Methodology for Sloshing Noise Measurements in Diesel Exhaust Fluid Tanks: Acoustic Target Definition and Psychoacoustic Investigations

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Introduction

In diesel engine vehicles with urea injection, an additional tank for the urea solution (diesel exhaust fluid solution) with a volume between 15 and 25 liters is located in the vehicle. During driving manoeuvers such as parking or braking, a sloshing noise can occur caused by multiple reflections of the liquid's wave inside the tank. This sloshing noise is perceived by the driver as annoying and depends on the geometry and filling levels of the diesel exhaust fluid tank.

Until now, no valid procedure for measuring the sloshing noise in SCR tanks, or specific acoustic target which the diesel exhaust fluid tanks need to fulfill have been defined. Therefore, Röchling Automotive developed a reproducible laboratory-based methodology to measure the sound generated by the tank and to compare it with a defined sound pressure level target.

Moreover, the engineers' attention focused on the subjective perception of the sloshing phenomenon. Therefore, various sloshing noises of different tanks were modified by Möhler + Partner, focusing on the number and level of audible reflections. With these signals, listening sessions were conducted to identify the most important parameters influencing the annoyance.

Generation of Sloshing Noise

Sloshing noise is generated by the DEF moving inside the tank and interacting with its surfaces. This noise can be transmitted to the cabin, where it can eventually be heard by the occupants and perceived as unpleasant or as a fault in the vehicle, since sloshing noise does not correlate with the engine and appears with a delay when the car stops.

The different mechanisms of noise generation were observed and can be found in [1].

"Hit" happens when a DEF wave impacts on the internal surface of the tank and generates impulse-like broadband noise.

"Splash" occurs if two or more waves hit each other. This generally produces a less intense noise in comparison with "hit" noise, but has a longer duration.

The "clonk" noise can arise if the shape of the tank permits the temporary forming of an air cavity separated by the liquid surface, for example in a corner or with a dome-like shape. When the air trapped temporarily is compressed by the moving liquid, low-frequency noise is generated.

"Bubble jet" is a mechanism discovered experimentally. It appears when the geometry of the SCR tank allows the air to be pushed through an opening by the moving liquid and forced to bubble through a layer of liquid.

Figure 1: An SCR tank in the typical position in a vehicle.

Optimization of the Tank Design with Regard to Sloshing Noise

The following variables have an influence on sloshing noise perceived by the vehicle occupants:

- External geometry of the tank: large flat surfaces have to be avoided as they trigger impulse-like sloshing noises and transmit them efficiently. Incidentally, it is generally not possible to change the outer shape of the tank to any great extent for reasons of packaging.
- Material: each material has different stiffness and damping characteristics. This leads to different acoustic transmission properties that can be adapted to meet the acoustic requirements.
- Thickness: a greater thickness of the tank can lower the transmission of the noise. For ecological reasons, it is desirable to produce parts which are as light as possible.
- Vibration dampers at the fixing points and isolating panels can be added to lower the transmission of acoustic energy.
- Masking noises: other noises than sloshing, such as those of an idling engine, have a masking effect, but this influence is not present in vehicles with a start & stop system.
- Aerodynamic noise at medium and high speeds can mask the sloshing, but these are not the critical driving conditions in terms of sloshing, since driving at low speeds leads to higher acceleration values.
- Filling level of DEF inside the SCR tank: an empty tank or a completely full tank does not generate noise because the liquid cannot move in the tank. Filling levels in between the minimum and the maximum are the ones that generate sloshing noise. Obviously, the tank has to be designed to restrain the noise throughout the entire filling range.
- Maneuvering: the movement of the car triggers the sloshing. Hard braking causes noise to come from the brake

system and from the interior cabin, for example when passengers move with respect to the seat and the seat belts block. In addition, strong braking is perceived as an emergency, and this temporarily lowers the expectations with regard to comfort in the vehicle. For this reason, softer maneuvers such as parking and stopping at traffic lights can generate noise which is more perceptible in the interior cabin.

- Car Transfer Path (TP): once generated, the noise is transmitted via air-borne and structure-borne paths to the passengers of the vehicle. The amount of acoustic energy reaching the cabin depends on the characteristics of the car TP.

In general, the acoustic requirements for the SCR tanks are that they must generate little sloshing noise.

At this point, because of the subjective evaluations of the acoustic behavior, it is necessary to know when the tank has been improved far enough in order to avoid over-engineering.

To achieve this, it is necessary to have a test procedure for the objective quantification of sloshing noise including a target to be met.

Sloshing Noise Test Procedure

The first step in defining the test procedure was to reproduce typical maneuvers occurring during the real driving experience that make sloshing noise audible in the cabin.

