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On the use of measured rotational responses in structural dynamic analysis

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Abstract. Testing is a very important task in structural dynamics and on its applications, namely on the characterization of the dynamic behaviour of structures or on the use of the structural responses to indirectly determine dynamic properties or parameters. The increasing availability of sensors, capable of measuring rotational responses, leads to the improvement of existing methods and to the development of new ones in several fields of application. In this work, an evaluation of the applicability and performance of the use of rotational responses is carried out considering applications ranging from the determination of rigid body properties to damage identification. Data acquisition using MEMS and piezoelectric sensors is covered and a set of results is discussed.

1. Introduction

Over the years, the structural dynamics research community has studied the dynamic behaviour of structures from different perspectives. In this field of engineering, the use of testing procedures along with modelling and simulation techniques has became standard, regarding the experimental and theoretical description of the structure under study. The dynamic characteristics of a structure are often derived from a set of experimentally acquired frequency response functions (FRF), the spatial model usually contains a more refined set of information, in terms of the available degrees of freedom (DOF) and response types. Thus, spatial models, often derived numerically using the finite element (FE) method, allow for the computation of physically inaccessible FRFs, although they require model validation, as there is always lack of knowledge, at some extent, concerning modelling assumptions and parameters. Whenever test and theoretical responses must be matched, the issue of model incompleteness arises, due to the fact that experimental data is usually collected at a few translational DOFs due to applied forces, using hammer or shaker exciters, over a limited frequency range. The limitations of testing, regarding inaccessible responses due to different aspects, continues to present a major challenge for the scientific community. This is due to the fact that the knowledge of a complete response model could enhance several procedures in different areas of application. Hence, one must cope with either the FE model reduction to the set of experimental points or the expansion of the experimental data over the FE model DOFs [1, 2]. Regarding the subject of model incompleteness, over the years, several model reduction techniques have been proposed and successfully applied [3–5], although experimental data expansion strategies are significantly fewer and the demand for efficient techniques is still an open issue [6].

Pursuing a complete response model, one must be able to measure and to excite the entire set of DOFs in the structure to acquire the complete FRF matrix. This implies the acquisition of translational and rotational responses due to excitations by forces and pure moments, although the measurement and excitation of rotational DOFs is still not standard. This limitation in testing leads to an incomplete response model. Using conventional testing techniques, one can only access at most 25% of the complete response model, assuming that one can measure all the translational DOFs and excite them with applied forces, which is still an unpractical assumption. Details on measuring and exciting rotational DOFs can be found in [7]. In the work [6], one can find a technique for expanding translational measured FRFs over the entire set of DOFs. This technique is based upon a modified Kidder's method and the principle of reciprocity, and it avoids the need for modal identification, as it directly uses the measured translational FRFs to estimate the entire response model. An experimental application of it is given in [8].

The demand for a complete response model has been very active in the structural coupling community, where the significance of assessing FRF at rotational DOFs was addressed in many studies, e.g. [9, 10]. Additionally, the knowledge of rotational responses proved to be essential on the identification of the dynamic characteristic of joints, the identification of unknown forces from measured responses or vibration isolation, among others. The use of piezoelectric accelerometers, with wide-spread usage in applications of structural dynamics, as well as the less used Microelectromechanical systems (MEMS) sensors have been considered by several researchers to acquire rotational responses [11, 12].

Aiming at stressing the capabilities of using rotational responses, this paper presents part of the work developed by a research group at NOVA UNIDEMI. The use of piezoelectric as well as MEMS sensors is covered, discussing some advantages and limitations of both, but highlighting their combined use on applications to determine the rigid body properties of a structure, to identify damage or to couple substructures. Some results of these are given and the reader is directed to the published works for further details.

2. Acquiring rotational responses

The authors of [12] presented a comparison between rotational FRFs indirectly measured using the T-block technique [13] and rotational FRFs directly measured using piezoelectric rotational accelerometers. From the presented results, the application of direct rotational piezoelectric accelerometers is promising, although this type of piezoelectric sensors is limited to measure the rotation in relation to a single axis and its commercial cost is high, comparing to the cost of MEMS sensors or even to the one of conventional translational single-axis piezoelectric accelerometers.

