Vibration response of composite structures

P. Kulhavý [1,a], J. Petřík [1], P. Srb [1], P. Lepšík [1]

[1] *Technical University of Liberec, Faculty of Mechanical Engineering, Studentská 2,*
461 17 Liberec 1, Czech Republic

[a] *Petr.Kulhavy@tul.cz*

Abstract: Nowadays development of composite materials, optimization of their properties, manufacturing processes and still expanding fields of using devotes constantly through all industry sectors. Pre-saturated fabrics known as prepreg have an indispensable position among the long fiber based composite materials. Their application seems to be very similar to the conventional methods, but in fact they have some specifications especially in view on their manufacturing process. In this article is with using an experiment and numerical model based on ACP pre- and post-processor evaluated the vibration transmission of this way created materials. These were mainly found options by changing the orientation of the individual material layers influence the shape of vibration transmission function and modal characteristics. At reduction of the vibration we are usually trying to improve parameters of created devices including their durability and eliminate resonance at the operating frequency range of the device. The excessive vibrations could significantly disrupt e.g. passengers and driver and this has an impact not only to their comfort but even safety. In real life, of course, we could find countless fiber directions and layers combinations for each applications. However, a four layers material with 2 constant and 2 variables plies was chosen as the default concept of this work. An expected dependence of the plies orientation onto a shape of the transfer function and even swapping of some MOD characters (bending, torsion and their combinations) have been found.

Keywords: composite material; modal analysis; comparison; vibration.

1 Introduction

The use of composite materials has been still growing especially because of their potential to target on a variety material properties to suit actual needs. A material composed of several elements is nowadays called as a composite when each of components still retain its self autonomy. It means that they are never chemically merged or dissolved, even though that in their interaction to environment they looks as a one independent part [1]. Long fiber composites offer generally the greatest flexibility for design specification. As well as knowledge of the basic mechanical properties of laminated materials is for us important to know their vibrational response, dumping characteristics and possibility of their modification by varying composition of the individual plies. Another important feature is the ability to specifically target the resulting synergistic effect - it means the considerable anisotropy of the materials considering for example a direction of the real load as can be seen in Fig. 1. To ensure high reliability of the structures, the actual behaviors of the laminated composite parts must be accurately predicted and carefully monitored. According to [2, 3] the material properties determined from standard specimens tested in laboratory may often significantly deviate from components manufactured in factory.

Reduction of production costs, improving quality and using of modern CAD technologies are the key points in the future of composite parts.

1.1 Material

Carbon fibers pre-impregnated with resin are the main constituent of so called prepregs. These are called "composites of the first degree" which has a dispersion of the solid phase. Used material is an Epoxy Carbon UD Prepreg with thickness of 0.2 mm. For this unidirectional material is the longitudinal Young's modulus in comparison with the transversal significantly lower. With the “rule of mixture” is possible to estimate the longitudinal modulus of a unidirectional long fiber composite with formula (1):

$$E_L = E_f E v_f + E_m v_m \tag{1}$$

Where E is a Young modulus appropriate to the uniaxial usually quasi-static stress; v_i is a constituent volume fraction and the index L, m and f mean longitudinal, matrix and fiber respectively [2].

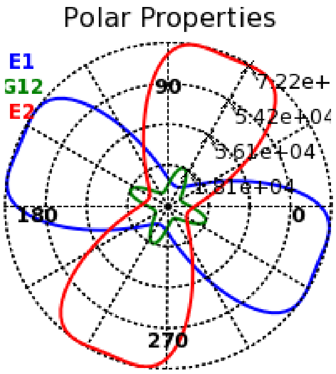

Fig. 1: The basic material properties

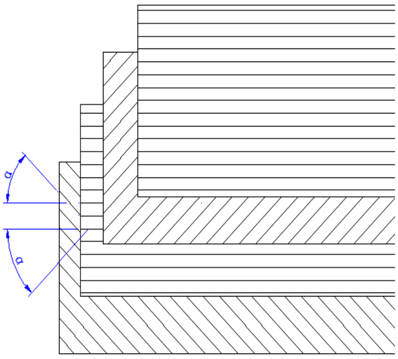

Fig. 2: One of the tested plies layout (0°/45°/0°/-45°)

Samples of size 120 x 40 mm arranged according to Fig.2 and Tab. 1 have been produced from a prepreg sheets and subsequently cured under the pressure and temperature of 150 °C for 15 minutes. The thickness of individual layers after their finishing was 0.16, 0.29, 0.4 and 0.52 mm.

