ON THE DESIGN OF A BROAD FREQUENCY BAND SOURCE FOR SCALE MODELLING OF SOUND PROPAGATION

K. V. Horoshenkov and D. C. Hothersall

Department of Civil Engineering, University of Bradford, Bradford, West Yorkshire England

1. INTRODUCTION

Scale model measurements of traffic noise as a cheap alternative to full scale experiment need to be provided with a source of sufficient acoustic energy throughout the desired spectrum extending to ultrasonic frequencies. Considering the physical aspects of the problem, one finds out that apart from the spectrum of sound energy radiated the source should satisfy the following requirements:

* omnidirectional emission;
* time stability of properties;
* lack of pertubations of the sound due to the air jet or screening by elements of the construction of the source;
* if comparison is to be made with theoretical predictions the source should conform as far as possible to the characteristics assumed in the theory;
* ease of maintenance.

There are several types of source which have been applied for scale modelling [1,2]. The best practical implementation has been achieved by using a pneumatic source, the so-called ultrasonic whistle. This has been found is to be a cheap source which is stable in time and represents a reasonable scaled replica of a vehicle on a road [1,2,4].

This paper describes an ultrasonic whistle having improved characteristics to already known types, developed to carry out scale model measurements of traffic noise levels on urban streets as an experimental part of the project on noise control in urban areas.

2. THE DESIGN

The simulation of a vehicle on a road, which in the theoretical assumptions is considered to be a monopole above the ground (0.5 m for a car and 1.0 m for a lorry) can be implemented by using a source having the acoustic energy output over the scaled spectrum corresponding to the spectrum produced by a real vehicle and elevated at the scaled height. The convenient scaling of the model is 1:20. The frequency span of major interest in the investigation of road traffic noise is from 100-4000 Hz, which after scaling transforms to a model source range from 2 kHz to 80 kHz. Such distribution of acoustic energy basically over ultrasonic frequencies can be created by using an air-jet outlet with a diameter chosen according to the following equality [3]

$$d = \lambda/M, \qquad (1)$$

where λ is the wavelength of the central frequency in the spectrum and M is Mach number.

The main disadvantage of an air-jet source is the jet itself, which introduces a strong influence on the conditions of propagation of sound. The other problem is brought about by generation of sound along the outcoming stream of air, rather than in the general vicinity of the outlet, and non-linear effects. These facts do not allow the simple jet source to be considered as a point source of monopole type.

The first trial design of the source (Figure 1) had a circular chamber (3) to avoid the strong air stream which would issue from a simple air-jet outlet. Air blown through inlet (1) and openings (2) generated sound inside the chamber. The generated sound was radiated through the open space on the top of the chamber [4].

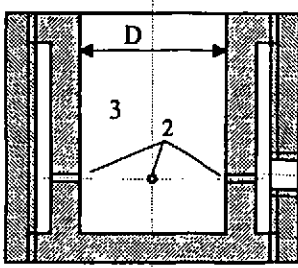

Figure 1. The trial design of the source.

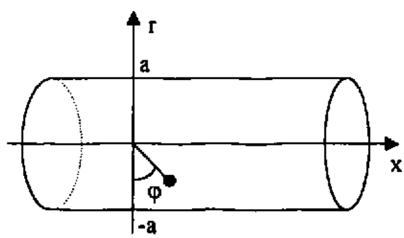

Figure 2. Waveguide with cylindrical cross-section.

The chamber of the first whistle had 10 mm diameter and 20 mm depth. It had four openings (2) having 1 mm diameter each. The idea was to check out the behaviour, characteristics, and output of such kind of radiator. The source did not have a strong upwards air stream due to the considerable diameter of the chamber and small size of the openings, though it did create turbulence around chamber's entrance. The acoustic energy output over the required frequency band was limited (Figure 3), which shows 1/3 octave sound pressure levels over the range.

The second design was based on a theoretical model of the chamber as a cylindrical waveguide of finite length. It was decided to limit the first cut-off frequency of radial oscillations of the waveguide to 20 kHz to allow the energy of oscillations to be concentrated basically in the ultrasonic band. Audio band oscillations were assumed to be generated by longitudinal resonances of the bounded waveguide.

