DUCT DIRECTIVITY INDEX APPLICATIONS

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This paper concerns the application of a recently developed chart for determining the directional properties of sound emitted from the open end of a ventilation duct. When designing a duct silencer to reduce noise from a large vertical discharge duct, it is useful to note that the first 5 to 10 dBA noise reduction may result from directivity losses at

90 degrees and can be accurately predicted. In 1971 the first author conducted sound directivity tests with 300 and 600 mm diameter ducts and the results were made into a rough chart of Duct Directivity Losses that ultimately found its way into the NSW EPA Environmental Noise Control Manual (5 June 1985, page 207.1). It is wrong in principle and rather inaccurate, but some users are unaware of its failings.

Over the last 13 years further duct directivity testing has been conducted and a new duct directivity chart drawn. It is based on sound directivity testing on ducts of 305, 400, 610, 915 and 1220 mm diameter. The directivity data has been related to the sound power level of noise emitted from the duct and the spherical dispersion of sound energy. The new 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

In this paper the basic principles of duct directivity are explained in order to reveal the basic errors of earlier directivity charts and to provide practical engineering applications for the improved Duct Directivity Chart shown in Figure 2.

A rough chart for calculating the Directivity Loss of an open-ended duct was prepared by the first author for Vokes Australia Pty Ltd in 1971 (see Figure 3). This chart was a poor 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 of noise emitted from the open end of a duct. The first author modified it for the Department of Public Works in 1984 and this has found its way into the NSW EPA Environmental Noise Control Manual – page 207.1 dated 5 June 1985 (see Figure 4).

DUCT DIRECTIVITY INDEX (DI)

If the noise emission from a ventilation duct were equal in all directions, it would be "omnidirectional". If the duct diameter were small compared to the measurement distance, it could be considered to be a point source and the sound pressure level could be calculated from the known sound power level using:

$$L_p = L_w - 10 \text{ Log } S - A_E$$

where:

L_p is the sound pressure level - dB re: 20 µPa

L_w is the sound power level -   dB re: 1 pW

S is the area of the measurement surface in m^2

A_E is the excess attenuation (dB) due to the ground effect, other reflecting surfaces, air absorption, obstacles between the source and receiver and meteorological effects.
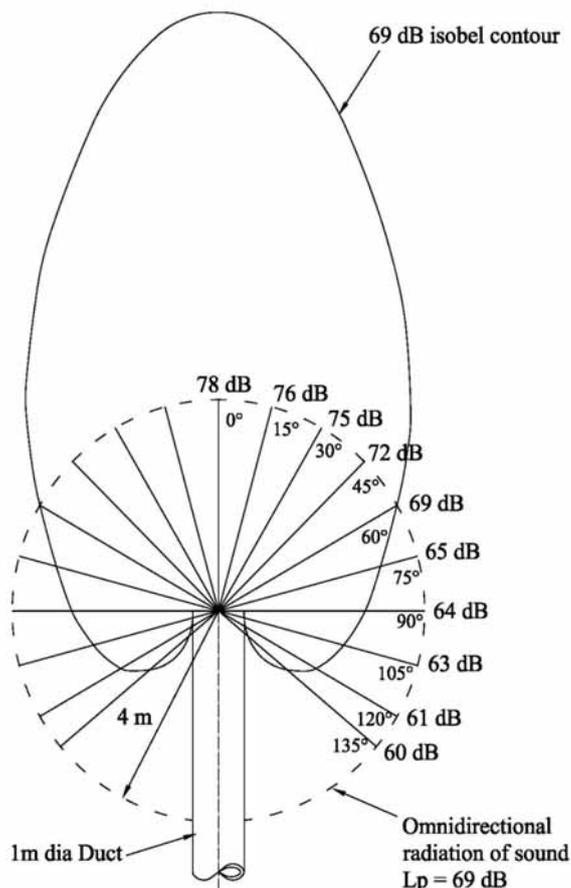

Figure 1. Typical Duct Directivity Isobel Plot

If the sound emitted from a duct termination with a sound power level of 92 dB at 500 Hz were omni-directional and if the excess attenuation were zero, the sound pressure level at 4 metres would be 69 dBA in a spherical pattern as shown in Figure 1. However, it has been established by rigorous testing

that noise emission from the end of a duct is quite directional. Using the Directivity Indices from Figure 2, the predicted sound pressure levels at a distance of 4 metres have been plotted. The 69 dB sound level Isobel curve is also shown.

