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.

1 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 manufactures (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 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.

2 Global analog circuit.

The global model is represented as an electrical analog circuit [1], 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 and the resistor-inductor combination, corresponding with the free air impedance, closes the circuit. In simulation, a collocated feedback controller conducts the control valve. In practice, other control strategies must be applied to handle the time delay between the valve action and its effect in the error sensor.

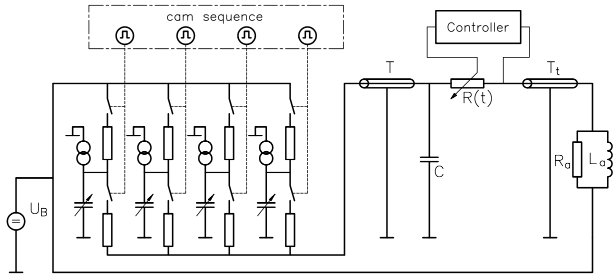
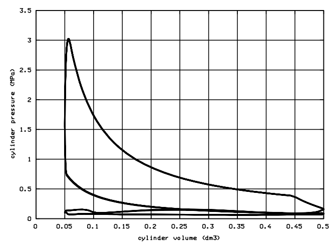


figure 1: Electrical analog model of engine equipped with the active exhaust system.

The simulation results are displayed in figures 2 and 3. In figure 2L(eft), an engine indicator diagram is presented. This diagram has no 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 2R(ight), the pressure in the tailpipe is presented. The controller is activated at 0.2 s.



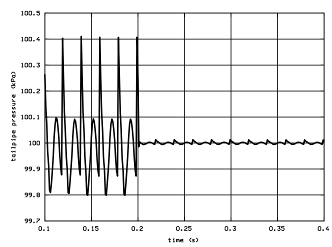
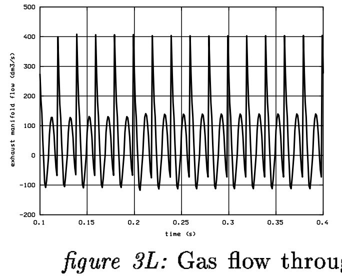


figure 2L: Simulated indicator diagram.
figure 2R: Tailpipe pressure. Control starts at 0.2 s.

Figure 3L represents the gas flow from the engine exhaust to the active silencer. This flow will be decomposed in its fourier components, presented in figure 3R. These components will be used as input data for the detailed active exhaust model.



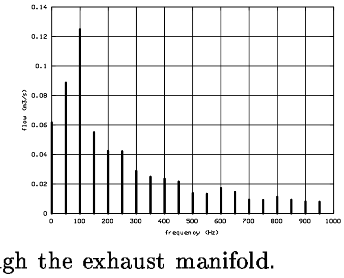


figure 3L: Gas flow through the exhaust manifold.
figure 3R: Fourier components of the gas flow.

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

3 Active exhaust system circuit.

When an optimal configuration is found, the control valve itself has to be developed. The electrical analog circuit, displayed in figure 4, contains the necessary elements how to construct the control valve. The control valve consists of a conical valve head which closes an orifice. The valve head is driven by a voice coil in a permanent magnet. The voice coil resistance is displayed at the left 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 function of the valve head displacement and the flow through the valve. The pressure drop Δp is generated by the voltage source b. The function to determine the pressure drop [2] is displayed in figure 5L. The generated pressure acts also on the valve head. This force is coupled 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 set of volume velocity sources, generating the disturbing gas flow, is connected. This gas flow is composed by the fourier components, obtained from the global circuit simulation, presented in figure 3R. At the electrical terminals, a collocated feedback controller is connected. The acoustic flow through the valve is used as error sensor.

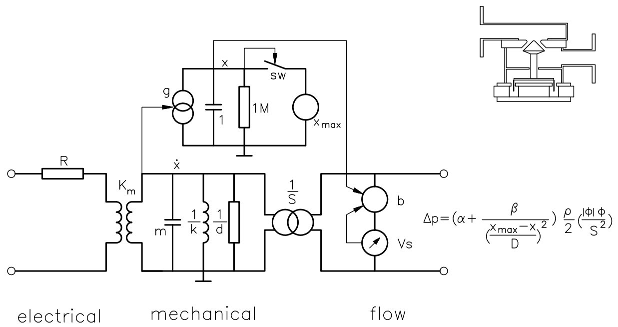
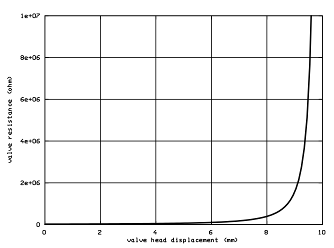


figure 4: Electrical analog model for the voice coil driven control valve.



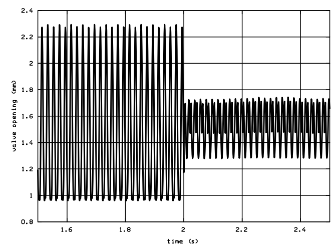
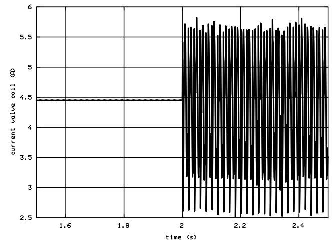


figure 5L: Control valve flow resistance as function of valve head displacement.
figure 5R: Valve head displacement. The control starts at 2 s.

From these simulation results, the mechanical dimensions of the control valve can be determined. Figure 5R 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 6L. 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 6R.



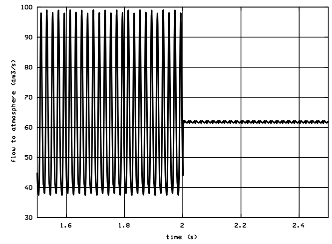
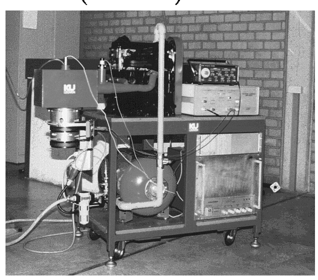


figure 6L: Current through the control valve voice coil. *figure 6R:* Attenuation of the gas flow pulsation in the tailpipe.

The design method is evaluated experimentally on an active exhaust system builded on a cold engine simulator [3,4], presented in figure 7L. In this setup, a feedback controller is applied. The resulting tailpipe pressure is displayed in figure 7R. The noise reduction outside the duct amounts 4 dBA (10 dBL) for a four cylinder engine at 400 rpm.



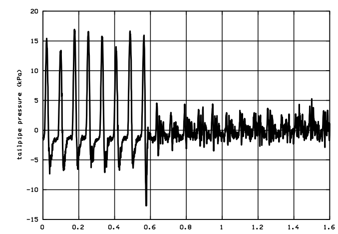


figure 7L: Active exhaust system experiments on a cold engine simulator. *figure 7R:* Pressure attenuation in the tailpipe.

4 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] Beranek L. L. "*Acoustics*", McGraw-Hill, 1954

[2] Idel'cik I.E. "*Memento des pertes de charge*", Editions Eyrolles, 1986

[3] Boonen R, Sas P, "*Development of a cold engine simulator for acoustic and fluid-dynamic experiments with exhaust systems of internal combustion engines.* ", Proc. of the Third European conference on Noise Control, Euronoise 98, Munich, 1998, Vol. II, 981-986

[4] Boonen R, Sas P, "*Development of an Active Exhaust Silencer for Internal Combustion Engines Using Feed Back Control*", SAE-paper 1999-01-1844