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Operational Modal Analysis of a Mobile Substation During Transport

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Abstract

Mobile substations can be defined as completely equipped electrical substations. There is a lack of existing scientific basis in the mechanical design of the structural components of the mobile substation. In concrete there are no capabilities to determine the dynamic behavior during transport and service conditions. Improper dimensioning of the structures results in an important degree of mechanical failures during transport. The dynamic response of structures on a mobile substation to transport-motions depends on their strength of construction, ductility, and dynamic properties. Lightly damped structures that have one or more natural modes of oscillation within the frequency band of transport excitations can experience considerable amplification of both the forces and deflections. Thus, items of mobile substation equipment whose natural frequencies lie in the normal frequency range of transport motion are particularly vulnerable to damage and fatigue. Therefore we are interested in analyzing the natural frequencies, damping ratios (modal parameters) and level of accelerations of those components. The analysis of the operational test data acquired during road testing requires more advanced output-only system identification methods. The modal identification methods recently developed at the Vrije Universiteit Brussel, allow for estimating the modal parameters from operational road testing data. The experimental results are compared with the the results of a finite element model.

INTRODUCTION

This paper is part of a project were we will analyze in depth the mechanical design of mobile substations taking in account the static as well as the dynamic loads occurring during transport. The most important goal is to develop the adequate design rules and design tools as well as recommendations in order to guarantee the mechanical integrity of mobile substations during transport and service conditions. The satisfactory operation of a mobile substation during and immediately after transport depends on the survival, without malfunction, of many diverse types of equipment. Not only must individual equipment be properly engineered, but their anchorage, services, and interconnections must be well designed. The inputs to the mobile substation are principally from road roughness and are generally not characterized by periodic inputs expect from pavement joints on concrete highways. As such, the truck receives random and impulsive inputs and tends to respond at the natural frequencies of various structures of the mobile substation. The dynamic response of a structure reaches its maximum at resonance, where the amplitude is inversely proportional to the damping ratio. So the damping is directly related to the maximum dynamic response. A high damping ratio means that the amount of steel needed to meet the specification of limited response can be reduced. In cases where the weight of the mobile substation is limiting the design, the weight reduction becomes fundamental. In this case dynamic problems can be reduced by introducing damping in either a passive or active way.

Figure 1: Mobile substation

In the design process of the critical components on a mobile substation, the damping ratios of the lower modes are important factors. Only these modes are situated in the transport spectrum and thus in fact only the few lower modes of vibration are important for determining the structure's response to transport loads. For such analysis both experimental tests and numerical studies of the dynamic behavior of the main substation components were performed. Road tests were performed on different substations. The aim is to get some information about the dynamic properties of some of the critical components mounted on the substation. Especially we are interested in analyzing the natural frequencies, damping (modal parameters) and level of accelerations of those components. The analysis of the operational test data acquired during road testing requires more advanced output-only system identification methods.

In this paper the emphasis is not to develop new estimators, but to use a state-of-the-art estimator in order to derive more reliable experimental dynamic models of mobile substations than possible with classical deterministic modal estimators and compare it with a Finite Element Model.

Operational Modal Analysis

More recently, system identification techniques were developed to identify the modal model from the structure under its operational conditions from vibration responses only [1] [3].These techniques, referred to as operational modal analysis (OMA) or output-only modal analysis, take advantage of the ambient excitation due to e.g. traffic and wind. During an experimental modal analysis (EMA), the structure is often removed from its operating environment and tested in laboratory conditions. The laboratory experimental situation can differ significantly from the real-life operating conditions. An important advantage of OMA is that the structure can remain in its normal operating condition. This allows the identification of more realistic modal models for in-operation structures.

In this paper output-only vibration tests were conducted on a mobile substation during road-tests in order to study the applicability of output-only frequency-domain identification techniques on mobile substation dynamics. These algorithms require the spectral densities of the outputs as primary data. It has beem shown that, under the assumption of the operational forces being white noise, output spectra can be modeled in a very similar way as Frequency Response Functions [3]. These output spectra form the basis for frequency-domain output-only modal analysis.

