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A framework for the efficient spectral analysis of large wind- and wave-loaded structures

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ABSTRACT: This paper deals with a fast spectral analysis of structures subjected to both wind and wave loadings. It hinges on the Multiple Timescale Spectral Analysis, which is a framework generalizing the Background/Resonant decomposition and offering therefore a very rapid computation of the statistics of the structural responses. The theory developed in this paper aims at the determination of the second-order response of a floating bridge. Similar concepts are applicable to other floating structures, whose natural frequencies lies between the typical frequency bands of wind and wave loadings.

KEYWORDS: Multiple timescale spectral analysis, perturbation, Volterra series, suspension bridge, floating bridge, modal cross-correlation

1 INTRODUCTION

Spectral analysis is widely used in the buffeting analysis of large structures. It is efficient for several reasons: (i) the wind load is typically specified in the frequency domain, by means of the power spectral density of the turbulence, (ii) the analysis provides a simple answer, which is easy to understand and helps the designer optimize the structural behavior in the right way, (iii) compared to a time series analysis, the spectral analysis can be made 100 to 1000 times faster with a decomposition of the response intro the background and resonant components.

The Multiple Timescale Spectral Analysis (Denoël, 2015) offers the possibilities to extend the Background/Resonant decomposition, which is widely applied for the analysis of single degree-of-freedom structures (or in a modal basis), to the computation of modal correlation, consideration of non-Gaussian or even nonlinear structural responses (Denoël & Carassale, 2015). This type of analysis generalizes the Background/Resonant decomposition introduced by Liepmann and further spread out by Davenport in the mid 1960s. It makes the spectral analysis very efficient in many more contexts.

In particular, some evidences show that the Multiple Timescale Spectral Analysis is a perfect tool to deal with the fast analysis of Volterra systems (Schetzen, 1980). Precisely, structures subjected to wave loads, such as floating wind turbines or more recently the very audacious floating bridges projects, can be modeled by means of Volterra models (Langen & Sigbjörnsson, 1980; Kareem & Zhao, 1994). Although the current trends in the modeling of wave loads on structures consists in the generation of time-space correlated wave fields, followed by a dynamic analysis of the structure by means of heavy time stepping simulations (Aas-Jakobsen, 2001; Wang et al, 2018), it is believed that there is still a lot to learn with spectral approaches. All the more, since these methods tends to be 100 to 1000 times faster than sample generation and time domain simulation, with a very small and controllable discrepancy, they appear as an optimal solution for the analysis of large floating supporting structures, which have to be designed for various erection stages and various load combinations.

In this paper, an academic example of a suspension bridge will be developed in order to illustrate the application of the different steps of the Multiple Timescale Spectral Analysis for the analysis of large structures.

