Acoustics 2008
Geelong, Victoria, Australia 24 to 26 November 2008

Acoustics and Sustainability:

How should acoustics adapt to meet future demands?

Directivity of Sound from an Open Ended Duct

Athol Day, Brian Bennett

Day Design Pty Ltd, Peakhurst, NSW

Abstract

This paper discusses the directional properties of sound emitted from the open end of a ventilation duct. When designing a duct silencer to reduce noise from a vertical discharge duct, it is useful to note that the first 10 to 15 dBA noise reduction may result from directivity losses at 90 degrees and can be accurately predicted. On two occasions in 1971, sound directivity tests were conducted by the author with 300 and 600 mm diameter ducts and the results made into a rough chart of Duct Directivity Losses that ultimately found its way into the EPA Environmental Noise Control Manual (5 June 1985, page 207.1).

Over the last 13 years further sound directivity testing has been undertaken on ducts of 305, 400, 610, 915 and 1220 mm diameter and re-analysed to produced a more useful Duct Directivity Chart. The directivity data has been related to the sound power level of noise emitted from the duct and the spherical dispersion of sound energy. While Strouhal numbers have been used to correlate the test data, the Duct Directivity Chart allows the directivity gain or loss to be obtained for any diameter from 100 mm to 10 metres, at angles from zero to 135 degrees without the need for complex calculations.

INTRODUCTION

This paper summarises the results of duct directivity testing with sufficient mathematical analysis to ensure an accurate method of predicting the Directivity Index (D.I.) of duct noise emission in most routine engineering applications.

A rough chart for calculating the Directivity Loss of an open-ended duct was prepared for Vokes Australia Pty Ltd in 1971 by the author. This chart was a simple attempt to correlate the levels in line with the end of the duct with those at various angles around the duct up to 135 degrees. These were not Directivity Indices that would accurately relate to the sound power emission from a duct, but has proved useful in that it is widely used in NSW, having found its way in a modified form in the EPA Environmental Noise Control Manual – page 207.1 dated 5 June 1985.

To maintain a correct balance of sound energy emission from a duct, there must be both gains and reductions. If there is a sound pressure reduction at a particular angle, then there must be sound pressure gain at a different angle to compensate. The Vokes chart shows only losses, hence it is not considered a proper Directivity Chart. The Directivity Chart Figure 9.25 in the text book by Bies and Hansson 1996 was based on research by Sutton inside an anechoic chamber and is valid in principle since it shows both gains and losses. The research was conducted with small tubes and employed acoustic modelling techniques to extrapolate data for larger duct sizes.

Knowing the weaknesses of the original Vokes chart, Day Design and the AAS (to Day Design) have sponsored a number of duct directivity testing programs with various individuals over a total period of 13 years. The testing included a number of larger size ducts, which are commonly found in industry.

The authors are pleased to present the graphic results in Figure 9 of this paper.

DUCT DIRECTIVITY MEASUREMENTS

Measurements were conducted using Type 1 precision sound instrumentation including CEL 593 and B&K 2260 sound level meters. All instruments used in this study had been laboratory-calibrated to national standards within the preceding two years and field-calibrated on the occasion of each sound survey.

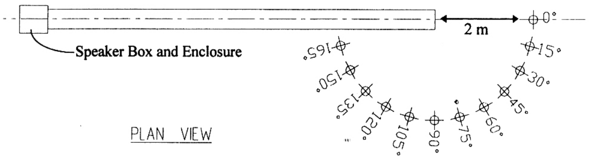
All staff employed in this study were experienced acoustical engineers, supervised by myself or other senior professional staff at Day Design Pty Ltd, consulting acoustical engineers.

Directivity Testing by Mr Murray Neish

In 1995, Murray Neish conducted sound directivity tests with 400 and 1220 mm diameter ducts [Neish 1997]. Flanking sound proved to be a significant problem at angles in excess of 90 degrees, so the 1220 diameter duct measurements were made with greater care, including a blocked end test to quantify worst case flanking transmission. The original third-octave sound data has been re-processed, related to Strouhal numbers and is reported herein.

