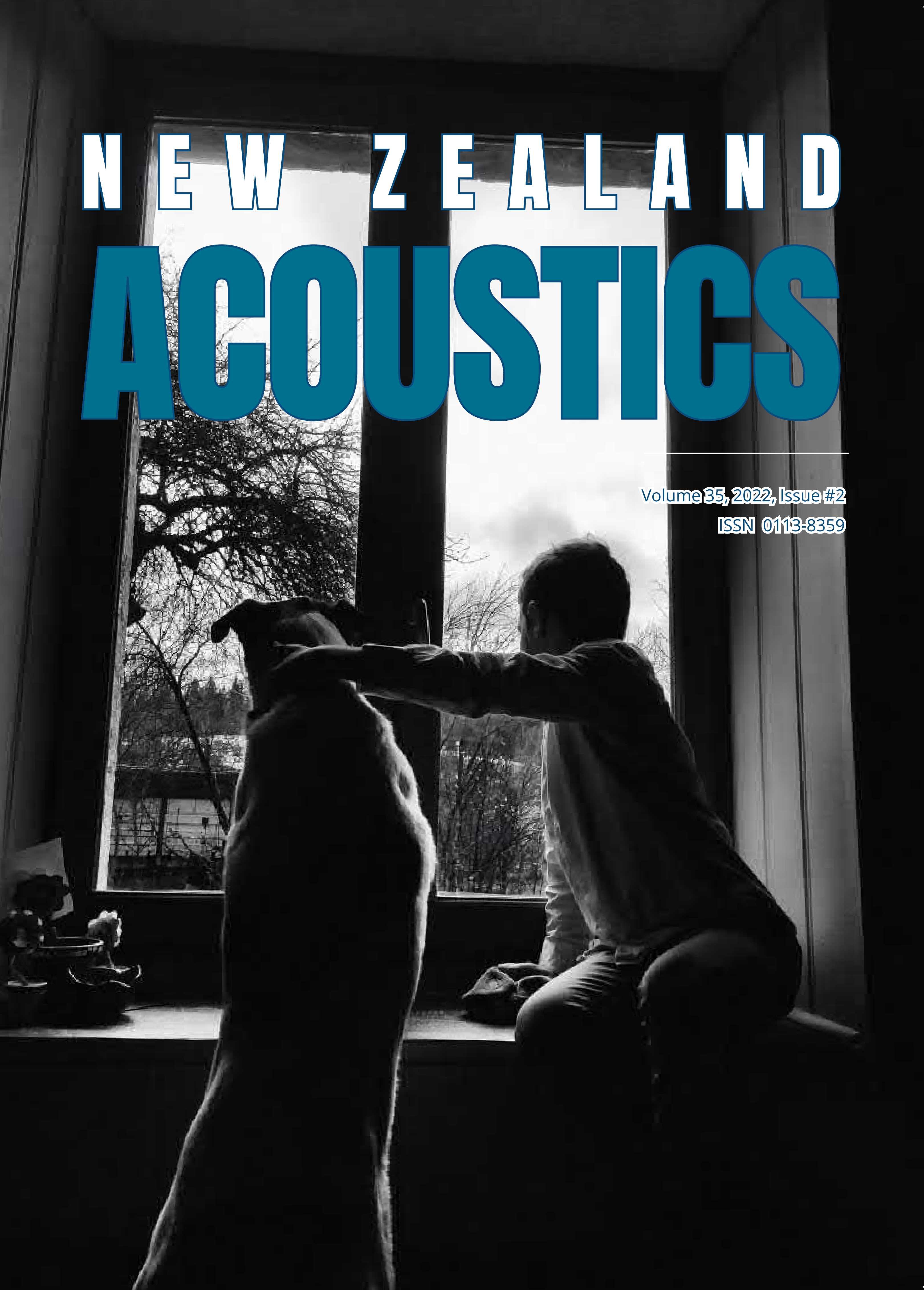

NEW ZEALAND ACOUSTICS

Volume 35, 2022, Issue #2
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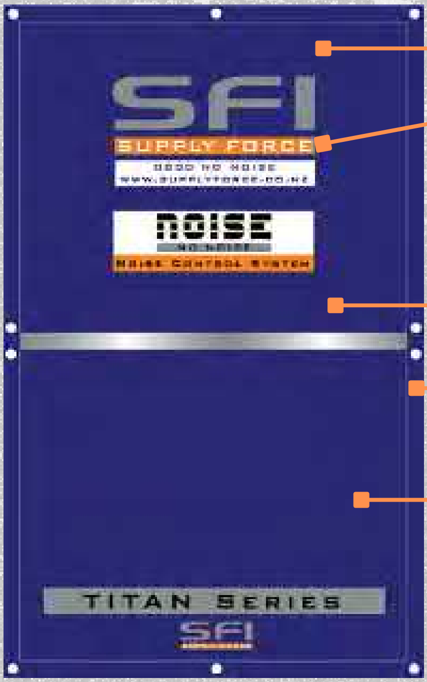

