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Use of optimization technique for design of scaled aeroelastic model for wind tunnel testing

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SUMMARY

Wind tunnel testing is necessary to predict wind-induced effects for complex buildings. Several types of wind tunnel testing exist with the aeroelastic type representing the highest fidelity for dynamic sensitive structures where aeroelastic effects are taken into account to consider cases such as flutter, galloping and vortex shedding. The design of aeroelastic models is often a complex process that requires a lot of time and effort. In this study, we present a novel approach for the design of aeroelastic model where a size optimization technique is used to design a scaled lattice tower for aeroelastic wind tunnel testing with the objective of minimizing the error between the natural frequencies and modal assurance criteria (MAC) between the scaled model and the required values from dynamic similarity. The results showed that the framework was able to design a model that achieves similarity requirements.

Keywords: aeroelastic Wind tunnel testing, dynamic similarity, optimization

1. INTRODUCTION

The complexity of the structural behavior of some buildings and infrastructure necessitates the use of wind tunnel testing to assess the wind-induced actions on the structures (Coutinho et al., 2016). Some of the most common types of wind tunnel testing are the high-frequency-balance (HFB) method, the high-frequency pressure-integration (HFPI) method, and the aeroelastic modeling method. The first two methods adopt rigid models which are considered adequate to measure wind pressure on the surfaces of the building models. For cases with flexible/slender buildings and other components with the risk of dynamic instability where aeroelastic effects seem to be significant, rigid wind tunnel testing is not always sufficient. This is because for flexible structures and components, it is expected that the large deformations will alter the wind actions on the structure. Also, wind-induced vibrations for dynamically excited structures can lead to instabilities that cannot be captured by numerical modeling. For example, aerodynamic damping can be negative, and hence amplify wind-induced response, such as in cases of galloping. Therefore, in these cases, there is a need to include the aeroelastic behavior in wind tunnel testing to accurately assess wind-induced vibrations and possible instabilities (Irwin et al., 2013). This type is called aeroelastic wind tunnel testing where scaled models, that replicate the dynamic properties of the full-scale model, are designed. To ensure similar behavior characteristics between the model and the prototype, similitude theory requirement should be met.

The design process of a model to satisfy similarity requirements for an aeroelastic wind tunnel test requires tremendous effort and time. Therefore, this motivated the authors to utilize available optimization techniques to reduce the cost of the iterative design. Several researchers applied optimization techniques to design aeroelastic models, especially in the field of aeronautical engineering. (Oliveira et al., 2022) used a topology optimization technique to design a wing structure with objective of matching natural frequencies while tracking modal assurance criteria (MAC) and reported the robustness of this method. In this study, we present a novel approach for the design of aeroelastic scaled model where a size optimization technique is used to design a scaled lattice tower for aeroelastic wind tunnel testing with the objective of minimizing the error between the natural frequencies and the MAC between the scaled model and the values based on similarity equations. The effect of different weight factors for the two objectives is also discussed.

2. METHODOLOGY

This study is focusing on the design of the aeroelastic model for wind tunnel testing by matching modal properties, namely natural frequencies and mode shapes. A finite element (FE) model for the full scale is developed and from which the requirements of similarity for a scaled model are derived. Then in order to design the scaled model, i.e., sizing of members, a simulated annealing optimization algorithm is implemented with sizes of individual members are chosen as the optimization parameters. Simulated annealing method was chosen since its robustness in design of truss members was reported (Tushaj and Lako, 2017) . The objective function of the optimization procedure, that include errors in both natural frequencies and mode shapes, is formulated as shown in the following equation:

$$Objective\ Function = A\sum_{i=1}^{n}\left(\frac{Freq_{iM}-Freq_{iC}}{Freq_{iC}}\right)^2 + B\sum_{i=1}^{n}(1-MAC_i) \qquad (1)$$

