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# Numerical investigations and experimental measurements on the structural dynamic behaviour of quasi-periodic meta-materials

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## Abstract

The periodic structures have various applications in vibroacoustic engineering fields since they introduce frequency band effects due to the periodic discontinuities in the geometrical or material configurations: this can lead to increased performances. This paper is focused on the analysis of quasi-periodic structures: instead of using strictly repeated patterns, a certain degree of irregularity is introduced. Quasi-periodic lattices are defined as assemblies of two different elements in two directions. The assembly follows a Thue-Morse Morphism sequence which results in asymmetry in both directions. Numerical studies and experimental measurements on two-dimensional periodic and quasi-periodic lattices are thus performed. First validations are carried out by comparing the quasi-periodic lattice modelled by using finite element model with a prototype manufactured by laser machine. The wave characteristics in quasi-periodic lattice introduce elements of novelty for designing wider frequency stop bands in low frequency ranges.

*Keywords:* Quasi-periodic structures, band diagram, frequency stop-band, forced response, metamaterials

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## 1. Introduction

Recent literature review shows the design of metamaterials as one of the central topics in the vibroacoustic analysis of periodic media. There are interesting subjects in the literature linked to the current investigation which is intended mainly to the design of new architected metamaterials (i.e. lightweight, easy-to-manufacture, and low frequency stop band properties, noise and vibration reduction)[1], [2].

Periodic structures create stop bands effect due to the geometrical and/or material impedance mismatches that can result in great vibroacoustic performances. In terms of material properties, there are various cases that show in-plane and out-of-plane elastic properties. For example the dynamical behaviour of a  $2D$  periodic waveguide, which exhibits in-plane elastic properties (Young's and shear modulus) compared to out-of-plane ones, are described in terms of elastic wave propagation in [3, 4]. The possibility of designing such smart materials or structures, that can partially reduce mechanical waves on certain frequency ranges, is addressed in [5, 6, 7]. Geometrical discontinuity also plays a central role in creating stop band effects; as an example, sandwich beams with periodic auxetic core, exhibiting impedance mismatch generated by varying elastic and mass properties of the core, are able to produce stop band effects [8, 9]. More complex shapes like star shaped honey-combs can be designed to provide frequency stop band behaviour in low frequency regimes [10].

The quasi-periodicity concept which is investigated in this paper can be interpreted as a certain degree of irregularity introduced in a periodic pattern. According to the literature, there are numerous examples of disordered periodicities and/or uncertainties in real structures, like bridges with column spans, and array of fuel tanks interconnected with each other by flexural links. The issues of the non-perfect periodicity in real structures can also be attributed to errors in manufacturing processes [11]. The presence of defects and imperfections in geometric and constitutive properties of the structures is generally referred as *disorder* [12]. Numerical solutions of these types of disordered systems can lead to the need of full stochastic approaches [13]. When the irregularity is localized in space (a 'defect in the periodic arrangement), phenomenon of Anderson

31 localization may occur, evidencing that the vibration propagation in a structure is not  
32 entirely regular and that could be impeded by the irregularities, giving rise on the av-  
33 erage to an exponential decay of vibration level [14, 15]. They also demonstrates an  
34 example of a string with regular and irregular spacing of added masses in order to use  
35 it as a sort of passive vibration control.

36 On the other hand, the imperfections can be engineered and used as design parameters  
37 to tailor the dynamic behaviour. Among others, sequences of impedance mismatches  
38 built on numerical series like Fibonacci, Thue-Morse or Rudin Shapiro can be consid-  
39 ered as design templates for the engineered irregularity [16].

40 Hou et al., [17], stated that robust quasi-periodic design may offer new vibroacoustic  
41 properties to the structures. This robust design refers to the investigation of the trans-  
42 mission properties and the frequency spectra of a Fibonacci composite material with  
43 different thickness ratio of two layers. Similarly Aynaou et al. investigated theory of  
44 acoustic wave propagation on  $1D$  phononic band gap structures made of slender tube  
45 loops pasted together with slender tubes of finite length following Fibonacci sequence  
46 [18]. In another example similar topological configuration of Fibonacci and Thue-  
47 Morse sequences are investigated with an experimental observation of the phononic  
48 scattering band structure in  $1D$  quasi-periodic systems[19]. A  $1D$  bar is designed using  
49 Fibonacci sequence for stop band distribution and prestress effects by [20, 21].

50 The current work is based on the analysis of quasi-periodic  $2D$  structures. A determin-  
51 istic approach is taken into account to introduce a two directional Thue-Morse sequence  
52 for creating a quasi-periodic meta-material to improve the vibroacoustic performances.  
53 In the literature there are various examples of  $1D$  quasi-periodic systems for the dy-  
54 namic analysis; on the contrary,  $2D$  quasi-periodic systems are very rare. Some se-  
55 quences are intrinsically ready to be used for  $2D$  cases as the Thue-Morse, while others  
56 like Fibonacci are well adapted to the  $1D$  cases.

57 In this paper, two dimensional lattices are built with the conventional finite ele-  
58 ment method (FEM) to comply with the Thue-Morse sequence in order to explore the  
59 opportunities offered in terms of reduction of the forced response in some frequency  
60 bands[22, 23]. Specifically, the work presents modified versions of star-shaped con-  
61 cave unit cells.

62

63 The tailored quasi-periodicity is defined by invoking a bi-directional Thue-Morse Mor-  
64 phism sequence on the meta-material. The geometrical impedance mismatch results in  
65 asymmetry and follows a combination of two different star-shape elements by variation  
66 of different corner angles. The main target of the study is the design of structural stop  
67 band/filters in order to isolate maximum vibration level in some frequency ranges.

68 The contents of this paper is structured as follows. In section 2, quasi-periodic struc-  
69 ture is presented. Section 3 introduces the Wave Finite Element Models: dispersion  
70 analysis. On the contrary, in section 4, experimental results are validated. Section  
71 5 describes the structural dynamic analysis using Finite Element models. A closing  
72 section summarise the conclusion of this work.

## 73 **2. Quasi-periodic structures**

74 In this paper the focus is on the application to  $2D$  domains of the Thue-Morse  
75 sequence for introducing irregularity in both directions. In this section a possible ap-  
76 proach is presented to analyse the vibration performances of quasi-periodic  $2D$  struc-  
77 tures.

78 Quasi-periodic structure section contains three sub-sections. The first one is ded-  
79 icated to the cells description, followed by the second sub-section that introduces the  
80 Thue-Morse Morphism sequence, while the third sub-section concludes with the peri-  
81 odic sequence.

### 82 *2.1. Cells*

83 The waveguide is a star-shaped lattice. The meta-material is made of two different  
84 unit cells (A and B). Fig. 1 shows the geometry of the two cells inspired from [24].  
85 The difference between the two unit cells is in the angles  $\alpha$ , which defines the corner  
86 opening in the concave shape.

87 Unit cells A and cell B have a side of  $22\text{ mm}$ , and the internal core with star shape is  
88  $20 \times 20\text{mm}^2$ . The thickness of the base plate is  $3\text{ mm}$  and the wall thickness of the cells  
89 is  $1\text{mm}$ . Cell A has an angle  $\alpha_A = 30^\circ$  and cell cell B has an angle  $\alpha_B = 20^\circ$ . The an-  
90 gles are variables of the sequences according to the generating order of the developed

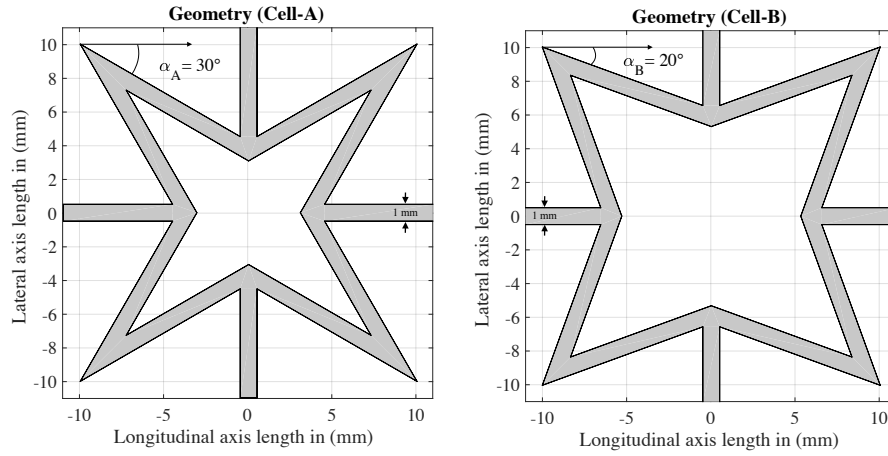


Figure 1: Meso-scale unit cell A and B preliminary design stage

91 sequence. Cells A and B will be arranged in a specific sequence presented in the next  
 92 section.

93 The properties of material used in the entire presented work are given in Tab. 1 Shell  
 94 elements with free triangular mesh are used in the FE model. Each unit cell has a total  
 95 of 28 nodes, where only 8 nodes are connected with the adjacent element along  $x$  and  
 96  $y$  directions. In addition each node has 6 degrees of freedom.

