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DETECTION OF DAMAGE LOCATION IN STRUCTURES USING OPERATING DEFLECTION SHAPE

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Abstract

It is important to figure out the dynamic characteristics of a mechanical system for the purpose of safe design. The most widely used method to grasp the inherent dynamic characteristics is Modal analysis which gives us information of modal parameters, such as natural frequency, damping ratio and mode shape vector. However, as mechanical systems get larger and more complicated, difficulties on how to set boundary and excitation conditions arise in modal analysis. Surely, the actual vibration of mechanical systems varies with surrounding conditions, which are temperature, rpm, air flow, pressure, load and so on. Therefore, another method known as Operating Deflection Shape (ODS) is needed to deal with those situations that Modal Analysis cannot do. ODS shows structural vibrations under real operating conditions. Also, rapid measurement not influencing the dynamic characteristics of the structure is required for ODS. It is desirable to use a Laser Scanning Vibrometer (LSV) which has no contact with the structure. In addition, if it is possible to check whether the structure is healthy or not, the structure could be prevented from being destroyed. For that reason, an ODS program is developed using LSV, and damage detection is introduced through this program. In this paper, damage locations of structures are detected using ODS and LSV.

1. INTRODUCTION

Operating Deflection Shape (ODS) is the real vibration pattern a structure has. Provided that ODS of an operating structure is well known, methods to reduce vibration can be taken. Also, Laser Scanning Vibrometer (LSV) is an attractive tool in spite of its high cost because it is possible to measure the vibration of a structure quickly without any structural change. Therefore, ODS program has been developed using EM4SYS LSV 100D. In this paper, a simple theory and measurement method and “Scale Factor” of ODS are explained. Also, damage detection is considered using this program.

2. LASER SCANNING VIBROMETER

Figure1. Laser Scanning Vibrometer (EM4SYS)

Laser Scanning Vibrometer (LSV) can measure the velocity of vibration on the surface of a structure without any contact with the structure. LSV uses the Doppler Effect, which is the change in frequency and wavelength of a wave that is perceived by an observer moving relative to the source of the waves. Compared with other measurement sensors such as an accelerometer, LSV does not cause structural change and is easy to detect information of the vibration on the structure with less time. Therefore, LSV is appropriate to measure ODS rapidly with accurate vibration information.

3. OPERATING DEFLECTION SHAPE

3.1 ODS vs. Mode Shape

Mode is defined in structural resonance frequencies and is inborn characteristics of the structure which are determined by its mass, stiffness and damping. In terms of mode, we consider three parameters such as modal frequency, modal damping and mode shape. However, ODS is the deflection of the structure at a particular frequency. For example, operating frequencies of a washing machine would change according to operating steps such as washing and dehydrating. Also, ODS would change due to variation of other operating conditions, which are RPM, load, pressure, temperature, flow and so on.

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = f(t) \tag{1}$$

The equation of motion for SODF is described as equation (1). According to the modal analysis theory, the homogeneous solutions of equation (1) are Mode Shapes, and the particular solutions are Operating Deflection Shapes. Table 1 shows how ODS is different from Mode Shape.

Table 1. Mode Shape vs. ODS [1].

Mode Shape	ODS
Modes are inherent properties of a structure.	Depend on loads applied to a structure.
Don't have unique values; however, mode *shapes* are unique.	ODS can have unique values.
Only defined for linear, stationary motion.	Defined for nonlinear and non stationary structural motion.

In terms of modal and ODS testing, ODS is shown as combinations of modes. Therefore, ODS would look like the first mode if excitation frequency is near the first natural frequency. Figure 2 to 4 [2] are the examples that show the relationship between Mode and ODS. Like Figure 4, ODS would look like combination of 1st and 2nd mode if excitation is between two frequencies.

