

Acoustic Valve Integration in Exhaust Line Systems

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Abstract: In recent years the demand for the acoustic performance of exhaust systems has increased and will further increase in the future. The main drivers are new pass-by-noise regulation and new powertrain technologies paired with exhaust muffler volume, weight and costs constraints. In the following paper several application examples for Adaptive Valve™ (self-actuated in-pipe valve), in-muffler valve and electric valve are shown and the related benefits on the system performance are assessed. It is shown that implementing a valve into an exhaust system has a significant influence on the NVH performance. The resulting backpressure penalties can be minimized using the right implementation strategy of the valves in the exhaust system. Hence the exhaust system has to be specifically designed for the integration of a valve. All three valve types have additional benefits to their standard application for overall noise reduction and muffler volume reduction, which are analyzed. The Adaptive Valve™, for example, is often used on cars with long pipe routing and has the additional benefit of reducing pipe resonance in the system. Another example, the electric valve, can be coupled with vehicle communication networks and hence the flexibility in application is significantly increased.

Key words: Exhaust, valve, system integration.

1. Introduction

The demands for solutions answering new powertrain and legislation trends have increased in recent years. More intelligent solutions have to be found, such as valve or active systems [1]. In cooperation with new products also new development tools need to be developed. Hence the implementation of such products asks for a better understanding on the component and system level [2].

In Fig. 1 an overview about the current market trends is shown. On the one side the powertrain impact, such as downsizing, hybridization, cylinder deactivation and down speeding, will have a significant influence on the acoustic performance and therefore lead to higher muffler volume demand. For downsizing and for cylinder deactivation the number of engine cylinders is reduced (either completely or in certain driving conditions), this leads to lower main harmonics of the engine excitation, which are then

traditionally damped by using an increased silencer volume. For hybridization the most challenging NVH demand is the switching between combustion and non-combustion mode. Here, the driver should feel no impact on the NVH performance between those modes, which is again a driver for more damping and hence more silencer volume. Down-speeding leads to driving in lower RPM (revolution per minute) ranges and hence lower frequencies are excited in the standard driving modes. Additionally to the powertrain trends there will be higher demands for pass-by-noise legislation and a demand for more premium sound, which also lead to the direction of increased silencer volume.

The platform evolutions demand smaller package and less weight. Here the main drivers are legislation for CO₂ emission (lightweight) as well as tighter packages due to battery and other technologies. One smart solution in response to these trends is the implementation of an exhaust valve. Valves are common used components in the exhaust industry [3-5] and well researched. In order to successfully

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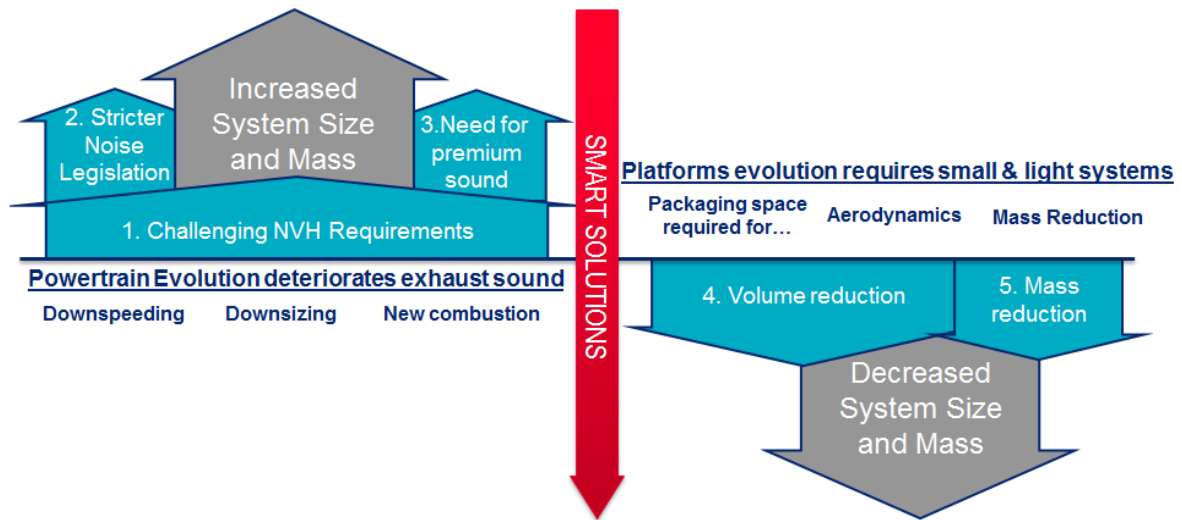


