Investigation into the airborne flanking sound transmission paths of wastewater pipes and acoustic lagging

Paolo Tommasini (1), Darren Tardio (1)

(1) Renzo Tonin & Associates (VIC) Pty Ltd, VIC, Australia

ABSTRACT

As it is becoming increasingly popular to do away with ceilings in some types of commercial buildings, is airborne sound transmission via plastic wastewater pipes likely to be a problem where there are residential tenancies above? There is much laboratory and practical evidence for the benefits of convoluted foam lagging with respect to reduction of turbulent fluid flow noise within pipes, but there is little knowledge available with respect to airborne noise transfer through PVC pipes, back up to the point of ingress. This study presents the findings of acoustic field testing intended to determine the effects of airborne sound transmission via wastewater pipes and the effect of lagging on such sound transmission. The study demonstrates that wastewater pipes could feasibly be considered a noise transmission path and that convoluted foam lagging improves the sound insulation of such pipes, specifically in the intelligible speech frequencies.

INTRODUCTION

As the boundaries of value engineering are continually pushed and the necessity of previously essential building elements such as ceilings is questioned, it becomes necessary to consider the acoustic effects that such an omission might have on the acoustic separation between tenancies in multiple storey, mixed use developments.

The impetus for the research outlined in this paper is the need to assess sound transmission via wastewater pipes between retail/commercial and residential tenancies. Specifically, where there is no ceiling installed in the retail/commercial space below, and the exposed wastewater pipes are subject to high sound pressure levels (in the speech frequencies) due to public address announcements.

This paper presents the results of acoustic field testing via wastewater pipes and considers the sound insulation afforded by typical plastic wastepipes, with and without acoustic lagging. The consideration of sound transmission between commercial/retail tenancies with respect to the likelihood of causing annoyance is also discussed.

BACKGROUND

Calculating the airborne flanking noise through exposed piping has until recently been generally unnecessary. However, as mixed-use developments and industrial type architectural features (such as exposed soffits or commercial ceilings) become more prevalent, the scenario of airborne flanking through exposed piping appears to be more common.

In order to simulate the potential for sound transmission via exposed wastewater pipes, field testing was conducted in a residential building during construction with a variety of simulated tests with both bare and lagged pipes.

EXPERIMENTAL METHODOLOGY

Airborne field testing was conducted in a multiresidential building in construction, between two stacked apartment bathrooms (having equivalent floor plans). As such, both rooms were completely bare (unfurnished) and only hydraulics and exhaust fans had been installed at the time of testing. The floor slab separating the two apartments was approximately 200mm thick. Each room had a volume of approximately $20m^3$.

There were several minor gaps in the walls of the source room, specifically around hydraulics penetrations which were filled with polyester insulation. These were not considered to be a significant flanking path.

The exposed pipes in the source room consisted of three main pipes:

- A 100mm (internal diameter) toilet waste having a wall thickness ≈3mm and a length of ≈3.7m;
- A 75mm (internal diameter) shower waste having an unknown wall thickness and a length of ≈1.2m, transitioning to a 100mm (internal diameter) pipe for an additional length of ≈0.9m;
- A 50mm (internal diameter) laundry waste having a wall thickness ≈2.5mm and a length of ≈0.3m penetrating the separating slab and turning immediately into the adjacent riser.

Figures 1 and 2 show the site installation in the source (exposed pipe) room and receiving (orifice room), respectively.

The three pipes were sealed airtight into the slab and extended above the slab of the receiver room by 100mm for the toilet waste and 340mm for the laundry waste. The shower waste was set into a collar, flush with the slab.

The pipe material was PVC and there was no water visible in the pipes at the time of testing.

The sound field in the source room was generated using a broadband noise signal from a JBL EON 2, 15 inch loudspeaker and a high powered amplifier and positioned in one of the corners of the source room.

Measurements were conducted for three scenarios:
1. Bare pipes (no lagging)
2. Partially lagged pipes
3. Fully lagged pipes

A further two sets of measurements were conducted by filling the openings of the pipes above with polyester insulation and capping with timber offcuts for the following scenarios:
4. Bare pipes (no lagging)
5. Fully lagged pipes

All lagging was conducted by a suitably qualified lagger using Pyrotek 4525C, a 5kg/m^2 mass barrier with convoluted foam, installed with overlap joints in accordance with the manufacturer's instructions.

Measurements were conducted with a B&K2250 sound level meter which is a class 1 instrument having accuracy suitable for field and laboratory use. The instrument was calibrated prior and subsequent to measurements using a Bruel & Kjaer Type 4231 calibrator. No significant drift in calibration was observed. The meter complies with AS IEC 61672.1 2004 "Electroacoustics - Sound Level Meters" and carries current NATA certification.