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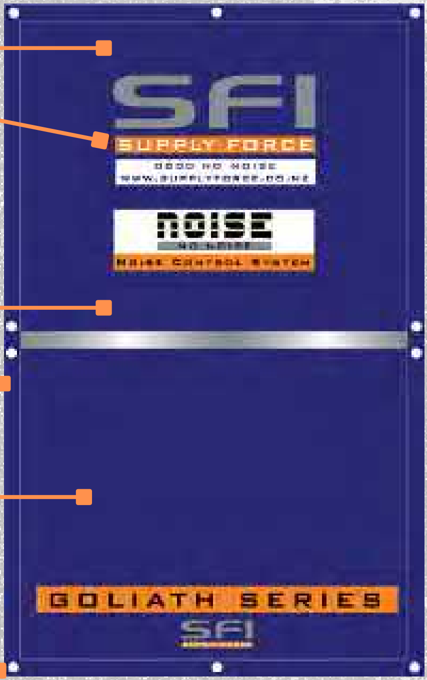

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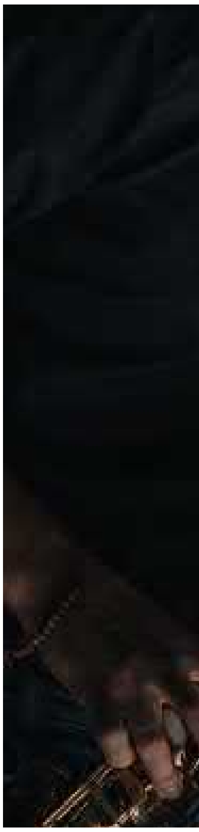