Tab. 1 Composition of the tested materials

Sample nr.	**Plies - angle α °**			
1	*0*	*0*	*0*	*0*
2	*0*	*20*	*0*	*-20*
3	*0*	*45*	*0*	*-45*
4	*0*	*60*	*0*	*-60*
5	*0*	*90*	*0*	*-90*

1.2 Modal analysis

Current destructive mechanical tests usually based on static loading are slow and expensive. As a non-destructive alternative for the classical tensile test can be applied a method based on using of resonant frequencies when the composite body is from one side vibrationally excited and on the second scanned. On the basis of transfer functions can be determined the modulus of elasticity and size of the Poisson constant. According to [4] theories of Lagrange, Euler-Bernoulli, Rayleigh and Timoshenko based on a vibration of thin beams are in this area mostly used.

Modal vibration tests are usually based on the measurement of modal frequencies, damping factors and the mode shapes on the specimens or parts [5]. They have potential quickly and enough precisely provide the basis of rapid and inexpensive characterization of elastic and viscoelastic properties of the tested materials. Generally, the damping in metal structures is low, which results in high amplitudes of the vibrations. The damping of the fiber reinforced composite materials is generally higher and significantly depends on the constitution of materials.

According to Gibson [6], an empirical relation for modal frequencies of a flat cantilever beam is (2).

$$f_n = \frac{(\lambda_n L)^2}{2\pi^2}\left(\frac{EI}{\rho A}\right)^2 \tag{2}$$

Where fn = frequency of n-th mode (Hz), E = modulus of beam material, I = moment of inertia of beam about its neutral axis, ρ mass density of beam material, A = cross sectional area of beam, λ_n = eigenvalue for n-th mode which depends on boundary conditions, L = beam length.

Laminated composite plates have been analyzed by many authors [2, 3, 6]. It is well documented that shear deformation can have significantly influence on the natural frequencies of such plates. The damping property of this kind of plate is usually expressed in terms of the modal loss factor η calculated for each vibration mode of the plate. The loss factor (3), a measure of internal damping, is calculated by applying the half-power bandwidth.

$$\eta = \frac{\Delta f}{f_n} \tag{3}$$

2 Experiment

The aim of the experiment is to assess the impact of the individual plies direction of the composite material on to the overall transfer function. To a console the composite plate was mounted with using the clamping jaws (Fig. 3, 4) fixed on three bolts - at the sides and one in the middle [7]. It was necessary to provide polished clamping surfaces for perfect fixing of the sample and to avoid possible undesirable vibrations. Accelerometer Acc1 was mounted near to the jaws and at the free end of the composite sheet was mounted the second accelerometer Acc2. The acceleration arising at Acc1 and its response in Acc2 depending on time for an angle of 20 ° and 60 ° are shown in Fig. 5. The excitation force and its response converted to the frequency spectrum and calculated ratio of these two functions is called the transfer function. In this function doesn't depend on the type of excitation. It is possible to excite harmoniously, randomly or by an impulse and the results of one type of excitation may be used for predicting response of the structure at a different type.

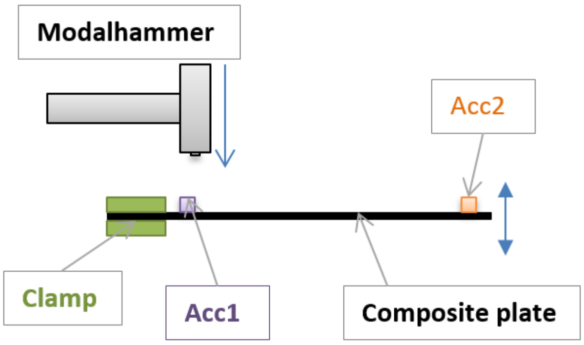

Fig. 3: Scheme of experiment

Fig. 4: Photo of the real device

In our case a modal hammer has been used. Another possibilities of excitation in similar cases could be using of hydraulic systems due to the possibility of a smooth speed control, shock absorbing and movement without "steps" typical e.g. for pneumatic systems due to the compressibility of the medium. According to the analyzed dynamic response, these methods can be subdivided into modal analysis, frequency domain, time domain and impedance domain. According to [9, 8] the excitation and the response signals are digitalized and processed by an analyzer of signals. The damping characteristics of the beams are deduced from the Fourier transform of the response to an input impulse by fitting this experimental response with the analytical response of the beam using the Ritz method.