Fig. 1 Market trends and influence on exhaust system.

implement a valve in an exhaust system some changes have to be considered in the exhaust layout. In the following, three different kinds of valves are described including an application guideline for each of them.

2. Overview and Application

2.1 Electric Actuated Valve

In the last years pneumatic actuated valves have been substituted by electric actuated ones. The benefits of electrically controlled actuators are multiple, such as reducing necessary mounting space, faster control activation, control of intermediate valve open angles. This offers a wider range of possibilities for acoustic and back-pressure tuning of the exhaust system than the original open/close dual-mode. In Fig. 2 a typical electric valve is shown:

The electric-actuated valve is an active valve located along the piping system of the exhaust system, outside the silencer. The valve will acoustically act as a variable-diameter orifice, corresponding to the valve open angle controlled by the actuator. Starting from a fully open position, the electric-actuated valve acts as a pipe of same diameter as the valve housing. Depending on flow profile before the valve, flow obstruction/turbulence generated by the valve in fully open conditions is in most applications very low. In

comparison to a system without electric-actuated valve, increased flow noise sources are not noticeable. With the valve open angle reducing, the valve acts as a pipe of smaller diameter increasing back-pressure. In cases where there is an alternative flow path throughout the complete exhaust system, the mass flow amount passing through the valve is reduced. In closed position, the valve acts as a closed acoustic boundary condition for the low frequency engine orders noise.

The design of the complete exhaust system and the location of the actuated valve are based on the tradeoff between expected acoustic attenuation, allowed flow noise level and backpressure. In the close position, the electric-actuated valve enables to maximize the comfort sound signature of the exhaust system. In the open position, the sporty sound signature of the exhaust system will be enhanced.



Fig. 2 Electric actuated valve with actuator.

2.1.1 Application Guidelines Electric-Actuated Valve

There are various possibilities of implementing an actuated valve along the exhaust system. In the following application example, the implementation of the electric-actuated valve on a single line exhaust system with 2 tail-pipes will be discussed. The same rules would apply on dual line exhaust system with even more tuning possibilities.

The exhaust system consists of an intermediate pipe, a rear silencer fitted with 2 tail-pipes whose length and diameters could be different, as shown in Fig. 3. The electric-actuated valve is mounted on the tail-pipe “OUTLET 1”. For a given rear silencer volume, main tuning parameters of the system are the length and diameter of both tail-pipes.

The internal silencer layout depends on various input parameters such as weight, manufacturing costs and constraints. The functional targets for the full system “engine + exhaust system”, provided by the OEM—like maximal allowed back-pressure value at nominal power, maximal allowed overall noise level and engine order noise levels over whole RPM range at the tailpipe—also have a large impact on the internal silencer layout design.

Especially, for a turbocharged engine, the OEM needs to provide the exhaust system supplier with an additional back-pressure target for a lower RPM range, which goes in line with their engine calibration. Otherwise, the RPM value at which the close-open transition occurs has to be decided together later on during the development timeframe. For a comfort application, the basic rules can be expressed as follows:

- Valve is closed up to ~3,000 RPM (normally

defined by OEM) in order to reduce low frequency content of tail-pipe noise and reduce potential booming feeling in the vehicle cabin. Therefore, “OUTLET 2” is designed as long as possible with a small diameter. Here, additional back-pressure target at lower RPM is also taken into account.

