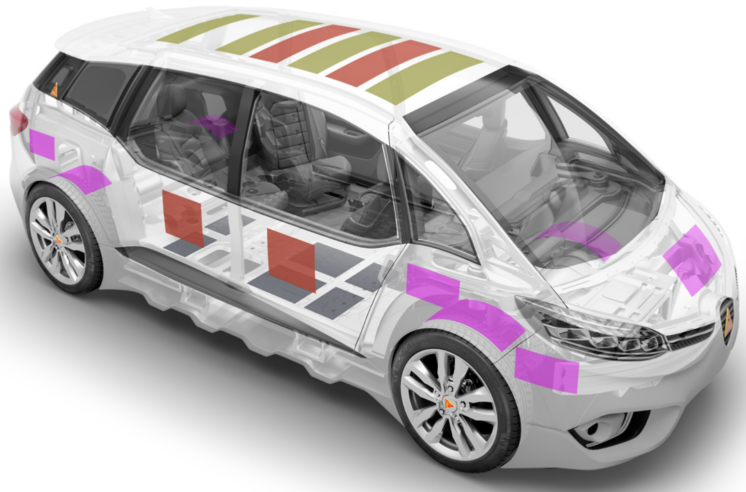
DAMPING OF STRUCTURE-BORNE NOISE IN AUTOMOBILES



Design guidelines for development and practical applications

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BUILDING TRUST

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CONTENTS

Acoustics as an element of comfort

At all times, developments in automotive technology were aimed at increasing the functionality of the vehicle as well as increasing driver and passenger comfort. At the beginning of series production, however, vehicle acoustics was only of limited importance. In fact, the focus was on basic manufacturing concepts to make vehicles affordable to a broader economic class. The primarygoal of acoustic optimizations was to reduce or eliminate undesirable noise which could negatively affect passenger comfort and traffic safety. Nowadays, targeted development of vehicle acoustics presents one of the many opportunities for an automobile manufacturer to define a vehicle's value, place it in specific car segments, and target specific groups of buyers.

Goals of the acoustic design

With car segments representing lower-priced vehicle models, customer requirements regarding passenger comfort are less important than satisfying mobility needs at a relatively low purchase price. In contrast, buyers of higher-priced vehicles have pronounced comfort expectations that include the acoustic optimization of their car. Door slam, for instance, is one of the first acoustic customer assessments while at a car dealership. A solid door slamming sound gives the impression of quality, soundness, and security, even before the customer drives the first yards. Criteria of quality rating also include the sealing-off of external noise and the possibility of conversing easily while inside the running vehicle. Acoustic expectations vary widely dependent on the individual car segment, although they are often not articulated explicitly. Instead, depending on the car segment there are some implicit expectations, for instance: It is more acceptable for subcompact and compact cars to sound rather tinny and noisy. Sports cars should sound harsh and loud also inside the car while luxury cars must exhibit a calm atmosphere while giving the impression of seclusion (Fig. 1).

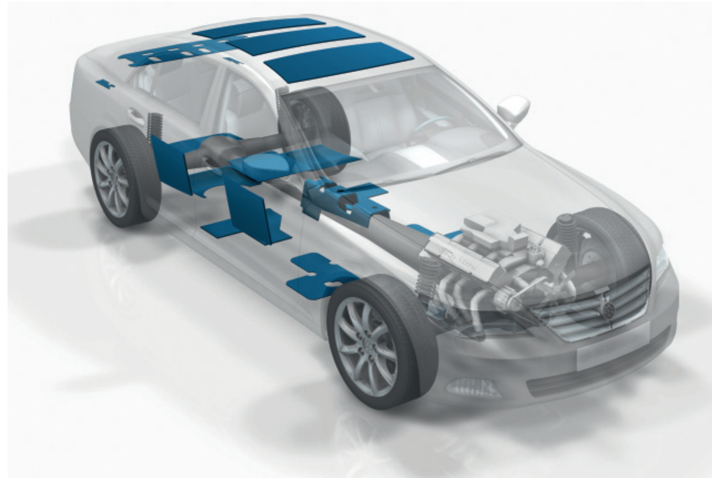


Fig. 1: Typical damping package for a sedan

When buying a new car, today customers are willing to spend more money for optional comfort features than in the past. Following the desire for comfort, expectations in vehicle acoustics are increasing even in the lower and middle car segments. The rapid development of communication systems and their use throughout all car segments requires additional measures that improve interior acoustics. Voice-controlled and hands-free equipment require a quiet environment with minimal noise.

Passive acoustic measures achieve special significance in interior vehicle acoustics. Prior to the development of more efficient sound damping and absorbing materials, acoustic measures in car interiors were limited to reducing the sound emission of the car body through the use of insulating films. Even prior to World War II, bituminous felt mats were used for sound reduction in car bodies.

The vibrating and sound-radiating car body still remains at the center of vehicle acoustic research and has moreover increased in significance. The reasons for this are the increasing acoustic requirements as a function of passenger comfort on the one hand and technical developments in car body construction on the other hand. More stringent legal requirements on vehicle emissions are forcing vehicle manufacturers towards a more lightweight mode of construction. This results in the use of new materials for car body construction. Multimaterial systems based on various steels as well as the use of aluminum, die-cast light alloys, fiber composites and other plastics, however, influence the vibration behavior and the resultant noise emissions.

Vehicle class and target group communication

Requirements for an increase in comfort and pressure to make structures lighter pose new challenges when designing sound damping concepts. They need to be integrated in general acoustics concepts to meet the demands of automobile manufacturers for specific target customer groups and car segments.

This book is dedicated to the damping of structure-borne noise as part of the passive acoustic measures in vehicle technology and is intended to provide design guidelines for practical application in vehicle design. It describes problems and possible solutions in the main application area of automobiles and provides an overview of the most important car body noise reduction products. This information conforms with state-of-the-art technology regarding quantification of the acoustic efficiency of these products and their application in car structures. The design of noise damping concepts will increase in importance in the future in order to tailor the acoustic comfort to specific car segments in a targeted manner.

Fundamentals of acoustics

Acoustics as a branch of physics deals with the emission and perception of sound. It examines vibrations caused by pressure and density variations in the frequency range audible for humans.

Sound waves

Unlike electromagnetic waves, sound waves can only propagate in a medium, not a vacuum. Acoustic vibrations in gaseous flexible media, such as air (airborne sound), can be distinguished from acoustic vibrations in solid or liquid flexible media (structure-borne or fluid-borne sound). Along with sound waves, energy is transmitted, but not matter.

The occurrence of local and temporal density variations in a flexible medium is presented in Figure 2. Due to binding forces, particles in their neutral position keep the required distances from their neighbors. Medium density is constant. If an external force deflects the particles from their neutral position, the neighboring particles are also moved through the existing bonds. The resultant compression and decompression zones propagate in the direction of the original excitation, resulting in a longitudinal wave. In the case of transverse waves, displacement is perpendicular to the direction of propagation. They can only develop in the lattice structure of a solid.

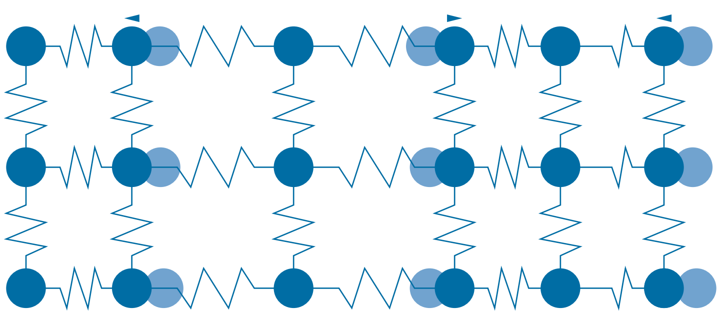


Fig. 2:
Vibration model for a flexible medium

Structure-borne sound compared to airborne sound

Structure-borne sound

Structure-borne sound should be understood as vibrations propagating in a solid, such as vibrations in cars and machines, and the transfer of vibrations in buildings (impact sound, sound power in walls), as well as vibrations and movements of the earth's crust caused by earthquakes. One only talks about structure-borne sound, however, specified when the vibration frequency exceeds 15 Hz.

Structure-borne sound is perceived by humans as vibrations. Structure-borne sound also radiates from surfaces as airborne sound and then becomes audible. Excitation is either mechanical or through airborne sound. In a frequency range of 15 Hz to 100 Hz, structure-borne sound causes pressure on the ear drum and anxiety. Particularly unpleasant is the range between 60 Hz and 100 Hz.

Structure-borne sound waves

Two types of sound waves can occur in solids: Longitudinal waves and traverse waves. With longitudinal waves, the solid particles oscillate around their neutral position parallel to the direction of propagation of the sound, resulting in local compression sections and zones with reduced density. In comparison, solid particles oscillate perpendicularly to the direction of propagation around their neutral position in

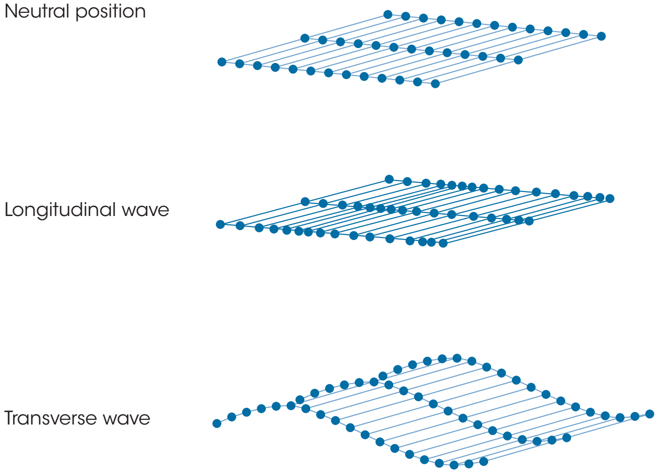


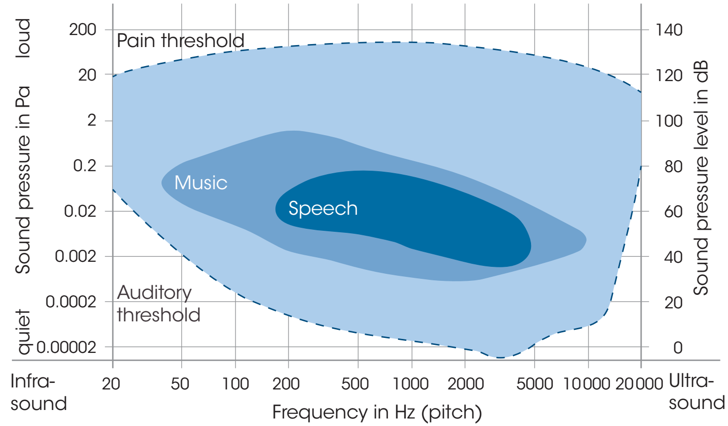
Fig. 3: Wave types in structure-borne sounds

transverse waves (Fig. 3). Sound velocity depends on the propagation medium, frequency, wavelength, and temperature. Structure-borne sound of very low frequencies can propagate almost undamped over distances of many miles.

Airborne sound

Airborne sound propagates as longitudinal waves in the air. It is perceivable to the human ear within the frequency range of approx. 20 Hz to 20 kHz which is referred to as the hearing range.

Figure 4 depicts the auditory sensation area of a human being. Speech perceptibility ranges from 200 Hz to 5 kHz, and the range of music perceptibility is broader. The actual hearing range of humans depends on their age and is reduced by ear damage. While a child is normally able to perceive frequencies up to approx. 18 kHz, the actual hearing range of a 65-year-



old is limited on average to 5 kHz in frequency. Frequent exposure to noise, such as in discos and concert halls or when failing to use hearing protection at the workplace, can even decrease the upper hearing range limit in young people to a maximum 4 kHz. Because of the ear's anatomy, the frequency range between 1 kHz and 2 kHz is transmitted directly. Between 2 kHz and 4 kHz an amplification takes place resulting in a particular sensitivity, such as with a baby's cry and signals of alarm systems.

Fig. 4: Auditory sensation area of a human

Acoustic levels

Level data are common in acoustics. The level of a physical quantity is calculated as the logarithm of the ratio of an effective value to a reference value; the common unit of level is called decibel (abbreviated as dB). If the measured effective value and the reference value are identical, use of the logarithm results in a level value of 0 dB.

For airborne sound, a sound pressure level of L_p applies:

Sound pressure level

$$L_p = 10 \cdot \log_{10} \frac{p^2}{p_0^2}\ \mathrm{dB} = 20 \cdot \log_{10} \frac{p}{p_0}\ \mathrm{dB}$$

where
- p effective value of airborne sound pressure in Pa
- p_0 reference value of airborne sound pressure: $p_0 = 2 \cdot 10^{-5}$ Pa – corresponds to the auditory threshold at 2 kHz (cf. Fig. 4).

The airborne sound pressure level range between 0 dB and 50 dB is perceived by humans as pleasant, while levels between 50 dB and 90 dB are discerned as annoying. Levels from 90 dB to 120 dB may present a health hazard, whereas levels higher than 120 dB lead to the pain threshold being exceeded.

