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Acoustical and Thermodynamic Optimization of Agricultural Vehicles

In the highly developed markets of agricultural machinery, manufacturers are striving for highest possible vehicle power as well as energy efficiency. Customers also expect greater acoustical comfort in the vehicle cabin from one to the next model series. Legal requirements and the increasing use of vehicles nearby residential areas result in increased efforts of the manufactures to keep the exterior noise at an acceptable level. To effectively reduce the sound pressure level in the driver's cabin the sound radiation into the cabin has to be diminished. Hereby the radiating sound source, the structure borne excitation, the transfer paths and the sound radiating structure as well as leakages have to be considered. For the thermodynamic optimization emphasis lays on the engine cooling, engine encapsulation, battery management, heat isolation and heat protection of parts. For the development of product solutions the material properties such as flammability, emissions, robustness as well as heat conductivity and emissivity have to be particularly noted.

Keywords
Acoustics, thermodynamics, sound, noise, noise insulation, noise absorption, heat protection, engine encapsulation

Abstract
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For (final) customers the acoustical properties are a very important attribute in developing agricultural vehicles. Decisive for the impact on the environment is the exterior noise level; for the driver, on the other hand, the interior noise level in the cab is most significant, and requires reduction for labour protection reasons as well as comfort.

Thermodynamic optimization also plays an increasingly important role, because the vehicles are becoming continuously more compact and powerful. Increasing electrification results in increasing thermal loads – for example on the battery systems. In terms of light-weight construction, energy efficiency and cost reduction, use of materials or material combinations tailored to the specific requirements of agricultural machine manufacturers is beneficial. The material properties allow many additional functions to be integrated into the components.

In designing the components it is also necessary to consider the special requirements in the agricultural branch resulting from using the vehicles in the field. Damage from unusual sources such as gnawing mice can also occur when the vehicle is parked. Protection against such damage must be taken into consideration when laying out the components relevant for the acoustical and thermodynamic factors. Moreover component development must ensure that cutting residues cannot collect behind the acoustical components or in intermediate spaces during operation in the field.

Acoustical product solutions for agricultural vehicles

High performance drive trains, downsizing and emission reductions are presently the trends in agricultural vehicle development. However many of these measures lead to increased exterior noise as well as high acoustical pressure levels in the cab. Additional drive boost features provide for short-term power increases of up to 20 percent, while simultaneously increasing the noise level significantly.

The design of the cabs also results in acoustical problems. Frequently large glass surfaces are used to improve the view around the vehicle in all directions. However the additional solar radiation heats up the interior highly. Reduction of the temperature requires air conditioning systems with high speed fans, resulting in broadband noise radiation. Electrical and hydraulic components for high performance power take-offs also produce loud noises with dominant tonal components. Coupled drives, for example in the form of crop choppers, blowers and fans, also result in high sound pressure levels in the cab in field use.

Frequently single components are replaced during development, for example by products with higher power output, resulting in increasing acoustical radiation. Various weight reduction measures such as reduction of panel thickness can significantly increase the tendency of the structure to vibrate resulting in noise radiation from structural parts with large surfaces.

The multivarious acoustical requirements can be summarised as follows:

- Low acoustical pressure level in the cab (damping and insulation for engine and equipment)
- Reduction of volume from individual assemblies/prevention of disturbing tonal noises
- Reduction of exterior noise radiation (engine encapsulation, encapsulation of equipment)
- Balance of individual component noise sources
- Psycho-acoustical optimization (engine presence/diesel knocking noise, sharpness, modulation, etc.)

Agricultural vehicles with high acoustical comfort give users a positive quality impression. Experience indicates that this correlates highly with the overall subjective acoustical impression.

Vehicles as well as component systems and individual components are analysed acoustically in semi-anechoic acoustical testing facilities, on window test benches or acoustical component test benches for acoustical analysis and development as well as verification of product solutions. These tests are repeated later with the pre-production parts after development (**Figure 1**).

The effectiveness of acoustical product solutions depends primarily on noise absorption as well as noise insulation. Components consisting of foam, felt, foil, material combinations or pre-shaped foam parts provide material as well as component-specific absorption. Generally acoustical energy is converted to heat when absorbed (**Figure 2**). Increasing the absorption in the vicinity of noise sources, e.g. in the engine compartment or in the cab, can significantly reduce the acoustical pressure level at the driver's ear. Absorption by plane materials or components with a diffuse acoustical field is measured in an so called "Alpha Cabin" by determining the reverberation periods in third octave bands.

