Design and tests of thermoplastic textile-reinforced composite trays for vibro-acoustic relevant applications

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Introduction

Driven by increasing customer demands, environmental and economical requirements, lightweight engineering gains in importance for various industrial and transport applications. Here, composite materials based on thermoplastic hybrid yarns offer new possibilities for multifunctional design due to its adjustable properties. So, requirements concerning high stiffness and damping as well as low weight and short cycle times during manufacturing can be met by an adapted composite lay-up and manufacturing process.

In the presented work, the vibro-acoustic behaviour of selected textile-reinforced thermoplastic composites (TTC) was characterized dependent on the kind of reinforcement and its fibre orientation. In addition, simulation models for the calculation of modal and acoustic parameters of textile-reinforced structures were developed. For the verification of the simulation models composite trays were manufactured in hot pressing technology with different lay-ups. The eigenfrequencies, mode shapes, modal damping values and transmission loss of the trays were measured. Subsequently, the experimental results were compared with the numerical simulations. The performed investigations illustrate how the vibro-acoustic behaviour of textile-reinforced composite trays is influenced by the complex interaction of geometry and material parameters. Thus, an optimal sound radiation behaviour can only be achieved by a material-adapted vibro-acoustic design.

Preliminary design of lightweight TTC-structures

Material characterization

The basis for the computational analysis of the structural dynamic behaviour is a set of dynamic material properties including the stiffness and damping values for the used TTC. These properties are measured using the bending resonance technique. Here, beam specimens with rectangular shape are fixed on one side in a special 4-point-clamping and harmonically excited on their wider surface. 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 (see e.g. [1], [2]).

The material characterization was carried out for TTC reinforced with different types of woven and knitted fabrics. As an example of these extensive investigations Figure 1 shows the characteristics of the dynamic Young's modulus and material damping of Polypropylene (PP) based composites reinforced with sateen woven and tricot knitted glas fabrics (GF), respectively [3].

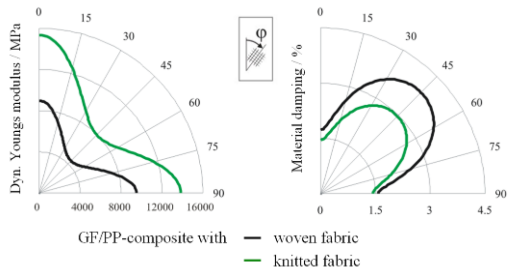


Figure 1 Dynamic Young's modulus and material damping of GF/PP composites with woven and knitted fabrics

The dynamic flexural Young's modulus shows a bidirectional characteristic caused by the specific textile architecture of the used specimens (see Figure 2).

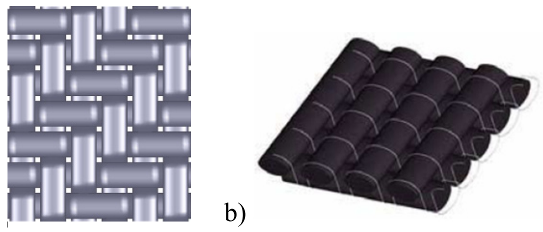


Figure 2 Used textile architecture for manufacturing the TTC-trays; a) woven fabrics, b) knitted fabric

The knitted TTC specimen is characterized by a straight fibre orientation, so that almost no fibre ondulation exists. This fact leads to higher flexural stiffnesses in 0°- and 90°-direction compared to the woven reinforcement. 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.

Structural dynamic simulation

As practically relevant technology demonstrators this paper focuses on new composite trays made of thermoplastic hybrid yarns, which have a practical relevance e.g. as spare-wheel wells. The adjustment of the structural-dynamics of these TTC-trays concerning operational demands is an essential basis to develop comfort-oriented dynamically loaded lightweight structures. Starting point of the structural-dynamic analysis of the 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. The developed FE-model allows the calculation of several eigenfrequencies and mode shapes for different geometry parameters (see Figure 3, [4]).