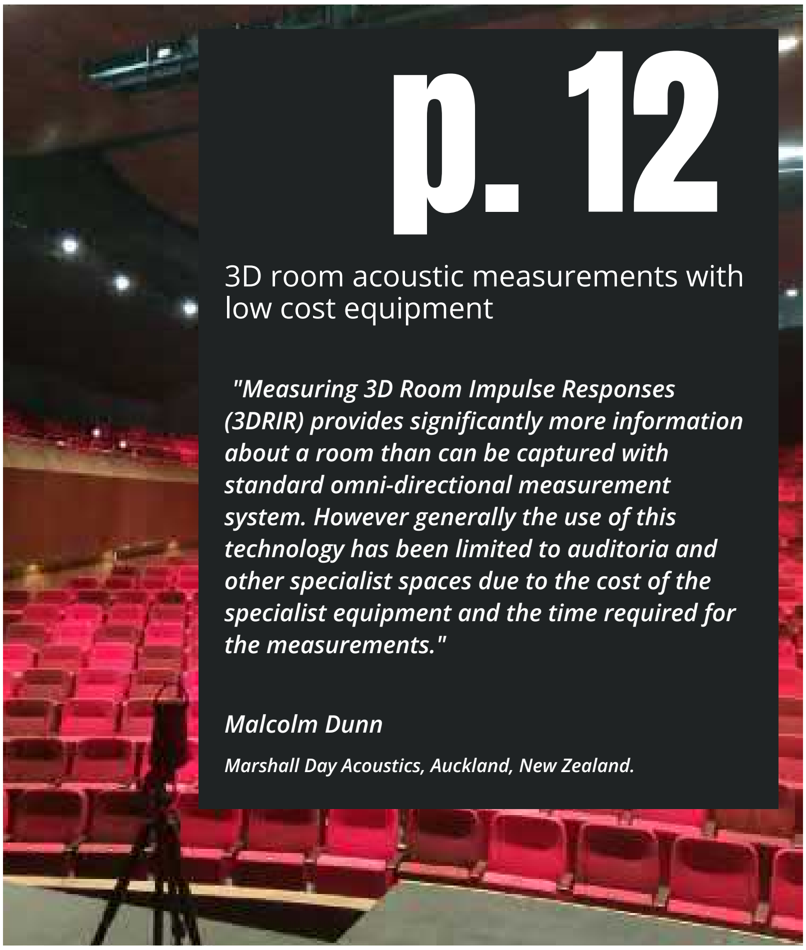

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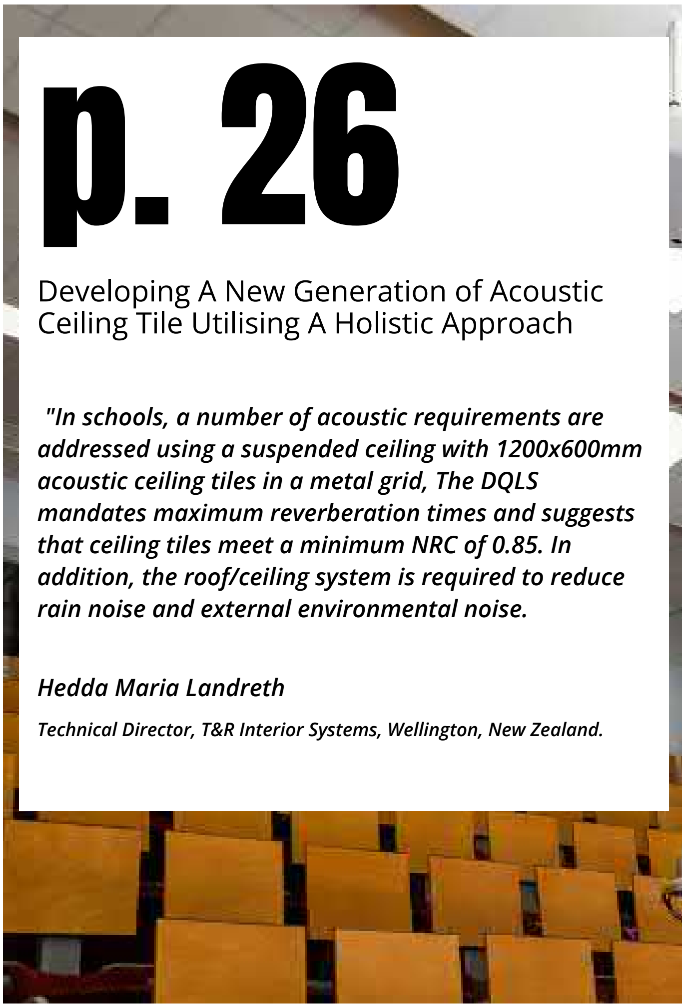
3D room acoustic measurements with low cost equipment

"Measuring 3D Room Impulse Responses (3DRIR) provides significantly more information about a room than can be captured with standard omni-directional measurement system. However generally the use of this technology has been limited to auditoria and other specialist spaces due to the cost of the specialist equipment and the time required for the measurements."

Malcolm Dunn

Marshall Day Acoustics, Auckland, New Zealand.



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Developing A New Generation of Acoustic Ceiling Tile Utilising A Holistic Approach

"In schools, a number of acoustic requirements are addressed using a suspended ceiling with 1200x600mm acoustic ceiling tiles in a metal grid, The DQLS mandates maximum reverberation times and suggests that ceiling tiles meet a minimum NRC of 0.85. In addition, the roof/ceiling system is required to reduce rain noise and external environmental noise.

