

# LABORATORY-SCALE VALIDATION OF MODAL EXPANSION FOR VIRTUAL SENSING OF OFFSHORE TUBULAR STRUCTURES

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## Keywords

Offshore structures  
Tubular structures  
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## Abstract

Digital twin is an emerging approach for structural integrity management and has gained significant attention from both academia and industry of offshore engineering in recent years. While it is a multi-faceted concept, virtual sensing is an indispensable functionality of digital twin. A prevalent technique for implementing virtual sensing is the modal expansion approach, where the responses of non-instrumented areas (i.e., without physical sensors) are predicted by inverse estimation of the structural mode shape amplitude through physical sensing in instrumented areas. However, this method lacks extensive validation, particularly through experimental data obtained in controlled environments. To address this gap, this paper uses wave tank test data from a tubular structure model to validate the modal expansion technique for stress/strain sensing in non-instrumented areas and investigate the associated uncertainties.

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## 1 INTRODUCTION

The blue economy including the harvesting of offshore energy stands as the backbone of the modern world [1]. However, this industry is rapidly evolving in response to changing societal and industrial demands. Offshore renewable energy sources such as wind, wave and tidal power are replacing traditional offshore oil and gas [2]. This shift in design and operational requirements suggests that conventional calendar-based preventive maintenance strategies may no longer be suitable due to insufficient operational experience. Therefore, it is necessary to adopt a predictive maintenance strategy for the new-generation blue economy infrastructures (e.g., support structures for offshore wind and tidal) to maintain structural integrity and ensure safety [3]. Digital twin technology emerges as a promising data-centric tool to enable predictive maintenance. While it is a multifaceted concept, virtual sensing is an indispensable functionality of digital twin [4]. A prevalent technique for implementing virtual sensing is the modal expansion approach, where the responses of non-instrumented areas (i.e., without physical sensors) are predicted by inverse estimation of the structural mode shape amplitude through physical sensing

in instrumented areas [5]. However, this method lacks extensive validation, particularly through experimental data obtained in controlled environments. To address this gap, this paper utilizes laboratory-scale model data developed from wave tank testing of a tubular structure, representative of offshore engineering applications. The objectives of this work are summarized as follows:

- Develop an experimental database in a controlled environment representative of offshore engineering application.
- Validate the modal expansion approach for virtual sensing using the developed experimental database.
- Investigate the uncertainty of physical sensing data.

In the remainder of this paper, an introduction to the fundamentals of the modal expansion approach is provided in Section 2, followed by the details of wave tank testing in Section 3. The analysis results are discussed in Section 4. Finally, conclusions and avenues for future research are presented in Section 5.

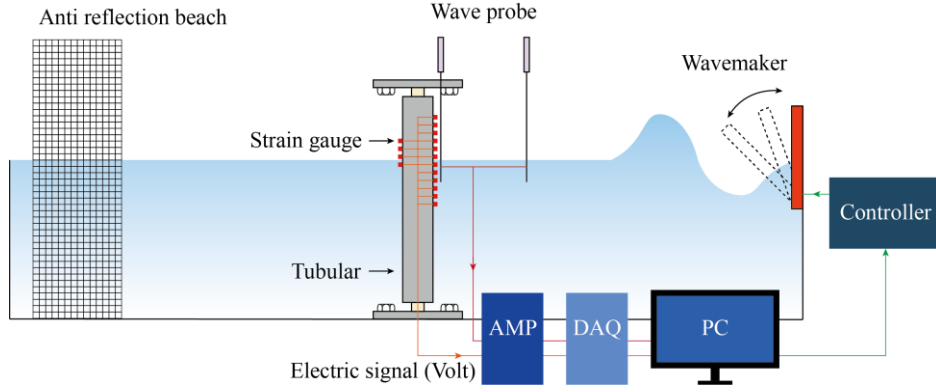


Figure 1: Schematics of test bed

## 2 FUNDAMENTALS OF MODAL EXPANSION

The modal expansion technique assumes that the dynamics of a structure can be decomposed into an infinite number of mode shapes with different modal amplitudes:

$$\mathbf{u}(x, t) = \begin{Bmatrix} \mathbf{u}_p^{i \times 1}(x, t) \\ \mathbf{u}_v^{j \times 1}(x, t) \end{Bmatrix} = \begin{Bmatrix} \Phi_p^{i \times k}(x) \\ \Phi_v^{j \times k}(x) \end{Bmatrix} \mathbf{Q}_p^{k \times 1}(t) \quad (1)$$

where  $\Phi_p^{i \times k}(x) \in \mathbb{R}^{i \times k}$  is the mode shape matrix of the physically sensing responses,  $\Phi_v^{j \times k}(x) \in \mathbb{R}^{j \times k}$  is the mode shape matrix of the virtually sensing responses and  $\mathbf{Q}_p^{k \times 1}(t)$  is the time-varying modal amplitude vector. The aim of modal decomposition and expansion is to convert the physically sensing response into responses at non-instrumented area, which constitutes virtual sensing. To do so, the modal amplitude  $\mathbf{Q}_p^{k \times 1}(t)$  needs to be estimated:

$$\mathbf{Q}(t) = [\Phi_p^T(x) \Phi_p(x)]^{-1} \Phi_p(x) \mathbf{u}_p(t) \quad (2)$$

The virtual sensing for non-instrumented area is then implemented from the following solution:

$$\mathbf{u}_v(t) = \Phi_v(x) \mathbf{Q}(t) \quad (3)$$

## 3 WAVE TANK TESTING

The proposed experiment is performed in the 3D compact wave tank located in the Kelvin Hydrodynamics Laboratory of University of Strathclyde. The tank has a dimension of  $9m \times 3.15m \times 1m$  (Length  $\times$  Width  $\times$  Depth). An eight-paddle force-controlled flap-type wavemaker is installed at one end of the tank, capable of generating both regular and irregular waves up to a maximum wave height of 0.3 m. At the other end of the tank, a wedge type porous wave beach is equipped to absorb incident, radiated and diffracted waves, to minimize wave reflection.

### 3.1 Test bed design

The test model is a tubular structure made of aluminium with 1303mm in length, 192mm in diameter

and 2mm in thickness (Figure 1). Two load cells are installed at each end of the tubular and the summation of the measurements from the two load cells provides the total global force acting on the monopile. At the wavemaker facing side of the tubular, 12 strain gauges and 8 pressure transducers are installed to measure the strain and pressure induced by incident waves. Four additional strain gauges are installed at the beach facing side of the tubular. A resistance type wave probe is deployed to measure the incoming wave elevation. All the sensors are powered and conditioned by their own amplifier and the measured signals are synchronized by feeding measurements to a central Data Acquisition System (DAS).

### 3.2 Test matrix

Four different wave conditions are tested including two regular wave conditions and two irregular wave condition (Table 1). Note: the wave height and wave frequency reported of No. 3 and 4 in Table 1 refer to significant value and peak value respectively. Each regular wave tests are repeated five times for assessing uncertainty in the physical sensing.

Table 1: Test matrix

No.	Wave height [m]	Wave frequency [Hz]
1	0.24	0.80
2	0.20	0.60
3	0.10	0.80
4	0.12	0.67

## 4 RESULTS

For tests in regular waves, a Fast Fourier Transform (FFT) is applied to the signal to extract the dominant amplitude for subsequent comparison. For tests in irregular waves, four performance metrics are utilised to assess the performance of modal expansion method, namely time response assurance criterion (TRAC), coefficient of determination (CoD), equivalent amplitude range's bias (b) and coefficient of variation (CoV). The results are

summarized in Figures 2 and 3. These figures include a representative comparison between the time series of virtual and physical sensing, response amplitude under regular conditions and its associated uncertainty, as well as TRAC and CoD for irregular wave cases and their equivalent amplitude range comparisons.

It can be observed that the virtual sensing algorithm is reasonably effective in replicating the overall time series. However, there is an inherent uncertainty associated with both the physical measurements (up to nearly 40% of CoV as indicated by the repetition tests) and the virtual predictions (up to 30% of CoV). Generally, higher uncertainty is observed in the regular wave cases compared to the irregular wave cases.