The group at NOVA UNIDEMI has invested in a home-made acquisition system that allows for the simultaneous and synchronous acquisition of different kinds of sensors, e.g., conventional translational piezoelectric accelerometers, strain gauges or tri-axial MEMS accelerometers and MEMS gyroscopes, all triggered by a conventional instrumented impact hammer. In this framework, our group has developed the capability to acquire rotational FRFs directly measured using MEMS gyroscopes [14]. The MEMS sensors are generally lighter and have a very lower power consumption when compared to piezoelectric ones. However, the MEMS gyroscopes are limited to a lower bandwidth, only up to 140Hz. This is a significant limitation for several applications, as modal studies, but it is not paramount regarding the interest in the rigid body properties, which is one of the applications covered in this paper (section 3.1). Note that this limited bandwidth is referred to the MEMS gyroscopes only, as the tri-axial MEMS accelerometers present a larger bandwidth, up to around 2kHz. The referred limitation can be mitigated by the expansion of translational FRFs, of course this has a price to pay, as the experimental data expansion is base upon a numerical model. Some details are given in section 3.3.

To summarize, the acquisition system of NOVA UNIDEMI is able to acquire FRFs at different points and directions on a structure, using piezoelectric and/or MEMS sensors, and an instrumented impact hammer, which triggers the experimental data acquisition. The acquisition system was built using a National Instruments (NI) DAQ 9172 chassis that collects the data from all sensors and a LabView implementation that is responsible for the signal management and processing, allowing the experimental data to be exported and then treated by other software for further developments.

In terms of sensors, the group at NOVA UNIDEMI has available tri-axial translational sensors, piezoelectric accelerometers (B&K 4506 B) and MEMS ones (ADXL326), and rotational sensors, MEMS gyroscope (IDG500). Note that the MEMS sensors are considerably cheaper, when compared to their piezoelectric equivalent, providing accurate enough measures in a certain measuring domain.

3. Cases of Application

In this section, the use of rotational responses regarding different cases of application is explained and results are discussed.

3.1. Determination of rigid body properties

The knowledge of the rigid body properties of a structure is very important in different fields, namely in multibody dynamics or flight control. Inertia Restraint methods (IRM) are a set of methods developed to determine the rigid body properties of a structure [15]. The IRM are based on the principle that the dynamic response of structures in free-free conditions are characterized, in the low frequency region, by a constant term designated as inertial restraint or mass line. This approach is suitable for structures where rigid and flexible modes are well separated. Note that the mass line is the modal constant at zero Hz of a typical accelerance (FRF with the response in acceleration units). As discussed in [16], the accuracy of the IRM heavily depends on the selection of the measuring locations, as well as, the conditions of the excitation. This work review a modified version of the IRM given in [17] to cope with rotational FRFs.

Consider a vector with the measured translations and rotations w.r.t. all the three axis at a measuring point i defined as,

$$\ddot{\mathbf{x}}_{m_i} = \left\{ \ddot{u}\ \ddot{v}\ \ddot{w}\ \ddot{\alpha}\ \ddot{\beta}\ \ddot{\gamma} \right\}^T_{m_i} \tag{1}$$

If one considers more that one sensor, one can define the vector with all the responses at k measuring points as,

$$\ddot{\mathbf{x}}_m = \left\{ \ddot{\mathbf{x}}^T_{m_1}\ \ddot{\mathbf{x}}^T_{m_2}\ \cdots\ \ddot{\mathbf{x}}^T_{m_k} \right\}^T \tag{2}$$

To transform the vector of experimental responses to the origin 0 of a global referential in the structure, one may use the following transformation,

$$\ddot{\mathbf{x}}_m = \mathbf{A}\mathbf{G}_{m0}\ddot{\mathbf{x}}_0 \tag{3}$$

where $\mathbf{A}$ is a boolean diagonal matrix that turns on and off channels of the sensors, allowing to use sensors of different kinds; $\mathbf{G}_{m0}$ is a transformation matrix from each local referential to the global one; and $\ddot{\mathbf{x}}_0$ is the vector of experimental responses at the origin of the global referential. Note that $\mathbf{A}\mathbf{G}_{m0}$ is often a rectangular matrix and the pseudo-inverse must be considered to obtain $\ddot{\mathbf{x}}_0$.