For structure-borne sound, acceleration level L_a applies:

Acceleration level

$$L_a = 10 \cdot \log_{10} \frac{a}{a_0}\ \mathrm{dB}$$

where
- a effective value of vibration acceleration in m/s^2
- a_0 reference value of vibration acceleration in m/s^2.

For acceleration levels, acceleration of gravity ($g = 9.81\ m/s^2$) is usually used as a reference value of vibration acceleration. Contrary to sound pressure, the reference value is not determined in a normative way.

Levels of separate (incoherent) sound sources cannot be summed but rather need to be added "energetically".

$$L_{ges} = 10 \cdot \log_{10} \left(\sum_{i=1}^{n} 10^{0,1 \cdot L_i} \right) \mathrm{dB}$$

where
- L_{ges} total level in dB
- L_i level of the i-th separate sound source in dB.

From a level difference of 10 dB, the lower level has no significant influence on the total levels.

The energetic mean value of many sound levels is calculated in the following manner:

$$L_{ges} = 10 \cdot \log_{10} \left(\frac{1}{n} \sum_{i=1}^{n} 10^{0,1 \cdot L_i} \right) \mathrm{dB}$$

Physics of structure-borne sound

Longitudinal and transverse waves, as well as their combinations, can occur in a solid. Wave forms occurring in a solid depend on its geometry or dimensions in relation to the wavelength (Fig. 5).

In bounded media, such as bars or plates, with non-negligible shear stress bending waves can occur. These are transverse waves whose sound velocity is a function of frequency. In this way, dispersion occurs, meaning that bending waves of different frequencies can traverse the solid at a different propagation time. In the case of broadband excitation, as with white noise generated by an electrodynamic shaker, waves of certain frequencies hit their response point sooner than waves of other frequencies. Bending waves carry much of the sound energy, and they are a significant cause for airborne sound radiation.

So-called Rayleigh waves which only have a limited penetration depth into the solid can propagate on the surface of the solid or in phase

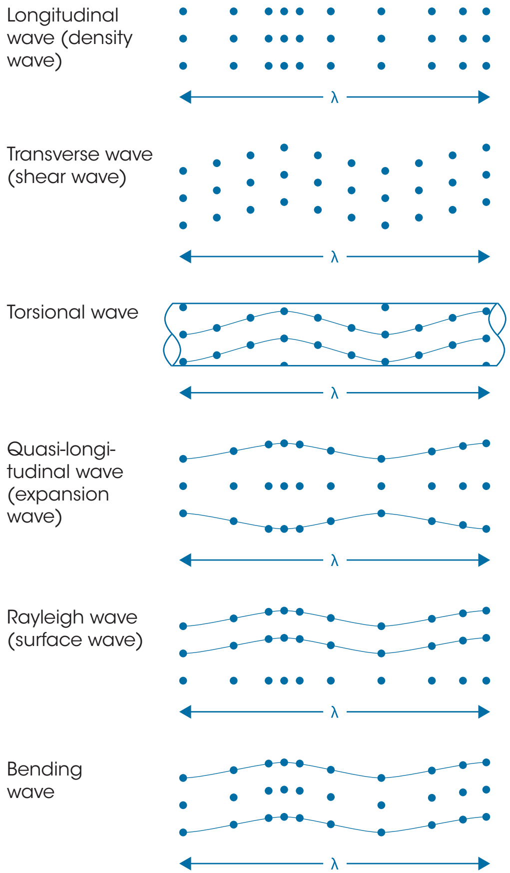


Fig. 5: Waveforms occurring in solids

boundaries. Acoustic surface waves are neither purely transverse nor purely longitudinal. Surface vibrations of individual surface areas can differ significantly even though they are located on the same item.

The propagation velocity of longitudinal waves is basically higher than that of transverse

waves. Thus, point mechanical vibration excitation of a system can result in various responses to this excitation being detected at a distant point at different times. This phenomenon does not occur in airborne and fluid-borne sound, as only longitudinal waves can exist in these media.

For quantification of wave propagation in a solid, its elastic properties must be known. Sound velocity is determined by density with Poisson's ratio μ, bulk modulus K, as well as shear modulus G (transverse waves), or Young's modulus E (longitudinal waves).

Perception and assessment of structure-borne sound

Structure-borne sound can be sensed in a tactile way by humans. Under certain circumstances, however, it is also discernible because of bone conduction to the inner ear. It is only airborne sound emitted from vibrating solids that is perceived by the outer, middle, and inner ear.

Mechanical vibration energy that reaches the ear in the form of airborne sound along with structure-borne sound (bone conduction), is translated in the inner ear as electrical impulses. These are transferred to the acoustic center in the brain through neural networks and are further differentiated there into speech, audio sound, and noise.

Psychoacoustic assessment

Subjective assessment of vibroacoustic comfort is oriented around the above-mentioned sensations caused by structure-borne sound. During an analysis, these sensations are directly inquired into and their influence on concentration abilities is researched.

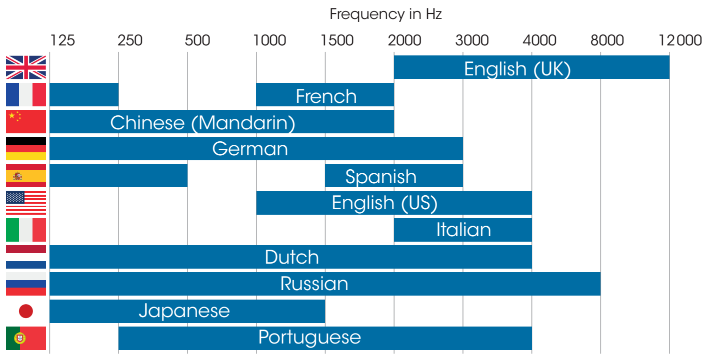


Fig. 6:
Dominant frequency ranges in various languages

The cultural background also influences acoustic perception. People born in Asia prefer a different frequency distribution to those born in Europe. The dominant frequencies in various languages that influence acoustic impressions from childhood on are presented in Figure 6. This results in culturally adapted noise designs. In a globalized world, however, such characteristic hearing patterns are becoming more and more uniform.

Structure-borne noise in vehicles

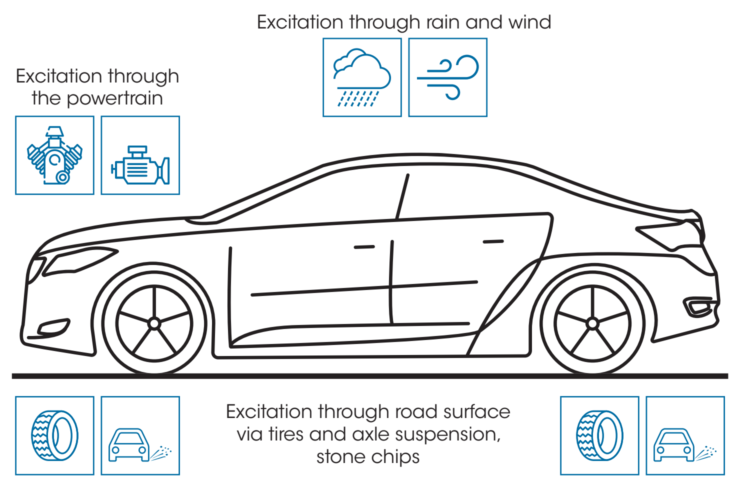
Vehicles are complex multi-component systems. On the one hand, vehicle acoustics deals with the exterior noise that is subject to legal regulation for homologation, and interior noise on the other hand. The latter is decisive for the comfort sensation of passengers. Structure-borne noise, as structure-borne sound is usually referred to in the context of automotive engineering, is a major cause for interior noise.

Excitation of structure-borne noise

Essentially, structure-borne noise in vehicles has three root sources (Fig. 7):

» Tire-road contact
» Wind load
» Powertrain.

Fig. 7:
Sources of vehicle interior noise



In most driving scenarios, whether within city limits or on highways, excitation through tire-road contact dominates. Aerodynamic excitation only becomes a dominant contributor to interior noise when traveling at very high speeds. Excitation through the powertrain dominates in automobiles only when constantly driving in a low gear or when accelerating.

Excitation through tire vibration

Both sources for structure-borne noise and sources for airborne sound (air pumping) contribute to noise generation when a tire rolls against a road's surface. The roughness of the tread pattern and the road's surface contribute to exciting radial and tangential vibrations in rolling tires (Fig. 8).

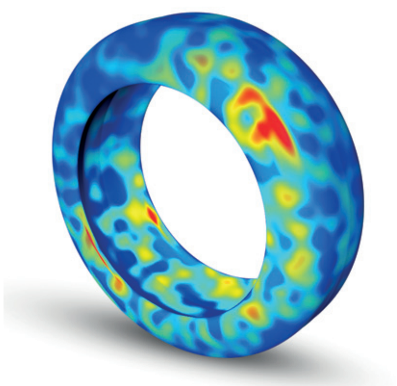


Fig. 8: Excitation of a rolling tire on a roller drum test rig, portrayal of structural amplitude (IBNM, Leibniz University Hannover)

Vibrational excitation of a tire mostly includes impact excitation through tread blocks hitting the road's surface at the run-in of the flattened tire. In the contact zone, tread blocks become stressed when the two-dimensionally curved tread is pressed against the contact surface (Fig. 9). This results in small slide movements of tread blocks on the road's surface. These stick-slip effects also contribute to the excitation of structure-borne noise in the tire's structure (Fig. 10).

Fig. 9: Impact excitation on tires

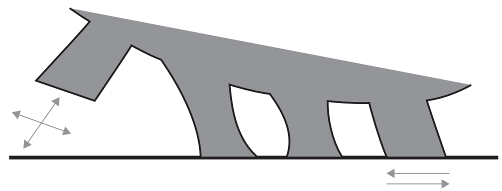
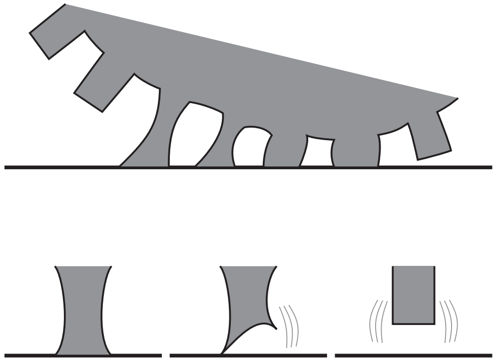


Fig. 10: Stick-slip effect during tire-road contact

The resultant shear stresses are reduced in outlet zones of the tire by pulsed "snapping out" of the tread blocks lifting off the road's surface. This leads to tread block vibrations that are further transferred into the tire carcass. This excitation is especially pronounced on flat roads where good contact between the tire and the road's surface leads to increased tangential friction forces in the contact area (Fig. 11).

Significant tire deformations occur through tread blocks hitting and lifting at tire-road contact and through road unevenness. Through these mechanisms, vibrations with specific

Fig. 11:
Adhesion at tire lift-off



frequency distributions are introduced through the chassis to the car body.

Excitation resulting from tire-road contact is strongly determined by the mechanical and structural properties of the tire; for example, excitation increases significantly with tire hardness. A larger tire width also leads to an increase in tire-road excitation; therefore, the predominant tendency of using wider tires leads to a significant increase in tire excitation. Moreover, favorable profile formation is of great importance. In the middle of the tire, where no drainage capacities are required, longitudinal profiles are favorable. Generally speaking, irregular profile divisions are used to avoid tonal noise components.

Tire vibrations are transferred into the car body through the chassis. The trend towards self-supporting tires with fail-safe properties (run-flat technology) considerably boosts the importance of this source of structure-borne noise. Structure-borne noise constituents of low frequencies significantly affect the noise level in the interior of a car.

Aerodynamic excitation

Wind load excitation in vehicles only becomes significant at high speeds (Fig. 12). It influences the roof and large side surfaces and, indirectly, the car body. The excited vibrations are transferred by the car body as structure-borne noise. A structure-borne noise component dominating interior noise lies in the

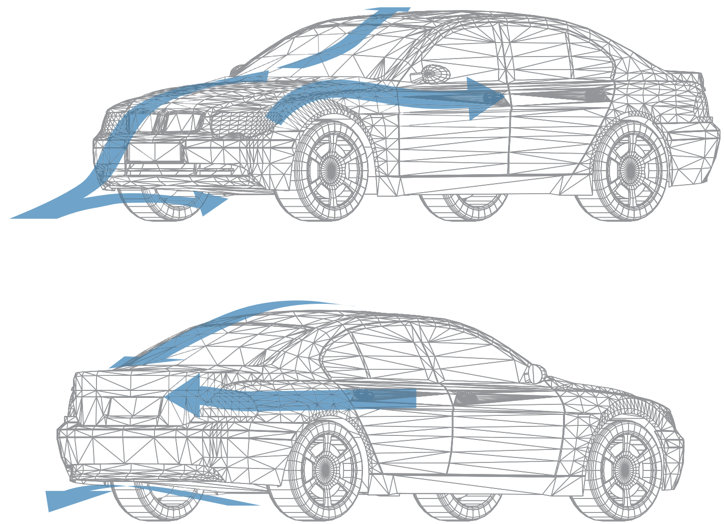


Fig. 12:
Wind load excitation in an automobile

frequency range between 40 Hz and 1500 Hz. Within this range, this share in structure-borne noise is also decisive for the sound pressure level in a car's interior and is perceived as humming.