If the noise emitted from the open the end of a duct is "directive", more of the sound energy goes in one direction than another. However, "directivity" does not affect the overall sound power level. If more noise is emitted along the axis of the duct, then less will be emitted in other directions. It can be seen in Figure 2 that for directions characterised by an angle from the duct axis of less than 60 degrees, the sound pressure levels are higher than the mean omni-directional sound pressure level and for angles greater than 60 degrees, the sound pressure levels are lower.

The Vokes chart shows only losses; hence it may not be considered to be an acceptable Directivity Chart. The Directivity Charts published by Bies and Hansen (2009), (Figures 9.29, 9.30 and 9.31) are all valid in principle since they all show both gains and losses. Figure 9.29 of the referenced textbook is based on research with small tubes and employed acoustic modelling techniques to extrapolate data for larger duct sizes. It may or may not be accurate. Also, Figure 9.30 in the text book is slightly different to Figure 2 below due to a small plotting error in the textbook figure. Figure 9.30 is based on directivity testing with a range of typical industry duct sizes by professional engineers and provides comparable but slightly more conservative results than the two other graphs in the textbook.
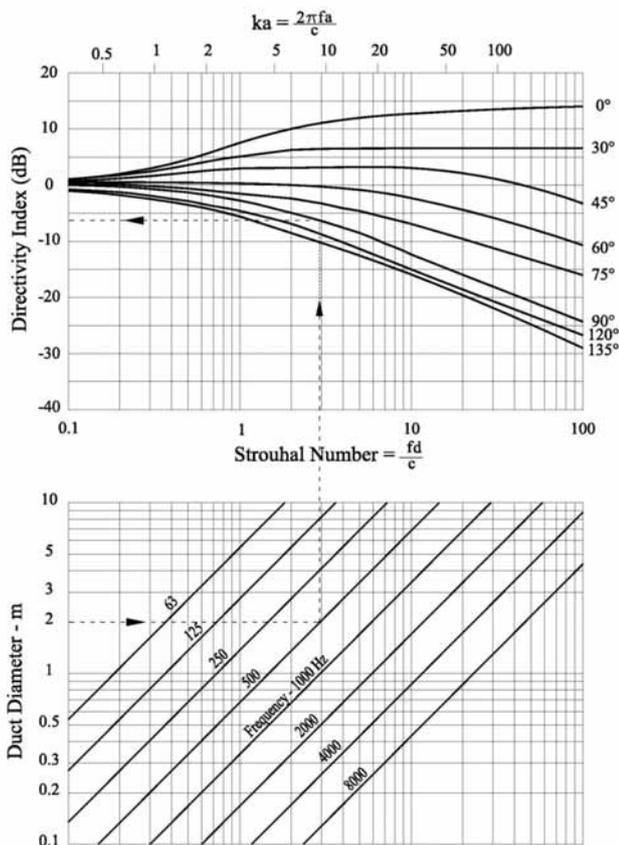
Example: By following the dotted lines in the Figure 2 chart, it can be seen that a 2 metre diameter duct has a 6 dB directivity loss in a direction at 90 degrees to the duct axis at a frequency of 500 Hz. At 4000 Hz the DI is -16 dB.

VOKES AUSTRALIA AND NSW EPA DUCT DIRECTIVITY CHARTS

The first author feels obliged to expose the errors of the older charts that he derived many years ago. These are presented below for reference purposes.
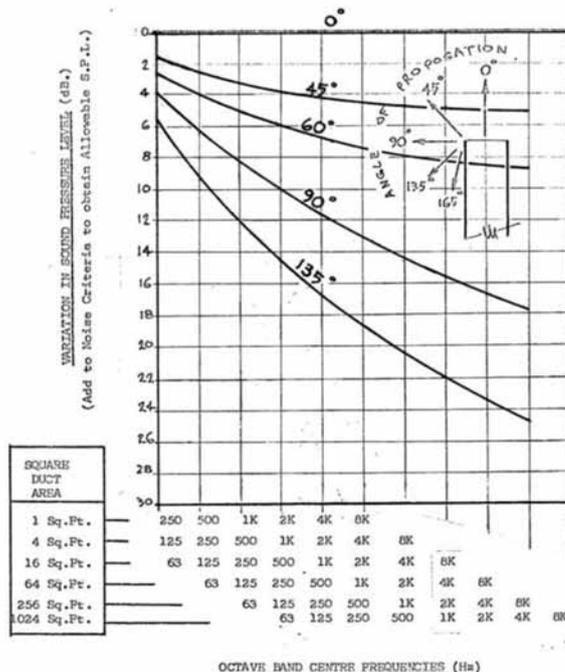

