MATERIAL CHARACTERIZATION, VIBRO-ACOUSTIC ANALYSIS AND MANUFACTURING OF TEXTILE-REINFORCED COMPLEX 3-D COMPOSITE STRUCTURES

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Abstract

Lightweight composite structures for high-technology applications increasingly have to fulfill high demands not only on low constructive weight and adequate stiffness but also on reduced vibrations and sound radiation. Here, especially textile-reinforced thermoplastic composites offer a high vibro-acoustic lightweight potential combined with the possibility for series-production.

Based on a detailed material characterization of textile-reinforced thermoplastics this paper makes a contribution to the development of vibro-acoustically optimized complex 3-D composite structures by using numerical and experimental design methods. A Finite Element Model for textile-reinforced composite trays was build describing the structural-dynamic behavior. On this basis, material-adapted manufacturing technologies were developed, which allow the production of these demonstrator trays. The vibro-acoustic characteristics of the demonstrators were experimentally determined and first material-adapted design rules were derived.

1 Introduction

The constantly increasing customer demands and the drastically shortened development times as well as the necessary weight reduction and function-integration are pressing influence factors for the design of new lightweight composite structures. In the course of these challenging demands textile-reinforced thermoplastic composites (TTC) offer totally new possibilities for a function-integrated design (see [1], [2]). The specific use of anisotropic material characteristics of TTC offers high stiffness and material damping as well as low constructive weight resulting in a high vibro-acoustic potential.

As practically relevant technology demonstrators this paper focuses on new composite trays made of thermoplastic hybrid yarns (Twintex®). The high vibro-acoustic lightweight potential of these TTC-trays can only be utilized, if secured dynamic material parameters as well as acoustic properties are known and implemented within the design process. Thus, specific material characterization methods, calculation models for the structural-dynamic and acoustic behavior as well as manufacturing techniques have to be developed considering the influence of the different kinds of textile architectures.

This paper makes a contribution to this challenging topic by presenting the results of an extensive characterization of the dynamic material properties of TTC. These textile-specific material data were used for the simulation of the structural-dynamics of composite structures. Furthermore, the developed vibro-acoustically adapted design of TTC-trays is transferred into a physical demonstrator by the application of a material-adapted production technology. The new processes are based on the implementation of a quick and material-adapted preheating of the thermoplastic textile preforms. Finally, the vibro-acoustic properties of the manufactured demonstrators are experimentally validated.

2 Material characterization

The determination of secured dynamic material properties is the fundament of both analytical and numerical structural-dynamic design. Here, the multilayered TTC are described by the combination of basic layers with bidirectional reinforcement. The material characterization of these basic layers requires the determination of dynamic elasticity and damping values using adapted experiments [3].

2.1 Determination of dynamic properties

The authors used a special resonance bending technique well adapted for composite materials in combination with the Fast-Fourier-Transformation (FFT) according to DIN 53 440 [4]. The dynamic properties are measured using beam specimens with rectangular shape excited harmonically on the wider surface. The specimens are fixed on one side in a special 4-point-clamping developed to minimize the energy loss within the clamping zone while the other end remains free. The amplitude of the forced flexural vibration is registered contactless with inductivity sensors. The resonance frequency and the appropriate damping can be determined from the resulting resonance curve.

The directional-dependent dynamic stiffness and damping values are investigated using tests of 0°, 30°, 45°, 60° and 90° reinforced specimens, where 0° corresponds to the direction of textile production (weft direction). Testing of 0° and 90° specimens enables to determine the dynamic Young's modulus parallel and perpendicular to the weft direction. Testing 30°, 45° and 60° specimens yields the shear modulus $G'_{\#}$ by using the following polar transformation (see [4])

$$\frac{1}{E'_x(\varphi)} = \frac{1}{E'_{\parallel}}\cos^4\varphi + \frac{1}{E'_{\perp}}\sin^4\varphi + \left(\frac{1}{G'_{\#}} - 2\frac{\nu_{\parallel\perp}}{E'_{\parallel}}\right)\sin^2\varphi\cos^2\varphi \quad . \tag{1}$$

The damping values $d_{\parallel}$, $d_{\perp}$ and $d_{\#}$ of the considered composites are measured according to DIN 53 440 [4] by determining the 3dB-bandwidth of the resonance curves. Testing of 0° and 90° specimens respectively yields to the damping values in weft $(d_{\parallel})$ and warp $(d_{\perp})$ direction. Analogue to the determination of the shear modulus, the shear damping $d_{\#}$ is calculated by polar transformation (see [3], [4]).