97

Table 1: Material properties

Material	Polymer
Modulus of elasticity(Pa)	$1.68 \times 10^9$
Density ( $\text{kg} \cdot \text{m}^{-3}$ )	818
Poisson's ratio	0.38
Structural loss factor	2.5 %

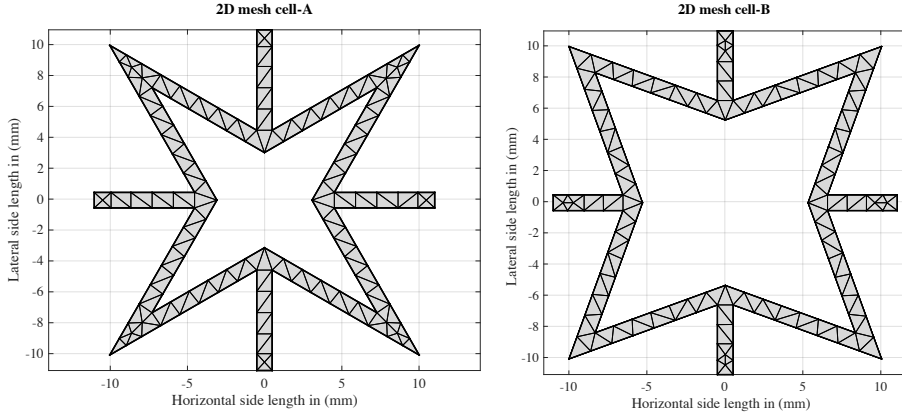


Figure 2: 2D mesh of cell-A and cell-B

98 *2.2. Thue-Morse Morphism sequence*

99 The Thue-Morse sequence is based on binary arrays. Starting from a 1D example,  
 100 the sequence can be derived by a function  $s$  from the set of binary sequences to itself  
 101 by replacing every  $A$  in a 1D sequence with  $AB$  and every  $B$  with  $BA$  [25]:

102

$$s(x,y) = s(x)s(y). \tag{1}$$

103 Eq.1 defines a map  $s$  for all strings  $x, y$ . Defining the Thue-Morse morphism  $s(A) = AB$ ,  
 104 leads to the relations for increasing the quasi-periodicity pattern in one direction. The  
 105 associated sequence starts with  $A$  then  $AB, ABBA, ABBABAAB$ , and so on, [26].

106 Considering the sequence in 2D, the first order starts from a  $2 \times 2$  matrix containing  
 107  $[A, B; B, A]$  which is equivalent to the second order  $s^2(A)$ . In the next steps, second or-  
 108 der matrix is translated to the right, left, and diagonal directions in order to built  $s^3(A)$   
 109 and so on. A loop is generated to translate the same order to the right and left with the  
 110 opposite entries and similar entries to the diagonal direction to fulfil the pattern of the  
 111 Thue-Morse sequence. The orders are detailed as follows:

112

113  $s(A) = AB$

114  $s^2(A) = s(s(A)) = AB \mid BA$   
 115  $s^3(A) = s(s(s(A))) = ABBA \mid BAAB$   
 116  $s^4(A) = s(s(s(s(A)))) = ABBABAAB \mid BAABABBA$

117

118 Each  $A$  and  $B$  represents cell  $A$  and cell  $B$ , respectively. In the present model, 64  
 119 combined unit cells are used: the Thue-Morse morphism map stops at  $s^4$ . The designed  
 120 quasi-periodic lattice in two direction is shown in Fig. 3.

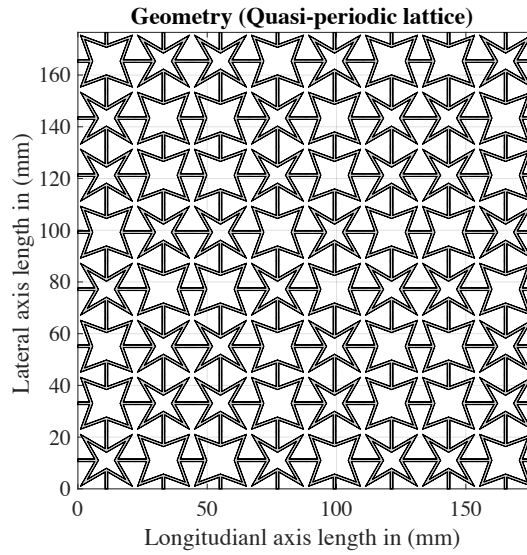


Figure 3: Quasi-periodic lattice combining unit cells A and B: following Thue-Morse sequence in two directions

121 **2.3. Periodic sequences**

122 For comparison purpose, two strictly periodic arrangements are also considered:  
 123 two finite panels composed of  $8 \times 8$  unit cell-A and  $8 \times 8$  unit cell-B in coherence with  
 124 the quasi-periodic case. Both periodic lattices are shown in Fig. 4

125 Fig. 5 shows another periodic lattice with alternated unit cells A and B. As for the  
 126 previous cases, the whole geometry includes 64 unit cells, in which 32 of them are  
 127 cells A and 32 cells B.



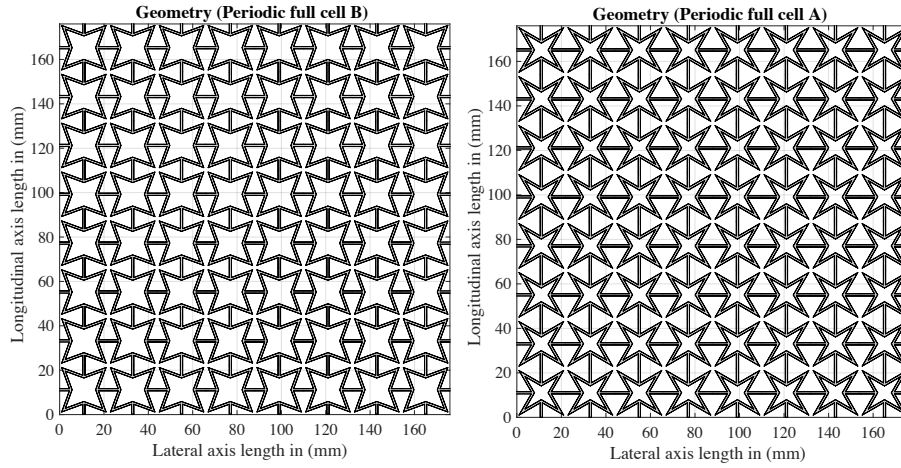


Figure 4: Finite periodic lattices, right with cell A and left with cell B

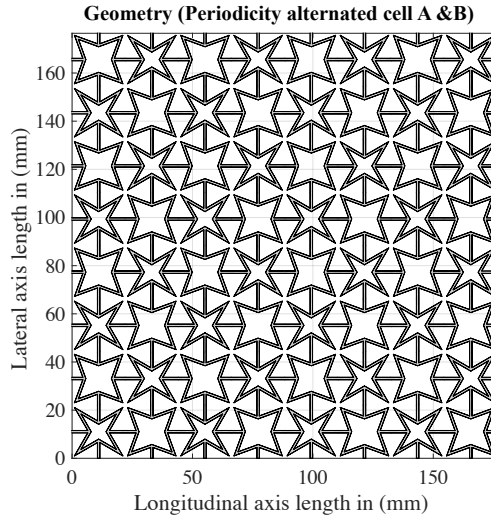


Figure 5: Periodic lattice with combined unit cell A and B in alternating pattern

128 **3. Wave and finite element models: dispersion analysis**

129 This section is divided into two subparts. The first one is related to the analysis of the  
 130 behaviour of infinite periodic  $2D$  lattices by computing the dispersion curves of unit  
 131 cells, for full cell-A and full cell-B configurations, depicted in Fig.4. The second is  
 132 dedicated to other infinite periodic  $2D$  lattices by computing the dispersion curve of

133 alternated (mixed periodic) A-B depicted in Fig.6, that consists of periodic lattice.

134

135 Eigenfrequency analysis is used to compute the band diagram of periodic structures

136 with first 25 Bloch modes for single cells and first 120 Bloch modes for the second

137 case with combined (mixed periodic) A-B [27, 28]. Floquet Bloch (FB) method is

138 used; the periodic boundary conditions are written as

$$u_{Rx} = e^{-jk_x D} u_{Lx}, \quad (2)$$

$$u_{Ry} = e^{-jk_y D} u_{Ly}, \quad (3)$$

139 where  $u_{Rx}$  and  $u_{Lx}$  are the right and left side displacement along the  $x$  axis, and  $u_{Ry}$  and

140  $u_{Ly}$  are the displacement along the  $y$  axis, respectively.  $D$  is the length of reciprocal or

141 unitary repeated element,  $k_x$  and  $k_y$  are the wavenumbers in the  $x$  and  $y$  directions.

