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

Acoustics and Sustainability:

How should acoustics adapt to meet future demands?

Characterisation of compressed air leaks using airborne ultrasound

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ABSTRACT

With increasing focus on climate change and greenhouse gas emissions there is renewed interest in minimising inefficiencies in compressed gas systems that result from leaks. Airborne ultrasound has been used for more than 30 years to locate such leaks, however traditional methods have had limited success in accurately quantifying the actual leak rate for a given leak and therefore the actual true cost. This paper will outline the in-depth study used to characterise a range of compressed gas leaks using air as the fluid medium across a range of pressures, leak types, shape and size.

INTRODUCTION

With rapidly rising fuel costs and environmental emission taxes, it is crucial that businesses reduce their energy usage. In an industrial plant, compressed air systems are typically the plants single largest users of electricity and a properly managed compressed air system can save energy, reduce maintenance, decrease downtime, increase production throughput, and improve product quality.

One of the most important facets of such a management program is air leak detection, and the simplest, least intrusive method of implementing a leak detection program is to use an ultrasonic leak detector. The rapid expansion of the leaking gas generates turbulence which in turn produces sound – both in the audible and ultrasonic spectrum. The shorter wavelength of ultrasonic sound results in a higher attenuation rate which leads to the ultrasonic sound generated by a given leak being far more directional than the corresponding audible sound. This directionality of the ultrasonic sound enables leaks to be identified in noisy industrial environments, without a plant being shut down. The level of ultrasound produced by a leak can then be used to calssify the size of the leak and therefore the relative importance of fixing it.

This paper reports the findings of an investigation into a number of the factors that affect the level of ultrasound measured at a leak and the corresponding leak rate. An experimental rig was built to enable the level of ultrasound from a variety of orifices and lengths of tubing to be measured using an ultrasonic leak detector. The test rig was set up in such a way as to allow measurement of the ultrasound level at a number of distances from a leak and at a variety of angles relative to the axis of the flow from a leak.

FACTORS AFFECTING THE ULTRASONIC SOUND LEVEL PRODUCED BY A LEAK

There are several factors that determine the level of ultrasound generated by a given leak, such as orifice shape, pressure differential and atmospheric conditions, all of which affect the level of turbulence and therefore generation of ultrasound. Additonal external factors such as the location and size of competing ultrasounds (background noise sources), distance between the ultrasonic detector used and the leak site also have a direct bearing on the level of ultrasonic sound level recorded for a given leak. Each of these factors impact on the level of measured ultrasound to a varying degree, and were evaluated to assess their relationship with the level of measured ultrasound for a given leak rate.

Evaluation of Leak Factors

As was previously stated, the turbulence generated by a compressed air leak produces the ultrasound measured by the ultrasonic leak detector. This turbulence is the product of pressure differential and orifice shape of the leak rather than being a factor in its own right. The pressure differential at a leak creates turbulent flow as each side of the leak tries to equalise with the other. While the pressure differential cannot be controlled, the effect of air line diameter and length on it must not be overlooked when calculating the leak rate for a given level of ultrasound. The shape and size of an orifice at a leak can also significantly affect the level of ultrasound being created, whether it has a rough or smooth edge, round or square geometry or, if it is a small pinprick or a gaping hole, these variables may, or may not, impact on the measured ultrasound level.

As the attenuation rate of ultrasound is relatively high, the distance from a leak at which the leak rate is measured is an important factor in air leak detection. Traditional ultrasonic air leak characterisation relies on charts that relate a decibel reading to a volume flow rate at a given pressure, all based on a measurement being taken at a fixed distance from the leak. This study included a review of this fixed distance and the potential impact of using a different distance in the future. This distance should be as close to the leak as possible without impacting on the reliability of the measured ultrasound level.

The inability to get close to a leak, or to the appropriate angle, can impact significantly on the level of the ultrasound being measured. Accessibility to the leak can be a major factor in ultrasound measurement and it is important to understand how, distance, and angle of approach affect the level of the detected ultrasound. By understanding the impact of these factors and being able to account for them, more accurate estimations of leak rate are achievable.

In an industrial plant using compressed air, there are often occasions where other sources of compressed air may interfere with the ultrasound being received by the ultrasonic leak detector. This additional ultrasound is commonly known as "competing ultrasound" and can affect the ultrasound level measured at a leak. Using one of several shielding or barrier techniques, as discussed in the UE Systems Airborne Ultrasound Level 1 Workbook (1997), these effects can be eliminated or at least minimised ensuring that the measured ultrasound comes solely from the desired leak.

The local atmospheric conditions at a site in most circumstances will have minimal impact on the ultrasound level measured as there will be minimal variation in the temperature and pressure. The exception to this is at altitude where the atmospheric pressure is lower and can have a noticeable impact.

LEAK FACTOR INVESTIGATION

Competing ultrasounds, as they can be easily managed, and atmospheric conditions, as they are measurable at each site, were excluded from the study. The following factors were investigated:

- Directionality
- Distance from the Leak
- Length Effect
- Orifice Shape

Directionality of Ultrasound

The angle of approach to a leak has a significant impact on the ultrasound level measured. The angle of the ultrasonic leak detector was altered relative to the direction of air flow from a leak to ascertain to what degree the ultrasound level varied, and to obtain the optimum angle of approach.

Distance from the Leak

The flow rate from a leak is based on a table using predefined values for a given ultrasound level at a given system pressure, it is important that the ultrasound level is measured at the same distance for every leak. UE Systems Inc., the manufacturers of the Ultraprobe 9000 used in this study, supply a guess-timator chart for which the standard measurement distance is 481mm (15in) from the leak. The impact of changing the distance of the ultrasound leak detector to the leak was investigated to assess how the level of ultrasound measured varied with distance.

Length Effect

When estimating the flow rate of air from a compressed air leak, especially from open ended tubing, two mistakes are commonly made. The first is the use of a "discharge from an orifice" chart to estimate the leak rate taking no account of the pressure drop through the tubing. The second is that many use the external diameter of the tubing which is often the quoted diameter when referring to a compressed air line; taking no account of the wall thickness of the tubing. To attempt to account for length effect, the flow was measured through three diameters of tubing and for a variety of lengths to develop correction factors that can be used to account for the variation in volume flow rate.