2.2 Dynamic material properties of TTC

The material characterization was carried out for TTC reinforced with different types of woven and knitted fabrics. As an example of these extensive investigations Fig. 1 shows the characteristics of the dynamic Young's modulus and material damping of polyetheretherketone (PEEK) based composites reinforced with sateen woven and tricot knitted carbon fabrics (CF/PEEK), respectively.

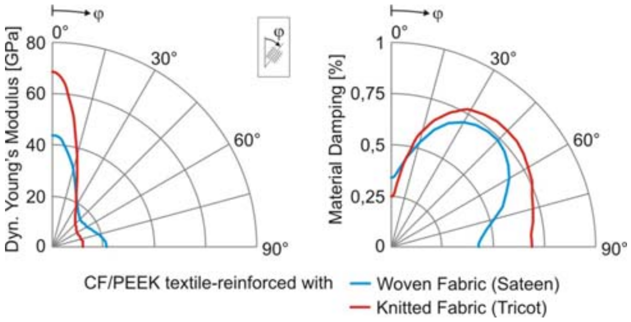


Fig. 1: Characteristics of dynamic Young's modulus and material damping for CF/PEEK composites with woven and knitted reinforcement

The dynamic Young's modulus shows a nearly unidirectional characteristic caused by the specific textile architecture of the used specimens (see Fig. 2).

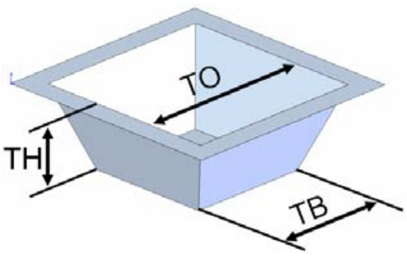
Fig. 2: Textile architecture of the investigated TTC (left: woven fabric, right: knitted fabric)

The highest stiffness values occur in weft direction for both woven and knitted TTC. The woven TTC specimen has a high amount of fibers oriented in weft direction in the outer layers. This causes a higher flexural stiffness in weft than in warp direction. The knitted TTC specimens contain whole layers of straight fibers, so that almost no fiber ondulation exists. This results in even higher flexural stiffnesses in weft direction.

The composite damping values show an inverse characteristic compared to the stiffness. Both composites have a small damping in 0°-direction and a high damping between 30° and 60°. The difference between the two materials in 90° direction is caused by the textile architecture analog to the Young's modulus.

3 Investigated tray geometries

As technology demonstrators composite trays are chosen which have a practical relevance e.g. as spare-wheel wells. The demonstrator tray has quadratic shape and constant outer dimensions (560x560 mm). Different tray heights (TH), openings (TO) and bottoms (TB) were defined in order to determine the influence of geometry on the vibro-acoustic behavior of the TTC-trays (see Fig. 3).



Part	TO [mm]	TB [mm]	TH [mm]
CT-1	0	0	0
CT-2	450	300	50
CT-3	450	300	100
CT-4	450	300	200
CT-5	450	50	50
CT-6	450	200	50
CT-7	450	400	50
CT-8	450	200	100
CT-9	350	200	100
CT-10	250	200	100

Fig. 3: Dimensions of the investigated TTC-trays

The chosen dimensions allow the generation of three series:

- *TH series* - variable TH, constant TO (450 mm) and TB (300 mm)
- *TB series* - variable TB, constant TH (50 mm) and TO (450 mm)
- *TO series* - variable TO, constant TH (100 mm) and TB (200 mm)

Exemplarily, the TB series consists of the parts CT-5, CT-6, CT-2 and CT-7 (increasing TB).

4 Computational structural-dynamic analysis

Complex 3-D TTC structures are highly sensitive to undesired structural vibrations because of their low weight and low forces of inertia. Thus, the fulfillment of the constant increasing comfort and safety requirements of lightweight structures gets difficult. Here, the interaction of excitation frequency as well as amplitude and the eigenfrequencies as well as mode shapes of the structural vibration determine the loss of comfort. The appearance of noise as an effect of the resonant coupling between air and structure is closely linked to this structural vibration. Thus, an adjustment of the structural-dynamics of TTC concerning operational demands is an essential basis to develop comfort-oriented dynamically loaded lightweight structures.

Starting point of the structural-dynamic analysis of the 3-D TTC structures is the determination of free standing vibration fields. These free standing waves show large resonances and thus create massive sound radiation.

