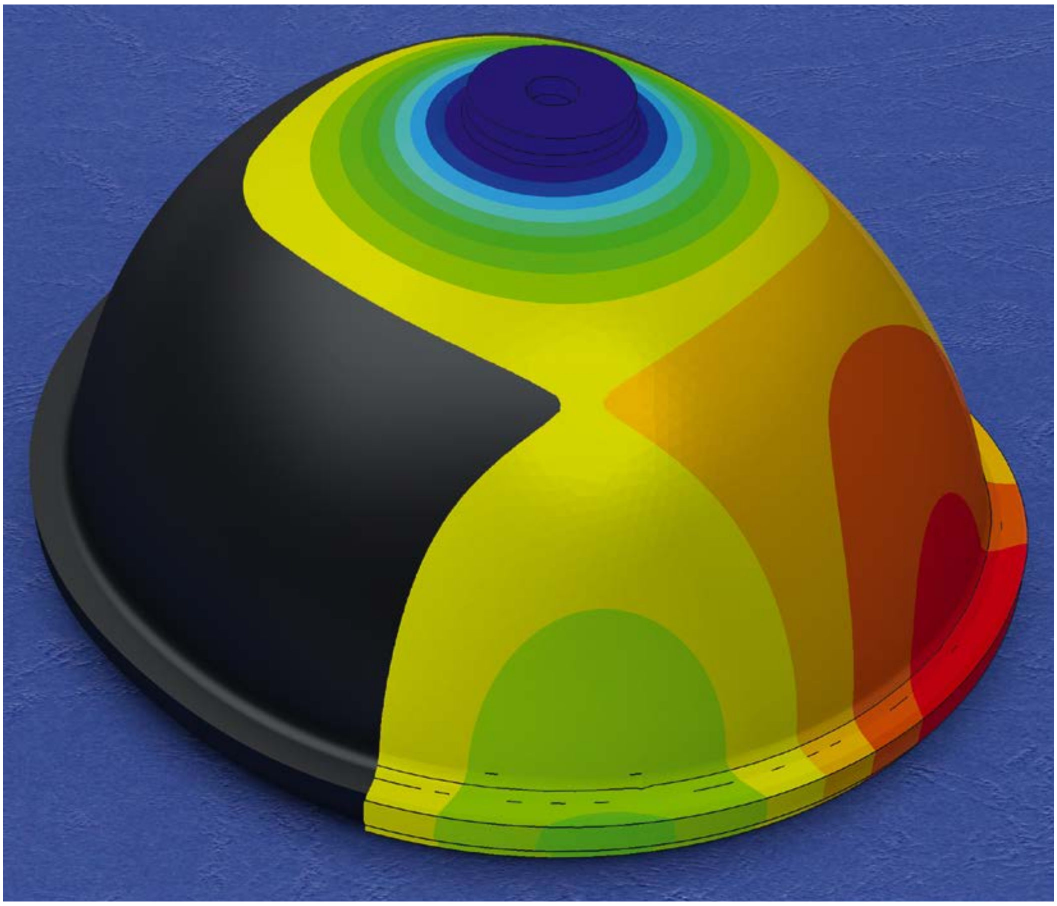
The Sound of Short Glass Fibers in Plastics

A New Integrative Simulation Concept Predicts the Directional Structure-Borne Sound Behavior of Short Glass Fiber-Reinforced Components

The knowledge of the precise oscillation behavior of plastics components plays a key role both for acoustic considerations as well as for fatigue predictions. In order to calculate the acoustic performance of short glass fiber-reinforced components depending on the local fiber orientations, a comprehensive simulation chain has been developed at the Institute of Plastics Processing (IKV) in Aachen, Germany. Based on the principle of the integrative simulation it enhances conventional acoustic simulations.

In their installation situation, technical plastics parts are often exposed to pulses and are thereby stimulated to radiate noise. The low density and rigidity of these materials lead to the unfavorable acoustic behavior that components do not only have a low inertia, but also swing with large displacement amplitudes at low loads. The knowledge of the acoustic behavior of plastics components also gains importance because legislation for noise protection becomes increasingly stringent. Moreover, the perceived sound quality of a product also increasingly arises as an important quality criterion, »



The simulated eigenfrequency shape of the model component is shown projected on its geometry (© IKV)