- At ~3,000 RPM the valve opens and the gas will mainly be released via a relative short “OUTLET 1” with a larger diameter, enabling thus to reduce the back-pressure value at nominal power.

For the fine-tuning several parameter variations have to be considered. In the case where the backpressure is too high in low RPM range, the obvious solution would be to increase the diameter of OUTLET 2, but this would lead to increased low frequency content. In the case where the backpressure is too high in higher RPM range, the diameter of either OUTLET 1 or OUTLET 2 needs to be increased. Here the consequence would be again an increased low frequency content. Obviously this fine tuning works also in the opposite way. In cases where the order levels are too high, the pipe diameters could be reduced with a potential negative impact on backpressure and flow noise.

2.1.2 Application Example Electric-Actuated Valve

In the following application example, a gasoline 4-cylinder with cylinder-deactivation can be seen. The acoustic performance of an 18-liter rear silencer with 2 tail-pipes and without valve is compared to that of a smaller 13-liter rear silencer with an electric actuated valve. Both silencers have 2 tail-pipes and both complete exhaust systems show same back-pressure value before closed-coupled catalyst at nominal rated RPM.

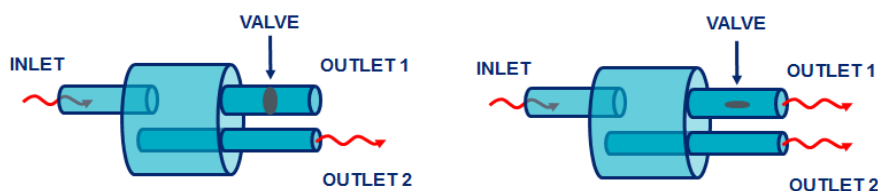


Fig. 3 Electric actuated valve on a dual tailpipe muffler.

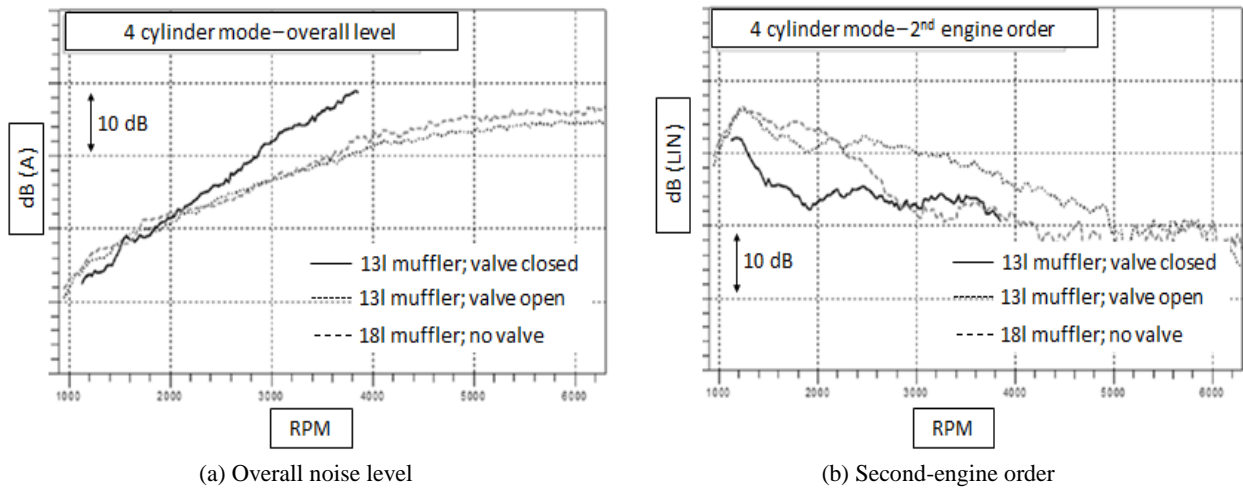


Fig. 4 4-Cylinder operating condition.