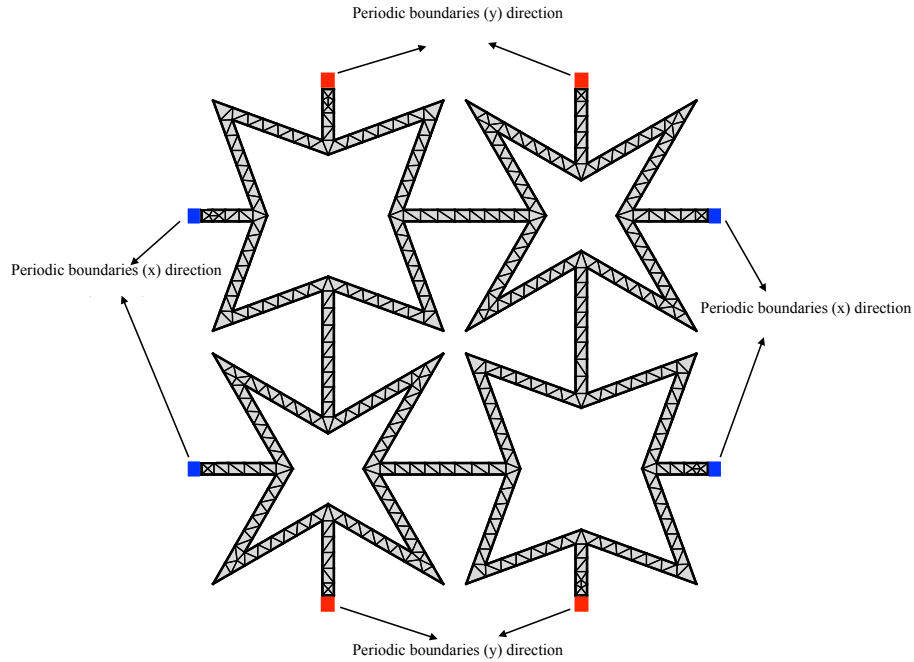


Figure 6: FE model of the combined (mixed periodic) A-B with periodic conditions

142 The FE model of the combined (mixed periodic) A-B unit cell in Fig. 6 is made of four

143 single A and B cells. The pattern is periodic and dispersion diagram results will be

144 compared to the Frequency Response Functions (FRFs) of the quasi-periodic pattern  
 145 in the next sections. The parametric eigenvalue analysis is performed according to the  
 146 edges of the first irreducible Brillouin zone Fig. 7. It starts from ( $\Gamma$ ) towards the  $x$   
 147 direction to  $M$ , and from  $M$  towards  $y$  direction to  $K$  and then back to ( $\Gamma$ ) [27].

148

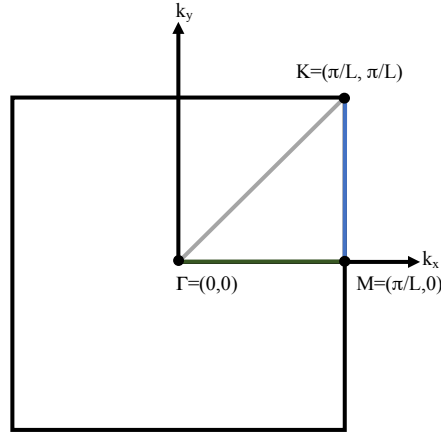


Figure 7: First irreducible Brillouin zone

149 The band diagrams of cell A and cell B are reported in Fig.8. In the dispersion  
 150 diagram all types of waves (i.e. bending, longitudinal, and shear) are considered,  
 151 [29, 30, 31, 32].

152 The analysis of cell-A shows three unidirectional frequency stop bands between 0 and  
 153 18kHz. The first band gap with a bandwidth  $\Delta f = 2.6$  kHz appears in 2808 – 5431 Hz,  
 154 then the second one has a slight wider band  $\Delta f = 2.64$  kHz in 7081 – 9725 Hz, while  
 155 the third frequency band gap with  $\Delta f = 1.86$  kHz is located in the frequency range in  
 156 11480 – 13340 Hz.

157

158 On the same frequency range, cell-B has a completely different behaviour in terms  
 159 of band gaps, only one wide band gap with  $\Delta f = 1.73$  kHz is observed at around  
 160 3157 – 4892 Hz. The second band gap starts at 5149 Hz and ends at around 5975 Hz,  
 161 following the third, fourth, fifth around 6896 Hz, 8623 Hz, and 9809 Hz with small

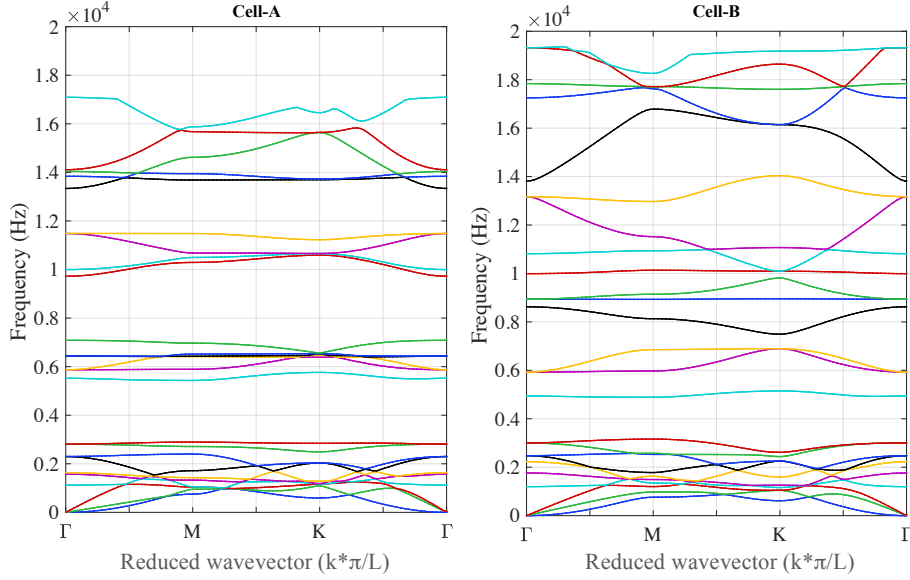


Figure 8: Band diagrams of infinite lattices: (left) unit cell A, (right) unit cell B

162 frequency stop bands.

163 The dispersion diagrams shown in Fig.9 corresponds to the combined A and B cells.

164 The first complete stop bands is observed in the ranges of 3000 – 4500 Hz, and the

165 second one is between 5000 – 5800 Hz. There is a slight narrow band-gap from 5800

166 Hz to 6000 Hz which disappears rapidly. The third one starts from 7000 Hz to 8000

167 Hz which is quite wider and the fourth one with  $\Delta f = 2$  kHz. There is also a very

168 narrow one after 11000 Hz just before the next wider stop band with the ranges of

169 12000 – 13800 Hz.

170 The overall results of the combined (mixed periodic) A-B show some kind of mix

171 between the dispersion diagram of single cells shown in Fig.8. Cell-A provides inter-

172 esting dynamics properties with a few wide band gaps. Cell-B has more band gaps,

173 but with narrow frequency width. The combination of the two in a periodic forma-

174 tion provides a large number of gaps, the largest ones being almost as wide as cell-A,

175 while keeping a number of gaps comparable to cell-B. In the next section, FRFs will

176 be computed on finite structures, in order to first, validate the applicability of the gaps

177 for real structures, and second to check whether or not a quasi-periodic arrangement