Measurements in each room were taken at five discreet points and spatially averaged to estimate the reverberant soundfield levels for each of two speaker positions. Additional 'spot measurements' were taken in the receiving room, within 200mm of each pipe orifice to better estimate the contribution of noise from the various pipe lengths.

Given the testing was conducted while the building was under construction, a moderate level of ambient noise from nearby road traffic entered the building via the unsealed façade.

Figure 1. Source Room Installation

THEORY

To date, almost all acoustic theory related to breakout and break-in sound transmission is based on experimental data provided by ASHRAE [1] for sheet metal ducting.

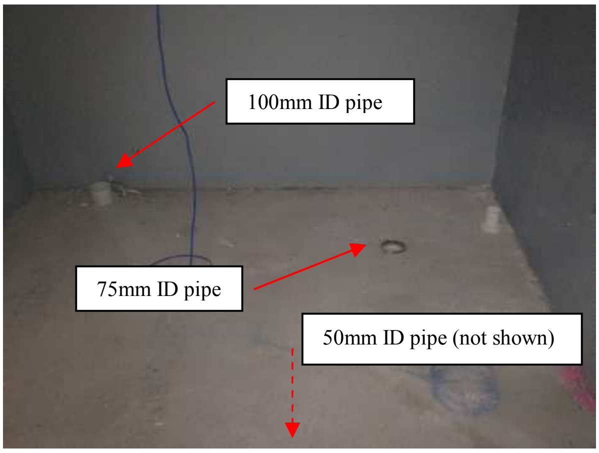

Figure 2. Receiving Room Pipe Orifices

In regards to pipe lagging, the Insertion Loss is typically determined experimentally in a laboratory using fluid excitation, due to its main purpose of reducing both structure-borne and airborne noise from pipe fluid flow. Therefore, little information is available to certify the pure airborne transmission loss through PVC pipe walls both with and without lagging.

While the formulae considered herein are mostly concerned with steel ducting, the authors are not aware of other algorithms to describe the transmission loss of PVC pipe walls (low mass, rigid cylindrical ducting).

In theory, circular duct of relatively small dimensions will have a high transmission loss at low frequencies with dips at ring and critical frequencies. Cummings [2] however finds that the idealised cylindrical duct overestimates low frequency performance when compared to measured data due to mode coupling.

Due to the difficulty of developing an accurate analytical model for circular ducts, the majority of transmission loss theory is centred on rectangular ductwork, however, formulae have been proposed to approximate the frequency curve segments of cylindrical ductwork, including Cummings [2], Reynolds [3], ASHRAE [1] and SMACNA [4]. In addition, rectangular duct formulae cited by Bies & Hansen [5] have been adapted for cylindrical pipes.

The Transmission Loss, TL_{out}, of ducting is normalised for duct breakout transmission and is independent of duct size or surface area [1] as follows.

At frequencies below the cross-over frequency, f_{cr}, the quantity TL_{out} is calculated by Equation (1):

$$TL_{out} = 10\log(fm^2/(a+b))-13. \qquad f < f_{cr} \qquad (1)$$

where

$$f_{cr} = 612/(a/b)^2 \qquad \text{Hz} \qquad (2)$$

f = band centre frequency, Hz
m = mass/unit area, kg/m^2
$a+b$ = may be considered as the diameter for cylindrical ducting, m

At frequencies above f_{cr} and below half the critical frequency, f_c:

$$TL_{out} = 20\log(fm)-45. \qquad f_{cr} < f < f_c/2 \qquad (3)$$

(Limited to 45dB).

Reynolds [3] and SMACNA [4] suggest that the transmission loss be given by the larger of the following two formulas:

$$TL_{out} = 17.6\log(m)-49.8\log(f) -55.3\log(d)+130.1 \quad (4)$$

$$TL_{out} = 17.6\log(m)-6.6\log(f) -36.9\log(d)+26.4 \quad (5)$$

(Limited to 50dB).

where

d = inside diameter of duct, m

Following the transmission loss values of reciprocity developed by Ver [6], the relationship between breakout and break-in transmission loss may be found by:

Above the cutoff frequency, f_{co}

$$TL_{in} = TL_{out}-3 \qquad f>f_{co} \quad (6)$$

and below the cutoff frequency, f_{co}, the larger value of

$$TL_{in} = TL_{out}-4-10\log(a/b) +20\log f/f_{co} \qquad f<f_{co} \quad (7)$$

$$TL_{in} = 10\log(2L/d) \qquad f<f_{co} \quad (8)$$

where

$f_{co} = c/2a.$ (9)
L = Pipe length exposed to break-in noise
S = Internal area
$a/b=1$ for a round cross sectional duct

The preceding formulae assume that natural duct losses do not occur without internal lining nor do energy losses occur due to duct wall vibration. It is anticipated that the effects of natural duct losses may be neglected for rigid PVC pipe over mostly short runs considered in this paper's experimental setup.

