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# Actuation and measurement of nondispersive near-cut-on guided resonances in a sandwich structure

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## Abstract

In this work, we establish a link between recent investigations on bending-to-shear conversion phenomena in sandwich structures, and the existence of a local group velocity plateau in the near-cut-on bandwidth of high-order guided resonances. The resulting non-dispersiveness allows the actuation and propagation of these elastic waves over a long range, which is unusual for such structures in the low acoustic bandwidth. The experimental set-up involves an array of piezoelectric patches, designed to produce a custom wave shape displacement field as predicted by Floquet-Bloch theory.

## 1 Introduction

The ability to predict, understand and exploit some of the singular wave propagation features of complex media is the cornerstone of most recent achievements in the fields of vibroacoustics, the scientific enthusiasm about metamaterials applications being one of its most recent exemplification.

The strive for lightweight structures with enhanced vibroacoustic performances - despite its many advantages - tends to make the structural health assessment more difficult. For decades, Guided Wave Testing (GWT) has been successfully used to perform long-range damage inspection in large-scaled aerospace and offshore parts [1, 2, 3, 4, 5, 6, 7, 8, 9]. In the transportation industry, the use of composite materials and increasingly complex micro-architectures is largely responsible for a limited applicability of GWT as well as state-of-the-art NDT/E techniques. Examples of such structures are typically meta-materials [10], locally resonant [11] or bio-inspired [12] structures. Additionally, many other periodic designs can be used to enhance a structure's vibroacoustic properties (see [13, 14] for example).

In honeycomb sandwich panels alone, the scattering of Lamb waves has been the subject of countless investigations. The actuation, measurement and scattering phenomena affecting so-called Guided Resonances (GR) which are a specific type of high-order modes propagating in waveguides with finite section, have received a very seldom attention in composites, and are hence the focus of the present work. Ring mode and high-order Lamb wave transducers have been widely investigated [15, 16, 17, 18]. Experimental observations of singular GR effects have been made recently by Droz et al. [19] and Serey et al. [20]. Such guided resonances have been rarely generated experimentally in composites. Near-cut-on guided resonances have never been studied, nor observed in sandwich structures. Despite their computational cost, numerical methods have shed new lights on the coupling and conversion effects affecting the propagation of guided waves in sandwich or multi-layer core topology structures. Numerical methods are critical to design such transducers as the knowledge of both the wave dispersion characteristics and the unit-cell mode shape are required for an effective actuation.

We propose in this work the synthesis of a numerical-experimental investigation of near-cut-on GR propagation in a sandwich panel. Floquet-Bloch formulation is used on the entire - finite - width of a honeycomb plate. The bending-to-shear transition effect is then analyzed, revealing a near cut-on bandwidth displaying a group velocity plateau, resulting in local non-dispersiveness. The actuation is based on an array of piezoelectric patches, while full-field velocimetry is used to observe the transient pulse conversion and dispersion over a 3 meters-long waveguide. Overall, this work aims to explore innovative solutions exploiting low/mid-frequency wave-based phenomenon, with the potential of extending GWT to large-scaled periodic structures such as metamaterials.

The paper is organized as follows: (i) the computation of wave dispersion characteristics using a direct Floquet-Bloch modelling technique (WFEM) on a finite cross-section ; (ii) the identification of a bandwidth where conversion phenomena enables non-dispersive propagation in a sandwich waveguide ; (iii) a concept of guided resonance actuator exploiting our knowledge of dispersion and detailed waveshape information, (iv) the experimental realization using full-field velocimetry.