where: A and B are weight factors applied to the error in frequency and error in mode shapes respectively, $Freq_{iM}$ is the natural frequency of the ith mode shape calculated from the modal analysis of the scaled model, $Freq_{iC}$ is the natural frequency of the ith mode shape calculated from similarity requirement and considered as the target for the optimization process, n is the number of mode shapes considered for the optimization process and MAC_i is the modal assurance criteria. MAC value of 1 represents good correlation whereas a value of zero represents no correlation. The MAC is calculated according to the following equation:

$$\mathrm{MAC}\left(\{\phi_X\}_i,\{\phi_A\}_j\right) = \frac{\left|\{\phi_X\}_i{}^T\{\phi_A\}_j\right|^2}{(\{\phi_X\}_i{}^T\{\phi_X\}_i)(\{\phi_A\}_i{}^T\{\phi_A\}_i)} \qquad (2)$$

where: $\{\phi_X\}_i$: the experimental ith mode shape, $\{\phi_A\}_j$: the analytical jth mode shape and the T of the superscript represent the transpose of the mode shape. In this study, a sensitivity analysis is carried out where different values of the weight factors A and B are considered to study their effects. A flow chart that outlines the main steps of the mentioned framework is shown in Fig. 1. The initial FE model, required for the optimization process, is developed in ANSYS APDL. The optimization process was done through an integration process between MATLAB and ANSYS APDL where the optimization algorithm and calculation of fitness function is performed in MATLAB while the structural modal analysis is performed in ANSYS APDL. The previous methodology is applied to design a scaled model of transmission tower prototype considering the first two fundamental modes. The full-scale transmission tower, as shown in Fig. 1, has an approximate height of 100 ft and approximate width at the base of 40 ft. The tower is constructed from steel angles of different sections. The chosen geometric scale factor for aeroelastic testing is 1/50. The results and discussion of the application of the framework, with different weight factors, is presented in the following section.

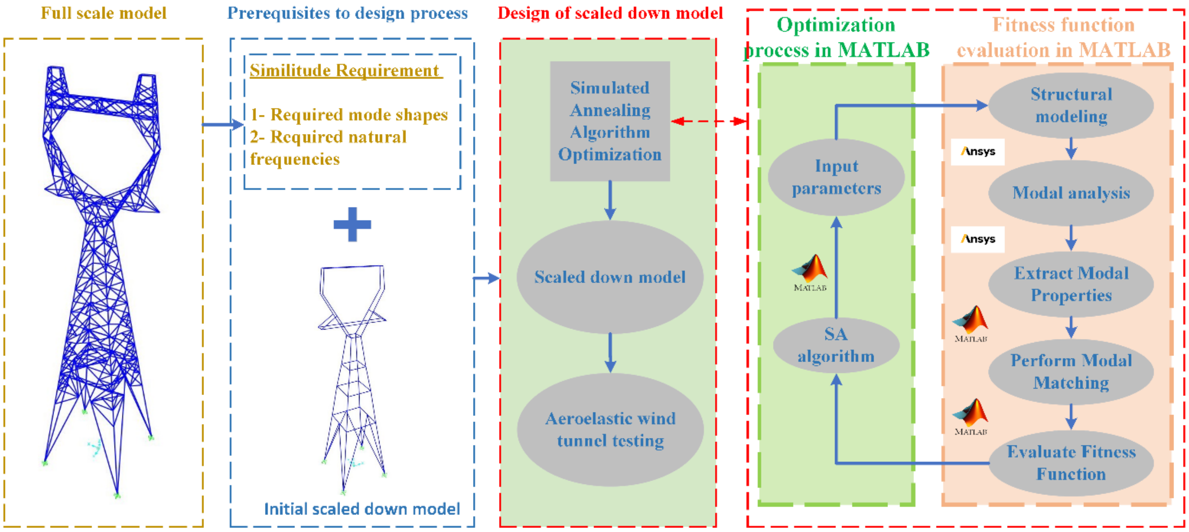

Figure 1. Flowchart of the proposed framework

3. RESULTS AND DISCUSSION

Table 1 compares the target value of natural frequencies with the values obtained through the implementation of the framework for the different weight factors cases. Also, the MAC matrix for each case is shown in Fig. 2. As shown, the proposed framework was able to design a model, achieve member sizes, that satisfies the similarity requirement as both natural frequency and MAC similarity are satisfied to an acceptable level for testing. As shown in Fig. 2, some correlation exists between orthogonal modes since off-diagonal MAC reached high values as high as 50%. This highlights the fact that the whole MAC matrix should be considered in the optimization process, not only the diagonal MAC values. Therefore, for this specific problem, it’s recommended to use the scale factor of 0.5 since it corresponds to the minimum off-diagonal error.