Effect of Orifice Size and Shape

The level of ultrasound measured at a leak in a compressed air system at a given air pressure varies significantly with orifice size, as the orifice increases in size and the velocity of the air from the leak reduces the ultrasound level decreases. The effect of shape on the level of ultrasound is less predictable and a series of experiments were performed to assess how differences in geometry affected the measured sound level.

EXPERIMENTAL SET – UP

To enable the leak factors to be investigated, a test rig was designed to allow the different leak types to be set up in such a manner that allowed the pressure at the leak site and the receiver to be measured, and also the volume flow rate of the air in the system. The rig design also enabled the distance from the leak and the angle of approach to the leak to be set to ensure consistency of the ultrasonic sound level being measured. The design of the test rig is discussed below.

Test Rig Design

A schematic outline of the test rig used for the experimental rig is depicted in Figure 1. Air flowed from the receiver at a pressure controlled by the flow regulator attached to the outlet. The pressure and flow rate of the air were measured using an electronic in-line meter which was able to log the data recorded. However, as there was a minimum flow threshold below which it was unable to detect the flow, two rotameters were available to measure the flow in these circumstances. The air then passed into a manifold that was used to allow various configurations of leak to be tested without the need to completely change the set-up. The configuration shown includes a mounting chamber used when testing a number of discs with a variety of leak geometries cut into them. An alternative configuration (not shown) consisted of valves tapped into the manifold that were connected to lengths of nylon tubing.

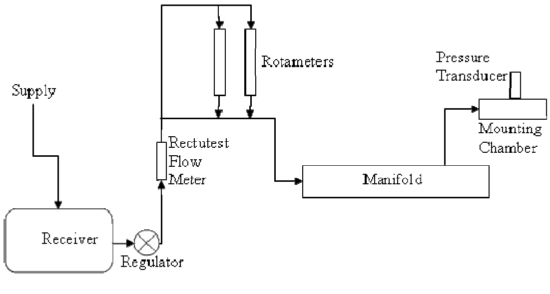


Figure 1, Schematic of the test rig

The various leak configurations were set-up in such a manner as to allow measurement of the ultrasound levels at a number of distances and angles from the leak using a leak orientation board as shown in Figure 2.

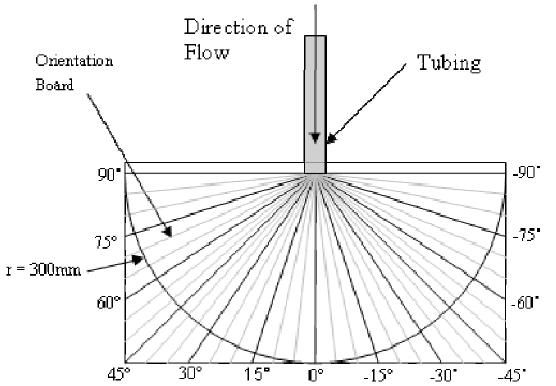


Figure 2, Leak orientation board, with marks indicating distance and angle from leak.

Leak Types

There were two main leak types included in the study:

- Open Ended Tubing
- Orifice Discs

Nylon tubing of outside diameters, 8mm, 6mm and 4mm as shown in Figure 3 were used to study the effect on the flow rate of varying the length.

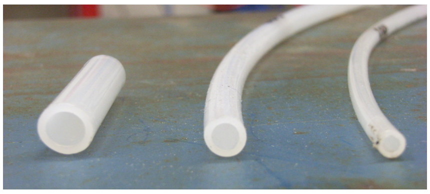


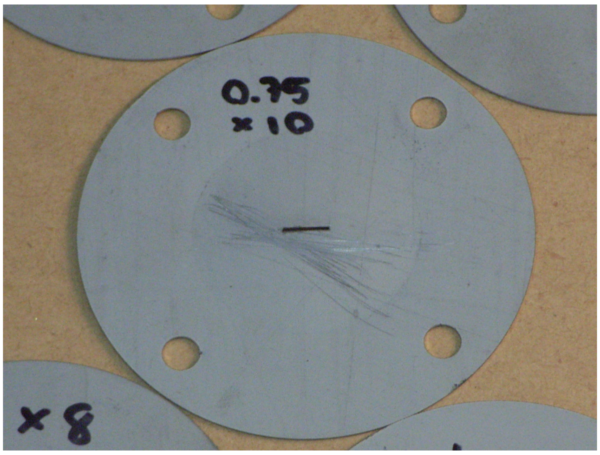
Figure 3, Examples of the three diameters of nylon tubing

The full dimensions of the tubing used for the study are displayed in Table 1.

Table 1: Tubing lengths at each diameter

	OD (mm)	ID (mm)	Tube Length (m)					
Open Ended Tube	4.0	2.5	1.0	2.5	5.0	7.5	10.0	25.0
	6.0	4.0	1.0	2.5	5.0	7.5	10.0	25.0
	8.0	6.0	1.0	2.5	5.0	7.5	10.0	25.0

Discs with a variety of round and rectangular orifices cut into them were used to simulate leaks of differing geometries. They were cut using a laser cutting machine, with a quoted accuracy of (+/- 100 Microns). An example of the leak discs can be seen in Figure 4.



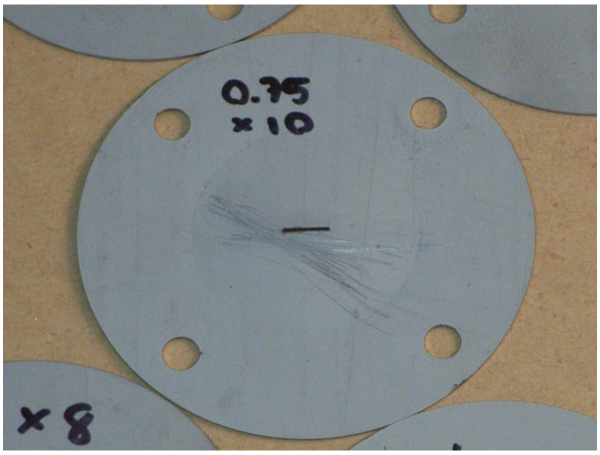


Figure 4, Disc with a 0.75mm x 10mm slot

The geometries of the leak discs included in the study are shown in Table 2.