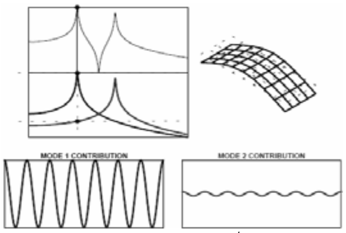


Figure 2. ODS at 1st Natural Frequency

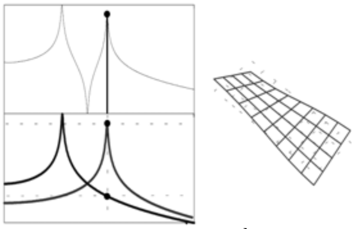


Figure 3. ODS at 2nd Natural Frequency

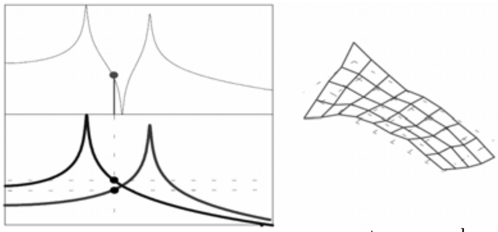


Figure 4. ODS at between 1st and 2nd Natural Frequency

3.2 Measurement of ODS

Like the following Figure 5, we obtain mode shapes by connecting peaks from each FRF of the structure's DOF. When we calculate Frequency Response Function (FRF), H_1 estimator for equation (2) or H_2 estimator for equation (3) are commonly used.

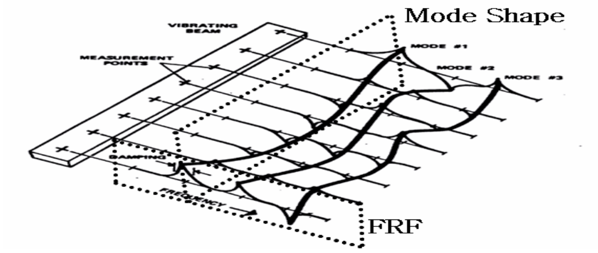


Figure 5. FRF and Mode Shape [7]

$$H_1(f) = \frac{X(f)F^*(f)}{F(f)F^*(f)} = \frac{G_{XF}}{G_{FF}} \tag{2}$$

$$H_2(f) = \frac{X(f)X^*(f)}{F(f)X^*(f)} = \frac{G_{XX}}{G_{FX}} \tag{3}$$

where $F(f)$: Frequency spectrum of an input signal $f(t)$

$X(f)$: Frequency spectrum of an output signal $x(t)$

$F^*(f)$: Complex conjugate of $F(f)$

$X^*(f)$: Complex conjugate of $X(f)$

ODS FRF can be calculated in a similar manner. Instead of information of input signal, reference signal is needed to calculate the phase of each measurement point. In order to obtain roving response signals and reference signals at the same time, three ways can be considered for reference signals.

1. Mount one fixed accelerometer.
2. Use another LSV.
3. Use input signal.

For case 2, it is too expensive to purchase LSV solely for the purpose of reference signal measurement. Also, for case3, it is impractical because input signals cannot be measured in most of cases. So, case1 is considered in order to measure Reference signals.

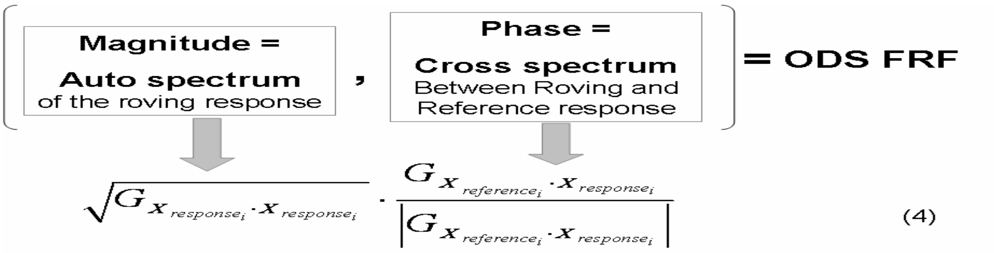


Figure 6. ODS FRF

To calculate ODS FRF, Auto-power Spectrum of roving responses and Cross-power Spectrum between roving responses and references are required. From equation (4) in Figure 6, the left part indicates magnitude while the right part does phase for between each measurement point and reference. The subscript *i* indicates measurement point. The dimension of the left part should be $\sqrt{(mm/s)^2}$ and the right part should be radian. Therefore, the final dimension of equation is $\sqrt{(mm/s)^2} \cdot \angle\theta$ and is easily transformed into the combination of real and imaginary values. Here, imaginary parts for displacement and acceleration and real parts for velocity are used in order to draw shapes. Therefore, using only the real part of equation (4), ODS FRF can be made.

