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A STUDY ON DYNAMIC CHARACTERISTICS OF STRUCTURAL MATERIALS USING MODAL ANALYSIS

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Abstract

Modal analysis is a process of describing a structure in terms of its natural characteristics which are the frequency, damping and mode shapes - its dynamic properties [1]. The change of modal characteristics directly provides an indication of structural condition based on changes in frequencies and mode shapes of vibration. This paper presents results of an experimental modal analysis of beams made with different materials such as Steel, Brass, Copper and Aluminum. The beams were excited using an impact hammer excitation technique over the frequency range of interest, 0–2000 Hz. Frequency response functions (FRFs) were obtained using OROS vibration analyzer. The FRFs were processed using NV Solutions modal analysis package to identify natural frequencies, Damping and the corresponding mode shapes of the beams.

Keywords: Modal analysis; natural frequency; damping; mode shape; free vibration

1. Introduction

Over the past decade, the modal testing has become an effective means for identifying, understanding, and simulating dynamic behavior and responses of structures. Experimental modal analysis (EMA) or modal testing is a non-destructive testing strategy based on vibration responses of the structures. One of the techniques widely used in modal analysis is based on an instrumented hammer impact excitation. By using signal analysis, the vibration response of the structures to the impact excitation is measured and transformed into frequency response functions (FRFs) using Fast Fourier Transformation (FFT) technique, the measurement of the frequency response function is the heart of modal analysis [2]. Subsequently the series of FRFs are used to extract such modal parameters as natural frequency, damping, and corresponding mode shape [1]. In a wide range of practical applications the modal parameters are required to avoid resonance in structures affected by external periodic dynamic loads. Practical applications of modal analysis span over various fields of science, engineering and technology. In particular, numerous investigations related to aeronautical engineering, automotive engineering, and mechanical engineering.

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Interestingly, not many are involved with structural engineering and dynamics of civil structural systems. In recent years, experimental modal analysis has received wide acceptance in structural engineering application, particularly for identification of modal properties of bridges, damage detection of structures using modal data, structural health monitoring, dynamic FEM updating, active vibration control, dynamic buckling of structures etc. The present investigation reports the dynamic characteristics of common structural materials.

2. Experimental Investigation

For carrying out the experimental modal analysis the test specimens made of different materials were selected. The dimensions and masses of the test beams are tabulated in Table.1. All the test specimens were tested under free-free condition. A completely free dynamic test setup is only aimed to eliminate the support influence to the dynamic characteristics [3]. The excitation points were marked on the top surface of the beams along the length. The number of excitation points was selected such that they represent the vibration modes of interest [4]. In this case, an accelerometer had a fixed position (at mid point), whilst an instrumented impact hammer was roved along the excitation points [2]. The measurement set up for the present experimental work is shown schematically in Figure 1. The force applied to the structure by an impact hammer and the corresponding response of the accelerometer attached to the specimen is measured by the OROS make dynamic analyzer.

Table 1. Dimensions and mass of the test specimens

Material	Length (m)	Breadth (mm)	Depth (mm)	Mass (kg)
Steel	1.14	10	10	0.833
Brass	1.08	10	10	0.76
Copper	1.18	10	10	0.93
Aluminum	1.14	16	16	0.79

The instruments used in this study were the PCB impact hammer (model 086D05) having sensitivity 0.00225V/N, an Accelerometer (DYTRON model 3055A1) having sensitivity 0.0010194V/M/s^2 and 8-channel OROS dynamic analyzer [5]. The mass and tip hardness of the impact hammer are varied to give the desired magnitude and duration of the force pulse at all test locations on the beams.

Input settings and analyzer settings made in the OROS vibration Analyzer to obtain good frequency response functions of beams for the given excitation are given in table 2 and 3. The obtained frequency response functions were processed to get the Modal Parameters (frequency, damping and mode shapes) using NV Solutions Smart Office software package

[6]. The driving point Frequency response functions of all beams are shown below.