Excitation through the powertrain

The trend towards turbocharged engines with limited cylinder capacity and higher speeds leads to a significant shift in the noise spectrum of the internal combustion engine. This has immediate consequences for structure-borne noise excitation through the powertrain.

Electrification of a car's powertrain also changes the acoustics. The contribution of the powertrain to vibration changes and as a result of this, high-frequency sources of structure-borne noise constituted by the auxiliary power units are no longer masked. The tire-road contact gains special importance in cars with an electrified powertrain.

Transfer paths in the vehicle's interior and sound radiating surfaces

Because motor vehicles are complex structures with a number of components, vibrations that are perceived in specific places in the passenger cabin may originate from distant sources of structure-borne noise. Vibration energy from powertrain components is transferred to the interior via different paths such as, e.g. through

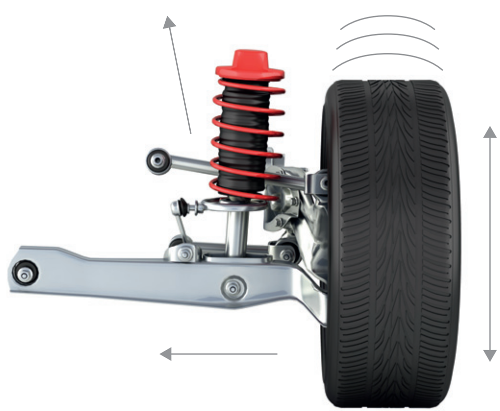


Fig. 13:
Transfer paths of tire-road excitation

the engine bearings, the mounting of the exhaust system or, indirectly, via the drive shaft and wheel suspension system. Another significant transfer path is the tire-road excitation via chassis components (Fig. 13).

Structure-borne noise is transferred from excitation points along the transfer paths into the car's interior. Surfaces facing the vehicle's interior are thus excited into vibration. Surface vibrations of the excited panels lead to periodic compression and decompression of adjacent air layers; i.e. to airborne sound radiation that can be perceived as annoying noise by passengers. To achieve a reduction in vibration contributors, it is thus necessary to analyze transfer paths in detail and identify their sources. With the contributions to specific paths well-identified, spots for efficient optimization also become apparent.

In order to meet comfort requirements for the interior, either the structure-borne noise has to be avoided at its source or its transfer along the transfer paths has to be cut off or dampened. Moreover, resonance effects of surfaces along these paths as a source of structure-borne noise amplification have to be eliminated.

Lightweight structures as a challenge

From an acoustic point of view, today's lightweight bodies present a challenge. The ongoing reduction of panel thickness for the purpose of weight optimization increases both the sensitivity towards structure-borne noise transmission and the resulting airborne sound emissions. Above all, large surfaces such as vehicle roof, doors, and side walls start to resonate and contribute to the negative perception of interior noise.

Technical concepts against structure-borne noise

Primary and secondary measures

Technical concepts for a reduction of structure-borne noise can be basically divided into two groups: measures close to the source (primary) and distant from the source (secondary). Whereas primary measures are intended to prevent the creation of structure-borne noise, secondary measures are aimed at damping structure-borne noise (energy transformation) or minimizing its effects (prevention of airborne sound emissions).

At the beginning of this section, major reasons for structure-borne noise in vehicles were described and their transfer path into the car's interior were explained. In the following text, it will be explained which structural approaches can be utilized to prevent structure-borne noise transfer into the vehicle body as much as possible. As described, the powertrain presents a significant source of structure-borne noise excitation in a vehicle. Depending on motorization concepts, various problems are brought to the foreground.

Vibrational masses of a piston engine together with pressure peaks during work phases of the piston induce a broad frequency spectrum. Contemporary piston engines are usually optimized for vibrations such that free mass forces and mass moments are minimized with sometimes very expensive measures such as counter-rotating balance shafts. With the goal of avoiding structure-borne noise, however, this is usually insufficient.

In electric engines, vibrations during operation usually occur as a result of commutation.

Fig. 14: Undercarriage of an electric vehicle

Energy densities generated through a magnetic field variable in time and space produce forces in radial and tangential direction and produce harmonic and cogging torques that generate the commutation noise that is typical for electric motors. Additionally, imbalances and fit tolerances in bearings generate noise that is transferred together with commutation noise as structure-borne noise to the car body (Fig. 14).

Manual or automatic gearboxes with various coupling types and connections to the drive wheels in the form of drive shafts also contribute to the transmission of structure-borne noise to the body structure.

Vibrational decoupling of the engine, gearbox, and drive shafts through passive and active bearing damping contributes significantly to reducing structure-borne noise. While passive bearings are limited in their efficiency spectrum, active bearings offer broader possibilities. The following bearing types have become popular:

As representatives of passive bearings, static rubber-metal bearings enable decoupling of the drive unit only in a limited frequency range that is determined by the structural design of the bearing (geometry, choice of materials).

Hydraulic bearings enable damping dependent on frequency and amplitude. This is implemented through the integration of a hydraulic damping system into the bearing. Hydraulic bearings enable damping and stiffness properties to vary dynamically depending on the load condition of the engine and thus provide optimal decoupling of the drive unit.

Classic vibration absorbers are also used in various versions to suppress critical resonance effects in a targeted manner. As a rule, we are dealing with freely vibrating masses that are adjusted in such a manner that their eigenfrequencies may eliminate a given frequency share of the arising vibration. Depending on the application, vibration absorbers as well as hydraulic bearings can be designed as passive (narrow frequency spectrum), semi-active (activation only after exceeding a defined threshold value) or active (controlled) elements.

Two approaches to secondary measures

When discussing measures for the damping of structure-borne noise (secondary measures), two approaches can be distinguished. The primary goal is to prevent structure-borne-noise induced emissions of airborne sound from vibrating car body surfaces or attachments or at least limit their intensity, as this airborne sound is ultimately, in the majority of cases, perceived as annoying noise by car passengers.

The first approach aims at mechanically preventing the surface from emitting airborne sound. This can be achieved by influencing the surface geometry by local stiffening, e.g. through corrugations or indentations, local

Fig. 15: Damping measures on a body in white: geometric measures and damping coatings are shown.

increases in mass, material stiffness, or a combination of these individual solutions (Fig. 15). These measures influence the local distribution of a car body’s natural vibration modes and the point emissions of airborne sound. Vibration energy is thus redirected to other car body areas. If these measures are efficient, however, there is the risk that the same problems arise in other places because the vibration energy is merely moved to another place in the car body. Additionally, there is a possibility of using composite panels. These are sandwich panels with a plastic foil inserted between two metal top panels. This foil decouples the metal elements. Optimally designed, such composite structures are characterized by very good internal damping. Therefore, they enable good damping of structure-borne noise. In practice, however, such solutions are not applied very often in vehicle construction because of the limited deform-

Classic damping of structure-borne noise: active and passive measures

ability, joining technology, and stiffness, as well as the unbalanced cost-to-benefit ratio.

The second approach mostly aims at the maximal reduction of vibration energy of the structure-borne noise by transforming it into heat. This classic damping of structure-borne noise can again be divided into active and passive measures.

Abbreviated ASAC (Active Structural Acoustic Control), active measures focus on eliminating vibration with exact phase-shifted vibration (Fig. 16). In theory, this works well for narrow-band vibrations, but in practice fails with complex mechanical problems. On the one hand, usually in structure-borne noise, we are dealing with a broadband mixture of many stochastically distributed individual frequencies and amplitudes that depend on many operational conditions of the vehicle. On the other hand, vibrations transverse the body structure in all possible directions and are deflected and amplified or reduced by superpositions. Vibration reduction with ASAC would need to generate exactly the same frequency spectrum phase-shifted in the same directions. Today, neither the necessary sensors nor the

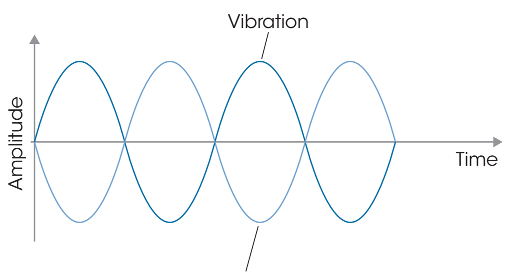


Fig. 16: Destructive inference

resulting real-time actuators are available to meet such requirements to a sufficient degree.

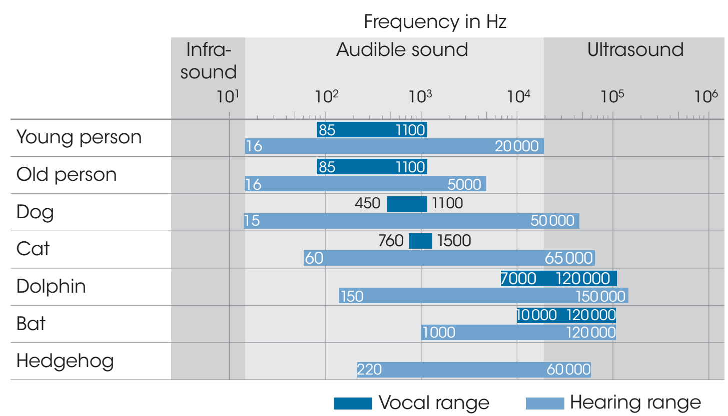
For these reasons, passive measures constitute the preferred solution. Vibration energy of the body is transformed mechanically into heat through a damping layer on the panels.

Passive measures as a preferred solution

Acoustic comfort requirements

The subjective perception of vibrations in vehicle acoustics is just as important as the subjective perception of airborne sound. Individual perception depends on the vibration frequency (Fig. 17). The tactile sensitivity of a human, with regard to vibrations, is the highest within a frequency range of 4 Hz to 10 Hz. At bodily contact, low-frequency vibrations up to 50 Hz are perceived by humans directly as vibrations. Vibrations in the frequency range of approx. 1 kHz are relevant in vehicles as structure-borne noise. Vibrations can be both heard and perceived by touch between approx. 20 Hz and 100 Hz.

Fig. 17: Human ranges of audibility and voice compared to other living creatures



Vibrations generated through tire-road contact, wind load and powertrain that are transferred to the car interior as structure-borne noise can be immediately perceived as annoying. Airborne sound excited by structure-borne noise is heard. Moreover, some vibrations can also be perceived by touch, such as through vibrations in bottom panels felt by the feet, vibrations in the seat rail transferred into the seats are felt by the buttocks, and vibrations of the steering wheel or the gearshift lever can be felt by the hands. Low-frequency natural vibrations of the car body cause resonance in inner organs. As a result of such resonance, passengers may experience discomfort or feelings of nausea.

Requirements for interior noise

Requirements regarding interior noise in vehicles vary a lot depending on the vehicle category. In the automobile sector there is a specific demand for acoustic comfort in each car segment. In sub-compact and compact cars, the passengers' level of tolerance towards annoying contributions to internal noise is estimated to be higher than in mid-size and luxury cars with premium requirements. Special requirements are set for vehicles used as rolling offices. In these vehicles, a feeling of seclusion is desired so that a private atmosphere could be created. The same applies to vehicles marketed as being comfortable for long-distance travel, such as crossover SUVs and minivans, that should provide a stress-free space.

The car segment of full-size vans can be divided into two parts. There are vehicle superstructures that in the literal sense of the word operate as pure transporters. They consist of a driver cabin and usually a closed loading space.

Generally, in such vehicles, only limited resources are used to increase acoustic comfort. However, increased resources for acoustic comfort are quite common in full-size vans that are used as mini-buses because of their design. In this way, high-value interior lines of equipment in the premium segment, such as those offered for VIP shuttles for example, are absolutely comparable with mid-size limousines with respect to their acoustic comfort.

In recent years, heavy trucks experienced a transformation into a comfortable workplace for the driver. On the one hand, the driver cabin serves as a living space during rest periods of the obligatory driving pauses. This should be well insulated from external noise to enable relaxation for the driver. On the other hand, the load on the driver during work should be kept to a minimum. Additionally, there should be superior acoustic comfort in this section of the vehicle. Structurally, driver cabins are decoupled from the chassis with hydro-pneumatic bearings that per se keep the structure-borne noise transfer relatively low. To account for inputs from the remaining transfer paths, coatings for the damping of structure-borne noise are applied to the large panel surfaces of doors and side walls and on the cabin floor.

Buses are used as a means of public transport and travel. When used for public transport, the primary concerns are as low as possible fuel/power consumption, as high as possible transport capacity, and good accessibility for passengers. In overland buses, the demands for passenger comfort must be added to this list. The structure of buses often comprises a load-bearing ladder frame with a decoupled frame set on top. This frame carries the interior superstructures, glazing, and external paneling. This principle significantly reduces the problems of structure-borne noise when compared to the self-supporting safety passenger compartment of an automobile. Acoustic measures in buses are thus aimed at reducing airborne sound rather than damping structure-borne noise.