One end of the eight metre long 400 mm diameter spiral wound steel duct was mounted on a children's climbing structure (at a nearby school) and the other end on scaffolding (as shown in Figure 2) with a centre height of 2.6 metres. The open end of the duct was located above mown grass to reduce sound reflections from the ground. A three-way loudspeaker was located inside an 18 mm particle board enclosure. Gaps between the duct and loudspeaker enclosure were sealed with plasticine.

In each sound directivity test, broadband pink noise was played through the loudspeaker and sound from the open end of the duct was measured (in third octave bands) at 15 degree intervals around the open end from 0 to 165 degrees.



Source: Murray Neish
Figure 1. Duct Directivity Test Angles

Source: Murray Neish
Figure 2. 400 mm duct testing

Measurements were made at a distance of 2 metres from the end of the 400 mm diameter duct in a horizontal plane in line with the centre of the duct. Several sets of readings were made and compensation made for background noise where necessary at the lower frequencies.

Eight sets of measurements were made at 15 degree intervals from 0 to 165 degrees around the open end of the 1220 mm diameter duct, in a horizontal plane level with the centre of the duct at a distance of 3 metres from the centre of the duct termination as shown in Figure 1.

The twelve metre long, 1.2 mm thick, 1220 mm diameter spiral wound steel duct was mounted on scaffolding with a centre height of approximately 2.4 metres. Once again, Murray conducted the directivity testing over mown grass to reduce any reflection from the ground. A powerful JBL loudspeaker was placed inside the duct near the blocked end. The end blocking was comprised of two discs of 18 mm particle board with glasswool insulation and a 100 mm airgap between them. The blocked end was semi-anechoic lined with 100 mm thick (32 kg/m^3) glasswool to reduce organ piping inside the duct.

The duct was draped with damp carpet to minimise flanking transmission as shown in Figure 3. The open end of the duct was then blocked and the sound measurements at 3 metres repeated to quantify worst case flanking sound transmission. All measurements at 3 metres were then adjusted for flanking noise contribution. The results were considered accurate.

Measurements were also made at 6 metres, but there were no measurements made for flanking and the results were found suspect and were discarded.

The presence of flanking sound can easily be detected in the measured data. As the angle of directivity increases, a small but significant sound reduction may be expected. Where the sound level increases with increasing angle, flanking sound must be present. Sound readings that increased with increasing angle were rejected.

Source: Murray Neish
Figure 3. 1220 mm duct - wrapped with carpet

Directivity Testing by Mr Daniel Potente

In 2006, further duct directivity tests were conducted by Daniel Potente using 305 mm, 610 mm and 915 mm diameter ducts [Potente, Gauld, Day 2006). The results of these tests are reported herein. Test set-ups with loaded-vinyl wrapping of ducts to minimise flanking are shown in Figures 4, 5 & 6.

The 305 and 610 mm diameter spiral wound steel ducts were supported with the centreline 2.7 metres above ground. The loudspeaker was located within an 18 mm particle board enclosure for the 305 and 610 mm diameter ducts.

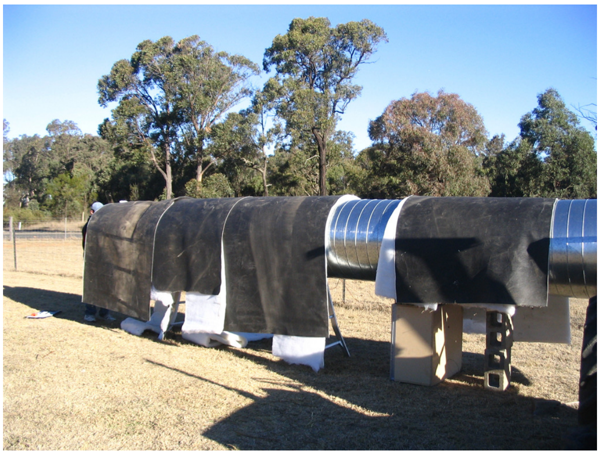
Source: Daniel Potente
Figure 4. 305 mm duct - loaded vinyl wrapped

The 305 mm diameter duct was 3 metres long, with measurements made at 1 metre and 3 metres from the open end of the duct. Flanking noise was apparent at angles in excess of 105 degrees, particularly for the 3 metre radius readings, which approached close to the loudspeaker enclosure.

