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Critical Experimental Issues of Cracked Aluminum Beam in Operational Modal Analysis

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ABSTRACT

Obtaining good experimental modal data in order to use it for further analysis is very essential in modal analysis. This paper investigates the dynamic characteristics of aluminium beam with a single crack at its centre using various identification algorithms in Operational Modal Analysis (OMA, or also called Output-Only or Ambient Modal Analysis). Algorithms such as Frequency Domain Decomposition (FDD), Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI) are applied in this study. For its simplicity and direct investigation purpose, the beam considered is a free-free end beam condition. Comparison of the results of these techniques will be shown to justify the validity of each technique used. Good modal data are obtained by examining and emphasizing on technical aspects in processing the experimental data which are critical issues to be addressed. The accuracy of the results is duly examined for each post-processing modification made

Keywords: *Cracked aluminum beam, Dynamic Characteristics, Modal Analysis, Operational Modal Analysis (OMA), and Frequency Domain Decomposition, Stochastic Subspace Identification*

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Introduction

Output (or response) measurements to estimate modal parameters such as natural frequencies, damping ratio and mode shapes from the use of artificial input (or excitation) is common in a traditional experimental modal analysis (EMA). In this controlled lab setting, it is quite impossible to emulate the actual excitation on real structures or mechanisms. Thus, EMA posts several limitations and most distinctively in its difficulty to excite artificially for many of civil and mechanical engineering structures due to their physical constraints in sizes, shapes or locations. This deems it necessary to actually carry out output measurements in actual environment rather than in a limited lab environment [1].

The technique of Operational Modal Analysis (OMA, or as often called Ambient Analysis), is carried out alternatively to overcome this notable limitation of EMA. The OMA technique provides a much needed tool for the determination of the dynamic characteristics of large and complex structures or mechanisms especially when input forces cannot be directly controlled or measured.

This technique is based on measuring only the output signals from a structure which is directly or randomly excited in an actual ambient condition from operating forces as an unmeasured input [2],[3],[4] In OMA, one basic assumption is that the unknown input is relatively broad band. If the loading has narrow banded components, non-physical “modes” might be estimated. This means that these estimated modes might not be related to the structure, but rather be related to the loadings, i.e. producing fake modes. This problem can be treated by testing the structure under different operating conditions in order to see changes in the fake modes related to the loadings. However, a better approach is to have techniques which allow estimation of the structural modes in cases of narrow band loadings [5], [6].

This study presents the technical aspect of the OMA technique to investigate the dynamic characteristics using a crack aluminum beam as a case study. The modal parameters of the structure were extracted under free-free end condition. The measurements were taken using Bruel & Kjaer PULSE^{TM} Multi-Analyzer System, MTCTM software and Operational Modal Analysis ProTM software.

Operational Modal Analysis

In this study, a beam with a single crack at its center under free-free boundary condition is considered. Its dynamic properties were obtained through measurements and post-data processing as follows. The measurements were made with a Bruel & Kjaer PULSETM Multi-Analyzer System and the Modal Test ConsultantTM (MTC) by constructing the geometry of the test structure, allocating measurement points and capturing the required modal data. The analysis was carried out using the Bruel & Kjaer Operational Modal Analysis ProTM software where post-data processing including signal processing and modal extraction were performed (Figure 1).

Figure 1: The Bruel&Kjaer PULSE^{TM} Multi-Analyzer System connect to a computer with MTC^{TM} software and Operational Modal AnalysisPro^{TM} software.

Figure 2: Aluminum beam is suspended with soft string to support the beam in free-free condition and the crack position is indicated

The specimen was an aluminum beam (1200mm x 50mm x 25mm) with its crack and orientation as shown in Figure 2.

Twenty (20) accelerometers, hence, with 20 DOF's, were used in this case study with only one measurement made. Since there was only one data set was generated on this beam there was no need for a reference accelerometer. With the lowest frequency of interest was around 70 Hz (obtained through a pre-test) a 120 seconds of data capture would be more than good enough to represent more than 8000 cycles of the lowest frequency of interest.