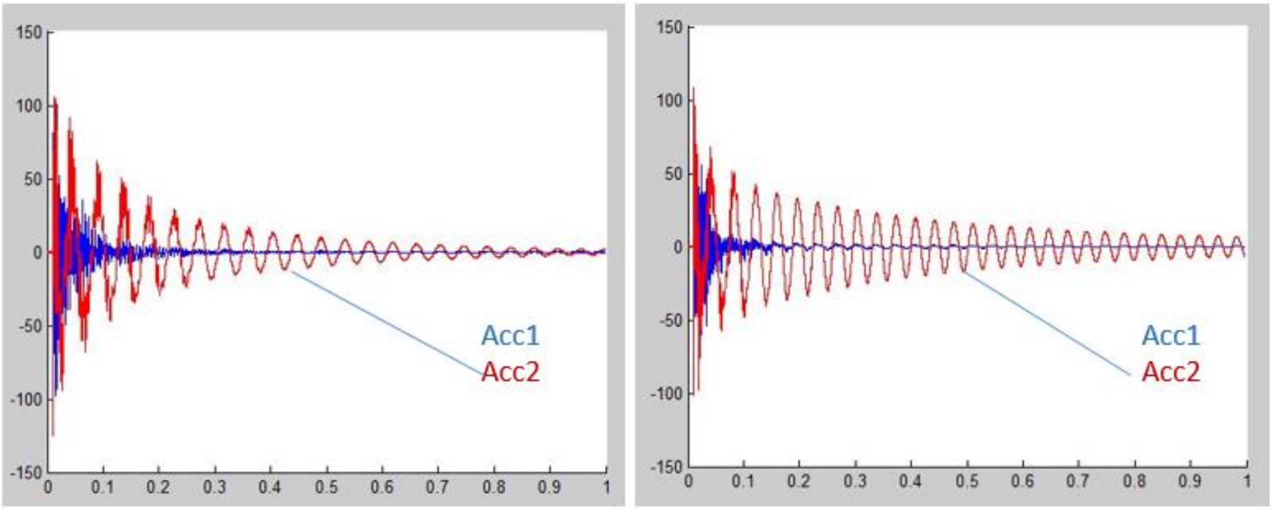

Fig. 5: Acceleration response to the excitation: 0/60/0/-60 (left) and sample 0/20/0/-20 (right)

3 The model section

Based on the CAD geometry and measured material characteristics [1] with using the ACP preprocessor a FEM model (Fig. 6) has been built [9]. The simulation itself was distributed into 2 parts - Modal analysis and frequency response. On the resulting visualizations (Fig. 7), are quite clearly see the individual natural frequencies and example of their swapping from bending to torsion simultaneously with changing the fibers direction.