Thus the main application area for measures towards the damping of structure-borne noise are automobiles from all car segments. The difficulty lies in targeted design for the special features of the specific car segments and in requirements of the vehicle manufacturers concerning vehicle positioning within the car segments.

Structure-borne noise damping

Damping of structure-borne noise is of outstanding importance for the automobile industry in order to cope with customers' comfort expectations regarding NVH behavior (NVH: noise, vibration, harshness). Through technological advancement towards powertrain electrification and autonomous driving, new challenges also emerge in the area of damping the structure-borne noise.

Function of damping

Damping means that mechanical energy is withdrawn from a vibrating system. Usually the withdrawn energy is converted into heat. As a consequence, waves in the structure become weakened and amplitudes in resonance areas are reduced. A common method involves the application of materials which provide excellent damping characteristics. In-depth knowledge of the vibrational system of a vehicle and the damping behavior of the applied materials in frequency and temperature range is essential for design optimization as well as for simulations targeted at the reduction of vibrations.

The application of damping material on vehicle body panels constitutes an essential tool to improve acoustic comfort and provide a subjective assessment of vehicle value. Damping materials are developed with the focus on the conversion of vibration energy of the body in white. Depending on vehicle class and the resulting customer expectations regarding comfort, damping packages of up to 30 kg in weight are integrated into a car body.

General information on materials

The theoretical basis for structure-borne noise damping was developed in the early 1960s by Dr. Hermann Oberst. Within the framework of the development of vibration-damping materials, new materials, including polymers on an acrylate and polyvinyl acetate basis as well as already known materials such as, e.g. bitumen and self-adhesive cardboard were analyzed for their suitability at that time. The suitability of a material is expressed by the loss factor determined in a standardized procedure: the Oberst Method (Table 1). The loss factor relates to a percentage value of the vibration energy that has been transformed into heat through internal friction in a test bar (cf. *Quantification of the performance*, p. 51).

The transformation of vibration energy into heat takes place in damping materials both at microscopic and macroscopic levels. At a microscopic level, long chains of branched polymer groups or asphaltenes in bitumen are subjected to expansion and compression stress. Through relaxation and a new grouping of chains, vibration energy gets transformed into

Material	Loss factor
Steel	0.0006
Aluminum	0.0001
Copper	0.002
Brass	0.001
Lead	0.02
Bituminous film	0.2–0.6
Sandwich system	0.2–1.0

Table 1:
Loss factors of common materials

heat at the molecular level. At a macroscopic level, the addition of appropriate fillers and materials increases internal friction.

Maximal damping

A vibration-damping coating exhibits maximal damping at the exact glass transition temperature of the material, meaning the temperature at which the material transfers from the solid into a viscous state. Damping capacities decrease both below and above the glass transition temperature. Most vehicle manufacturers want maximal damping at room temperature or slightly above.

Bitumen naturally exhibits very good damping properties at room temperature, whereas as the result of inner and outer plasticization, the glass transition of polymers has to be put at around room temperature. Therefore, and for economic reasons, bitumen as a raw material has become very popular among the manufacturers of sound-damping coatings. Today, polymer films have been widely replaced by films with bitumen content and extrudable damping compounds based on aqueous acrylates or cross-linkable natural rubbers.

Fig. 18:
Single-layer and sandwich systems

Today, damping materials manufactured from suitable raw materials are used in various fields of car body construction as stamped parts or extrudable compounds (Fig. 18).

Overview of damping systems

Materials for the damping of structure-borne noise which are applied to the body panels as classic secondary measures are subdivided into three basic system structures:

Three system structures ...

» Single-layer systems
» Multi-layer systems
» Sandwich systems.

Single-layer systems are applied directly to the substrate without another intermediary layer. Adhesion is achieved through adhesion of the damping material to the car body. The acoustic efficiency of single-layer systems lies at the lower end of the performance scale of classic sound damping systems.

The group of multi-layer systems differs from single-layer systems in that the laminate of real damping materials is joined to the substrate with an additional adhesion layer. Self-adhesive and hot-melt adhesive multi-layer systems can be distinguished. For example, with the damping materials, fleece lamination can be applied as an additional surface layer. It takes over such functions as absorption of airborne sound or stiffening in the case of hybrid structures.

Multi-layer systems generally offer the possibility of tailoring the application of structure-borne noise damping to the customer's process sequence. They can be applied in the body-in-

white construction, after cataphoretic coating, or as late as after applying a topcoat. In addition, the damping of structure-borne noise can be influenced to a high degree. Thus on the performance scale, multi-layer systems can be placed above single-layer systems.

Sandwich systems mostly differ from multi-layer systems in that their performance can be greatly influenced by the combination of layers with various moduli of elasticity (E moduli) and adhesives. Very thin systems, very light systems and systems acting over a very wide range (high performance in broad temperature and frequency ranges) can be implemented as well as various mixed forms in between these extremes. This puts sandwich systems at the top of the performance scale of systems for the damping of structure-borne noise. These systems are able to satisfy diverse requirements with respect to vehicle acoustics (Fig. 19).

... with different performance capacities

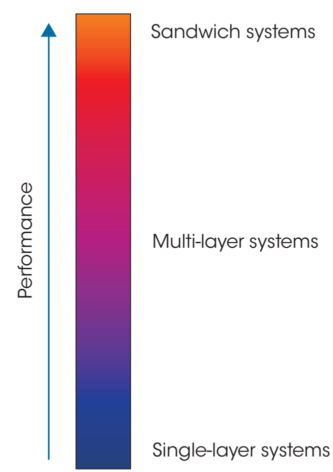


Fig. 19: Classification of damping systems according to performance

$$d = f(d_2, E_2/E_1, h_2/h_1)$$

- d Loss factor for a combination of panel and damping material
- d_2 Loss factor for damping material
- E_1 Modulus of elasticity – panel
- E_2 Modulus of elasticity – damping material
- h_1 Panel thickness
- h_2 Thickness of the damping material

Fig. 20: Influences on the loss factor of a single-layer system

Single-layer systems and special extrudable compounds are preferred for the floor areas in the body. Damping efficiency reaches its maximum at or near room temperature, and the damping level is moderate and limited in temperature range (Figs. 20 and 21, see also Fig. 24, p. 45). In comparison, sandwich systems and also multi-layer systems have considerably broader temperature ranges for efficiency and a significantly higher damping effect (Figs. 22 and 23, see also Fig. 26, p. 47).

We will explain various systems in more detail below. The presented materials provide an

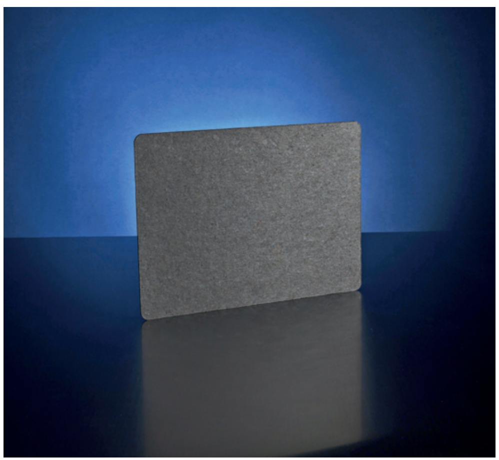
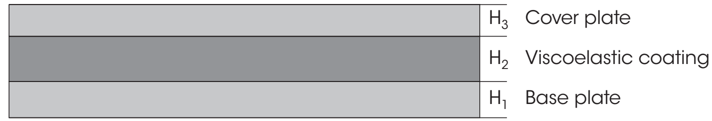


Fig. 21: Single-layer system consisting of a bituminous film



$$d = \frac{d_2 Y g}{1 + (2 + Y)\, g + (1 + Y)\,(1 + d_2^2)\, g^2}$$

$$Y, g = f\,(G_2, H_1, H_2, H_3, E_1, E_3, B_1, B_3, f)$$

- G_2 Shear modulus of the intermediate layer
- d_2 Loss factor of the intermediate layer
- E_i Modulus of elasticity
- H_i Material thickness
- B_i Bending stiffness

Fig. 22: Influences on the loss factor of a sandwich system

Fig. 23: Aluminum-butyl rubber sandwich system

insight into the wealth of various design possibilities of usual damping elements in the automobile industry. Through combination and lamination, multi-layer systems or sandwich systems can be produced based on single-layer systems. Through a combination of coverings with a lot of tensile stiffness, such as aluminum, glass fibers or organic fibers, an additional stiffening effect can be generated. This meets the needs of the increased complexity in car body construction, where hard and soft steels, aluminum alloys, magnesium alloys, and fiber-reinforced plastics are used in various combinations.

Single-layer systems

Single-layer systems (materials consisting only of a single homogeneous layer) constitute a basic framework of materials for the damping of structure-borne noise in the car industry. Typical examples include bituminous films without an additional adhesive or sealing application as well as extrudable compounds.

Bituminous films

Bituminous films are used as an economical damping material in the car industry. Depending on the mineral filling materials used, magnetic and non-magnetic bituminous films can be produced that vary in density. The advantage of magnetic materials lies in the simple application in the car body production process, as the bituminous film adheres to the steel background due to magnetic forces. Aluminum substrates do not offer such an application advantage. Disadvantageous is the high surface weight that results from a high material density necessary for a high acous-

tic efficiency. Typical densities of magnetic bituminous films lie in the range of 1.7 g/cm^3 to 2.5 g/cm^3, whereas non-magnetic bituminous films only exhibit a density of 1.0 g/cm^3 to 1.8 g/cm^3. A lot of weight can be saved by using non-magnetic materials as at a thickness of 2 mm, for example, the typical surface weight is only 3 kg/m^2 instead of 5 kg/m^2. An achievable loss factor with bituminous films varies between 0.1 to 0.2. With single-layer film systems, limited storage and transport capacities are a disadvantage. When the thermal load is high, single-layer systems display a tendency to block. Single-layer film systems exhibit deficits in adhering at low temperatures as there is no adhesive layer.

Extrudable compounds

Apart from film systems, extrudable compounds are the second largest group of single-layer systems. These are extrudable, solvent-based materials that are applied to the car body by a machine. A significant advantage of extrudable compounds lies in the possibility of automatic application. However, these materials can only be applied to the body-in-white construction and in the paint shop because a drying oven temperature is required for their drying. Chemically, three types of extrudable compounds can be distinguished based on epoxy, natural rubber, and acrylate. Bituminous compounds can also be applied as pumpable damping systems. They do not require drying, as hot-applied compounds cool down at ambient temperatures. Above all, the acrylate-based system has gained popularity because it exhibits the best damping properties. The acoustic efficiency of these damping coatings depends on their thickness; for example, at a surface weight of 4 kg/m² it achieves a maximal loss factor of 0.3.

Multi-layer systems

Multiple-layer damping materials with a higher level of performance are created on the basis of the above-mentioned single-layer systems. Depending on specific customer requirements for low-temperature impact strength, a layer of adhesive or hot-melt adhesive can be required. The combination of two different layers leads to a decrease in weight. If layers exhibit different moduli of elasticity, however, the acoustic efficiency can additionally be increased, for example, by laminating a soft bituminous film with a stiffer one.

Self- or hot-melt-adhesive multi-layer systems

Multi-layer systems can be equipped with self-adhesive or hot-melt adhesive. Self-adhesive materials exhibit immediate adhesion at room temperature, whereas hot-melt adhesive materials only adhere to the substrate and melt after applying heat. The place of application – floor area, vertical structure (e.g. doors) or overhead assembly (e.g. roof area) is pivotal for the choice of material. Moreover, the individual step of the production process (body-in-white construction, paint shop, and assembly) needs to always be taken into account.

In body-in-white construction, only self-adhesive materials can be used because before the oven processes, the car body is driven through a pre-treatment bath and cataphoretic coating bath and hot-melt adhesive materials are not necessarily stable during these processes. Because a lack of adhesion can lead to corrosion problems, it is better to use a magnetic bituminous product to guarantee a tight seal with complete adhesion.

In the paint shop, mostly self-adhesive magnetic films are used because they can be easily positioned, and they melt well in a drying oven. In critical positions, such as roof areas, self-adhesive magnetic materials are used for safety reasons. In the floor area, non-magnetic melt-films are also used to reduce weight.

In the assembly shop, only self-adhesive films can be applied because the body is no longer subject to temperature influences. These films can be magnetic or non-magnetic.

Film multi-layer system

Thus, there are many bituminous multi-layer systems that can be adjusted optimally depending on the application. Typical self-adhesive bituminous films reach maximal acoustic efficiency in the temperature range between 10°C and 30°C, whereas the maximum for hot-melt adhesive bituminous films lies between 30°C and 50°C. The exact position of the maximum depends, apart from material thickness, on the adhesive used. With self-adhesive systems, adhesives based on bitumen, natural rubber, and above all acrylate, are used. In contrast, hot melts are mostly based on ethylene-vinyl acetate (EVA).

Non-magnetic bituminous multi-layer systems achieve a loss factor of 0.2 to 0.3 with a surface weight of 3 kg/m² to 4.5 kg/m². Because of their higher density, magnetic materials with similar acoustic properties exhibit a surface weight of 3.2 kg/m² to 7 kg/m².