Table 2: Dimensions of orifice geometries in discs

		Disc Thickness (mm)	Hole Diameter (mm)									
Mild Steel Discs	Round Holes	0.6	1.0		1.6		3.2		6.4			
		2.0	1.0		-		-		6.4			
	Slots	Disc Thickness (mm)	Width (mm)	Length (m)								
		0.6	0.5	-	5.0	-	-	10.0	15.0	-	30.0	-
		0.6	0.8	-	5.0	-	-	10.0	15.0	20.0	-	-
		0.6	1.0	2.0	5.0	-	8.0	10.0	15.0	-	-	32.2
		0.6	2.0	-	5.0	7.5	-	-	-	-	-	-
		2.0	1.0	-	5.0	-	-	-	15.0	-	-	-

One issue with the leak discs was that with the size of the slots required, even laser cutting was not entirely accurate and small variations were present in both the size and geometry of the cuts. The discs were measured with a microscope to allow an area correction to be calculated, however the geometrical variations meant that there were still small inaccuracies present in the dimensions.

EXPERIMENTAL RESULTS

Normalising the volume flow rate

By normalising the volume flow rate (at standard conditions) with respect to the line pressure a volumetric flow rate that is uncorrected for pressure was obtained. This flow rate changes below the critical flow point, which occurs at a specific pressure ratio. Once the ratio of the supply pressure to the atmospheric pressure rises above this, the flow rate is constant at any point in the system. This normalised flow rate can be converted back to the actual volume flow rate at any leak site in the distribution network if the atmospheric pressure and supply pressure at that point are known. From here on, the volumetric flow rate will be the uncorrected flow rate in the distribution network unless otherwise stated.

Critical Flow

A common assumption when carrying out compressed air leak surveys is that as pressure increases the flow rate of the air will also continue to rise proportionately. However this takes no account of the critical flow effect.

Critical flow occurs when a gas flowing through an orifice reaches sonic velocity. Once the ratio of upstream pressure (p_1) to downstream pressure (p_2) reaches a specific value the volumetric flow rate is unable to increase any further.

This pressure ratio is calculated using

$$p_1 / p_2 = [(k+1)/2]^{k/(k-1)} \quad (1)$$

For air, the ratio of the specific heats, k, equals 1.4, giving,

$$p_1 / p_2 = 1.89 \quad (2)$$

If p_2 is atmospheric pressure, then we get

$$p_1 = 1.89 \times 1.01 = 1.91 \text{Bar} \quad (3)$$

This shows that at standard conditions of temperature and pressure, critical flow will occur at 1.91 Bar (absolute).

The validity of the critical flow effect with respect to compressed air leaks was explored as part of the study and to confirm how the experimental critical flow point compared with the theoretical value above, a graph of volumetric flow rate ($\dot{V}_{sys}$) as a function of supply pressure was plotted for three air lines of ID 2.5, 4.0 and 6.0mm respectively. Applying a best fit line of the data gives a representation of the transition to critical flow as is shown in Figure 5. This shows that experimentally the transition to critical flow occurred close to the theoretical pressure calculated of 1.9 Bar_a.

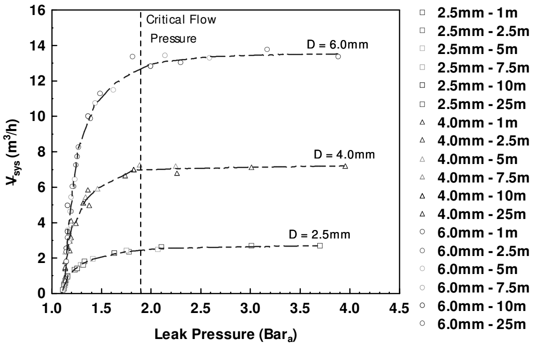
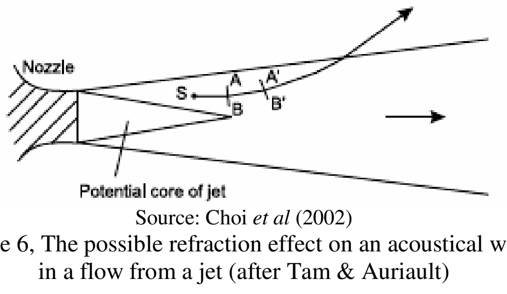


Figure 5, Volumetric flow rates for tubing of various lengths at diameters of 2.5, 4.0 and 6.0mm highlighting the critical flow pressure.

Directionality of Ultrasound

Studies carried out by C.K.W. Tam & L. Auriault showed that a radial gradient in gas flow velocity leads to acoustic refraction, as depicted in Figure 6 which shows a wave front at AB which, at a time t later, has moved to A´B´. This assumes that the component at point B travels at a faster velocity than at A, so that the wave will refract or bend outwards. This results in a region of low intensity sound intensity or "cone of silence" along the axis of the flow, which accompanies divergence of the sound field.



Source: Choi *et al* (2002)

Figure 6, The possible refraction effect on an acoustical wave in a flow from a jet (after Tam & Auriault)

This effect helps to explain the fall in ultrasonic sound level in the central flow axis and further analysis in the experimental studies profiles the directionality of the ultrasonic sound level around a leak.

The angle of approach of the ultrasonic leak detector to a leak source was altered, with the dB level being measured at 15° intervals in a 180° arc, from 90° to -90°, with 0° being on the leak axis as shown in Figure 2. The ultrasonic level was measured at a distance of 0.3m from the leak. The experiment was repeated for a number of supply pressures. Two key findings can be taken from Figure 7, which shows the variation of the ultrasonic sound level when measured around the leak. (The pressures used are the leak pressures measured at a distance of 30mm from the end of the tubing.)

