The influence of the configuration of the fiber-metal laminates on the dispersion relations of the elastic wave modes

Marek BARSKI, Aleksander MUC, Adam STAWIARSKI
Cracow University of Technology, Faculty of Mechanical Engineering,
al. Jana Pawła II 37, 31 - 864 Kraków, Poland,
marek.barski@pk.edu.pl, aleksander.muc@pk.edu.pl, adam.stawiarski@pk.edu.pl

Abstract

The current work is devoted to the determination of dispersion curves for elastic wave modes. The studied elastic waves propagate across metal-fiber hybrid composites. In order to solve the problem, special software has been developed with the use of C++. This software works with the MS Windows operating system and the proposed solution is based on the multi-threading mechanism. It makes possible to significantly speed up the calculations. The relatively new approach is used namely the stiffness matrix method. At the very beginning, the dispersion curves are determined for the traditional composite materials of cross-ply configuration, for which the layers are made of glass fiber/epoxy resin and carbon fiber/epoxy resin. The impact of the total number of layers on the dispersion curves is investigated. Next, the influence of the thickness of the layers, which are made of aluminum alloy, on the dispersion characteristic is studied. In the second case, it is assumed that the total thickness of the composite material wall for all cases is identical.

Keywords: FML, GLARE, elastic wave modes, dispersion curves, stiffness matrix method.

1. Introduction

Nowadays different kinds of composite materials become one of the most important aspects of modern engineering. It is especially visible in the case of the aircraft industry. The whole structure of Airbus A350 and Boeing 787 "Dreamliner" is made of composites. However, the use of such materials entails the need to develop new, effective non-destructive methods (NDT) of damage detection. For example, one of the potential possibilities is the use of active infrared thermography (Pastuszak et al.[1]). However, very interesting seems the possibility of creating an advanced system, which can control the structure or selected part of it in online mode. These solutions are known as structural health monitoring (SHM) systems (Giurgiutiu [2]). They are manly based on the analysis of the elastic wave propagation through the investigated structure (Zhongqing Su, Lin Ye [3]). The main disadvantage is that the elastic waves are strongly dispersive and they have a multimodal character. The schema of the fundamental wave modes is presented in Fig. 1.

The present work is mainly devoted to the determination of the dispersion curves for relatively new materials, known as fiber-metal laminates (FML). The FML's are the hybrid composites which consist of the layers made of metallic materials, like aluminum alloys or steel. Among many potential possibilities of creating this kind of material, the most frequently applied FML materials are GLARE (glass laminate aluminum reinforced epoxy). Similarly, as in the case of traditional composite materials, the problem of detection and evaluation of a different kind of damages are very important. Besides the flaws, which are present as the effect of the manufacturing process, there are many other sources of damages. Here can be quoted, for example, fatigue (Wang et al. [4]) or low-velocity impacts (Bieniaś et al [5]).

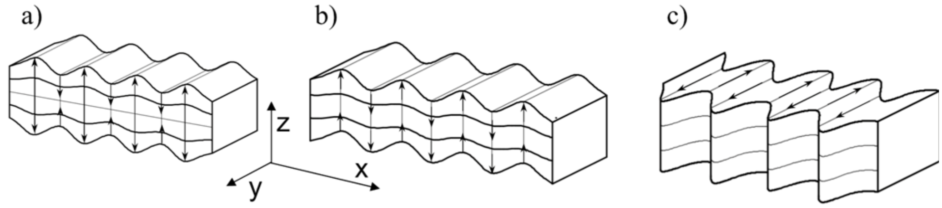

Figure 1. Fundamental a) symmetric S0, b) anti-symmetric A0, c) shear horizontal SH0 wave mode

In the present work the impact of the variable number of layers in the case of cross-ply laminates as well as the impact of the thickness of the metal layers on the dispersion characteristic is investigated.