For this purpose, some vehicles were tested and speed, acceleration and interior noise were recorded. From this data, one maneuver was chosen so as to have both noise generation and a low masking noise from the car.

At this point, a linear bench with programmable motion was designed and built to reproduce the movement profile (Figure 2) under controlled conditions.

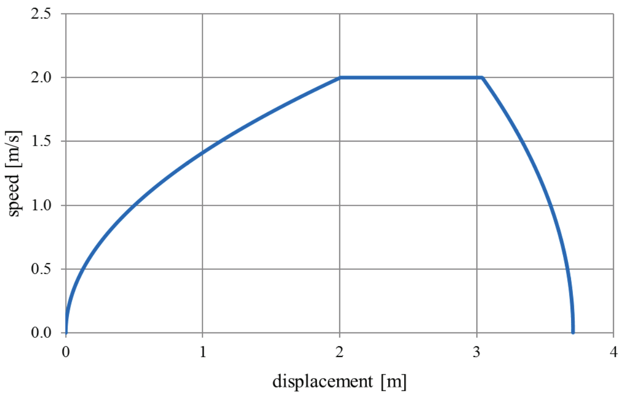

Figure 2: Movement applied to the tanks on the linear bench. This reproduces speed and acceleration values typical for the maneuvers that proved most critical in tests with real vehicles as a combination of capabilities which trigger the noise while causing little background noise.

To obtain an objective quantification of sloshing noise, a microphone is positioned 50 cm above the upper surface of the tank. The wall surfaces around the bench are equipped with absorbent panels to avoid reflections.

The sound pressure captured by the sensor is then visualized as an overall level A-weighted function of time. Sampling, windowing, averaging and time step are chosen to emphasize the transient characteristic of sloshing. Time 0 is defined as the time when the tank stops after the profile movement.

The tank is tested in a forward direction, as this is the most common situation.

Various filling levels are tested to take the whole spread of possible values from full to empty tank into account. For each filling level, several repetitions are recorded and represented on the same graph. This allows the repeatability of the test to be verified while taking the chaotic nature of sloshing into account.

The main advantages of the described procedure are that it is repeatable and objective, so that it permits different designs and filling levels of the same tank or even of different tanks to be compared, and that it is reproducible in the laboratory without the need for a vehicle, although it is derived from real driving situations.

Sloshing Noise Target Definition

The procedure described in the previous chapter was used to perform benchmarking on several SCR systems.

All of the information coming from the benchmarking carried out on the linear bench and in the on-vehicle tests results was collected.

The ranking of all of the combinations of tank and filling level with respect to the annoyance they cause led to the definition of the sound pressure target versus time that an optimized tank has to fulfil, see for example Figure 3.

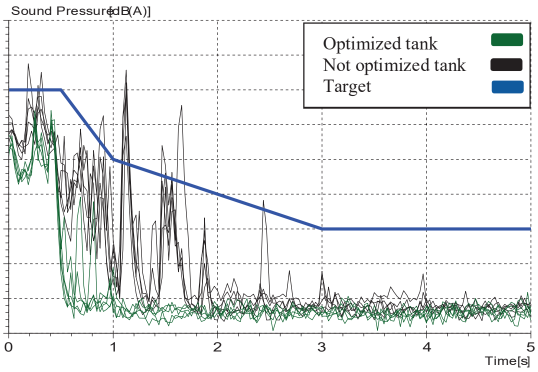

Figure 3: Example of sloshing noise target line. This time-dependent target is accomplished if the overall sound pressure level measured following the procedure described stays below the line. With the green line is presented one optimized tank, the black curves represent a tank before the sloshing optimization.

The most remarkable advantage of application of the sloshing test procedure and the outlined target is that evaluation is done at SCR system level without the involvement of the car, but the vehicle characteristics are nevertheless taken into consideration in the target itself.

The acoustic transmission of the vehicle is taken into account by measuring the car TP, and the expectations in terms of comfort are derived from subjective evaluations performed in collaboration with automakers. As a consequence of these considerations, the target at tank level has to be adapted to suit the different automotive segments.

A further improvement in the definition of the noise target is the analysis of sloshing from a psychoacoustic point of view.

Psychoacoustic Annoyance of Sloshing Noises

The annoyance of sloshing noise was studied in two separate listening sessions. For the first session, the peak levels of the signals measured on the test bench were modified systematically to quantify the influence of the single temporally delayed peaks on the psychoacoustic annoyance.

In the second session, measurements of different variants (prototypes) were compared among each other regarding their annoyance.

The stimuli were evaluated by 12 subjects aged between 20 and 52 years. The signals were presented via electrostatic headphones (Stax SR-307) in a quiet and neutral surrounding at Möhler + Partner. Before the listening sessions the subjects have been informed about the phenomenon of sloshing noise. Apart from that, subjects have not been any experts on this topic.