3.3 Scale Factor

ODS FRF equation (4) does not deal with the non-stationary signals; that is, proper calculation of ODS FRF would not be possible if the excitation force level varies for each measurement. To obtain accurate ODS FRF regardless of variable excitation force levels, compensation of magnitude in ODS FRF must be considered. There might be many scale factors, but let five cases be in this paper's consideration.

$$\sqrt{G_{X_{response\ i}} \cdot G_{X_{response\ i}}} \cdot \frac{G_{X_{reference\ i}} \cdot G_{X_{response\ i}}}{\left| G_{X_{reference\ i}} \cdot G_{X_{response\ i}} \right|} \cdot (Scale \quad Factor) \tag{5}$$

Table 2. Scale Factors

Case 1	1
Case 2	$\sqrt{\frac{\sum_{i=1}^{M} G_{X_{reference\ i}} \cdot G_{X_{reference\ i}}}{M \times G_{X_{reference\ i}} \cdot G_{X_{reference\ i}}}}$
Case 3	$\frac{\sum_{i=1}^{M} G_{X_{reference\ i}} \cdot G_{X_{reference\ i}}}{M \times G_{X_{reference\ i}} \cdot G_{X_{reference\ i}}}$
Case 4	$\sqrt{\frac{M \times G_{X_{reference\ i}} \cdot G_{X_{reference\ i}}}{\sum_{i=1}^{M} G_{X_{reference\ i}} \cdot G_{X_{reference\ i}}}}$
Case 5	$\frac{M \times G_{X_{reference\ i}} \cdot G_{X_{reference\ i}}}{\sum_{i=1}^{M} G_{X_{reference\ i}} \cdot G_{X_{reference\ i}}}$

The effect of five different scale factors will be shown in numerical beam, stationary and non-stationary experimental results.

3.3.1 Numerical Beam

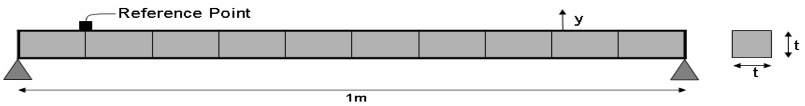


Figure 7. Numerical Beam

Assuming the material is steel, the velocity response at one point of the beam is expressed in equation (6). With velocity data from equation (6) [8], the effects of five scale factors are shown in Table 3.

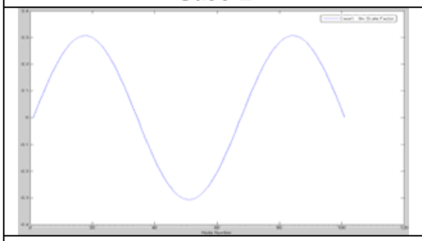
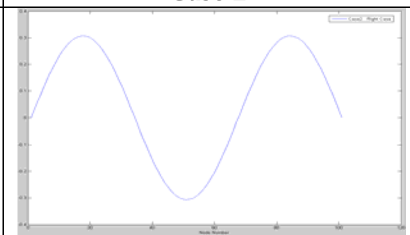
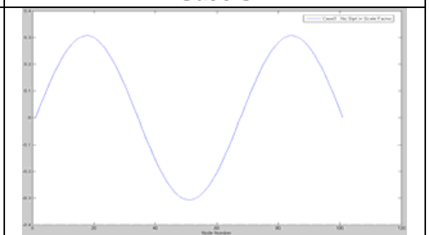
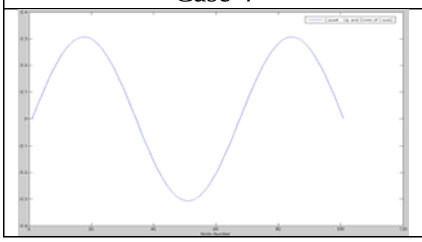
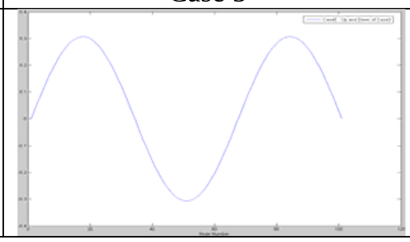
$$v(t) = \sum_{n=1}^{N} g_v(t) \cdot \phi_n(x_f) \cdot \phi_n(x_o) \tag{6}$$

where $g_v(t) = -\frac{\omega_n}{m\omega_d} e^{-\zeta\omega_n t} \cdot \sin(\omega_d t - \varphi)$, <Impulse Response> $\varphi = \tan^{-1} \frac{\sqrt{1-\zeta^2}}{\zeta}$ (7)

$$\phi_n(x_f) = \sqrt{2}\sin\left(\frac{n\pi x_f}{L}\right)$$ <Modal Response at the forcing point> (8)

$$\phi_o(x_f) = \sqrt{2}\sin\left(\frac{n\pi x_o}{L}\right)$$ <Modal Response at the observation point> (9)

Table 3. Results

Case 1	Case 2	Case 3
		
Case 4	**Case 5**	**Comments**
		Shown ODSs are near the third natural frequency. Results are all the same because force level is not varying and five scale factors don't affect any change to the magnitude of ODS.