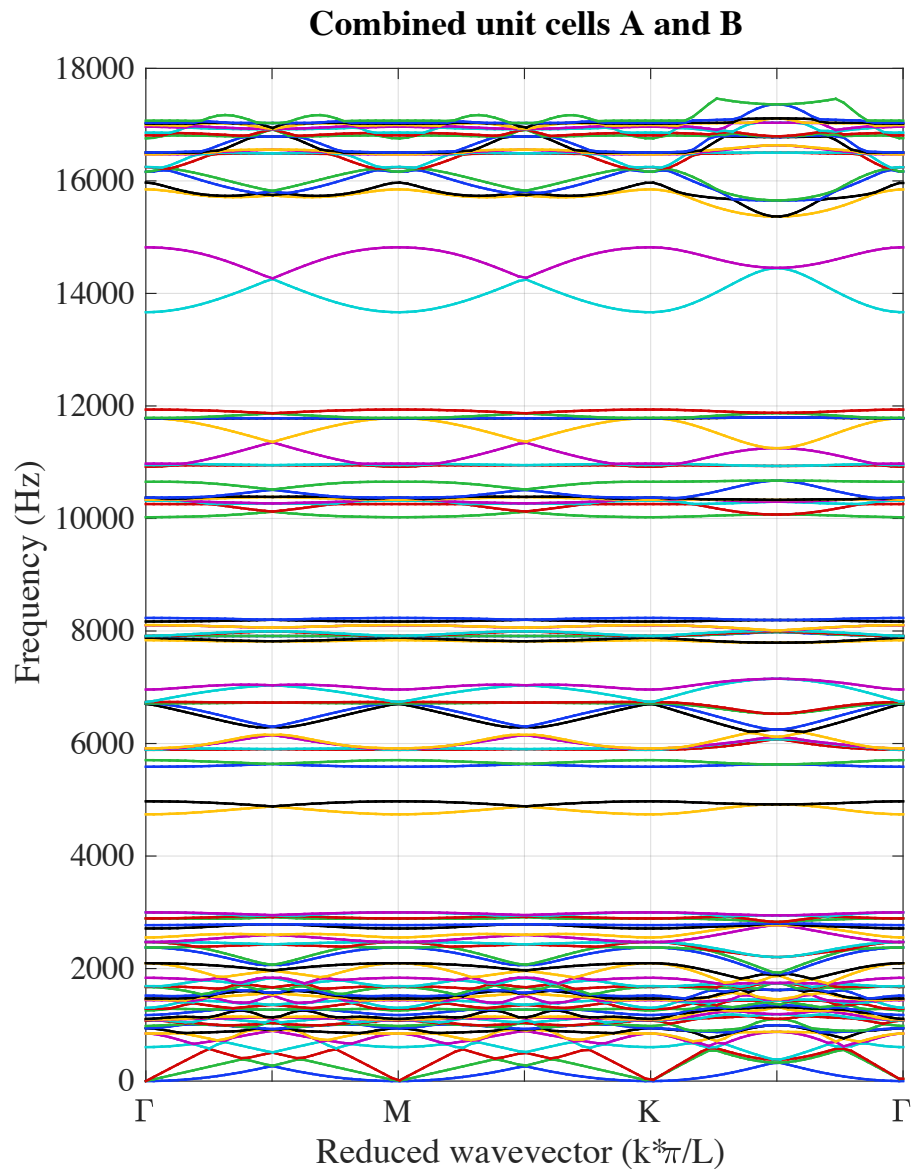


Figure 9: Band diagram of combined A-B lattice

178 can provide added value for engineering applications.

179 **4. Experimental measurements**

180 In this section, the dynamical response of the lattice is validated with experimental  
181 tests. The quasi-periodic panel is manufactured by laser cutting as shown in Fig.10.  
182 The material properties of this test-article are already responded in Tab. 1.

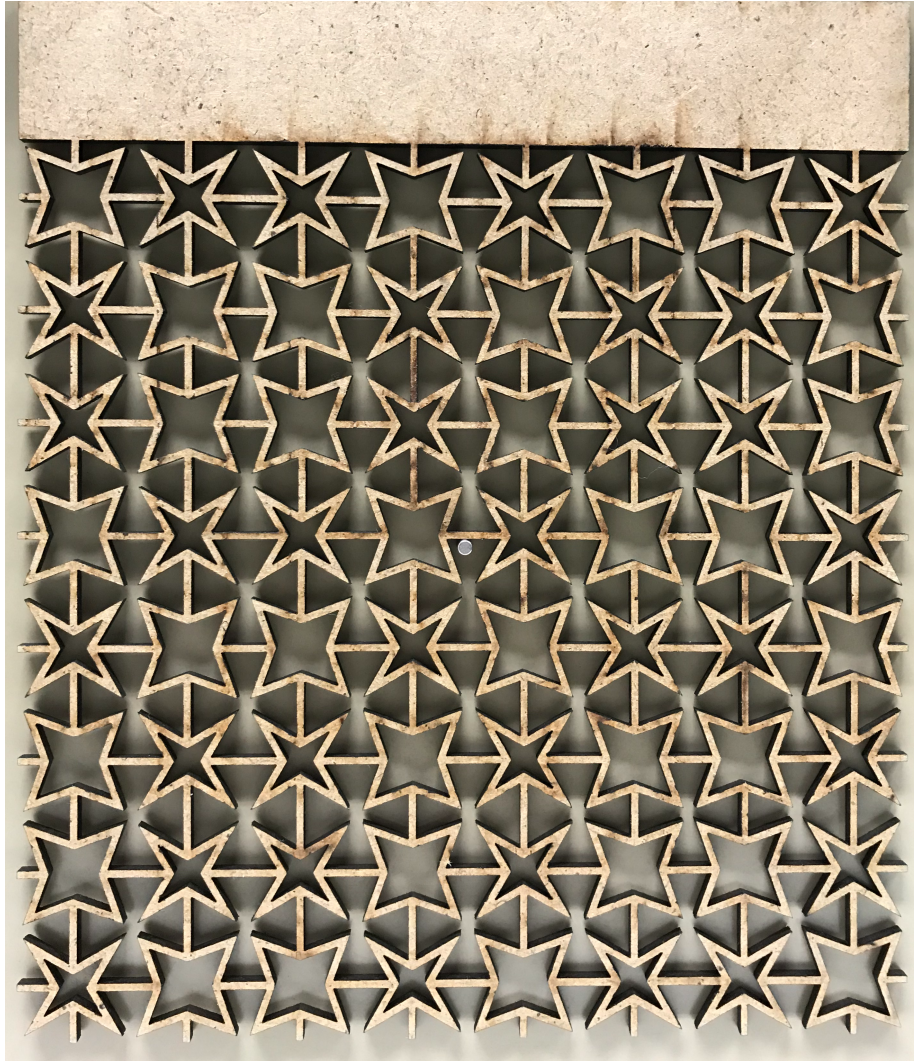


Figure 10: Meta-material prototype under experimental test

183 For the experimental campaign the lattice has an extra flat panel part which is used

184 as boundary support (clamped) during the dynamic tests. The lattice is vertically posi-  
185 tioned and clamped with the fasteners shown in Fig. 10. The shaker is attached to  
186 the structure on the left corner that is very close to the boundary support. A white  
187 noise excitation source generates signal from 1 kHz to 11 kHz. The measurements are  
188 recorded using a laser vibro-meter at the input and output points as shown in Fig. 11.

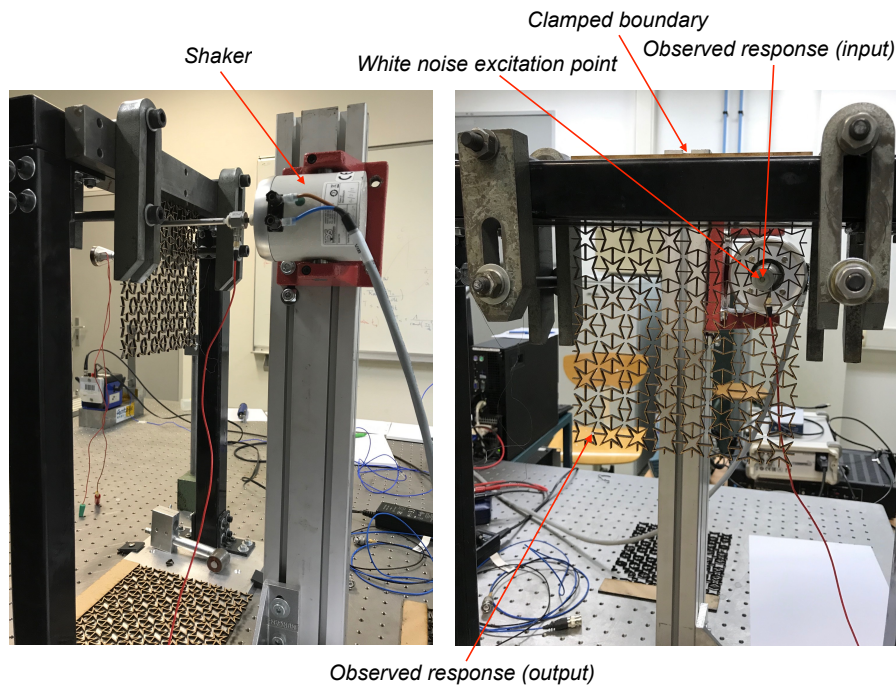


Figure 11: Manufactured meta-material with laser cutting

189 The first eigenfrequencies of the structure are characterised with the numerical  
190 modal analysis of quasi-periodic configuration to check the values of the material and  
191 geometrical properties.

192 Fig. 12 shows a measured FRF which is measured between 0 – 100 Hz for the low fre-  
193 quency ranges. On this figure, the eigenfrequencies of the numerical model are shown  
194 using vertical lines. The first 3 modes are very well correlated in terms of frequency,  
195 which means that the low frequency behaviour of the structure is well captured by  
196 the FE model. In a second step, measurements are performed up to 10.9 kHz. The  
197 corresponding FRFs are shown in Fig. 13.