2. Method of analysis

One of the most important stages of the design of the SHM systems based on the elastic wave propagation is the estimation of the dispersion characteristic of the elastic wave modes for the considered composite material. However, this task is rather difficult and demands a lot of effort. It seems that the most effective are the methods, which are known as matrix method, namely: transfer matrix method (TMM) (Nayfeh [6], Maghsoodi et al.[7]), global matrix method (GMM) (Lowe [8] Pant et al.[9]) and stiffness matrix method (SMM) (Wang and Rokhlin [10], [11]). The last method seems to be the most effective and robust mainly due to the fact that it is unconditionally numerically stable. The theoretical fundamentals of the SMM in the case of its application for the composite materials are detailed discussed by Kamal and Giurgiutiu [12]. Generally, in order to determine the dispersion curves, the following general equation has to be solved, namely:

$$\det\left(\left[\ A(c, f) \ \right] \right) = 0 \,, \tag{1}$$

where *A*, in general case, is the square matrix of the size 6x6. The elements of matrix *A* depends on the mechanical properties of the material of the layer, the thickness of the particular layers, the total number of the layer, etc. The solution to the problem can be found by assuming, for example, the value of frequency *f* and looking for the value of the phase velocity *c*, which satisfies the Eq. (1) or vice versa. The SMM method was successfully utilized, among the others, by Barski and Pająk [13] or Huber and Sause [14]. It should be stressed here that the process of generation of the dispersion curves is a very time-consuming. Especially if the advanced software of general use is applied, like MATHLAB or SCILAB. Therefore, it seems that the better solution is to develop a dedicated program in C++ written by the authors. Moreover, the use of the multithreading mechanism enables a further significant reduction in the time of computations. Thus this approach has been realized presently in order to effectively generate a large number of the dispersion curves for different kinds of multilayered composite materials.

3. Results of analysis for cross-ply laminates

In the case of the cross-ply composites, the dispersion curves are determined for the laminates of configuration [0º, 90º, 0º, 90º, 0º, 90º, 0º, 90º, 0º, 90º, 0º, 90º], (12 layers). For simplicity, the mentioned laminate configuration will be written further in the text as $[0º, 90º]_6$, where the subscript "6" means the total number of pairs [0º, 90º] in the composite. The thickness of each layer is identical and equal to t = 0.25 [mm]. Thus the total thickness of the considered composite is equal to t = 3 [mm]. The studied composites are made of glass fiber/epoxy resin (GFRP) and carbon fiber/epoxy resin (CFRP). The mechanical properties of the layer are presented in Tab. 1. The investigated range of frequency and phase velocity is as follows: 0.05 [MHz] ≤ f ≤ 1.25 [MHz] and 0.2 [km/s] ≤ c ≤ 10 [km/s]. It is assumed that the elastic wave propagates along the principal axes of the material. The obtained dispersion curves are presented in Fig. 2.

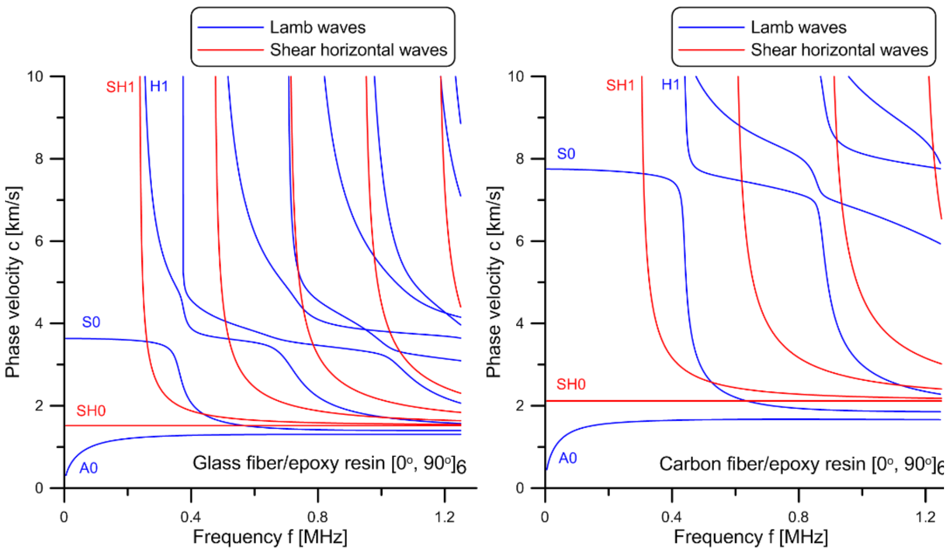

Figure 2. Dispersion curves determined for laminates of cross-ply configuration

From the practical point of view, the most important is the knowledge about the phase velocity of fundamental modes: antisymmetric A0, shear horizontal SH0 and symmetric S0. Moreover, the useful range of frequency is limited by the frequency, for which the first higher mode appears.