3.3.2 Experiments of Beam (Stationary Force Level)

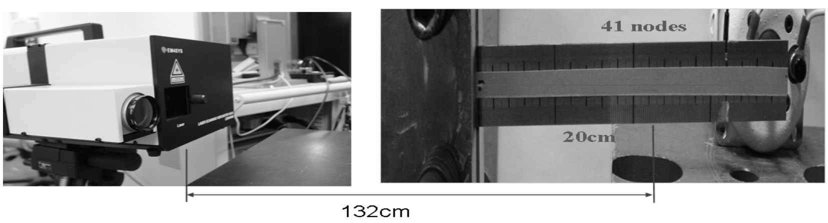
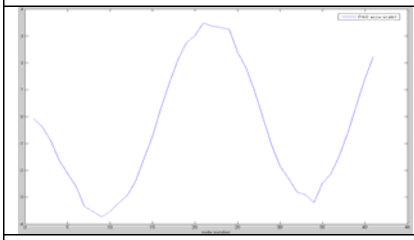
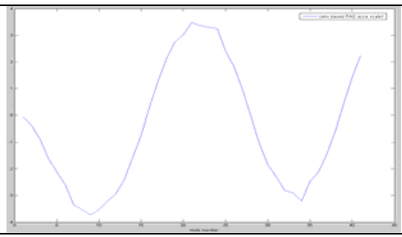
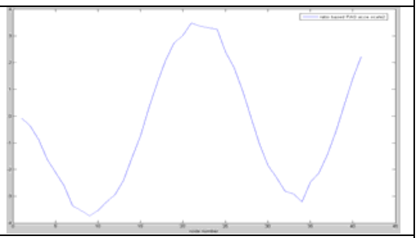
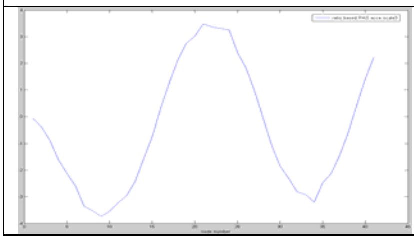
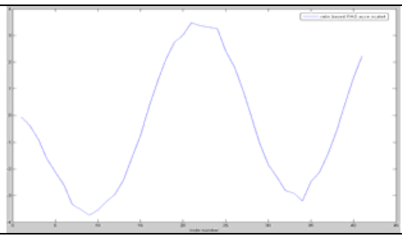


Figure 8. Experiment Set-up

Experiments of the beam have been done like Figure 8. The beam was excited near the fourth natural frequency with same force levels. The effects of scale factors are shown in Table 4.

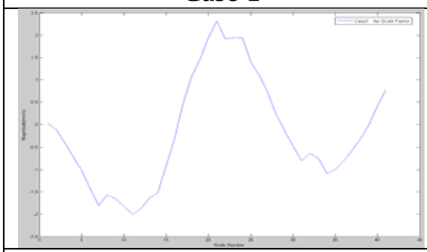
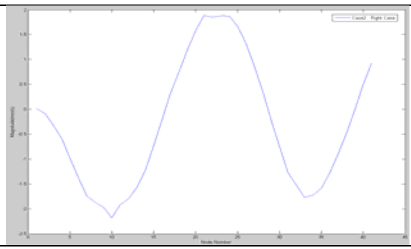
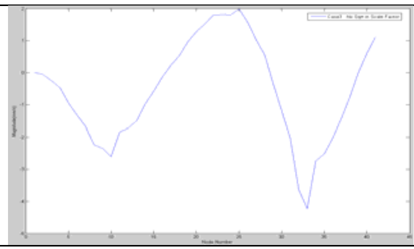
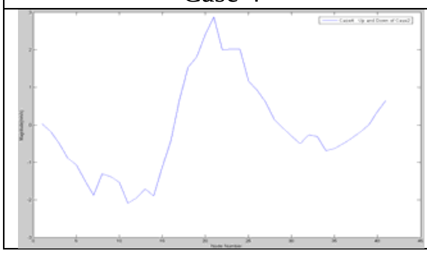
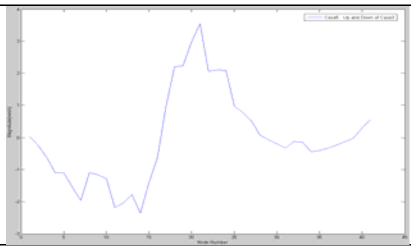
Table 4. Results

Case 1	Case 2	Case 3
		
Case 4	Case 5	Comments
		Results are all the same because force level is not varying and five scale factors don't affect any change to the magnitude of ODS .