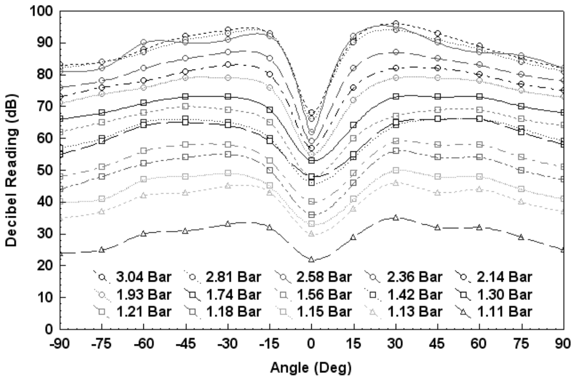


Figure 7, Directionality of ultrasound at a distance of 0.3m from the leak for a 2.5m length of 4mm ID tubing at a range of leak pressures.

Firstly, the work of Tam & Auriault was shown to be valid for the flow of air from a compressed air leak. The ultrasonic sound level dropped off steeply in the central axis of the flow for all the leak pressures included in the study, with a reduction of 25dB to 30dB measured between 0° and 15° at a leak pressure of 3.04 Bar for this type of leak. The extent of the reduction, in this localised region of ultrasound, reduced as the pressure in the system was lowered. The peak ultrasonic sound level was located between 15° and 45° of the central axis of the leak flow, most commonly at about 30°, with the sound level generally reducing by 5dB to 10dB in the region between 45° and 90° for this leak type. This result was consistent for all pressures included in the test.

Secondly, the ultrasound generated at a round orifice was mirrored on both sides of the central axis in the direction of the flow. This showed that for air flow from a symmetrical leak the ultrasound generated is also symmetrical.

In an industrial situation the exact angle to, and geometry of a leak will seldom be known, and it is therefore important when conducting a leak survey that scanning is performed in all directions around the leak until the highest level of ultrasound is detected to ensure consistent results. Although the lowest ultrasound level will also be consistent the rate of ultrasound increases very rapidly when the detector is not directly in line with the axis of the air flow and there is greater potential for error.

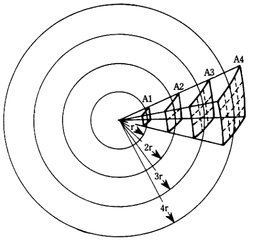
Distance from the Leak

As ultrasound has a shorter wavelength than sound in the audible range the attenuation rate is significantly higher. Due to the divergence of ultrasonic sound, in combination with factors such as the attenuation, reflection and refraction, the sound level changes as the distance of an ultrasonic leak detector from a leak is altered. This suggests that the level of ultrasound should be measured as close to the leak as will give consistent results.

The inverse distance law shown in equation (4) is used to calculate the sound level at different distances from a sound source. It is designed for use in perfect conditions for example an anechoic chamber and is predominantly used in the audible sound range.

$$L_2 = L_1 - 20\log_{10}\left(\frac{r_2}{r_1}\right) \tag{4}$$

Where L_1 and L_2 are the sound levels at the respective r_1 and r_2 distances which are shown in Figure 8, and can be demonstrated when a single sound source propagates uniformly in all directions in the form of an expanding spherical shell.



Source: Everest, F. A. (1994)
Figure 8, Spherical propagation of a pulse

In enclosed spaces for the audible sound range, as the distance from the source increases, the level of direct sound approaches the level of reverberant sound. This distance is called the critical distance and beyond it the sound level will not reduce further until the sound begins to attenuate and the inverse distance law is valid. Figure 9 shows how the inverse square law can be applied at short distances in both the audible sound range and the ultrasonic sound range. At greater distances, reverberation in the audible sound range, and more likely, attenuation in the ultrasonic sound range, render the law invalid.

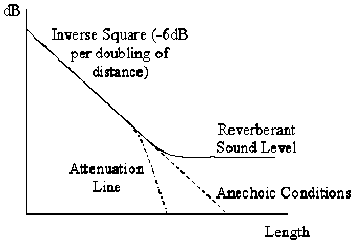


Figure 9, How the Inverse Square Law is affected by reverberation in the audible sound range and attenuation in the ultrasonic sound range.

The boundaries of use of the inverse distance law, when quantifying compressed air leaks by ultrasonic detection, were examined to determine how the recorded level of ultrasound was affected by reverberation and attenuation.

The impact of either increasing or decreasing the distance to the leak was tested to confirm if consistent results could be obtained within the 481mm (15in) distance currently used by UE Systems. The ultrasonic sound level was measured at a range of distances from the leak, initially 0.1, 0.15 and 0.3m. Measurements were not taken at the leak site itself as ultrasound recorded at a compressed air leak is caused by the turbulence created at the leak and this could adversely affect any dB readings taken. Further experiments at 0.6, 1.2 and 2.4m were also conducted to examine how the ultrasound level reduced over greater distances.

Effect of distance inside 0.3m

An experiment was carried out with a 2.5m length of open ended nylon tubing of 4mm internal diameter at system pressures of 7.01, 4.01, 2.01 and 1.41 Bar with respective leak pressures of 2.94, 1.67, 1.15 and 1.08 Bar. Measurements were taken at distances of 0.1, 0.15 and 0.3m from the leak to see how the dB level decayed with distance and how the rate of decay was affected at different pressures.

Three distinct regions were present in the ultrasonic sound level profiles. These were at, 0°, from 15° to 45° and from 45° to 90°. There were slight variations between the ultrasound levels in these regions caused by geometrical differences between different leaks but they were generally consistent to within a few degrees.

Figure 10 shows the results for a leak pressure of 2.94 Bar_g, the profiles of the ultrasonic sound levels for each distance were relatively consistent, with the levels at 0.1, 0.15 and 0.3m being very similar. The sound levels from 0.1m to 0.15m, and 0.15m to 0.3m reduced in line with the inverse distance law due to attenuation. The ultrasonic sound level round the circumference of the leak site was lower in the centre of the axis of flow as a result of the “cone of silence effect”.

