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Enhancing the Dynamic Characterization of a Wharf Structure Through Optimal Impact Load Direction: A Stochastic Subspace Identification Approach for Revealing Dominant Modes

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Abstract

This study investigates the effectiveness of impact load application in revealing the dynamic characteristics of a wharf structure. Finite element analysis was conducted to simulate impact loads time history analysis in the x, y, and z directions, both individually and simultaneously. Accelerations were extracted at nine points on the structure and processed using stochastic subspace identification (SSI) to determine mode shapes and vibration frequencies. The results were compared to those obtained from modal analysis to assess the success of stimulation in different directions. It was found that simultaneous application of impact loads in all three directions effectively excites the structure in all directions, leading to the extraction of more frequencies and mode shapes. While this approach may not be universally applicable, it is recommended for structures where it is feasible such as wharf structures. These structures are subjected to the impact of mooring vessels. So, it enhances the extraction of dynamic characteristics.

Keywords: Vibration frequencies, Mode shapes, Impact load, Operational Modal Analysis, Stochastic subspace.

1. Introduction

One of the methods of determining the modal characteristics of the structure is exciting the structure and investigating the responses at different points of the structure.[1] [2] There are various methods for exciting the structure, including harmonic loading, impact loading, and wind loading.[3] The Operational modal analysis (OMA) is a non-destructive testing technique used to identify the dynamic characteristics of a structure, such as natural frequencies, damping ratios, and mode shapes, solely based on its response to excitation. It is a valuable tool for assessing the structural health and integrity of various structures, including buildings, bridges, and industrial equipment. [4] Stochastic Subspace Identification (SSI) is a popular operational modal analysis method that is particularly useful for handling complex, large-scale structures with high modal density. [5] [6] when impact excitation is used, the direction of the impact load can affect the observed modal parameters [5] [7] [8] Therefore, finding the right place and direction to introduce the impact load is considered a challenge for stimulating the structure. While impact loading of structures can be a challenging task, it is relatively more feasible for wharf structures that experience impact from the mooring of vessels. [9][10]. The OMA method utilizes the SSI technique, which is renowned for its exceptional accuracy in extracting physical parameters from stabilization diagrams. SSI's ability to minimize noise modes results in remarkably clear and precise results. [4] [7] [11] [12] Among the available SSI variants, Extended Unweighted Principal Component (SSI-UPCX), Unweighted Principal Component (SSI-UPC), Principal Component (SSI-PC), Canonical Variate Analysis (SSI-CVA), and Unweighted Principal Component Merged Test Setups (SSI-UPC-Merged) offer diverse approaches to optimizing the OMA analysis.[13] Cho and Cho, employed SSI to quantify modal parameter uncertainty and utilized a clustering algorithm to effectively identify distinct modes. The efficacy of their approach was demonstrated through its application to data collected from three diverse bridge types.[11] Similarly, Malekjafarian and OBrien utilized stochastic subspace identification to extract strain-based modal parameters for a bridge structure. [14]. Peeters and Roeck, conducted a comprehensive review of stochastic system identification techniques employed to determine the modal characteristics of vibrating structures under operational conditions. Their findings revealed a notable correlation between numerous traditional input-output methods and their output-only equivalents.[15]. Pourgholi & Mahdavi, utilize stochastic subspace identification to estimate modal parameters from ambient vibration data, subsequently updating the FEM. Testing on a 2D frame and a 6-story building demonstrated successful mode extraction and close agreement between identified modes and the updated FEM, highlighting the method's effectiveness in enhancing FEM accuracy.[17].

In this article, a 9-pier wharf structure is subjected to different impact loads in the finite element software to investigate the effect of different angles of loading in revealing the frequencies and mode shapes of the structure. The SSI-UPCX method was employed to process the simulated data and identify the dominant structural modes using the ARTeMIS software. The methodology is presented in Section 2, Section 3 presents the results, showing that the impact load direction significantly influences the excitation of the structure's various modes. Certain angles are more effective in revealing the dominant frequencies and mode shapes. The conclusion is provided in Section 4.