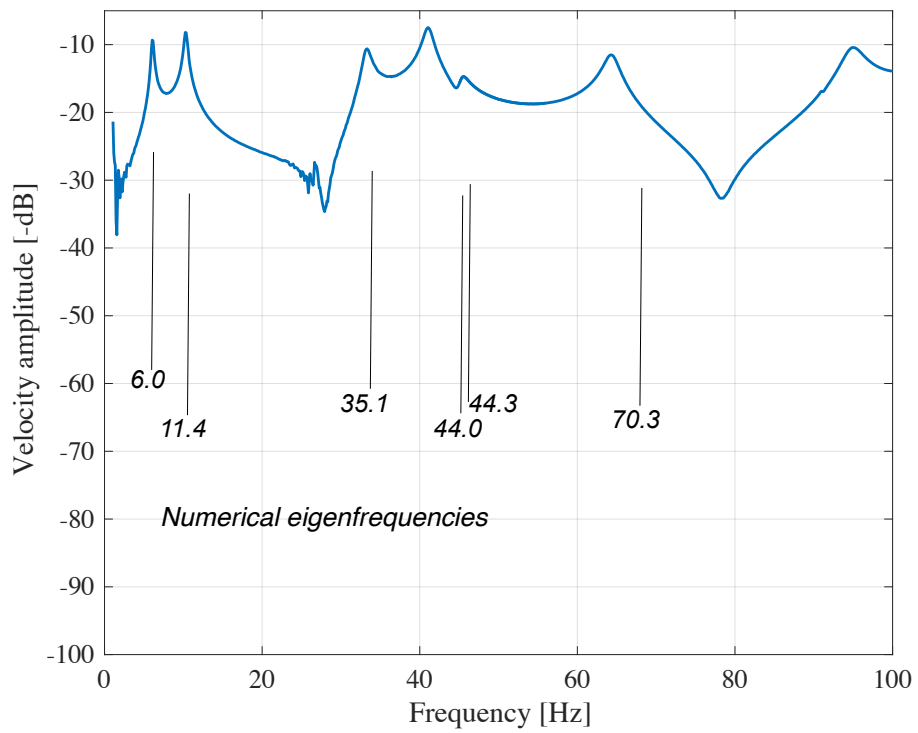


Figure 12: Measured FRF in low frequencies

198 Three subplots represents the amplitude, phase angle and coherence. The response is  
 199 measured at the input point.



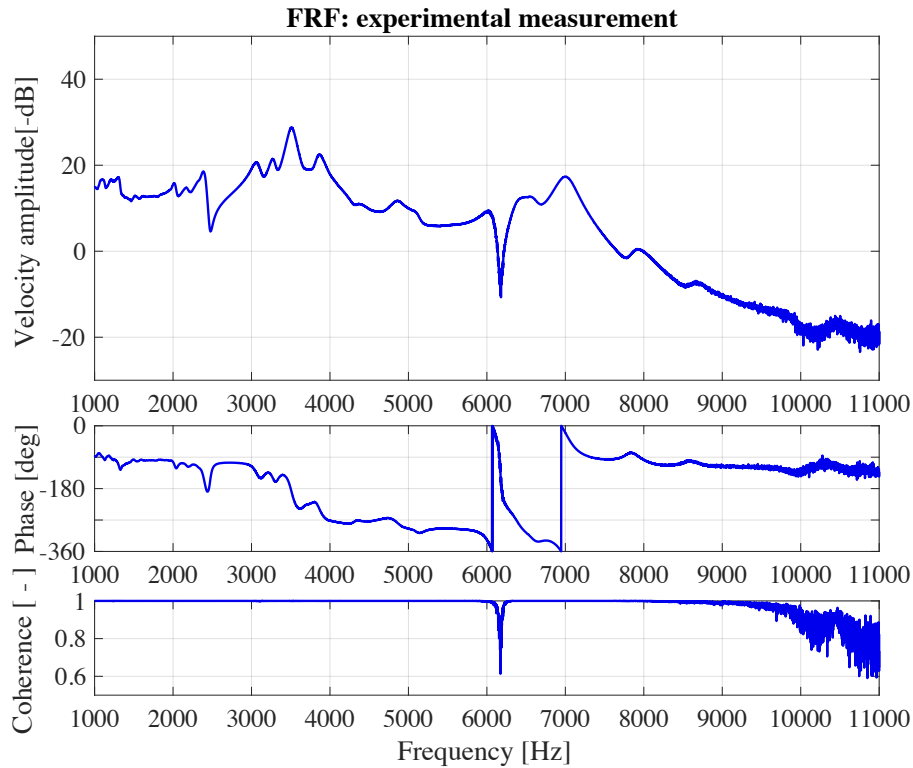


Figure 13: Velocity response measured in the input point

200 Similarly the experimental FRF of the output reference point is in Fig. 14. It can be  
 201 seen that there is a loss of elastic wave propagation while measuring the response in  
 202 far fields. The coherence plot shows some falls, meaning that a background noise is  
 203 measured in correspondence with possible band gaps. For instance the first stop band  
 204 appears from 2.5 kHz to 5.2 kHz with a peak in the middle of the attenuation zone and  
 205 second one from 7 kHz to 8 kHz and the last one starts after 8.2 and continues to higher  
 206 frequencies. It should be mentioned that above 8.2 kHz the stop band effect is observed  
 207 up to the maximum frequency which can be reached by the experimental setup.

208

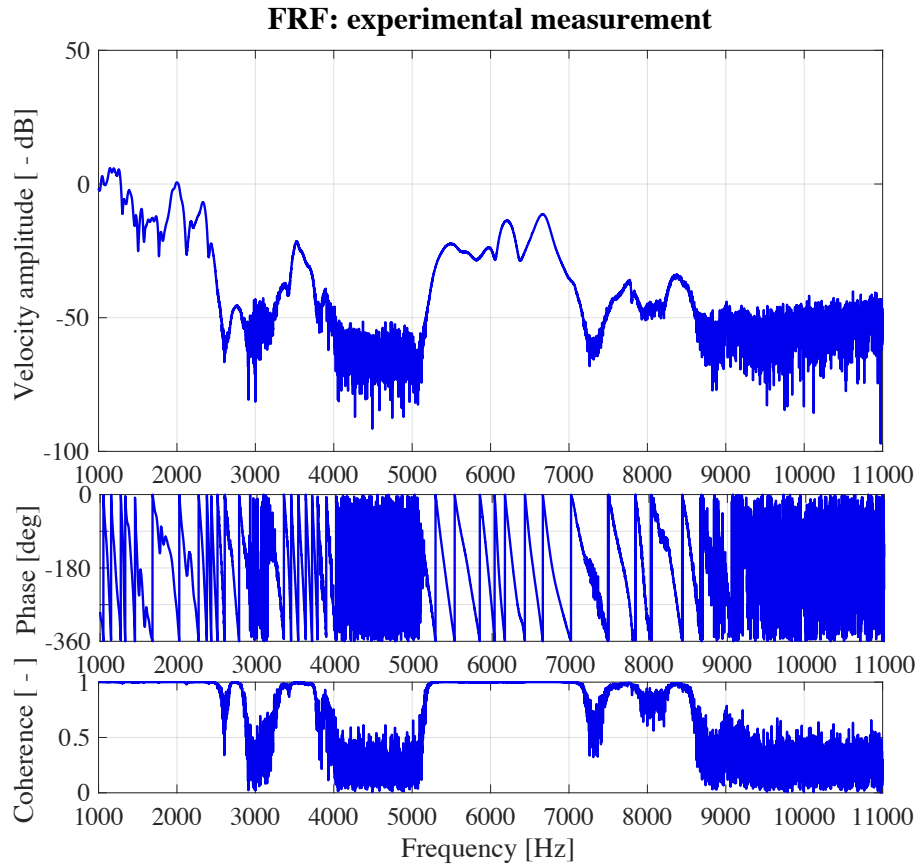


Figure 14: Velocity response measured in the output point

209 **5. Finite element analysis**

210 In this section, two periodic and one quasi-periodic lattices are considered. The first  
 211 two periodic lattices are modelled as finite meta-materials made of cell A and cell B  
 212 in two separate lattices. The aim is to verify whether those stop bands predicted in the  
 213 previous section are maintained for this specific finite element configuration i.e. with a  
 214 finite domain. Secondly the quasi-periodic meta-material in Fig. 15 is compared with  
 215 a combined cell A and cell B (periodic lattice), and in the last subsection an FRF of a  
 216 meta-structure (filter junction) with a pure quasi-periodic lattice is described in details.

217

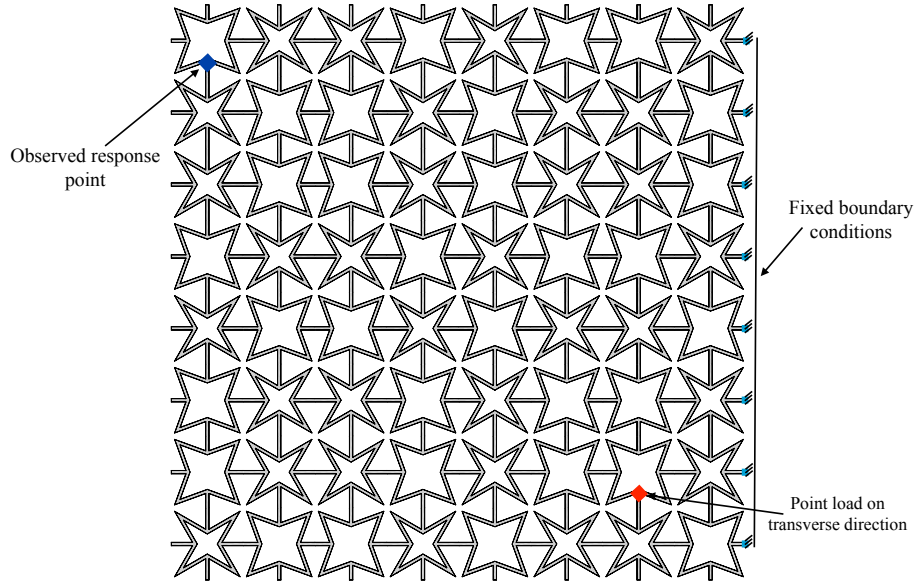


Figure 15: Quasi-periodic lattice, numerical model setup for FRF analysis

218 *5.1. Frequency response of meta-materials*

219 The numerical models are clamped on the right edges and a harmonic point force is  
 220 applied in the region close to the fixed boundary condition in Fig. 15 with a frequency  
 221 ranging from 0 – 35kHz. The model is meshed by 1061 free tetrahedral and 840 bi-  
 222 quadratic triangles element 6 node. Frequency range of 35 kHz is selected for all the  
 223 FRFs to check how the various cases behave in the higher frequencies.