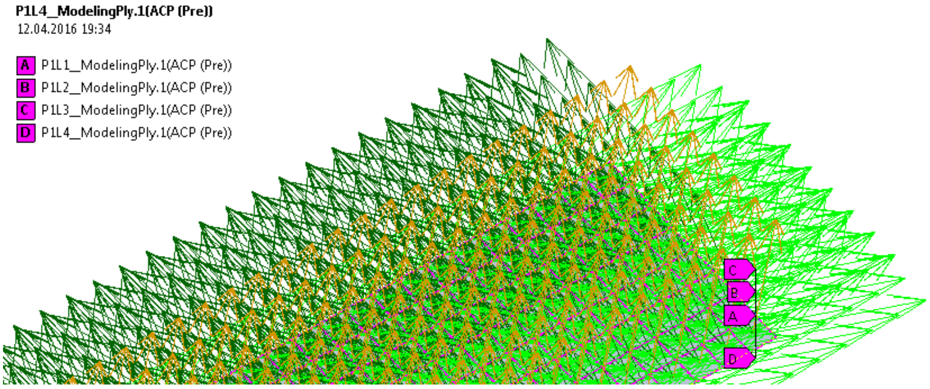

Fig. 6: Directional vectors of the individual plies

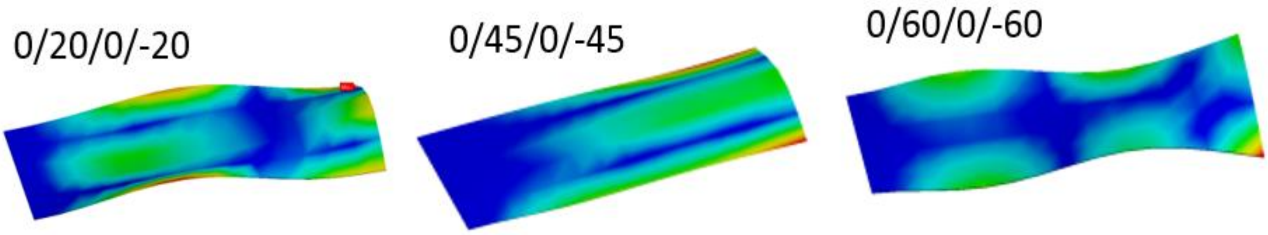

Fig. 7: Example of modifying shape of the fourth mode by changing direction of two from 4 plies

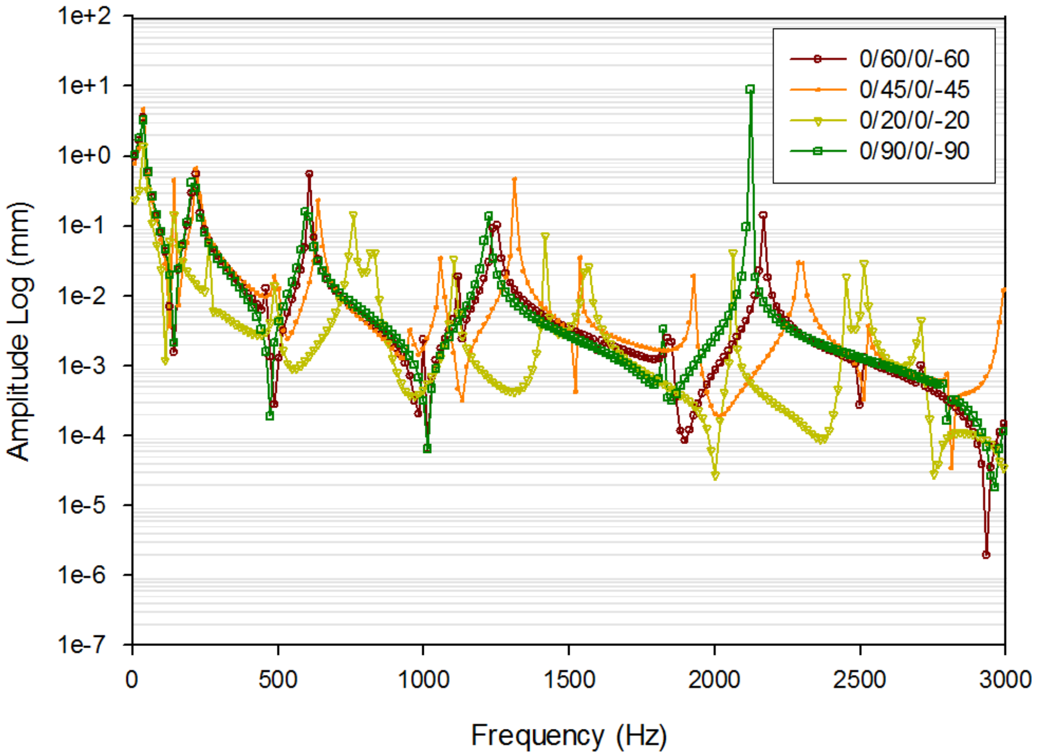

Fig. 8: Transfer function for 4 different plies angles – experimental

The material model was defined as a volume and presented by the necessary tensile and shear moduli of elasticity for each direction, density and Poisson's ratio. The resulting transfer characteristics for various angles of individual plies direction solved in ACP Ansys we can see in Fig. 8 above. Finite element analysis allows us to derive the different strain energies stored in the material directions [9] of the constituents of composite materials, and next, the energy dissipated by damping in the materials and the composite structure can be obtained as a function of the strain energies and the damping coefficients associated to the different energies stored in the material directions [10]. A Finite element model using layer-wise theory [11]. It is assumed that the same displacement distribution in the individual layers is capable of representing displacement discontinuity conditions at interfaces between layers.