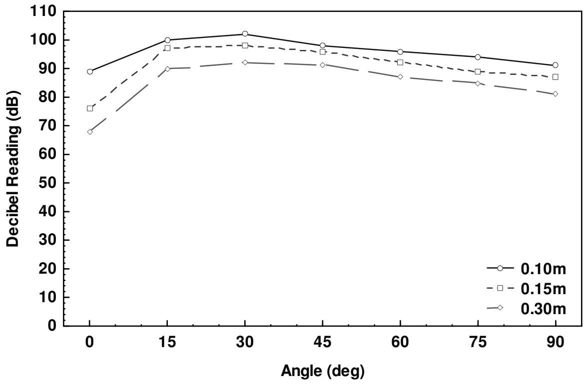


Figure 10 , Decibel Readings taken at a distance of 0.10, 0.15 and 0.30m from a round leak source of 4mm diameter. Pressure at leak 2.94 Bar_a.

Table 3 shows the dB reduction for each of the pressures tested as the distance from the leak was increased. From 0.1m to 0.15m the theoretical reduction in ultrasound level due to the inverse distance law was 3.5dB, and from 0.15m to 0.3m, it was 6dB. The reduction in ultrasonic sound level from 0.1m to 0.15m at 0° was much higher than the level obtained using the inverse distance law. Looking at the profile of the ultrasonic sound level for 0.1m, it reduced less between 15° to 0° than for either the 0.15m or 0.3m readings in this region. This suggests that the proximity of the detector to the leak may have interfered with the developing turbulence, causing higher than expected readings at 0.1m.

The ultrasound reduction in the 15° to 45° region was generally consistent from 0.1m to 0.15m, and from, 0.15m to 0.3m and was generally close to the theoretical 6dB reduction. There were one or two anomalies where the dB readings did not match the general trend which may have been caused by fluctuations in the air supply due to loading and unloading of the compressor or errors in the measurement of the ultrasonic sound level, however this would require further investigation for confirmation.

Between 45° and 90° the ultrasonic sound level reduced slowly, as the angle relative to the flow direction increased. Again there were fluctuations in this region and further investigation would be required to establish the reasons for this.

Table 3, Decibel level reduction between 0.1 - 0.15m, and 0.15 - 0.3m, from 0-90° for leak pressures of 2.94, 1.67, 1.15 and 1.08 Bar.

	Angle	0°	15°	30°	45°	60°	75°	90°
Dist. To Leak	Exit Press.	dB Drop (+/-1 dB)						
0.1m - 0.15m	2.94 Bar	13	3	4	2	4	5	4
	1.67 Bar	14	5	4	3	5	2	1
	1.15 Bar	11	4	4	4	4	2	5
	1.08 Bar	6	4	4	3	4	2	5
0.15m - 0.3m	2.94 Bar	8	7	6	5	5	4	6
	1.67 Bar	8	8	8	6	5	7	9
	1.15 Bar	3	6	7	6	5	8	6
	1.08 Bar	7	6	6	6	5	8	6

Figure 11 shows the results with the maximum sound level for each leak plotted against the distance from the leak. The logarithmic scale allows a true comparison of the rate of decay of the ultrasound signal. The rate of decay is consistent for each of the four pressures tested which shows that the rate at which ultrasound decays is unaffected by pressure. The decay of the ultrasound from 0.1m to 0.15m and from 0.15m to 0.3m was plotted and shows that the rate of decay for the maximum ultrasound signal at both distances was the same. This suggests that the level of ultrasound could be measured at 0.1m from the leak as there is consistency between the different pressures, however due to the unpredictability of the ultrasound level in the flow axis and a less stable profile overall, 0.15m was taken as being a more reliable distance.

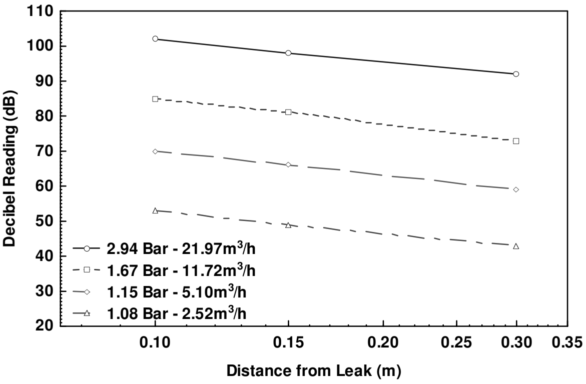


Figure 11, Rate of decay of ultrasonic sound level with increasing distance from an open ended tube of length 2.5m and diameter 4mm (nom.), for a range of pressures.

Effect of distance greater than 0.6m

To ascertain if the inverse distance law could still be used at greater distances, tests using orifice plates of two leak geometries were carried out. One had a 1.6mm diameter round hole and the other a 1mm x 15mm slot. The tests used nominal pressures of 1.41, 2.01, 4.01 and 7.01 Bar_a, and measurements of the ultrasonic sound level were taken at 0.6, 1.2 and 2.4m from the leak site. As previous experiments had shown that dB peaked between 30° and 45° for a round jet measurements were taken at 15° intervals between 0° and 45°.

There were two distinct regions, 0°, and 15° to 45°. Figure 12 shows that there are significant variations between results in the axis of the flow (0°) while the results for the 15° to 45° region can be seen to be more consistent.

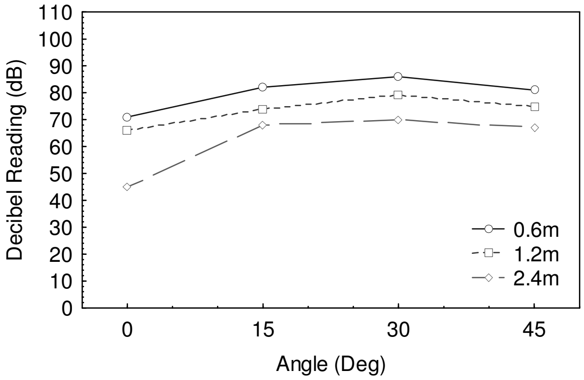


Figure 12, dB Reading taken at a distance of 0.6, 1.2 & 2.4m from a round leak source of diameter 1.6mm at a line pressure of 7.01 Bar_a.