An effective acoustical abatement measure is insulation (**Figure 3**), which, for example, can be accomplished by coating a component or the entire wall of the cab with a heavy layer material. The additional mass increases the impedance, resulting in high reflection of the acoustical waves and effectively reducing the interior noise.

The insulation can be increased significantly by use of double wall systems (**Figure 4**). Here the heavy layer is kept away from the vibrating cab panelling by a soft intermediate layer (air gap, soft foam). At medium and high frequencies this double wall system provides significantly higher airborne noise insulation (up to approx.18 dB/octave) than a single wall (max. 6 dB/octave) above the resonant frequency of the double wall system (**Figure 5**). For this reason double wall systems have been used successfully for insulation of the dash panel between the engine compartment and the passenger compartment in the automotive branch. The effectiveness of such systems can also be verified on a window test bench for measurement of the insulation of plane materials, components, modules or even entire systems such as the front cab area or vehicle doors. For this purpose the panels or components are fixed in a test window. A diffuse noise field is generated on the transmission side. A receiver chamber is located on the other side of the window. Here the insertion attenuation is charted by means of robot-controlled measurement and subsequently evaluated.

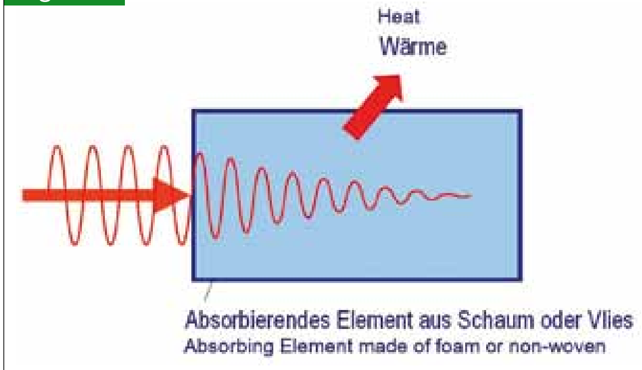
Exemplary Solutions

The acoustical functions of exemplary product solutions are explained below including descriptions of the materials and production methods being used.

Fig. 1

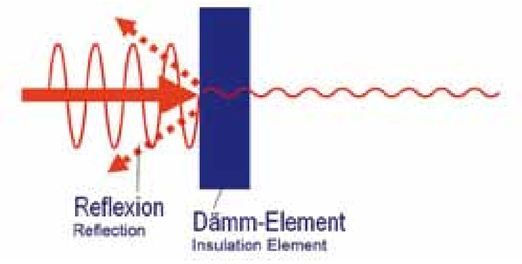
Example for measurement setup in an semi-anechoic room (microphones, artifical head measurement system)

Fig. 2



Absorption resp. damping of air borne sound, absorbed energy is transferred into heat

Fig. 3

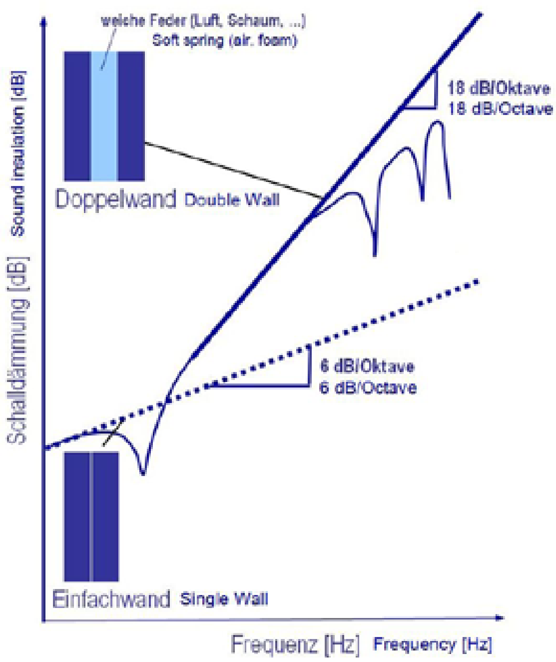


Insulation of air borne sound, reflection by an insulation element (e. g. wall with heavy layer)

Fig. 4

Sound insulation: Double wall system

Fig. 5



Single Wall vs. Double Wall: significant increase of sound insulation with double wall system

Integrated engine undershield attached below the engine can be used to reduce external noise radiation. Additional chamber absorbers (= resonators) allow noise to be absorbed (**Figure 6**). Airborne sound absorption can also be increased further with an additional layer of micro-perforated aluminium sheeting. The engine undershields are distinguished by their excellent resistance to various agents and are therefore resistant to environmental influences. They are produced in one operation using the blow moulding process.