The structural-dynamic analysis was performed using the experimentally determined TTC material data and the Finite Element (FE) Method. Fig. 4 shows a characteristic mode shape of the TTC-tray which is one of the boundary conditions for the acoustic analysis.

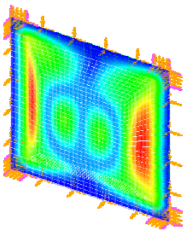


Fig. 4: Characteristic mode shape of a TTC-tray

The developed FE models allow the calculation of several eigenfrequencies and mode shapes. Furthermore, parameter studies on the influence of the tray geometry on the dynamics can easily be performed. These data are the basis for a validation done by the experimental investigations.

5 Manufacturing of TTC-trays

The developed design of the TTC-trays has to be verified by vibro-acoustic tests. Thus, physical demonstrators were manufactured using special production technologies adapted to process 3-D woven hybrid yarn semi-finished products made from glass fiber and polypropylene.

The production process can be divided in four steps. The first step is to mill a pre-mold from a wooden block (see Fig. 5).

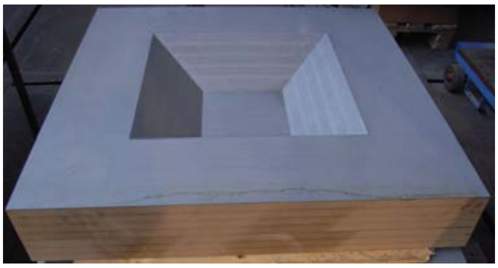


Fig. 5: Wooden pre-mold

This pre-mold is used to produce the final mold from a carbon fiber-reinforced tooling prepreg (see Fig. 6).

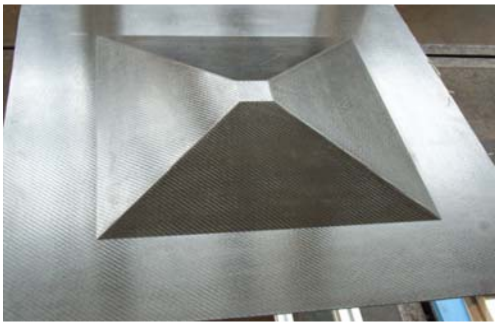


Fig. 6: Mold made of tooling prepreg

The textile preforms are then draped on the mold and consolidated within an autoclave (see Fig. 7).

Fig. 7: ILK high-performance autoclave

Using this procedure representative trays of each geometry series (TO, TB, TH series, see Fig. 3) have been manufactured (see Fig. 8).

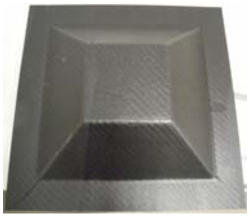


Fig. 8: TTC demonstrator tray

To transfer this initial autoclave based manufacturing process to a close-to-production press technology investigations were made to preheat the thermoplastic textile preforms in order to reach short cycle times. The difficult handling of the preforms at working temperature as well as the high temperature sensitivity of the hybrid yarns requires special adapted melting technologies, which have been developed at the ILK.

As possible melting techniques applicable for preheating the physical processes heat conduction, convection and radiation were evaluated (e.g. [6], [7]). Infrared radiation offers the most capability for heating of large surface hybrid yarn preforms. These emitters have very short start-up times and high power density. An additional advantage is the contactless heat transfer. Further investigations performed at the ILK show, that infrared radiation is an effective technology for a fast and material-adapted heating of hybrid yarn structures if the emitters are specially adjusted to the used thermoplastic material. These tests show that a fast and deep penetrating heat transfer requires infrared emitters with a wavelength between 380 und 2250 nm due to the high transmissivity for this wavelengths. At the ILK, two different infrared emitters of this wavelength range were analyzed, which are predestinated for heating of thermoplastic materials. The short wave emitter has the optimum power for a wavelength between 1000 and 1400 nm. The carbon emitter has a widespread spectrum with an optimum power at approximately 2000 nm. Fig. 9 shows the heat penetration times of these two emitters for heating a different number of Twintex® layers to a temperature of 200°C in the middle of the preform.

