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Energy flow prediction in built-up structures through a hybrid finite element/wave and finite element approach

Y. Fan [a,b], M. Collet [a], M. Ichchou [a,*], L. Li [b], O. Bareille [a], Z. Dimitrijevic [c]

[a] *Laboratoire de Tribologie et Dynamique des Systemes, Ecole Centrale de Lyon - 36, Avenue Guy de Collongues, 69134 Ecully, France*
[b] *School of Energy and Power Engineering, Beihang University - 37, Xueyuan Road, 100191 Beijing, China*
[c] *PSA Peugeot Citroën - F-78943 Vélizy-Villacoublay Cedex, France*

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ABSTRACT

This paper presents a rapid and accurate numerical tool for the energy flow evaluation in a periodic substructure from the near-field to the far-field domain. Here we suppose that the near-field part contains a point source characterized by the injected power in the structure. The near-field part is then modeled by Finite Element Method (FEM) while the periodic structure and the far-field part are regarded as waveguides and modeled by an enhanced Wave and Finite Element Method (WFEM). Enhancements are made on the eigenvalue scheme, the condensation of the unit cell and the consideration of a reduced wave basis. Efforts are made to adapt substructures modeled by different strategies in a multi-scale manner such that the final matrices dimensions of the built-up structure are largely reduced. The method is then validated numerically and theoretically. An application is presented, where a structural dynamical system coupled with periodic resistive piezoelectric shunts is discussed.

1. Introduction

Wave propagation characteristics are of utmost significance to the vibration and acoustic performance of structures. At low frequencies, a structure can be regarded as a closed system. The structural motion is dominated by well separated global stationary modes induced by the reflected waves from the boundaries. While at higher frequencies, the waves could be transmitted through the boundaries and power is radiated or absorbed in the remote parts of the structure [7]. Consequently, the structure is more suitable to be treated as an open system where resonance behavior is less apparent. In terms of vibration mitigation, at low frequencies efforts are mainly addressed on the control of the dominating modes [17]. However at mid- or high frequencies it is more common to concentrate efforts on the energy distribution and flow [16].

It is well known that periodic structures feature the frequency band gaps in which certain propagating waves become evanescent. Hence these waves cannot transfer energy in the structure. In the absence of any damping, the propagation constants of such waves remain unchanged (0 or $\pm\pi$) in the band gaps. Langley [15] showed that these waves in the band gaps do not contribute to the overall modal density of a finite periodic structure. In other words, the periodic structure tends to have less natural modes in the band gaps, therefore it probably would have lower response. It finally came to the idea of integrating periodic waveguides into the host structure and intentionally design the frequency locations of band gaps so that they cover the

* Corresponding author.
E-mail address: mohamed.ichchou@ec-lyon.fr (M. Ichchou).

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excitation frequencies. This idea has been examined in numerous literature, as reported by Spandoni et al. [24] and Chen et al. [3] on plate-like structures or Xiao et al. [29] and Yu et al. [30] on 1D waveguides. It was shown that band gaps can be caused by the inhomogeneity in the unit cell (termed Bragg gap) or the local resonance (termed LR gap). Mead [19,20] proved that the frequency locations of the band gaps are equal to the natural frequencies of a unit cell of the periodic structure with certain boundary conditions. This connection was further explained by Xiao et al. [28] with a rather simplified model. This feature enables one to design the frequency locations of band gaps simply by a structural modal analysis without the knowledge of the whole dispersion curves. In most of the literature [27,11,3,24] where band gaps are considered, finite periodic structures were used. The reduction of structural vibrations were examined by evaluating the frequency response function inside the band gaps.