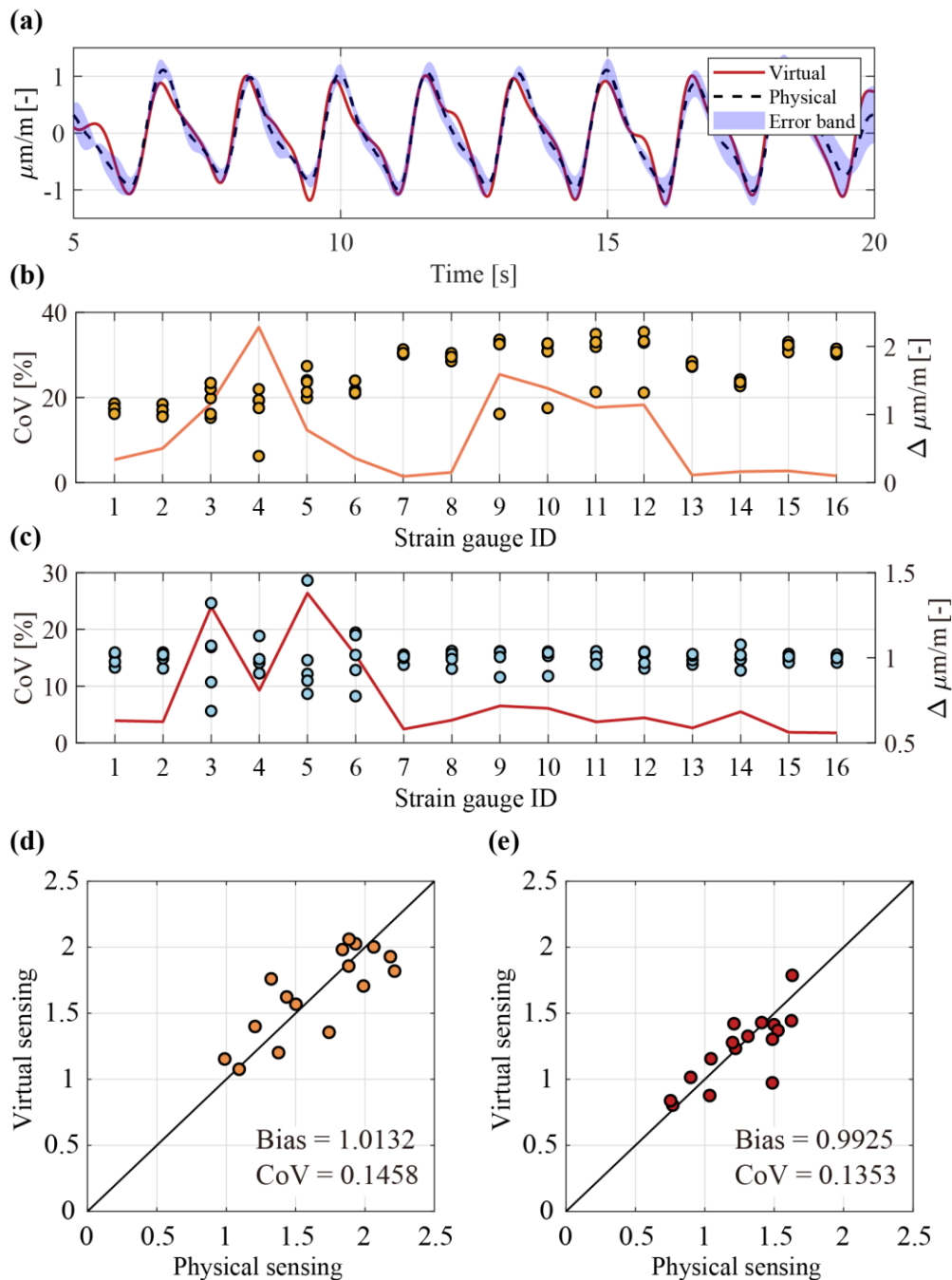


Figure 2: (a) Representative comparison between virtual and physical sensing (SG1 – ID2), error band = 2×standard deviation; (b) Response amplitude – ID1; (c) Response amplitude – ID2; (d) Response amplitude comparison between virtual and physical sensing – ID1; (e) Response amplitude comparison between virtual and physical sensing – ID2