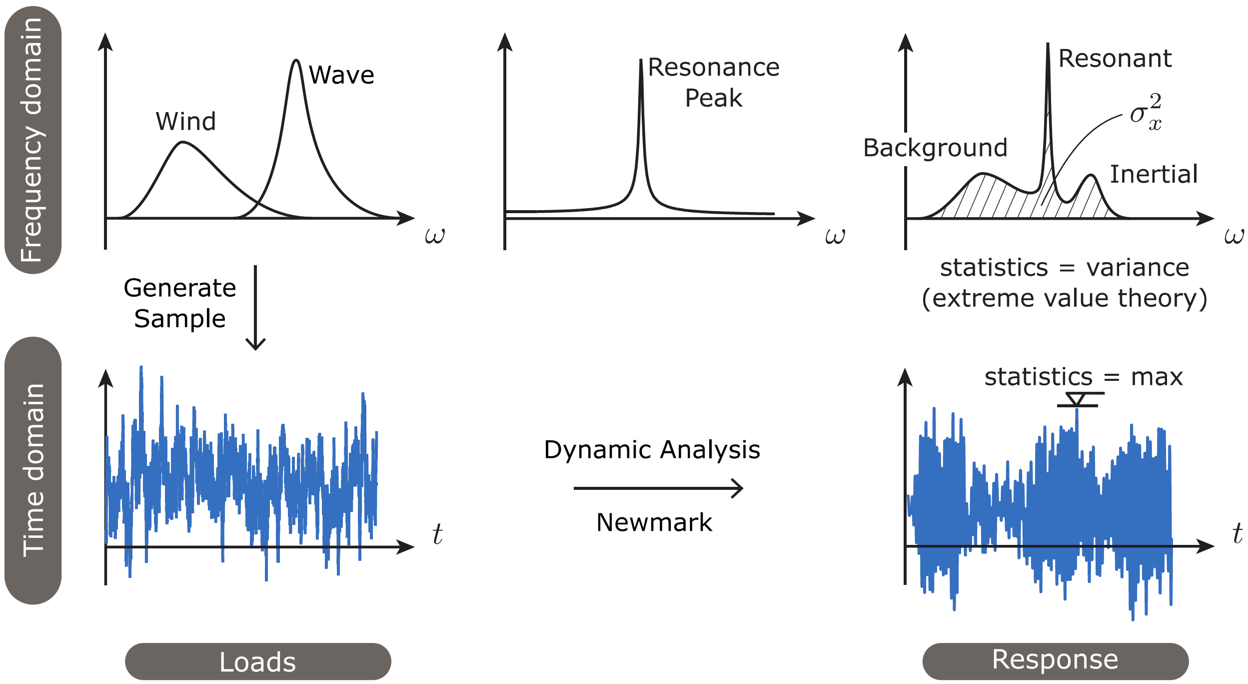

Figure 1. Illustration of the time and frequency domains approaches.

2 TIME VS. FREQUENCY DOMAIN APPROACHES - THE MULTIPLE TIMESCALE SPECTRAL ANALYSIS

Figure 1 illustrates the principles of the time and frequency domain analyses. Although taking place in specifically different domains, Parseval's theorem guarantees the equivalence between the two methods. In other words, the statistics of the maximum values in the time domain (bottom right corner) might be equivalently obtained in the frequency domain (top right corner). This fact has been well known and exploited in the context of structures with linear behavior and under Gaussian input. Many other major contributions (which will be recalled in the full paper, for consistency) have extended the theories in the frequency domain to non-Gaussian processes and extreme value theories for non-Gaussian processes.

More recently, the Multiple Timescale Spectral Analysis has been formalized in order to accelerate the spectral (frequency domain) analysis. By generalizing the well-known Background/Resonant decomposition, this theory builds up on the existence of several timescales in the structural response. In particular, for wind and wave loaded structures, it turns out that the natural frequencies of floating structures happen to be in the frequency range between the slow wind loading and fast wave loading. The structural response might therefore be seen as a summation of three components: a (quasi-static) Background response resulting from the slow wind load, a Resonant response resulting from the wind and wave energy in the frequency band located around the natural frequency, and an Inertial response resulting from the fast dynamics of the wave loading, with respect to the slower timescales of the floating structure (see Figure 1). In that case, the total response of the structural system is expressed as a sum of these three components, each of them being evaluated at very low computational cost.

A particular case of the Multiple Timescale Spectral Analysis concerns the evaluation of the cross-correlation of modal responses (Denoël, 2009). The available theories cover the buffeting analysis (but not the wave loading, to the author's knowledge) and, again, the cross-correlation of modal responses in several modes can be obtained in closed form with a simple formula. One objective of this paper is to present the extension of this approach to wave loaded structures, i.e. in the inertial regime, so that the combined wind and wave loading can be considered in a spectral approach, see Figure 2.

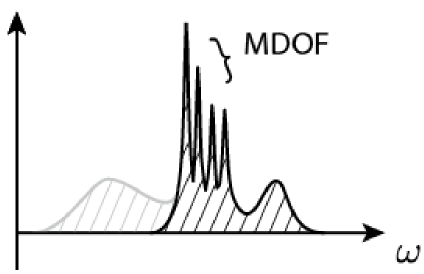

Figure 2. Conceptual extension to multi degree-of-freedom systems.

3 CONTRIBUTIONS OF THE PAPER

The novelties reported in the full paper are multifold: (i) application of these existing concepts for the single degree-of-freedom case (a modal response), (ii) development and summary of the theory to determine the second-order response of multi degree-of-freedom system (i.e. essentially the modal correlation), (iii) at last but not least application to a large-scale structure.

The large-scale structure is a low-dimensional model of a prototype floating bridge. The structural model has been linearized by means of a statistical linearization approach, since the analysis mainly focuses on the second-order response (variances and covariances of modal responses).

4 CONCLUSIONS

In all cases treated so far, the Multiple Timescale Spectral Analysis has shown remarkable accuracy in estimating the statistics of the response. This is because the method relies on clear assumptions of timescales separation, which can be very simply assessed. The method provides simple analytical solutions and captures the most important features of the response. In this paper, it has been applied to the analysis of multi degree-of-freedom structures subjected to wind and wave loading. The analysis is limited to second-order statistics. Future works will focus or applying the same concept to the higher order statistics, in order to capture the non-Gaussian features of the response.

5 ACKNOWLEDGEMENTS

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