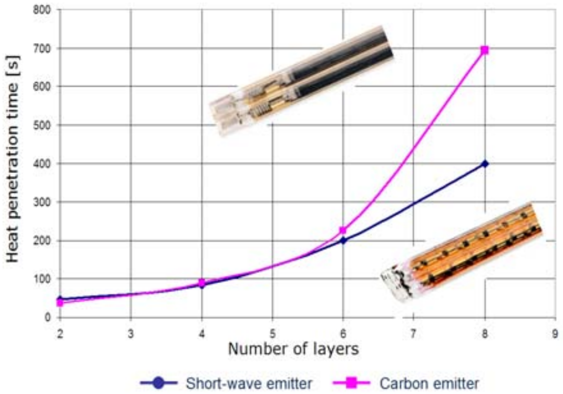


Fig. 9: Heat penetration times of short-wave and carbon emitters

Up to 4 textile layers no significant difference between these two emitters is observed. Whereas, for thick walled preforms (6 and more layers) the transmissive effect of the short-wave infrared radiation can explicitly reduce the heat penetration times.

6 Experimental vibro-acoustic investigations of TTC-trays

6.1 Structural-dynamic tests

For the experimental determination of the eigenfrequencies and mode shapes of the manufactured TTC-trays a multifunctional Acoustic Window Test Stand (AWS) in combination with a shaker and eight accelerometers was used. Within this AWS, the composite tray is mounted in special bearings inside a test window (compare Fig. 10).

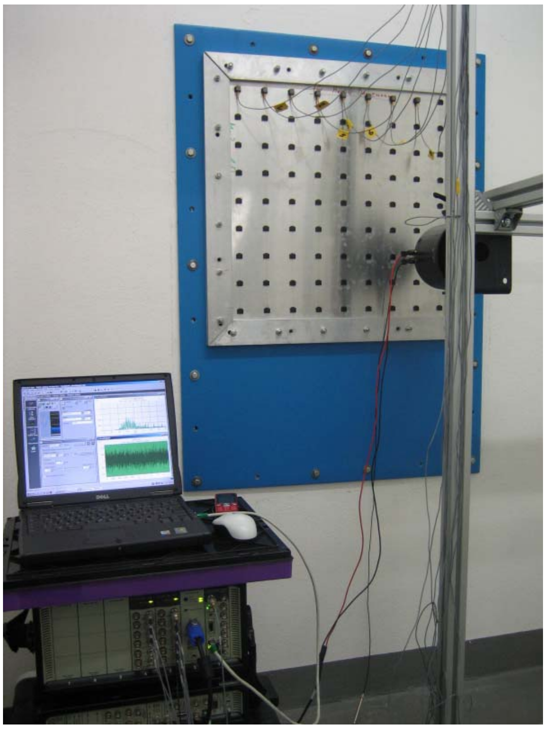


Fig. 10: Measurement setup for structural-dynamic tests

As excitation signal a swept sine between 20 and 1600 Hz with an adapted sweep rate was chosen. Eight roving monoaxial accelerometers were used to measure the frequency response functions (FRF). After recording all FRF a modal analysis was performed using Me'Scope VES software. Fig. 11 exemplarily shows a mode shape at 81 Hz of the CT-2 tray.

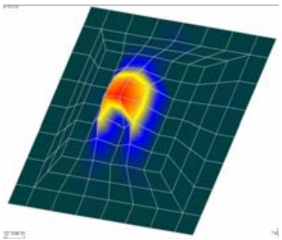


Fig. 11: Measured mode shape of the CT-2 tray

The performed experimental modal analysis allows a comparison of simulation and test results. A selected pair of acoustically relevant calculated and measured mode shapes of the TTC-tray is shown in Fig. 12.

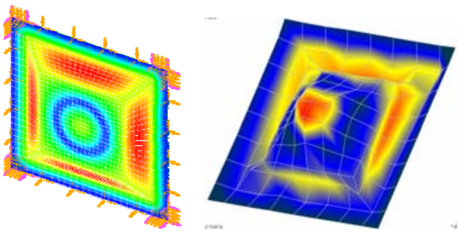


Fig. 12: Comparison of calculated and measured mode shapes

Here, a good agreement between the calculated and experimentally determined mode shapes is found. This reveals that the developed material-adapted structural-dynamic FE-model describes the dynamic behavior of textile-reinforced thermoplastic composites with sufficient accuracy. Thus, the model can be used for further parameter studies and is a helpful tool for the calculation engineer.

6.2 Measurements of Transmission Loss (TL)

The AWS was used for the determination of the Transmission Loss (TL) R of different tray geometries. The principle test setup is shown in Fig. 13.