## 2 Floquet-Bloch modelling

The wave dispersion characteristics are computed using a WFE framework. A periodic cell of the waveguide is modelled using standard FE. Then, denoting  $\mathbb{K}$ ,  $\mathbb{C}$ ,  $\mathbb{M}$  the finite element stiffness, damping and mass matrices of the unit-cell and  $\mathbf{u}$  the discretized displacements, the governing equation writes:

$$\mathbb{M} \frac{\partial^2 \mathbf{u}(t)}{\partial t^2} + \mathbb{C} \frac{\partial \mathbf{u}(t)}{\partial t} + \mathbb{K} \mathbf{u}(t) = \mathbf{f} \quad (1)$$

Introducing the dynamic stiffness sub-matrices denoted  $\mathbb{D}_{ab}(\omega) = \mathbb{K}_{ab} + j\omega\mathbb{C}_{ab} - \omega^2\mathbb{M}_{ab}$  with  $a$  and  $b$  the left and right sides degrees of freedom of the unit-cell, the dynamic equation becomes:

$$\begin{bmatrix} \mathbb{D}_{LL} & \mathbb{D}_{LR} \\ \mathbb{D}_{RL} & \mathbb{D}_{RR} \end{bmatrix} \begin{Bmatrix} \mathbf{u}_L \\ \mathbf{u}_R \end{Bmatrix} = \begin{Bmatrix} \mathbf{f}_L \\ \mathbf{f}_R \end{Bmatrix} \quad (2)$$

The WFEM exploits the periodicity of the waveguide to derive the propagation constants  $\Lambda$  and eigenvectors  $\Psi$  from the direct Bloch formulation:

$$[\mathbb{D}_{RL}(\omega)\Lambda^{-1} + (\mathbb{D}_{RR}(\omega) + \mathbb{D}_{LL}(\omega)) + \mathbb{D}_{LR}(\omega)\Lambda]\Psi = 0 \quad (3)$$

Interested reader can refer to [21, 22, 23] for details about the WFEM implementation and computational aspects. In classic metamaterial or periodic structures, inner degrees of freedom are also present. A common strategy for Direct formulation of the spectral eigenproblem consists in achieving a direct condensation of the inner DOFs. Matrix  $\mathbb{D}$  then denotes the condensed dynamic stiffness matrix. Alternatively, the dispersion relation can be written without dynamic condensation with the following form:

$$\mathbf{X}(\lambda) \begin{Bmatrix} \mathbf{u}_L \\ \mathbf{u}_I \end{Bmatrix} = \begin{Bmatrix} \mathbf{0} \\ \mathbf{0} \end{Bmatrix},$$

where  $\mathbf{D}(\lambda)$  is a function of  $\lambda$  whose coefficients are the non-condensed dynamic stiffness sub-matrices:

$$\mathbf{D}(\lambda) : \mathbf{D} \longrightarrow \begin{bmatrix} \mathbf{D}_{RL} & \mathbf{D}_{RI} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \frac{1}{\lambda} + \begin{bmatrix} \mathbf{D}_{RR} + \mathbf{D}_{LL} & \mathbf{D}_{LI} \\ \mathbf{D}_{IL} & \mathbf{D}_{II} \end{bmatrix} + \begin{bmatrix} \mathbf{D}_{LR} & \mathbf{0} \\ \mathbf{D}_{IR} & \mathbf{0} \end{bmatrix} \lambda.$$

The solutions of this quadratic eigenvalue problem are written as pairs  $(\lambda(\omega), \Phi(\omega))$  using a wavematching procedure, where  $\lambda = \exp(-jkd)$  and  $\Phi$  are respectively the propagation constant and the waveshape. The spectral problem admits twice as many solutions as DOFs in the chosen state vectors, which may lead to numerous evanescent solutions. A filtering can therefore be used to eliminate waves exhibiting a high spatial

decay. A wavematching algorithm is used to track the frequency-dependent wavenumbers and derive the group velocities.

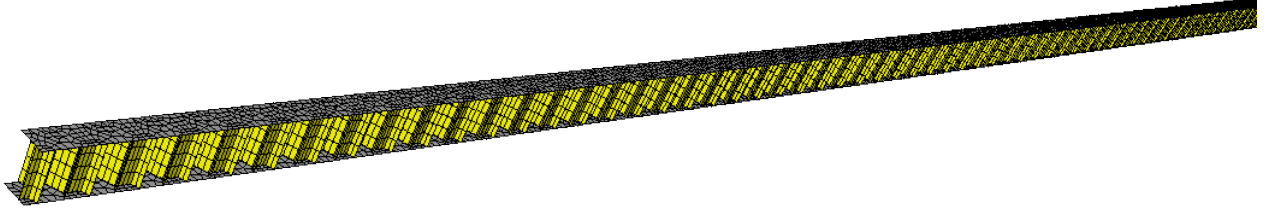


Figure 1: Periodic unit-cell of the honeycomb sandwich plate.