Table 1. Mechanical properties of the composite layer [15]

Material	E_1 [GPa]	E_2 [GPa]	G_{12} [GPa]	ν_{12}	ρ [g/cm³]
GFRP	38.6	8.27	4.14	0.26	1.8
CFRP	181.0	10.3	7.17	0.28	1.6

As can be observed, initially in both cases the phase velocity of the fundamental A0 mode strongly depends on the frequency. But for the frequency $f > 0.2$ [MHz] the value of the phase velocity of these modes starts to increase very slowly. The phase velocity of the A0 modes in the case of GFRP is equal to $c = 1.203$ [km/s] and in the case of CFRP $c = 1.570$ [km/s] for the frequency $f = 0.2$ [MHz]. The phase velocity of the fundamental shear horizontal mode SH0 does not depend on the frequency in both cases. For the GFRP $c = 1.517$ [km/s] and for CFRP $c = 2.117$ [km/s]. For the low frequency, the phase velocities of the fundamental symmetric S0 modes decrease slightly together with increasing the frequency. For the beginning frequency $f = 0.05$ [MHz] these velocities are equal to $c = 3.635$ [km/s] and $c = 7.749$ [km/s], respectively. However, after reaching a certain value of the frequency, the phase velocity of these modes rapidly falls down. The first higher modes (SH1) appear for the frequency equal to $f = 0.238$ [MHz] and $f = 0.305$ [MHz] for GFRP and CFRP composite, respectively. Generally, all the discussed phase velocities are higher for the composites, which is made of a material with a higher E_1 modulus. Additionally, it is worth noting that in the case of glass composite the number of higher modes in the studied range of frequency is significantly larger in comparison with the number of higher modes observer for carbon composite.

In Fig. 3 and 4 there is presented the influence of the number of layers (total thickness of composite) on the fundamental elastic wave modes, namely A0, SH, and S0. The computations are performed for the following cross-ply laminates: $[0^o, 90^o]_5$ (10 layers), $[0^o, 90^o]_4$ (8 layers), ... , $[0^o, 90^o]_2$ (4 layers). The total thickness of the studied laminates is equal to $t = 2.5$ [mm], 2 [mm], ... , 1 [mm], respectively. As can be observed the values of the phase velocities are almost identical. The most significant effect is that the frequency, for which the phase velocity of the symmetric mode S0 suddenly drops down, increases together with decreasing the total thickness of the composite. Moreover, the frequency *f*, for which the first higher shear horizontal mode SH1 appears, also increases. In the case of studied GFRP these frequencies are as follows: 0.238, 0.286, 0.358, 4.77, 0.715 [MHz] and in the case of CFRP: 0.305, 0.365, 0.457, 0.609, 0.911 [MHz].

4. Results of analysis for FML composites.

The total thickness of the whole studied the FML composites is identical and equal to $t = 3$ [mm] and the studied composite configurations are shown in Fig. 5 and 6.