For a cylindrical waveguide (Figure 2) Helholtz's equation is written as

$$\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial r^2}+\frac{1}{r}\frac{\partial P}{\partial r}+\frac{1}{r^2}\frac{\partial^2 P}{\partial \varphi^2}+k^2 P=0. \qquad (2)$$

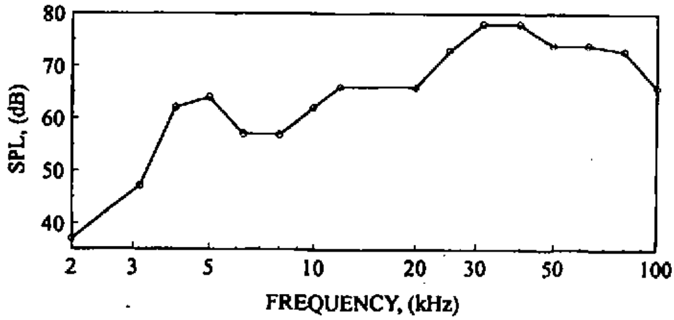

Figure 3. Spectrum of the output of 10mm whistle measured on the axis at 1m. Air pressure 5.8 atm.

We will try to find the solution in the following form

$$P(x,r,\varphi) = R(r)\Phi(\varphi)\exp(\xi x). \tag{3}$$

Substituting (3) into (2) we obtain

$$\ddot{R}\Phi + \frac{1}{r}\dot{R}\Phi + \frac{1}{r^2}R\ddot{\Phi} + (k^2 - \xi^2)R\Phi = 0. \tag{4}$$

Multiplying (4) by $(R\Phi)^{-1}$ and assuming periodic behaviour of Φ

$$r^2\{\frac{\ddot{R}}{R} + \frac{1}{r}\frac{\dot{R}}{R} + (k^2 - \xi^2)\} = -\frac{\ddot{\Phi}}{\Phi} = m^2. \tag{5}$$

To provide a periodic dependence of the function with period 2π m should be an integer. Equation (5) gives

$$\ddot{\Phi} + m^2\Phi = 0, \tag{6}$$

and

$$\ddot{R} + \frac{1}{r}\dot{R} + (k^2 - \xi^2 - \frac{m^2}{r^2})R = 0. \tag{7}$$

The boundary condition for the rigid walls is

$$\left(\frac{\partial R}{\partial r}\right)_{r=a} = 0. \tag{8}$$

ON THE DESIGN OF A SOURCE FOR SCALE MODELLING

Solution of the equation (7) is represented by function $J_m(\vartheta r)$, where $\vartheta = (k^2 - \xi^2)^{1/2}$ and eigenvalues ϑ_n can be obtained from (8). Setting m = 0 and assuming that the walls are absolutely rigid, the waveguide has a zeroth mode, which is characterized by $\vartheta_n = 0$, so, as a result, there is equal energy distribution over the cross-section, and non-dispersive propagation. The common solution for an arbitrary m is written as

$$P_m(x, r, \varphi) = J_m(\vartheta r)\cos(m\varphi)\exp(i\sqrt{k^2 - \xi^2}\, x). \tag{9}$$

Setting m = 0 we obtain the dispersion equation for the eigenvalues

$$\frac{\partial}{\partial r}(J_0(\vartheta r))_{r=a} = -J_1(\vartheta a) = 0. \tag{10}$$

The first cut-off frequency is required to be f_1^R = 20 kHz. The first zero of $J_1(x)$ rather than x = 0 is x_1 = 3.85..., which gives the required radius of the chamber by putting $\vartheta_1 = k$ and $\xi = 0$:

$$a = x_1 \frac{c_0}{2\pi f_1^R} \cong 0.01m.$$

As already mentioned, such a waveguide has a zeroth mode which represents just the case of oscillations inside a bounded pipe of small ($\lambda >> a$) cross-section. Having one end of the pipe closed by an absolutely rigid lid and open at the other, we know that the set of cut-off frequencies correspond to normal oscillations along a pipe and can thus be determined from the following equation

$$k_n = (2n - 1)\frac{\pi}{2L},$$

where L is the length of the pipe (chamber). Setting $k_n = k$ and the first cut-off frequency f_1^L = 2000 Hz we find

$$L = \frac{c_0}{4 f_1^L} \cong 0.04m.$$

So, from this discussion the optimum dimensions of the chamber are R_c = 1 cm and L_c = 4 cm.