Greater attention must focus on accuracy of the modal data obtained in Operational Modal Analysis (OMA) especially on the technical aspects to implement the experiment and on the processing the random data. As such, it represents one of the best examples of how the technical effort, characterized by a good modal data can yield important results. This is further presented in results and discussions section.

In order to obtain and define all modes of interest, the beam was randomly excited by scrubbing over its entire length with enough energy to generate the broadband input signal. MTC software was used to set up and integrate the hardware, create the geometry, assign measurement points and performs the test. The raw data which consists of geometrical values and series of measurements were then directly exported to the Operational Modal Analysis Pro^{TM} software for post-data processing. Signal processing calculation and modal extraction were subsequently performed after all data were exported.

Different algorithms in OMA were used to identify the modal parameters and were compared to indicate their relative accuracy /validity. They are Frequency Domain Decomposition (FDD), Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI) techniques finally were done for modal determination.

Frequency Domain Decomposition (FDD)

Frequency Domain Decomposition (FDD) which is also known as non-parametric method is an extension of the Basic Frequency Domain (BFD) technique [7]. In this technique, the vibrational modes can be obtained from spectral densities calculated in which case the modal parameters are estimated directly from the signal processing calculations. The modes are constructed using Singular Value Decomposition (SVD) of each Power Spectral Density (PSD) matrix generated.

Enhanced Frequency Domain Decomposition (EFDD)

In contrast to the FDD, Enhanced Frequency Domain Decomposition (EFDD) is parametric technique. It computes the auto and cross-correlation functions in order to extract the frequency and damping of a particular mode [7]. The PSD which is identified around a peak of resonance is converted to time domain using the Inverse Discrete Fourier Transform (IDFT). In this case, the numbers of zero crossing times are required in order to obtain the respective natural frequencies. The damping ratio is then obtained using the logarithmic decrement of the corresponding single degree of freedom (SDOF) of the normalized auto correlation function.

Stochastic Subspace Identification (SSI)

Similar to the EFDD, this is another parametric method where in this technique modal parameters are estimated by utilizing a parametric model fitted to the signal processed data. The relevant modal parameters are identified based on the output-only covariance-driven and data-driven SSI [8] where correlation function is used in covariance-driven SSI method while raw time data is used in data-driven SSI method. The standard three identification classes for SSI method namely Unweighted Principle Components (UPC), Principle Components (PC) and Canonical Variate Analysis (CVA) can be employed for the modal identifications. However in this paper, only result from PC and CVA will be presented.

Results and Discussions

Critical Issues in Operational Modal Analysis

Exploring the critical issues in OMA are result driven as this will be a good step for further data analysis especially in expansion technique. This paper will discussed further the result obtained previously by the author [9], where adjusting the technical aspects will result better and consistent modal data especially in damping estimation from SSI method. The discussion on some of the experimental setup and planning issues are enlightened in Table 1.

For this study, in order to cover a large range of frequency spectrum, the sampling frequency was set at 8192Hz where its nyquist frequency was 4096Hz. This will set the sampling interval (T) as 0.00012207s before it was decimated. This yields a total sample of 988160 at every channel before decimated.

However,the frequency range of interest in this case is limited to 2000hz and the sampling and nyquist frequency are decimated by two. This yields a new number of sample at every chnnel which is 493824 sample with new sampling interval (T) of 0.00024414s. The Singular Value Decomposition(SVD) plot before and after decimation are shown in Figure 3(a) and 3(b).

Table 1:Discussion on the technical aspects in OMA

Critical Issues	Discussion
1. Number of data set.	The number of data set to be taken plays an important role for post-processing since any measurement must guarantee the correct magnitude and phase at all responses. This can be done by measuring the response at all points simultaneously. Hence, a single data set was implemented in this study for fast processing and data consistency.
2. Time of data taken.	The total time of data to be taken need to be considered carefully as this will minimize the random error and suppress the leakage. Thus for this study, the duration of the test was selected at 120 seconds, which is about eleven times more than what is needed according to the commonly accepted rule of thumb of a duration of minimum 1000 times the period of the lowest mode (first natural frequency of the cracked-beam was at 91Hz).
3. Number of transducers used.	The number of tranducers that are used in OMA reflect DOF. In OMA, it is essential to make sure the rank of the spectral density matrix is enough to accomodate all modes that are contributing to the OMA responses in any frequency band. The measurement system must clearly identify all sources of noise and any physical responses so that the rank of the problem is not limited. Hence, in this study, twenty (20) accelerometers are used which spread over the beam to make sure every measurement does not mainly repeat any information of each channels.