Estimation of spectral densities

In order to use output spectra for the identification of modal parameters from output-only data, accurate estimates of the spectral density functions are to be obtained from finite sequences of measured time samples. During this project the estimation of the spectral densities was done by using Welch's method. The input signals were divided into 8 segments with 50% overlap. A Hanning window was applied to each segment to reduce the effect of leakage. An FFT is applied to the windowed data. The (modified) periodogram of each windowed segment is computed. The set of modified periodograms is averaged to form the spectrum estimate. The resulting spectrum estimate is scaled to compute the power spectral density. A higher amount of data samples in each segment reduces the effect of leakage. Moreover, a higher spectral resolution will be obtained in the frequency-domain. On the other hand, increasing the amount of samples in each segment will decrease the number of averages what leads to a higher uncertainty on the estimate. In practice, a compromise will have to be made between the mentioned contradicting aspects.

Frequency domain estimator

In this paper we will test the the applicability of the polyreference Least-Squares-Complex-Frequency-domain estimator (p-LSCF)[2] adapted for output-only data. Commercially also known as PolyMAX, this algorithm and its application was presented as a new future standard for modal testing [4] because of its speed and the clear stabilization charts produced by the algorithm. This estimator can be viewed as a frequency-domain implementation of the well-known Least-Squares Complex Exponential (LSCE) estimator. The p-LSCF is realized by means of a so-called Right Matrix Fraction Description. With this approach, the modal participation factor can be estimated directly together with the poles and can be used in constructing the stabilization charts. The main benefit of the polyreference method are the facts that the SVD step to decompose the residues can be avoided and that closely spaced poles can be seperated. Polymax was introduced and validated using industrial data sets in [2] [4] . The present paper gives an application where Polymax can be applied to operational data obtained during roadtests when appropriate pre-processing is applied.

Mobile substation

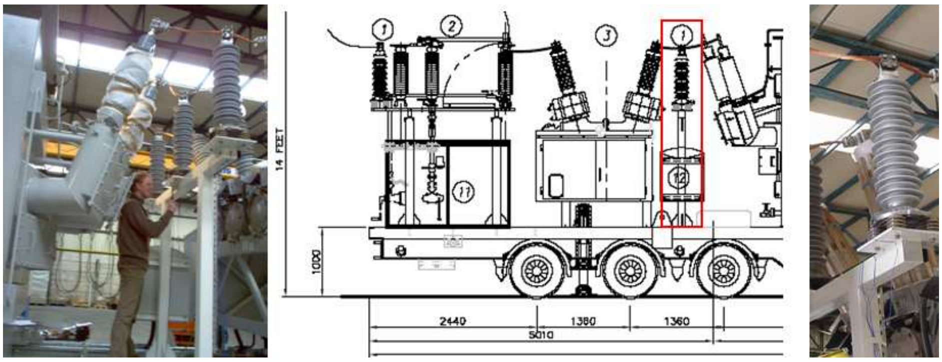


Figure 2: Mobile substation: investigated component (marked in red)

In this contribution a support structure with three insulators mounted on a mobile substation was investigated (Figure 2). The vibration response of the structure was measured simultaneously by means of 5 accelerometers placed at the bottom, middle and tip. At the truck level (bottom, fixation point between support structure and truck-base) the accelerations in the Z direction were measured in order to have an idea about the spectrum and level of accelerations that may occur during transport. At the interconnection point between the right insulator and the support structure the accelerations both in the X and Y direction were measured and also at the tip of the right insulator the accelerations in the X and Y direction were obtained. This configuration was considered to be sufficient to detect and investigate the modes in the frequency range of transport. This configuration does not allow identifying the complete mode-shapes of the structure since not enough measurement points are considered, however during this experiment we are more interested to identify the natural frequencies and damping ratios of the modes within our interested frequency range. This already allows us to perform a simple but efficient modal updating of our FE model.