A different situation appears when we try to find the right diameter of the opening, d. Equation (1) gives d ~ 2 cm for the wavelength at 40 kHz and M = 2.5, which is estimated from Bernoulli's equation. Such a big hole is unrealistic as a massive air flow would result. So, we decided to reduce the diameter to 2 mm, which enabled a stable air supply to be obtained at 4 atm from a HYDROVANE general use compressor.

A whistle of the same shape as that shown in Figure 1 was constructed, but with the dimensions given from the calculations. In spite of considerable variation in the value of d from that predicted by formula (1), the whistle provided an appropriate output of acoustical energy throughout the required band (Figure 4).

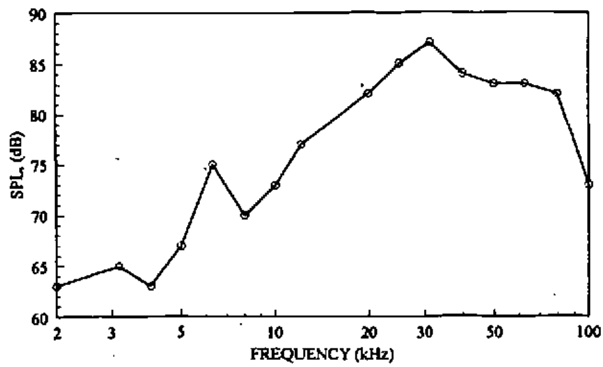

Figure 4. Spectrum of the output of 20mm whistle measured on the axis at 1m. Air presure 4.25 atm.

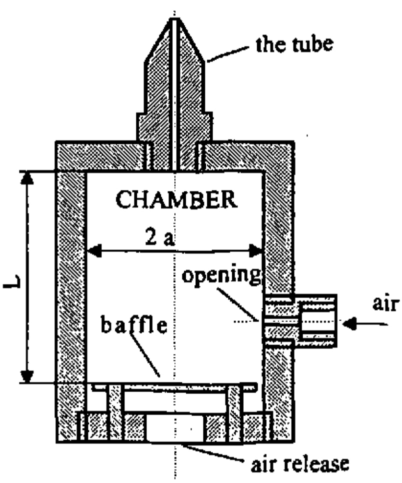

Figure 5. Final design of the ultrasonic whistle.

The main disadvantages of this source were the presence of a strong air stream coming upwards and the large dimension of the effective radiating area. The large radiating area meant that the source was a poor approximation of a monopole radiator, especially at high frequencies, when the source was elevated above the ground.

To correct the problem we made a few modifications in the design. The first was a hole in the bottom of the whistle (Figure 5), which served as an air release. The second was the solid top with a tube in the centre along which the sound energy generated inside the chamber propagated. The third modification was an acoustically rigid baffle in the vicinity of the bottom. It was smaller than chamber's diameter and designed to reflect sound, but allow air to escape through the gap between the baffle and the wall. The hole in the bottom was made much bigger than the diameter of the tube on the top to allow sufficient amount of air to escape downwards from the chamber rather than upwards through the pipe with acoustic energy.

This last design showed good characteristics despite a considerably reduced area of sound radiation in comparison with the previous one. The diameter of the tube was chosen as 2 mm (half of the maximum wavelength of the interest) to provide an appropriate radiation pattern up to this frequency. To simulate a car and lorry pipes of 25 and 50 mm were manufactured.

