The Influence of Off-centred Crack on the Dynamics of Beam

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ABSTRACT: Structural defects have an adverse effect on the service life of mechanical structures. They alter the dynamic characteristics excessively and may possibly lead to catastrophic failure. These defects are characterized by changes in the eigen-parameters. Thus, defect detection even at the initiation stage is an important consideration to guarantee the component safety and prolong the service life of the structure and hence save costs. This paper discusses the effect of variations in the dynamic properties with respect to the present of a single crack in beam with free ends using output-based modal analysis. The validity of the results is verified with the well-established experimental modal analysis.

Keywords: Structural modes of vibration, natural frequency, damping ratio, experimental and operational modal analysis

1 INTRODUCTION

To ensure continuous safety operations of a machine or structure it is necessary to monitor constantly the health of its critical components. Structural components exhibit different dynamic characteristics whenever there are changes in its structural properties such as mass, stiffness, and damping values. This requires the need for a continuous assessment of changes in their static and/or dynamic behaviour. The changes very often originate from the local reduction of the structural stiffness caused by cracks or crack-like defects (Friswell 1997; Schulz 1997; Martin 1998). The development of a crack does not necessarily make a component instantly unusable, but it signal a message that its behaviour needs constant monitoring before eventual replacement. This has made the vibration based monitoring of components with cracks or crack-like defects during service very important and therefore the study of vibration of components with crack becomes important (Schulz 1997; Zheng 2004).

Cracks identification and detection using vibration signal was investigated as an alternative non-destructive evaluation (NDE) methods (Shifrin 1999; Zheng 2001), since hidden cracks inside the structure is rather difficult to detect using conventional methods (Bammios 2002). Relatively larger cracks located away from sensor can be detected by means of change in the vibration response of the structure. However, interpretation of the vibration response is often difficult, and detection of a crack at its initial stage also difficult since it has a small effect on the vibration response (Fernandez-Saez 1999). Some approaches store pre-damage or healthy vibration responses, and detect cracks by changes in the structural modes of vibration. These techniques require storage of large data sets and the response can vary due to changes in the environment such as temperature, and also changes in the boundary condition of the structure. Another difficulty was to discriminate between changes due to the environment and the crack itself (Rizos 1990; Sekhar 1999).
This paper presents the influence of off-centred crack on the dynamic behaviours of beam with free-free ends. In order to identify this influence, classical modal analysis and operational modal analysis techniques were applied.

2 OPERATIONAL MODAL ANALYSIS AS A DIAGNOSTIC TOOL

This section provides a brief theory of operational modal analysis techniques applied to vibration of a beam. Special consideration is given to the end condition with free-free ends. The classical experimental modal analysis techniques are well known and will not be discussed. The detailed discussion of these techniques can be found for instance in (Ewin 2000) and (Allemang 1999)

2.1 Frequency Domain Decomposition (FDD)

The FDD method is an extension of the Basic Frequency Domain (BFD) method or commonly known Peak-Picking method. The technique is a non-parametric in nature that estimates the modal parameters directly from signal processing data calculations. This approach the utilize the properties that the mode shapes can be estimated from the calculated spectral density for the condition of random noise input or stochastic input applied to lightly damped structure where the modes are well separated (Moller 2001).

In contrast to the classical techniques where the power spectral density (PSD) matrix is directly and easily estimated via Fast Fourier Transformation (FFT), in the frequency domain decomposition (FDD), it is not directly processed, but decomposed using the singular value decomposition (SVD) at each spectral line. The PSD matrix is decomposed into auto spectral density functions consist of single degree of freedom systems. The modes are simply picked by locating the peaks in SVD plots. The accuracy of the estimated natural frequency depends on the FFT resolution with no modal damping is calculated (Brincker 2000).

2.2 Enhanced Frequency Domain Decomposition (EFDD)

The EFDD technique is an extension to the FDD technique. It gives an improve estimate of both the mode shapes and the natural frequencies and also provides modal damping. In EFDD, the SDOF Power Spectral Density function which is identified around a resonance peak is transformed back to time domain using Inverse Discrete Fourier Transform (IDFT). The frequency is obtained the number of zero crossing as function of time and the damping by logarithmic decrement of the normalized auto correlation function. The SDOF function is predicted using shape previously determined using FDD which is used as reference vector in the correlation analysis based on Modal Assurance Criteria (MAC). This value is calculated between the FDD vector and a single vector for each frequency line(Jacobsen 2007).

3 EXPERIMENTAL METHODS

The experimental procedure was carried out to obtain the mobility in the form of a frequency response functions (FRF) using both classical and operational modal tests. The good or healthy beam and the beam with a single off-centred crack were used in the experiment. Only the type of free-free beam end condition was investigated.

3.1 Classical Modal Analysis

3.1.1 Modal Test

In this test, the excitation is exerted to the test structure by applying an impulse force from a roving impact hammer in a single Z- direction, see Figure 1. The force was applied at 9 different locations while the fixed accelerometer at a single location captured the response signal. The FRFs at different positions of the impact hammer are stored for further post processing.
ME’Scope was then used as post processing software to extract dynamic properties such as natural frequencies and damping ratio, and to simulate the vibration modes of a beam. The measurement utilized Bruel&Kær PULSE Frontend Type 3560D Analyzer data acquisition system.