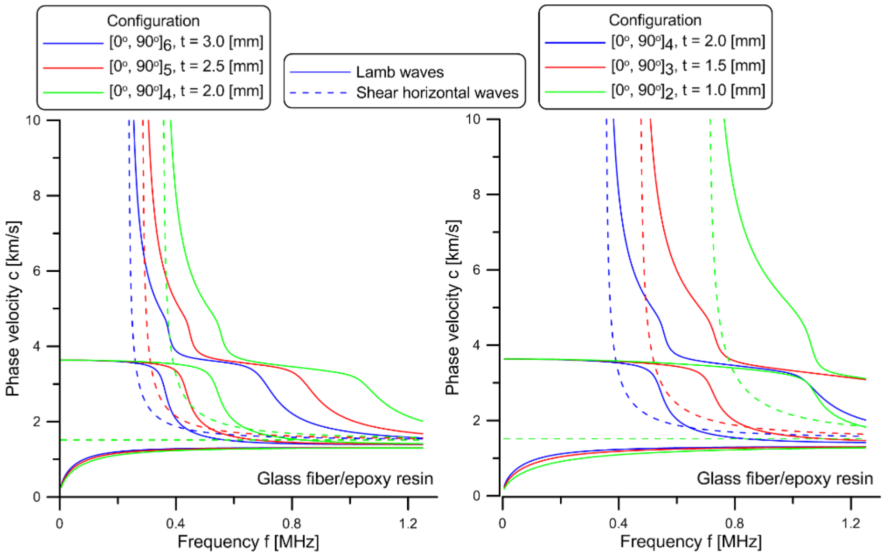

Figure 3. The impact of the total thickness of the cross-ply laminate on dispersion curves, the material of layers: glass fiber/epoxy resin

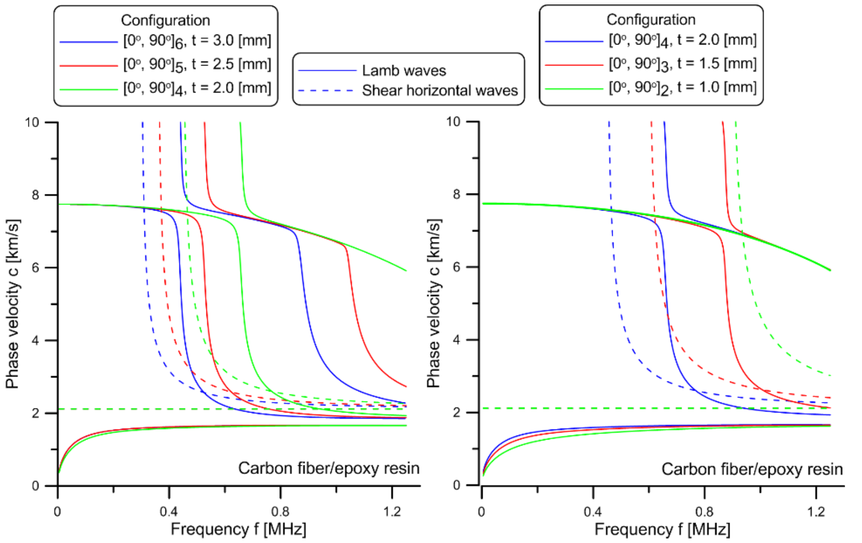

Figure 4. The impact of the total thickness of the cross-ply laminate on dispersion curves, the material of layers: carbon fiber/epoxy resin

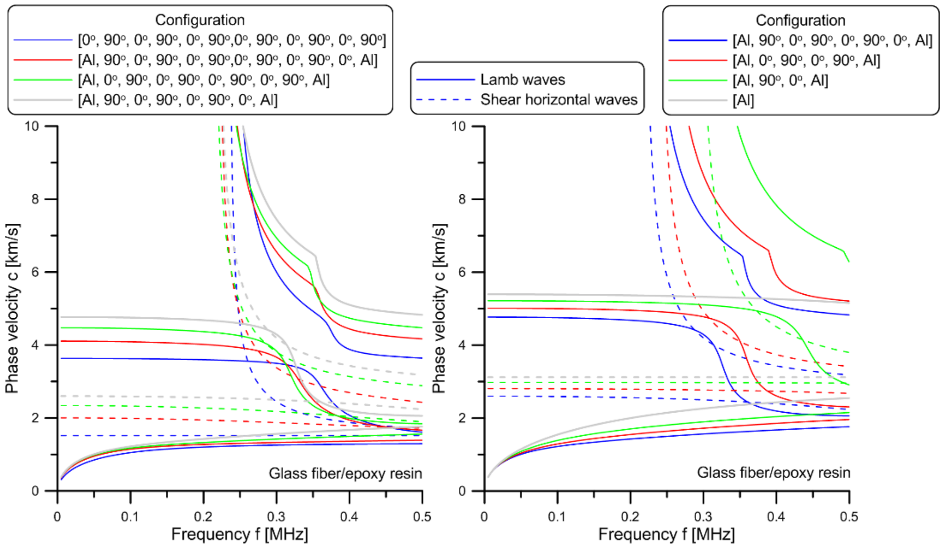

Figure 5. The impact of the aluminium layer thickness on the dispersion curves, composite material: glass fiber/epoxy resin