Hedda Maria Landreth

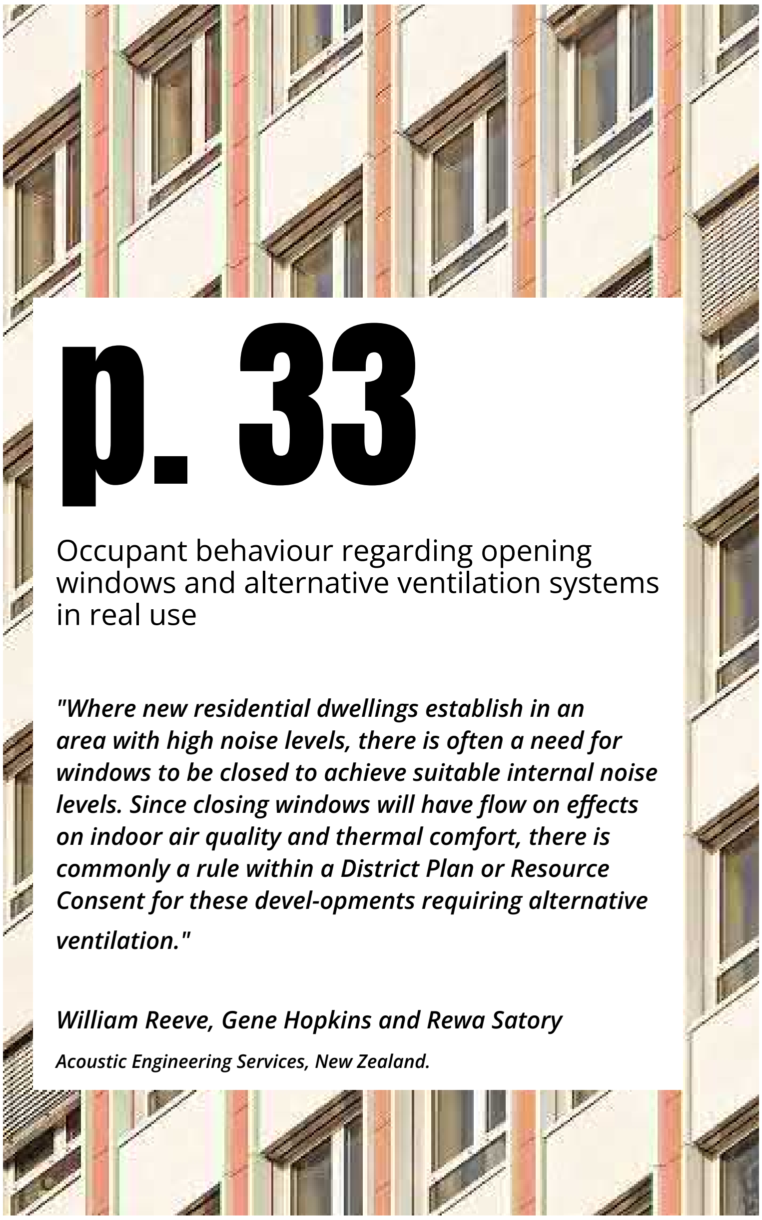
Technical Director, T&R Interior Systems, Wellington, New Zealand.

p. 17

Designing and 3D printing the ultimate saxophone reed

"A series of reeds were fabricated using additive manufacturing. Playable reeds were produced by adjusting the reed geometry. They were also fabricated by inserting aluminium and steel into the reed to increase the longitudinal stiffness."

Jonathan Everett, Daniel Clark, Dr Andrew Hall, Dr George Dodd.



p. 33

Occupant behaviour regarding opening windows and alternative ventilation systems in real use

"Where new residential dwellings establish in an area with high noise levels, there is often a need for windows to be closed to achieve suitable internal noise levels. Since closing windows will have flow on effects on indoor air quality and thermal comfort, there is commonly a rule within a District Plan or Resource Consent for these devel-opments requiring alternative ventilation."

William Reeve, Gene Hopkins and Rewa Satory

Acoustic Engineering Services, New Zealand.

Greetings all,

This year seems to be zipping by quite quickly with a relatively mild, but wet, winter up here in Auckland already seemingly coming to an end. I trust that others around the country have made it through the colder months unscathed and got to enjoy those winter activities which will be over for another year.

The ASNZ Acoustics 2022 conference at Te Papa, Wellington is drawing ever nearer (31 Oct to 2 Nov 2022), and I hope that those who submitted abstracts have finalised their papers in time. This conference is gearing up to be a world class event with a record number of papers, multiple streams, a great venue and an unusual amount of overseas interest. The AAAC are planning their AGM to occur in Wellington adjacent to our conference, so we can expect to see a few more Australian acoustical consultants along for our conference as well.

Unfortunately, earlier this year the ASNZ Council received a complaint from a member of the public against an ASNZ Member. The Council formed an independent disciplinary panel subcommittee to review the complaint against the Rules of Conduct and Disciplinary Measures for the Acoustical Society of New Zealand, and it was found that there was some substance to the complaint, resulting in disciplinary action being taken. The complaint review process was time consuming and difficult, and I thank those Councillors involved. I'm highlighting this issue because of its importance to the integrity of the Society. All Members must understand that we have an obligation to uphold a certain standard of professionalism, competency, objectiveness and reliability in whichever field of acoustics we operate.