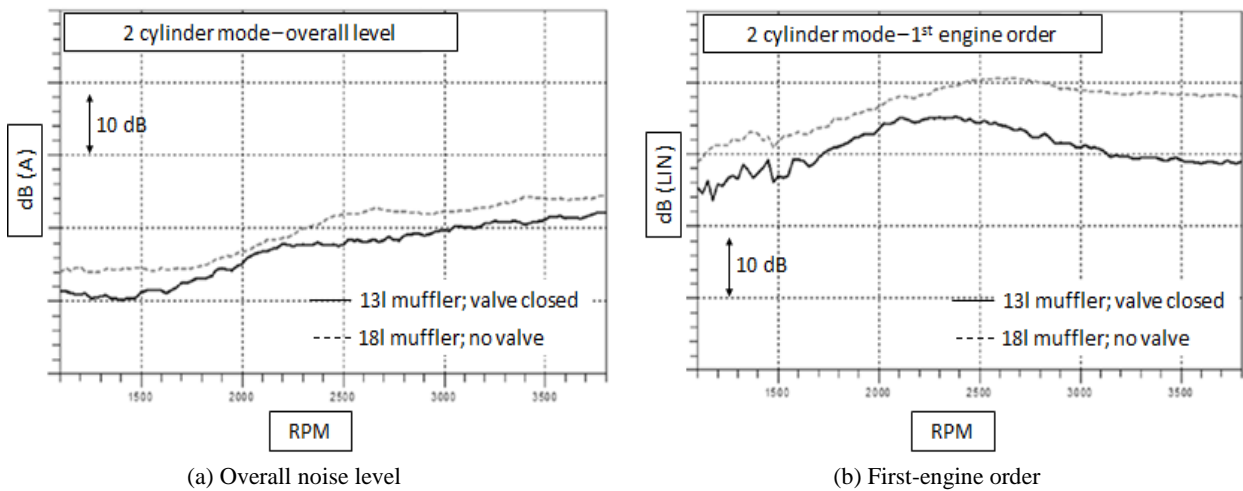


Fig. 5 2-Cylinder operating condition.

The measurements for the 4-cylinder operating conditions are shown in Fig. 4. The 13-liter silencer with electric-actuated valve in open position shows same overall noise as the 18-liter silencer without valve. This confirms that the valve in open position at tail-pipe location does not generate additional flow noise.

The measurement results for the I4 engine with only 2-cylinders operating are shown in Fig. 5. When operating in 2-cylinder mode, the engine delivers no more than half the mass flow of the 4-cylinder. Flow noise contribution is dramatically reduced and overall noise is then dominated by engine orders noise contribution. Thus, the 13-liter silencer with valve in closed position shows the same or even lower overall

noise level than 18-liters silencer without valve.

The other main NVH difference between 2-cylinder and 4-cylinder mode is that the first engine now dominates the engine order noise contribution to tail-pipe noise, leading to a potential booming feeling in the vehicle cabin. Here, the 13-liter silencer with valve in closed position shows clear improvement in comparison to the 18-liter silencer without valve: first engine order is significantly reduced above 2,500 RPM, as requested by customer.

2.2 Adaptive Valve™

The Adaptive Valve™, as shown in Fig. 6, is a passive valve, through which all the exhaust gas must flow. It has been applied mainly to mitigate increasing



Fig. 6 Adaptive Valve™.

low frequency noise due to down-sizing and cylinder-deactivation and avoiding the necessary increase in muffler volume that these technologies would otherwise drive. The attenuation is achieved in two ways:

- Reduction of pulsation noise due to restriction (local pressure drop through valve).
- Suppression of acoustic standing waves in the pipe in which it is located and acoustic system modes.

2.2.1 Application Guidelines of Adaptive Valve™

The adaptive valve™ is a passive valve with a vane obstructing flow, connected to a shaft that allows the vane to rotate in response to the forces acting on it, which is in turn connected to a torsional spring which opposes the motion of the vane away from its resting position. The valve is located in a pipe with at least one muffler element downstream of it. The vane position is a function of the pressure drop across the valve and the return torsion created by the spring. As the exhaust mass flow increases, the pressure drop across the valve increases which results in the valve opening a little further until the forces are balanced.