Through the use of an approx. 0.5-mm-thin magnetic bituminous film in combination with a non-magnetic bituminous film at a significantly lower density, the application advantage of magnetic materials is retained with a simultaneously minimized surface weight. A thin magnetic layer is enough because only an area of several tenths of a millimeter becomes magnetized in the production process, and only this lower part of the film has contact with the substrate. Due to the avoidance of a fully magnetizable film, the overall density drops, and with the same surface weight, better acoustic efficiency can be achieved when compared to conventional magnetic bituminous films. Using this method, the loss factor can be increased by 25%.

Foam multi-layer system

A multi-layer system consisting of bituminous foam with a density of 0.35 g/cm³ and a top layer of stiff bituminous film combines both advantages: weight reduction and an increase in loss factor. This is a lightweight product that can contribute to weight optimization of the whole vehicle and thus to a reduction of pollutant emissions. Through the variation in thickness of the bituminous foam and bituminous film, multi-layer systems can be produced that reach a loss factor of more than 0.25 with a surface weight of 2.4 kg/m².

In Figure 24, the loss factors of foam multi-layer systems with various surface weights have been presented. With low surface weights, they are characterized by their excellent acoustic properties. In comparison to hot-melt bituminous films, a similar acoustic efficiency is achieved with approx. 50% less weight (Fig. 25).

Hybrid multi-layer system

The lamination of bituminous films with an epoxy layer leads to the creation of a hybrid product that is both damping and stiffening. This material achieves a loss factor of approx. 0.2 as well as exceptional stiffening and is used as a standard in many areas of a car body.

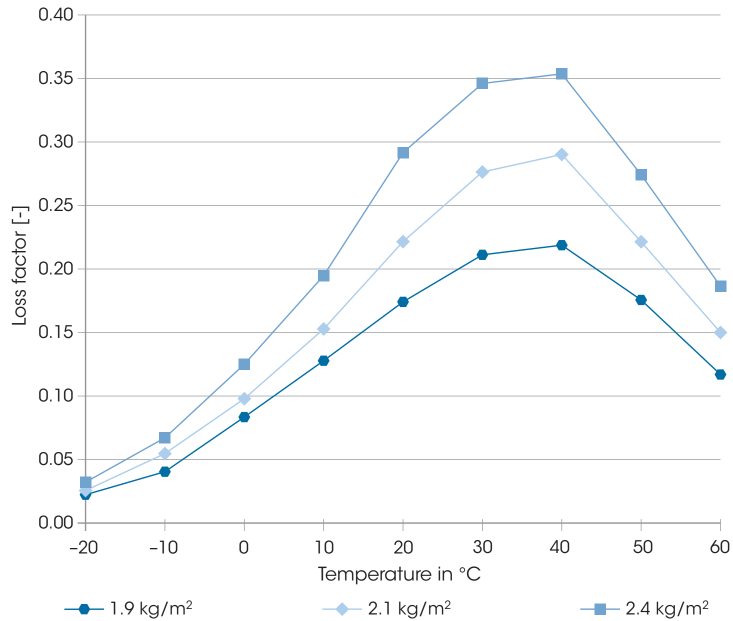


Fig. 24: Temperature dependency of the loss factor in foam multi-layer systems with various surface weights

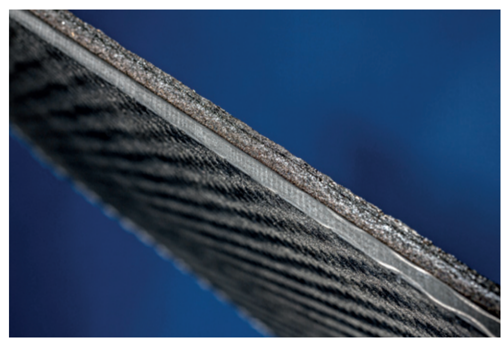


Fig. 25: Foam multi-layer systems consisting of bituminous film and bituminous foam

Sandwich systems

Through the combination of a substrate, a bitumen-based or natural rubber-based compound, and a stiff cover layer, a sandwich system is created that is characterized by its significantly increased acoustic efficiency. Vibration energy is transformed into heat by shearing the film between both stiff layers (cover material and substrate). With such systems, loss factors between 0.25 and 0.45 are achieved with low surface weights between 1.3 kg/m^2 and 3.5 kg/m^2.

Aluminum-bitumen sandwich system

Through lamination of self-adhesive bituminous film and aluminum foil with the aid of a layer of adhesive, a very acoustically efficient system is achieved with a loss factor of 0.35 and surface weight of 2.5 kg/m^2. The lower adhesive layer is mostly responsible for the resistance to high and low temperatures, but the adhesive layer between the aluminum foil and the bituminous film can influence the position and maximum of the acoustic efficiency. Similarly, with single-layer systems, an increase of thickness in the bituminous layer can also improve damping properties. Moreover, the loss factor can be influenced by the thickness of the aluminum foil.

In order to transform this aluminum-bitumen sandwich system into a lightweight construction product, the bituminous film with a minimal density of approx. 1 g/cm^3 is replaced with bituminous foam at a density of only 0.3 g/cm^3. Two adhesive layers are also required to bind the bituminous foam with the substrate and the aluminum foil.

At both low and high temperatures, the adhesives ensure secure joints and strongly influence the acoustic efficiency of the material. By selection of adhesives and layer thicknesses, the position of maximal acoustic efficiency can be varied between 10°C and 40°C. The maximal level depends above all on the thicknesses of the adhesive layers used. The thickness of the aluminum foil is another factor that influences acoustic performance. The loss factor is strongly influenced as shown in Figure 26. An increase in thickness of 0.1 mm to 0.3 mm, with otherwise identical material structure, leads to an increase of the loss factor from 0.25 to 0.4. Thus an increase in acoustic efficiency of 60% can be achieved with the surface weight only increasing from 1.3 kg/m^2 to 1.7 kg/m^2, or by 30%. A tailor-made lightweight construc-

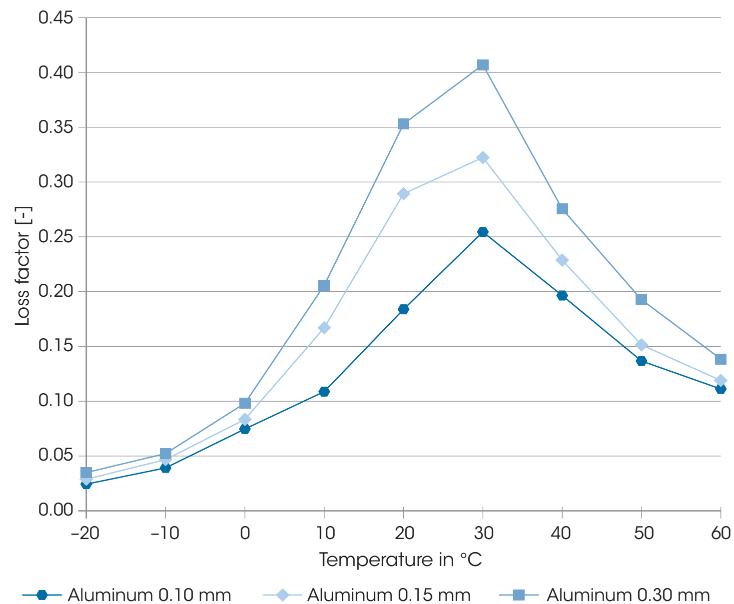


Fig. 26: Temperature dependency of the loss factor of aluminum-bitumen sandwich systems with various thickness of the aluminum covering

tion that exactly matches customer expectations can be created by appropriate selection of not only the thickness of the bituminous foam and aluminum foil – both of which significantly influence the weight of the sandwich system – but also of the requisite adhesives.

Aluminum-butyl rubber sandwich system

Using a filling compound consisting of natural rubber (butyl rubber) instead of bitumen has the advantage of being self-adhesive. Therefore, no adhesives are necessary. Lamination with aluminum foil creates a high-efficiency damping material. The self-adhesive butyl compound can be used during all three phases of vehicle manufacturing (meaning the body-in-white construction, paint shop, and assembly shop). It is especially suitable for the body-in-white construction as the non-polar adhesive sticks well to oily and fatty surfaces and guarantees complete bonding. Apart from the composition of the rubber-based filling compound, the layer thickness and the thickness of the aluminum foil essentially determine the acoustic efficiency.

Figure 27 shows the influence of layer thickness of the butyl compound and aluminum foil. An increase of thickness of the butyl compound from 1.6 mm to 1.9 mm causes an increase of the loss factor from 0.28 to 0.35. Further improvement in damping is achieved by utilizing an aluminum-butyl rubber sandwich system with an aluminum foil of 0.3 mm thickness. It has a loss factor of 0.45 with a surface weight of 3.6 kg/m². This product meets top requirements for the damping of structure-borne noise. Even door wobbling can be completely eliminated, i.e. the annoying excitation of the car doors at higher speeds.

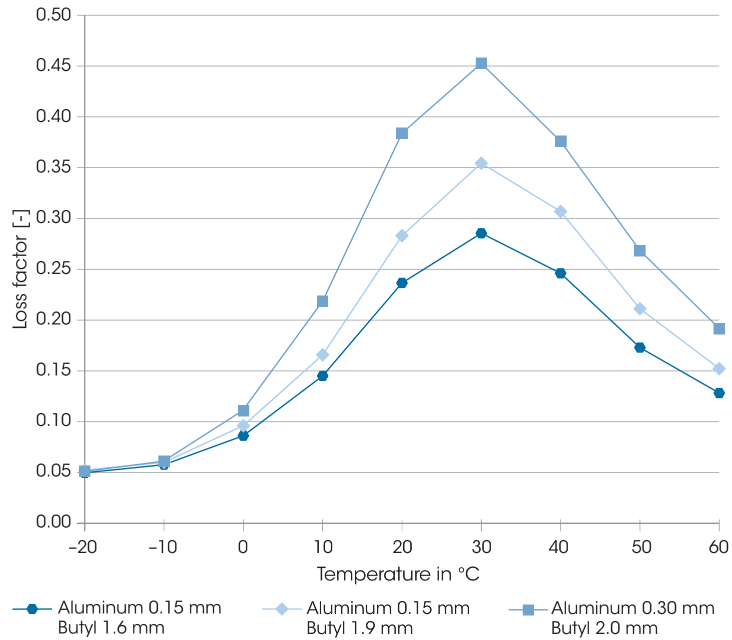


Fig. 27: Temperature dependency of the loss factor of aluminum-butyl rubber sandwich systems

Lamination with other materials

Bitumen and butyl rubber can be laminated with extensional stiff materials other than aluminum foils. Specifically, aluminum compounds, glass fleece compounds, and glass fibers work well with bitumen and butyl rubber. Glass fibers also have the advantage of being electrically non-conductive. Depending on the assembly location, intended use and customer requirements, prepregs (mostly impregnated glass-fiber fabrics), cardboard, and natural fiber compounds can also be used. Whether or not a given material is suitable as a cover layer for butyl or bituminous compounds depends to a great degree on its extensional stiffness.

Lamination with glass fiber fabric

Lamination of a butyl compound with glass-fiber fabric generates a high-efficiency acoustic element that can be used in the body-in-white construction. Acoustic properties are strongly influenced by the layer thickness of the butyl compound and strength of the glass-fiber fabric. Loss factors can be generated which are comparable with those of aluminum-butyl rubber sandwich systems.

Glass-fiber fabrics with bitumen-based compounds yield a hybrid material characterized by excellent acoustic properties and acceptable stiffening effects. Because of the weight reduction in car bodies, the substrate panels are also becoming thinner and thinner. Thus there is a need for additional stiffening of the panels with light materials. So far, stiffening elements have been used in addition to damping elements. The sandwich system comprising glass-fiber fabric and bituminous compound combines acoustic and stiffening effects. In the body-in-white construction, where stiffening elements are mostly used, the use of magnetic bitumen layers is particularly advantageous.

Quantification of the performance

Damping materials are used in the automotive industry as well as other industries to reduce vibrations and noise. These materials have viscoelastic properties. In order to quantify their performance both at various temperatures and frequencies, it is necessary to analyze these materials.

Measurement methods for characterization of products

Oberst Method

Standard method ...

The Oberst Method is today's standard for characterizing the performance of damping materials (Fig. 28). With this procedure, a bar of predefined thickness, length, and width, on which the sample is applied, is rigidly clamped in vertical position from the top end. On the top end and on the lower, free end of the bar, there are inductive actuators and sensors for excitation and measurement of bending waves. Dependent on the resonance behavior of the test bar with the sample under examination, the damping behavior is characterized, for example, by the loss factor.

The loss factor relates to a percentage value of the vibration energy that has been converted into heat in a test material through internal friction. Measurement values for the loss factor are determined for the relevant temperature range. For products used in the automotive industry, a range of –40°C to +80°C is used.