Source: Daniel Potente
Figure 5. 600 mm duct - loaded vinyl wrapped

The ducts and speaker enclosures were wrapped in 75 mm polyester insulation (8.7 kg/m^3) and covered with loaded vinyl (8 kg/m^2) as shown in the photographs to minimise flanking sound transmission. In each sound directivity test, broadband pink noise was played through the loudspeaker and measured in third octave bands at 15 degree intervals around the open end from 0 to 165 degrees.

The 610 mm diameter duct was tested in both 3 metre and 6 metre lengths, with measurements made at 2 metres and 4 metres radii from the centre of the open end. Flanking noise was again noticed at the larger angles and the affected measurements were rejected.



Source: Daniel Potente
Figure 6. 915 mm duct - loaded vinyl wrapped

The 915 mm duct was tested in both 4.8 and 7.8 metre lengths, with measurements made at 3 metre and 6 metre radii. Flanking noise was again noticeable at high angles as the measurement location approached the speaker box. Some measurements made at higher angles had to be rejected from the analysis because they were affected by flanking noise.

The centreline of the 915 mm duct was 1.4 metres above ground level as shown in Figure 6. The loudspeaker for the 910 mm diameter duct tests was located inside the duct and the end was blanked off with an 18 mm particle board plug.

DIRECTIVITY INDEX CALCULATIONS

Most ventilation ducts are small compared to the distances at which their noise emission is of interest, so they may be assumed to be point sources. Noise from a point source is omni-directional and radiates sound energy in a spherical manner. We have observed that noise emission from the open end of a duct also radiates in a spherical manner, but tends to be directed in a direct line from the open end. Our measurements show that the larger the duct diameter and the higher the sound frequency, the greater the directivity effect.

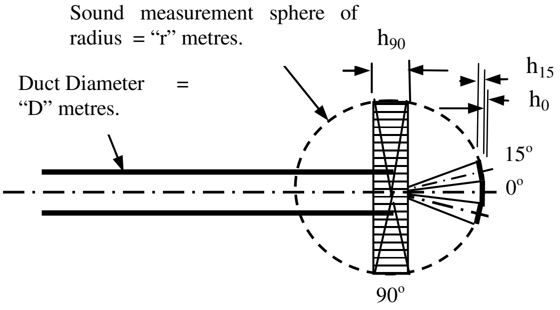


Figure 7. Diagram of Sound Radiation from an Open Ended Duct

In the above Figure 7 it can be seen that the area of the sound measurement sphere subtended by the 0 or 15 degree angle is significantly less than the area of sphere subtended by the 90 degree angle.

The Duct Directivity Index is the difference in decibels between the sound pressure of an omni-directional noise source and that from the open end of a duct. The surface area of a sphere is $4 \pi r^2$ where r is the radius of the sphere. The annular surface area of a sector of a sphere is $2 \pi r h$, where h is the height of the sector at that directivity angle.

The sound power emitted from a duct at a certain angle is equal to the sound intensity multiplied by the radiation area of that segment and may be quantified as follows.

$$L_w = L_p + 10 \log 2 \pi r h$$

The total sound power level of the source is the sum of the individual measured sound power levels of all the segments from 0 to 180 degrees.

For an omni-directional sound source, the L_p at any specific distance will be the same all around the sphere. The mean omni-directional $L_p = L_w - 10 \log$ (area of sphere)

$$= L_w - 10 \log (4 \pi r^2)$$

The Directivity Index in any particular direction is the difference between the measured sound pressure level and the mean L_p from an omni-direction sound source.