The road test that was performed contained different driving conditions:

- Constant speed of 20 km/h, 25 km/h,. . . , 50 km/h
- Types of roads (rough roads, well-paved roads, . . .)
- Brake tests at different initial conditions (important decelerations)

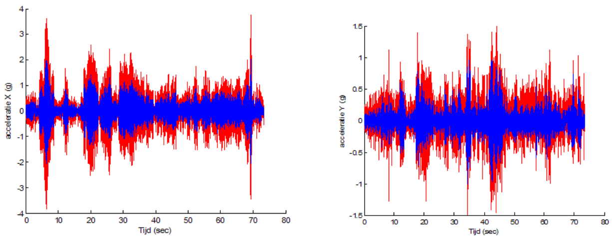


Figure 3: Measured accelerations in X and Y direction (top: red, middle: blue)

All signals were measured simultaneously during 550s at a sampling frequency of 200Hz (Figure 3). These settings more than cover the real frequency band of interest for the investigated component (about 0-50Hz) in which most dominant resonance frequencies of the device under test, as well as the main disturbance frequencies of transport excitations are situated.

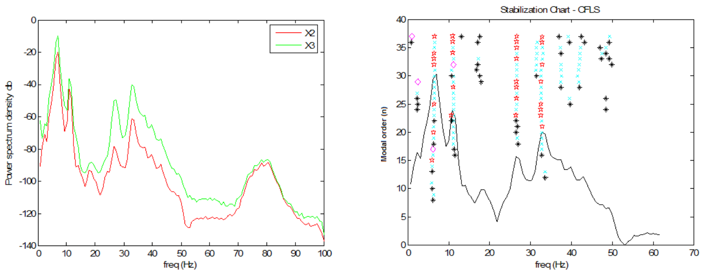


Figure 4: Power spectrum densities and Stabilization chart of measurements in X direction

The Polymax estimator is directly applied to the spectral densities. From the least-squares estimation the stable poles of our system can be determined with the help of a stabilization diagram (Figure 4). In modal analysis, a stabilization diagram is an important tool that is often used to assist the user in separating physical poles from mathematical ones. A stabilization chart is obtained by repeating the analysis for increasing model order n. The stable poles (i.e. the poles with a negative real part) are then presented graphically in ascending model order in a so-called “stabilization chart” (Figure 4). Estimated poles corresponding to physically relevant system modes tend to appear for each estimation order at nearly identical locations, while the so-called mathematical poles, i.e. poles resulting from the mathematical solution of the normal equations but meaningless with respect to the physical interpretation, tend to jump around. These mathematical poles are mainly due to the presence of noise on the measurements. During these tests stable poles are denoted by a star, this means that the variation over consecutive model orders of the damped natural frequency is smaller than 1%, while the damping ratio varies with less then 5%. It turns out that in many applications, the discussed frequency-domain estimator is able to generate quite clear stabilization diagrams compared with the well known LSCE approach.

	X-Spectra		Y-Spectra		X- and Y-Spectra	
Mode	Freq[Hz]	ξ[%]	Freq[Hz]	ξ[%]	Freq[Hz]	ξ[%]
X1	6,49	1,76			6,55	1,71
X2	10,02	1,42			10.18	1,54
Y1			13,64	5,07	13,76	5,02
X3	25,81	2,83			25,86	2,46
Y2			27,46	3,24	27.48	3,08
X4	33,07	1,65			33,11	1,76
Y3			35,26	2,87	35,25	2,77

Table 1: Estimated damping ratios and natural frequencies.

By using the spectral densities from the measurements obtained in the X-direction four stable modes could clearly be distinguished in the frequency range of interest. By analyzing the spectral densities in the Y direction another 3 different modes could be identified (Table 1). We can conclude that the 3d mode in the X direction and de 2nd mode in the Y direction are closely spaced. The same conclusions can be made for the 4th and 3d mode in respectively the X and Y direction. Applying the identification algorithm directly to the averaged spectrum of both the spectral densities in the X and Y direction it is clear that the closely spaced modes are indeed different modes and are easily identified by our estimator (Figure 5). The estimated modal parameters can be found in Table 1.