... with limited potential

Depending on the system, loss factors up to 0.3 can be reliably determined by this proce-

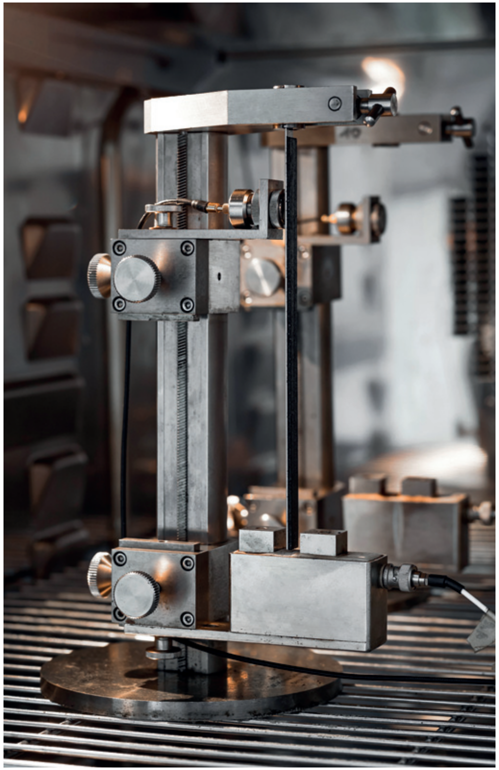


Fig. 28: Test rig for the determination of loss factors for damping materials according to the Oberst Method

dure, however, above this threshold, the measurement results are imprecise. Exact values can only be determined for resonant frequencies where the bar's natural vibrations are excited. For other frequency values, loss factors are calculated with linear interpolation or extrapolation. Such linear damping behavior relating to frequency is at best applicable to single-layer systems.

For a determined frequency (140 Hz or 200 Hz), the measurement results obtained

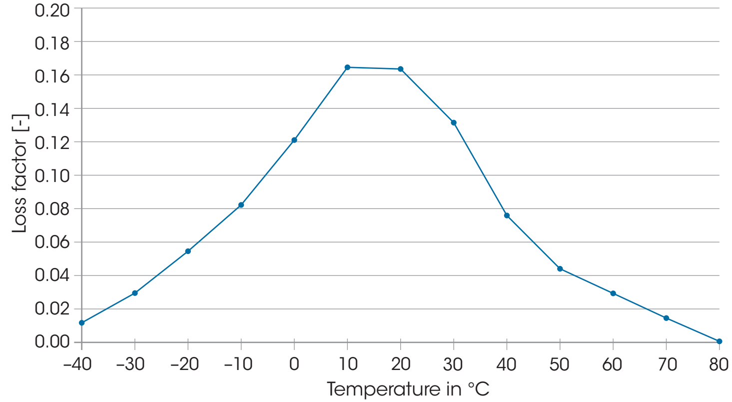


Fig. 29: Measurement result according to the Oberst Method: interpolated loss factor (here at 200 Hz) for all the measured temperatures

with the Oberst Method are usually presented in a diagram versus temperature (Fig. 29). However, this frequency usually does not correspond to the resonance frequency, and the presented loss factor is thus interpolated. Another kind of presentation contains real measurement values at the second-order and third-order resonance frequency, but these shift with temperature.

Because of the inductive sensors, only magnetic test bars can be used in the Oberst Method. Non-magnetic sample materials can only be tested after application of small magnetic plates. Moreover, it is hard to excite highly damping samples to vibration with this contactless induction method, so that the measurement of their loss factors is not possible.

OLF Method

OLF stands for "optical determination of loss factor," and this method (Fig. 30) enables high-frequency resolution over a wide temperature spectrum and allows for exact determination of

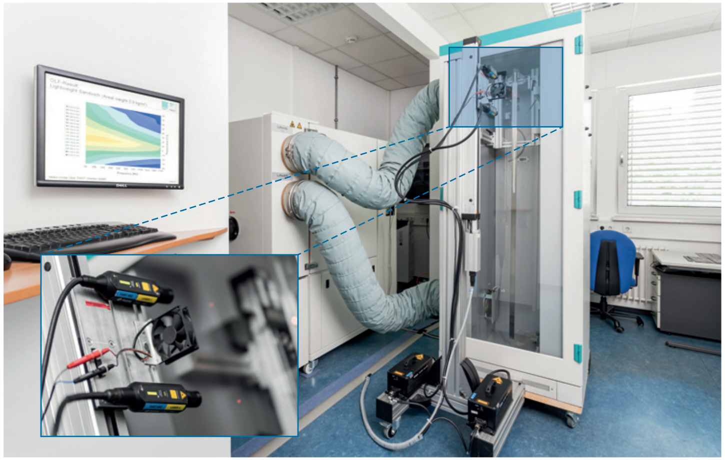


Fig. 30:
Test rig for optical loss factor determination according to the OLF Method

the damping behavior without limitations concerning the frequency or temperature range.

A broadband signal is used to excite the sample material applied to the measurement bar at the clamped top end. Bending waves run to the lower, free end of the bar with the amplitude reducing along with the corresponding damping behavior of the applied material. Amplitude values are measured with single-point lasers at two positions along the bar. The loss factor of the material is calculated from the transfer function resolved according to the frequency. Measurements are taken over temperature ranges standardized for the Oberst Method which are from –40°C to +80°C

Contrary to the Oberst Method, which is based on stationary waves, the bending waves in the OLF Method are measured along the bar. For this purpose, bending waves need to die out completely before reaching the free end of the bar (Fig. 31); otherwise, reflection will occur at

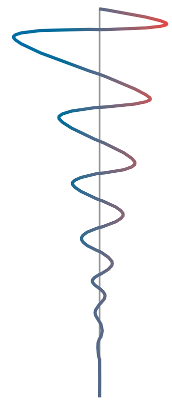


Fig. 31:
Bending wave dying out along the bar, visualized with measurement of a laser vibrometer

the free end, and reflected waves would interfere with the original ones and interfere with measurement results. Therefore, the measurement bar needs to be significantly longer than in the Oberst Method (approx. 2 m). With broadband excitation and the loss factor calculation from transfer functions, a result with a very high resolution in the frequency range is achieved.

Exact and high-resolution measurement result

Figures 32 to 34 show representative 3D diagrams for OLF measurements. The temperature (y-axis) is presented versus frequency (x-axis), and the color scale identifies the loss factor. Figure 32 presents measurement results for an aluminum-butyl rubber sandwich system. The material exhibits a high damping level (loss factor > 0.4) with a slight frequency dependency, comparable with the frequency behavior of bituminous film in Figure 33. However, it can be clearly seen that bituminous film with the same surface weight has

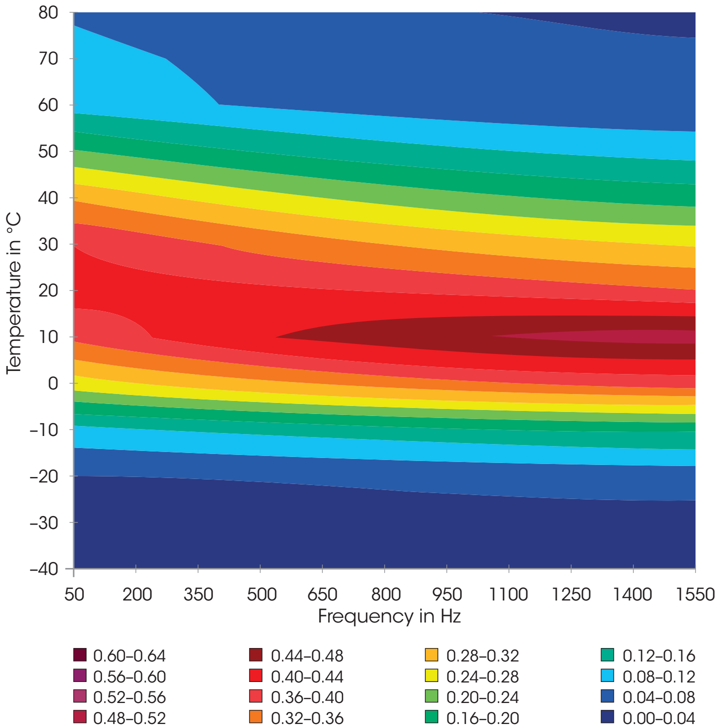


Fig. 32:
Color-coded loss factor of an aluminum-butyl rubber sandwich system (surface weight 2.8 kg/m²) over frequency and temperature, determined with the OLF Method

significantly worse damping properties (loss factor of approx. 0.2). In contrast, Figure 34 shows a clear dependency between frequency and loss factor. The loss factor diminishes significantly at higher frequencies. This damping characteristic is typical for the material class of special, lightweight sandwich systems. The result from the measurement of a multi-layer concept with a surface weight of 0.9 kg/m² has also been presented, that is only about a third of the surface weight of the materials discussed before. Despite this, the concept achieves a loss

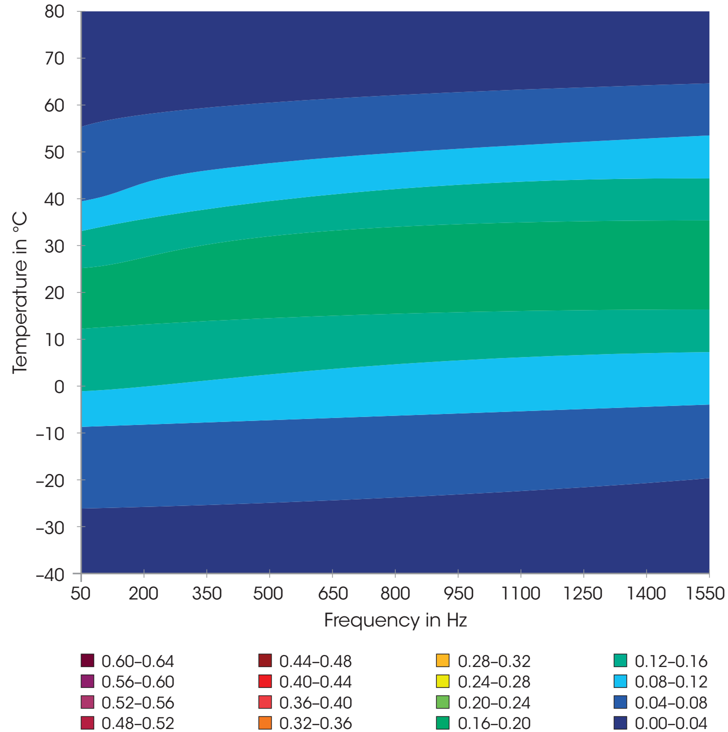


Fig. 33:
Color-coded loss factor of a bituminous film (surface weight 2.7 kg/m²) over frequency and temperature, determined with the OLF Method

factor of approx. 0.3 in a frequency range up to 800 Hz.

The curves in Figure 35 compare the values for 200 Hz in the OLF measurements and Oberst values of the corresponding materials calculated for the same frequency. The curves with the lowest loss factors are those from measurements with bituminous film. As expected for such a single-layer material with an adhesive, the curves from both methods lie one above the other. In contrast, the loss factors for sandwich systems measured with the OLF

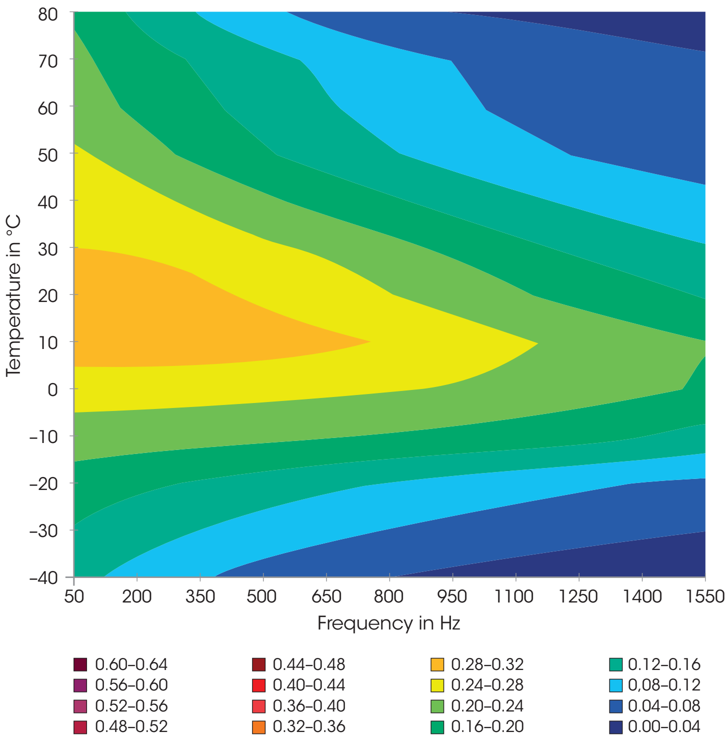
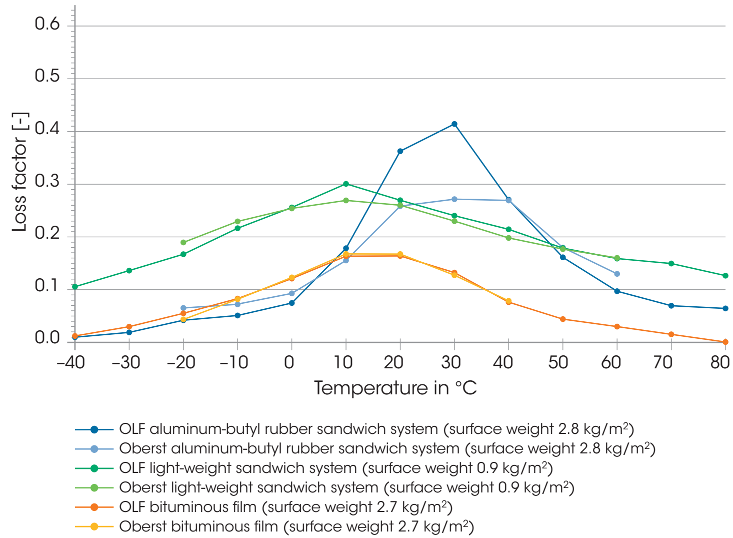


Fig. 34:
Color-coded loss factor of a light-weight sandwich system (surface weight 0.9 kg/m²) over frequency and temperature, determined with the OLF Method

Method are higher than those determined using the Oberst Method. These results, as described above, confirm that loss factors can only be calculated for resonant frequencies when using the Oberst Method. In the case of high loss factors, however, resonance peaks are too wide to enable detection. Therefore, the maximum for the lightweight product and the aluminum-butyl rubber sandwich system is capped because of system-related limitations. As the comparison shows, the materials are



significantly undervalued with the standardized Oberst Method.