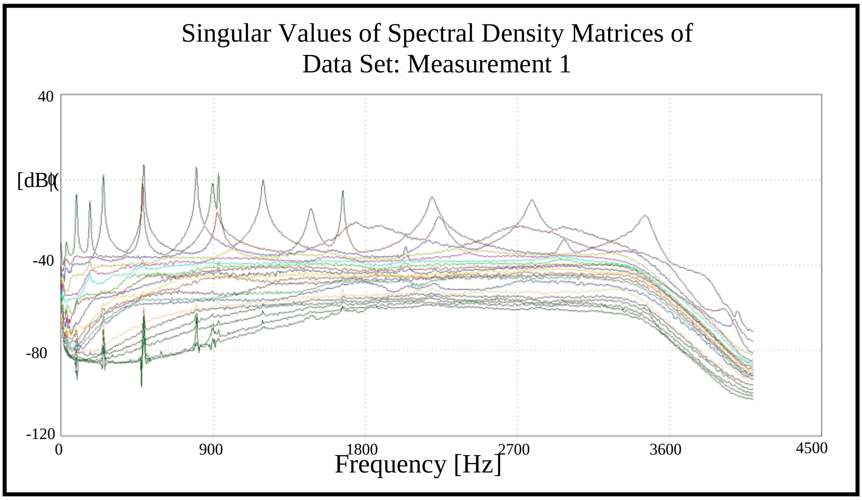


Figure 3(a): Singular value decomposition plot before decimation with 4096Hz nyquist frequency.

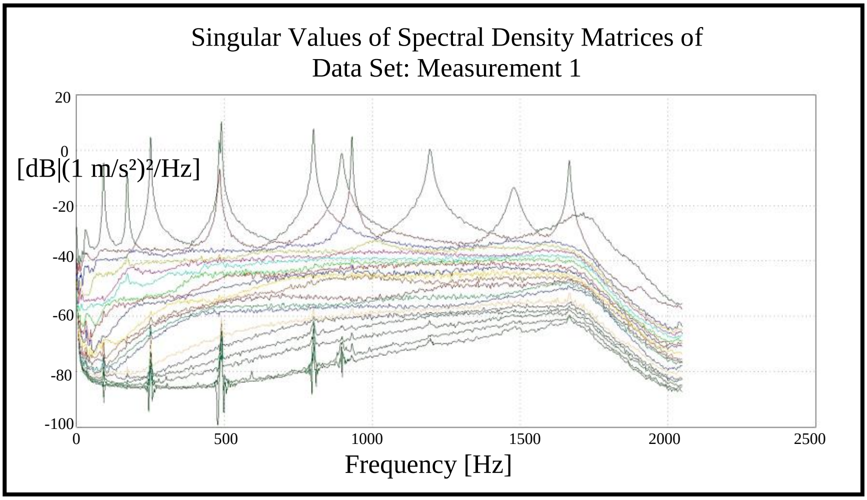


Figure 3(b): Singular value decomposition plot after decimation with 2048Hz nyquist frequency.