Listening Session "Peaks Modification"

Stimuli and Method

Figure 4 shows the original time structure of the signal measured on the test bench. The signal was segmented in three single sections enlarging in time. The first section was determined from 1.0 to 2.0 seconds after the main slosh, the second section from 2.0 to 3.5 seconds and the third from 3.5 to 5.5 seconds.

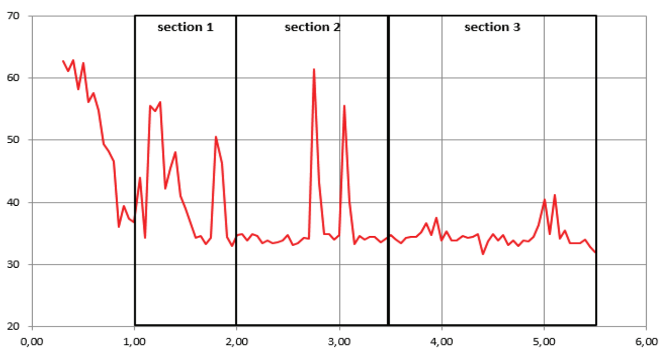

Figure 4: Original signal "sig_01" and the segmentation in sections for the following peaks modification.

In these three sections the peaks have been eliminated as specified in Table 1.

To determine quantitatively the influence of the peak levels on the annoyance the psychometric method of "magnitude estimation with anchor sound" was applied. The unmodified signal ("sig_01") served as anchor sound. Each sound pair had to be evaluated of each subject four times in randomized order.

Table 1: Stimuli of the listening session 1: Systematically elimination of peaks in defined sections.

code	modification		
	section 1	section 2	section 3
sig_01	original	original	original
sig_02	original	no peaks	no peaks
sig_03	original	no peaks	original
sig_04	no peaks	original	original
sig_05	original	no peaks	no peaks
sig_06	no peaks	original	no peaks
sig_07	no peaks	no peaks	original
sig_08	no peaks	no peaks	no peaks

Results

Figure 5 shows the results (median of 11 subjects) for the evaluation of annoyance for the stimuli described in Table 1. The anchor was recognized 100% by the subjects, the maximum elimination of the peaks in all three sections reduced the annoyance by almost 50%.

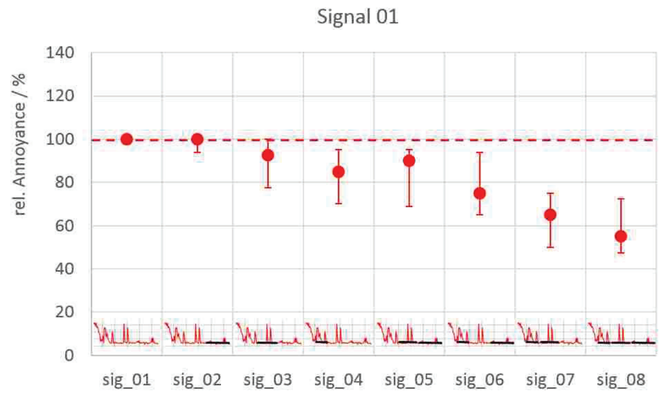

Figure 5: Relative annoyance for the peaks modification of signal 01.

As the eliminated peaks in the single sections had different peak levels, the connection between the eliminated peak level and the impact on the annoyance reduction has to be considered. Therefore, for each signal the relative peak level according to formula (1) was calculated.

$$rel.PL = \frac{\left(L_{main\,peak} + w_1 \cdot L_{\max sec1} + w_2 \cdot L_{\max sec2} + w_3 \cdot L_{\max sec3}\right)_{with\ elimination}}{\left(L_{main\,peak} + L_{\max sec1} + L_{\max sec2} + L_{\max sec3}\right)_{without\ elimination}} \quad (1)$$

By adapting the weighting factors for the single sections, the correlation between the magnitudes relative peak level (PL) and relative psychoacoustic annoyance (PA) can be tuned.

Figure 6 shows the result of six different sloshing noises with the respective level modifications and weighting factors for the sections w_1=0.6; w_2=0.4 and w_3=0.5. This means that the peaks in the late section seemed to be more important for the subjects' evaluation than the peaks in the middle section.

In this way, a first approach shows the possibility to deduce the signals' annoyance from a measurement with various delayed peaks. A detailed investigation and verification of this approach with further unmodified signals should be done.