RESULTS

Figures 3 and 4 show the measured Insertion Loss values from the experimental reverberant and nearfield setups, with and without pipe lagging installed in four stages:

- ≈50% total area of pipes lagged with 5kg/m^2 barrier and 25mm thick convoluted foam;
- 100% total area of pipes lagged with 5kg/m^2 barrier and 25mm thick convoluted foam;
- 100% total area of pipes lagged with 5kg/m^2 barrier and 25mm thick convoluted foam with orifices "capped" to demonstrate a best case scenario for Insertion Loss with lagging;
- All pipes unlagged with orifices "capped" to demonstrate a best case scenario for Insertion Loss without lagging.

While site conditions were not optimal, the data shows good agreement with anticipated performance. Flanking transmission (through the floor) may have affected results in the lower frequency range, however this is outside the range of interest of the case study considering that in any hypothetical case the pipe lagging predominantly only performs above ≈500Hz, as demonstrated by the experimental data.

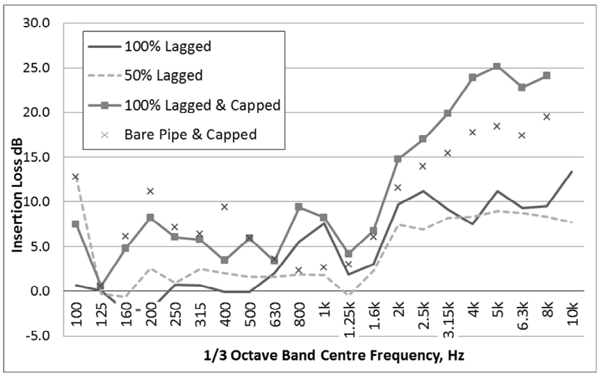

Figure 3. Insertion Loss – Average Room Measurements

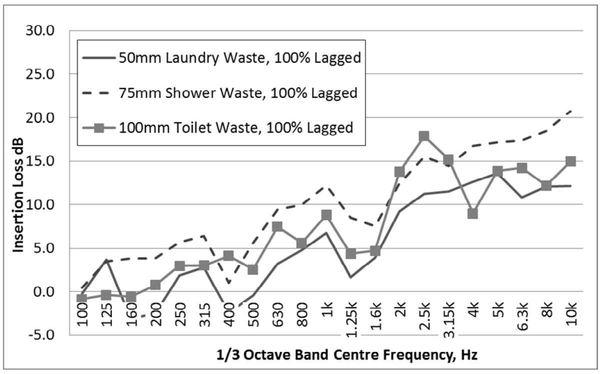

Figure 4. Insertion Loss – Nearfield Measurements

Furthermore, airborne noise issues involving speech break-in (from retail public address systems typically producing very little low frequency content) are more likely to be due to mid-high frequencies.

Also as anticipated, negative Insertion Loss was observed in the 160Hz and 200Hz bands due to the increased surface area [4] and additional degrees of freedom being introduced into the transmission system [2].

The greatest Insertion Loss performance from the lagging was demonstrated above 1.6kHz (approximately 10dB). However, it was also observed that simply lagging the pipes did not reduce the flanking transmission through the pipe to a level equal to that through the floor (or other transmission paths). This was observed by "capping" the pipes both with and without lagging, which demonstrated greater Insertion Loss performance up to 8dB to 15dB above lagging alone (i.e. sound transmission above 1.6kHz still dominated the soundfield through the pipes and not through other transmission paths).

The experimental measured data was compared to the theoretical data following the formulae in the preceding section. Following ASHRAE [1], the in-pipe Sound Power Level was calculated by:

$$L_{w(in)} = L_{w(out)}-TL_{in}-3. \quad (10)$$

where

$L_{w(in)}$ = SWL of sound transmitted into the pipe and then propagated up and downstream of the point of entry, dB
$L_{w(out)}$ = SWL incident on the outside of the pipe walls, dB
TL_{in} = Break-in Transmission Loss, dB

The experimental setup was largely dominated by the reverberant field and therefore the incident (diffuse) Sound Power Level for comparisons with theoretical models is simplified to [7 Long]:

$$L_{w(out)} = L_p + 10\log(PL) - 4.2 \qquad (11)$$

where

L_p = Average reverberant Sound Pressure Level measured in the source room
P = Circumference of pipe, m
L = Pipe length exposed to break-in noise, m

The theoretical model considered the following material properties for PVC pipe:

Table 1. Material Properties

Material	Density (kg/m^3)	Young's Modulus (10^9 N/m^2)	Poisson's Ratio
PVC Pipe	1,400	2.8	0.4

Each of the three pipe paths were calculated separately and summed in the receiving room for the purposes of the comparison.