Measurements of the spectrum and radiation pattern have been carried out for the mentioned lengths of the tube both for the source flush with a plane surface (baffled) (Figures 6 and 7) and in the absence of any obstacles (Figures 8 and 9). Figure 10 shows 1/3 octave spectrum for a number of angles taken from the main axis of the baffled whistle equipped with a 25 mm tube. Apart from the 2000-4000 Hz band the source provided a miminum signal to noise ratio of 20 dB in the anechoic chamber. This low emission at low frequencies can be explained by the rather small diameter of the tube which does not satisfy the radiation conditions for low-frequency oscillations.

Due to the considerably reduced air stream coming upwards with sound through the tube it was possible to achieve an approximate omnidirectional radiation pattern practically over the whole required spectrum, which enables us to classify the source as one of monopole type.

3. CONCLUSIONS

A design methodology has been developed for an air-jet source for acoustic modelling. The characteristics of the final design indicate that the source is appropriate for the requirements for modelling of noise propagation from a monopole isotropic source, which enables us to develop a simple theoretical simulation of the experimental conditions.

4. REFERENCES

1. J. Novak, "Sound source for scale model measurements of traffic noise." *Applied Acoustics* **24** (1988) 63-70.

2. G. S. Anderson, "Acoustic scale modelling of roadway traffic noise: A literature review," *Bolt Beranek and Newman Inc.*, September 1978, Cambridge, MA 02138.

3. A. P. Dowling and J. E. Ffowcs Williams, "Sound and sources of sound", *Ellis Horwood Limited*, Chichester, 1983.

4. Rapin, J. M. and B. Favre, "Community noise evaluation by model studies," *Internoise '77 Proceedings*, 1977, pp. A52-A59.

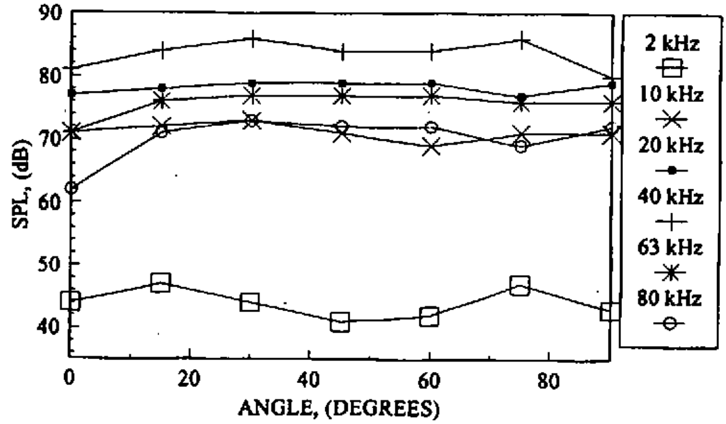

Figure 6. Angular-frequency dependence of the output of the source of final design, which has been baffled and equiped with 25mm pipe, taken at 1m. Air pressure 4 atm.

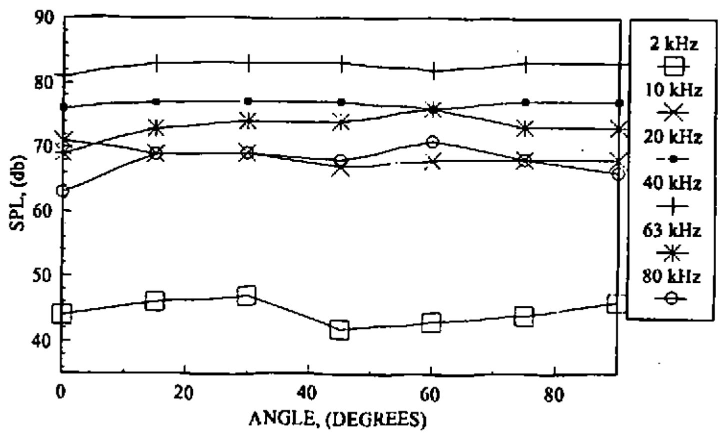

Figure 7. Angular-frequency dependence of the output of the source of final design, which has been baffled and equiped with 50mm pipe, taken at 1m. Air pressure 4 atm.