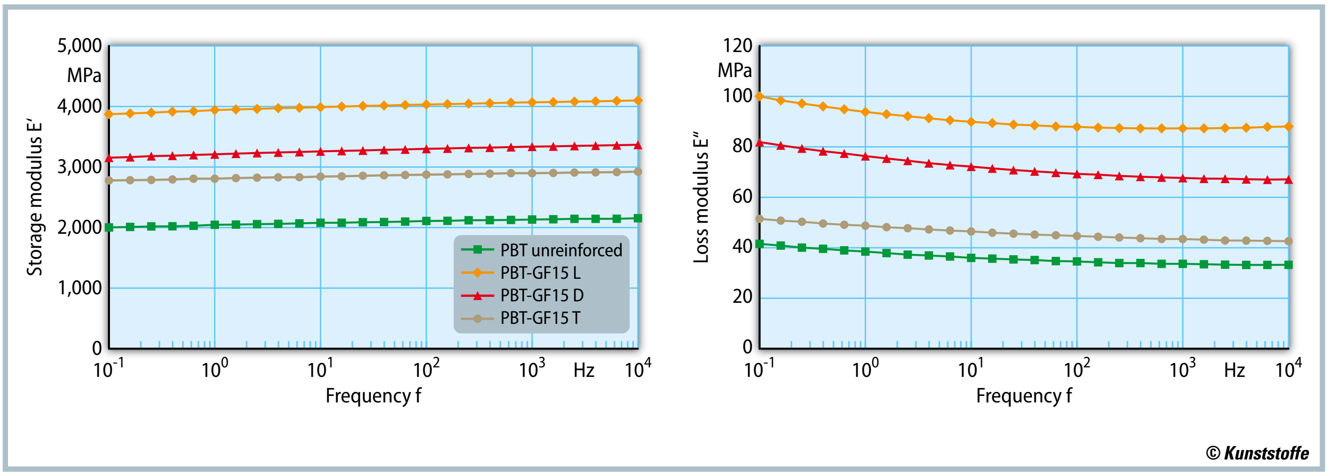


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Fig. 1. As characteristics of the viscoelastic material behavior, the frequency and direction-dependent stiffness and damping are determined (source: IKV)

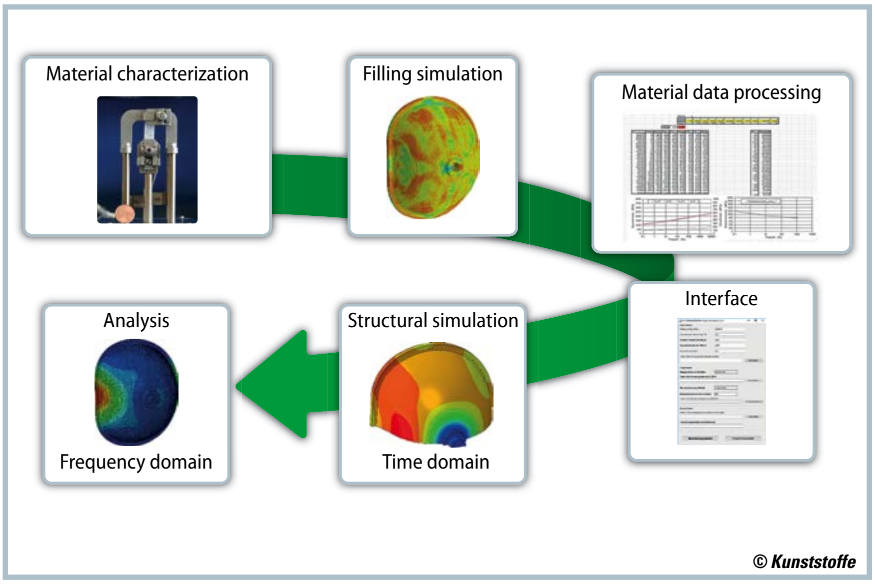

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Fig. 2. The procedure for the anisotropic structure-borne sound simulation is based on classical integrative simulation concepts (source: IKV)

which can influence the purchasing decisions significantly [1, 2].

A promising opportunity to characterize the acoustic behavior of components at an early stage of development and hence being an enabler to reduce costs, is the numerical simulation using the finite element method (FEM) or the boundary element method (BEM) [3, 4]. However, thermoplastics are consistently modeled with isotropic mechanical behavior in acoustic simulations.

Anisotropic short fiber-reinforced thermoplastics, which are often used for acoustically relevant components such as intake manifolds or cylinder head covers, cannot accurately be modeled in this way [5]. As part of a publicly funded research project, the work group "Part Design/Acoustic/Fatigue" at the Institute of Plastics Processing (IKV) developed a method to simulate the anisotropic acoustic component behavior. This method especially takes the relevant direction-dependent mechanical properties stiffness and damping into account.

Analysis of the Frequency-Dependent Anisotropic Composite Behavior

The direction-dependent viscoelastic material behavior of selected short glass fiber-reinforced thermoplastics is analyzed under quasi-static and dynamic loads in order to gain knowledge about the material behavior. Both a polyamide 6 with 30 wt.-% short glass fibers (PA6-GF30, type: Durethan BKV30 H2.0) in the dry and in the conditioned state and a polybutylene terephthalate with 15 wt. % short glass fibers (PBT-GF15, type: Pocan KL1-7265; manufacturer in both cases: Lanxess Germany GmbH, Cologne, Germany) have been considered. This material selection allows not only studies on the acoustic behavior of different matrix materials, but also on different reinforcement grades.