The finite section serving as a periodic unit-cell for the sandwich panel is shown in Figure 1. Note that the unit-cell FEM extend on the entire width of the structure. Conditions at the edges is set to free-free.

### 3 Transition and non-dispersiveness

The spatial decay of a wave pulse propagating in a dispersive media is related to the chromatic dispersion. We define the group velocity dispersion as the chromatic dispersion per unit-length. Therefore, the knowledge of the frequency-dependent group velocity is necessary to predict the dispersive and non-dispersive bandwidth. In other words, the spatial dispersion of a wave pulse increases with the slope of the group velocity in a given bandwidth. In the low acoustic range, the dispersion behavior of sandwich composites can be described using a 4<sup>th</sup>-order wavenumber ( $k$ ) - frequency ( $\omega$ ) relation:

$$Sk^4 - \mu\omega^2k^2 - \mu\omega^2\frac{S}{D} = 0 \quad (4)$$

where  $D$ ,  $S$  and  $\mu$  are the bending stiffness, transverse shear rigidity and mass per unit-area, respectively. One can then predict the two asymptotic bending  $\left(c_g^{LF} = 2\sqrt{\frac{D}{\mu}}\sqrt{\omega}\right)$  and shear  $\left(c_g^{MF} = 2\sqrt{\frac{S}{\mu}}\right)$  group velocities. In between the flexural wave is subjected to a conversion process called bending-to-shear transition [24, 25] centered around a local maximum  $\left(\frac{\partial c_g}{\partial \omega} = 0\right)$  called the transition velocity, and responsible for the only non-dispersive point achievable in the low frequency bandwidth [26]:

$$c_g(\omega_T) = \frac{4}{3}\sqrt{\frac{2S}{3\mu}} \quad (5)$$

In addition, the non-dispersiveness predicted in the shear region upon this model is rarely achievable due the appearance of a local skin bending behavior at higher frequencies (i.e. 6<sup>th</sup>-order dispersion relation). This transition frequency is therefore the only possible non-dispersive point in the low acoustic range.

The group velocities computed using the Floquet-Bloch formulation and the finite element model depicted in Figure 1 are displayed in Figure 2a. Note that despite their similarity in terms of dispersion curves, the guided resonances are not to be confused with Lamb waves. For comparison, the dispersion curves of an homogeneous thick plate of same dimensions are given in Figure 2b. Noteworthy, no transition is present in the second case (b), resulting in high dispersiveness within the entire bandwidth, while the sandwich structure (a) exhibit the expected asymptotic behavior around 4 kHz. Note however that high-order modes are producing an early conversion before reaching their asymptotic shear behavior. Although the generation of high-order GRs at low frequency is usually limited by the strong chromatic dispersion near the cut-on frequency, this near-cut-on plateau on the group velocities is expected to produce almost non-dispersive waves shortly above the cut-on frequency of each GR.