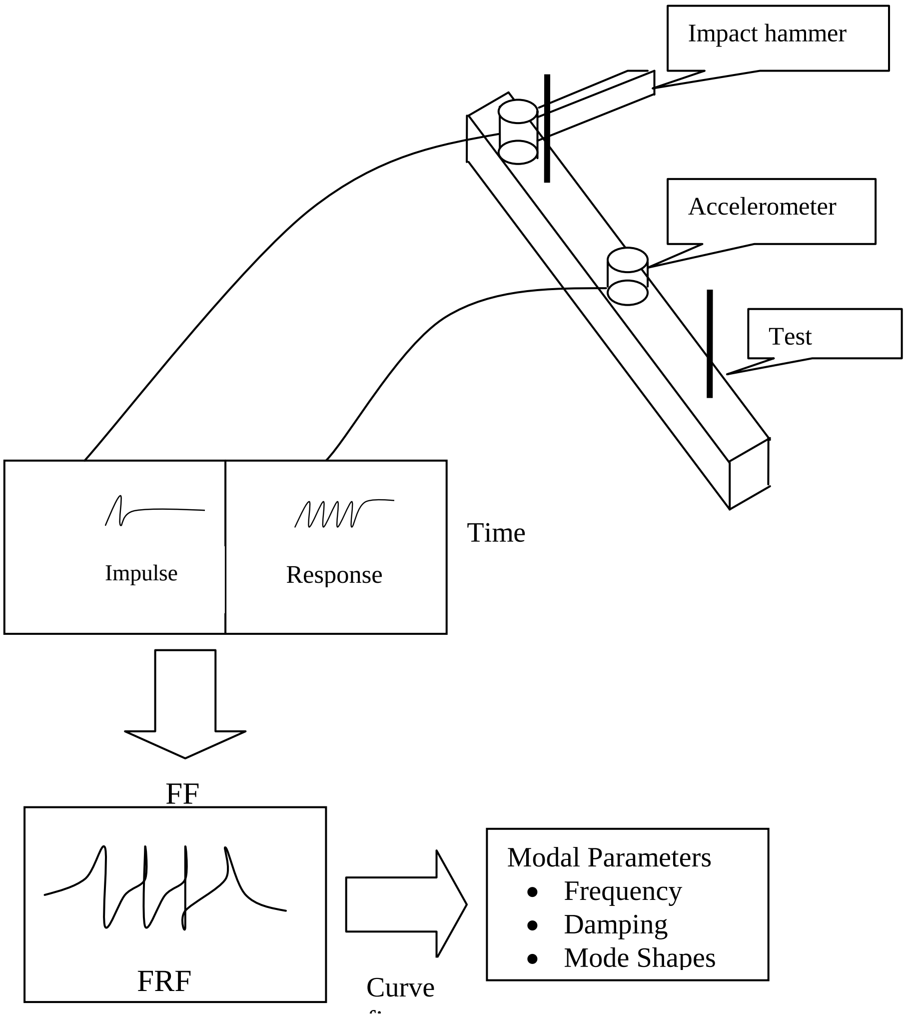


Figure 1. Schematic representation of test setup

Table 2. Input settings

Input Channel	Range	Gain	Coupling	Unit	Transducer	Sensitivity
Ch. 1	31mV	40 dB	ICP	N	IMPULSE	0.00225 V/N
Ch. 2	3,16V	0 dB	ICP	m/S^2	DYTRAN	$0.0010194\ V/M/s^2$

Table 3. Analyzer settings

Frequency	***Range***	**0-2kHz**	***Resolution***	**801**	***Zoom***	**Without**	***Envelope***	**OFF**
Analysis	*Overlap*	Retrigger	*WeightW1*	Force	*W2*	Response	--	--
Average	*Domain*	Spectral	*Mode*	Linear	*Number*	3	*Refresh*	1
Trigger	*Mode*	Level	*Channel*	Ch.1	*Thresh.%*	10%	*Delay*	-0.02 S
Tach	*Mode*	OFF	*Channel*	External	*Thresh.%*	10%	*Tach/rev.*	1.000
Arming	*Mode*	Free Run	*Channel*	--	--	--	--	--
Generator1	*Mode*	Stopped	*Freq.*	0.100kHz	*Level*	1 V	--	--
Generator2	*Mode*	Stopped	*Freq.*	0.100kHz	*Level*	1 V	*Phase*	0^o
Waterfall	*Mode*	Single	*Type*	Off	*Number*	5	--	--