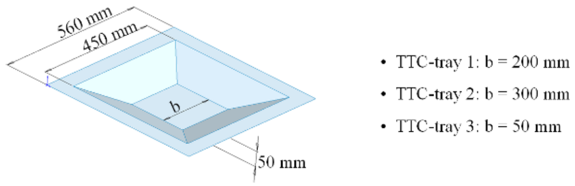
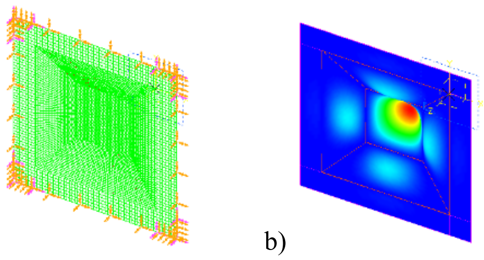


Figure 3 Dimensions of investigated TTC-trays

With the FE-model extensive parameter studies concerning influence of fibre orientation or geometry on the structural dynamic behaviour were performed. Figure 4 shows the used FE-mesh and an exemplarily chosen mode shape.



a) b)

Figure 4 a) FE-model for structural-dynamic simulation; b) calculated mode shape

Furthermore, the eigenfrequencies and modal damping values for the TTC-tray 1 with "free-free" boundary conditions and different fibre orientations were calculated (see Figure 5).

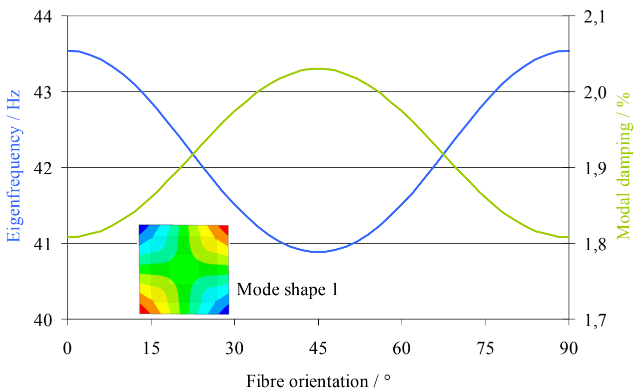


Figure 5 Calculated modal damping and eigenfrequency against the fibre angle for the first mode shape

The first eigenfrequency over fibre orientation shows a minimum in the range of 45° while the maximum is at 0° and 90°. The modal damping has an inverse behaviour to the eigenfrequency causing the highest damping value at 45°.

Manufacturing

The virtually designed TTC-trays have to be verified by vibro-acoustic tests. Thus, physical demonstrators were manufactured using special production technologies adapted to process woven hybrid yarn semi-finished products made from glass fibre and polypropylene.

Within a first step, a pre-mould is milled from a wooden block. This pre-mould is used to produce a final mould from carbon fibre-reinforced tooling prepreg. The textile preforms are then draped on the mould and consolidated in an autoclave. Using this procedure selected TTC-trays (compare Figure 3) have been manufactured (see Figure 6).

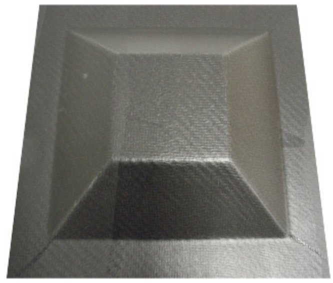


Figure 6 Manufactured TTC-tray

To transfer this initial autoclave based manufacturing process to a close-to-production press technology continuative investigations at the ILK were done [1].

Experimental vibro-acoustic investigations

The vibro-acoustic investigations of the TTC-trays include experimental modal analyses as well as acoustic measurements of the transmission loss.

Structural-dynamic tests

For the experimental determination of the eigenfrequencies, mode shapes and modal damping values a multifunctional Acoustic Window Test Stand (AWS) was used. Within this AWS, the composite tray is mounted in special bearings inside the test window. The experimental modal analysis was performed using hammer excitation (see Figure 7).

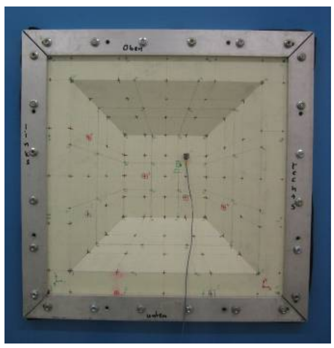


Figure 7 Experimental modal analysis with hammer excitation

Different eigenfrequencies, modal damping values and the corresponding mode shapes of the investigated TTC-trays are determined in the experimental modal analysis (see Figure 8).

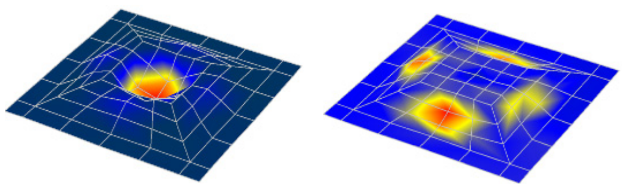


Figure 8 Characteristic mode shapes of the TTC-tray 1

A comparison of the measured and the calculated modal parameters shows a good agreement, as it is demonstrated in Figure 9 for two mode shapes of the TTC-tray 1.