4 Results

The experiment is a quick way how to find out the basic modal and transmission characteristics. Then, primarily based on the practical knowledge, it is possible to determine which modes are significant and what are just some e.g. sidebands. The numerical model could give us clear overview of the modes shape, however, their real size and relevance is necessary to verify. As is shown below in Tab. 2 for the selected case of ply orientation 0/45/0/-45° are the numerically and experimentally found eigenvalues quite similar. Significant differences are primarily at low frequencies and perhaps just there is the place where the all imperfections of manufacturing process, mass of the accelerometers and idealization in the material model will be reflected.

Tab. 2: Overview of the found eigenfrequencies [Hz].

Model	35	143	222	640	1061	1314	1536	1925	2295	2295	2988
Experiment	29	144	173	648	1012	1237	1429	1894	2241	2241	3107
Deviation	17%	-1%	22%	-1%	5%	6%	7%	2%	2%	2%	-4%

5 Conclusion

In this presented work, the experimental and numerical determination of the own frequencies and transient response for prepreg plates with 4 layers were carried out. Two layers (1st and 3rd from the top) were oriented still in the longitudinal direction, for the 2nd the angle was variable in range 0; 20; 45; 60 and 90° and the last remaining was invert to the 2nd. It has been found dependency of the transition function, its shape and particle models including their size on to the individual plies orientation. On the basis of the experimentally obtained material data [1, 7] the numerical model has been compiled. Using this model was possible to thoroughly track the process, changes in the shape of individual modes and the response of the whole structure. Results of model simulations and experiment are in good agreement. For composite parts will be error of the simulation every time bigger than for e.g. steel parts. This is caused by many parameters and conditions, that we have to consider, during the part creation (grease, pressure, temperature, imperfect vacuum, real thickness of plies) and this fact, whether we like it or not, will almost always significantly affect the final mechanical parameters. As would be expected and as was confirmed by this work, even if the weight is still the same, the fiber orientation has significantly influence to the overall rigidity. Changing orientation of the fibers we can shift the individual peaks and modify the transmission, even is possible to change character of own frequencies, as for example, change bending to torsion. The presented results are important particularly for the possibility of finding the response of the whole structure due to changes in the angle of individual layers. This could help us in our concepts to shift the modes or avoid developed devices to operate in the critical frequency areas.

Acknowledgement

This publication was written at the Technical University of Liberec as part of the project "Innovation of technical systems structures with the use of composite materials" with the support of the Specific University Research Grant, as provided by the Ministry of Education, Youth and Sports of the Czech Republic in the year 2016.

References

[1] Kulhavy P., Srb P. Syrovatkova M. *Methods for determining the tensile properties of a fiber composite rods*. In: Book of Proceedings of 56th International Conference of Machine Design Departments. Slovak University of Agriculture in Nitra, 2015

[2] Lesieutre G. A., *Modeling Frequency-Dependent Longintudinal Dynamic Behavior of Linear Voscoelastic Long Fiber Composites*, Journal of composite materials, *vol. 28 no. 18* 1994

[3] Wang W.T., Kam T.Y., *Material characterization of laminated composite plates via static testing,* Composite Structures Vol. 50, Issue 4, Elsevier, 2000

[4] Vozkova, P., *Víceúrovňové modelování mechanických vlastností textilních kompozitů*, Disertation thesis, Technical University of Liberec, Liberec, 2008

[5] Socienty of Automotive Engineers, *Test procedures for automotive structural composite materials*. Sufrace vehicle standard, Automotive Composites Consortium, 1995

[6] Gibson R.F., *Modal vibration response measurements for characterization of composite materials and structures,* Elsevier, Composites Science and Technology 60, 2000

[7] Petrik, J., Kulhavy, P. Pasek, M. Sasek, J. *Vibration and Noise Reduction Analysis of Sheet Metal Structures with Damping Layer,* Applied Mechanics and Materials, Vol 732, 2014

[8] Whitney JM. *Shear correction factors for orthotropic laminates under static load*. Journal of Appl Mech; 40:302-4, 1973

[9] Zou Y., Tong L. and Steven G.P., *Vibration based model dependent damage identification and healt monitoring for composite structures*. Journal of Sound and vibration 230, 2000

[10] Petru M.; Syrovatkova M.; Martinec T.; Lepšík P.: *Analysis of Changes in the Surface Quality of a UD Prepregs Composite due to Mechanical Loading*, Material Science Forum, Vol.818, 2015

[11] Barbero E. J. and Reddy J. N. *International Journal of Solids and Structure* 28.Modelling of delamination in composite laminates using a layerwise plate theory, 1991