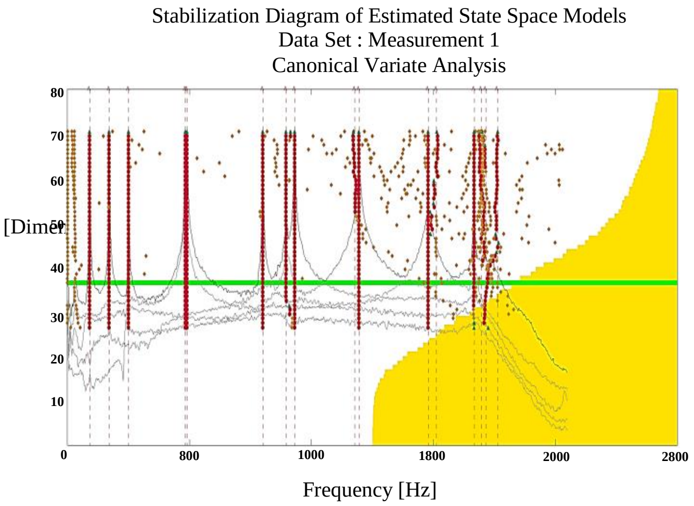
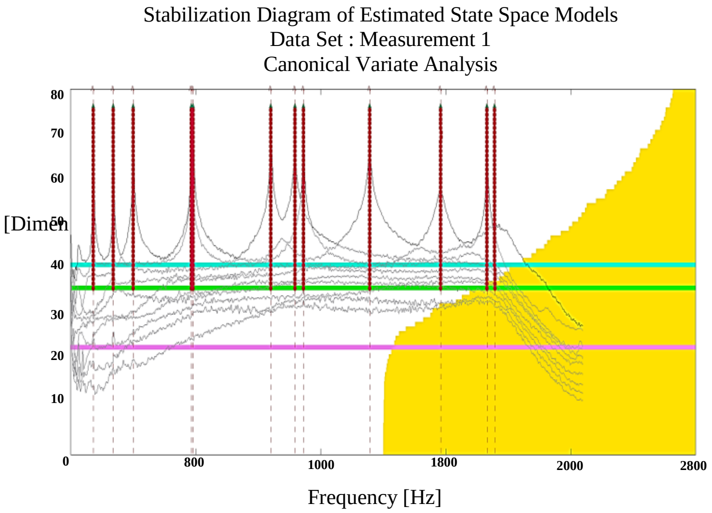
The signal to noise ratio (S/N) plays an important role to check the quality of modal data where its compare the level of desired signal to the background noise. This desired signal will provide meaningful information of the modal data as compared to the unwanted signal. In this study, the value for S/N is observed from SVD plot in Figure 3 and the value obtained indicates a good S/N which is around 80-90dB

In additon, harmonic detection was used to eliminate any harmonic components with the help of Kurtosis check indicator. This study showed that there were no harmonic components since the experiment was implemented in control environment and using random excitation.

The number of projection channel used is among the important aspect to get the better result especially in SSI technique. It is important to know how many channels are enough for the analysis since projection channels help to reduce redundant information (there are only a few independent row or columns exist,where many row or columns are linear combination of the others, hence much unnecessary (redundant) information exist). The correlation techniques are used to find the measurement channels with maximum information. This will reduce the linear dependent columns by proper choice of projection channels. In order to check for the optimum number of projection channel, the SVD plot as in figure 3(a) and 3(b) was studied and it can be seen that a few SVD lines will provide the needed information.

In FDD and EFDD methods, the result obtained does not depend much on the number of selected projection channels but the processing time will be reduced. This is not the case for SSI method especially in CVA algorithm and its results and differences that were obtained from 5, 10, 15 and 20 projection channels are shown in Table 2. It is found that 10 channels are the optimum numbers of projection channels for CVA analysis as this provide the most information and stable modes estimated withthout noise modes indicated. There are less noise modes for 5 projection channels as compared to the results obtained from 15 and 20 projection channels. The state space dimension need to be adjusted for 15 projection channels in order to produce stable modes.