However, from a more practical point of view, the results concerning periodic structures in the literature need to be further extended for the following reasons. Firstly, it might be very hard to have pure periodic structures in practice due to the unavoidable non-periodic geometric or material complexity. Let us consider integrating a periodic substructure in a car chassis to control the energy injected from the engine, shown in Fig. 1. The geometric and material properties near the excitation (the engine) are non-periodic and cannot be largely modified. Though periodic substructure can be designed on the subsequent frame, the overall system (the chassis) is not pure periodic. Secondly, ‘how many unit cells are sufficient for the vibration reduction of the host system?’ remains a question which could not be directly answered by the free wave characteristics summarized in the dispersion curves. Instead, the question can be addressed more intuitively by evaluating the forced response and energy flow in the built-up structure. Thirdly, it is more appropriate to examine the performance of periodic waveguide in an open system context in terms of energy flow. It is due to the fact that the Bragg band gaps are generally mid- and high frequency phenomena where the waves and energy could be transmitted through the boundaries.

The mechanical model considered in this paper can be used to target these problems. As shown in Fig. 2, the considered structural system consists of (1) *near-field* part which is subject to external excitation; (2) *far-field* part which is located after the intentionally designed periodic substructure, and at mid- and high frequencies can be regarded as an infinite and uniform media; and (3) *periodic substructure* located between near-field and far-field (with several unit cells).

The proposed assembled model is not only for a more realistic representation of the engineering applications, but also for the full investigation of the performance of the designed periodic substructure in terms of wave and power diffusion. In the

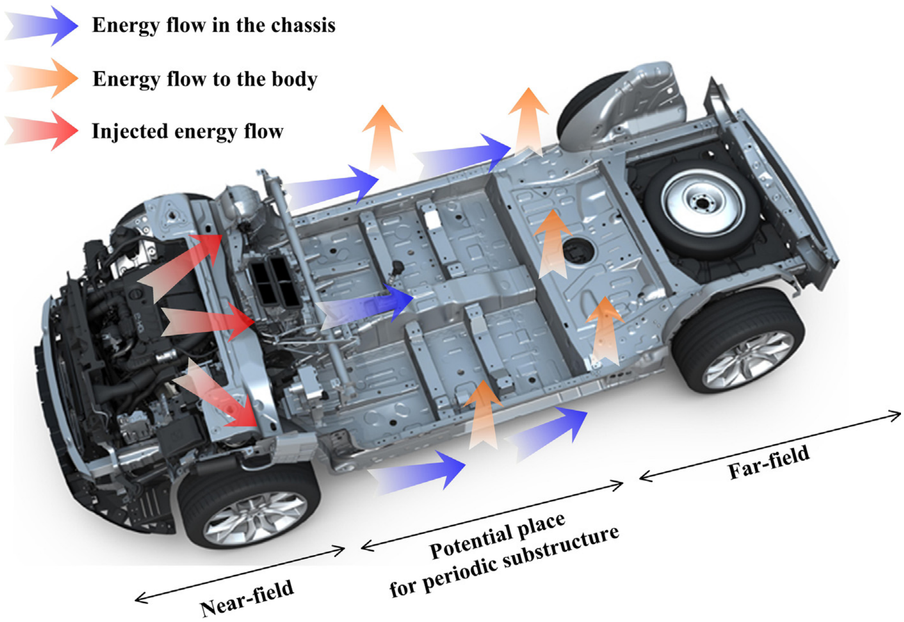

Fig. 1. Illustration of energy flow in a car chassis.

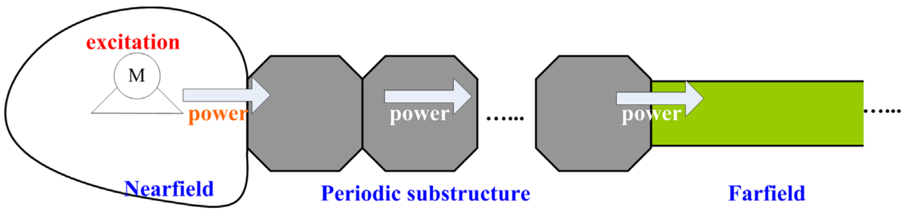

Fig. 2. The proposed mechanical model for evaluating a periodic substructure.