2. Methodology

The research methodology for this study comprises several interconnected steps: Step 1: Creating a Finite Element Model of the wharf structure in ANSYS software, Step 2: assigning impact loading time history analysis, Step 3: Getting the acceleration responses in three orthogonal Directions, Step 4: Creating the ARTeMIS model and importing the accelerations, Step 5: doing SSI-UPCX analysis and obtaining the natural frequencies and mode shapes. Step 6: doing modal Analysis obtaining the natural frequencies and mode shapes and comparing the results. The following sections were conducted in these steps:

2.1 Finite Element Model

The Finite Element Model (FEM) of the 9-Pires Wharf Structure was prepared using ANSYS software, incorporating beam188, shell181, and mass21 element types. Each pile has a length of 6 meters, with spacings of 3 meters and 5 meters in the short and long directions, respectively. The pipe diameter and thickness are 155 millimeters and 10 millimeters, while the deck thickness is considered to be 50 millimeters. All material properties were assumed to be those of carbon steel, with a modulus of elasticity of 2e11 N/m², a density of 7850 kg/m³, and a Poisson's ratio of 0.3. Dead and live loads were represented by concentrated mass21 elements equal to 100 kilograms placed atop each pier at the deck level. To address symmetry and eliminate symmetric mode shapes, an additional mass of 100 kilograms was added at node number 2, the corner where the impact load is applied.

2.2 Impact Load Time History Analysis

Impact time-history analysis in ANSYS is a powerful simulation technique used to understand how structures behave when subjected to sudden, intense loads like a vessel impacting a wharf. Four time-history impact analyses are conducted to excite the structure. The impact load is applied at the wharf's corner, with the direction evaluated individually in the X, Y, and Z directions, as well as in a triple-direction impact (Figure 2 (a)). the considered loading protocol for impact load is depicted in **Figure 1**. The forced vibration happened in 0 to 0.24 seconds, after that up to 24 seconds, the wharf has free vibration. The damping coefficient in time history analysis is considered 3 percent. The acceleration responses are recorded at 9 nodes which are depicted in Figure 2 (b) and these accelerations are used in operational modal analysis.

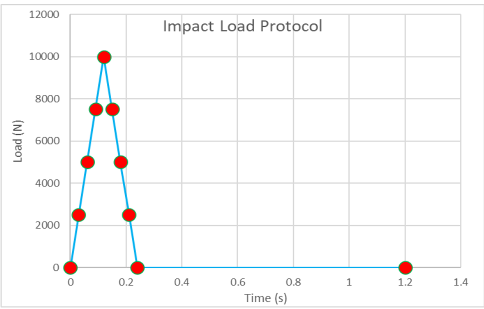
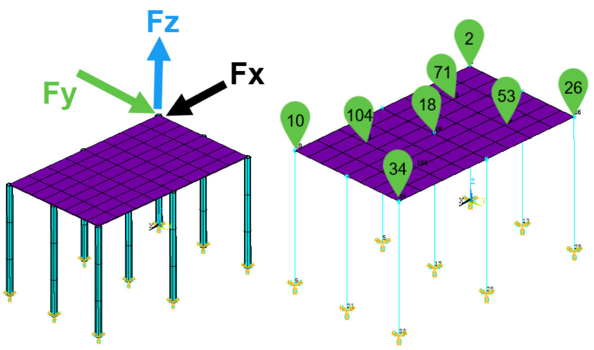


Figure 1. The Loading Protocol for Time History Impact Loading Analysis



(a) impact load (b) response locations

Figure 2. The location and direction of assigned impact loadings (a), the location and node numbers selected for extracting accelerations

3. Results and Discussion

The obtained natural frequencies and mode shapes from modal analysis and Operational Modal Analysis (OMA) are compared in this section. Due to the difficulty of detecting all modes in OMA, it was necessary to perform modal analysis to identify all modes. Therefore, the comparison between these two methods demonstrates the ability of the angle of force to reveal the number of mode shapes and natural frequencies. The results are compared here.

3.1 Modal Analysis Result

The obtained natural frequencies and modal participation ratios in each direction are illustrated in the Table 1. The summation of mass participation in two horizontal directions is more than 90 percent. The obtained mode shapes for the 7th initial modes are shown in Table 2.

