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Operational mode-shape normalisation with a structural modification for small and light structures

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ABSTRACT

When dealing with small and light structures, difficulties occur when measuring the modal parameters. The resonant frequencies are usually relatively high and therefore a wide frequency range is needed for the measurement. Furthermore, the mass that is added to the structure by the sensors causes structural modifications. To overcome these difficulties, an improved method using an operational modal analysis instead of an experimental modal analysis is proposed in this study. It is derived from the sensitivity-based operational mode-shape normalisation with a consideration of the mode-shape variation. The measurement of the excitation force is not needed, because the operational modal analysis is used and only two simultaneous response measurements at an unknown excitation are required. The proposed method includes the cancellation of the added mass, resulting in mode shapes and resonant frequencies of the unmodified structure. The numerical and experimental results on small and light structures are compared with the results of the experimental modal analysis. The comparison shows that the proposed approach allows measurements over a wide frequency range and increases the accuracy of the results compared to the sensitivity-based operational mode-shape normalisation and also compared to the particular experimental modal analysis method that was used in this study. The advantages of the proposed method can be seen whenever the mass that is added to the structure by the accelerometer is not negligible and therefore a variation of the mode shapes occurs.

1. Introduction

Modal analyses are used to identify modal parameters (resonant frequencies, mode shapes and damping) [1–3]. The experimental modal analysis (EMA) [2], with a simultaneous measurement of the excitation force and the response of the structure, is the prevailing technique. If the excitation force and the response of the structure are known, the frequency-response functions (FRFs) can be calculated and the identification of the mass-normalised mode shapes (independent of the excitation) is possible. The operational modal analysis (OMA), on the other hand, is a technique for performing a modal analysis when the structure is excited by unknown operational loads. It was initially used as an addition to FRF measurements to define the modal parameters of the structure during the operation [4]. OMA was also employed in rare cases, when people were dealing with large structures and a controlled excitation was hard to achieve [5], which means that only a modal

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identification with unknown operating loads was possible. The main drawback of OMA in comparison with EMA is that it cannot identify the mass-normalised mode shapes [6] and the main advantage is that an excitation-force measurement is not needed for the OMA, which simplifies the experimental procedure.

The EMA is, in some cases, extremely hard to perform due to accessibility difficulties or the characteristics (dimensions, mass) of the measured structure [7]. One example of this is when relatively small and light structures (mass <50 g) are measured. The main reason is the mass added to the structure by the transducers (force sensor, accelerometer), which changes the structure's modal characteristics. This effect was researched by Huber et al. [8], Ozdoganlar et al. [9], Silva et al. [10], Rovščcek et al. [11], and others. In [11] a light, custom-made, force sensor, which adds only 0.4 g to the structure was used. The sensor can operate at high frequencies (up to 20 kHz), which is suitable for small structures, because they usually have higher resonant frequencies [9]. OMA was rarely used on small and light structures in the past, especially because the mode shapes could not be mass normalised and therefore the modal description of the structure was not complete [2]. But in 2002 a new method was introduced by Parloo et al. [12], which makes the mass normalisation of the operational mode shapes possible. The operational mode shapes are normalised by multiplying them by scaling factors, which are derived from the modal sensitivity of the structure on a change of the mass matrix. Therefore, the term mass-change strategy is frequently used to denote Parloo's method. This mass-change strategy does not require the measurement of the excitation force and it was first used on larger structures, for instance on a bridge [13], on a sprayer boom [14,15], etc. The possibility and difficulties of using the mass-change strategy on small and light structures have not yet been analysed in detail.

The mass-change strategy works with the presumption that the resonant frequencies shift, but the mode shapes remain almost the same when the mass is added to the structure, as shown by Parloo et al. [12]. The results are relatively good, when the quantity of the added mass is just right (about 5% of the whole mass of the structure), as Lopez-Aenlle et al. [16] concluded. Furthermore, the added mass needs to be well distributed over the structure. But when measuring small and light structures, the added mass can be too high and not well distributed. For this reason, not only do the resonant frequencies shift, but the mode shapes also change.

In this study an improved method that takes into account the mode-shape variation due to accelerometer added mass is presented. The normalisation of the operational mode shapes is based on a sensitivity analysis and a structural modification of the modal parameters. Two simultaneous measurements of the response are needed (for the OMA) and the excitation force is unknown. The reference response is measured by a lightweight accelerometer and the second response measurement is performed by a Laser Doppler Vibrometer (LDV). The results of the proposed operational mode-shape normalisation method are compared to the results of the EMA procedure presented by Rovščcek et al. in [11] and to the numerical model. The method proposed in this study gives significantly better results than the EMA, especially at low frequencies (under 500 Hz), and is simpler to use, since the measurement of the excitation force is not needed. It can be used on any similar small and light structure.

Parloo et al. [13,14] tested larger structures and the masses of the accelerometers were very small compared to the measured structures. Therefore, the mass-loading effect of the accelerometers was negligible. However, when measuring small and light structures this effect is significant and it should be compensated in the modal analysis. The main advantage of the method presented in this study compared to the sensitivity-based operational mode-shape normalisation proposed by Parloo et al. [12] is that it also takes into account the mode-shape variation, which occurs due to the added mass of the accelerometer. There is also a possibility of using only non-contact measuring devices (like LDVs) for the measurement to avoid the mass-loading of the structure; however, in some cases the LDVs cannot be used. For instance, by a laser beam unreachable crevices due to application environment and/or fixation setup. In addition, the measurements at high frequencies with relatively small vibration amplitudes can easily reach the limit of the LDV's dynamic range. Therefore, the approach proposed in this study is applicable.

This study is organised as follows. Section 2 presents the theoretical background of this paper. The sample that was used for the numerical model and the measurements is presented in Section 3. The numerical model and its results are described in Section 4. Section 5 presents the experiments (EMA and OMA) and the comparison of the experimental and numerical results. A summary of the work is given in Section 6.

2. Theoretical background

2.1. Sensitivity-based operational mode-shape normalisation

The operational mode shapes are not mass normalised, since the excitation force is not measured when performing the OMA. Therefore, a new approach was proposed by Parloo et al. [12] to mass normalise the operational mode shapes on the basis of the modal sensitivity of the structure. The main idea of the method proposed by Parloo et al. is to normalise the measured mode shapes by multiplying them by scaling factors. By adding a known mass to the selected points of the structure the resonant frequencies shift. From these shifts the scaling factors for each mode shape can be calculated using the sensitivity analysis. The term mass-change strategy is frequently used to denote this method.

The use of the modal sensitivity to properly scale the operational mode shapes was later more thoroughly analysed by other researchers. Lopez-Aenlle et al. [16–19], Fernandez et al. [20,21] and others [22] gave suggestions about how to accurately normalise the mode shapes using different types of mass-change strategies. In [17] the equations for the calculation of the scaling factors were analysed and an iterative procedure for better accuracy was developed by Lopez-Aenlle et al. In [19] the