EXPERIMENTAL STUDY OF THE ACOUSTIC EFFECT OF MICROPORE MUFFLER ON PULSED JETS AND RING JETS

Ch He, H Rosenberg

University of Kaiserslautern, Institute of Fluid Dynamics, D-6750 Kaiserslautern Germany

1. INTRODUCTION

The exhaust noise of internal combustion engine is a kind of aerodynamical noise. In order to reduce the noise, different forms of muffler such as the expansion-chamber muffler, Helmholtz resonators and their different combinations have been investigated and applied in the past. All of them belong to the passive noise control. Another method is the noise source control, for example, the micropore muffler in the exhaust canal, which are often applied in the aviation industry and valve industry. The application of the micropore muffler for reduction of the exhaust noise of internal combustion engines has been studied over the last 10 years. But at the present time, neither theoretical prediction method of noise reduction nor satisfactory example for the application of micropore muffler have been reported in the literature.

Erhard et al[1] and Beck[2] studied experimentally for the honeycomb type muffler in the exhaust canal of type 1,3-S Opelmotor by steady flow with cold air. The results indicated that the exhaust noise was reduced 20 dB and the flow loss coefficient ratio was 3 ~ 10.

It is well known that the working fluid of internal combustion engine is released periodically, producing an intermittent or pulsed exhaust and that the flow through the exhaust valve is as through an ring valve. In reference to experiment from Erhard et al by "cold engine" this work will experimentally study the acoustic effect of micropore muffler on pulsed jets and ring jets in the laboratory, in order to facilitate the understanding of noise generation by unsteady flow and the possibility of the application of micropore muffler by internal combustion engines and other gas-powered devices such as air motors, pneumatic impact tools and control valves in automated production machines.

2. EXPERIMENTAL INSTALLATION

The experimental equipments are schematically represented in Fig. 1. The air current used in the experiment was supplied from centre compressor, flown into a reservoir tank (10 bar, 20 m^3), through a steel pipe (70 mm I.D., about 20 m length), a hose pipe (53 mm I.D., about 5 m length), a rotating valve simulator and a metallic pipe (60 mm I.D., 3 m length) to an opening in the middle of an anechoic chamber ($5.2 \times 2.83 \times 2.7$ m^3), on the opening horizontal convergent round nozzle (diameter D = 17.5 mm) and ring nozzle (D = 17.5 mm d = 12.5 mm) were mounted respectively. Different sizes of muffler were fitted on the nozzles. The stagnation pressure of flow and hence the jet velocity and density were adjusted by varying the control valves. The pressure before the nozzles (stagnation pressure) p_2 vary from 1 through

3.5 bar (absolute). The jet velocity were from 120 m/s to sonic. The volumen flow rate were within 0.004 ~ 0.020 m^3/s. The measurements were made with constant volume flow rates Q and constant pressure ratios R ($R=p_2/p_3$) respectively.

The simulated exhaust flow was produced by periodically releasing high pressure air through a globe valve. The globe valve (globe diameter D_g = 73 mm, diameter of cylindrical passage globe d_c = 52 mm) was belt-driven from a variable speed motor giving a pulse frequency range of 0 to 66.5 Hz (E-motor speed n = 0 ~ 2000 [1/min]). Experiments show that the results were only slightly affected by the globe valve, and accordingly no measure was taken to reduce noise from the globe valve.

The micropore mufflers were made of metal braid of honeycomb type, which are applied in the aviation industry. In the experiments the micropore muffler with the edge lengths of b = 2.3, 4.0 mm and different lengths L = 20, 26, 34, 44, 50, 59 mm were tested. The size of micropore muffler were so selectet that the jet orifice were completely covered.

Sound pressure measurements were made with condenser microphone type Brüel & Kjaer 1/2" 4133. through a amplifier type Brüel & Kjaer 2609 and read on ROCKLAND system/90 signal analysis workstation. The microphone revolved around the nozzle every 15° from 30° to 165° to jet axis with a radius of 1 m in the horizontal plane containing the jet axis. The sound power level were calculated according to DIN 45635 with the ten readings. The narrow band. 1/3 octave-band spectra and overall sound pressure levels were taken. The microphone was calibrated with a pistonphone.