As an established way to determine the material behavior under dynamic cyclic loading, the Dynamic Mechanical Analysis (DMA) is used. In case of thermorheologically simple materials [6], the material characteristics measured in the DMA are also shifted to higher frequencies of up to 4,000 Hz by the principle of time/temperature shift (tts). This step is necessary in order to cover the frequency range of up to 4,000 Hz that is relevant for acoustic considerations.

The evaluation of the ZTV master curves differentiates between specimens of the composite material with different fiber orientation and specimens of the matrix material (**Fig. 1**). In the case of the composite, the specimens are dissected longitudinally (L), diagonally (D) and transversally (T) to the filling direction from injection molded plates. The plotted material parameters storage modulus (left) and loss modulus (right) represent the stiffness and damping behavior in the frequency domain. For specimens with different fiber orientations, the curve progressions depend on the frequency. In contrast to the almost constant curves of the storage moduli, the loss moduli fall significantly with increasing frequency.

Furthermore, the illustrated curves of the unreinforced PBT indicate that the properties of the matrix material are similar to those of the composite material in case of the frequency dependence.

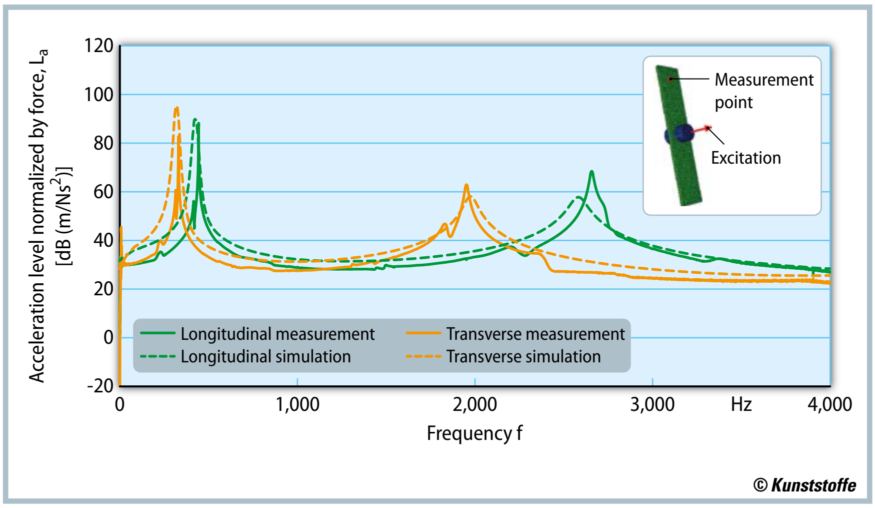

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Fig. 3. A detailed reproduction of the directional-dependent structure-borne sound behavior of rectangular bars enables the validation of the newly developed simulation method (source: IKV)

Concept of the Integrative Acoustic Simulation

The central element of the developed method is a newly programmed anisotropic linear viscoelastic material model to calculate the composite behavior. Acoustic simulations are mechanic simulations of the structure-borne sound and are mostly analyzed in the frequency domain in order to describe the vibration behavior at eigenfrequencies. Therefore it is appropriate to calculate directly in the frequency domain. But until recently, the necessary user-defined material models in the form of subroutines have only been available in classical FE programs for the time domain. Accordingly, the simulation method has been designed for calculating in the time domain using the FE solver Abaqus/Explicit (supplier: Dassault Systèmes Simulia Corp., Providence, Rhode Island, USA) by implementing a new user-defined material model (vumat) (**Fig. 2**). As Abaqus introduced user-defined material models in the frequency domain (umat) with version 6.14, an implementation based on the research results would also be possible in the future.

Efficient Modeling of the Composite Using the Matrix Behavior

For short glass fiber-reinforced thermoplastics it can be assumed that only the matrix behaves viscoelastically while the fibers deform elastically. Accordingly, the characteristic times of the material functions match for composite and matrix. Moreover, the so-called arrheodictic behavior for t = 0 and t = infinite is given by the elastic solution. When the retardation behavior of the matrix is known, the retardation behavior of the composite can be derived consequently.

The input data for the calculation of orthotropic material behavior therefore is based on the elastic properties of fibers and the viscoelastic properties of the matrix. Additionally, the local fiber orientations are used. Based on this data, the stiffness is determined per-element using micromechanical models in a further developed Java interface. This interface uses the equations by Halpin/Tsai and Tandon/Weng [7, 8]. Based on the properties in the fiber coordinate system of an element, the properties of the unidirectional composite are determined using the orientation averaging by Advani/Tucker [9]. The necessary information in the form of a second-level orientation tensor are derived from filling simulations that have been carried out with the software Sigmasoft (supplier: Sigma Engineering GmbH, Aachen, Germany).

