frequency of vibration can be shifted other than uncoated frequency of 26.095 Hz for Aluminum and 26.311 Hz for Alloy Steel significantly by coating the specimen. Except for Natural rubber and butyl rubber frequency is increasing due to coating. Otherwise damping increasing with coating to some extent for Chrome, Silicone and Natural rubber and still increasing for Vinyl (PVC) and Butyl rubber. Damping ratio ζ is increasing for Vinyl (PVC) and Butyl rubber. While for Silicone, hard chrome and synthetic rubber it first increases and attained the maximum value at apparently 2 mm. Hence for reduction of structural vibration, butyl rubber and Natural rubber are suitable material over an operating medium frequency range.

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