The comparison of measured and predicted data (following the greater of Equation (1) through (9)) is presented in Figure 5.

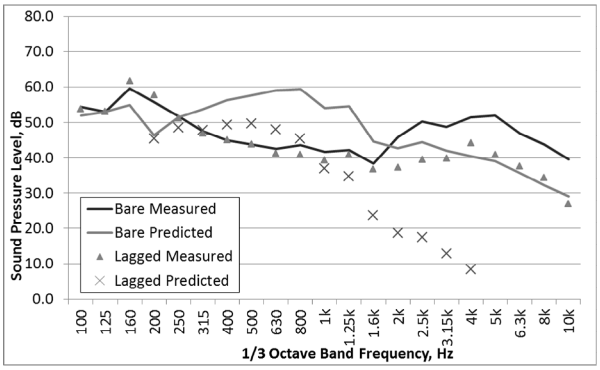

Figure 5. Measured vs. Theoretical Results – Experimental Setup

The predicted model included the preceding formulae for transmission loss of the PVC pipe wall, end reflection loss [1] at the orifices and laboratory measured Insertion Loss values equal to the pipe lagging material used [8].

The comparative results between the experimental setup and predictive analysis show good agreement in some regions of the spectrum and curve shape, however in particular the predicted SPL with PVC pipe and lagging appears to be exceptionally overestimated above 1.6kHz.

CASE STUDY

The specific application relevant to the research involves a mixed use development having a retail store with apartments above. The design of the building resulted in exposed wastewater pipes (from above apartments) visible in the retail tenancy below, with no ceiling providing any protection from noise exposure due to store operation. Given a concern from the retail tenant regarding the potential for noise nuisance to residents above, specifically in relation to noise associated with the public address system, it was decided to conduct the study documented herein.

The case study considered unlagged 100mm PVC piping of up to 6m in length connected to a bathroom floor waste orifice (i.e. no additional insertion losses due to plumbing fixtures).

Using a typical 1/3 octave voice spectrum with amplitudes measured in the field for similar scenarios, results were calculated based on the theoretical algorithms (Equation (1) through (11)) and using the experimental data measured by the authors. The spectral results are presented in Figure 6 with a summary of the expected dB(A) levels presented in Table 2.

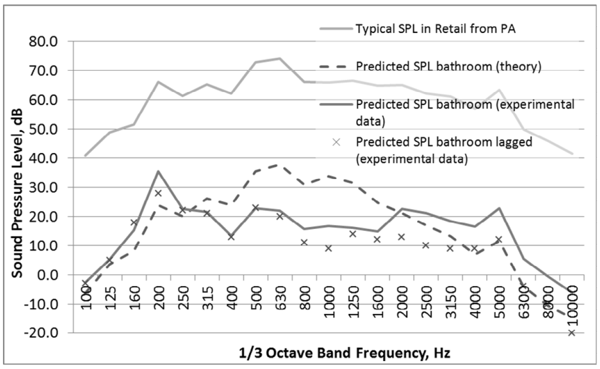

Figure 6. Calculated Results – Case Study

Table 2. Case Study Results Summary (dBA)

Typical PA SPL During Announcement in Retail	79dB(A)
SPL at Receiver Based on Theoretical Algorithms	42dB(A)
SPL at Receiver Based on Experimental Data for Bare PVC Pipes	33dB(A)
SPL at Receiver Based on Experimental Data for Lagged PVC Pipes	31dB(A)

Considering that background noise levels of <30dB(A) can be anticipated in bathrooms of residential apartments (without services running and assuming that on-suite doors are often left open during the night), the above results indicate that speech during announcements would be audible and potentially intelligible. While the lagged pipe does not appear to provide significant overall Noise Reduction (dBA) due to higher levels of voice energy in the 500Hz region, its benefits would be in the reduction of speech intelligibility frequencies (>1.6kHz) in the order of ≈10dB.

