JOURNAL OF ACOUSTICS AND VIBRATION RESEARCH (JAVR)
ISSN: XXXX-XXXX
VOL. 2, ISSUE 1, 62 – 71

Predicting Frequency Response Function of a Bolted Flanged Pipe Assembly using Frequency Based Substructuring

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ABSTRACT

This study explores the Frequency-Based Substructuring (FBS) analysis of a Bolted Flanged Pipe Assembly (BFPA) to investigate its dynamic behaviour. The motivation for employing the FBS method lies in its potential to integrate different sources of results of substructures for dynamic behaviour evaluation. In this study, the FBS method is utilized to couple the finite element (FE) model of a Flanged Pipe (FP) substructure with the FE model of Bent Elbow Pipe (BEP) substructure for investigating the coupled FRF of the assembled system, which is the BFPA. Bolted joints within the BFJA are represented with rigid elements. The FBS method is used to compute the coupled Frequency Response Functions (FRFs) of the BFPA. The coupled FRF is compared with the FRF obtained from experimental modal analysis (EMA). This comparison evaluates the accuracy of the method and shows possible way to improvement it. The importance of this study may be seen in many applications such as aerospace, automotive and civil engineering.

Article History

Received: 09/05/2024

Revised: 15/10/2024

Accepted: 25/10/2024

Published: 15/12/2024

Keywords: Frequency based substructuring; coupled frequency response function; experimental modal analysis; bolted joints.

INTRODUCTION

Vibrations in piping systems are a common phenomenon with significant effects in various industries such as automotive, aerospace, construction, nuclear power plants and municipal water supply. This phenomenon is particularly common when the excitation frequency closely matches one of the natural frequencies of the piping systems. Consequently, the economic and accurate determination of the natural frequencies of piping systems and their response to excitation frequencies is a key concern prior to their use. The use of Dynamic Substructuring (DS) methods [1-4] offers a viable approach to address this particular phenomenon by dividing large, complicated structures into subsystems that are analysed individually prior to assembly.

FBS is the most flexible of the DS techniques. It can flexibly couple the experimentally derived and the analytically derived FRFs [5-11]. Two scenarios show the main advantage of the FBS method. First, for complex structures, it is challenging to create a reliable FE model for certain substructures. This can be exacerbated if there are no specific properties or geometries, leading to lengthy and gruelling development. Secondly, it is noticeable that in the design phase with the FBS method, only the FE FRFs of the modified substructure are used, with the exception of a single substructure, while the assembled structure needs to be modified. These can then be used together with the experimental FRFs of the assembled structure to evaluate its performance after the additions. Therefore, the FBS approach enables the direct combination and efficient processing of analytically derived FRFs from the FE model with experimentally derived FRFs from the modal analysis.

With the FBS approach, complex vibration problems can be solved quickly and cost-effectively, especially if some system components are difficult to model analytically or only need to be analysed. For example, in the field of machining, the FBS approach has been used by researchers to predict the dynamic behaviour of a machining tool without a working machine [12-14] by coupling the measured FRF of a complex working machine with some substructures. In addition, FBS has been successfully used to predict the dynamic behaviour of working machines in isolation systems with an acceptable level of effort [15, 16]. [5–9]: It has also been used to analyse the dynamic behaviour of assembled structures with bolted joints. These cases illustrate the efficiency and cost-effectiveness of the FBS method in predicting the dynamic behaviour of complex structures. However, the coupling method in this case, e.g. for piping systems, is not clear and well defined and is an area that still needs to be thoroughly investigated and clearly clarified.

In this study, the capability of the FBS-based approach to predict the dynamic behaviour of a Bolted Flange Pipe Assembly (BFPA) is investigated. The test BFPA consists of two substructures, a Flanged Pipe (FP) and a Flanged Elbow Pipe (FEP), connected with four bolted joints. The FBS method is then used to couple the FRFs of the FP and FEP substructures to obtain the coupled FRFs of the BFPA. The accuracy of the FBS is evaluated by comparing the FRFs of the BFPA with the FRFs resulting from the EMA of the test BPFA.

