# Design of an active exhaust attenuating valve for internal combustion engines.

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**Abstract**

*A two stage procedure is proposed to design an active exhaust attenuator based on a valve concept. First, a global model containing an engine with a linearized active exhaust system is simulated. Secondly, the resulting flow from the engine is applied to a detailed non-linear valve model. All the important parameters to construct the active exhaust can be extracted from these simulations.*

# Introduction

The reduction of noise emission is an important issue in car development. The attenuation of exhaust noise using passive systems results in voluminous or high restrictive silencers. Active systems can attenuate the exhaust noise less restrictive with smaller volumes, particularly for the lower frequencies (below 200 Hz). A lot of academic research has been carried out, and the technology is now under investigation at several exhaust manufacturers (KEBA, Ricardo, Faurecia, Bosal, etc...). The two different technologies under investigation are loudspeakers and valve systems.

The proposed approach in this paper is the combination of an electrically controlled valve and a buffer volume. The valve concept has much higher efficiency as a loudspeaker concept, particularly at very low engine revolutions. Basically, the engine behaves as a volume velocity source. The combusted gas is swept out the cylinder by the piston. These flow pulses charge the buffer volume. The control valve, directly connected to the buffer volume, controls the flow from the buffer volume to the atmosphere such that only the mean flow is passed. This flow is free of fluctuations and consequently free of noise.

The purpose of the presented simulation models is to develop the actuator for the silencer, to create a prototype.

# Global analog circuit.

The global model is represented as an electrical analog circuit, as illustrated in figure 1. The left part is the engine model. The four capacitors represent the four engine cylinders, who's volume varies sinusoidal between maximum and dead volume. The combustion is simulated by charging the capacitor by a pulsing current source parallel over the capacitor. The upper set of switch-resistors represent the intake valves, the lower set the exhaust valves. The switches are actuated in the same sequence as the camshaft actuates the engine valves. The intake side is connected to a voltage source $U_B$ representing the atmospheric pressure. The right part represents the active exhaust system. The silencer is connected to the engine via the duct represented by the transmission line $T$. The capacitor $C$ represents the buffer volume and the variable resistor $R(t)$ the control valve. The transmission line $T_t$ represents the tailpipe. The resistor-inductor combination $R_a$-$L_a$ corresponds to the free air impedance. In simulation, a collocated feedback controller regulates the control valve using the pressure signal behind the valve. In practice, other control strategies need to be applied to handle the time delay between the valve action and its effect in the error sensor.

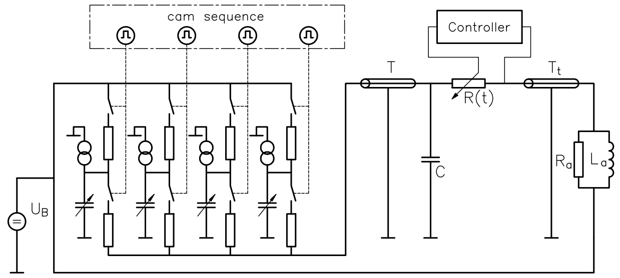


**Figure 1:** Electrical analog model of an engine equipped with the active exhaust system.

The simulation results are displayed in figures 2 and 3. In figure 2(left), an engine indicator diagram is presented. This diagram has no direct physical significance, because it is an isothermal simulation. Only the remaining pressure at the exhaust valve opening time point is deterministic for the exhaust noise. In figure 2(right), the pressure in the tailpipe is presented. The controller is activated at 0.2 s.

Figure 3(left) represents the gas flow from the engine exhaust to the active silencer. The gas flow will be used as input data for the detailed active exhaust model.

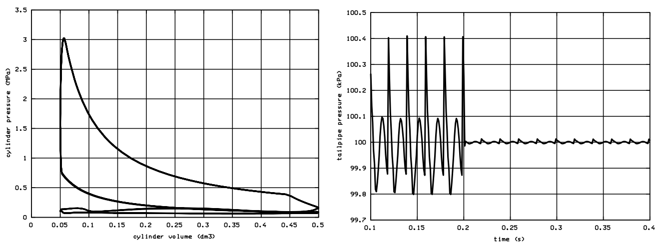

**Figure 2:** *left:* Simulated indicator diagram. *right:* Tailpipe pressure. Control starts at 0.2 s.

During this simulation stage, the back pressure to the engine, the exhaust system resistance. etc... are investigated to optimize the active exhaust system configuration.

# Active exhaust system circuit.

Once an optimal configuration is found, the control valve itself has to be developed. The electrical analog circuit, displayed in figure 4, embeds the necessary elements how to construct the control valve. The control valve consists

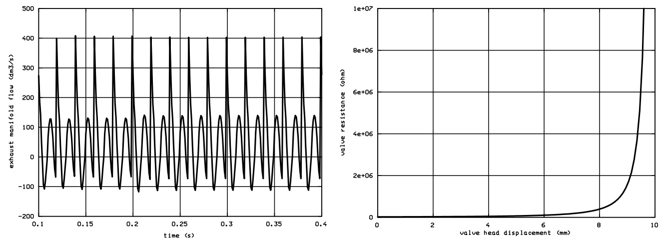

**Figure 3:** *left:* Gas flow through the exhaust manifold. *right:* Control valve flow resistance as function of valve head displacement.

of a conical valve head which regulates an orifice opening. The valve head is driven by a voice coil in a permanent magnet. The voice coil resistance is displayed in the electrical part. The magnet assembly transforms the electrical current in mechanical force by the transformer $K_m$. The force acts on the valve head mass $m$ suspended on a spring $k$ with damping $d$. The resulting velocity $\dot{x}$ is integrated to obtain the valve head displacement $x$. The displacement is limited by $x_{\max}$, where the valve is completely closed. The gas pressure drop over the valve is a function of the valve head displacement and the flow through the valve. The valve resistance characteristic is displayed in figure 3(right). The pressure drop $\Delta p$ is generated by the voltage source $b$. The generated pressure acts also on the valve head. This force is coupled back to the mechanical circuit by the gyrator $S$, representing the valve orifice surface.