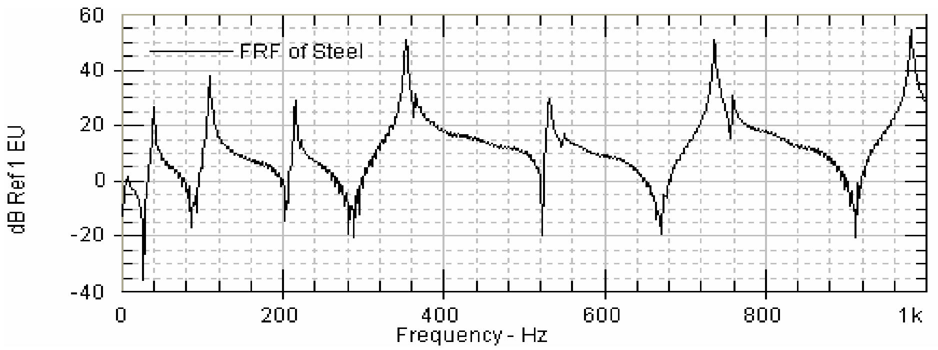


Figure 2. Frequency response function of steel beam

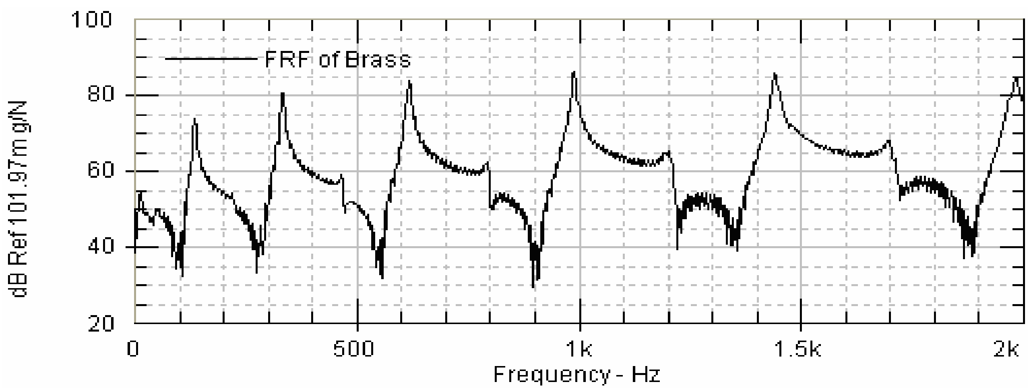


Figure 3. Frequency response function of brass beam

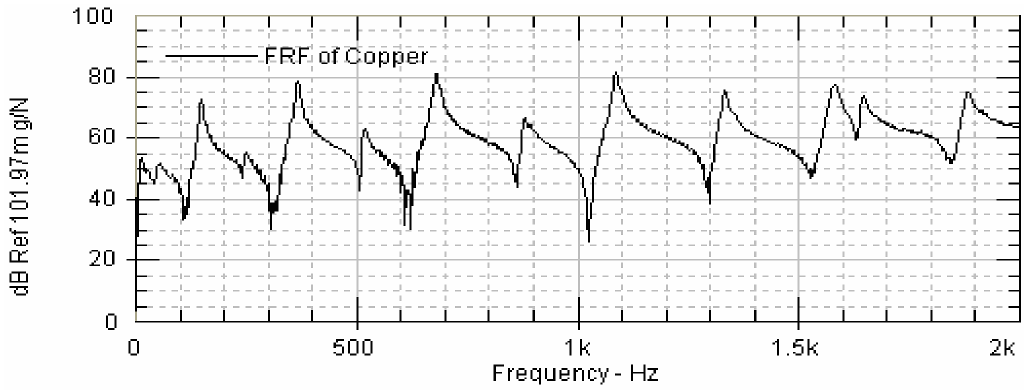


Figure 4. Frequency response function of copper beam

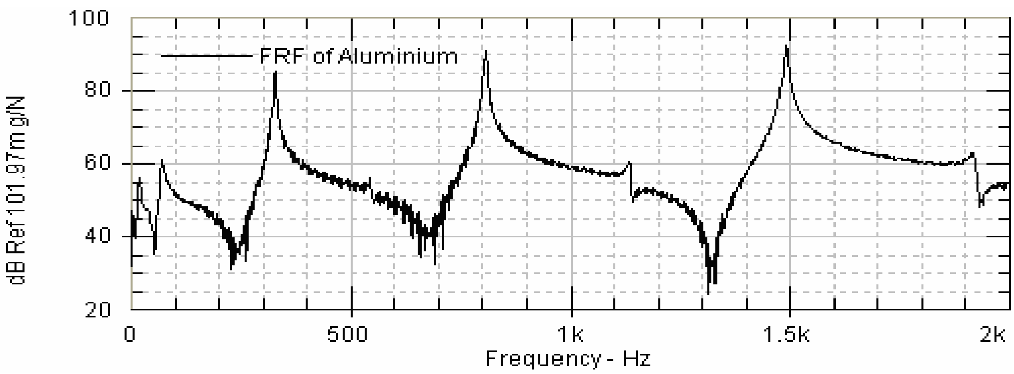


Figure 5. Frequency response function of aluminum beam

3. Theoretical Natural Frequencies

In order to validate the experimentally obtained natural frequencies, Theoretical natural frequencies of the specimens which were tested under free-free condition also calculated based on the free vibration analysis of distributed (continuous) systems [7]. As the initial modes are significant in the vibration analysis, the calculated theoretical natural frequencies of the first six modes are shown in the Tables 5-8.