METHODOLOGY

This section describes in detail the methods used to achieve the study objective. The FE models of the BPFA and its substructures FP and BEP as well as their FRFs are created and predicted using MSC software. The FRFs of the test BPFA are measured using LMS Test Lab.

Finite Element Modelling of the BFPA

The approach adopted in this study to construct the FE models of the FP, BEP and BFPA, as shown in Figure. 1, is consistent with the work of previous researchers [8-10]. For the

FE model of the BFPA, 122372 CTETRA elements with 32439 nodes were used. 520 RBE2 elements were used to represent the bolted joints between the two flanges and 426 elements were used to represent the bolted joints in the soil. The detailed material properties for the FE model can be found in Table 1. Figure 2 shows the schematic representation and detailed dimensions of the BFPA.

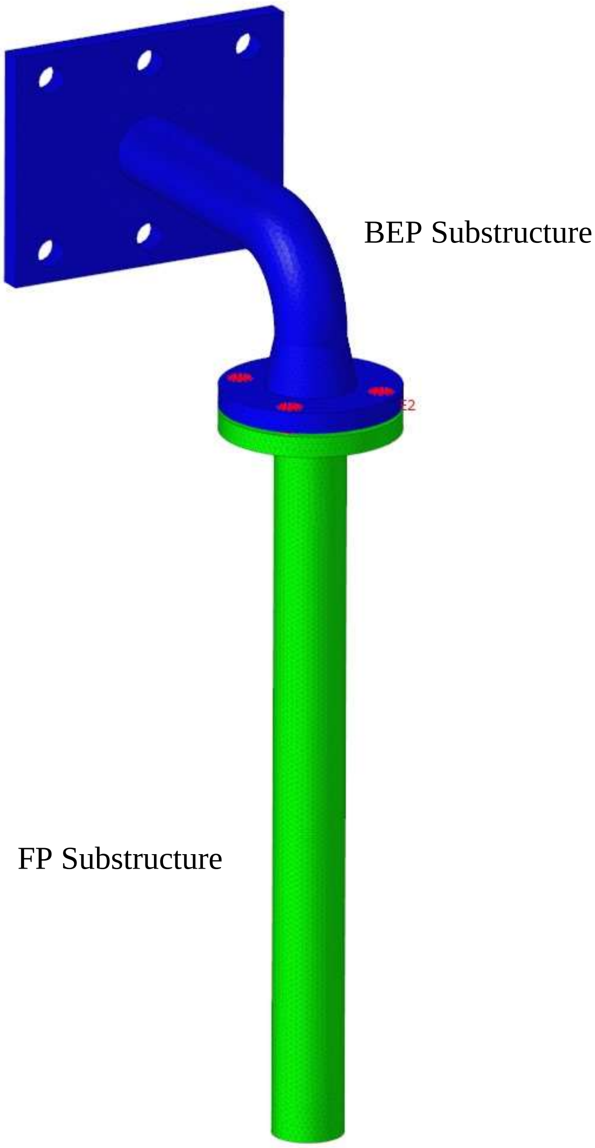

Figure 1. FE model of the BFPA with the two substructures (FP and BEP).

Table 1. Material Properties of the BFPA.

Property	Nominal Value	Unit
Young's modulus	210	GPa
Poisson's ratio	0.3	Unit less
Mass density	7.89×10^{-6}	kg/mm^3