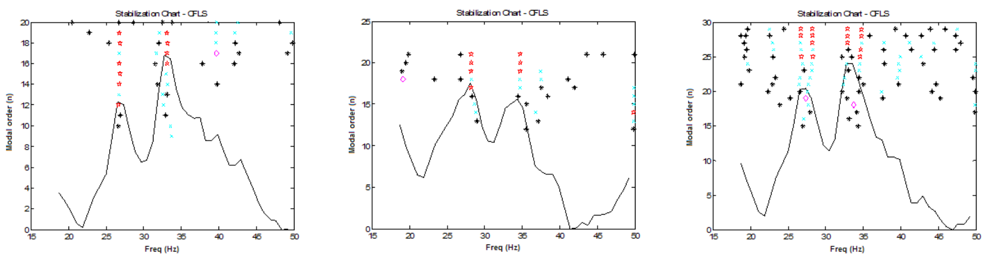
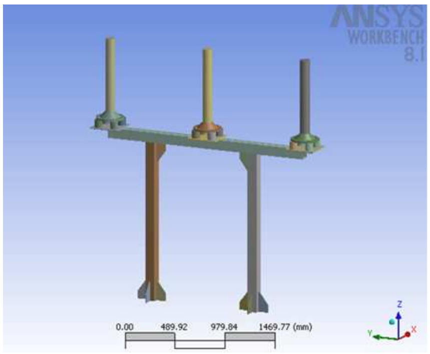


Figure 5: Zoomed stabilization charts: a. Stabilization diagram obtained by only using measurements in X direction in the frequency band 15-50Hz (2 stable modes identiefied), b. Stabilization diagram obtained by only using measurements in Y direction in the frequency band 15-50Hz (2 stable modes identiefied), c. Stabilization diagram obtained by using the full set of measurements both in X and Y direction in the frequency band 15-50Hz (4 stable modes identiefied).

FE-model

The FE-package ANSYS 8.0 was used to model the support structures and the insulators(Figure 6). Elastic 3D shelf elements were used to model the support structure with the well known material properties of steel. The insulators were modeled as simple solid cylinders with a specific weight that equals the real complex insulators that contain porcelain and oil.



	FE-Model	Experimental
Mode	Freq[Hz]	Freq[Hz]
X1	6,65	6,55
X2	9,64	10.18
Y1	14,71	13,76
X3	25,81	25,86
Y2	27,85	27.48
X4	32,37	33,11
Y3	37,42	35,25

Figure 6: FE-model+Comparison results with experimental results

Considering the complexity of the structure the correspondence between the experiment and the FE-model is remarkable good, as is shown in Figure 6. We can clearly distinguish the modes with the main movement in the X-direction and those with the movement in the Y-direction (Figure 7). These modes were also separately seen by the accelerometers respectively oriented in the X and Y direction, during the road test. The small differences we have between the experimental eigenfrequencies and the analytical ones are probably due to the boundary conditions. In the real structure we had asymmetric boundary conditions a the fixation. The left leg is directly connected on a very stiff trailer beam and the right leg is placed on a rather thin plate (Figure 8). In order to correctly model these differences springs should be added to the base.

SUMMARY

A road test was performed on a mobile substation to estimate the modal parameters of a structure mounted on the truck. The modal parameters were successfully extracted from the acceleration measurements using a proposed frequency domain technique. The used method was able to generate clear stabilization diagrams and to identify closely spaced modes. The experimental derived eigenfrequencies are in good agreement with the analytical Finite Element results.

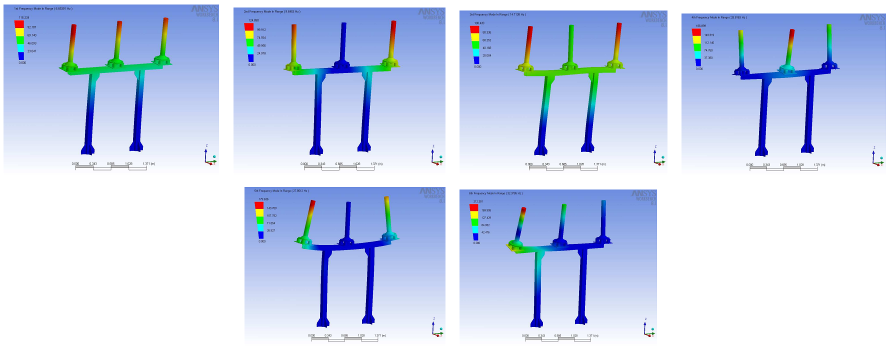


Figure 7: First 6 modes calculated by the FE-model

Figure 8: Support fixation

ACKNOWLEDGMENTS

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