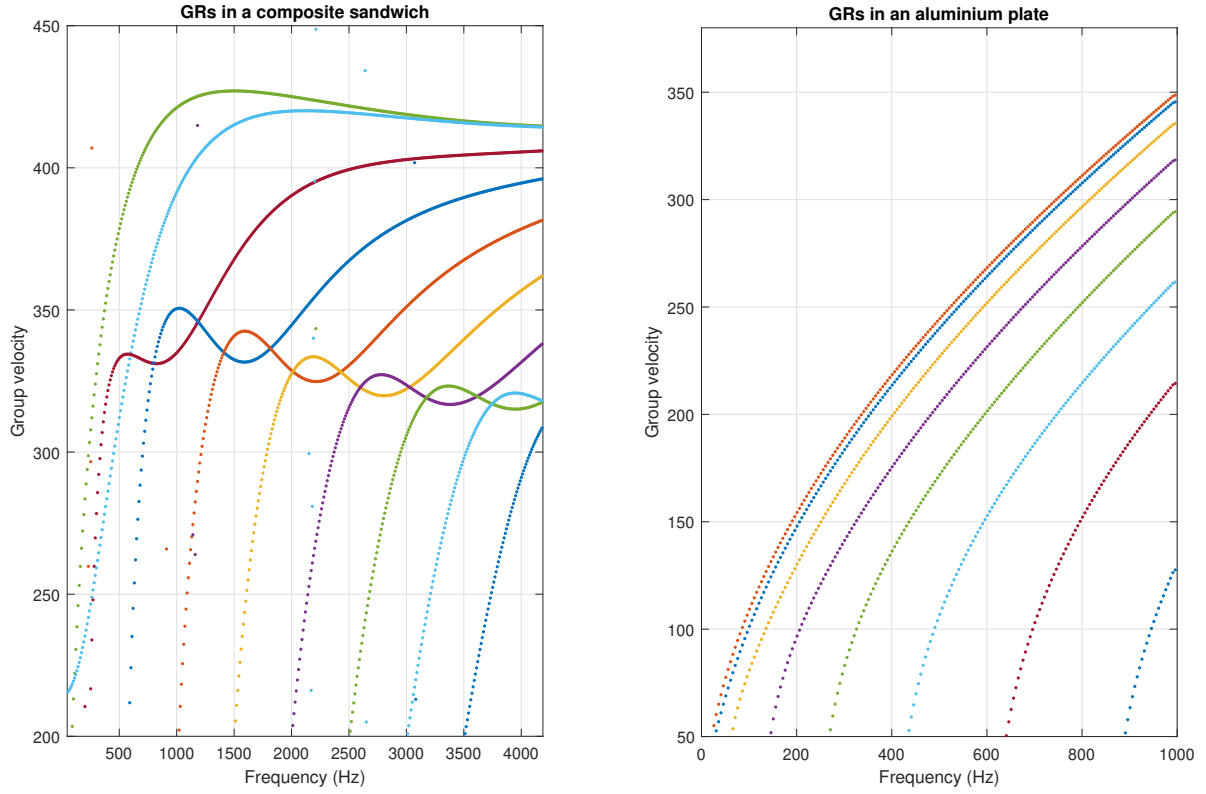


Figure 2: (a) Group velocities of the sandwich structure. (b) Group velocities for an homogeneous plate. Both structure have a finite cross-section responsible for the appearance of the high-order guided resonances (GR).

## 4 Guided resonances and GR Transducer concept

The generation of guided resonances over a large cross-section is more challenging than the one of Lamb waves. Note beforehand that although the wave shapes are generally frequency-dependent, the GRs observed in Figure 2 are fairly frequency-independent (some minor edge localization effects can be observed during the transition). This property can advantageously be used to design custom wave transducers using mode force appropriation techniques and exploitable over a broadband frequency range. The concept can be seen as the excitation of a normal mode of the cross-section, at a selected frequency, as described in 3. It was shown in [27] that the application of punctual loads corresponding to a given GR shape could be sufficient to generate the corresponding GR, without conversion into evanescent or high-order GRs. Note that this is generally not applicable in higher frequencies.

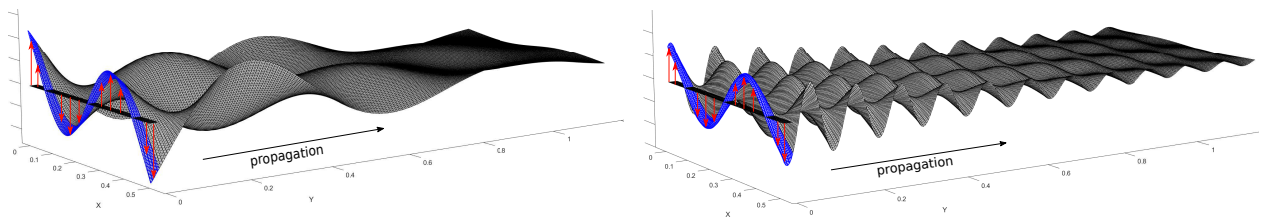


Figure 3: Illustration of the concept of frequency-dependent GR actuation (reproduced from [19]).