Installation of thermoformed absorbers with a large surface area in the engine compartment allows the resulting airborne sound to be absorbed close to the radiating engine surfaces. Use of a number of absorbing components can significantly increase the acoustically effective “equivalent absorption area” (sum of the surfaces multiplied by the effective absorption values). Thermoformed components can also have a sound insulating effect depending on their thickness, density and sealing. **Figure 7** shows various thermoformed components installed in the engine compartment.

Another example is this acoustical timing belt cover (**Figure 8**). The component consists of an injection moulded frame to which a thermoformed component is attached for absorption and insulation of the engine noise in the area of the belt drive.

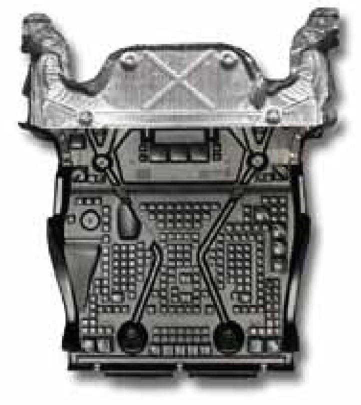
Components attached directly to the surface of the engine allow effective reduction of the acoustical radiation on the corresponding subsurfaces. Examples here are polyurethane damping systems (**Figure 9**), applied directly to the engine block (frequently also beneath a plastic engine cover). The foam parts adapt perfectly to the irregular surface of the engine providing particularly effective acoustical attenuation. They can also have a positive effect on the sound quality of the engine perceived by the driver (psychoacoustics).

In the vicinity of cutting equipment on choppers or similar acoustically radiating zones with high sound pressure levels, highly effective lofted PET fleece absorbers can be used effectively. These are surrounded by wire mesh or perforated sheet metal (**Figure 10**). The acoustical absorption effect can be varied by the thickness of lofted PET fleece, the covering scrim, the pressure and the percentage of perforations. Lofted PET fleece absorbers are highly resistant to rodent gnawing and depositation of cutting residues.

The noise radiated by thin sheet metal surfaces can be reduced by affixing stiffening pads which increase the buckling rigidity and resonant frequencies. This reduces the noise radiated from sheet metal panels excited by low frequency engine vibration (**Figure 11**).

Custom-fit die cutted parts can be used effectively for acoustical insulation in the vehicle interior (**Figure 12**). They can be produced in any desired shape from single or multiple layer slab material (foam or matting) and can also be coated with an acoustically effective, non-woven scrim cover. In addition to scrim covers, the adhesive systems also have acoustical properties. Scrims and foams can also be selected according to their resistance to UV light, their tendency to absorb water or oil or

Fig. 6



Integrated engine undershield with airborne noise absorbing chamber absorbers for the reduction of exterior noise and increase of sound absorption in the engine bay

Fig. 8

Timing belt cover, to reduce the acoustical emission and increase absorption

Fig. 9

Polyurethane damping on the engine: Precise fitting to the surface contour of the engine, reducing the noise emission of the cylinder head and valve covers

special fire prevention requirements. Die cutted parts can also be designed to provide protection against wear, sealing or mechanical protective functions. The initial materials for die cutted parts have thicknesses starting in the range of foils and increasing up to 10 cm. Economical, three-dimensional products can also be produced from die cutted parts by folding, bending, bonding etc.

Close fitting foam parts welded in foil (**Figure 13**) can also be used for insulating critical acoustical paths to the vehicle interior - for example in the area of the wheel wells. The foils make the built-in part resistant to oil and water. In many cases air-tight sealing is also required to prevent pressure losses from blowers. Use of foils can also prevent mould forming in air-conditioning systems. A foil backing can also be applied to knobbed foam to achieve higher noise absorption rates (**Figure 14**). The nubs allow the foil to make contact only at defined points, forming intermediate spaces for vibration to absorb the energy from incoming sound waves.

Frequently manufacturers require simple and economical solutions to help deaden acoustical paths or fill existing hollow cavities shortly before SOP. A simple, economical and highly effective solution was developed here in the form of chip foam bags (**Figure 15**). These can be applied in a compressed state in noise-conducting channels, in cab corner pillars or in hollow cavities. The chip foam bags are delivered compressed or evacuated to facilitate handling.