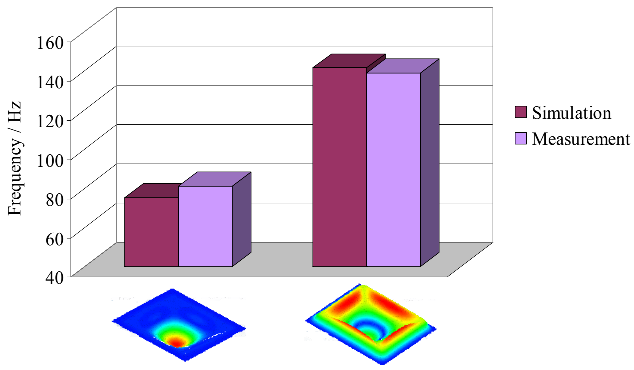


Figure 9 **Alignment of simulation and measurement from TTC-tray 2**

This reveals that the developed material adapted structural-dynamic FE model in combination with the determined material properties describes the dynamic behaviour of textile-reinforced thermoplastic composites with sufficient accuracy.

In further investigations the influence of the fibre orientation on eigenfrequency and modal damping was analyzed. Therefor, TTC-trays with different fibre orientations were manufactured from hybrid yarn with knitted textile architecture. Figure 10 shows the frequency and damping values of a selected mode shape for different fibre orientations.

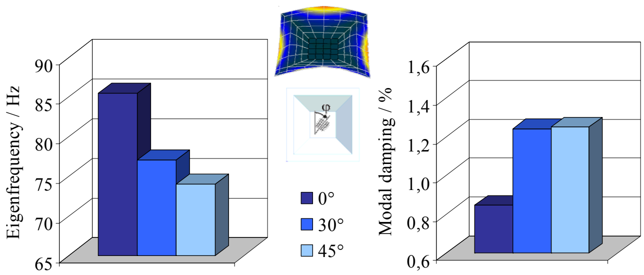


Figure 10 **Eigenfrequency and modal damping of TTC-tray 1 with different fibre orientations**

With an increasing fibre angle the eigenfrequency of the TTC-tray 1 decreases. At 45° the eigenfrequency exhibits a minimum. The modal damping shows an inverse behaviour where, the highest damping value occurs at 45°.

Acoustic measurements

The AWS was used for the determination of the Transmission Loss (TL) of different tray geometries and fibre orientations. The test setup is shown in Figure 11.

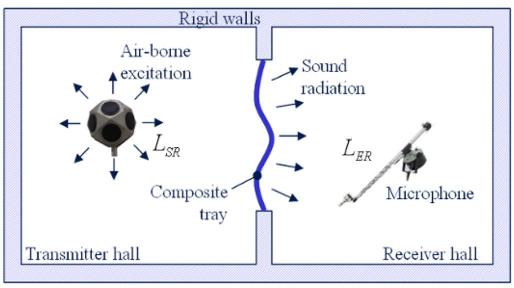


Figure 11 **AWS-setup for acoustic measurements**

The TTC-tray is fully clamped in the test window and acoustically excited by a dodecahedron sound source. By measuring the averaged sound pressure levels L_{SR} and L_{ER} it is possible to calculate the transmission loss TL of the investigated trays using the following equation:

$$TL = L_{SR} - L_{ER} + 10 \cdot \log\left(\frac{S}{A}\right) in\ dB$$

where S is the surface of the test window and A the equivalent sound absorption surface calculated from the reverberation time of the receiver hall.

With the TTC-tray 1 the correlation between structural-dynamic and acoustic properties is visualized. Therefor, a 1/24-octave TL spectrum and acoustically relevant eigenfrequencies with corresponding mode shapes were compared (see Figure 12).