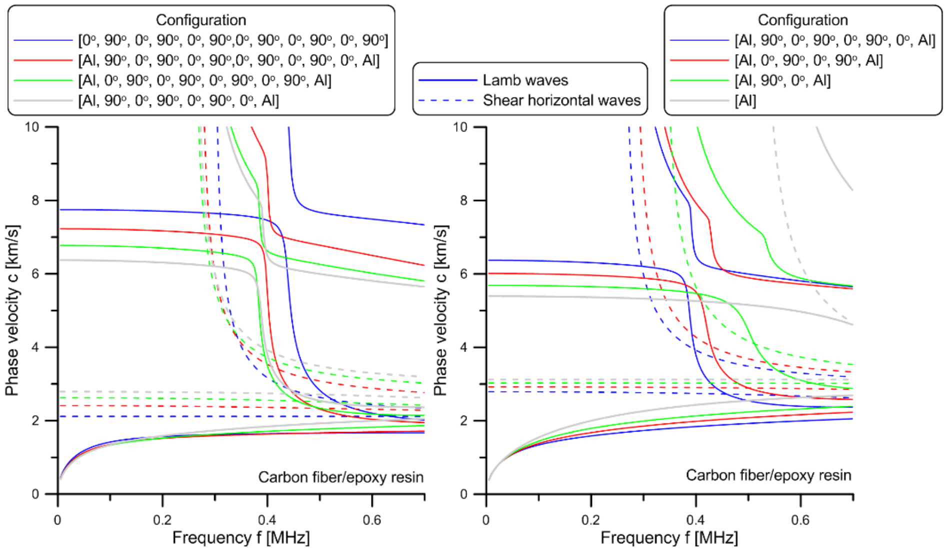

Figure 6. The impact of the aluminium layer thickness on the dispersion curves, composite material: carbon fiber/epoxy resin

As before, the thickness of the single glass or carbon layer is equal to t = 0.25 [mm]. The isotropic metallic layer is made of aluminium alloy AW-6060 of following mechanical properties: E = 70.0 [GPa], ν = 0.33 and density ρ = 2.7 [g/cm^3]. The dispersion curves, which are determined in this case are shown in Fig. 5 and 6.

To the contrary to the effect discussed in the former section, the introduction of the metallic layers instead of the composite ones causes the significant change of the phase velocities of the fundamental elastic wave modes A0, SH0, and S0. In the case of aluminum alloy and glass composite, where the Young modulus E_1 of the glass layer is less than the Young modulus of the aluminum alloy, together with increasing the total thickness of the metallic layer the phase velocities of the fundamental shear horizontal mode SH0 and symmetric mode S0 increase. For the fundamental symmetric mode S0 and for frequency f = 0.05 [MHz] the phase velocity varies from c = 3.635 [km/s] for GFRP $[0^o, 90^o]_6$ to c = 5.394 [km/s] for pure aluminum alloy layer with thickness t = 3 [mm]. The similar effect is observed also for fundamental shear horizontal mode SH0. The appropriate velocities are as follows: for GFRP c = 1.517 [km/s] and for aluminum single layer with thickness t = 3 [mm] c = 3.122 [km/s]. The phase velocity of the fundamental antisymmetric mode A0 also increases. However, together with increasing the frequency and the thickness of the aluminum layer this effect is more significant.

A reverse tendency is observed in the case of carbon composite and aluminum layers only for fundamental symmetric mode S0. Because of the fact that the Young modulus E_1 of the carbon layer is of the order of magnitude greater than the Young modulus E of the aluminum alloy, the phase velocity of the fundamental symmetric mode S0 decreases together with increasing the total thickness of the metallic layers. However, for the rest of the fundamental modes, the observed tendency is identical as described earlier. This effect can be considered as quite surprising. It can be explained by the fact that the Kirchoff modulus of the layer made of aluminum alloy is much greater in comparison with the Kirchoff modulus of the layer made of CRFP.