Table 4 shows the ultrasonic sound level reduction from 0.6m to 1.2m and from 1.2m to 2.4m for each angle and pressure, the theoretical reduction in ultrasound level was 6dB for this set of experiments. At 0° the reduction in ultrasonic sound level varied significantly between tests, the ultrasound level from 15° to 0° at 1.2m reduced significantly less than at other distances and was higher than at 0.6m in several cases. This may have been caused by inconsistent leak geometry but additional testing would be required to confirm this theory. As the sound level in this region was not crucial, as discussed previously, no further investigation was undertaken as part of the study.

Table 4, Decibel level reduction between 0.6 - 1.2m, and 1.2 – 2.4m, from 0-45°, for a 1.6mm diameter hole at leak pressures of 7.03, 4.00, 2.01 and 1.40 Bar.

		Angle	0°	15°	30°	45°
Leak Type	Dist. To Leak	Exit Press.	dB Drop (+/-1dB)			
1.6mm Diameter Hole	0.6 - 1.2m	7.03 Bar	5	8	7	6
		4.00 Bar	-2	5	7	7
		2.01 Bar	-7	6	7	6
		1.40 Bar	-1	6	7	7
	1.2m - 2.4m	7.03 Bar	21	6	9	8
		4.00 Bar	26	9	8	8
		2.01 Bar	26	7	7	8
		1.40 Bar	23	9	10	9

At 0° between the distances of 1.2m and 2.4m, a reduction of more than 21dB was measured in all cases. The results indicated that the cone of silence effect, in combination with the rate of attenuation, meant that the level of ultrasound reaching the central core at 2.4m from this region was lower than the theoretical value of 6dB, hence the ultrasonic sound level had reduced more rapidly in the jet core.

From 15° to 45° the profiles of the sound levels corresponded more closely for each leak pressure, although there is a degree of variation in the results. The data showed that from 0.6m – 1.2m the dB drop was still relatively consistent with the inverse distance law for both leak geometries, but with slightly more variation than at shorter distance. However between 1.2m and 2.4m the reduction in the ultrasonic sound level has increased considerably due to attenuation of the short wavelength ultrasound.

As with the results for the ultrasound level reduction from 0.1m to 0.3m the results in Figure 13 have been plotted on a logarithmic scale. The fluctuations in the rate of the ultrasound level reduction from 0.6m to 1.2m, and, 1.2m to 2.4m for the different leak pressures, show that the level of ultrasound is less consistent at greater distances, which is most probably as a result of attenuation or reverberation.

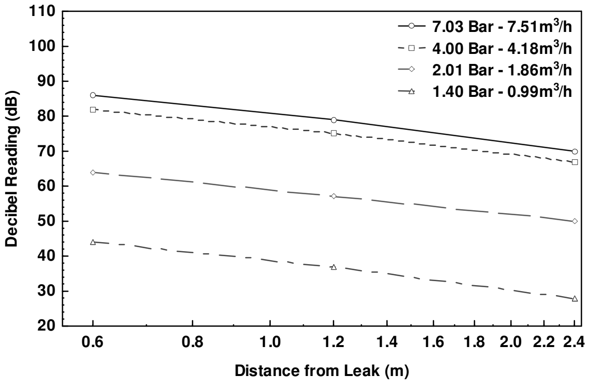


Figure 13, Rate of decay of ultrasonic sound level with increasing distance from a round hole of diameter 1.6mm, for a range of pressures

Effect of Length on the Flow Rate

The length of air line prior to a leak was tested to determine its influence on the flow rate of the air escaping at a leak site.

To examine the impact on the leak pressure of increasing the length of the tubing, 1.0, 2.5, 5.0, 7.5, 10 & 25m lengths of nylon tubing were tested at line pressures of 0.4, 0.6, 1.0, 3.0 and 6.0 Bar_g to examine how the pressure and hence volume flow rate of the air in the tubing reduced for each length. The tests were carried out for three diameters of tubing, 2.5, 4.0, 6.0mm to determine the effect on the rate of decay.

The line pressure was measured in advance of the manifold to which the tubing was attached, and the leak pressure was measured using a pressure transducer 30mm prior to the exit of the tubing. The results are displayed as a ratio of leak pressure, p_L, to supply pressure, p_S, for a given length. The ratio of p_L to p_S was calculated at gauge pressure as the curve tends to a least asymptote of zero. If absolute pressure was used then the Leak pressure would never reduce below 1.01 Bar_a and the pressure ratio would never reach zero.

The effect of length can be clearly seen in Figure 14 for a system pressure of 6 Bar_g where there is approximately a 50% reduction in flow in a 1m length of tubing.

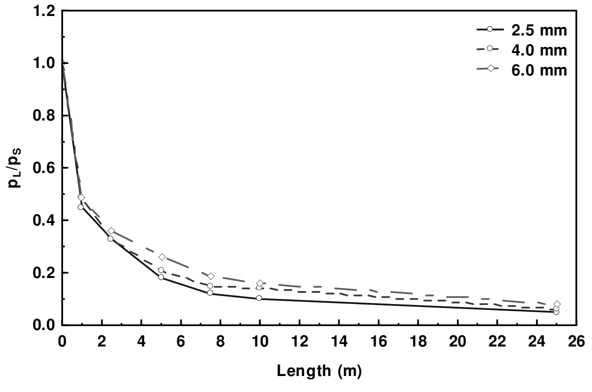


Figure 14, Profile of pressure drop ratio for 2.5, 4.0, 6.0mm diameter tubing of lengths 1, 2.5, 5, 7.5, 10, 25m at a supply pressure of 6 Bar_g

Comparing the pressure drop ratio at high and low pressures, the ratio was similar in all cases for a 1m length of tubing. At higher pressures, (e.g. 6 Bar_g), as the length increased and the leak pressure reduced, there was a large pressure differential and the ratio became very small. At lower pressures (e.g. 0.4 Bar_g), this pressure differential was much smaller, with the leak pressure stabilising at 0.1 Bar_g, and hence the pressure drop ratio was much larger. Although this leak pressure may reduce further with increased length, the rate is so slight that it can be ignored.