At low flow rates, backpressure is higher than normal, this leads to significantly lower tailpipe sound levels at these conditions than one would see with a non-valve solution with the same exhaust system volume. As the Adaptive Valve™ progressively opens, it becomes less restrictive and the contribution of the

valve relative to the full exhaust system backpressure becomes much less. Nevertheless, the backpressure impact of the valve must be mitigated so that customer backpressure targets at rated engine speed are met. This means that the other muffler components must be made less restrictive.

Additionally, the inserting of a restrictive component, such as a valve, into the flow means an increase in flow noise. This means that there should always be an element downstream of the valve to clear up flow noise, as shown in Fig. 7.

2.2.2 Application Example of Adaptive Valve™

One program that has been in production for several years that utilizes the Adaptive Valve™ is the GM Large SUV & Pick-Up Truck program. Architecture similar to that shown in Fig. 7 was used. There is a front pipe connected to the largest muffler volume which is in a front location. The front muffler is immediately followed by the Adaptive Valve™ which is in one end of the longest pipe in the exhaust system—the inter-pipe. The inter-pipe is connected to the rear muffler which is used to clean up any flow noise generated by turbulence caused by gas flowing past the valve. Finally we have the tailpipe from which the exhaust gas exits to atmosphere and where we measure the acoustic performance of the exhaust system.

The location of the Adaptive Valve™ is very important. Passive valves through which all the gas passes can suppress acoustic standing waves that would otherwise form but only in the pipe in which the valve is located. In this case, the Adaptive Valve™ will do a good job of suppressing any standing waves in the inter-pipe/tailpipe. In this particular system, the inter-pipe/tailpipe can be regarded as one long

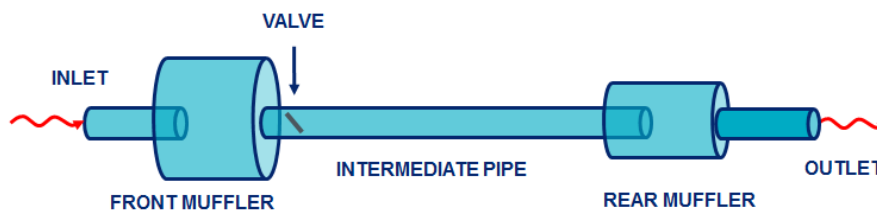


Fig. 7 Adaptive Valve™ system layout.