Sound absorption in the cab

A variety of products has been developed as acoustical components to reduce the noise pressure level in the cab. Acoustical headliners are particularly effective due to their large surface area (**Figure 16**). A material design with multiple layers guaran-

Fig. 7

Thermoformed parts for the engine compartment for the increase of absorption and insulation to the passenger compartment. From left: transmission tunnel insulation, engine hoodliner, dash panel insulation (engine side), oil pan absorber, engine cover absorber for truck engines

Fig. 10

Lofted PET fleece with cover fleece, installed behind mesh for protection against rodent damage, as a robust airborne absorber directly at the sound sources

Fig. 12

Custom-fit, multifunctional die cut parts with acoustic performance, right: Example of a 3D part with bonded layers of material

Fig. 11

Acoustically effective stiffening pads, for increased rigidity, to raise the resonant frequency, vibration damping

Fig. 13

Close fitting foam parts welded in foil for dampening and insulation of noise paths

tees high absorption rates for these thermoformed components in the frequency ranges critical for cab noise. Also acoustically very effective are pillar absorbers attached to the cab pillars (**Figure 17**).

To keep the noise level in the cab low, it is necessary to minimize leakages effectively by a sound-proof design. **Figure 18** shows examples of moulded parts for sealing the shift linkage passing into the cab. Other points requiring sealing include the area around the steering wheel, on the heater/air-conditioning unit, in the pedal and cable passages as well as in the area of the cab pillars, the longitudinal elements and cross-members.

In the simplest case the insulation inside the dash panel developed for the noise insulation between the cab and engine compartment (**Figure 19**) is designed of a layer of polyurethane foam combined with a layer of heavy material (polyurethane or EPDM). These provide extremely high noise insulation values (double wall system) for engine noise in the relevant frequency range. Partial mass distribution of the heavy layer can optimize the acoustical effectiveness of the firewall insulation while simultaneously reducing the component weight.

Broadband noise from air-conditioning systems (fan and flow noises) are usually transferred into the interior by injection moulded tubing. Noises can be reduced considerably by acoustical optimization of the air ducts, e.g. by attaching baffles or absorber pads (**Figure 20**) of foam or lofted PET fleece in the vicinity of the source.

Figure 21 gives an example of the effect of a sound package developed from various airborne sound absorbers and insulating elements for reduction of the noise in the vehicle interior. Depending on the product, acoustical measures can provide significant reductions in the sound pressure level; in many frequency ranges up to 10 dB(A).

Fig. 14

Contour-foam, welded in foil, with high airbourne noise absorption

Fig. 15

Acoustically effective chip-foam bags, for cavity sealing

Fig. 16

Acoustical headliner

Fig. 17

Acoustical pillar absorber

Fig. 18

Moulded Polyurethane or PE parts for sealing around the gear lever

Thermodynamic product solutions for agricultural vehicles

Measures for increasing the engine performance or increasing power density rates of the power units can lead to thermodynamic problems on commercial vehicles for agricultural applications. Thermodynamic optimization may be required in the following areas:

- Engine cooling (to prevent overheating)
- Engine encapsulation (reduction of heat losses, increasing efficiency of the drive)
- Battery heat management (protection against thermal overload, particularly on hybrid and electric vehicles)
- High temperature insulation (e.g. exhaust system)
- Component heat protection (e.g. plastic components in engine compartment)

Thermal problems usually result from undesired or uncontrolled heat transfer (**Figure 22**).

Heat transfer requires differentiation between three physical phenomena. In the case of “convection” the heat is transferred by the air flowing past a component. Controlled guidance of the air, for example with baffle plates, allows forced convection to be used for cooling or heating critical components. In the case of “heat conduction” the heat is transferred at a contact point between two components. Components can be thermally decoupled by installing insulating material in between. Heat transfer by “radiation” is pronounced on internal combustion engines particularly in the area of the exhaust system. Propagation of radiation can be prevented almost completely by reflectors (heat shields). Thermally sensitive components, as well as acoustical absorbers, can be protected against radiated heat with thin, frequently micro-perforated aluminium foil.

The product solutions below focus primarily on thermodynamic requirements. Many of the acoustical absorbers introduced in the previous section also have thermal insulating properties due to the materials used (foam, fleece etc.).

Aluminium is ideal for product solutions for heat shields due to its high reflection rate in the infrared range i.e. extremely low emissivity (tendency to radiate heat when heated).

