Method for Simulating the NVH Behavior of Plastic Materials

Dr.-Ing. Christoph Steffens
FEV Motorentechnik GmbH

Dipl.-Ing. Martin Atzler
Institute for Combustion Engines, RWTH Aachen University

ABSTRACT

Lightweight construction is one of the key points for the automotive industry to achieve the ambitious targets for fuel consumption. As a consequence, plastic components are increasingly being used in automobile manufacture. This includes engine components which emit a considerable degree of noise, such as valve covers or oil pans. It is therefore necessary for polymer components to be taken into consideration during the NVH development process of internal combustion engines.

FEV uses a comprehensive simulation approach to predict the acoustic behavior of plastics accurately. The simulation is based on the finite element method (FEM) in conjunction with material-related modeling. For applications in the engine compartment, this means that the specific boundary conditions prevailing there must be taken into account. In general, the acoustic properties of the plastics used in this area are subject to the influences exerted by temperature, frequency and filler materials on the stiffness and damping behavior of the materials. In the case of the hygroscopic polyamide often used in the engine compartment, the moisture content is also a significant factor. By integrating this simulation technique into the engine development process, the acoustics of plastic parts can be optimized at design stage.

INTRODUCTION

With a view to reducing manufacturing costs and achieving lower fuel consumption through lightweight construction, plastic components are increasingly being incorporated into internal combustion engines. For example, it is now commonplace for inlet manifolds, valve covers and other covers to be made of plastic materials. These components are often considered to be critical factors affecting the overall noise emission behavior of an engine structure. It is therefore necessary for complex systems consisting of a combination of several metal and polymer components which interact under acoustic stimulus to be taken into consideration during the development phase.

Within the context of a ZuTech\(^1\) research project carried out at the Institute for Internal Combustion Engines (VKA) and the Institute of Plastics Processing (IKV) at RWTH Aachen University, a method of predicting the acoustic behavior of plastics was developed [4]. The simulation technique is based on the finite element method (FEM) in conjunction with material-related modeling. For applications in the engine compartment, this means that the specific boundary conditions prevailing there must be taken into account. In general, the acoustic properties of the plastics used in this area are subject to the influences exerted by temperature, frequency and filler materials on the stiffness and damping behavior of the materials [1]. In the case of the hygroscopic polyamides often used in the engine compartment, the moisture content is also a significant factor.

---

\(^1\) Program for Future Technologies for SME of the German Federal Ministry of Economics and Technology
DMA measurements on test specimens

Effects of moisture, frequency, filler material and temperature on stiffness and damping behavior

Material model

Verification

Verification

Structure-borne noise measurement at cylinder head cover

Structure-borne noise measurement at cylinder head assembly

Fig. 1 Development of the simulation technique

The calculation technique set out in this paper was developed in several stages using the example of the cylinder head cover of an internal combustion engine (see Fig. 1). First of all, a comprehensive series of Dynamic Mechanical Analysis (DMA) measurements were taken on the plastic test specimens. The material parameters determined in this way were firstly used in simulations of the individual components which are then validated on the basis of component measurements. Finally, the verified part results were collated in a subsystem consisting of plastic cylinder head cover, elastomer seal and aluminum cylinder head which was similarly verified and evaluated by carrying out corresponding measurements.

This approach establishes the preconditions for the acoustic design of complex systems consisting of different materials to be carried out on the basis of a simulation. By integrating the technique into the development process of engine structures, acoustic weaknesses in plastic components can be predicted at design stage. This enables noise emissions to be minimized whilst at the same time reducing development times and associated costs.

MAIN SECTION
CHARACTERIZATION OF MATERIALS

In order to describe the structure-borne acoustic behavior of plastics, both stiffness and damping properties must be considered. A suitable technique for measuring this is DMA, the measuring equipment for which is shown in Fig. 2. The test sample is clamped in place and loaded dynamically in longitudinal direction. The Young's modulus and the loss factor can be determined by measuring the force and the displacement. However, since this procedure only permits measurements of up to approx. 100 Hz to be made, the frequency range relevant to an acoustic analysis of can only partly be covered. This can be overcome by using the time/temperature shift principle (TTS principle). This is based on the relationship between the strain velocity and the temperature for the viscoelastic material behavior of plastics. This makes it possible to extrapolate the behavior of the material at higher frequencies by lowering the test temperature [2]. The Arrhenius approach was used for the time/temperature shift function.
Fig. 2 DMA measurements carried out on the tests specimens [source: IKV]

For two reference temperatures (23 °C and 95 °C) and also for the various conditioning states and filler materials, master curves were determined for the storage modulus (E') and the mechanical loss factor (tanδ). It was demonstrated that all parameters have a distinct effect on the dynamic material behavior of the plastics under investigation. The various filler materials give an increase in the storage modulus, i.e. they stiffen the behavior of the material. At the same time the mechanical loss factor, which is indicative of the damping effect of the material, is considerably lower with filled materials. This is due the lower damping effect of the filler material when compared to the plastic matrix.

The glass transition temperature of the materials was determined by temperature sweeps. This range describes the transition from the glass range to the rubber elastic range and is characterized by a marked reduction in stiffness and a maximum in damping. With increasing moisture content, the glass transition temperature of the polyamide 6.6 is shifted to lower temperatures with the result that the stiffness decreases as the damping increases. However, under actual operation, the engine components made of plastic regularly heat up, causing the moisture contained in the material to be expelled.