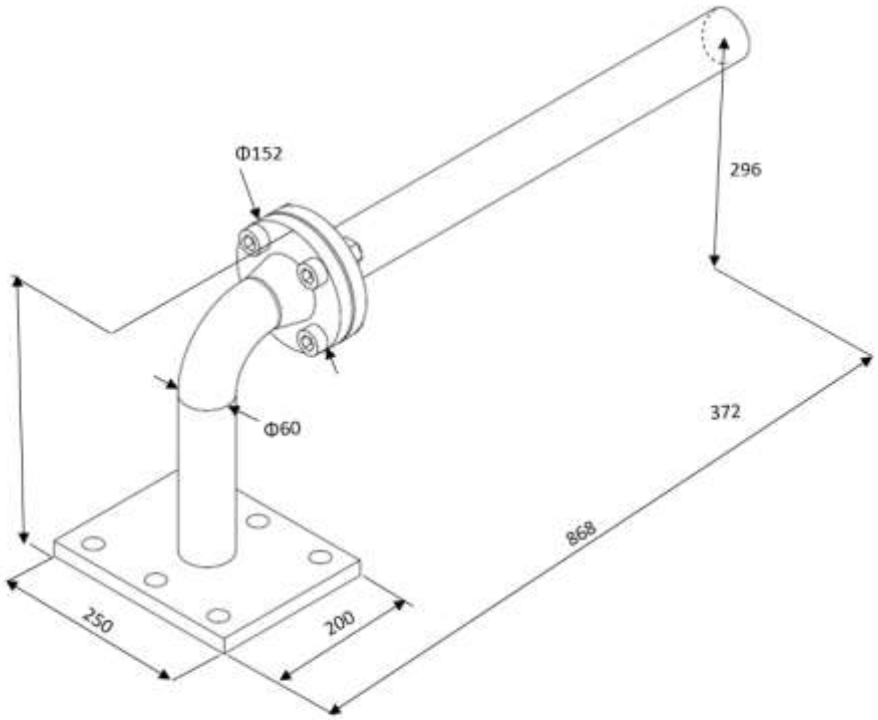

Figure 2. Detailed dimensions of the BFPA

Frequency Based Substructuring of the BFPA

The FBS method is an effective approach for incorporating FRFs derived from different sources, either numerically or experimentally. In this way, it is possible to combine FRFs for analytical and analytical, experimental and experimental, or experimental and analytical techniques. The references [5-9, 17] are a good source for further elaborations and mathematical formulations.

In this study, a coupling approach between the two FE-FRFs were implemented. The FRFs of the substructures were calculated separately and coupled with the FBS method to obtain BFPA-coupled FRFs. The FRFs of the BFPA were then calculated using the coupling of the FRFs of the substructures under free-free boundary conditions. The BFPA FE model was constructed using rigid coupling elements, which are commonly used for coupling [5-7, 10, 11] the two substructures. The application of the FBS method to the BFJA is shown in Figure 3.