Exact Calculation of the Oscillation Behavior

To validate the simulation method, the vibration behavior of the composites was investigated in four stages, starting from a simple geometry in the form of rectangular bars and a plate geometry to two practice-relevant model components. These components were measured on the institute's own acoustic test bed, in which the specimens oscillate freely excited by an electrodynamic shaker. In order to evaluate the measured component behavior and compare results to simulations, it is crucial to consider the resonance frequencies: The position of resonance peaks in the frequency band allows conclusions on the material stiffness. The material loss can be assessed using the resonant height.

The comparison of results of measurements and structure-borne sound simulations for rectangular bars made of dry PA6-GF30 already shows the advantage of the integrative simulation method (**Fig. 3**). The FE-models used for longitudinally and transversely oriented specimens are identical; the material models differ only in the fiber orientations. In the illustrated frequency range up to 4,000 Hz, these bars have two resonant peaks that are reflected by measurement and simulation in the same way. Additionally, the simulation results of the rectangular bars of PBT-GF15 also match with corresponding tests in case of the stiffness behavior. The damping behavior described by the peak height is also reproduced well.

The model component "coconut" (manufacturer: Lanxess Germany GmbH) resembles the first step towards a practical three-dimensional component with a correspondingly complex oscillation behavior (**Fig. 4**). The developed simulation method calculates the resonant frequencies for this part also well. However, the calculated magnitude of the acceleration peaks differs between simulation and measurement results. With an identical material card, the vibration behavior has been calculated for the rectangular bars and the model plate made of PBT-GF15 with good to very good correlation compared to the measured results. Therefore, the variance of the simulation of the model part is also due to a modeling strategy using larger finite elements in order to shorten the calculation time. However, this is accompanied by a loss of accuracy in the anisotropic material behavior, as with correspondingly less elements differences in local fiber orientations may dissolve only partially. »

The Authors

Dipl.-Ing. Pascal Brandt is research assistant at the Institute of Plastics Processing (IKV) at RWTH Aachen University, Germany, in the field of part design, acoustic and fatigue;
pascal.brandt@ikv.rwth-aachen.de
Prof. Dr.-Ing. Christian Hopmann holds the Chair of Plastics Processing at RWTH Aachen University and is the Head of the IKV.

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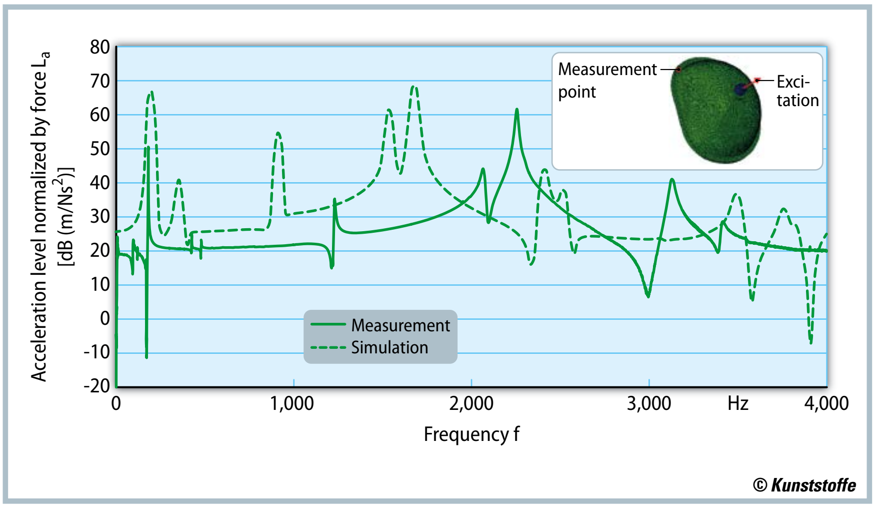

Fig. 4. Regardless of simplifying assumptions in the modeling, the calculated vibration behavior of the model component is good. However, the material behavior can be further improved (source: IKV)

Conclusion

In order to develop an integrative calculation method for acoustic simulations of short fiber-reinforced thermoplastic components and to implement it in a commercial finite element program, IKV researchers analyzed the stiffness and damping behavior of the considered materials dependent on frequency and fiber orientations in the first instance. Subsequently they designed a linear viscoelastic material model for calculations with explicit FE solvers. After its calibration using DMA measurements, the calculation method has been tested and successfully validated in a four-step process on specimens and model components of different geometric complexity.

Especially for planar specimens, the anisotropic oscillation behavior can be calculated well both quantitatively and qualitatively in the structural simulation. The transfer to the three-dimensional oscillating model components succeeded as well. However, compared to isotropic simulations, the modeling and computational effort of the integrative method has increased significantly due to the complexity to model anisotropic material properties. ■