For applications within the engine compartment it is particularly important to consider the temperature level. Previously, test bench trials had been carried out to determine the temperature of the plastic valve cover during engine operation. The measured cover temperature was approx. 85 °C for an oil sump temperature of 90 °C. Fig. 3 contrasts the master curves of the storage modulus and mechanical loss factor for a dry reinforced polyamide 6.6 reinforced with 35 weight percent short glass fiber for the two reference temperatures of 23 °C and 95 °C. It can be seen that the stiffness decreases considerably as the temperature rises. At the same time, there is a several-fold increase in the damping effect. This is because the dry polyamide matrix is still in its glass state at 23 °C. The higher temperature applicable in the engine compartment on the other hand is in the region of the glass transition temperature, so that the maximum damping effect prevailing there is more pronounced.

STRUCTURE-BORNE NOISE MEASUREMENTS

In order to verify the method of simulation, a series of empirical tests were carried out. In addition to taking measurements on the individual plastic components, the installation situation in the actual engine was taken into account by investigating the cylinder head assembly. This consists of the components cylinder head, front cover, valve cover and elastomer seal. As with the complete engine assembly, the plastic cylinder head cover and the front cover were fastened by bolts. The entire subsystem is suspended on expanders. The force was induced by means of a pneumatic hammer at the roof of the combustion chamber of the second
cylinder in vertical direction. The measurement of the impulse response was carried out at ten measuring points on the plastic cover. Tests were carried out on plastic components made of the three material variants in their various states of moisture conditioning.

**SIMULATION METHOD**

In the first step, the individual model of the plastic cover was verified by measurement. These tests showed that the correlation with the measurements was considerably better than using the material values available from data bases. This applies in particular to the damping level at component temperatures encountered in the engine compartment. With regard to the Noise-Vibration-Harshness (NVH) development process of complex engine structures, the assessment of the dynamic behavior of the components in their actual installation condition is of great importance [5]. This is achieved by considering the cylinder head assembly. The model of the plastic cylinder head cover was attached to the cylinder head and the front cover by means of an elastomer seal and the equivalent stiffness of the bolts. The elastomer seal was modeled by means of solid elements according to the specifications described in [3]. Fig. 4 shows the corresponding FE model. The boundary conditions for the calculation were selected according to the verification measurements. The harmonic unit force excitation at the roof of the combustion chamber of the second cylinder corresponds to a Dirac impulse in the time range, similar to the impulse hammer excitation in the verification measurements.

Fig. 5 gives a comparison of the measurements and calculated values for non-reinforced plastic at standard moisture content levels. The left-hand graph shows measuring point 9 (MP9) in the area of the timing drive and the right-hand graph shows measuring point 5 (MP5) at the rear end of the inlet side. A good correlation can be obtained in frequency and amplitude for both measuring positions over the entire frequency range. The pronounced damping effect of the assembly is accurately reflected in the calculation. Also, the significant resonance peak at 1250 Hz from measuring point 9 is accurately mapped in amplitude and frequency by the simulation. Outside the area of this distinct peak, there are some deviations in level between measurement and calculation. The consistently inconspicuous curve at measuring point 5 is accurately depicted in the simulation.

![Fig. 4 FE model of the cylinder head assembly](image)

Fig. 5 Measured and simulated transfer functions of the cylinder head assembly

In the NVH development process, the effects of variations on the dynamic behavior of the components must be correctly predicted. In order to assess how well the dynamic simulation developed during this project does justice to this requirement, the effect of the choice of material is presented below. Here the three variants under investigation are plotted graphically, each separated into measurement and calculation (see Fig. 6). For conditioning purposes, the saturated wet condition is chosen, since this is where the most pronounced differences in the measurements occurred. The analysis is carried out at a measurement point at the rear end of the valve cover on the inlet side. At this measuring point, the non-reinforced material (A218) has a noise level of about 5dB higher in the 1200 Hz resonance, reflecting the results of the calculation. Similarly, the significant reduction in the amplitudes of the non-reinforced plastic up to 2500 Hz was correctly mapped. The slight difference in the dynamic behavior of the two reinforced plastics (V35 and MX40) is similarly predicted by the calculation.
All trend statements relevant to the acoustics in this example are also reflected in the simulation.

CONCLUSION

The article describes a FEM-based technique for predicting the acoustic behavior of technical plastic components. The need for material-related modeling was demonstrated by empirical tests which clearly showed the distinct effect of temperature, moisture content and filler material on the dynamic material characteristics of polyamide 6.6. The technique was verified by measurements and calculations on the basis of a close-to-production cylinder head cover. This was performed with increasing degrees of model complexity, from the single component to the subsystem consisting of cylinder head and valve cover. For the individual sub stages, the models were analyzed and verified by the findings of empirical tests. The simulated structure-borne noise velocity showed a close correlation with the values determined by measurement. In particular, the effect of the parameters filler material, moisture content and temperature were accurately mapped in the material description.

FEV has integrated the simulation technique for plastic components in the engine development process using the in-house tools FEV-DIRA (Dynamic Impact Response Analysis) for structural noise transfer calculation and FEV-FERS (Fast Estimation of Radiated Sound Power) for radiated sound power evaluation. This allows on one hand to save costs and time on the manufacture of prototypes and subsequent experimental tests and on the other hand to achieve an overall improvement in the noise levels of plastic components due to the considerable variability of the simulation-aided design process.

REFERENCES


CONTACT

Dr.-Ing. Christoph Steffens
Department Manager Vehicle Physics / Acoustics
FEV Motorentechnik GmbH, Aachen (Germany)
E-Mail: steffens@fev.com
Internet: www.fev.com