4. Discussion of Test Results

4.1 Modal parameters

The experimental modal results (model frequency, model damping ratio and mode shapes) are discussed in the following section.

4.2 Natural frequencies

The Smart Office (modal analysis) package gave the values of natural frequencies. These natural frequencies were calculated using SDOF and MDOF estimation algorithms. Again in SDOF estimation the modal parameters are calculated using finite difference and quadrature methods [6]. Theoretical natural frequencies are also calculated for the beams using the distributed mass concept. The experimental and theoretical natural frequencies of Steel, Copper, Brass, and Aluminum beams for the first six modes are given in the Table 4-7.

Table 4. Natural frequencies of steel beam

Mode No	Experimental			Theoretical (Hz)
	SDOF(Hz)		MDOF (Hz)	
	Finite Difference	Quadrature		
1	40.27	41.07	40.133	39.412
2	110.34	110.00	110.076	109.475
3	216.50	216.25	215.955	214.57
4	353.72	353.75	353.852	354.698
5	532.22	532.52	532.00	529.86
6	533.75	532.5	737.74	740.049

Table 5. Natural frequencies of brass beam

Mode No	Experimental			Theoretical (Hz)
	SDOF(Hz)		MDOF (Hz)	
	Finite Difference	Quadrature		
1	40.00	43.86	38.353	34.60
2	105.52	105.76	105.879	96.04
3	224.83	225.23	226.033	188.25
4	333.61	333.18	333.84	311.18
5	469.46	470.00	469.96	464.86
6	619.46	620.00	619.425	649.26

Table 6. Natural frequencies of copper beam

Mode No	Experimental			Theoretical (Hz)
	SDOF(Hz)		MDOF (Hz)	
	Finite Difference	Quadrature		
1	24.43	24.73	23.06	27.40
2	45.21	49.09	50.71	76.05
3	150.78	150.00	150.43	149.05
4	250.108	249.77	249.51	246.40
5	367.85	367.73	368.68	368.06
6	518.46	517.50	518.47	514.10

Table 7. Natural frequencies of aluminum beam

Mode No	Experimental			Theoretical (Hz)
	SDOF(Hz)		MDOF (Hz)	
	Finite Difference	Quadrature		
1	70.71	70.00	70.48	64.00
2	170.29	172.05	184.89	177.43
3	329.16	330.00	329.16	347.77
4	548.42	549.77	548.96	574.88
5	808.60	807.5	808.54	858.77
6	1136.87	1137.5	1136.99	1199.44

5. Damping

The Smart Office (modal analysis) package gave the values of damping ratio. The Table 8-11 show damping in percentage both in SDOF (finite difference and quadrature) and MDOF methods.

Table 8. Damping ratio of steel beam

Mode	SDO (%)		MDOF (%)
	Finite Difference	**Quadrature**	
1	2.02	1.70	1.38
2	0.78	0.89	0.50
3	0.33	0.37	0.29
4	0.18	0.22	0.18
5	0.13	0.20	0.17
6	0.10	0.24	0.11

Table 9. Damping ratio of brass beam

Mode	SDOF (%)		MDOF (%)
	Finite Difference	**Quadrature**	
1	14.53	12.74	29.90
2	1.78	2.97	1.81
3	1.02	1.90	1.27
4	0.7	1.24	0.76
5	0.56	0.92	0.59
6	0.47	0.70	0.50

Table 10. Damping ratio of copper beam

Mode	SDOF (%)		MDOF (%)
	Finite Difference	**Quadrature**	
1	39.21	36.30	38.76
2	17.44	13.34	15.59
3	1.96	3.15	2.01
4	1.28	1.99	1.25
5	1.01	1.37	0.96
6	1.71	1.04	0.74
7	0.62	0.71	0.54

Table 11. Damping ratio of aluminum beam

Mode	**SDOF (%)**		**MDOF (%)**
	Finite Difference	**Quadrature**	
1	6.12	6.22	4.90
2	1.48	1.82	2.03
3	0.51	0.87	0.50
4	0.31	0.53	0.304
5	0.22	0.36	0.224
6	0.24	0.28	0.23
7	0.19	0.23	0.19

6. Mode Shapes

The mode shapes obtained using NV solutions modal analysis software is presented in following Tables.