Given the thickness of the plate, it is therefore preferable to apply surface moments corresponding to the desired wave shape using bending transducers. The shape of the 8<sup>th</sup>-order GR is shown in Figure 4. Excluding the edges, one can identify 7 anti-node locations. Using the actuation concept described in [19], 14 piezoelectric patches are placed on the section to produce GR 8 without conversion.

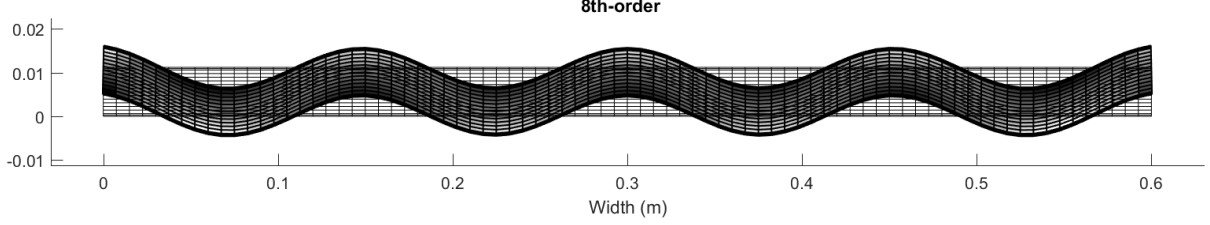


Figure 4: Shape of the 8<sup>th</sup>-order GR, computed at 4 kHz using Floquet-Bloch theory.

## 5 Experimental setup

The sandwich structure is 600×2890mm, composed of 0.6mm-thick CFR skins and a 10mm-thick Nomex honeycomb core core.