DISCUSSION

It is not known if the data disparity is simply due to the intricacies of the experimental setup or the difficulty of modelling break-in noise and flanking transmission through rigid PVC pipes. However, given the bare pipe prediction shows better agreement than the predicted lagged pipe, there is merit in further analysing the Insertion Loss performance differences between limp mass barriers with porous layers tested in the laboratory via fluid/mechanical excitation and airborne excitation. We note that ASTM E1222 [9] presents a simple method for quantifying the Insertion Loss using an airborne source, however the preference in Australia appears to be towards the use of fluid filled systems. Additional materials may also need to be considered that do not rely on a porous interlayer used to reduce fluid-borne noise, but may not greatly impact on the performance of airborne noise reduction.

The measured results indicate that pipe lagging is beneficial at reducing the total noise transmission and in particular, above 1.6kHz where:

- Speech intelligibility is critical
- Small pipe diameters are likely to more efficiently transmit higher frequency noise flanking

Further investigation is required to better understand the transmission loss of PVC pipe walls, including the mass/stiffness ratio of typical PVC pipe, the relationship between pure airborne sound transmission through pipe lagging installed over PVC pipe as well as transmission through fluid vs. air-filled pipes.

As the testing scenario was not able to quantify the effects of the complete plumbing system, such as the effects of P-traps or S-traps, fluid retained in the system and the potential amplifying effects of basins, further testing should be conducted in a commissioned building for validation.

However, considering a worst-case scenario with a bathroom floor waste orifice, calculated results using both theoretical and experimental data suggest that speech during PA announcements in retail areas below would be audible, and potentially intelligible without lagging.

To this end, the potential for noise transfer via lagged or unlagged pipes may be practically mitigated by reducing the actual sound pressure level incident on pipe surfaces as follows:

- Designing a PA system having a greater number of distributed speakers at a lower volume as opposed to fewer speakers at a higher volume;
- Positioning speakers as far from exposed pipework as possible (as close to the selling floor as possible);
- Reducing the overall level of the public address system to the minimum required for intelligibility on the selling floor.

In addition, minimising the low frequency content of announcements and program material made through the PA system by introducing a High Pass Filter in the signal chain (which maximises the overall apparent effectiveness of pipe lagging given its effectiveness predominantly above 500Hz) is also expected to reduce the overall resultant sound pressure level in the residential space above.

CONCLUSION

Airborne sound transfer via exposed wastepipes and subsequently through drainage orifices may feasibly be considered an issue with respect to the potential for causing nuisance to residential inhabitants above. Pipe lagging is beneficial at increasing the overall airborne transmission loss of PVC pipe but may not perform as well as expected by the Insertion Loss values measured via fluid induced testing.

While the effects of airborne break-in noise via low mass PVC piping and lagging do not appear to be well researched, a basic analytical model was considered here based on the work and research conducted in relation to air ducts to assess its appropriateness in typical acoustic consulting.

Further work is required to validate measurements and theoretical models presented in this paper and it is suggested that, as a starting point, both the transmission loss of PVC pipe walls and the Insertion Loss of pipe lagging due to airborne sound be investigated further.

Finally, the mitigation of noise transfer via wastewater pipes between commercial/retail and residential tenancies above may be achieved by reducing the overall sound pressure level incident on pipe surfaces.

ACKNOWLEDGEMENTS

The authors would like to thank Pyrotek Pty Ltd and St Hilliers Construction for their assistance with field testing.

REFERENCES

[1] American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc, ASHRAE Handbook 2007, *HVAC Applications (SI)*, Atlanta, GA, ch. 47.

[2] A. Cummings, 2001, *Sound Transmission Through Duct Walls*, Journal of Sound and Vibration

[3] D. D. Reynolds, 1990, *Noise Control, Circular Ducts*, SMACNA, Chantilly, VA.

[4] Sheet Metal and Air-conditioning Contractors National Association, 2004, *HVAC Sound and Vibration Manual*, SMACNA, Chantilly, VA.

[5] D. Bies & C. Hansen, 2009, *Engineering Noise Control, Fourth Edition*, SponPress, New York, NY.

[6] I. Ver, 1983, *Prediction of Sound Transmission Through Duct Walls; Breakout and Pickup, Report 5116*, ASHRAE, Atlanta, GA.

[7] M. Long, 2006, *Architectural Acoustics*, Elsevier Academic Press, San Diego, CA.

[8] Pyrotek, 2012, *Soundlag® Information Page*, Pyrotek, <http://www.pyroteknc.com>.

[9] ASTM 2009, *Standard Test Method for Laboratory Measurement of the Insertion Loss of Pipe Lagging Systems*, ASTM E1222-90:2009, American Society for Testing and Materials, West Conshohocken, PA.