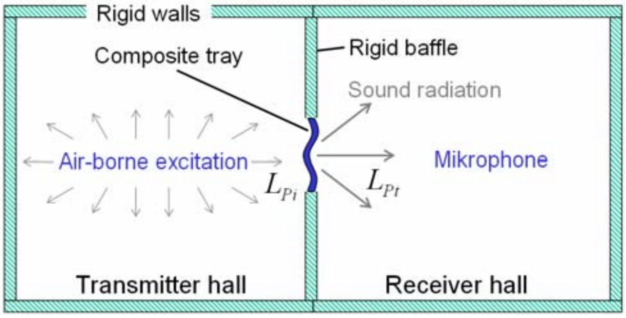


Fig. 13: AWS setup for transmission loss measurements

Within this AWS, the TTC-tray is mounted in special bearings inside a rigid baffle. This baffle separates the AWS into a rigid transmitter hall and a rigid receiver hall. Inside the transmitter hall an acoustic sound source generates a diffuse sound field. Thus, the tray is acoustically excited and radiates sound into the receiver hall. By measuring the averaged sound pressure level L_p it is possible to determine the radiated sound power level L_P in both halls using the following equation:

$$L_P = L_p - \left[\begin{array}{l} 10\lg\dfrac{T}{T_0} + 10\lg\dfrac{V}{V_0} - 10\lg\dfrac{B}{B_0} \\ +10\lg\left(1+\dfrac{s\lambda}{8V}\right) - 14 \end{array} \right] dB\,, \qquad (2)$$

where T is the reverberation time, V the volume, s the wall surface of the room, λ the wavelength and B the humidity.

The TL is then calculated as the ratio between the sound power levels of the transmitter hall L_{Pi} and receiver hall L_{Pt}

$$R = 10\lg \frac{L_{Pt}}{L_{Pi}} dB\,. \tag{3}$$

Fig. 14 shows the frequency averaged measured TL of the TB-series.

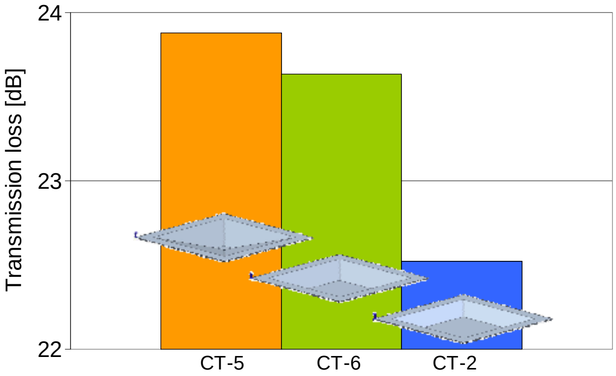


Fig. 14: TL within the TB-series

The TL decreases with increasing surface of the tray bottom (increasing TB) although the tray mass increases. Here, the large bottom surface of the CT-2 variant results in a large structure air-coupling at low frequencies. This causes a high energy flow into the surrounding air volume. In contrast to this, the radiation effect of the side faces of the CT-5 variant is smaller due to the higher frequencies and smaller surfaces.

The frequency dependent TL of the same series is shown in Fig. 11.

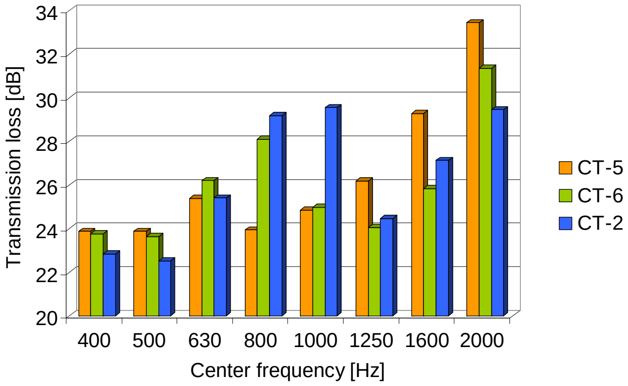


Fig. 15: TL frequency characteristics of composite trays within the TB-series

The measured data show that the CT-5 variant with large side faces radiates much sound power in a frequency range of 800-1000 Hz. This is probably caused by large vibrations of the side faces within this frequency range.

The performed investigations illustrate that the vibro-acoustic behavior of textile-reinforced thermoplastic composite trays is influenced by the complex interaction of geometry and material parameters. Thus, an optimal sound radiation behavior can only be achieved by a material-adapted vibro-acoustic design.

7 References

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