On a lighter note, the "lunch bunches" are starting up again, scheduled for the last Friday of every month. These are a great opportunity to expand our knowledge of acoustics (sometimes they're very practical, sometimes very esoteric; but always interesting), in an informal and social lunchtime session. Sessions have been traditionally held in Auckland, in conjunction with the University of Auckland, but we are making an effort to include live streaming and recording of the sessions for those across the country. We also welcome any presentation offers from other centres – please contact me or our Secretary, James Whitlock, if you would like to get involved.

All the best,
Tim Beresford
President of the Acoustical Society of New Zealand

Kia ora and welcome to the second issue of New Zealand Acoustics for 2022. We hope that you have weathered the ongoing challenges of COVID (and the weather) as we return to some sort of normality. We hope you are looking forward to the Acoustics 2022 conference at the end of October, here in Wellington.

In this issue, we have a selection of varied papers across a range of topics, from low-cost room acoustic measurement to occupant behaviour regarding opening windows and using mechanical ventilation systems when provided. There is a varied range of news items, all with QR codes so you can scan them and quickly access the extended content. And finally, we have a 10-question quiz, where some of the answers are linked to one of the news items, enjoy!

Lindsay Hannah & Wyatt Page
Principal Editors

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Tim Beresford

Lindsay Hannah

Wyatt Page

NEWS

The people eavesdropping on life underground - Why soil is a surprisingly noisy place

https://www.bbc.com/future/article/20220225-the-people-eavesdropping-on-life-underground

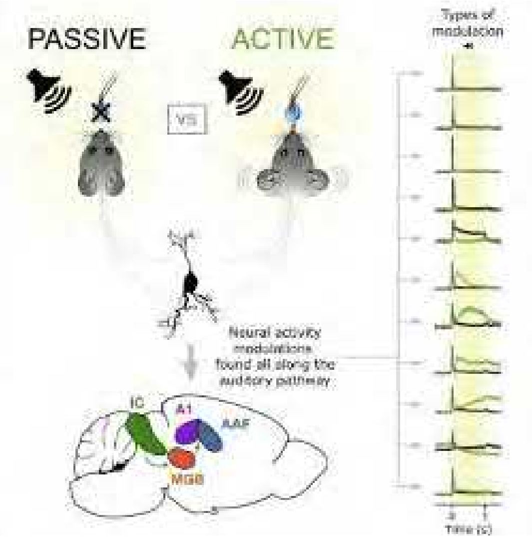
Noise pollution - How the world has forgotten to listen

Noise, like the saturation of 21st century urban life, can keep our bodies in a state of alarm, or can help our brains grow stronger, scientist Nina Kraus says.

https://www.rnz.co.nz/national/programmes/sunday/audio/2018833114/noise-pollution-how-the-world-has-forgotten-to-listen

When the brain switches from hearing to listening

What happens in the brain when simply hearing becomes listening? To answer this question, researchers have traced the neuronal fingerprint of the two types of sound processing in the mouse brain.



These Sound Waves Could Make You Feel High

In the never-ending quest to either get high or feel better, people are using a sound technology, called “binaural beats,” to mellow their minds. This recording technique uses tiny differences in frequency to generate two close tones and a third, phantom tone.

A new mechanism responsible for controlling auditory sensitivity

Researchers identified a new mechanism by which auditory sensitivity is regulated. The mechanism can temporarily reduce sensitivity in the auditory system to protect itself from loud sounds that can cause hearing damage.

https://neurosciencenews.com/auditory-sensitivity-mrechanism-21094/

Amsterdam Schiphol's capacity to be cut due to noise pollution

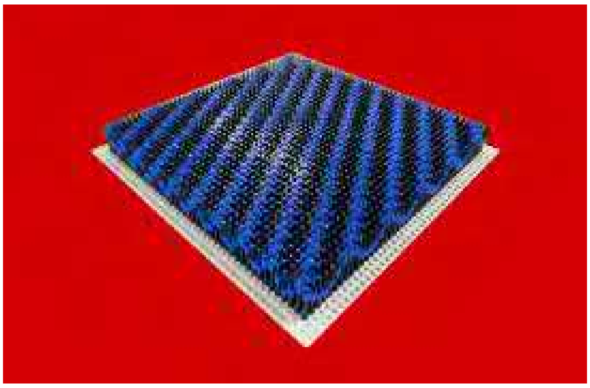
The Dutch government will cut the maximum number of flights allowed per year at Amsterdam Schiphol airport in a bid to reduce noise and air pollution. It is expected to go into effect in November 2023, and equates to a 20 percent cut in flights per year.