Table 2: The result from CVA algorithm using different projection channels

<table>
<tr><th>No.</th><th>SSI-CVA Plot</th></tr>
<tr><td>5 Projection channels</td><td>
</td></tr>
<tr><td>10 Projection channels</td><td>
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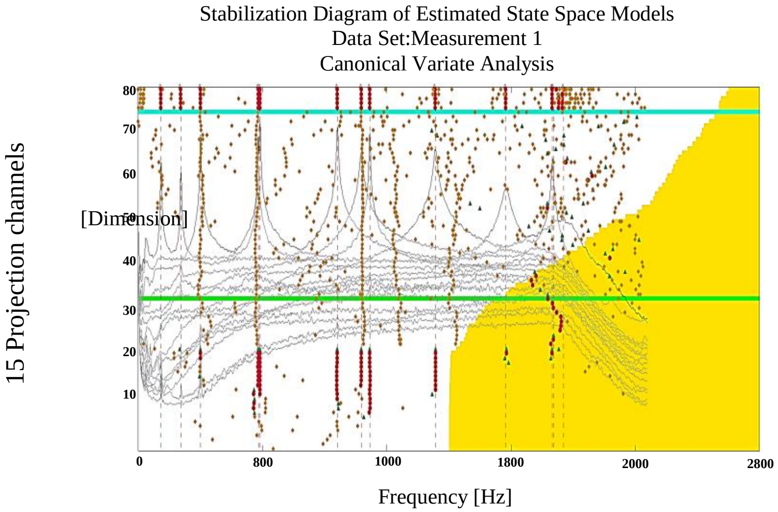
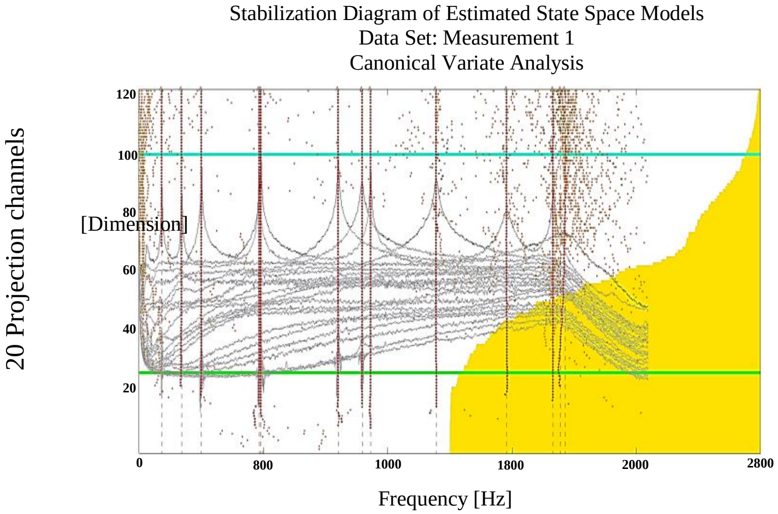

15 Projection channels
Stabilization Diagram of Estimated State Space Models
Data Set:Measurement 1
Canonical Variate Analysis
[Dimension]
80
70
60
50
40
30
20
10
0
800
1000
1800
2000
2800
Frequency [Hz]


20 Projection channels
Stabilization Diagram of Estimated State Space Models
Data Set: Measurement 1
Canonical Variate Analysis
[Dimension]
120
100
80
60
40
20
0
800
1000
1800
2000
2800
Frequency [Hz]

In order to use projection channel, the are few advantages and disadvantages as discussed in Table 3.

Table 3: The effect of projection channels on the result that is processed
.

Advantages	Disadvantages
1. Increased computational speed where in SSI reduced the calculation time dramatically	1. missing modes if number of projection channels are too low (i.e. case with repeated roots)
2. Reduced redundant information	2. missing modes not appearing in projection channels (i.e local modes)
3. Better stabilization of physical modes (In SSI method)	
4. Reduced error in damping estimation (In SSI method)	
5. reduced the scatter of noise modes in stabilization diagram (SSI) – clear and better stabilization of the physical modes	

In SSI method, the state space dimension setting also important. The state space dimension means that the modal data is search and look between the range of eigenvalues specified in the setting. The question of the lower the better or the higher the better inspire this study to look into the results obtained for different state space dimension. It is observed that the stable mode could be detected if the state space dimension apply within the correct region. The observation was done on the CVA stability diagram where two set of state space dimension were compared. From Figure 4, only 1 stable mode is obtained using 30-80 state space dimension (red dotted line in Figure 4 (a)), while 11 stable modes are indicated for 1-80 state space dimension setting (red dotted lines in Figure 4(b)). The range of state space dimension is clearly seen from the mode indictors in the diagram(as indicated by the range of stable, unstable and noise dots) . Dimension of state space can also be selected using the cursor model.