At the gas flow terminals of this circuit, the buffer volume capacitor and a volume velocity source, generating the disturbing gas flow presented in figure 3(left), is connected. At the electrical terminals, a collocated feedback controller is connected. The acoustic flow through the valve is used as error signal.

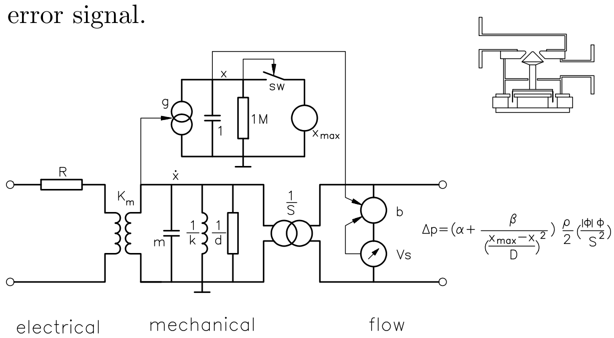


**Figure 4:** Electrical analog model for the voice coil driven control valve.

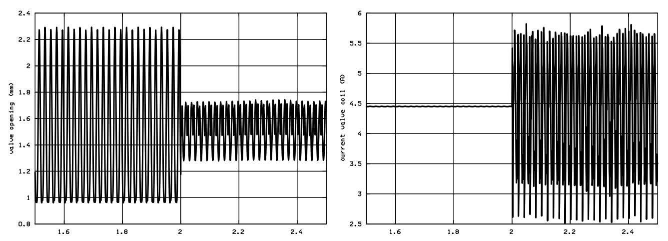

**Figure 5:** *left:* Valve head displacement. The control starts at 2 s. *right:* Current through the control valve voice coil.

From these simulation results, the mechanical dimensions of the control valve can be determined. Figure 5(left) presents the valve head displacement. The controller starts at 2 s. The displacement of the valve head under control remains below 0.5 mm around a mean opening of 1.5 mm. The voice coil stroke and optimal position is a direct consequence of the valve displacement. The electrical current to drive the voice coil is displayed in figure 5(right). This current depends on the drive magnet, the moving mass and the displacement. The DC-current can be adjusted by pretensioning the suspension spring of the valve head. For this valve, the DC-current is 4.5 A, the AC-current is 1.5 A RMS. This results in 90 W total power, wherein 80 W is needed to position the valve against the backpressure in the exhaust system. The resulting attenuation of the flow pulsation through the tailpipe is presented in figure 6(left).

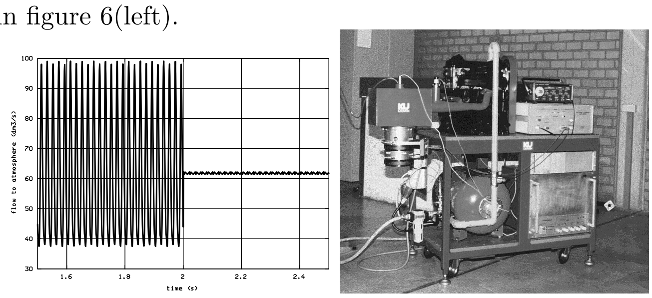

**Figure 6:** *left:* Attenuation of the gas flow pulsation in the tailpipe. *right:* Active exhaust system experiments on a cold engine simulator.

The design method is evaluated experimentally on an active exhaust system builded on a cold engine simulator [1], presented in figure 6(right). In this setup, a feedback controller is applied. The resulting tailpipe pressure is displayed in figure 7(left). The noise reduction outside the tail pipe amounts 10 to 15 dB (3 to 5 dBA). Figure 7(right) shows that the noise attenuation performance in terms of the backpressure does not alter until the backpressure drops below a critical value. The backpresurre can be minimized in terms of the engine regime.

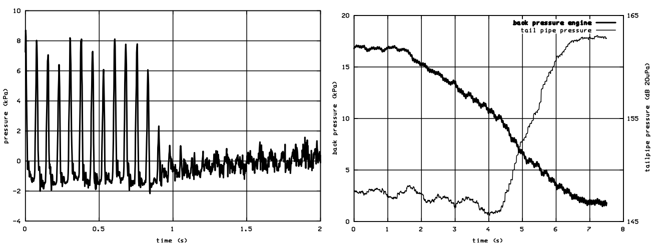

**Figure 7:** *left:* Pressure attenuation in the tailpipe. *right:* Tail-pipe RMS-pressure while the engine backpressure drops from 17 kPa until 2 kPa.

# Conclusion.

An active exhaust system actuator can be dimensioned using electrical analog circuits. In the global circuit, the active exhaust system can be optimized. This simulation provides the necessary data for the simulation model wherein the actual control valve itself is developed. From these simulation results, a prototype active exhaust can be generated.

# References

[1] René Boonen, Paul Sas, Design of an active exhaust attenuating valve for internal combustion engines, proc. of the ISMA2002 conference, Leuven, Belgium, **1** (2002), 33-42 (*also available at* `www.isma-isaac.be`)