Tonga Eruption was the loudest sound on Earth since 1883, with a wave reaching higher than the International Space Station

The Hunga Tonga undersea volcanic eruption on 15 January 2022, was one of the most powerful recorded, with audible sound detected more than 10,000 kilometres from the source. It released atmospheric waves with an energy that has not been seen in 139 years. It was the loudest sound on Earth since the Krakatoa eruption of May 20, 1883.

Creating the smallest SHOCKWAVE!

Join the Action lab - This is what happens when you smash two giant steel ball bearings together! You get an amazing shock-wave that can burn paper and send it flying at sonic speeds!

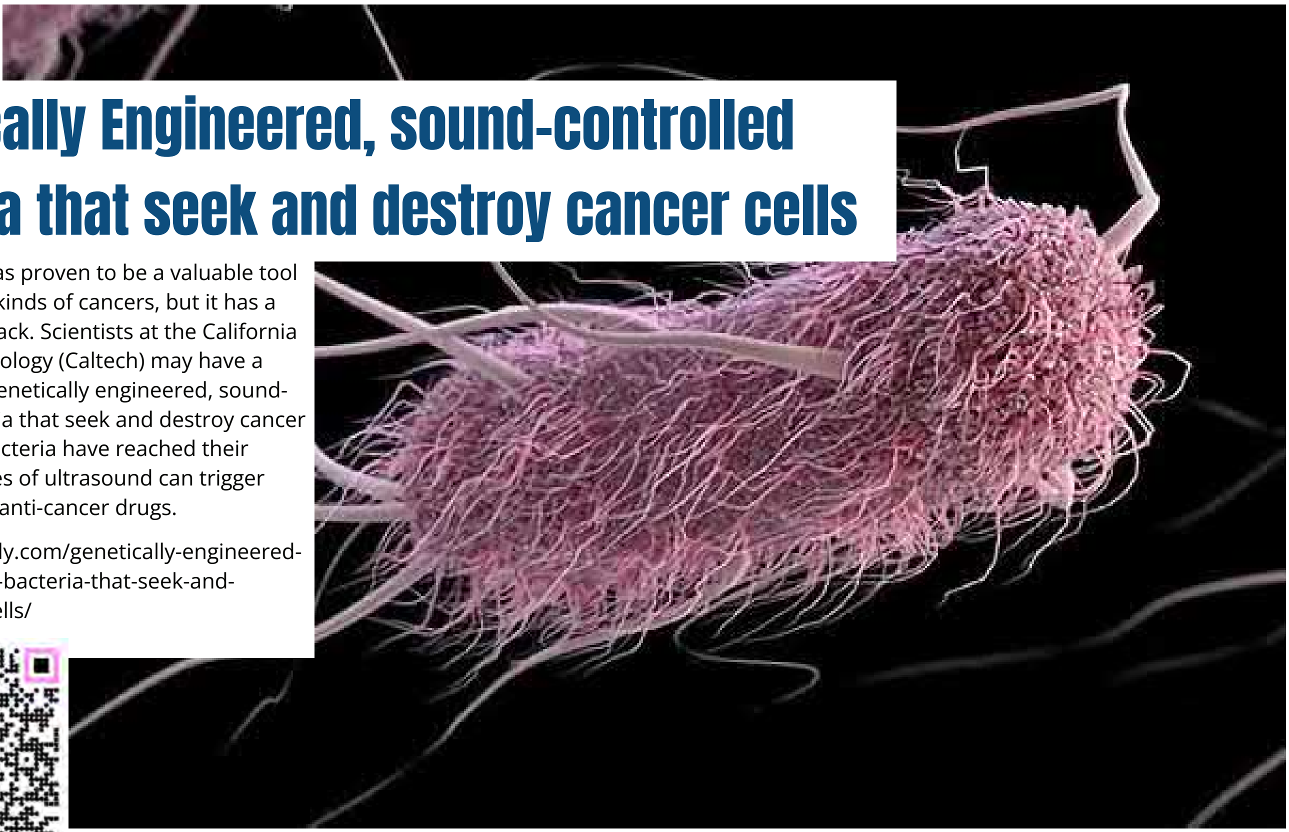


Forget Lasers - The hot new tool for Physicists is sound

From acoustic tweezers to holograms, engineers are taking inspiration from the field of optics—and riding the sound wave.