A summary of the pressure drop ratios is given in Table 5. As only the 6 Bar_g and 3 Bar_g supply pressures are relevant for the majority of industrial compressed air systems these columns have been highlighted for clarity.

Table 5, Ratios of leak pressure to supply pressure for tubing of diameters 2.5, 4.0 and 6.0mm.

		Pressure Drop Ratio (p_L / p_S)				
	Length (m)	6bar	3bar	1bar	0.6bar	0.4bar
2.5mm Diameter	1.0	0.45	0.36	0.32	0.37	0.38
	2.5	0.33	0.25	0.22	0.25	0.35
	5.0	0.18	0.13	0.14	0.22	0.30
	7.5	0.12	0.09	0.14	0.18	0.28
	10.0	0.10	0.08	0.13	0.18	0.28
	25.0	0.05	0.05	0.11	0.18	0.25
4.0mm Diameter	1.0	0.49	0.42	0.32	0.37	0.38
	2.5	0.33	0.24	0.22	0.25	0.35
	5.0	0.21	0.15	0.14	0.23	0.30
	7.5	0.15	0.11	0.14	0.18	0.28
	10.0	0.14	0.10	0.13	0.18	0.28
	25.0	0.06	0.05	0.11	0.18	0.25
6.0mm Diameter	1.0	0.49	0.43	0.38	0.42	0.53
	2.5	0.37	0.27	0.26	0.33	0.45
	5.0	0.27	0.20	0.22	0.28	0.38
	7.5	0.19	0.14	0.18	0.30	0.40
	10.0	0.17	0.12	0.15	0.25	0.35
	25.0	0.08	0.08	0.15	0.23	0.35

While there are variations in the pressure drop ratios for the various diameters, when applied to an air leak in an industrial plant they offer a significant improvement to the accuracy of any estimation of leak rate. At 6 Bar_g a correction factor of 0.49 at 1m or 0.22 at 5m could easily be applied to the flow rate for a given orifice size quoted in the “Discharge of Air Through an Orifice” table included in the UE Systems “Compressed Air Guide”. It is worth highlighting that when quoting the line diameter to obtain a flow rate it is imperative that it is the inside diameter that is used and not the outside diameter. For example, in the table, the difference when quoting a 6.35mm (1/4in) line as opposed to a 3.175mm (1/8in) is approximately 120m^3/h (71cfm) at 6.2 Bar_g (90psig). A 1m line with a correction factor of 0.49 applied will over estimate the flow rate by about 60m^3/h (35cfm).

Aspect Ratio

Orifices of different shapes and sizes were set up to represent a variety of leaks in a compressed air distribution network. The relationship between cross sectional area, diameter and aspect ratio were investigated to identify any obvious trends between the ultrasound level from a leak and the geometry of the orifice. If obvious trends were identified correction factors could included in the leak characterisation chart.

To ascertain if aspect ratio affected the flow rate and ultrasonic sound level from a specific size of leak the orifice plates were tested at system pressures of 1.41, 2.01, 4.01 and 7.01 Bar. If there were obvious variations in the flow rate or ultrasonic sound level for leaks with the same cross sectional area but different aspect ratio, a correction factor could be developed to account for these when doing a leak survey.

A number of orifice plates were manufactured with a common cross sectional area but different aspect ratios to enable flow rates and ultrasonic sound levels for these conditions to be compared. There were minor differences in the cross sectional areas of the test pieces due to the tolerances inherent in the manufacturing process. This was visible in the results of the tests, as small variations in the geometries made a high level of accuracy very difficult. There were three groups set up for aspect ratio comparison with a minimum of two test pieces for comparison. These groups were as follows (corrected dimensions in brackets):

1) 5mm^2 1mm x 5mm Slot…………….($5.47mm^2$)
0.5mm x 10mm Slot…………($6.05mm^2$)
2) 7.5mm^2 0.75mm x 10mm Slot………..($7.69mm^2$)
0.5mm x 15mm Slot…………($9.37mm^2$)
3) 15mm^2 0.5mm x 30mm Slot………..($18.75mm^2$)
0.75mm x 20mm Slot………($15.75mm^2$)
1mm x 15mm Slot…………($15.08mm^2$)
2mm x 7.5mm Slot…………($14.92mm^2$)

Figure 15 shows the volumetric flow rates of the four 15mm^2 slots corrected for area to take account of the variation in size as a result of the manufacturing process.

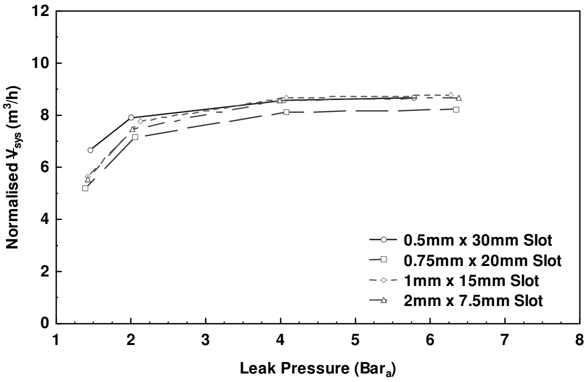


Figure 15, Volumetric flow rate normalised to a cross sectional area of 15mm^2 at line pressures of 1.41, 2.01, 4.01, 7.01 Bar$_a$, nominal as listed above.

The ultrasonic sound level was measured in each of the tests to ascertain if the sound generated at the leak was affected by variations in aspect ratio. The ultrasound was measured in an arc around the leak site at a distance of 0.3m and the highest level of ultrasound recorded for each leak. Figure 16 shows the maximum ultrasonic sound level at a number of system pressures. When these were compared to the plots of the area corrected flow rates it showed that the lower ultrasonic sound levels correspond to the lower flow rates.