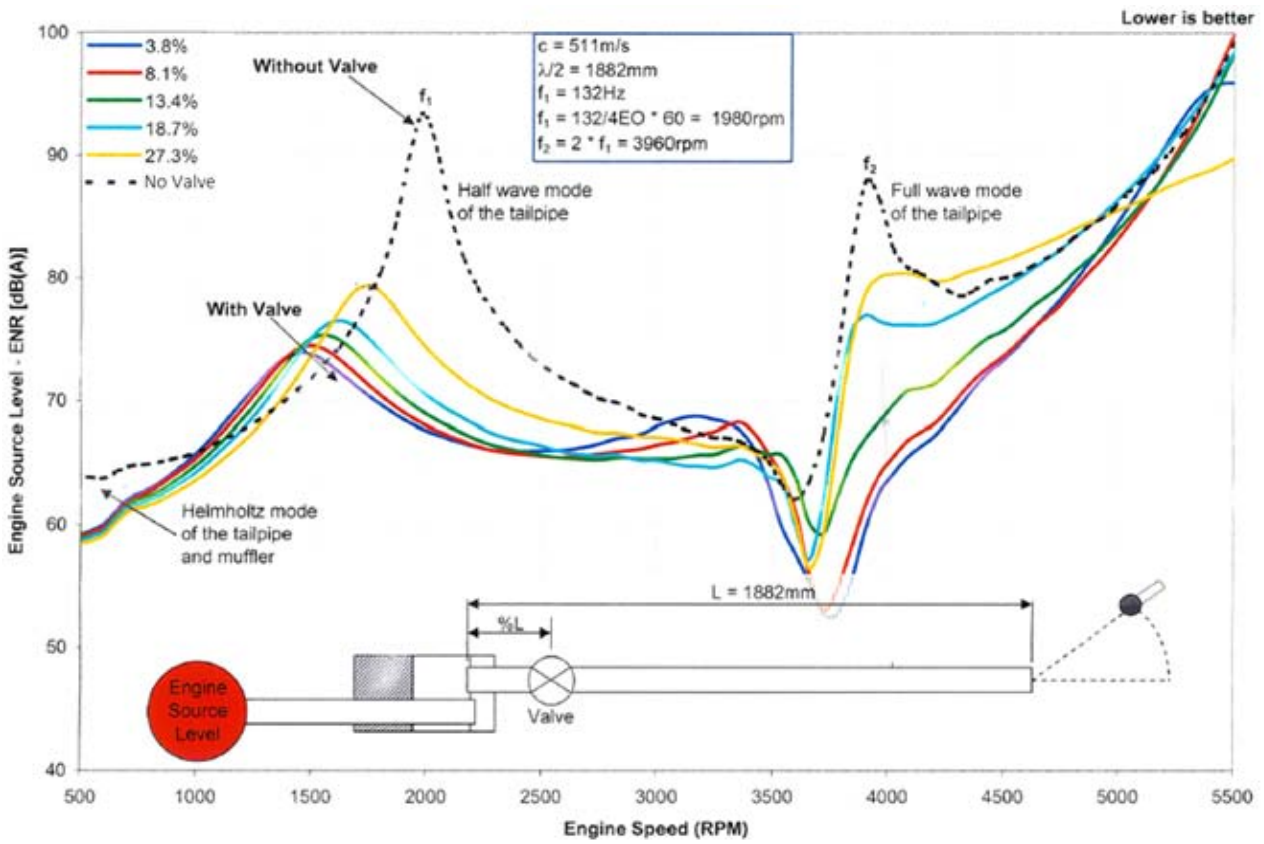


Fig. 8 Implementation of Adaptive Valve™ along an exhaust system.

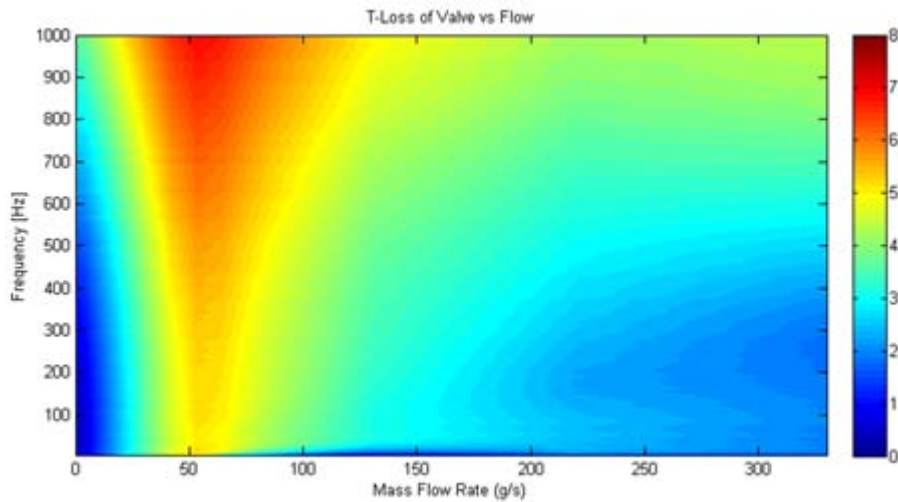


Fig. 9 Transmission loss for an Adaptive Valve™.