Fig. 19

Dash panel inner insulation as double wall system (mass-spring-system)

Fig. 20

HVAC / Air Conditioning systems: Absorber pads to reduce the air-flow noise

Figure 23 shows several typical examples of aluminium heat shields.

An ultra thin sheet of aluminium combined with a glass fibre layer just a few millimetres thick (**Figure 24**) also provides an effective heat shield capable of being easily attached at critical points when provided with an adhesive backing.

Figure 25 shows a thermoformed component provided with micro-perforated aluminium foil as a heat shield in the engine compartment. In comparison to non-perforated aluminium foil, micro-perforations provide for much higher broadband acoustical absorption in the medium and high frequency ranges.

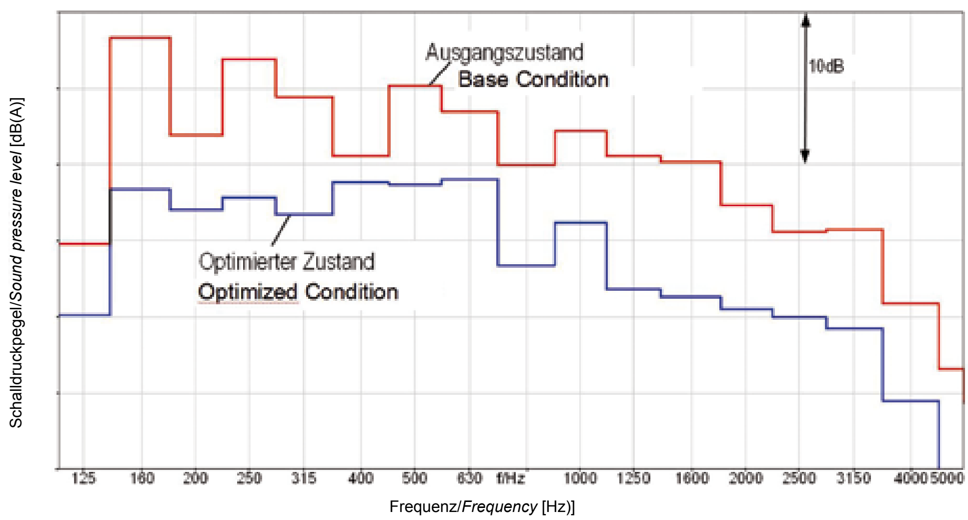
Another example of thermal component protection is shown in **Figure 26**. Here a fuel filler hose is protected against the effects of heat by a PE foam jacket.

Electrification of equipment and drives can create a variety of new thermodynamic problems. Vacuum formed PE foam insulation is used for protection of high performance batteries against temporary overheating, e.g. after longer periods of operation at full load followed by standstill (**Figure 27**). Acoustical encapsulation of noise-emitting components also poses an easy risk of overheating.

Conclusions

Acoustical and thermodynamic optimization of agricultural vehicles is particularly complex due to the extreme conditions of use, such as operation in the field. Improvements in the acoustical comfort in the cabs on tractors, choppers and harvesters require an interdisciplinary approach to achieve high quality results. This necessitates development of tailor-made functional parts. In the face of thermal loads in the vicinity of the engine or for battery systems, special solutions are required to protect components against heat conduction and radiation. An optimum

Fig. 21



Example of an vehicle measurement at constant speed, base condition vs. optimized condition (with acoustical measures) combination of materials as well as production technologies is required in each individual case to achieve ideal product solutions in terms of function, cost and weight.

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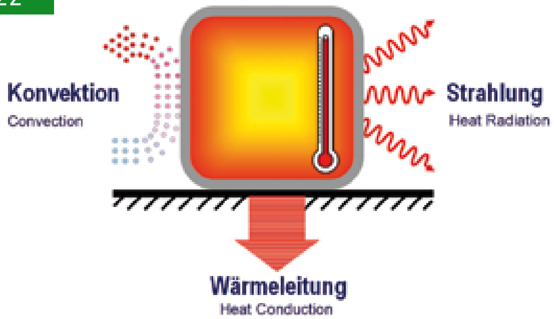
Fig. 22



Mechanisms of heat transfer

Fig. 23

Heat shields for reflection of/protection from radiated heat

Fig. 24

Ultra thin heat insulation with aluminium foil and glass fibre

Fig. 25

Sound absorbing part with micro-perforated aluminium foil for heat protection

Fig. 26

Fuel filler pipe with PE foam jacket for thermal isolation

Fig. 27

Vacuum formed PE Foam batery insulation to protect against overheating