Center Impedance Method and Power Injection Method

With the Center Impedance Method, the damping behavior is determined based on the intensity of a response signal to an introduced force signal. Both signals are measured directly with an impedance head. Just as with the OLF Method, the Center Impedance Method is not subject to the limitations of magnetic sample materials. Sufficient excitation is guaranteed by an electrodynamic shaker. The test bar is excited in the center and both ends are free. With this test structure, only odd-numbered vibration modes occur. Temperature-dependent measurements are conducted in a climate chamber.

Fig. 35:
Comparison of measurement values according to the Oberst Method at 200 Hz with measurement values according to the OLF Method for damping materials from Figures 32 to 34

Direct measurement of force and response signal

The loss factor is determined for the occurring resonance frequencies from the transfer function, i.e. from the response of the system to the introduced excitation.

The Power Injection Method (PIM) determines the damping behavior of two-dimensional structures (plates) with vibrations excited by an electrodynamic shaker. In this process, the excitation point is located outside the symmetry axes of the item under investigation. With acceleration measurements taken at several positions distributed on the item, the damping characteristic is determined through comparisons of the dissipated energy with the introduced excitation. With this method, the weight of the higher number of accelerometers applied changes the vibrational behavior of the tested plate. This method also confirms the findings in other procedures that the damping properties of sandwich systems decrease with increases in frequency.

Relevant frequency and temperature ranges for acoustic problems from radiating surfaces

When designing a damping package for a car body, one needs to take into account the mounting locations, the temperature to be expected in operation, and the construction materials used to achieve optimal damping efficiency. In the design department, fundamental changes in the selection of raw materials are currently taking place in order to follow the trend towards lighter vehicles. In the so-called hybrid structure, high-strength steel, aluminum, magnesium alloys, and composite materials such as carbon-fiber-reinforced plastics are used besides conventional body steels.

Frequency range depending on material

With thin high-strength steels, as well as aluminum and carbon-fiber-reinforced plastics, there is a tendency for vibration excitation to occur within the frequency range exceeding 500 Hz. In thick, conventional body steels, the problematic frequency range is rather low and is below 500 Hz.

With the frequency-optimized design of the damping coatings, a damping material suitable for each substrate material used can be prepared. Soft steels have a tendency to be dampened adequately with single-layer systems. Special sandwich elements laminated with aluminum foil are used with aluminum and carbon-fiber-reinforced plastics. In order not to nullify the weight savings achieved by using aluminum and carbon-fiber-reinforced plastics with heavy damping coatings, lightweight construction damping coatings are being used more and more frequently.

Efficiency at operation temperature

Vibration damping materials convert vibration energy into heat best at or around the materials' glass transition temperature. At temperatures significantly below and above the materials' glass transition temperature (under 0°C and above 60°C), the loss factor drops significantly. Therefore, when designing vibration damping systems for higher-value vehicles, the relevant temperatures of operation are determined. Individual areas in the vehicle can be provided with temperature-adjusted damping coatings and thus receive targeted noise damping. For high-temperature areas, such as over the catalytic convertor, muffler, or over the gear tunnel, but also

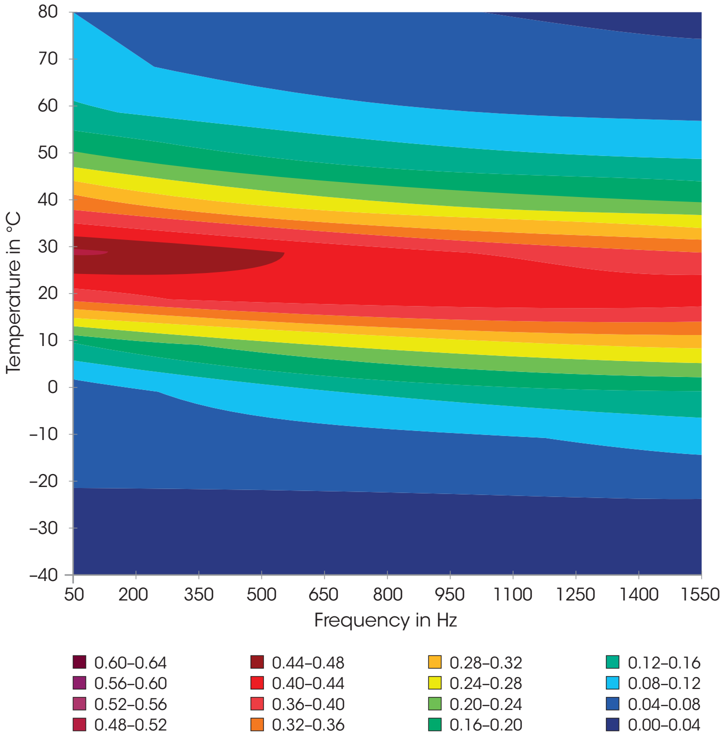


Fig. 36: Color-coded loss factor for a damping element optimized for high temperatures over frequency and temperature, determined with the OLF Method

towards the engine compartment, sandwich materials with a high glass transition temperature are preferred (Fig. 36).

Design of damping concepts

The design of damping measures in a vehicle takes place in the design and development phase. It can either happen very early (in the construction phase) or very late (shortly before the first prototype phase). Selection of appropriate materials takes place within the framework of development of the actual acoustic package consisting of structure-borne noise damping, insulation, and absorption measures. Often, a well-proven surface allocation is copied from the previous model and adapted for the new one at the end of the development phase.

Simulation and optimization

Early in the development process, a package for the damping of structure-borne noise can be determined through computer simulations that provide body-in-white data and the characteristics of damping materials. Hotspot analyses of vibration amplitudes are performed using laser-vibrometry, as described in the following sections. For this purpose, is it necessary to have a body-in-white available. The analysis of the acoustic properties of a new vehicle ready for series production concludes the development phase. This takes place during a driving test, and all possible load and temperature conditions, ranging from arctic cold to tropical heat, are extensively tested.

Because classic damping products are seldom critical with regard to tooling costs and development time, development results that were already approved are often re-worked after finishing the test phase, and the detected weak points are eliminated. It happens time and again even in the series phase that identified and described optimization goals in the design of a damping concept are changed or improved.

Design on different car segments

For the design on different car segments, issues such as the temperature conditions during vehicle operation, the selected damping material, and the acoustic problem in the respective component are decisive factors. For the damping package as part of the general acoustic concept, high loss factors even with low surface weights of the damping material should be realized, even though a combination of sound deadening and improvement of sound transmission is desired, especially in the floor area. Sound transmission from the exterior, such as road noise, is reduced only through the application of heavy damping coatings. Thus the vehicle manufacturer will conduct a detailed analysis of the acoustic weak points of the car body to determine suitable configurations. Furthermore, possibilities of automated application also influence the selection of damping materials. However, these possibilities are limited due to poor accessibility.

Economic viability

Beyond the technical possibilities, economic factors also play a decisive role when choosing materials. With the conflicting priorities of acoustically optimal and economically acceptable acoustic package design, a big difference appears across all car segments from subcompact cars to full-size luxury cars, SUVs, and minivans.

With sub-compact and compact cars, the economic viability at a sufficiently good acoustic level is the predominant factor. The usual amount of materials needed for the damping of structure-borne noise varies from 2 kg to 4 kg per vehicle. As a rule, standard materials, single-layer systems, and extrudable compounds are used.

With mid-size cars, the damping of structure-borne noise varies depending on the desired level of acoustic comfort. Typically, between 5 kg and 12 kg of materials are used per vehicle. Here, the borders between standard and premium vehicles are blurred. Acoustic comfort gains importance and becomes decisive for perception of the vehicle's high level of quality. Besides standard materials, also multi-layer systems, high-value sandwich systems, and lightweight products are used to a greater extent in mid-size cars.

With the exception of thoroughbred sports cars (where different acoustic level standards apply), between 15 kg and 30 kg of damping materials are used in a full-size or luxury car. A whole range and multitude of acoustically efficient products can be found here that focus on utilizing high-value and high-performance damping materials.

Analysis of vibrations in body-in-white systems

Today, comfortable vibration behavior is expected from each mid-size car. In years past, this was the case for only luxury-class vehicles. Such acoustic comfort depends essentially on the damping materials used, which are developed specifically for the purpose of reducing car body vibrations. This material needs to be applied to areas with the highest vibration amplitudes (also known as "hotspots") in order to achieve optimal efficiency. Detailed knowledge of the position of these weak points is a prerequisite for an efficient damping concept.

Hotspot analyses

Hotspot analyses are mainly performed on the body in white with a laser Doppler vibrometer (Fig. 37). Excitation takes place with the

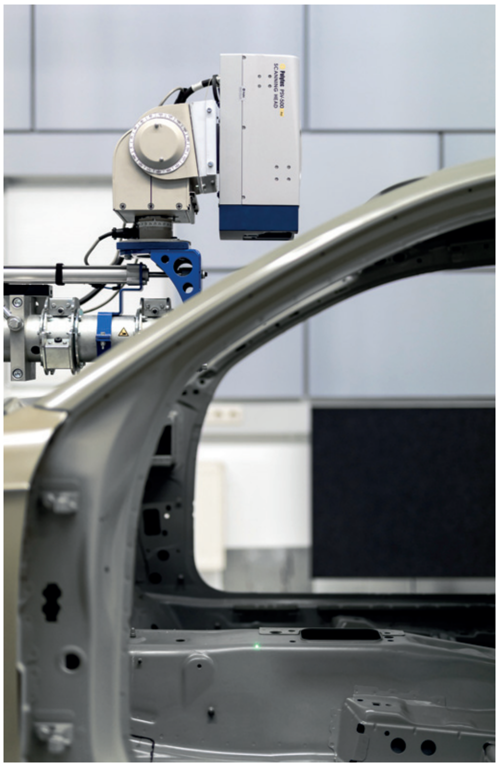


Fig. 37: Laser Doppler vibrometer at hotspot analysis on a body in white

use of electrodynamic shakers at significant points for the introduction of structure-borne noise.

The functional principle of a laser Doppler vibrometer is based on measurement of the velocities of vibrating surfaces with optical interferometry. Because of the Doppler effect, the vibrating surface causes a periodic shift in the frequency of backscattered light of the normal incident laser beam. This shift is determined by the velocity of the surface vibrations and wavelength of the laser. The signal laser beam is equalized in an interferometer with a reference laser signal of known frequency so that the velocity information, as well as an amplitude of the vibration at the measurement point, can be extracted. Numerous measurement points on a surface, such as the front floor driver's side, provide information on the behavior of this area with regard to structure-borne noise. To prevent the structure measured from being

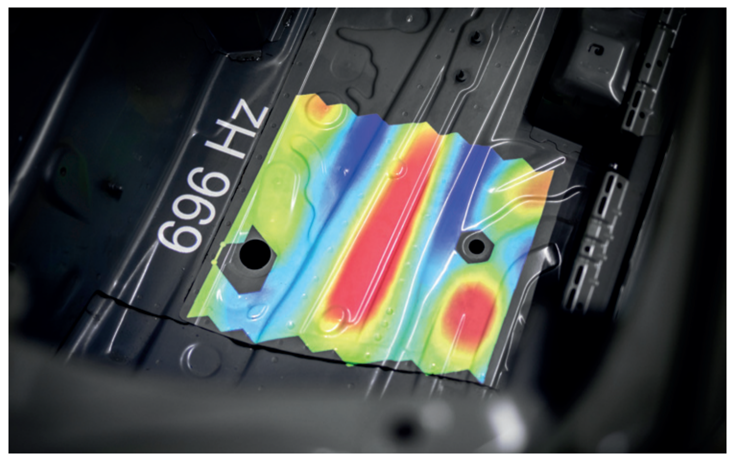


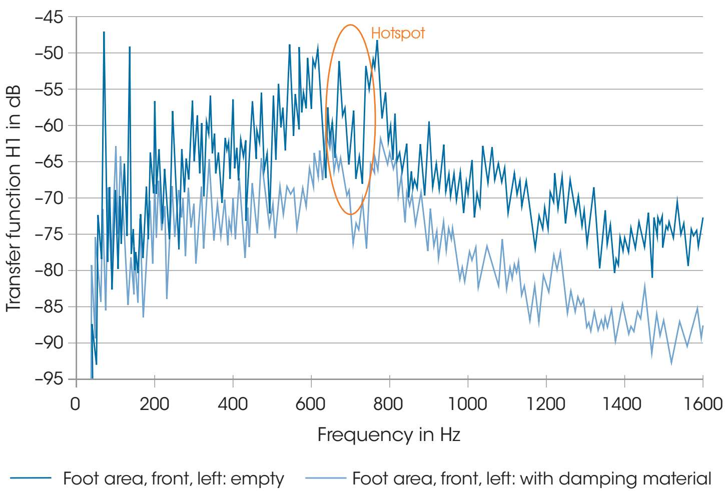
Fig. 38: Hotspot in driver's foot area of a body in white

influenced by the measurement procedure, the test is contactless.