Hence, for a given force vector $\mathbf{f}_0$, defined in relation to the origin of the referred global referential, one has the equilibrium equation,

$$\mathbf{f}_0 = \mathbf{M}_0\ddot{\mathbf{x}}_0 \tag{4}$$

where $\mathbf{M}_0$ is a generalized mass matrix,defined at the origin of the global referential, containing all the inertia terms, namely: mass, coordinates of the centre of mass and inertia tensor.

Details on the modification of the IRM given in [17] can be found in [18]. In that work, a experimental application, using i) tri-axial piezoelectric accelerometers and ii) tri-axial MEMS accelerometers and MEMS gyroscopes, shows that the accuracy of the estimated rigid body properties is quite similar for both implementations, showing no evidences to prefer the use of conventional, more expensive sensors. Moreover, one of the major advantages of using rotational responses with the IRM is related to the independence of the measuring locations, refuting the well-known restrictions given in [16]. Additionally, it was observed that one only needs to use six responses, three translations and three rotations, that can be obtained using just one MEMS sensor, in the limit. Instead of using at least three tri-axial piezoelectric accelerometers, with a distribution in the structure that must agree to the referred set of restrictions.

3.2. Damage identification

Within the framework of damage identification, the group at NOVA UNIDEMI considered the use of well-establish frequency domain damage indicators with rotational FRFs. The transmissibility damage indicator (TDI) and the weighted damage indicator (WDI) proposed in [19, 20] are based on the response vector assurance criterion (RVAC) [21]. The TDI and WDI are successfully used to detect damage and they are usually computed from a set of translational FRFs. In our research, these damage indicators may now be computed also for a set of measured rotational FRFs, following the standard procedure.

From the observation of fig. 1, it is evident that the use of rotational responses to compute the referred damage indicators enhance the sensibility of them to detect damage. This is also true, when the difference between rotational FRFs for the healthy and for the damaged structure is computed, aiming at localizing damages.

This results are obtained with simulated test data, but they are promising even when noisy data is considered. The experimental application of these adapted indicators is an ongoing work.

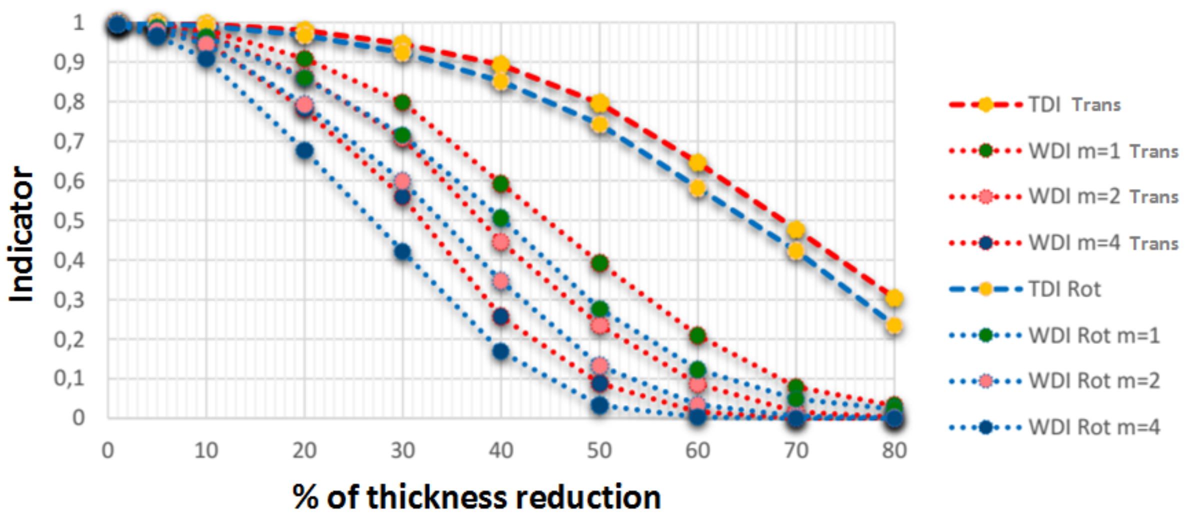

Figure 1. TDI and WDI for different exponents m.