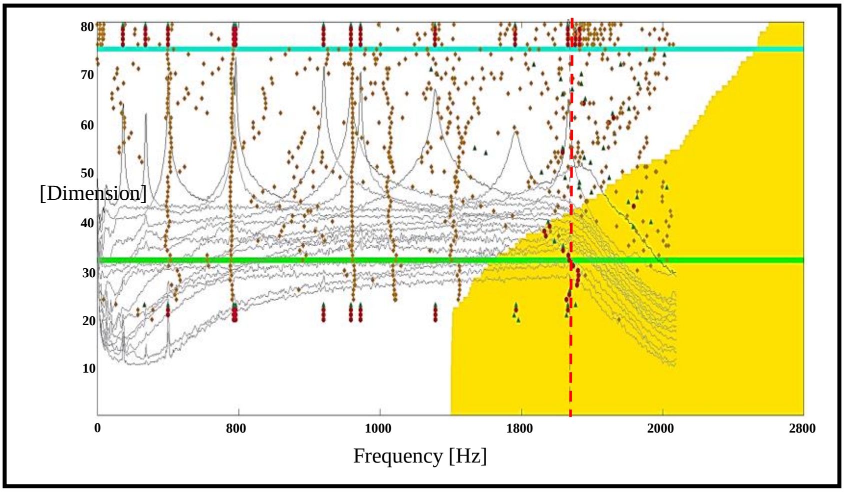


Figure 4(a): Canonical Variate Analysis (CVA) stability diagram for 15 channels with 30-80 state space dimension as can be seen from range of mode indicators.

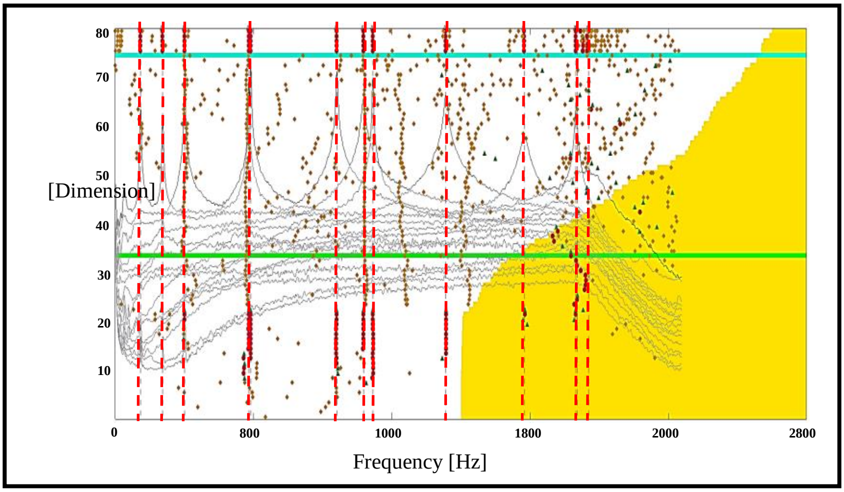


Figure 4(b): Canonical Variate Analysis (CVA) stability diagram for 15 channels with 1-80 state space dimension as can be seen from range of mode indicators

Based on the aforementioned technical issues that were discussed, a good estimation of modal parameters were obtained from 20 channels of FDD and EFDD algorithms and 10 channels of SSI algorithms as presented in Table 4. It is observed that the results estimated were improved in terms of its consistency across different algorithms as compared to the previously presented in [9].

Table 4: Natural frequencies from OMA tehcniques

Mode	FDD (Hz)	EFDD (Hz)	SSI–PC Identification (Hz)	SSI – UPC Identification (Hz)	SSI – CVA Identification (Hz)
1	91	91.29	90.74	91.38	91.17
2	171	171.4	171.6	171.5	171.4
3	251	250.8	250.7	250.8	250.7
4	483	482.5	482.4	482.5	482.4
5	490	489.7	489.7	489.8	489.7
6	801	801.2	801.2	801.3	801.2
7	898	896.6	896.8	897.1	896.8
8	931	931.2	931.2	931.2	931.2
9	1194	1195	1195	1196	1195
10	1479	1479	1479	1481	1479
11	1666	1666	1666	1666	1666