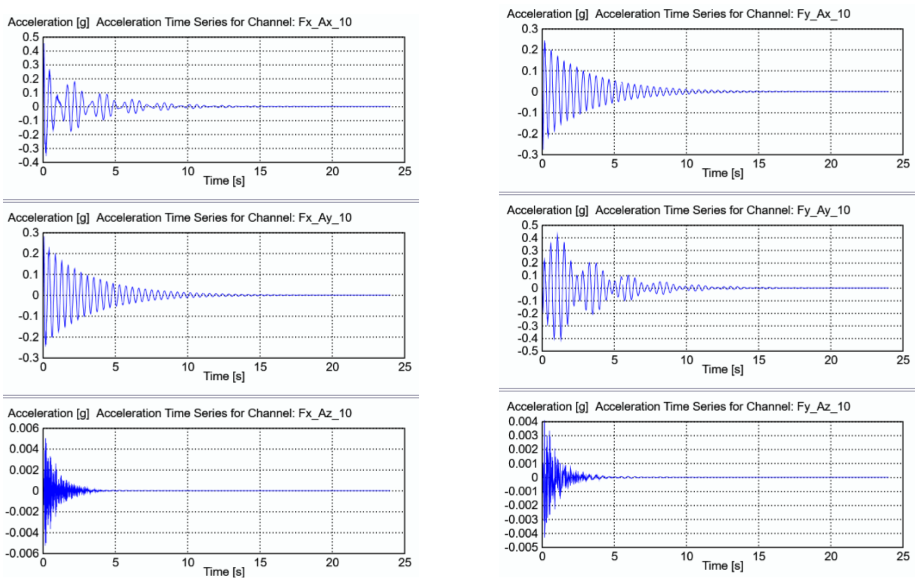
Table 1. Modal Participation Mass Ratios in Each Direction

Mode Number	Fr(Hz)	Modal Participation Mass Ratio		
		X Direction	Y Direction	Z Direction
1	1.776791	0.949529	6.42E-07	0
2	1.836699	8.09E-07	0.95018	0
3	2.285342	4.85E-05	0.000192	0
4	7.684748	6.86E-05	0	3.7E-09
5	9.325207	0	0	0.54897
6	9.664525	0	0	1.14E-08
7	10.6301	0	8.02E-05	1.82E-08
8	17.25651	5.94E-06	0	2.15E-08
9	18.00885	0	0	0.000336
10	23.17663	0	6.62E-06	1.93E-07
Summation		0.949653	0.950459	0.549306

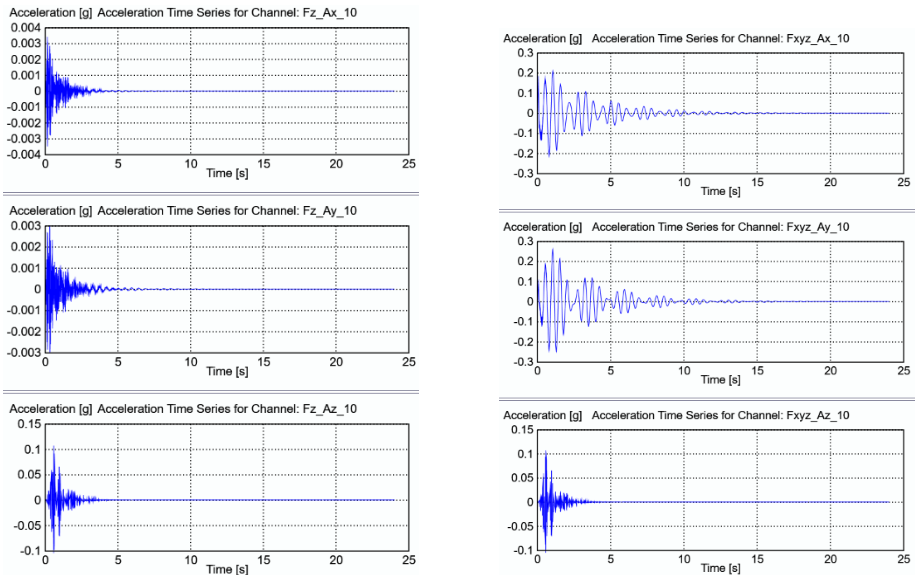
3.2 OMA Results

The OMA using SSI-UPCX is a powerful technique employed in system identification and modal analysis to extract essential modal parameters, such as natural frequencies, damping ratios, and mode shapes, from measured data. [8] [12] It is particularly effective in dealing with stochastic, noisy data, making it a valuable tool for a wide range of applications, including structural health monitoring, mechanical systems analysis, and control systems design. SSI-UPCX works by creating a Hankel matrix from collected data. This matrix represents how the system moves. Using SVD, we break down this matrix to understand the system's internal workings. This understanding is expressed in a mathematical model called a state space model. This model shows how the system behaves based on its internal state, what goes into it, and what comes out of it. By analyzing the eigenvalues and eigenvectors of the system matrix, the modal parameters can be extracted.[16] [17]. In this article, this method was implemented using the ARTeMIS software on the response accelerations obtained from the time history analysis in the previous step.

