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Modal mass estimation from ambient vibrations measurement: A method for civil buildings

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ABSTRACT

A new method for estimating the modal mass ratios of buildings from unscaled mode shapes identified from ambient vibrations is presented. The method is based on the Multi Rigid Polygons (MRP) model in which each floor of the building is ideally divided in several non-deformable polygons that move independent of each other. The whole mass of the building is concentrated in the centroid of the polygons and the experimental mode shapes are expressed in term of rigid translations and of rotations. In this way, the mass matrix of the building can be easily computed on the basis of simple information about the geometry and the materials of the structure. The modal mass ratios can be then obtained through the classical equation of structural dynamics. Ambient vibrations measurement must be performed according to this MRP models, using at least two biaxial accelerometers per polygon. After a brief illustration of the theoretical background of the method, numerical validations are presented analysing the method sensitivity for possible different source of errors. Quality indexes are defined for evaluating the approximation of the modal mass ratios obtained from a certain MRP model. The capability of the proposed model to be applied to real buildings is illustrated through two experimental applications. In the first one, a geometrically irregular reinforced concrete building is considered, using a calibrated Finite Element Model for validating the results of the method. The second application refers to a historical monumental masonry building, with a more complex geometry and with less information available. In both cases, MRP models with a different number of rigid polygons per floor are compared.

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1. Introduction

The interest in experimental modal analysis for civil structures has strongly increased in the last years, because of its relevance in several engineering applications, such as model updating [1], structural health monitoring [2], vibration serviceability [3]. The classical Experimental Modal Analysis (EMA) [4], is based on the measurement of the dynamic response and of the applied excitation, from which the Frequency Response Functions (FRFs) or the Impulse Response Functions (IRFs) of the system are built. The knowledge of FRFs or IRFs, in turn, allows to identify a complete modal model of the structure, i.e. natural frequencies, damping ratios and scaled mode shapes [5]. In the Operational Modal Analysis (OMA), on the other hand, modal parameters are identified from measurement of the structural response only, even maintaining mostly of the

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EMA theoretical background [6]. If compared with EMA, OMA presents a series of objective advantages, first of all the use as input of freely available ambient excitation by natural sources (wind, traffic, micro-tremors, pedestrian and vehicles passage, etc.) instead of expensive and invasive excitation device, as large shaker or drop weight [7,8]. Moreover, OMA measurements are taken in the working condition of the building without any service interruption, obtaining a model in its real-life operating condition [9]. Beside the above advantages, the OMA approach for modal parameter identification also presents a series of drawbacks. One of the most important is that only unscaled mode shapes can be obtained, because the scale factors of the estimated operational mode shapes depend on the ambient excitation, which is unknown. In these conditions, the modal participation factors cannot be determined and the same is for the modal mass ratios. Unfortunately many engineering applications, ranging from the field of damage assessment [10] to that of the seismic response prediction [11], require the knowledge of the modal masses. Several experimental methods for the estimation of the mode shapes scaling factors have been proposed, even for civil buildings [12]. Some authors propose to estimate these factors by adding mass in selected points of the building. In these mass-change methods several tests are performed, making a correlation between the added mass and the relative frequency shift [13]. In order to improve the accuracy in scaling the first vibrational mode, also methods based on both mass and stiffness changes are proposed [14]. At present, however, all of them are related to scale models of the building, whereas no tests are performed in real civil habitation. The condition for bridges is different: these methods for the modal mass estimation have been successfully applied in more than a real situation [15]. Sometimes the human-induced dynamic excitation is sufficient to have reliable values of modal mass for the footbridge vibration modes [16,17]. This underlines a critical aspect of these methods, i.e. they cannot be applied to real civil buildings, because of some obvious difficulties: the added mass, required to induce a significant variation of the dynamic properties of the building, is often incompatible with the acceptable loads. In addition, the transport of these added mass into the buildings (in particular at its top floor, where it should be more effective for frequency shift) is often particularly onerous and without eligible costs. A way to overcome these problems and to obtain scaled operational mode shapes is using a Finite Element Model (FEM), calibrated according to experimental modal parameters obtained by OMA [18,19]. Such a model, although efficient, requires the knowledge of the mechanical properties of the building and the needing of further investigation about structural elements. This kind of survey often implies a significant cost and time overrun, losing many of the OMA advantages.

As an alternative, in this work, a new method for computing scaled mode shapes and modal mass ratios of real buildings is illustrated, using the Multi Rigid Polygons model (MRP) instead of a more onerous FEM. The MRP model is a kinematic-inertial model in which all the masses are squeezed into the horizontal elements (floors), which, in turn, are divided into one or more rigid polygons according to their complexity in terms of geometry and mechanical features. For the actual implementation of such a model, only a rough knowledge about the building geometry and the inertial properties of the materials is required. The terms of the mass matrix can be calculated evaluating the translational and rotational masses concerning all the defined polygons. It is worth pointing out that this kind of kinematic-inertial model can be refined increasing the number of polygons and it is particularly suitable for historical complexes for which the classical rigid floor assumption is not appropriate. Obviously, the increase in the number of polygons is reflected in the corresponding increase of the measuring points required, which must be at least two per polygon.

In the Section 2 of this paper the theoretical background is presented and the equations used to compute the mass matrix and the other model parameters are given. The Section 3 presents three FE models with increasing complexity and the results in terms of modal mass ratios with those calculated with the suggested method are compared. An application of the proposed method to a real concrete building located at Barberino di Mugello (FI) is shown in Section 4: the results of the numerical multi-polygon model and those of the FE calibrated model are compared, in order to validate the obtained modal mass ratios. In Section 5 the same results are determined for a historical masonry building at Recanati (MC), showing the suitability of the method in the case of complex and irregular buildings, for which the implementation of a reliable FEM is particularly onerous.

2. Theoretical background

In the Multi Rigid Polygons (MRP) model, described in the following, reference is made to a building composed of N stories or floors, endowed only with horizontal degree of freedoms (DOFs). The i-th floor is ideally subdivided in n_i polygons which are assumed to move rigidly, so that the total number of rigid polygons is $P = \sum_{i=1}^{N} n_i$. It is noted that the position of every point of a floor is known if the translations and the rotation of all the polygons are known. In the centroid of the j-th polygon of the i-th floor are assigned the mass m_{ij} and the polar moment of inertia I_{ij}, such that the kinetic energy $\mathscr{T}$ of the whole building can be written as:

$$\mathscr{T} = \frac{1}{2}\dot{\mathbf{U}}^T\mathbf{M}\dot{\mathbf{U}} \tag{1}$$

where, if X_{ij}, Y_{ij} are the two components of the horizontal rigid translation and Θ_{ij} is the rigid rotation of the polygon ij around the vertical axis, the vector $\mathbf{U}$ $(3P \times 1)$ is defined as:

$$\mathbf{U}^T = \left[X_{11}, Y_{11}, \Theta_{11}, X_{12}, .., X_{1n_1}, Y_{1n_1}, \Theta_{1n_1}, .., X_{Nn_N}, Y_{Nn_N}, \Theta_{Nn_N}\right] \tag{2}$$

and $\mathbf{M}$ is the mass matrix $(3P \times 3P)$ of the system, having the following structure:

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