224

225 The response is observed in dark blue spot location in Fig. 15. Fig. 16 shows  
 226 an FRF for the three types of lattices. Two of them are fully periodic with cell A  
 227 and cell B and the third one is quasi-periodic lattice. It can be seen from the plots  
 228 that the predicted band gaps in the dispersion diagram of periodic lattices (Fig. 8)  
 229 have similarities with the FRFs of the finite counter parts. There are basically three  
 230 full band gaps, which are associated with the resonant and Bragg type band gaps. As  
 231 there is no theoretical definition too generic to classify the types of band gaps in this  
 232 dispersion diagram, however at least the first are resonant band gaps. Fig. 16 provides

233 four band gaps marked as (*BG1*, *BG2*, *BG3*, and *BG4*). In *BG1* the response are almost  
 234 the same for all the cases, A, B and quasi-periodic arrangement (maybe even random  
 235 arrangement of A and B) provides similar results.  
 236 *BG2* has almost the same width for the 3 cases. It is the largest one but possesses a  
 237 localised mode in the middle for the case A. The quasi-periodic is as large as case B  
 238 but starts lower in frequency.  
 239 In *BG3* the band gap is visible only in case A, very narrow on quasi-periodic but not  
 240 visible as in case B. *BG4* almost same width for case A and quasi-periodic, the quasi-  
 241 periodic fall starts before than case A, no band gap for case B. In conclusion quasi-  
 242 periodic can be seen as a good *compromise* between case A and case B.

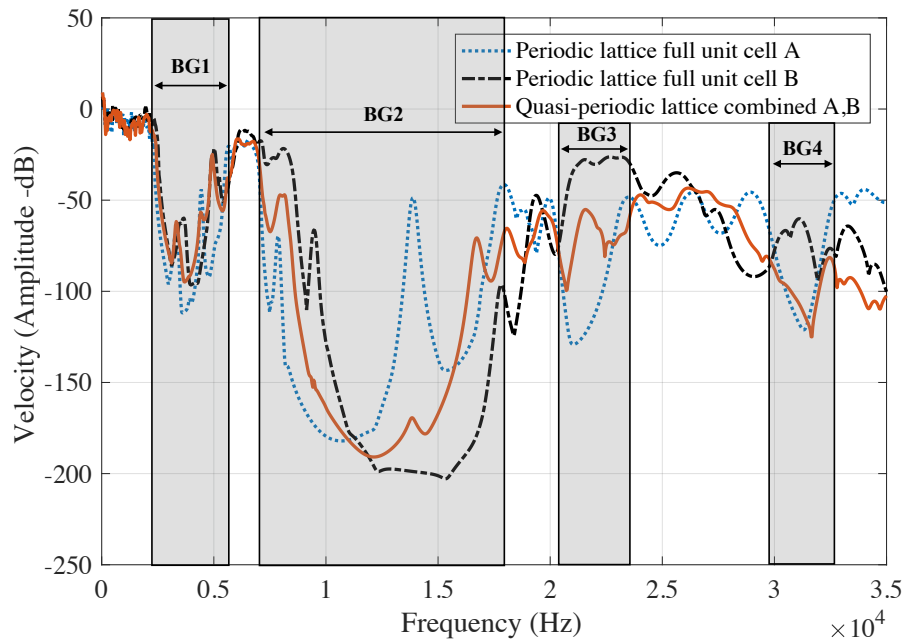


Figure 16: FRF of the two periodic and a quasi-periodic lattices

243

244 So, after analysing the data sets it seems that all periodic and quasi-periodic lattices  
 245 have specific performances in terms of band gaps. In the next step, the combined (pe-  
 246 riodic) A-B case is compared to the quasi-periodic arrangement. The FRFs are shown

247 in Fig. 17. The two lattices are similar in terms of in-plane dimension and volume  
 248 fraction.  
 249 The responses provided in Fig. 17 in terms of velocity amplitude show similar dy-  
 250 namic effects with a slight difference. Only small difference can be observed as an  
 251 higher depth around 15-dB for quasi-periodic one in blue line compared to strictly  
 252 periodic in red line. The second difference is due to the wider frequency stop bands  
 253 around 11 – 19 kHz. The quasi-periodic curve has lower peaks starting from 16 kHz  
 254 and continues up to higher frequencies around 25 kHz. In conclusion both designs have  
 255 almost similar dynamic effects with a slight difference. The generated combination of  
 256 quasi-periodicity in the lattice could give reduced response in the attenuation level of  
 257 frequency range 3.5 – 5 kHz compared with the regular periodic combinations. It also  
 258 has a similar band gap wide in the medium frequency range 11 – 19 kHz, with lower  
 259 attenuation level and peaks after 25 kHz.

260

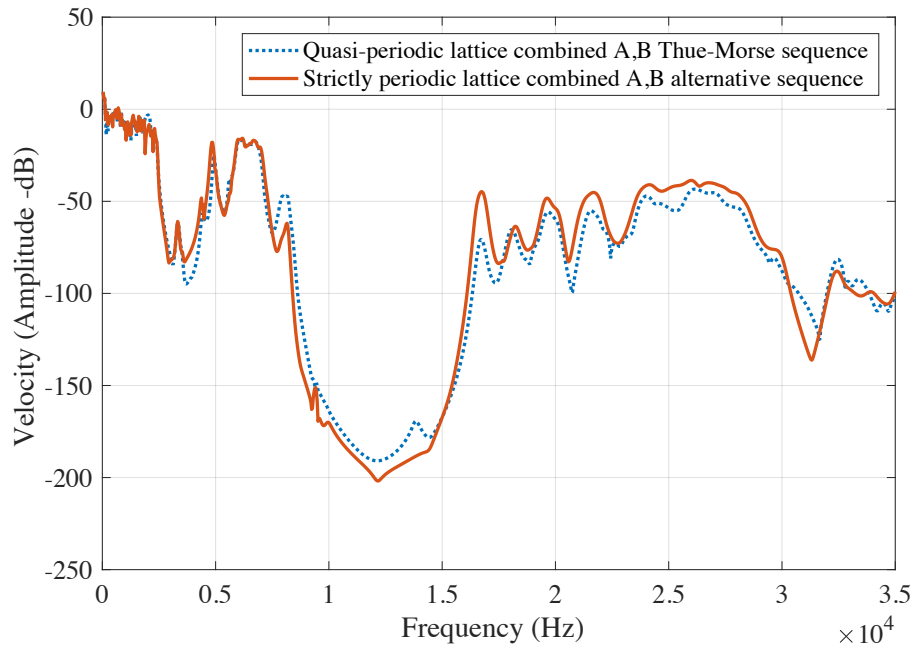


Figure 17: FRF of the periodic and quasi-periodic lattices

261 *5.2. Frequency response of a meta-structure*

262 In order to illustrate the applicability of the quasi-periodic arrangement for wave fil-  
 263 tering, a meta-structure that filters the elastic wave propagation from one component  
 264 to another is proposed. The meta-structure is located at the interface between two flat  
 265 bare panels. The connection between the met-material and two bare panels are made  
 266 by linking the side branches of the meta-material lattice with the side walls of the bare  
 267 panels in right and left sides respectively. The cross section area of the meta-material  
 268 branches are  $1 \cdot 3mm^2$ , in total there are 16 links, 8 connections in the right and 8 con-  
 269 nections in the left with the bare panels. Two cases are investigated. First, the dynamic  
 270 response in terms of square velocity amplitude over all nodes of the panels, is com-  
 271 puted. Secondly, four specific frequencies are selected and the response is checked to  
 272 visualise the elastic energy transfer from one side of the panel to the other side. A  
 273 harmonic point force is applied in the transverse direction on the first component and  
 274 the response is computed in the first and second components of Fig. 18.