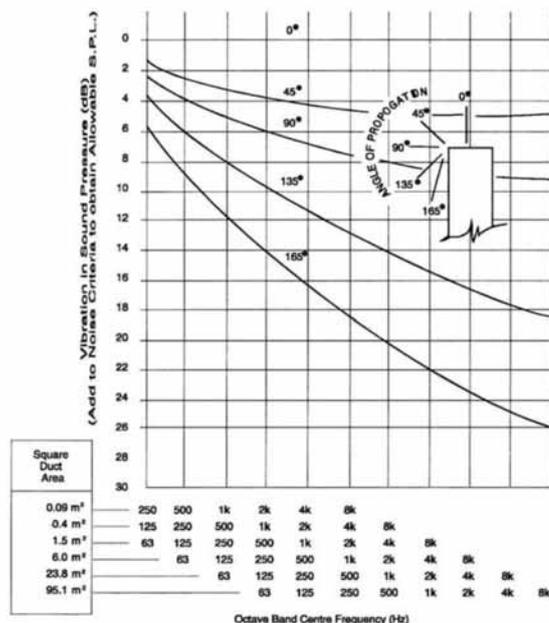Figure 3.   Vokes Australia – Duct Directivity Chart

Figure 2 Duct Directivity Chart

Figure 4. NSW EPA Duct Directivity Chart 1985

Figure 4 indicates that a 2 metre diameter duct with a cross sectional area of 3.14 m^2 has a directivity factor of 6.5 dB at 500 Hz and 90 degrees. At 4000 Hz the directivity loss is 8 dB. These differences are fortunately small. However at 0 degrees, Figure 2 shows an 11 dB gain while Figure 4 shows a 0 dB gain, which is a gross error.

DUCT DIRECTIVITY MEASUREMENTS

In 1995, sound directivity tests were undertaken for 400 and 1220 mm diameter ducts by Neish [5]. 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.

Source: Murray Neish
Figure 5 Murray Neish Testing a 400 mm Duct

In 2006, further duct directivity tests were undertaken using 305 mm, 610 mm and 915 mm diameter ducts [4].

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

DIRECTIVITY INDEX CALCULATIONS

The Duct DI of an open-ended duct is the difference in decibels between the sound pressure of an omni-directional noise source and that from the duct termination.

Most ventilation ducts are small compared to the distances at which their noise emission is of interest, so they are often assumed to be point sources. However, noise from a true point source is omni-directional and radiates sound energy in a spherical manner. It has been observed that noise emission from the open end of a duct radiates in a directional manner, tending to be higher along the duct axis. Measurements show that the larger the duct diameter and/or the higher the sound frequency, the greater is the directivity effect.
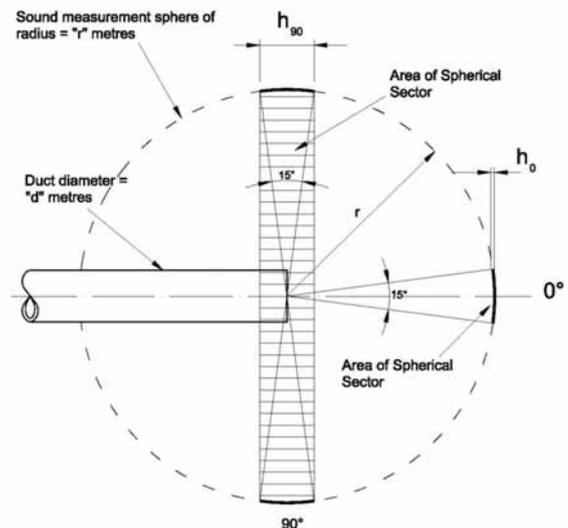

Figure 7. Diagram of Sound Radiation from an Open Ended Duct

In Figure 7 it can be seen that the area of the sound measurement sphere subtended by the 0 degree angle is significantly less than the area of sphere subtended by the 90 degree angle. 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 $2\pi rh$, where h is the height of the sector and where the centre of the sector corresponds to the particular directivity angle. The sound power emitted from a duct for each angular sector is equal to the average sound intensity for that sector multiplied by its radiation area and may be quantified as follows.

$$L_w = L_p + 10 \log (2\pi rh)$$

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

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

$$= L_w - 10 \log (4\pi r2)$$

The DI corresponding to any particular angle is the difference between the measured sound pressure level at that angle and the mean L_p that would be produced at the same location by an omni-directional sound source of the same total sound power level.