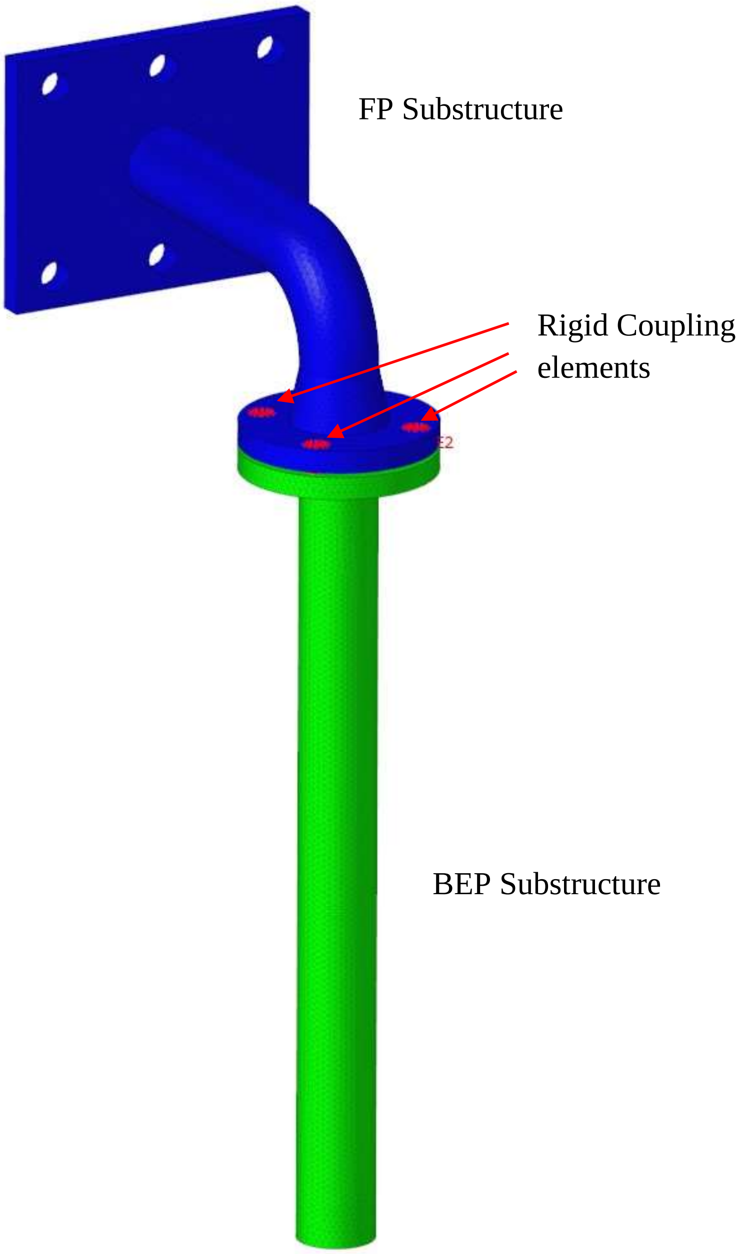

Figure 3. Coupling the FP and BEP substructures using the FBS method

Experimental Modal Analysis of the Bolted Flange Joint Assembly (BFPA)

Experimental studies often help to understand the dynamic behaviour of engineering systems [6, 15]. In this study, the EMA was performed on the BFPA to determine its FRF. Figure 4 shows a schematic description of the EMA with impact testing, accelerometers and the LMS system. In order to achieve free-free boundary conditions in accordance with the FE model and in agreement with other research teams [18-20], the test BFPA was suspended from a mounted test rig using rubber bands.

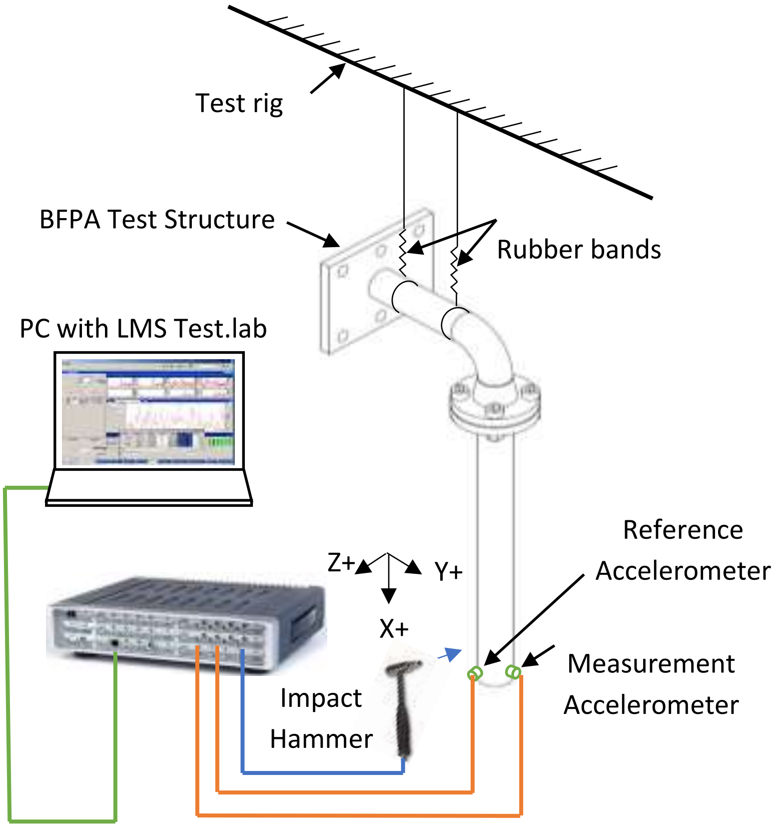

Figure 4. EMA setup for the test BFPA.

RESULTS AND DISCUSSION

In this study, the FRFs of the BFPA consisting of the FP and BEP substructures were calculated using the FBS method. The FRFs measured with the EMA were used as a benchmark comparison to the coupled FRFs.

The two FRFs of the substructures were combined using the FBS method to obtain a coupled FRF of the substructures. The FRFs calculated with the FBS method are shown in Figure 5. Six modes in the frequency range of 900 Hz were determined using the FBS method. This result shows that it is possible to use the FBS method in this study with a satisfactory level of accuracy.