3.3.3 Experiments of Beam (Non-stationary Force Level)

When the beam was excited near the fourth natural frequency with variable force levels, the effects of scale factors are like below. The Experiment set-up is shown in Figure 8.

Table 5. Results

Case 1	Case 2	Case 3
		
Case 4	Case 5	Comments
		Every Scale Factor except case 2 gives wrong ODS when excitation force levels are varying. Sizzling points in Case 1 indicate the changes in excitation force level. Other scale factors make the distortion worse.

Therefore, Case 2 $\sqrt{\dfrac{\sum_{i=1}^{M} G_{X_{reference_i}} \cdot G_{X_{reference_i}}}{M \times G_{X_{reference_i}} \cdot G_{X_{reference_i}}}}$ is suggested for the proper Scale Factor of ODS FRF.

Finally, ODS program using LSV has been developed as shown in Figure 9.

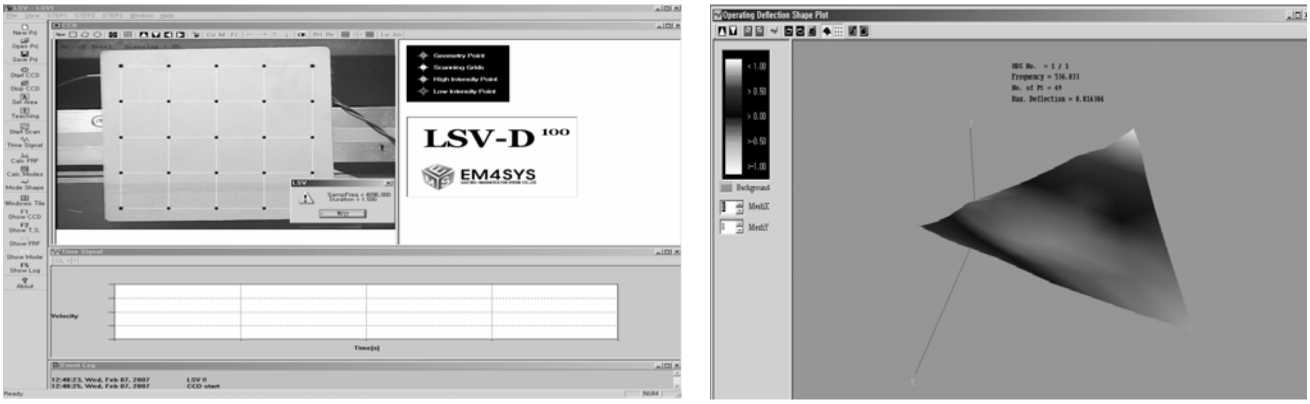


Figure 9. Operating Deflection Shape Program

4. DETECTION OF DAMGE LOCATIONS

When a structure is operating at certain conditions, its ODS would be determined according to its boundary conditions, rpm, load and so on. However, something different from its original structure such as crack on the surface might cause the variation of its ODS. In this paper, the damage detection and locations are considered through experiments of the clamped-clamped plate.

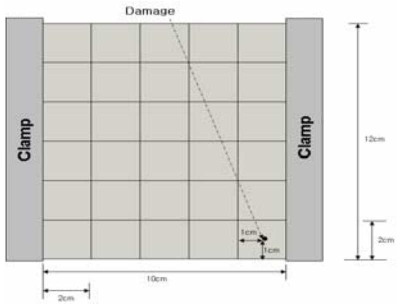


Figure 10. Damaged Plate (Case1)

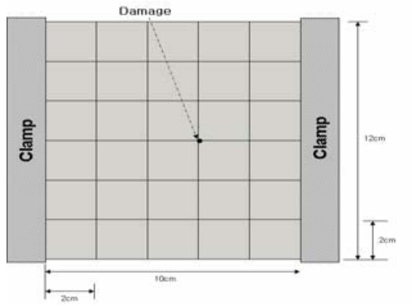


Figure 11. Damaged Plate (Case2)

Figure 10 and 11 are the plates compared with the intact one. Figure 12 to 14 are their ODS near 3rd natural frequencies. It would be impossible to find the damage locations by direct comparison. So, equation (10) is considered to compare damaged cases with the undamaged one.