When plotted against the Strouhal Number, Directivity Indices were found to follow the curves in Figure 9. The Strouhal Number (Str) is a dimensionless number that relates the frequency (f) and duct diameter (D) and the speed of sound (c) as follows:

$$Str = f D / c$$

COMMENTARY

The Directivity Index was measured with five different diameter ducts, of lengths ranging from 3 metres to 12 metres and found that a common directivity pattern prevailed. Directivity was not significantly influenced by duct length.

Since the 90 degrees directivity will be of greater interest, we have presented, in Figure 8, a typical graph of raw D.I. results for the five duct sizes at 90 degrees.

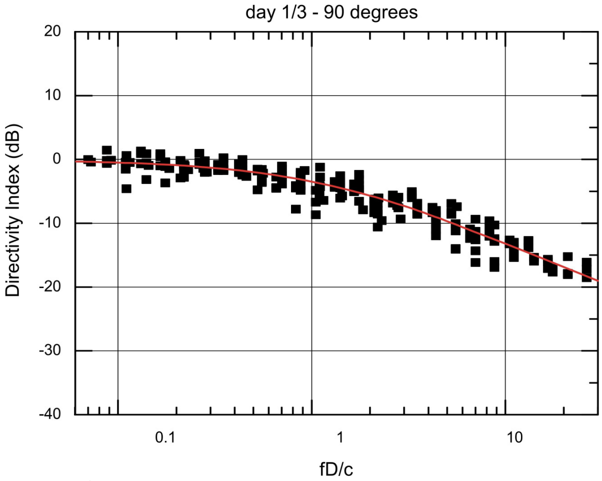


Figure 8. Scatter of raw D.I. data at 90 degrees**.**

The title "day 1/3 – 90 degrees" of the above graph identifies sound level data as being measured in 1/3 octave bands at an angle of 90 degrees (for the five different duct diameters).

The main reason for directivity of sound from an open-ended duct is plane wave propagation. A plane wave suffers no loss of energy due to spherical radiation. Because there are no lateral restraints, plane pressure waves gradually turn into spherical waves after they exit the duct. The larger the duct diameter, the greater the tendency for sound pressure waves to remain planar and therefore directional.

Part of the reason for the scatter of results in Figure 8 is simple experimental error. D.I. variations are typically ± 1 dB at the small Strouhal Numbers, increasing to ± 4 dB at the higher Strouhal Numbers. The smaller scatter of data about the trendline at the low Strouhal numbers indicates the level of experimental error is about ± 1 dB. There is no reason why the experimental error would increase with the Strouhal Number, so we may assume that there must be another reason for the larger scatter at the higher Strouhal Numbers.

Inside a wave-guide such as a ventilation-duct there is a strong tendency for transverse waves (cross modes) to cancel and plane waves to form. Plane waves conduct sound energy without radiation losses. Below a cut-off frequency where the wave length is significantly greater than the duct width, plane waves will always form. Above the cut-off frequency both plane waves and transverse waves can co-exist. The cause of the D.I. variations is probably resonant transverse waves.

The Strouhal Number is proportional to the duct diameter, so a wider scatter of results occurring as the Strouhal number increases, supports the assumption that variations are caused by resonant transverse waves.

DIRECTIVITY INDEX PREDICTION

The following chart is based on the directivity data measured in the above-described five duct diameter tests.