The following figure (Figure 2 (b)) shows the response acceleration at node number 10. The accelerations are damped over time due to the 3% damping applied in the time history analysis. While this study does not consider the effect of noise, it is important to note that noise can significantly impact real-world scenarios. The obtained acceleration results are depicted in Figure 3 and Figure 4. These figures show that applying an impact load in the x-direction can reveal the first, third, and fourth natural frequencies and mode shapes. The natural frequency values obtained from both methods are identical. An impact load in the y-direction reveals only the second and third natural frequencies and mode shapes. Additionally, there is a 5% deviation in the natural frequency value for mode number 4 between the modal result (Fr_modal=1.8 Hz) and the OMA result (Ff_OMA=1.9 Hz). Impact loads applied in the z-direction activate mode shapes related to the deck section of the wharf. Modes 4, 5, 6, and 7 were detected using OMA. The discrepancies between the natural frequencies of modal analysis and OMA for modes 4 to 7 are 4%, 5%, 5%, and 5%, respectively. Finally, applying a load simultaneously in all three directions (x, y, and z) can activate the maximum number of mode shapes in the wharf structure. In this case, modes 2, 3, 4, and 7 were revealed with natural frequency deviations of 5%, 0%, 4%, and 5%, respectively.



(a) Ax, Ay, Az Due to Fx (b) Ax, Ay, Az Due to Fy



(c) Ax, Ay, Az Due to Fz (d) Ax, Ay, Az Due to Fxyz

Figure 3. The Acceleration Responses (Ax, Ay, and Az) in Node Number 10, Wharf FEM Due to Impact Load in X, Y, Z Direction (a, b, c) Respectively and Simultaneously in X, Y, and Z directions (d)