3. EXPERIMENTAL INVESTIGATION

The noise reduction by the muffler (l = 35 mm. a = 2.3 mm) with the volume flow rates is shown in Fig. 2. It is found that the sound power level can be reduced with mufflers up to 5 dB by the round nozzle and up to 16 dB by the ring nozzle.

Fig. 3 shows the affect of the muffler length on the noise reduction by constant pressure ratios. It is found that the optimal muffler length is between 2~3 time nozzler diameter (De = (D + d)/2) for the ring nozzle. For the round jet. however. there is no such an optimal muffler length. The longer the muffler is, the more noise reduction were obtained. It seems that there is connection between the optimal length of muffler and the potential-core length of the ring jets.

The affects of micropore mufflers on the frequency spectrum are shown in Fig. 4a and b. It is found that the sound pressure level difference are greater within higher frequency then within lower frequency.

There are a little difference for the overall sound pressure level (SPL)between the steady flow and unsteady flow in our experiment. Typical spectra for the pulsed jets are shown in Fig. 4c. d and a spectrum for a steady jet (simulator not rotating) is also included. There are two distinctive characteristics of the noise produced by the pulsed jet. At low frequencies the noise is composed of discrete tones at the pulse frequency and its harmonics. At high frequencies (1000 ~ 20000 Hz) the spectra show a broadband characteristic similar to that of a steady jet.

The distributions of overall SPL around the jet were determined for all supply pressure and for both round nozzle and ring nozzle. The quadrupole sources are the dominant sources of steady jet noise. The directivity paterns for the various frequency components show that the pulsed jet acts as simple monopole sources.

4. THEORETICAL ANALYSIS

Noise from Jet Turbulence. The main engineering predictions for the pure jet mixing noise can be summarized in the following formulae[3]:

$$I(r,\ \vartheta) = \frac{k \rho_m^2 U_j^8 D^2}{\rho_o a_o^5 r^2} \frac{D(\vartheta)}{(1 - M_c \cos\vartheta)^5} \qquad (1)$$

$$I(r,\ \vartheta,\ f) = \frac{k \rho_m^2 U_j^8 D^2}{\rho_o a_o^5 r^2} \frac{D(\vartheta)}{(1 - M_c \cos\vartheta)^5} F\left[\frac{fD}{U_j}(1 - M_c \cos\vartheta)\right] \qquad (2)$$

where I is the sound intensity W/m^2; ρ_o and ρ_m are the ambient density and source density, kg/m^3, respectivly; a_o is the ambient speed of sound, m/s; k a constant ($k = 0.3 \times 10^{-4} \sim 1.2 \times 10^{-4}$). U_j the jet velocity, m/s; D the jet diameter, m; r the distance from source to observer, m; $D(\vartheta) \approx 1$, the directivity factor; $M_c = 0.62\, U_j/a_o$ the convection Mach number based on a_o; f the frequency, Hz; ϑ the angle to downstream jet axis; F [...] is the spectrum function. Formula (1) and (2) are applicacable to subsonic and low supersonic jet.

To facilitate computations, the empirical relation for the power spectral density of turbulent jet was used:

$$\frac{1}{W}\frac{dW(x)}{dx} = \frac{4}{\pi}\frac{x^2}{(1 + x^2)^2} \qquad x = \frac{5 D_{ch} f}{M_{co}} \qquad (3)$$

where W is the total acoustic power radiated, x the Strouhal number of the jet flow, and dW(x)/dx the power spectral density with respect to unit Strouhal number. D_{ch} the characteristic length, $D_{ch} = D$ for round nozzles. From the relation for the sound power and the sound intensity, we obtain the sound spectral level $L_t(f)$:

$$L_t(f) = 10\lg\left[\frac{4}{\pi} \frac{\left(\frac{5D}{U_j}\frac{a}{a_o}\right)\left(\frac{5D}{U_j}\frac{a}{a_o} f_s\right)^2}{\left[1 + \left(\frac{5D}{U_j}\frac{a}{a_o} f_s\right)^2\right]^2} \frac{k \rho_m^2 U_j^8 D^2}{a_o^5 \rho_o r^2 I_o} \frac{D(\vartheta)}{(1 - M_c \cos\vartheta)^5}\right] \text{ dB} \qquad (4)$$

where a is the local sound velocity of the jet: $I_0 = 1 \times 10$ W/m , the reference sound power. The constant k ($k = 0.8 \times 10^{-4}$) was choiced to coincide with the experiment .