Table 5: Damping ratio for each mode from EFDD and SSI algorithms

Mode	Damping - EFDD (%)	Damping - SSI- PC (%)	Damping - SSI- UPC (%)	Damping - SSI- CVA (%)
1	0.7921	1.117	2.54	0.7104
2	0.4897	0.3015	0.7836	0.4102
3	0.2941	0.1863	0.2225	0.1885
4	0.1668	0.08694	0.1033	0.0884
5	0.1564	0.09691	0.1177	0.09868
6	0.1925	0.1541	0.16	0.1579
7	0.5395	0.5667	0.5584	0.5593
8	0.1023	0.0704	0.0792	0.07104
9	0.4211	0.4181	0.4316	0.4236
10	0.8746	0.7862	0.7581	0.801
11	0.1348	0.118	0.1299	0.1227

As for the damping values all techniques have produced the estimated damping values except for the FDD method. The corresponding damping values for each mode are illustrated in Table 5. The values obtained in this study were better as compared to the results in [9]. There was no indication of 100% damping as found previously and all damping values were less than 3%.

Conclusion

Operational Modal Analysis (OMA) was successfully carried out on a crack aluminium beam at its center under free-free end condition. The modal parameters of this structure in the form of its natural frequencies, mode shapes, and damping ratio were successfully obtained. The reliability of results depends on the free vibration of the structure as it is characterized by the inherent modal parameters of the beam. Parametric and non-parametric techniques in OMA for modal determination were made. Comparison of natural frequencies between the two techniques gave satisfactory results and in good correlation. However, since the understanding of dynamic behaviours of this structure provides such a valuable insight into the nature of the response and remarkable enhancement of its model, strength and vibration, it is recommended that future work using Finite Element Analysis (FEA) be accommodated for comparison with this modal analysis. Comparison between the results obtained in this study with that of FEA approach is required for further validation purposes. Well correlation of FEA and OMA can be obtained and is best done using Modal Assurance Criterion (MAC). The corresponding results are useful in modal expansion through Local Corresponding (LC) method which will provide information at all degrees of freedom of a structure.

References

[1] D.J.Ewins, “Modal Testing: Theory and Practice,” , *2nd ed. Letchworth, Hertfordshire, Engl. Res. Stud. Press LTD*, 1986.

[2] M. Batel, “Operational Modal Analysis - Another Way of Doing Modal Testing,” *Sound Vib.*, vol. 36, no. August, pp. 22–27, 2002.

[3] R. Brincker, C. E. Ventura, and P. Anderson, “Why Output-Only Modal Testing is a Desirable Tool for a Wide Range of Practical Applications,” in *Proceedings of the 21st International Modal Analysis Conference on Structural Dynamics*, 2003, pp. 1–8.

[4] R. Brincker, L.Zhang, and P.Andersen, “Modal Identification from Ambient responses using Frequency Domain Decomposition,” in *International Modal Analysis Conference (IMAC), San Antonio, Texas*, 2000.

[5] L. Zhang, R. Brincker, and P. Andersen, “An overview of major

developments and issues in modal identification," *International Modal Analysis Conference (IMAC)*, no. 1. Detroit, Michigan, pp. 1–8, 2004.
[6] R. Brincker and P. H. Kirkegaard, "Special issue on Operational Modal Analysis," *Mech. Syst. Signal Process.*, vol. 24, no. 5, pp. 1209–1212, Jul. 2010.
[7] M. Batel, G. S., M. N., and H. Herlufsen, "Ambient Response Modal Analysis on a Plate Structure," in *Proceedings of 21st International Modal Analysis Conference (IMAC-XXI)*, 2003.
[8] M. Goursat, M. Döhler, L. Mevel, and P. Andersen, "Crystal Clear SSI for Operational Modal Analysis of Aerospace Vehicles," in *Structural Dynamics, Volume 3 SE - 125*, T. Proulx, Ed. Springer New York, 2011, pp. 1421–1430.
[9] M. Azhan Anuar, A. A. Mat Isa, and R. Brincker, "Comparison of Parametric and Non-Parametric Operational Modal Analysis Methods on Crack Aluminum Beam," vol. 8, no. 24, pp. 296–300, 2014.