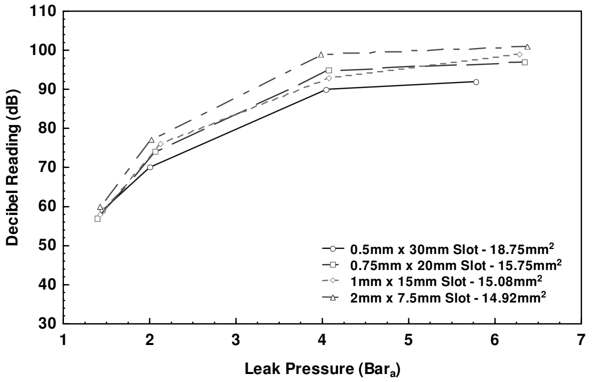


Figure 16, Ultrasonic sound level at 0.3m from source, for orifices of 18.75mm^2, 15.75mm^2, 15.08mm^2 and 14.92mm^2 at line pressures of 1.41, 2.01, 4.01, 7.01 Bar$_a$, nominal.

While these results could be revisited through the testing of more accurate test pieces to confirm the relationship between the ultrasound level and the aspect ratio, the results indicated that as with the flow rates, there was a negligible effect on the ultrasound level due to variations in aspect ratio.

In addition to the aspect ratio comparison, two groups were set up to compare slot leaks with round leaks for a common cross sectional area. The measured cross sectional area of the orifices is shown in brackets.

1) 2mm^2 1mm x 2mm Slot…………….($1.76mm^2$)
1.6mm Diameter Hole……….($2.11mm^2$)
2) 8mm^2 1mm x 8mm Slot…………….($8.54mm^2$)
1.6mm Diameter Hole……….($8.46mm^2$)

As with the aspect ratio comparison, to allow the effect of the differing geometries of the test pieces to be compared the volumetric flow rates were corrected for area to take account of the variation in sizes, as shown in Figure 17.

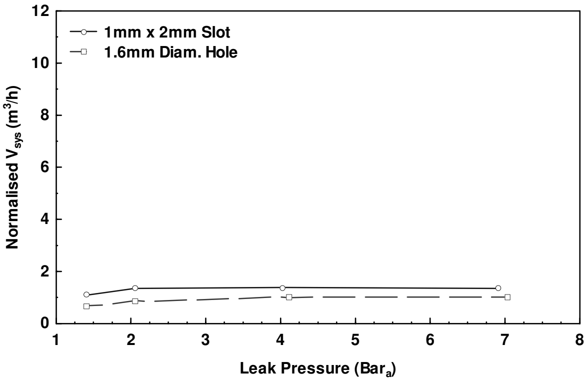


Figure 17, Volumetric flow rate normalised to a cross sectional area of 2mm^2.

The ultrasonic sound level in Figure 18 shows very little variation between the round hole and the slot suggesting that the shape of the hole has a negligible effect on the sound level.

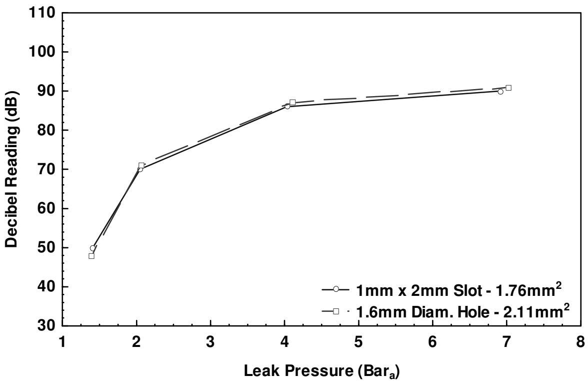


Figure 18, Ultrasonic sound level at 0.3m from source for orifices of 1.76mm^2 and 2.11mm^2 at 1.41, 2.01, 4.01, 7.01 Bar$_a$, nominal.

Discussion

Updated Leak Characterisation process

This paper was concerned with addressing some of the issues that make ultrasonic leak surveys and audits unpredictable. There are two areas of interest, the first addresses the procedural aspects of conducting a leak survey, and the second deals with the application of a correction factor to account for the effect of length on the flow rate.

Procedural changes to leak rate estimation

As a result of the findings included in this paper there are two main procedural changes that should be made to the current process.

1) When a leak is located and the gross to fine method has been used to isolate the leak, rather than drawing the ultrasonic leak detector directly back from the leak, which will give a very low reading, the peak signal from the leak source should be identified and the ultrasonic leak detector drawn back the appropriate distance from the leak.

2) The measurement of the ultrasound level should be taken at 150mm from the leak source rather than the current 380mm (15”). As there is no detrimental effect to the consistency of the ultrasound signal having the leak detector at this distance it will be beneficial to be closer top the leak site as it reduces the chance of external factors influencing the measurement.

Volumetric Flow Rate Correction Factor

When estimating the flow rate of the air from a length of open ended tubing, the current process involves taking the ultrasound measurement and supply pressure and looking up the corresponding flow rate. The new process will involve applying correction factors to the leak rates, to more accurately represent the leak rate.

The length effect factor varies with supply pressure, but for a 6 Barg supply pressure can be taken as 0.5 at 1m or 0.22 at 5m.This is shown in the abbreviated table 6.

Table 6, Correction factors for length effect

Length effect (D = 2.5, 4.0, 6.0mm)	Correction Factor
1m (Supply pressure 6 Bar_g)	0.5
5m (Supply pressure 6 Bar_g)	0.22

CONCLUSION

While ultrasonic leak detection is not an exact science, understanding the type of leak allows a more accurate estimation to be made. This paper outlines the study used to improve the processes undertaken when undertaking an ultrasonic leak survey and highlights the importance of a consistent procedure. As shown, there are significant variations in the ultrasound level measured at different points around a leak site. It has been shown that for symmetrical leaks of similar size there is little variation in the ultrasound level, however the leak rate is considerably affected by distance from the distribution network. The ultrasonic leak detection process could be further improved by the testing of specific leak types such as thread leaks and flange leaks to see how the ultrasound level for a given leak rate is affected by the change in geometry.

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