At 90° to the jet axis. equation (2) suggests that the level at a given Strouhal frequency (fD/U_j = constant) should vary as the eighth power of jet efflux velocity. At other angles, the effect of convection of the source towards the observer is to Doppler shift the source frequency f_s to generate an observed frequency:

$$f = \frac{f_s}{(1 - M_c \cos\vartheta)} \quad (4a)$$

and the level at given reduced frequencies: $(fD/U_j)(1 - M_c\cos\vartheta)$ = constant. should vary as $U_j^8(1 - M_c\cos\vartheta)^{-5}$

Fig. 5a and b show the comparison of the calculation with the measured frequency spectrum. The agreement between the calculation and the experiment is satisfactory.

Noise from Pulsating Air Volume of Exhaust. One calculation method for the pulsed jet was suggested by Li et al[4]. It is surmised that discrete frequency noise arises from pulsating air volume, and continuous spectrum noise arises from jet turbulence as each is independent and can be estimated separately.

The acoustic pressure p_m from a pulsating air volume and the exhaust flow rate Q are calculated with Li's method:

$$p_m = \frac{1}{4\pi r}\frac{\partial Q}{\partial t} \quad (5)$$

$$Q(\vartheta) = 236\, A(\vartheta)F(R) \quad \text{for the globe valve} \quad (6)$$

$$Q = \rho(\vartheta)AU(\vartheta) \quad \text{for the pulsed jets} \quad (6a)$$

F(R) is the function of pressure ratio. The density $\rho(\vartheta)$ and the velocity $U(\vartheta)$ were measured with the hot wire anemometer and numerically calculated with the unsteady method of characteristics. The time function of the exhaust area for our globe valve was calculated with the geometrical size.

The spectrum level from pulsed jet was calculated with linear sum of the pure turbulent jet noise and the noise from the pulsating air volume of exhaust.

Noise from the pulsed jets. The equation for the calculation of spectrum level from pulsed jet is:

$$L_p(f) = L_t(f) + L_m(f) = 10\lg(10^{L_m(f)/10} + 10^{L_t(f)/10}) \quad \text{dB} \quad (7)$$

The calculation of the total noise level in the reference [4] is in good agreement with the experiment. But the calculated spectra were 10 dB lower as the measured spectra. Fig. 5c and d show the calculated spectrum with eqs. (4), (5), (6) and (7) at exhaust frequency 66.5 Hz and chamber pressure ratio 1.6. Measured data are also given in the figure. A satisfactory coincident is found.

5. CONCLUSION

The honeycomb type muffler were mounted on the round nozzle and ring nozzle respectively. The noise from such microjets were measured. The noise were reduced about 5 dB by the round nozzle and about 16 dB by the ring nozzle. It seems that there is an optimal muffler length for the noise reduction by the ring nozzle.

The noise from the pulsed jets were measurd. The influence of the jet pulsation can be treated as the monopole source, its contribution to the overall noise level and the spectrum density can be calculated.