Coherence is also taken into consideration when selecting the placement of the sensor so that the influence of noise to the signal is minimized. In general, coherence decreases as the accelerometer is closer to the boundary or edge of the structure. For all measurements, coherence over 0.98 is considered for a reasonable accuracy since the structure is very simple.

![Figure 1 – A roving hammer and a measurement point](image)

### 3.1.2 Modal Identification

The modal identification was performed using the well established curve fitting and direct parameter estimation techniques in the frequency range of zero to 3200 Hz. Six distinct modes of vibration were extracted along with the corresponding natural frequencies and damping ratios.

![Figure 2 – FRF with curve fitting and Modal peaks function](image)
3.2 Operational Modal Analysis

3.2.1 Operational Modal Test
To assess the relevant structural vibrations of both healthy and cracked beams in operation using the operational modal analysis technique, the beams were randomly excited at various locations in the z direction. Accelerations were measured with 9 uniaxial accelerometers simultaneously with the accelerometer at point or node 1 was selected as a reference since it exhibited most information about the vibration, see Figure 3. The measurement utilized the same Brue&Kaer PULSE Frontend Type 3560D Analyzer data acquisition system. A total of 9 measurement degrees of freedom were taken in order to obtain the overall modes of vibration.

The measurements were repeated several times in order to obtain an accurate observation of the structural properties of the beam and also to exhibit the effectiveness of the OMA technique. Figure 4 shows a typical time record of the history of the random excitation signal.

![Figure 3 – Measurement points and a reference accelerometer](image)

![Figure 4 – Typical time record of random excitation](image)

3.2.2 Operational Modal Identification
To identify the operational modes of vibration governing the response of the beam, two different operational modal analysis techniques were applied: 1) FDD and 2) EFDD. The time data were measured in both techniques where the spectral density matrix was calculated utilizing a 2048 point FFT. The overall operational natural frequencies of vibration were obtained from two different measurement sets. Both techniques also exhibited good modal coherence.
Figure 5 – FRFs of a good beam using FDD and EFDD

4 RESULTS AND DISCUSSION

All the results from the experimental studies were tabulated and comparisons were presented. The results for the cracked beam were compared to the results for the uncracked beam according to the technique used.

A comparison of results from the two operational modes of vibration using FDD and EFDD and the modes identified by classical experimental modal analysis techniques on the healthy and cracked beams clearly indicate changes in dynamic properties. The two techniques yield consistent results. Both the OMA and EMA techniques show no change in the mode shapes for the two beams at all modes, however, the natural frequencies at which these modes occurred and the corresponding modal damping indicate significant reduction except at the fifth mode. Table 1 and Table 2 compare the modal natural frequencies of the healthy or good beam and the beam with a single off-centred crack for the first five modes of vibration. Table 3 compares the damping ratios calculated using EFDD techniques for the same modes of vibration.

Furthermore, the identification of mode shapes and the natural frequencies utilizing the FDD and EFDD yielded the same modes with very small differences in the natural frequencies. It is understandable that the frequencies for the uncracked or healthy beam are higher than that of the cracked beam. This is due to the reduction of the stiffness at the cracked location.

| Table 1: Natural Frequencies for the Uncracked or healthy Beam |
|------------------|--------|--------|--------|
| MODE   | THEORY (Hz) | EMA (Hz) | OMA (Hz) |
|        |             |         | FDD     | EFDD   |
| 1      | 174.73      | 183     | 184     | 184.6  |
| 2      | 566.17      | 499     | 496     | 495.8  |
| 3      | 1181.1      | 964     | 952     | 952.1  |
| 4      | 2019.9      | 1560    | 1544    | 1543   |
| 5      | 3082        | 2270    | 2246    | 2246   |

| Table 2: Natural Frequencies for the Single off-centred Cracked Beam |
|------------------|--------|--------|--------|
| MODE   | THEORY (Hz) | EMA (Hz) | OMA (Hz) |
|        |             |         | FDD     | EFDD   |
| 1      | 174.73      | 175     | 172     | 172.7  |
| 2      | 566.17      | 491     | 486     | 486.7  |
| 3      | 1181.1      | 950     | 940     | 939    |
| 4      | 2019.9      | 1510    | 1494    | 1494   |
| 5      | 3082        | 2270    | 2246    | 2247   |
Table 3: Modal Damping for the Uncracked and Cracked Beam

<table>
<thead>
<tr>
<th>MODE</th>
<th>Damping Ratio</th>
<th>Uncracked</th>
<th>Cracked</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.004</td>
<td>0.7078</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.3236</td>
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<td></td>
</tr>
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<td>5</td>
<td>0.2193</td>
<td>0.4524</td>
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</table>

Though different excitations were made, the OMA method yielded consistent structural properties of the beam.

5 CONCLUSIONS

The measured modal natural frequencies and mode shapes of the rectangular beam using EMA and OMA for both the healthy beam and the beam with a single off-centred crack are in good agreement. The crack clearly influences the dynamic properties of the beam with free ends. The modal damping frequencies of the cracked beam are generally lower than the frequencies of the uncracked beam. The lower values are due to the reduction of the stiffness at the cracked area. The mode shapes of the beam, however, are not affected by the presence of the crack and that the two techniques, OMA and EMA, yield essentially the same modes of vibration.

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REFERENCES