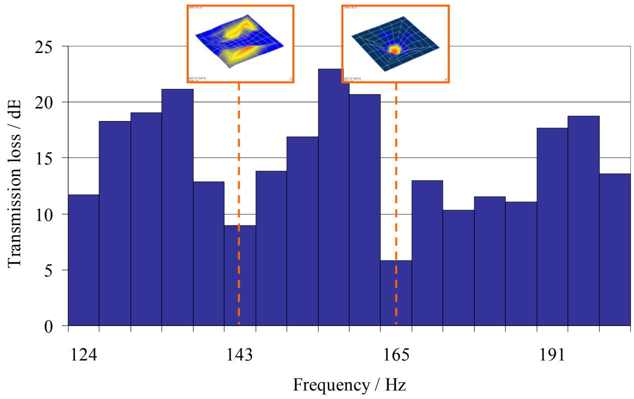


Figure 12 **Interaction between structural dynamic and acoustic behaviour**

As expected, the lowest TL values were measured at the eigenfrequencies of the TTC-tray within the considered frequency range.

Moreover, the TL of the TTC-tray 1 with different fibre orientations was measured and rated on the basis of DIN EN ISO 717-1 [5] (see Figure 13).

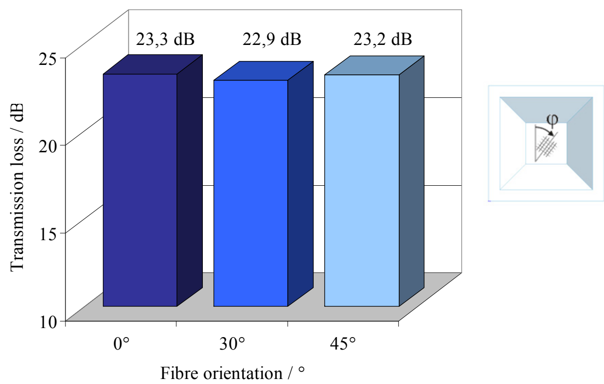


Figure 13 **Averaged TL of the TTC-tray 1 with different fibre orientations**

The averaged TL is not significantly influenced by the fibre orientation. Thus, shifting the eigenfrequencies by varying the fibre orientation does not affect the averaged TL.

Furthermore, the influence of textile architecture on the sound insulation was investigated. Therefor, TTC-trays with woven and knitted fabrics were manufactured. The measured spectrums of the TL for different textile preforms are shown in Figure 14.

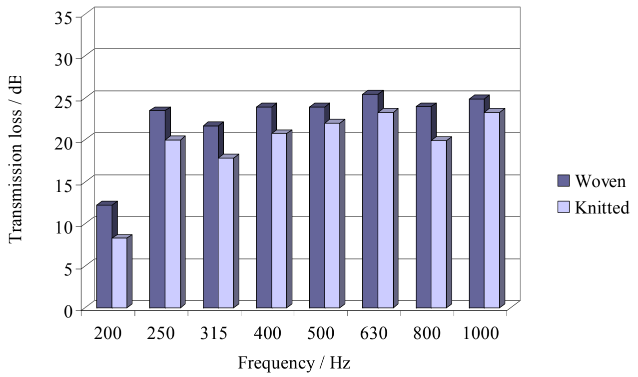


Figure 14 TL-spectrum for TTC-tray 3 with different textile reinforcements

The preform with woven fabric leads to a higher TL of the TTC-tray 3 than the knitted fabric. This is due to the higher material damping causing higher vibration energy absorption, which results in a lower sound radiation. Additionally, the knitted fabric leads to a slightly higher surface weight of the layup by producing same thicknesses off TTC-trays. So the sound radiation of the TTC-tray with woven fabric has a slightly higher sound insulation.

Conclusions

The anisotropic structural-dynamic material properties of textile-reinforced thermoplastic composites offer the possibility to design assemblies with an adapted vibro-acoustic behaviour. Therefor, a FE model was developed as a helpful tool for performing parameter studies in order to construct damping adapted laminates with a low sound radiation. In extensive vibro-acoustic tests on different TTC-trays the FE model was verified.

Furthermore, the correlation between structural-dynamic and acoustic properties was analyzed on different TTC-trays.

With the extensive numeric and experimental vibro-acoustic investigations concerning vibration, damping and acoustic behaviour first construction and design guidelines for damping and sound radiation adapted TTC-trays are given:

- The fibre orientation of textile reinforcement has a high influence on the eigenfrequencies and damping values and has to be considered in design process.
- The shifting of eigenfrequencies by changing fibre orientation is drawn in the 1/24-octave spectrum of TL.
- The fibre orientation has a marginal influence on the transmission loss of the investigated TTC trays.
- The kind of textile reinforcement influences the TL and has to be considered in the design process.

With these guidelines the engineer is able to design material adapted textile-reinforced thermoplastic assemblies for acoustically relevant applications.

References

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