The honeycomb type muffler has the advantages of less flow loss, simple construction, effective noise reduction and are suitable to be used in the exhaust canal of internal combustion engine. More experiment with the real engine will be made to study the possibility of application of the honeycomb type muffler in the internal combustion engines.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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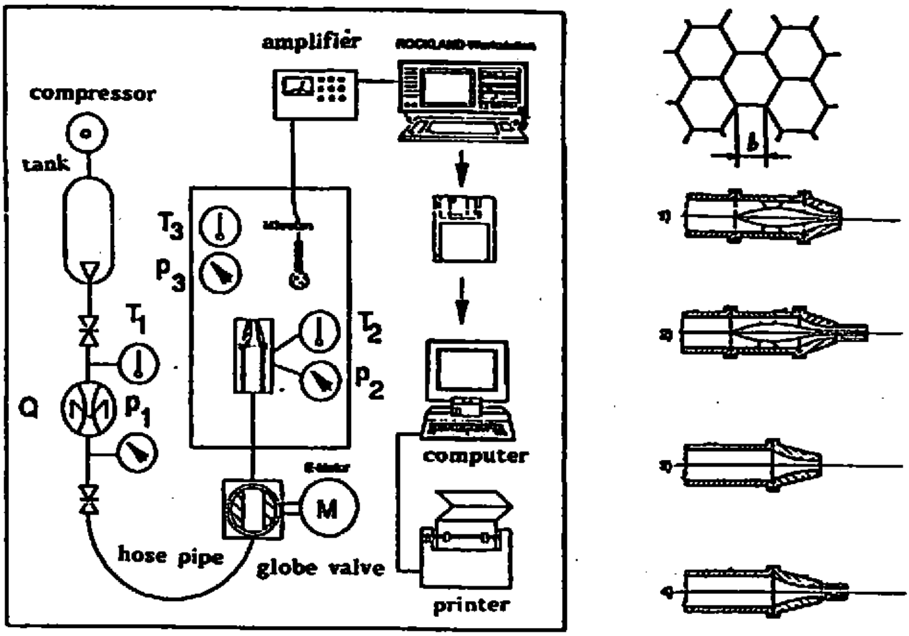

Fig. 1 Experimental equipments and nozzle with muffler

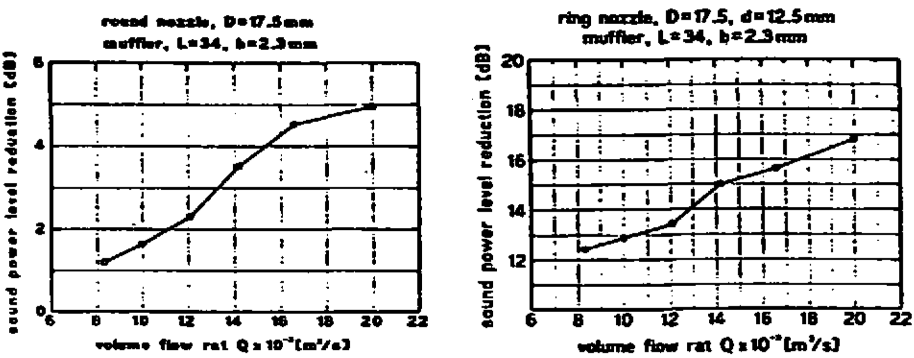

Fig. 2 Noise reduction with the volume flow rats

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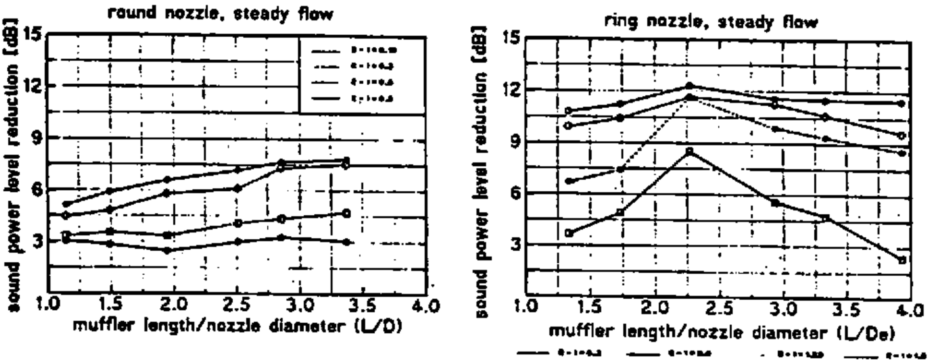