275

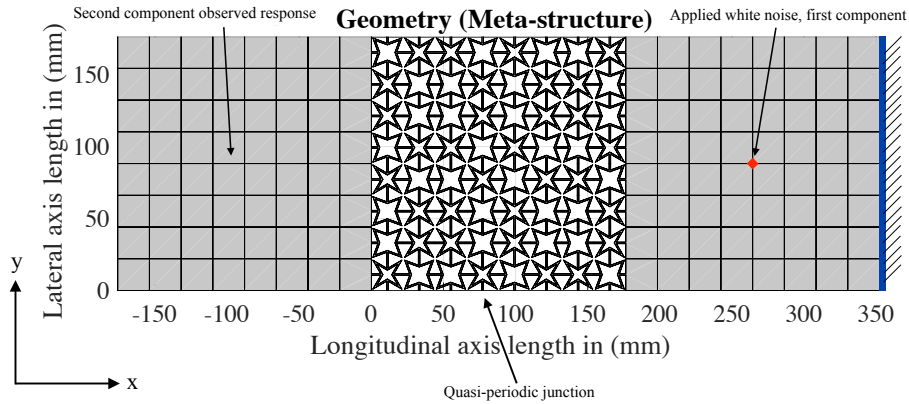


Figure 18: Geometrical model of the meta-structure

276 Fig. 19 shows the structural response of the meta-structure. The orange curve cor-  
 277 responds to the RMS (Root Mean Squared) response, in terms of velocity amplitude  
 278 of the first component of the meta-structure where the point load is applied. When  
 279 the elastic wave energy starts propagating, it is totally confined in the first component,

280 thanks to the meta-material that blocks some frequency bands in order to not transfer  
 281 to the neighbouring flat panel.

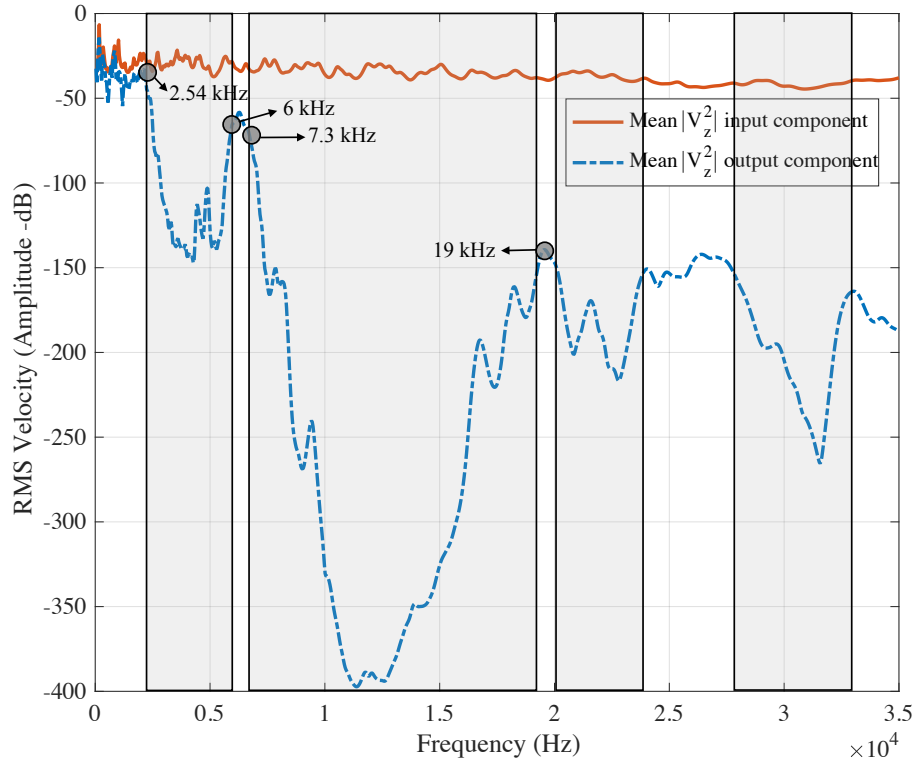


Figure 19: FRF of the meta-structure

282 The frequency stop bands starts from 2.5 kHz and it continues up to 6 kHz. After a  
 283 short peak around 6 – 7 kHz the level of attenuation drops down back and continues  
 284 to higher frequencies up to 19 kHz. It also follows two other small full stop bands  
 285 from 20 – 24 kHz, and around 28 – 33 kHz. Ultimately, the quasi-periodic interface  
 286 creates stop band effects and reduces the elastic wave propagation in above-mentioned  
 287 frequency ranges when the wave energy crosses the filter junction.

288

289 In the second case, four points of the selected frequency bands are observed with op-  
 290 erational deflections. The first point is at the beginning of the first frequency stop band  
 291 at 2.54 kHz, following the second, third, and fourth at 6 kHz, 7.3 kHz, and 19 kHz

292 respectively. As in Fig. 18, the excitation point is on the right panel and the receiving  
293 panel is left one. Fig. 20 shows operative deformed modes. It can be observed from  
294 the Fig. 20 that the energy is partially transported by the meta-material to the other side  
295 (second bare panel) in the low frequency band gap. On the contrary as the frequency  
296 increases, within the second band gaps start edge at 6 kHz, energy is transferred par-  
297 tially to the left panel. In the third operative deformed mode at 7.3 kHz the energy does  
298 not pass the meta-material and the second bare panel becomes stall without vibrating.  
299 Same behaviour is happening to the fourth mode at 19 kHz.

300

301 Fig. 21 shows contour of iso-surface of the meta-structure for three specific frequen-  
302 cies. The iso-surface shows the wave front by blue lines that crosses the meta-material.  
303 The colour bar in the right hand side of each iso-surface curve shows the velocity am-  
304 plitude for the first frequency step  $f = 35$  Hz, second frequency step  $f = 70$  Hz and  
305 the start point of first frequency stop band at around  $f = 2520$  Hz.

306

307 It can be seen from Fig. 21 that the contour of iso-surface propagates as the wave  
308 front starts migrating by crossing the meta-material and continues to the end of meta-  
309 structure. For the second case at frequency 70 Hz, wave energy get circular shapes and  
310 crosses the meta-material again. When the frequency range reaches 2520 Hz, the total  
311 induced energy is confined in the right panel with a partial cross over the meta-material  
312 and stops propagating almost in the half length of the meta-material and the left panel  
313 (i.e. stop band effects are evident).

314



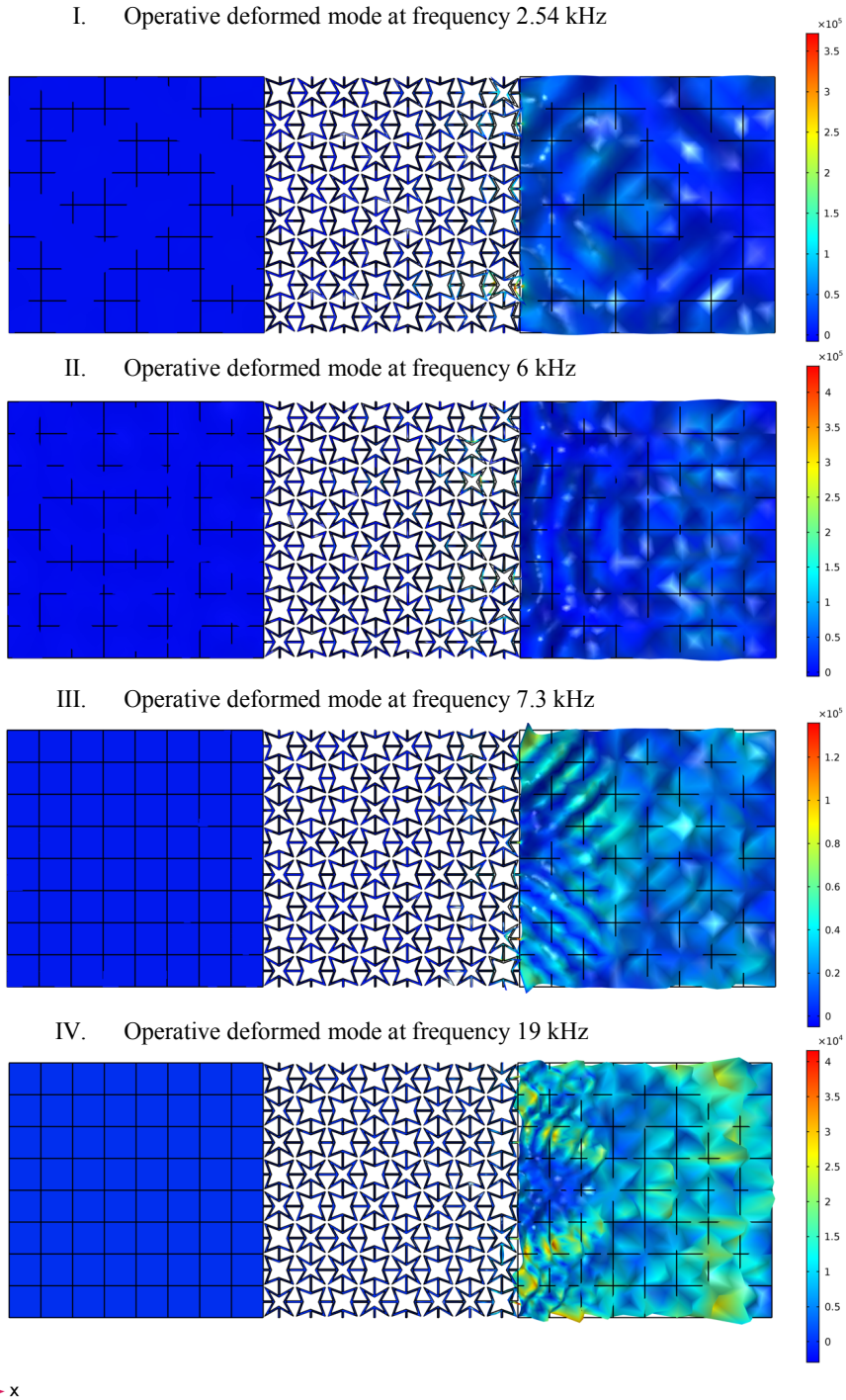


Figure 20: Operative modes of the meta-structure in four frequencies[5].