pipe—especially for the first standing wave—because the rear muffler is not a great acoustic impedance at these frequencies. The first standing wave occurs at around 120 Hz. In order for a valve to suppress any standing waves it must not be located close to a particle velocity node for the acoustic mode. Fig. 8

shows the influence of the valve position on the tailpipe noise for a system similar to the one shown in Fig. 7. A broadband source was used as a noise source rather than an engine model. With no valve (black dashed line), the half wave (f_1) and full wave (f_2) acoustic standing wave resonances are clearly visible

at 132 and 264 Hz. With an Adaptive Valve™ located 27.3% along the length of the pipe the f1 resonance is much better suppressed than the f2 resonance. As the valve is moved closer towards an open end of the pipe (in this case, the inlet end), the suppression of the half wave resonance becomes a little better, whilst the suppression of the full wave is significantly better. The majority of the improvement is realized by the time the valve is located at ~15% along the length of the pipe.

The TL (transmission loss) of an Adaptive Valve™ vs. mass flow is shown in the colormap in Fig. 9. It can be observed that the TL increases from a minimum at low flow to a maximum (corresponding to the valve beginning to open) and then decreases as flow continues to increase and the valve continues to open. There are no resonances in the range 0 to 1,000 Hz though the valve is slightly (about 1.5 dB) more effective at 1,000 Hz than at 100 Hz.

2.3 In-Muffler Valve

The in-muffler valve is a passive valve whose design is based on dual-mode behavior approach. This component is intended to be implemented within the silencer internal layout (Fig. 10) and has been designed to withstand gas temperature observed at rear silencer location. In the following application example, implementation of the in-muffler valve on a single baffle internal layout will be discussed.

At low mass flow, a spring forces the valve to remain in closed position, thus generating significant pressure loss. At higher mass flow, as the force applied on the valve by the mass flow is higher than the force applied by the spring, the valve opens, lowering the pressure loss of the silencer. A typical example of this dual-mode behavior is shown in Fig. 11.

The pressure loss measurements of a fully passive silencer, without valve and 80 $\text{Ø}3.5$ holes on the baffle, are compared to those of a silencer with first-generation valve, where holes number has been reduced to 50 $\text{Ø}3.5$ holes. At low mass flow, the valve remains closed and pressure loss evolution over mass

flow is the same as the one of the silencer without valve and 80 holes of the baffle. When mass flow passing through the valve generates a higher torque than the spring torque, valve starts to open. Silencer with valve shows then a significantly lower back-pressure than the fully passive silencer without valve. Recently, a second generation of in-muffler valve has been developed. Fig. 12 shows both generations of valves.

From a design point of view, main evolution is the replacement of the coil spring by 2 leaf springs. Comparison of pressure loss performance for both valve generations is shown in Fig. 11. In the low mass flow range, before the valve starts to open, the second-generation valve enables to generate as much as 50% more back-pressure than the first-generation

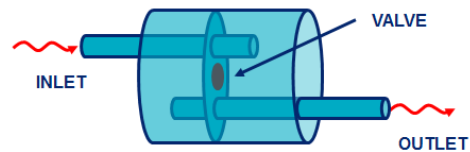


Fig. 10 Silencer with single-baffle internal layout.

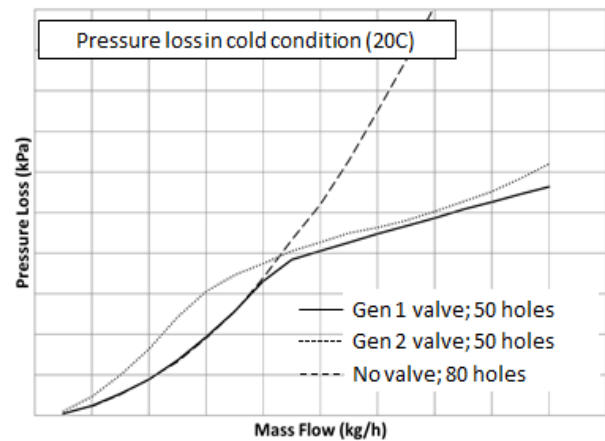


Fig. 11 Pressure loss in cold conditions of 3 silencers.