Directivity Indices when plotted against the Strouhal Number were found to follow the curves shown in Figure 2. The Strouhal Number, *Str* is a dimensionless number that

relates the frequency, f duct diameter, d, and the speed of sound, c, as follows:

$$Str = f\,d\,/\,c$$

We have added dimensionless "ka" values to Figure 2 for comparison with values found in Bies and Hansen [1].

APPLICATION OF DI DATA

To calculate the Sound Pressure Level at a receptor location at a given distance from an open-ended duct, one should calculate the level based on omnidirectional radiation then apply the Directivity Indices (DIs) in octave bands and sum the resulting levels to predict the overall level at the receptor. From Figure 2 we would determine the DI results at 90 degrees from a 2 metre diameter duct as follows in Table 1.

Table 1. Typical Predicted DI

Frequency Hz	63	125	250	500	1k	2k	4k	8k
Strouhal	.37	.73	1.5	2.9	5.8	12	23	47
DI	-1	-2	-4	-6	-9	-13	-17	-21

The scatter of data shown in Figure 9.33 on page 512 of Bies and Hansen [1] is both above and below the curve of best fit. At 90 degrees, the scatter of data is mainly within plus or minus 3 to 4 dB. We consider that for broadband noise the DI should have an accuracy of ± 3 dB. For noise characterised by a narrow band of frequencies, the accuracy of the DI prediction may be ± 4 dB.

When calculating the Sound Power Level based on field measurements of Sound Pressure Level near the open end of a duct, it is necessary to record the distance from the centre of the duct termination and the angle of measurement from the duct axis. Care should be exercised to ensure that ambient noise from other sources is excluded. Measurement on the duct axis is often impossible because of noise generated by airflow over the microphone. Measurements at 45, 60, 75 and 90 degrees to the axis are recommended. These can be corrected for directivity to determine the omnidirectional equivalent Sound Pressure Level from which the Sound Power Level is calculated. The omnidirectional Sound Pressure Level can be approximated by measurement at 60 degrees, because the DI is close to zero at this angle.

When calculating the Sound Pressure Level from a duct discharge of known Sound Power Level we use:

$$L_p = L_w - 10\,\text{Log}\,(4\pi r^2) - A_E + \text{DI}\quad\text{at the angle of interest}$$

The DI must be determined at each octave band for a given duct diameter and angle from the duct axis. If the duct is above and adjacent to hard ground and there are no other excess attenuation effects, A_E = -3 dB.

Noise from large lantern vents on factory rooftops has been found to be very directive. Davy's theory on directivity from roof openings indicates that it may be quantified using Figure 2 assuming a diameter equal to the width for directivity normal to the long side and diameter equal to the length for directivity normal to the short side [2].

If the sound pressure from a duct is measured at a specific angle to the duct axis and at a distance r_b, it is not necessary to calculate the sound power level in order to determine the sound pressure level at any other angular location or at any other distance, r_a from the duct outlet. The sound pressure level at location a can be calculated from that measured at location b using:

$$L_{pa} = L_{pb} - 20\,\text{Log}\,(r_a/r_b) + \text{DI}_a - \text{DI}_b$$

where DI_a is the directivity index corresponding to the angular location of point a and DI_b is the directivity index corresponding to the angular location of point b. The equation holds provided that:

- all locations are sufficiently far from the duct outlet to be in the far field;
- the difference in excess attenuation effects from one location to another is taken into account; and
- breakout from the walls of the duct is contributing negligibly to the sound levels at locations a and b.

DI OF LINED DUCTS

Bies and Hansen [1] point out in Section 9.15 of the referenced textbook that: "Ducts lined with sound absorbing material radiate more directionally so that higher on-axis sound levels are produced."

CONCLUSION

The Directivity Index chart presented in Figure 2 of this paper is based on comprehensive testing by acoustical engineers using calibrated precision instrumentation [3]. Figure 2 is considered suitable for general use by acoustical engineers for the prediction of duct directivity gain or loss.

The Directivity Index results published in Section 9.15 of the textbook by Bies and Hansen [1] use the dimensionless parameter ka, which can be found by multiplying the Strouhal Number by π. Values for ka have been added to Figure 2 to allow comparison with the charts in the Bies and Hansen textbook. Please note the close agreement.

ACKNOWLEDGEMENTS

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