Dynamic analysis and optimisation using morphological indicators

Thomas VANDENBERGH
Civil Engineer
Vrije Universiteit Brussel
Brussels, Belgium
tvdbergh@vub.ac.be

Thomas Vandenbergh, born 1982, received his civil engineering degree from the Vrije Universiteit Brussels (VUB) in 2005. In 2005 he started working at the dept. of Mechanics of Materials and Constructions at the VUB as a PhD student.

Willy Patrick DE WILDE
PhD, Civil Engineer
Vrije Universiteit Brussel
Brussels, Belgium
pdwilde@vub.ac.be

W.P. De Wilde, °1946, was HOD of Mechanics of Materials and Constructions at the Vrije Universiteit Brussel. He is now (part time) full professor and dedicates his time to research and teaching in the Department of Architectural Engineering.

Pierre LATTEUR
PhD, Civil Engineer
University of Gembloux
Tractebel-TDE (Brussels)
Belgium
Pierre.latteur@tractebel.com

Pierre Latteur, born 1969, graduated from the Université Catholique de Louvain and the Vrije Universiteit Brussels. He is professor of Mechanics of structures at the University of Gembloux and also in charge of the TT of Civil Engineering at Tractebel-TDE Belgium.

Summary

This paper presents a basic analysis methodology to predict if a structure meets the design requirements concerning dynamic behaviour at conceptual design stage, combining a single degree of freedom model and morphological indicators (MI). MI are dimensionless numbers allowing to represent a structural property (volume, displacement, eigenfrequency,…) with a limited numbers of variables. The theory of MI is based on the use of a fully stressed design and optimisation from the point of view of resistance (Ultimate Limit State). Achieving satisfying vibration behaviour of a structure is a serviceability constraint (Serviceability Limit State) and is therefore not necessarily met by ULS-optimised solutions, especially in lightweight design. If the vibration behaviour is not acceptable the possibilities offered by a tuned mass damper, topology modification and stress level reduction are discussed. In this case, the use of MI as a design tool is no longer advantageous.

Keywords: conceptual design; volume minimisation; morphological indicators; tuned mass damper; resonance.

There appears to be a trend in structural engineering towards the use of more slender and larger structures. Therefore structural engineers are much more likely to be required to design dynamically responsive structures than in earlier decades. Without underestimating the importance of a complex dynamical study of a structure during its detailing phase, there is a need to be able to predict potential problematic dynamic behaviour as early as the conceptual phase of the project. The sooner a problem is identified, the easier the project can be adapted.

The aim of the first part of this paper is to give a general overview of existing vibration guidelines with focus on excitation sources due to people, machines, traffic and wind. The second part offers a design analysis at conceptual design stage considering dynamic effects like resonance, e.g. induced by (synchronized) walking people. Aerodynamic effects are not considered, since they ask very often for a detailed analysis and/or experiments in wind tunnels. Earthquake induced vibrations also ask for a more specific and detailed approach and are therefore not treated here.

The vibration to which a structure may be subjected is usually considered with respect to its effect on the structure itself, and not on its occupants, equipment or machinery. Nevertheless, it is important to underline that even when the level of structural vibration is considered intolerable by the occupants, the risk of structural vibration is usually very small. Hence, in order to achieve acceptable vibration behaviour of a building and its structural members (under serviceability conditions) not only the functioning of the structure or its structural members has to be guaranteed but also the comfort of the user. Nowadays there are two main concepts for satisfying serviceability: the first requires a calculation of the actual dynamic response and checking if it is within acceptable limits, usually expressed as an upper limit on the maximal acceleration of the structure. The second approach is based on the request to avoid structural natural frequencies within the excitation range

https://doi.org/10.2749/222137908796293910

since this can potentially yield resonance.

By solving the differential equations describing the movement of a single degree of freedom system, one can plot the non-dimensional acceleration of the system as a function of the relative excitation frequency. The non-dimensional acceleration is defined as the maximal vibration acceleration multiplied by the generalized covibrating mass and divided by the generalized excitation force. The relative frequency is the ratio of the excitation frequency on the natural eigenfrequency of the structure.

The concept of morphological indicators enables to predict the fundamental eigenfrequency at conceptual design stage without detailed dynamic analysis, using a reduced number of variables describing the shape and topology of the fully stressed structure. Given the range of excitation frequencies, it is possible to evaluate the relative frequency excitation interval and the non-dimensional acceleration under harmonic excitation for systems with structural damping. This result should be compared to the limit acceleration values given in norms and design guidelines. If the vibration constraint is not met, one can opt for different solutions:

Frequency modification: by changing the design (shape and topology), the first eigenfrequency (and therefore all others) can be increased outside the resonance region. The impact of shape and topology modification on the displacement and the volume can be evaluated with the indicator of displacement and volume.

In order to lower the acceleration one can decide on the use of a *TMD*, positioned at the anti-node of the vibration mode, in order to be effective. This paper enables to assess the impact of a *TMD* on the dynamic response of a structure. If the acceleration exceeds the tolerated level outside the resonance region a *TMD* is of no use, since it is tuned to be efficient at resonance. The undamped *TMD* has a narrow bandwidth, which implies that small perturbations of the excitation frequency yield a very large and unacceptable acceleration. Therefore, the use of undamped *TMD*s is of very limited effectiveness, since the excitation frequency is usually not precisely determined. Numerical simulations yield optimal *TMD* characteristics in order to minimize the non-dimensional acceleration for every *TMD* mass ratio.

Finally, one can decrease the allowable stress level and by this mean increase the self weight of the structure. The eigenfrequency only varies slightly since both the stiffness and the covibrating load increase. Though, the extra covibrating load leads to a higher allowed non-dimensional acceleration and therefore results in acceptable accelerations. Within the frame of volume optimization this last solution of radical mass increase is to be avoided.

Finally, it should be mentioned that this method is valid under the following assumptions:

- the structure can be modelled by a single degree of freedom;
- the indicator of fundamental eigenfrequency can be predicted with the indicator of displacement;
- only planar vibration modes are considered;
- the self weight of the structure is small compared to the external load and/or is assumed to be distributed like the external forces;
- the structure is excited by a harmonic load.