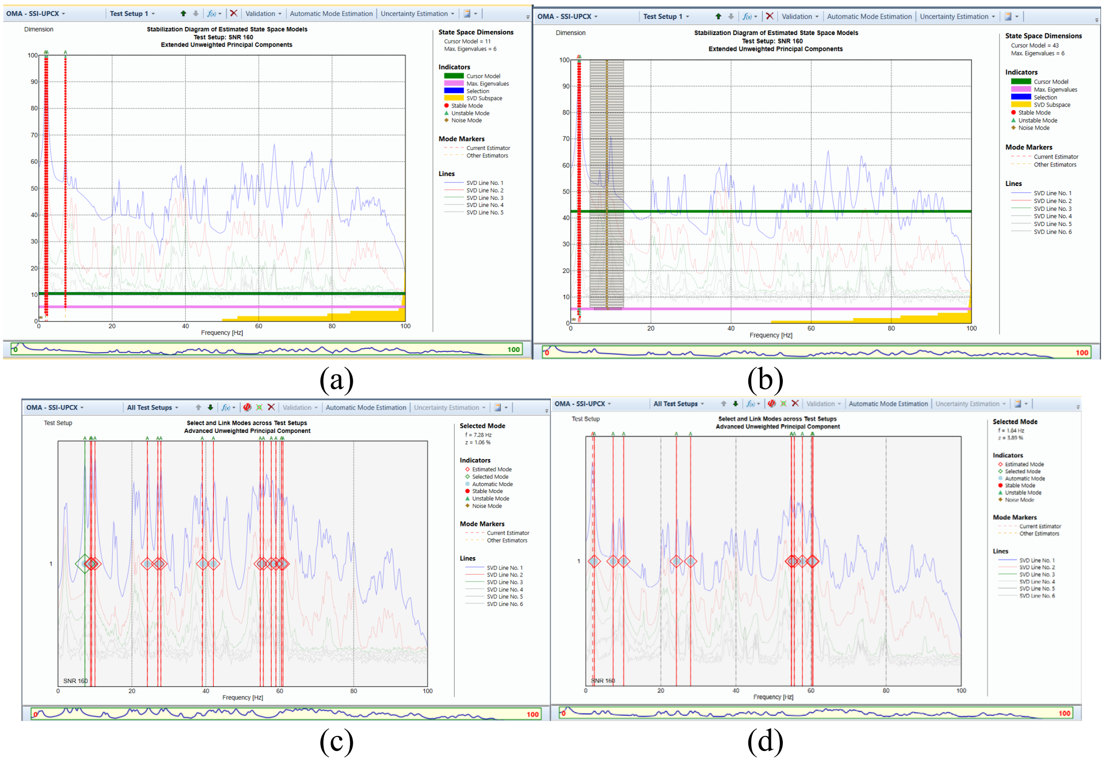
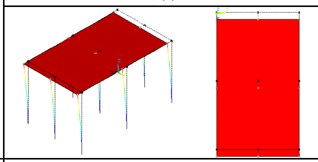
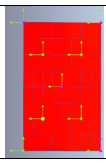
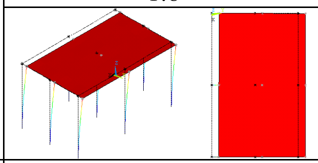
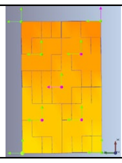
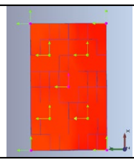
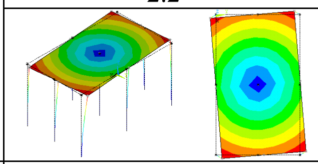
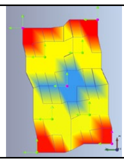
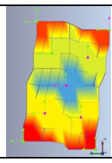
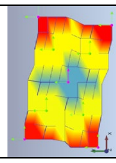
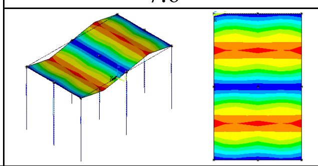
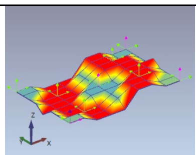
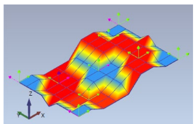
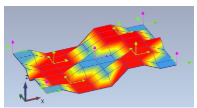
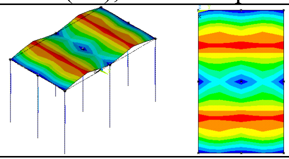
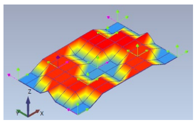
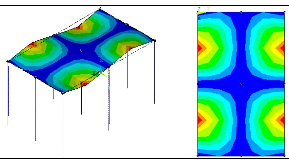
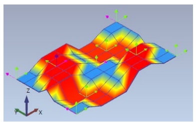
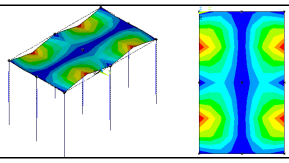
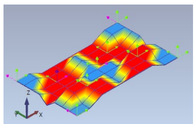
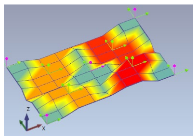


Figure 4. Detected Frequency of Vibration of the Wharf FEM Response Due to Impact Load in X, Y, Z Direction (a, b, c) Respectively and Simultaneously in X, Y, and Z directions (d) in ARTeMIS Software

Table 2. The Comparison Between Modal Analysis Result and OMA Results for the Wharf Structure, due to Single and Triple Impacts THAAR in ARTeMIS

Mode	Modal Analysis Fr (Hz), Mode Shape	Fx	Fy	Fz	Fx, Fy and Fz
1	1.7	1.7	-	-	-
			Not Detected	Not Detected	Not Detected
2	1.8	-	1.9	-	1.9
		Not Detected		Not Detected	
3	2.2	2.2	2.2	-	2.2
				Not Detected	
4	7.6	7.6	-	7.3	7.3
			Not Detected		
5	9.3	-	-	8.8	-

Mode	Modal Analysis Fr (Hz), Mode Shape	Fx	Fy	Fz	Fx, Fy and Fz
		Not Detected	Not Detected		Not Detected
6	9.6	-	-	9.1	-
		Not Detected	Not Detected		Not Detected
7	10.6	-	-	10.0	10.1
		Not Detected	Not Detected		

4. Conclusion

The results demonstrate that the location and angle of the impact load significantly influence the ability to identify the modal characteristics of a wharf structure. By applying the load with three components (x, y, and z), it was possible to reveal a more comprehensive set of modes. This is because all three components excite the structure in all translational directions, leading to the identification of horizontal translation modes, twist modes, and deck modes. These findings highlight the importance of carefully considering the load application point and direction when conducting modal testing on wharf structures.

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