Fig. 3 Noise reduction with the muffler lengths

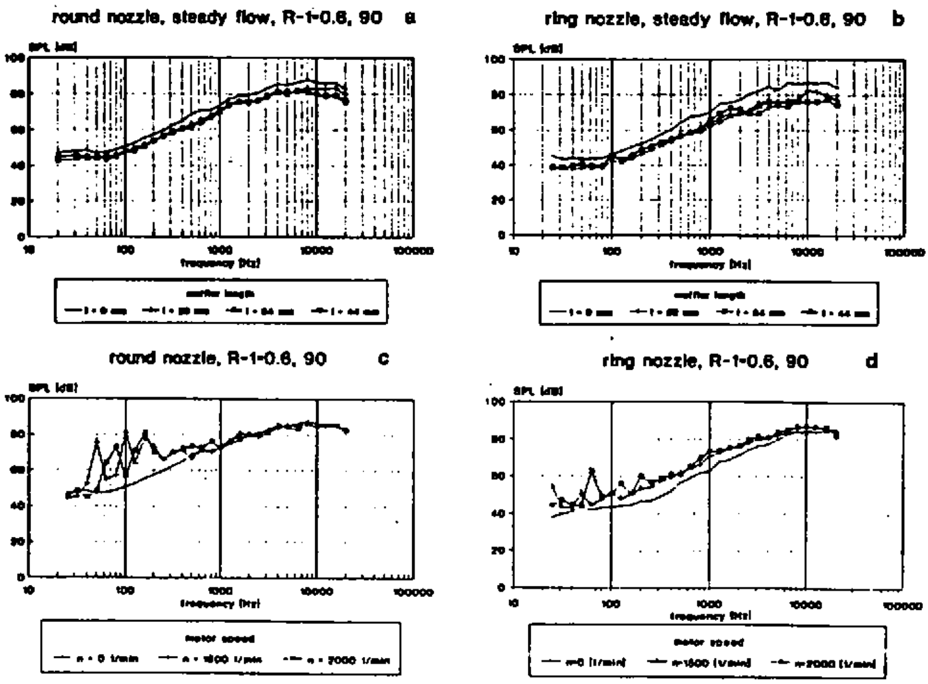

Fig. 4 Affects of mufflers and jet pulsation on the noise spectrum

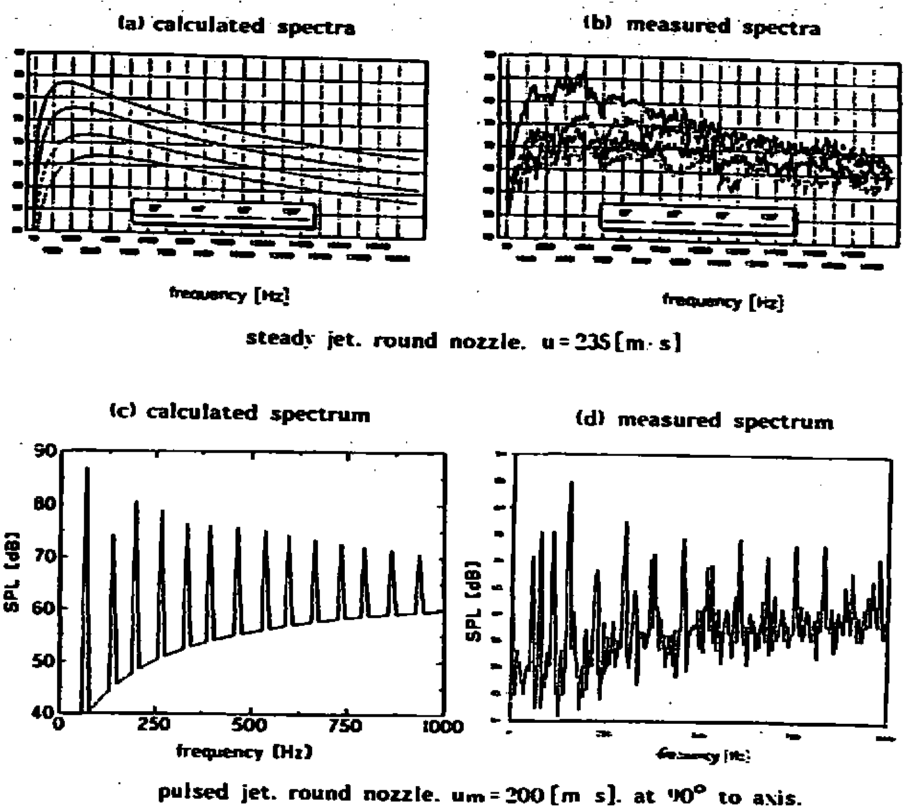

Fig. 5 comparison of calculated spectra and measured spectra