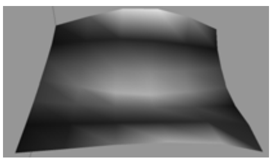


Figure 12.ODS of intact one

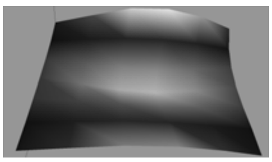


Figure 13.ODS of damaged case1

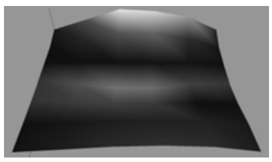


Figure14.ODS of damaged case2

$$ODS \quad Comparison = \left(\phi_{u\ i} - \psi_{d\ i}\right)^2 \tag{10}$$

where $\phi_{u\ i} = i^{th} \quad component \;\; of \;\; ODS \;\; vector \;\; for \;\; Undamaged \;\; Structure$

$\psi_{d\ i} = i^{th} \quad component \;\; of \;\; ODS \;\; vector \;\; for \;\; Damaged \;\; Structure$

If there is no damage, equation (10) would give zero to all measurement points theoretically. However, some high values would be present near the damage location if there is damage. These results can be easily shown through bar graphs of two experiments like Figure 15 and 16. Some peaks near the damages can be easily found.

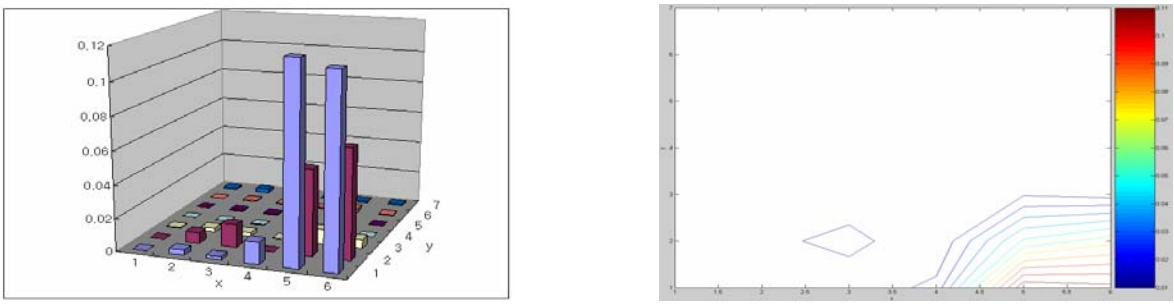


Figure 15. ODS Comparison for Damaged case1 (Bar Graph and Contour)

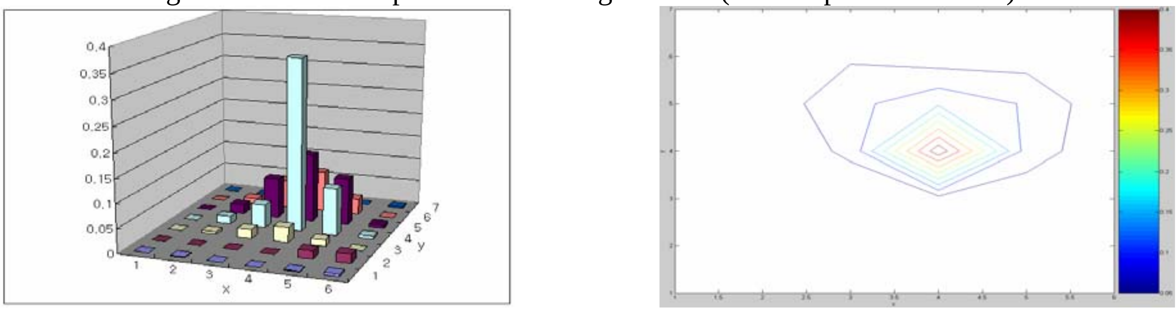


Figure 16. ODS Comparison for Damaged case2 (Bar Graph and Contour)

6. CONCLUSIONS

The way of how to realize ODS program properly has been considered. In the developed ODS program, auto-power spectrum of roving responses measured by LSV and cross-power spectrum between roving responses and references are simultaneously measured by an accelerometer. For non-stationary operating conditions, the scale factor was suggested successfully in order to compensate its magnitude. Finally, ODS is used to find the location of the damages.

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