Once the hotspots are identified (Fig. 38), the areas where damping materials need to be applied to improve vibration comfort are located. The material used depends on many factors, including the required loss factor, available space, as well as weight and cost targets.

Figure 39 shows the effect of a damping material applied as an example to a 700-Hz hotspot in the driver's floor area. The surface response to the excitation with an electromagnetic shaker has been represented in frequency resolution (transfer function). At the hotspot (marked red), the levels have been reduced by approx. 10 dB. Subjectively, a reduction of 10 dB translates into cutting the structure-borne noise perception in half.

Fig. 39: Reduction in hotspot amplitude through application of damping materials



The hotspot analysis is performed for all relevant surfaces of the body in white, including the floor areas, tunnel, areas in the front wall, heel areas, back seat, trunk, spare wheel well, loading floor, wheelhouses, roof, side walls, and doors. Appropriate materials need to be selected for each application area. For example, the materials for the tunnel are adapted to suit higher temperatures. For the heel area, the front wall, wheelhouses, roof, and doors, magnetic or self-adhesive systems for vertical or overhead assembly are used.

Damping concept

According to this procedure, a damping concept for the body in white is developed step-by-step by selecting appropriate damping systems for optimal results under consideration of all aspects.

Selection of appropriate damping measures

The basic damping concept is defined early in the vehicle concept phase. Depending on the vehicle manufacturer, vehicle category, and the development philosophy followed, two totally different approaches can be distinguished regarding surface pattern and acoustic efficiency of materials.

» Minimal surface allocation with maximal material performance
» Maximal surface allocation with minimal material performance

Minimal approach

With the first approach (minimal approach), the basic concept provides few or even no damping coatings. In line with this development philosophy, damping measures are only taken when they are deemed necessary for vehicle development to achieve the desired car acoustics. In this case, such systems are applied in a solution-oriented manner that allows the problem to be solved. This approach allows for the greatest flexibility in material selection. However, the fact that the costs are difficult to predict should be mentioned as a disadvantage.

Maximal approach

In the second approach (maximal approach), a basic package of damping measures is defined depending on the car segment and based upon experience from previous vehicles. Ideally, this basic package covers a large surface of the car body and reserves as much construction space as possible for the thickness. Necessary costs are planned and approved for such a package. Over an extended period of time used for vehicle development, the basic package is only optimized if any components are changed in the vicinity. This period ends as soon as the vehicle reaches the design level at which reliable noise measurements can be performed. If necessary, the findings will lead to an adjustment of the damping package by deleting measures, adding them, or changing the materials used. The advantage of this procedure is the extensive planning security, but there is the disadvantage of reduced flexibility in concept adjustments. This is particularly true when automation concepts are included in the basic concept.

For technical reasons, vehicle manufacturers using extensively automated production styles prefer damping concepts with a high degree of automation. For example, extrudable acoustic compounds are only used commercially when the basic package of maximal approach requires few changes. If some areas are dropped, or alternative materials need to be used, extrusion automation can lead to a financial disaster.

Automation concepts capable of bringing conventional damping coatings into the vehicle body do not have this disadvantage. They enable significant flexibility in material application because it is possible to apply different, efficient material systems in key areas without calling the whole automation concept into question. At the same time, an opportunity presents itself to use significantly more favorable material systems when compared to extrudable acoustic compounds.

Lightweight structure concepts

Lightweight structure concepts are becoming more and more important to keep harmful emissions and fuel consumption at a relatively low level. The right choice is lightweight materials that enable great weight savings without drawbacks regarding physical properties. This, however, frequently leads to conflicts in the area of vehicle acoustics. There are high-quality material systems available that exhibit only 25% of the surface weight compared with conventional systems and simultaneously have significantly better acoustic efficiency. In contrast, lightweight body structures often require local applications of two to four times heavier damping systems to compensate for the loss in airborne sound damping caused by the lighter body materials. Because these measures are only applied in a very focused manner, the minimal approach described above is best suited for such challenges.

Outlook

No other industry has made technical developments or advances so dynamic as the car industry. For some time, autonomous driving and electromobility (e-mobility) have not been works of fiction but instead are becoming a part of reality.

Over the past few years, clear developments towards improving driving comfort can be observed. Vehicle acoustics are being increasingly perceived as a significant contributor to comfort. Likewise, the demand for acoustic measures in cars keeps increasing.

The need for continuous development and adjustment of damping concepts derives from the advancements in body construction. New concepts in multi-material mixes, including the use of high-strength and ultrahigh-strength steels, aluminum, magnesium, and composite materials, such as carbon-fiber-reinforced plastics, also lead to a change of the parameters for car acoustics.

With the trend towards more driver assistance systems and, as a result, noticeable relief for the driver, the acoustic perception of car passengers will change. Already, the increase in popularity of speech control systems confirms the need for acoustic improvement in vehicles.

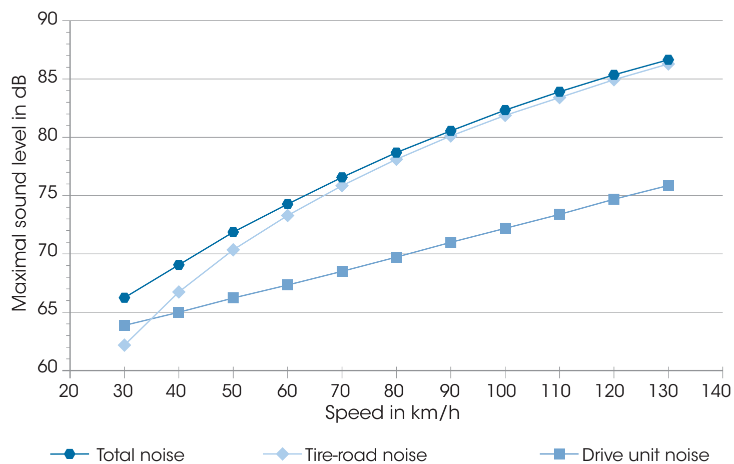
Cars in the future

Cars in the future will be partially, or even completely, autonomous, making drivers less involved in the driving process (Fig. 40). Thus, the car can be transformed into a mobile workplace or simply into a place for entertainment and communication. Because of the growing sensitivity towards annoying noise, new acoustic concepts are a necessity. The damping of structure-borne noise will continue to make a significant contribution to this.

Fig. 40: Autonomous driving

The combustion engine also contributes to the excitation of structure-borne noise, but this is not the case in all driving scenarios. At approx. 60 km/h, excitation from tire-road contact via the chassis exceeds the noise produced by the engine. Therefore, eliminating the com-

Fig. 41: Contributions to structure-borne noise



bustion engine can only have a positive influence on the excitation of structure-borne noise at low velocities, for instance, in city traffic (Fig. 41). Thus, the need for measures that aim at reducing structure-borne noise remains valid also with increasing electrification. However, this poses completely new challenges for car development.

Electric cars

The noise spectrum of an electric car is significantly different to that of conventionally driven cars. Electrification of the powertrain and elimination of the typical combustion engine sound leaves room for other noise sources. Whether it is a door humming at higher speeds, stones hitting the wheelhouse and/or undercarriage, noise from the auxiliary units, or simply rain pattering on the roof, all these annoying noises can be minimized with the damping of structure-borne noise.

An increase in demand for lightweight structure solutions is associated with electrification of the powertrain. Today, lightweight concepts are the biggest focus for car manufacturers simply because emission guidelines are continuously becoming more stringent. However, in contrast, the primary driving force behind developments in electrified vehicles is to increase their range. Because of this development, classic damping products are being replaced more and more by high-performance multi-layer systems or equally efficient lightweight structural products.

Technical terms

Adhesion Adhesion is understood to be binding forces between an adhesive surface and the substrate surface generated through interaction of adhesive molecules with the substrate surface.

Amplitude The maximal deviation of a sinusoidal wave is referred to as amplitude. Amplitude is necessary for description of the vibration.

Bitumen Bitumen is extracted from petroleum and is the portion of the individual petroleum fractions with the highest boiling point. This is thus a raw material completely different from tar, which is extracted from coal.

Butyl compound Butyl compound is based on various natural rubbers, e.g. polyisobutylene rubber.

Epoxy Describes materials which are based on epoxy resins. These are reactive resins that generate hard plastics in combination with other components.

Fit tolerance In machine construction, the fit tolerance is the dimensional relationship between two components. It is derived from the dimensional tolerances of both parts.

Glass transition temperature The glass transition temperature corresponds to the temperature at which a polymer or glass makes a transition from solid to viscous state.

Imbalance Imbalance is the case of a rotating body if the rotation axis does not correspond to the mass centroid axis. Imbalance leads to vibrations.

Impedance head Measurement sensor for measuring resistance resulting from propagating vibration in a structure. Impedance is the quotient of force and velocity.

Longitudinal wave A longitudinal wave is a physical wave vibrating in the direction of propagation. Longitudinal waves can propagate in any medium, regardless of whether it is solid, liquid or gaseous.
Loss factor The loss factor relates to the percentage of vibration energy that has been transformed into heat in a test material through internal friction. It is a measure to characterize damping materials.
Low-temperature impact strength Property of a material to adhere even at low temperatures down to –30°C and not to chip off after an impact on the car body in winter
Poisson's ratio Material property in mechanics and strength theory, belonging to the elastic constants of material and serving the purpose of calculating lateral contraction – named after Siméon Denis Poisson
Prepreg Abbreviation for *pre-impregnated fibers*: this material is mainly used in the aviation industry.
Real-time actuators Actuators that transform signals in mechanical and other physical factors in real time, i.e. without time lag
Resonance frequency Frequency of excitation leading to the locally maximum deviation (resonance amplitude)
Transverse wave Transverse wave – also called sliding or shear wave – is a physical wave in which vibrations run perpendicular to the direction of propagation. Transverse waves can only propagate in solids.

Sources and literature

[1] Biermann, Jan Welm: Geräuschverhalten von Kraftfahrzeugen [Noise behavior of motor vehicles]. University lecture transcript, Institute for Automotive Engineering, RWTH Aachen, 1988

[2] Tyre/road interaction. Last update 9 February 2012 by Patrik Andersson. Research in the Vibroacoustics Group, Division of Applied Acoustics, Department of Civil and Environmental Engineering, Chalmers University of Technology, Gothenburg, Sweden. http://www.ta.chalmers.se/research.php?page=vibgrptyre, accessed on 22.06.2017

[3] Möser, Michael; Kropp, Wolfgang: Körperschall – Physikalische Grundlagen und technische Anwendungen [Structure-borne sound: Physical basics and technical applications]. 3rd updated edition. Berlin, Heidelberg: Springer, 2010 (originally published under: Cremer, Lothar; Heckl, Manfred)

[4] Eisele, Georg; Genender, Peter Josef; Wolff, Klaus; Schürmann, Gregor: Electric vehicle sound design - Just wishful thinking? In: Proceedings AAC 2010: Aachen Acoustics Colloquium, 23rd–24th November 2010, Aachen. P. 47–59

[5] Kollmeier, Birger: Physikalische Grundlagen der Akustik [Physical basics of acoustics]. Medical Physics, Faculty VI, Oldenburg University. http://medi.uni-oldenburg.de/download/docs/lehre/kollm_phystechmed_akustik/aku1.pdf, accessed on 22.06.2017

[6] Wikipedia – The Free Encyclopedia. https://de.wikipedia.org/wiki/Reifen-Fahrbahn-Geräusch [tire/road noise], accessed on 22.06.2017

[7] Yu, Xiongying; Pang, Jian; Min, Fujiang; Wen, Wei; Gong, Shichao: Structural transfer path analysis of automobile tire/road noise. Inter.noise, Melbourne, 16.–19.11.2014

[8] Zeller, Peter (ed.): Handbuch Fahrzeugakustik: Grundlagen, Auslegung, Berechnung, Versuch [Handbook of vehicle acoustics: basics, design, calculation, tests] 2nd ed. Wiesbaden: Vieweg&Teubner, 2012 (ATZ/MTZ-Fachbuch)

Sika Automotive

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