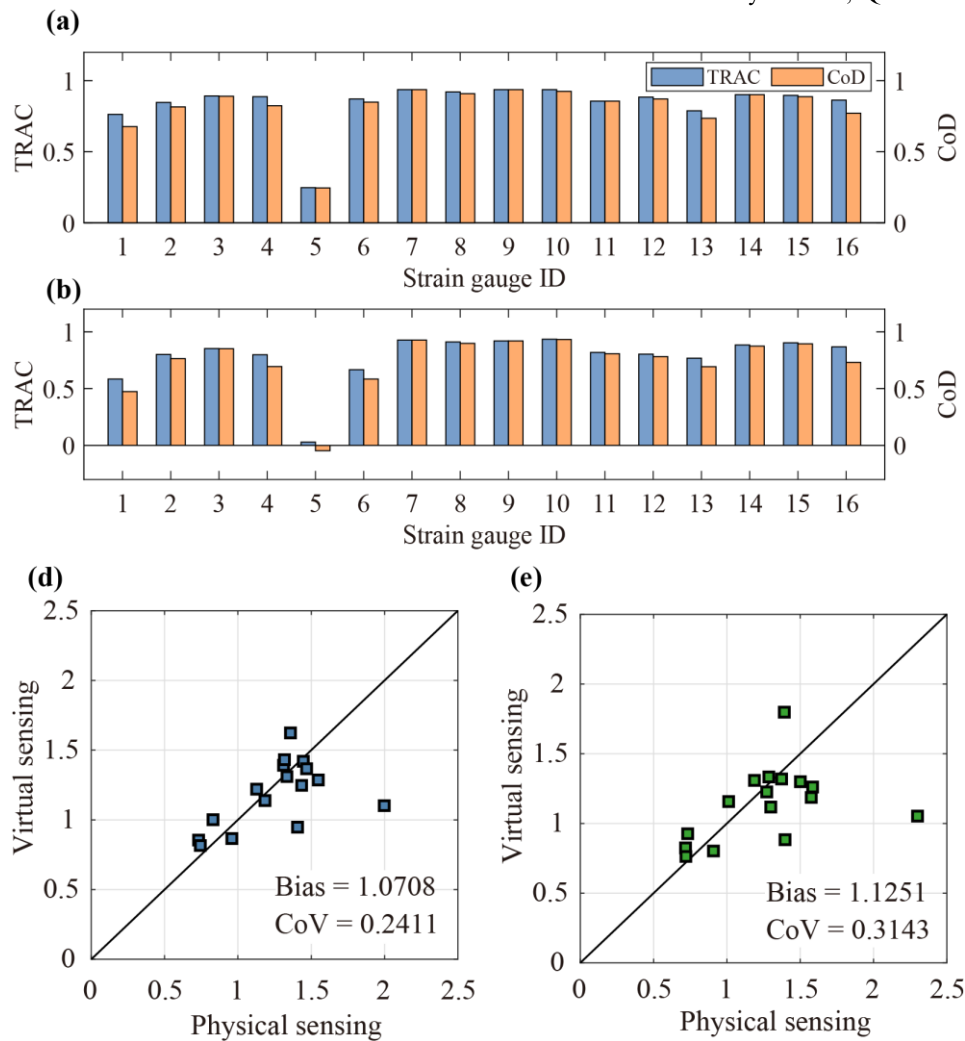


Figure 3: (a) TRAC and CoD – ID3; (b) TRAC and CoD – ID4; (c) Equivalent amplitude range comparison between virtual and physical sensing – ID3; (d) Equivalent amplitude range comparison between virtual and physical sensing – ID4

## 5 CONCLUSIONS

A laboratory-scale model test on an offshore tubular structure was conducted to validate the modal expansion technique for stress/strain sensing in non-instrumented areas. The technique proved reasonably effective, but significant uncertainties were noted in both physical sensing and virtual prediction. Further work is needed to better quantify these uncertainties and integrate them into maintenance decision-making.

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