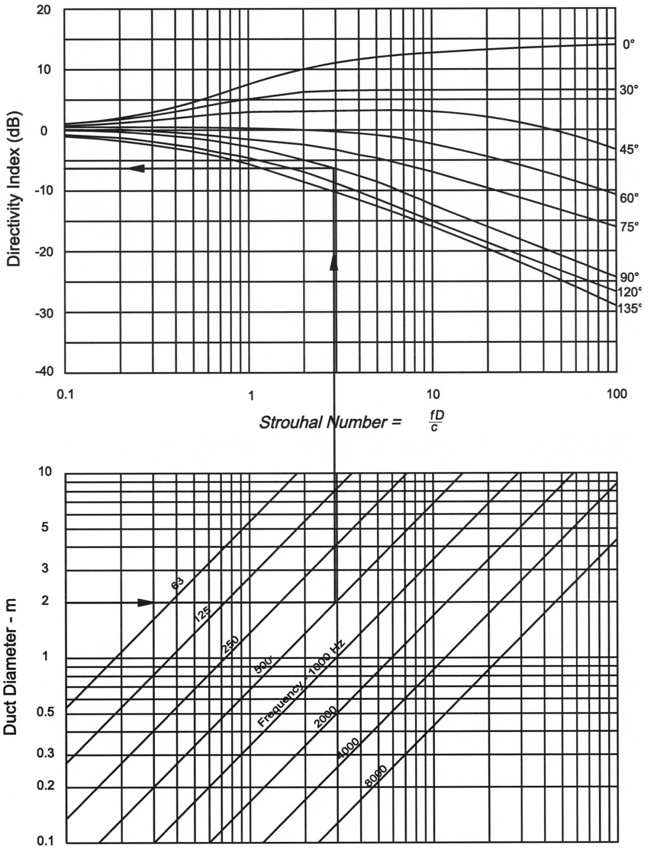


Figure 9. Duct Directivity Chart

When calculating the Directivity Index of an open ended duct, it is common practice to calculate the D.I. in octave bands and sum the resulting levels to predict the overall dBA level at the receptor. From Figure 9 we predict the following Directivity Indices at 90 degrees from a 2 metre diameter duct as follows in Table 1.

Table 1. Typical Predicted D.I.

Frequency – Hz	63	125	250	500	1k	2k	4k	8k
Strouhal No.	.37	.73	1.5	2.9	5.8	12	23	47
90 degree D.I.	1	2	4	6	9	13	17	21

Variations in the measured D.I. are both positive and negative at each octave bend. Therefore it is probable that for broadband noise, the variation from one octave band to the next will largely cancel and dBA predictions made in Table 1 would probably be within ± 2 dB. However, if the sound is comprised largely of a narrow band of frequencies, the accuracy of dBA prediction may be in the order of ± 4 dB. Predictions for smaller ducts would tend to be more accurate since the measured variations were less at the low Strouhal numbers.

CONCLUSION

The Directivity Index chart presented in Figure 9 is based on comprehensive testing by professional acoustical engineers using calibrated precision instrumentation.

Within the limits described in the above Commentary we commend this chart for general use by acousticians.

ACKNOWLEDGEMENTS

The work by both Murray Neish and Daniel Potente in organising and measuring the directivity of sound from a range of typical duct sizes is gratefully acknowledged. They used considerable initiative and acoustical skill in assembling all the necessary gear and conducting rigorous testing of sound directivity.

During the course of preparing this paper, extensive reference was made to Professor Colin Hansen of the Adelaide University and Associate Professor John Davy of the Royal Melbourne Institute of Technology. We cannot thank them enough for their scrutiny and comments on our measured results and Directivity Index calculations. They have both made in-depth and dedicated contributions to this work.

References

Bies DA & Hansen CH 1996, *Engineering Noise Control*, Book ISBN 0 419 20430 X, published by E & FN Spon, London, pp 395-398.

Neish, MJ 1997 *Predicting Sound Directivity at a Ventilation Duct Termination,* Final Year Project, School of Mechanical Engineering, University of Technology, Sydney.

Potente, D, Gauld, S, Day, A 2006 *Directivity Loss at a Duct Termination* Proceedings of Acoustics 2006, Noise of Progress, First Australasian Acoustical Societies Conference, Christchurch, NZ, November 20-22, edited by T. McMinn, ISBN: 978-0-909882-25-9, ISSN: 1446-0998, pages 283-289, publisher Australian Acoustical Society, Castlemaine.