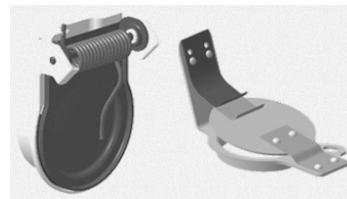
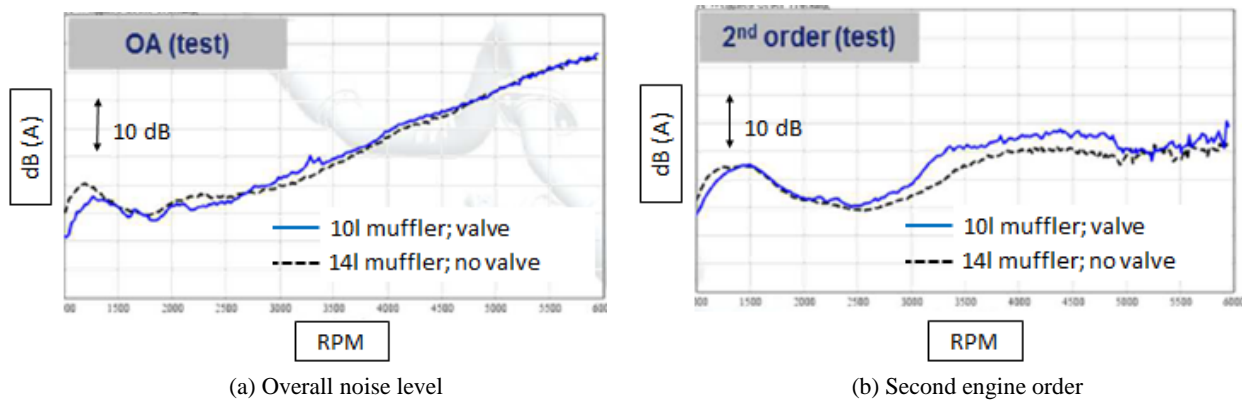


Fig. 12 Two generations of in-muffler valve; Left: first generation, Right: second generation.



(a) Overall noise level

(b) Second engine order

Fig. 13 4-Cylinder engine with in-muffler valve application.

valve. This enables to increase the acoustic attenuation of the silencer. In the high mass flow range, as the valve starts to open, pressure loss increase of the second-generation valve is significantly reduced.

2.3.1 Application Example of In-Muffler Valve

The design of an exhaust system could benefit from in-muffler valve properties in 2 different manners:

- Implementing in-muffler valve without reducing silencer volume enables to increase noise attenuation in low RPM range with a limited impact on back-pressure at nominal RPM
- Implementing in-muffler valve and reducing silencer volume at the same time enables to keep unchanged the noise attenuation in low RPM range with a limited impact on back-pressure. This is presented in Fig. 13.

In comparison to the fully passive 14-liter silencer without valve, the 10-liter silencer with valve shows same overall noise level over the whole PRM range. Acoustic performance for the second engine in the low RPM range remains unchanged. Only complete system back-pressure at nominal RPM has been slightly increased.

3. Conclusions

The previous chapters presented and discussed are different application examples of 3 types of valves. It has been shown that valves can be used to decrease order noise levels by keeping similar backpressure levels. This damping effect can also be used in order to

reduce silencer volume. For the electric valve application a reduction from 18l to 13l with improved NVH behavior has been presented. Overall the biggest benefits of all three valves for NVH can be shown using an electric actuated valve, but at the same time the effort of application and the costs of such a valve is higher than of a self-actuated valve. All valves are well suited to create a comfort sound or volume reduction. With a smart application especially the electric valve can also be used to create a sporty sound. Due to upcoming legislation changes more and more valves will be seen in the future on the market.

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