3.3. Estimation of rotational FRFs

As referred, the MEMS gyroscopes have a limited bandwidth. In several applications, this limitation makes this kind of sensors useless. On the other hand, the measured rotational FRFs are usually only due to exciting forces. Thus, one cannot access the complete response model. In this sense, a method to expand experimental FRFs was proposed and successfully used to estimate rotational FRFs, due to exciting forces and moments [6]. This technique is based upon a modified Kidder's method and the principle of reciprocity, and it avoids the need for modal identification, as it directly uses the measured FRFs $\mathbf{H}_{pj}(\omega)$. Hence, if one acquires a set of FRFs, it can be shown that a FRF vector expanded for the unmeasured degrees of freedom (DOF) is given by,

$$\mathbf{H}_{sj}(\omega) = -\left(\mathbf{K}_{ss} - \omega^2\mathbf{M}_{ss}\right)^{-1}\left(\mathbf{K}_{sp} - \omega^2\mathbf{M}_{sp}\right)\mathbf{H}_{pj}(\omega) \tag{5}$$

where $\mathbf{K}$ and $\mathbf{M}$ are the stiffness and mass matrices, p denotes the measured DOFs and s the unmeasured ones, and j sets a given force location. Note that damping can also be considered in this process.

This expansion method is robust to experimental noise and it can be applied with just a reduced set of measured translational FRFs, as shown in [8]. It is quite relevant to mention that the correctness of the numerical model used to expand the data is not a paramount issue, although it must have a certain degree of similarity, regarding the structural behaviour. The estimated or expanded FRF shown in fig. 2 was obtained for a steel beam, using only two translational piezoelectric accelerometers (two measuring locations) and ten impact points (rover hammer test). Details on this case of application are given in [8]. Figure 2 shows the comparison between a direct rotational FRF (H_{θ_a,τ_a}), that is the relation between a rotational response θ_a due to a pure moment τ_a, obtained via: i) experimentally using a T-block (dotted line); ii) a damped finite element (FE) model, used in the expansion process (dashed line); and iii) the expansion process, using only experimantal translational FRFs as reference (solid line).

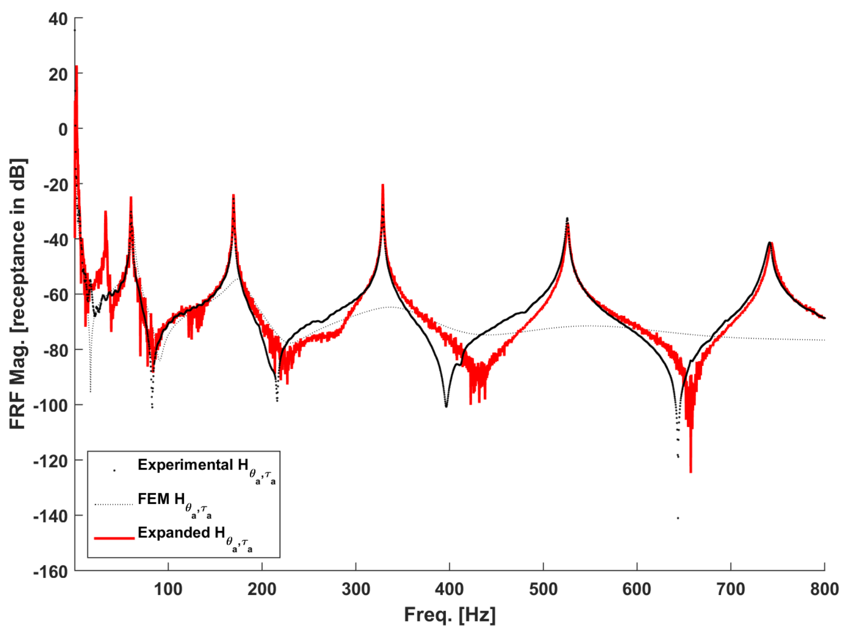

Figure 2. Direct rotational FRF (H_{θ_a,τ_a}).