Table 12. Mode shapes of steel beam in SDOF (finite difference method)

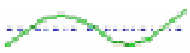
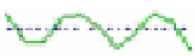
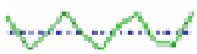
Mode No.	**Mode.1**	**Mode.2**	**Mode.3**	**Mode.4**
Mode shape				
Frequency	40.27Hz	110.34 Hz	216.50 Hz	353.72 Hz

Table 13. Mode shapes of steel beam in SDOF (quadrature method)

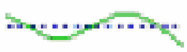
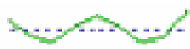
Mode No.	**Mode.1**	**Mode.2**	**Mode.3**	**Mode.4**
Mode shape				
Frequency	41.07 Hz	110.00 Hz	216.25 Hz	353.75 Hz

Table 14. Mode shapes of steel beam in MDOF method

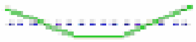
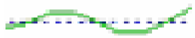
Mode No.	**Mode.1**	**Mode.2**	**Mode.3**	**Mode.4**
Mode shape				
Frequency	40.133 Hz	110.075 Hz	215.955 Hz	3563.852 Hz

Table 15. Mode shapes of brass beam in (finite difference method)

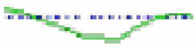
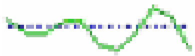
Mode No.	**Mode.1**	**Mode.2**	**Mode.3**	**Mode.4**
Mode shape				
Frequency	40 Hz	105.52 Hz	224.83 Hz	333.61 Hz

Table 16. Mode shapes of brass beam in SDOF (quadrature method)

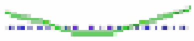
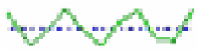
Mode No.	**Mode.1**	**Mode.2**	**Mode.3**	**Mode.4**
Mode shape				
Frequency	43.86 Hz	105.76 Hz	225.23 Hz	333.18 Hz

Table 17. Mode shapes of brass beam in MDOF method

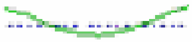
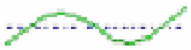
Mode No.	**Mode.1**	**Mode.2**	**Mode.3**	**Mode.4**
Mode shape				
Frequency	38.353 Hz	105.879 Hz	226.033 Hz	333.84 Hz

Table 18. Mode shapes of copper beam in SDOF (finite difference method)

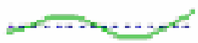
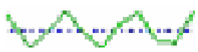
Mode No.	**Mode.1**	**Mode.2**	**Mode.3**	**Mode.4**
Mode shape				
Frequency	24.43 Hz	45.21 Hz	150.78 Hz	250.108 Hz

Table 19. Mode shapes of copper beam in SDOF (quadrature method)

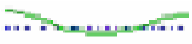
Mode No.	Mode.1	Mode.2	Mode.3	Mode.4
Mode shape				
Frequency	24.73 Hz	49.09 Hz	150.00 Hz	249.77 Hz

Table 20. Mode shapes of copper beam in MDOF method

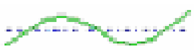
Mode No.	Mode.1	Mode.2	Mode.3	Mode.4
Mode shape				
Frequency	23.06 Hz	50.71 Hz	150.43 Hz	249.51 Hz

Table 21. Mode shapes of aluminum beam in SDOF (finite difference method)

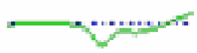
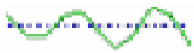
Mode No.	Mode.1	Mode.2	Mode.3	Mode.4
Mode shape				
Frequency	70.71 Hz	170.29 Hz	329.16 Hz	548.42 Hz

Table 22. Mode shapes of aluminum beam in SDOF (quadrature method)

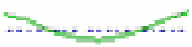
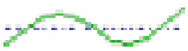
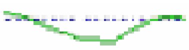
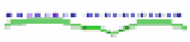
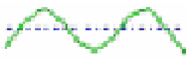
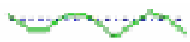
Mode No.	Mode.1	Mode.2	Mode.3	Mode.4
Mode shape				
Frequency	70.00 Hz	172.05 Hz	330.00 Hz	549.77 Hz

Table 23. Mode shapes of aluminum beam in MDOF method

Mode No.	Mode.1	Mode.2	Mode.3	Mode.4
Mode shape				
Frequency	70.00 Hz	184.89 Hz	329.16 Hz	548.96 Hz

7. Conclusion

The dynamic parameters such as the natural frequency and inherent damping value of their components are very important in compliant structures. Modal testing is a non-destructive testing strategy based on vibration responses of the structural members. In this paper, the application of experimental modal testing to various beams based on the impact hammer excitation is attempted to assess the natural frequency, damping constant and associated mode shapes of these examples. The modal testing has proven to be an effective and non-destructive test method for estimation of dynamic characteristics of beams.

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