In common practice adopted by researchers, they tend to give more credence to experimental results and consider them the gold standard against their analytical counterparts. In this context, the FRF of the BFPA should be available to evaluate the performance of the FBS method. Figure. 6 shows the FRFs measured with the EMA for seven modes in the frequency spectrum of 900 Hz.

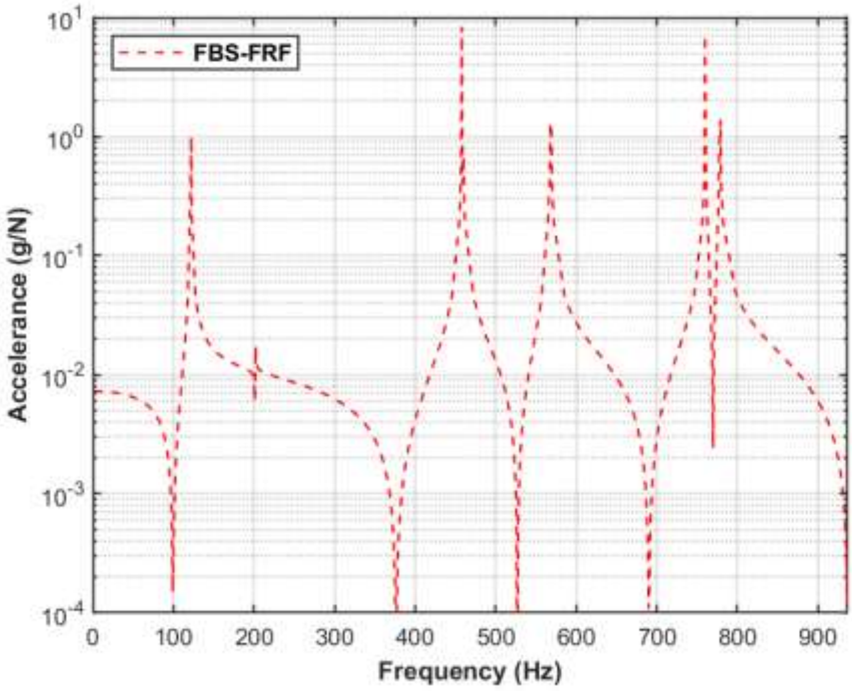

Figure 5. FBS-FRF of the BFPA

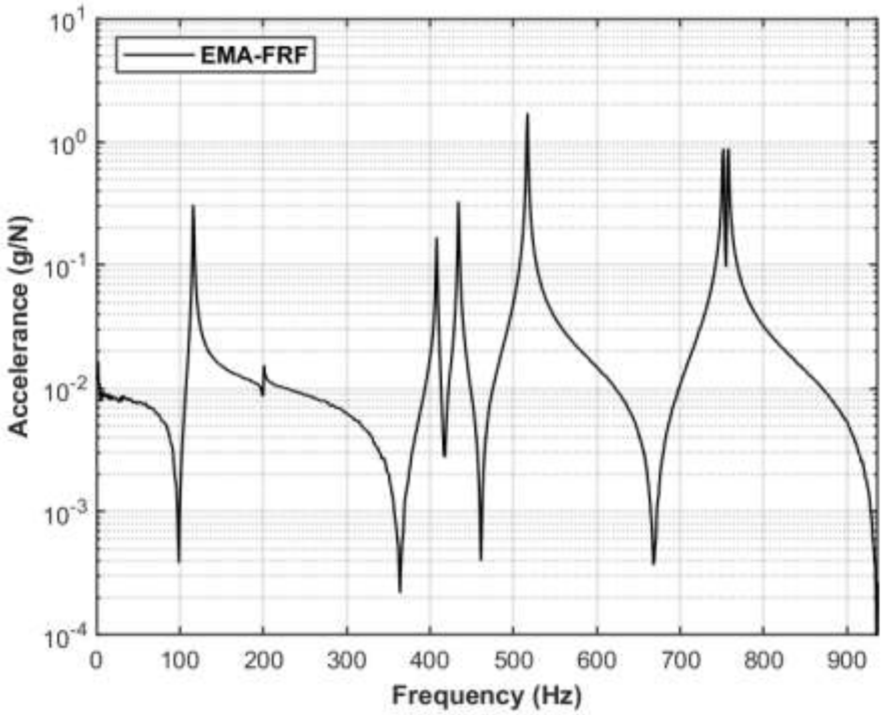

Figure 6. EMA-FRF of the BFPA

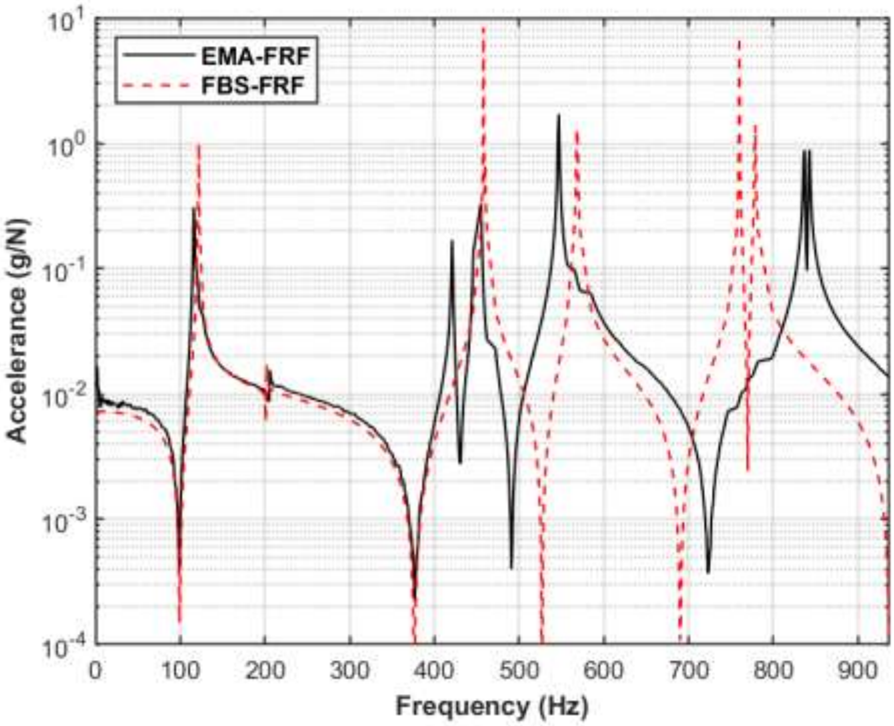

Figure 7. Direct comparison between the FBS-FRF and EMA-FRF of the BFPA

Figure. 7 shows a direct comparison of the FRFs obtained with the EMA and those calculated with the FBS method. The comparison shows excellent agreement between the 1st and 2nd modes obtained with the EMA and the FBS method. However, there are clear deviations for the other modes. In particular, the comparison shows that the FBS method overestimates the 3rd, 4th, 5th and 6th modes and underestimates the 7th mode. These discrepancies and overestimations could be due to incorrect assumptions regarding the material properties used in the FE model of the BFPA. The deviations may be improved if model updating is adopted but in this study the application of model updating to improve the FE models is not addressed and is considered as a future research project.

CONCLUSIONS

An analysis of the dynamic behaviour of a bolted flange joint (BFJA) using the FBS method and the EMA has been presented and discussed. The study shows that the FBS method accurately reproduces the 1st and 2nd modes of the EMA FRFs. However, the accuracy of the FBS method in predicting the other modes of the BFPA within the frequency range of interest was not satisfactory. These discrepancies are probably due to the invalid assumptions of the material properties used in the FE model and can be addressed by updating the model.

The FBS method is a valuable tool for researchers and engineers to study structural dynamics efficiently and economically, especially in aerospace, automotive and civil engineering. However, as shown in this study, the accuracy of the FBS method strongly depends on the quality and accuracy of the FE models. It is recommended model updating the FBS method.

ACKNOWLEDGEMENTS

This study is supported by the RMC, Universiti Teknologi MARA (UiTM) through the Strategic Research Partnership (SRP): RMC 5/3/SRP (086/2022). The authors would like to thank the member of SDAV UiTM Shah Alam for their technical support.

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