The other effects, which have been discussed for cross-play laminates, are also present but they are not as intensive as before. Only for the pure aluminum single layer of thickness t = 3 [mm] the first higher mode SH1 is significantly shifted in frequency. This mode appears at the frequency equal to f = 0.548 [MHz].

5. Conclusions

The implementation of SMM method in the form of a multithreading standalone application (executable file) dedicated to the Windows operating system significantly reduces the calculation time. The reduction of time is over 10 times in comparison with the calculation conducted with the use of SCILAB software. In addition, the involvement of 4 threads at the same time for a single task results in a further 4-fold reduction in calculation time.

The change of the number of layers, and, in consequence, the total thickness of the composite, in the case of cross-ply laminates, results mainly in the change of the frequency at which the higher modes appear. In the case of the investigated FML composites, depending on the relation between the Young modulus of the metallic and composite layer, the phase velocity of the fundamental symmetric mode increases or decreases. However, phase velocities of the rest fundamental modes, namely A0 and SH0, increase together with the increase of the thickness of the metallic layers.

References

1. P. Pastuszak, A. Muc, M. Barski, *Methods of infrared non-destructive techniques: Review and experimental studies,* Key Eng. Mat., 542 (2013) 131 – 141.
2. V. Giurgiutiu, *Structural Health Monitoring with Piezoelectric Wafer Active Sensors,* Elsevier 2008.
3. Zhongqing Su, Lin Ye, *Identification of Damage Using Lamb Waves, From Fundamentals to Applications,* Lecture Notes in Applied and Computational Mechanics Vol. 48, Springer - Verlag, Berlin - Heidelberg 2009.
4. W. Wang, C. Rans, R. Benedictus, *Analytical prediction for non-symmetric fatigue crack growth in Fibre Metal Laminates,* Int. J. Fatigue, 103 (2017) 546 – 556.
5. J. Bieniaś, P. Jakubczak, K. Dadej, *Low velocity impact resistance of aluminum glass laminates - Experimental and numerical investigation,* Compos. Struct., 152 (2016) 339 – 348.
6. A. H. Nayfeh, *The general problem of elastic wave propagation in multilayered anisotropic media,* J. Acoust. Soc. Am., 89(4) (1991) 1521 – 1531.
7. A. Maghsoodi, A. Ohadi, M. Sadighi, *Calculation of Wave Dispersion Curves in Multilayered Composite-Metal Plates,* Shock Vib., (2014), Article ID 410514, http://downloads.hindawi.com/journals/sv/2014/410514.pdf.
8. J. S. Lowe, *Matrix Techniques for Modeling Ultrasonic Wave in Multilayered Media,* IEEE T-UFFC 42(2) (1995) 525 – 542.
9. S. Pant, J. Laliberte, M. Martinez, B. Rocha, *Derivation and experimental validation of Lamb waves equation for an n-layered anisotropic composite laminate,* Compos. Struct., 111 (2014) 566 – 579.
10. L. Wang, S. I. Rokhlin, *Stable reformulation of transfer matrix method in layered anisotropic media,* Ultrasonics, 39 (2001) 413 – 424.
11. S. I. Rokhlin, L. Wang, *Stable recursive algorithm for elastic wave propagation in layered anisotropic media: Stiffness matrix method,* J. Acoust. Soc. Am., 112 (2002) 822 – 834.
12. A. Kamal, V. Giurgiutiu, *Stiffness Transfer Matrix Method(STMM) for Stable Dispersion Curves in Anisotropic Composites,* Proceedings of SPIE, 9064, (2014), http://www.me.sc.edu/research/lamss/pdfnew/CONFERENCES/C228_9064_39.pdf.
13. M. Barski, P. Pająk, *Determination of Dispersion Curves for Composite Materials with the Use of Stiffness Matrix Method,* Acta Mechanica et Automatica, 11(2) (2017) 121 – 128.
14. A. M. A. Huber, M. G. R. Sause, *Classification of solutions for guided waves in anisotropic composites with large numbers of layers,* J. Acoust. Soc. Am., 144(6) (2018) 3236 – 3251.
15. A. Muc, *Mechanics of fiber composites (in Polish),* Księgarnia Akademicka, Kraków, 2003.