This expansion technique was then implemented in conjunction with the frequency based structuring (FBS) method [22] in the context of structural coupling, with quite good results (work to appear in proc. of VETOMAC XIV, 2018). Note that this work is similar to the one of [10], but one avoids modal identification and the use of expensive rotational piezoelectric accelerometers. Figure 3 shows the comparison between a transferred rotational FRF (measured rotation and excitation with pure moment at different locations). The agreement between both curves is quite good in a broad frequency range. In this application, one assumes that the rotational FRFs are inaccessible, and by this the comparison is only made based on the reference complete FE model responses.

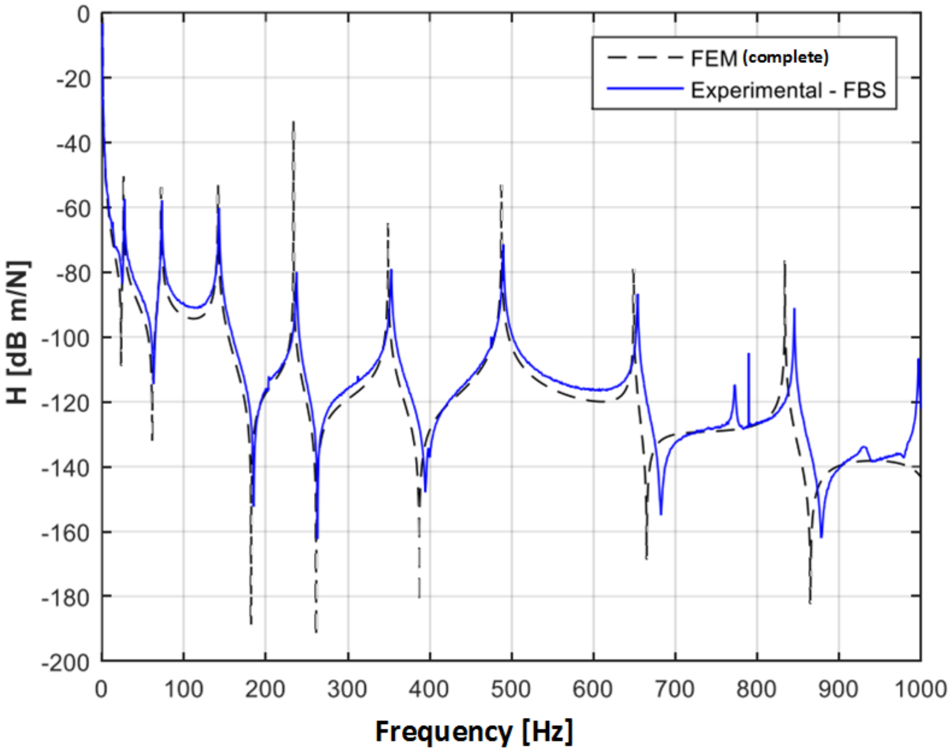

Figure 3. Rotational FRFs due to a exciting moment: numerical FRF of the complete structure (dashed line); estimated FRF by the FBS method using experimental data (solid line).

4. Conclusion

This paper summarizes part of the the work developed by a research group at NOVA UNIDEMI, regarding different applications of measured rotational responses in structural dynamics. The use of less conventional sensors and a non-commercial data acquisition system is briefly presented and some results are discussed, stressing some advantages and limitations of the use of both translational and rotational sensors. It is argued that the use of MEMS gyroscopes enhance the identification of rigid body properties of a structure, as it makes this process independent from any specific location of measuring points. In this case, one must only to assure that all the rigid body modes are excited. Additionally, concerning damage detection, the use of rotational responses with well-established damage indicators increase the sensitivity of those indicators to damage. On the other hand, knowing one of the major limitations of MEMS gyroscopes, the limited maximum frequency, one discussed the capability to estimate rotational FRFs from a set of measured translational ones. The estimated FRFs were experimentally assessed and successfully used in the context of structural coupling.

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