Table 1. Frequencies of the two mode shapes of the model compared to target values.

Frequency Weight Factor (A)		0.9	0.8	0.7	0.6	0.5	0.4
Mode 1	Target	12.1	12.1	12.1	12.1	12.1	12.1
	Model	11.86	12.00	12.33	12.33	12.49	10.42
Mode 2	Target	12.3	12.3	12.3	12.3	12.3	12.3
	Model	12.175	12.45	12.10	11.94	12.75	12.45

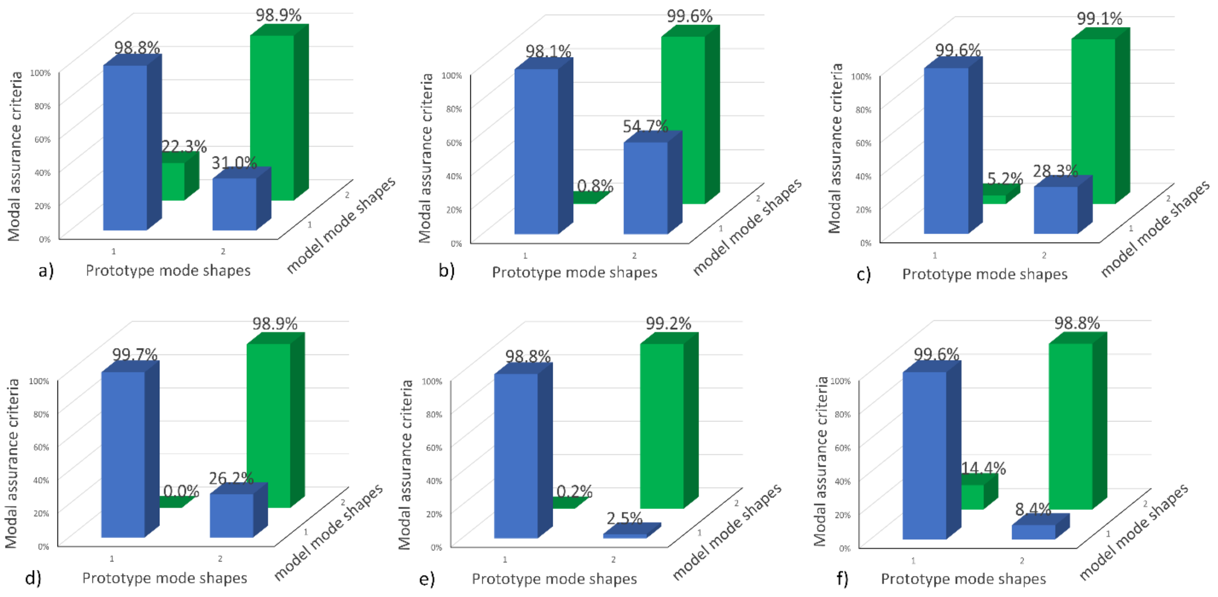

Figure 2. MAC for weight of a) 0.9, b) 0.8, c) 0.7, d) 0.6, e) 0.5, f) 0.4.

4. CONCLUSION

The proposed optimization framework was able to yield a satisfactory design of the aeroelastic model of a lattice tower while limiting the error in natural frequencies and MAC. Also, this work highlighted the need to consider the whole MAC matrix in the optimization process. For this particular case, it's recommended to use the case with scale factor of 0.5 since it yielded the minimum error in off-diagonal MAC matrix.

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