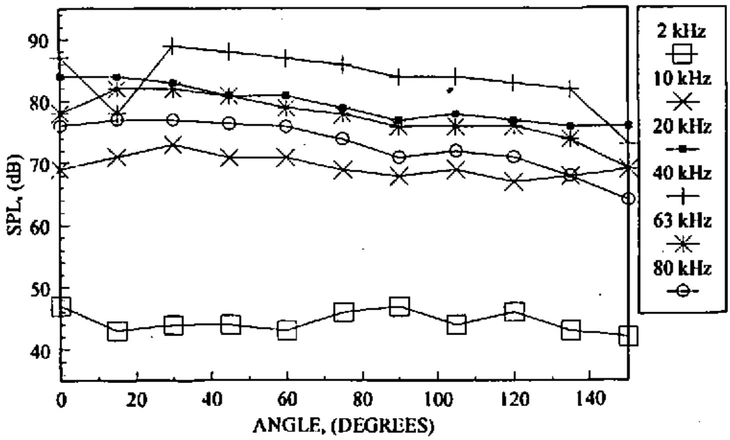

Figure 8. Angular-frequency dependence of the output of the source of final design, which has been equiped with 25mm pipe, taken at 0.5m. Air pressure 4 atm.

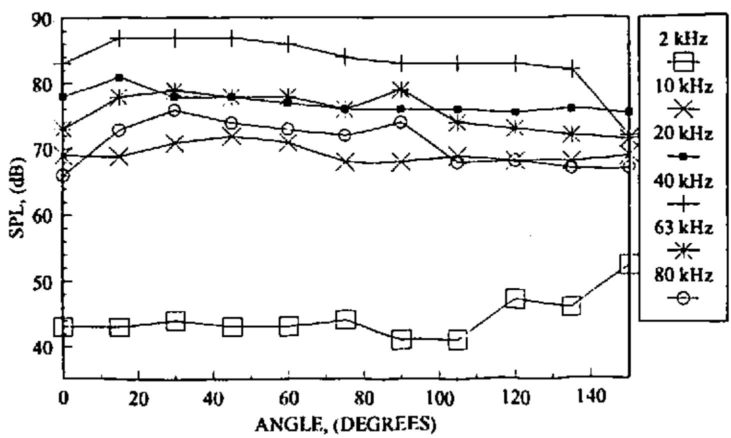

Figure 9. Angular-frequency dependence of the output of the source of final design, which has been equiped with 50mm pipe, taken at 0.5m. Air pressure 4 atm.

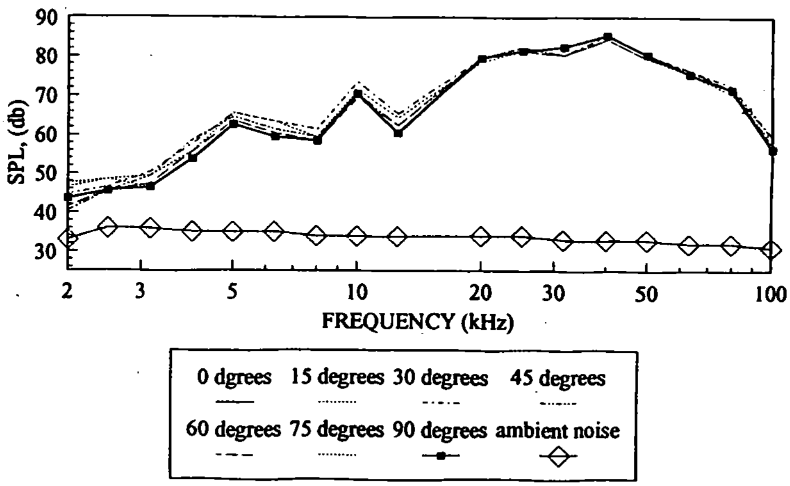

Figure 10. Angular dependence of the spectrum produced by the source of the final design, which has been baffled and equiped with 25mm pipe, taken at 1m. Air pressure 4 atm.