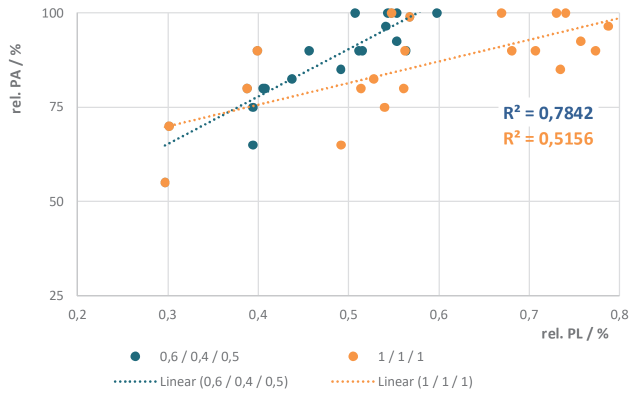

Figure 6: Relationship between relative PL according to formula (1) with different weighting factors and the resultant relative PA.

Listening Session "Variants"

Stimuli and Method

Additionally to the investigation on the systematically modification of the peaks, measurements of various prototypes (variants) of different vehicles have been compared regarding their annoyance. Different development stages of different vehicles were investigated as well as different filling levels. Table 2 shows all evaluated stimuli of this session.

Table 2: Stimuli of listening session 2: different variants and filling levels.

Vehicle	Variant		
	filling level	development stage	
A	14,4	not optimized	optimized
	19,2	not optimized	optimized
B	8	variant 2	
	16	variant 2	
	22	variant 2	
C	20	variant 2	variant 4
	23,8	variant 2	variant 4

For this evaluation the psychometric method "Random Access" was applied. Therefore, the subjects had to rank the different sloshing noises regarding their annoyance. Figure 7 shows the interactive screen display for each evaluation. Subjects are allowed to listen to the signals as often as they like. By drag and drop the symbols have to be ordered regarding their perceived annoyance.

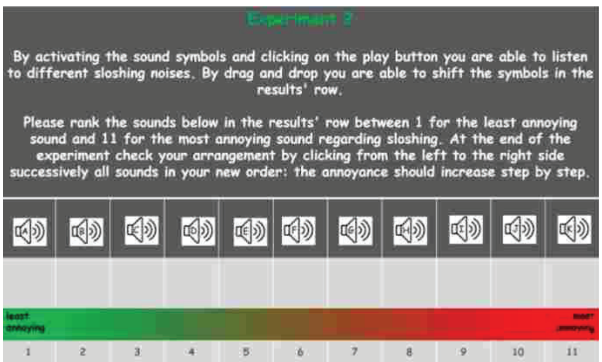

Figure 7: Interactive display screen for the evaluation of annoyance by the method of "Random Access".

Results

Figure 8 shows the results (median of 12 subjects) for this listening session.

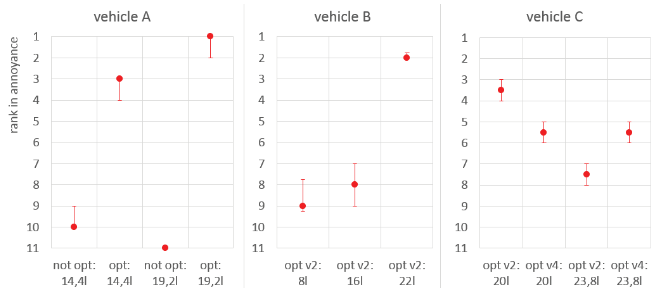

Figure 8 Rank in annoyance for 11 different sloshing noises.

Vehicle A shows for both filling levels obvious and homogeneous result: the optimized variant is evaluated evidently superior to the not optimized variant.

The influence of filling level can be observed for vehicle B: the filling levels 8 l and 16 l are both estimated as quite annoying, the maximum filling level of 22 l however is evaluated clearly better.

The optimization of the tank of vehicle C shows for the two observed filling levels a rather differentiated result: whereas for the filling level of 20 l a deterioration between variant 2 and 4 arises, for the filling level of 23.8 l an improvement in annoyance can be determined.

Conclusion of the Psychoacoustic Approach

In two different examples, the psychoacoustics was applied to evaluate the annoyance of sloshing noise.

In the first approach, the prediction based on the analysis and weighting of peak levels in single time sections of the signal was presented. A combination of weighted maximum levels of different time sections of the signals resulted in a predictable value for the subjective evaluated annoyance.

In the second case, by applied psychoacoustics the annoyance of various sloshing noises of different prototypes was compared. This example illustrated how to use psychoacoustic tools in the development process to acquire pragmatically data about subjective magnitudes.

Literature

[1] Wachowski, C., Biermann, J.-W., Schala, R.: Approaches to analyse and predict slosh noise of vehicle fuel tanks.

[2] Zwicker, E. and Fastl, H.: Psychoacoustics – Facts and Models. Second Updated Edition. Springer-Verlag, 1999.