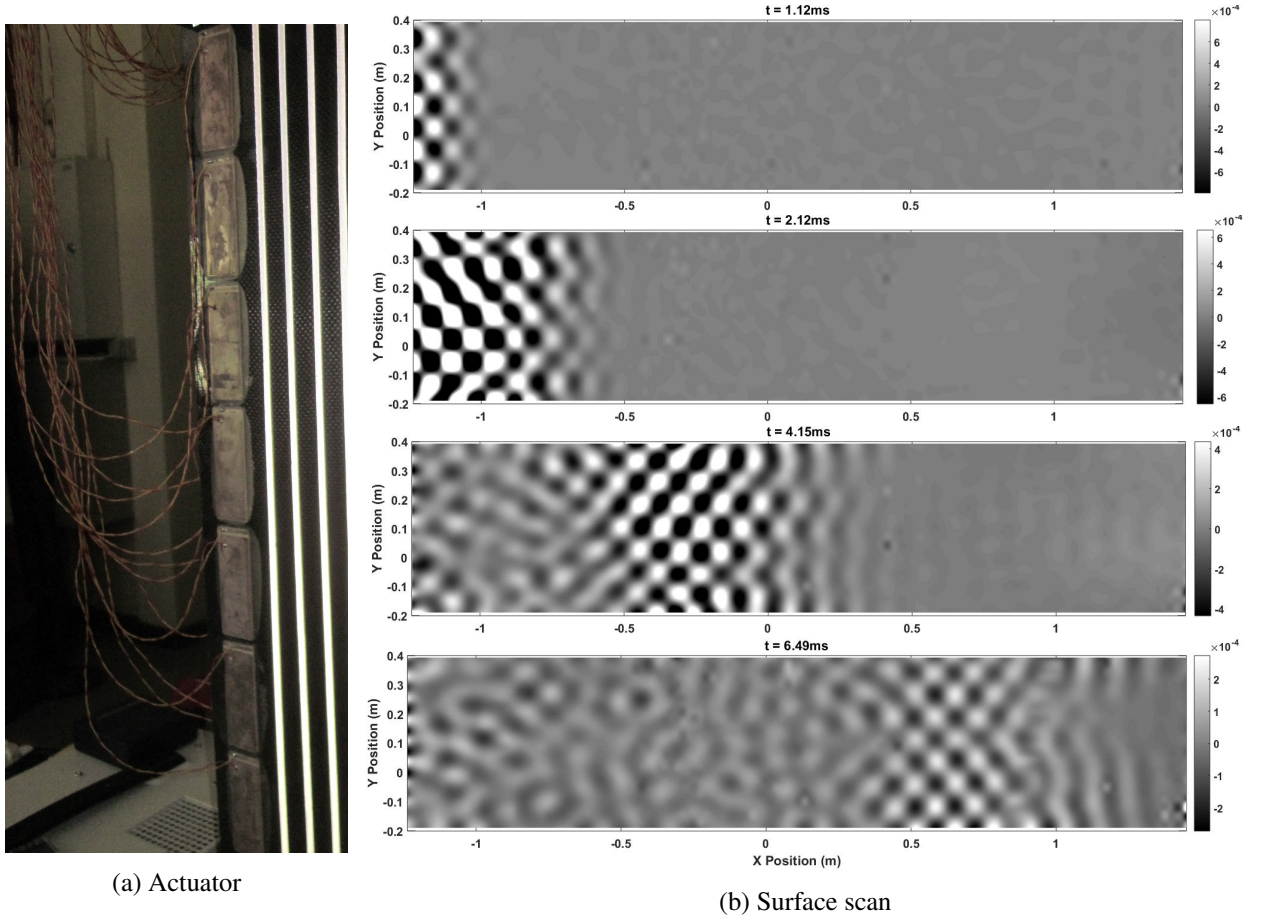


Figure 5: Description of the experimental set-up: the piezoelectric patches are located on the left side of the plate. The transient propagation of GR 8 over the entire structure (3 m long) is measured using full-field velocimetry. The time snapshots are shown at  $t = 1.1, 2.1, 4.2$  and  $6.5$  ms.

Measurements are made using a PSV-400 velocimeter. The cut-on frequency of the targeted wave is located around 2.7 kHz, while the non-dispersive region is observed between 4 and 4.5 kHz. Details on the experimental protocol are given in [19]. The transducers are actuated at 50 V using an 8-cycles impulsion centered at 4 kHz. Results and wavefield processing technique are described in [28]. A picture of the actuation device is shown in Figure 5a.

The results show a propagation of the wave pulse over nearly 3 m with almost negligible spatial dispersion. The noticeable amplitude decay observed is expected in a sandwich composite. The imperfection of the actuator yields higher- and lower-order wave components which are visible in the last time frame of Fig. 5a. Low-order GRs propagate at higher velocities and are therefore observed in front-end of the pulse, while higher-order GRs are on the back-end of the pulse. Note that since the actuated GR is close to its cut-on frequency, higher-order GRs are mainly evanescent or have almost 0 group velocity. This phenomenon explains the residual displacement field close to the piezoelectric patches in Fig. 5a. The quasi-non-dispersiveness obtained at 4 kHz is due to the group velocity plateau identified in Fig. 2a.

## 6 Conclusions

In this work, Floquet-Bloch theory was used to design near-cut-on guided resonance transducers in a sandwich composite. The wave are propagating over a long distance thanks to a local non-dispersiveness resulting from a group velocity plateau associated with a bending to shear conversion of high-order waves. Noteworthy, these conversion are producing veering between pairwise GRs (i.e. GR 2 - GR 4, GR 3 - GR 5, GR 4 - GR 6 etc.). A possible explanation for the two-step transition of higher-order GRs lies in the existence of a different transverse shear modulus in the X and Y directions. There are therefore two transitions, associated with two different asymptotic shear velocities. The relation between the extent of the group velocity plateau and the occurrence of these two consecutive transitions deserves further investigation. However, taking advantage of reduced formulations for the Wave Finite Element Method, this work was able to link previous research on transition phenomena and experience on normal mode-force appropriation to generate high-order propagating waves in a composite structure near their cut-on frequency.

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