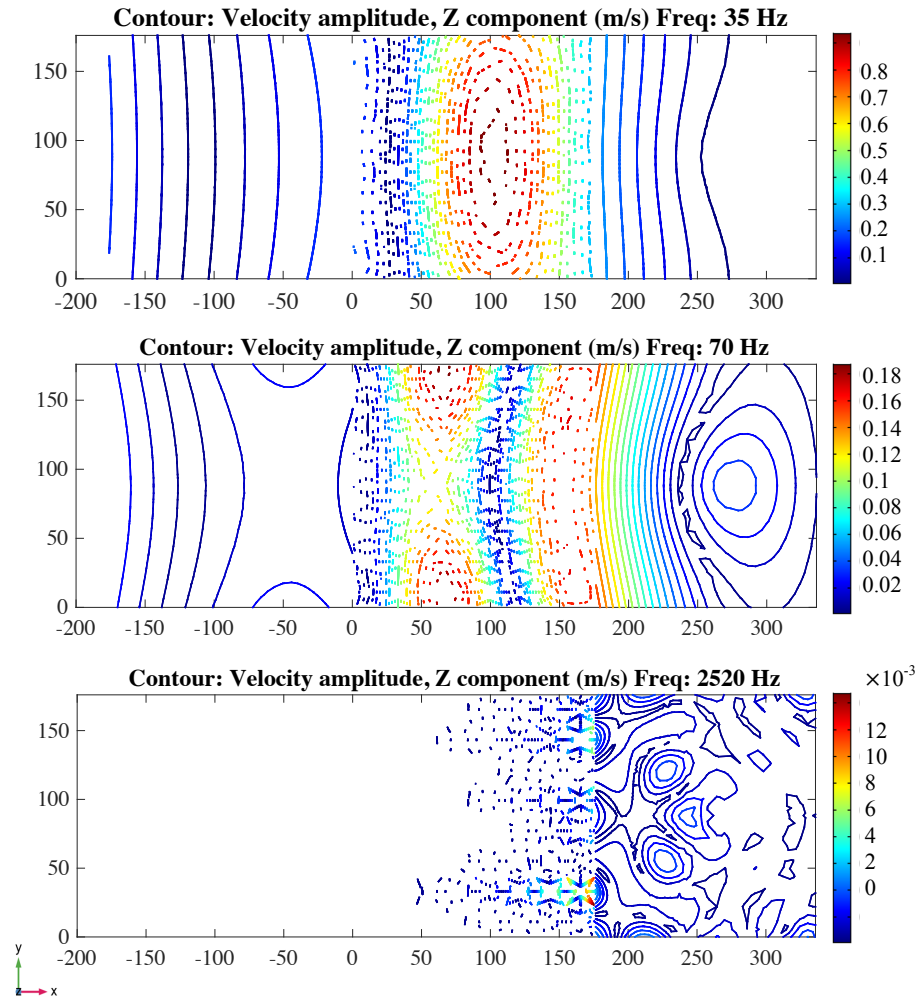


Figure 21: Iso-surface of three selected response frequencies

315 A comparison between the numerical models and the measurements is made in Fig.  
316 22. Two band gaps can be seen in the plot for both numerical and experimental cases.  
317 The first band gap between 2.5 and 5 kHz is almost similar in terms of width for both  
318 cases but with a low fall for the experimental part. The second band gap which starts  
319 from 8.1 kHz and continues to higher frequencies over 10.9 is similar too, for both  
320 cases. As it can be seen the second band gap in the experimental measurement has  
321 again low fall compared to the numerical one. The different depth of numerical and  
322 experimental band gaps can be function of many concurrent parameters. For exam-  
323 ple, for very response amplitude in the experimental measurements, the measured data  
324 are strongly influenced by the fundamental noise. On the contrary, the computed re-  
325 duction of the structural response is simply a function of the numerical approximations.  
326

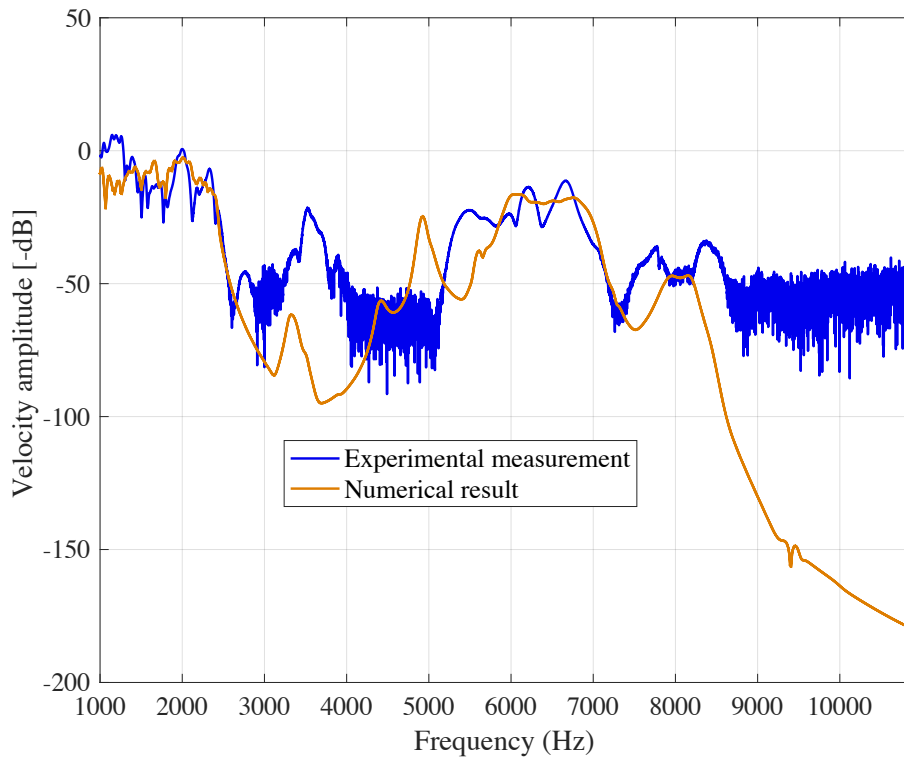


Figure 22: Comparison of numerical and experimental FRFs

327 **6. Concluding remarks**

328 This paper proposes an analysis of meta-materials and meta-structures for vibroacous-  
329 tic applications. The modelling strategy provides key factors to increase the order of  
330 quasi-periodicity in two directions in order to create lattices based on quasi-periodic  
331 sequence.

332

333 Numerical simulations are done using FE analysis both for dispersion diagram and  
334 harmonic response analyses. According to the results of numerical analysis the pre-  
335 dicted stop bands in the dispersion diagram of infinite lattice matches to the response  
336 of experimental measurements. Experimental measurement is considered mainly to  
337 validate the numerical results obtained by the developed model. The possibility of ob-  
338 serving frequency stop bands in the lattice is carried out by post processing of FRFs  
339 for lower, medium and high frequencies. White noise excitation response shows that  
340 the degree of consistency between the numerical and experimental results are highly  
341 predicted. The velocity amplitudes and coherence plots shows that even though with a  
342 different excitation the results are comparable in terms of validation.

343

344 In the last section the structural dynamic behaviour of quasi-periodic lattice is com-  
345 puted by FE analysis and compared with the experimental results. The results show an  
346 acceptable agreement. In another case study, the FE model of quasi-periodic lattice  
347 is embedded between two bare panels which is used as a junction filter. The induced  
348 vibration energy transfers through the junction, and it acts as a meta-material filtering  
349 property to the elastic waves due to the impedance mismatch in the star-shaped unit  
350 cells. The results of FRF in terms of RMS of velocity amplitude gives some elements  
351 of novelty to reduce maximum unwanted vibration from the host structure.

352

353 The star-shaped unit cells sequences can thus be considered as a viable starting  
354 point to the optimisation of the final configurations for designing structures with de-  
355 sired frequency stop-bands.

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363 **References**

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