https://www.wired.com/story/acoustic-sound-waves-engineers-physics/

Genetically Engineered, sound-controlled bacteria that seek and destroy cancer cells



Chemotherapy has proven to be a valuable tool in treating many kinds of cancers, but it has a significant drawback. Scientists at the California Institute of Technology (Caltech) may have a better solution: genetically engineered, sound-controlled bacteria that seek and destroy cancer cells. Once the bacteria have reached their destination, pulses of ultrasound can trigger them to produce anti-cancer drugs.

https://scitechdaily.com/genetically-engineered-sound-controlled-bacteria-that-seek-and-destroy-cancer-cells/

Humans can learn to 'echolocate' in just 10 weeks, experiment shows

With enough training, most humans can learn how to echolocate, using their tongue to make clicking sounds and interpreting the echoes that come back, reflected from the surrounding environment.

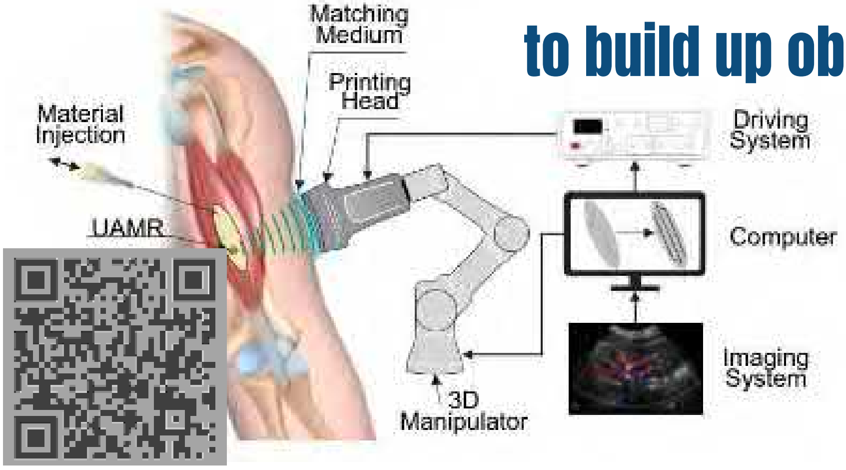
https://www.sciencealert.com/most-humans-can-learn-how-to-echolocate-in-just-10-weeks-experiment-shows

New bird scaring regulations not for all

While Whakatāne District Council plans to lower the decibel levels allowable for bird scaring cannons the new regulation will not apply to orchardists currently using them.

https://www.rnz.co.nz/news/national/470951/new-bird-scaring-regulations-not-for-all

New type of 3D printing uses sound waves to build up objects



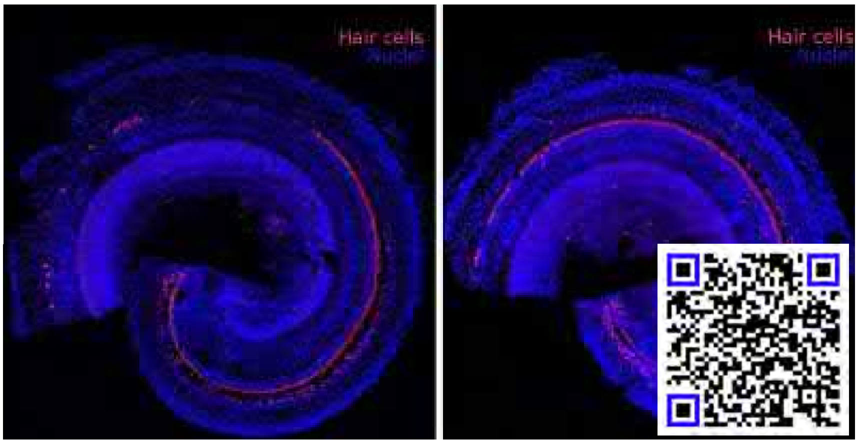
Direct sound printing (DSP) uses ultrasound to create microscopic oscillating bubbles, which in turn cause resin to solidify at specific locations. Utilizing this technique, it is conceivable that implants could be 3D printed within a patient's body, without the need for surgery.

https://newatlas.com/3d-printing/direct-sound-3d-printing/

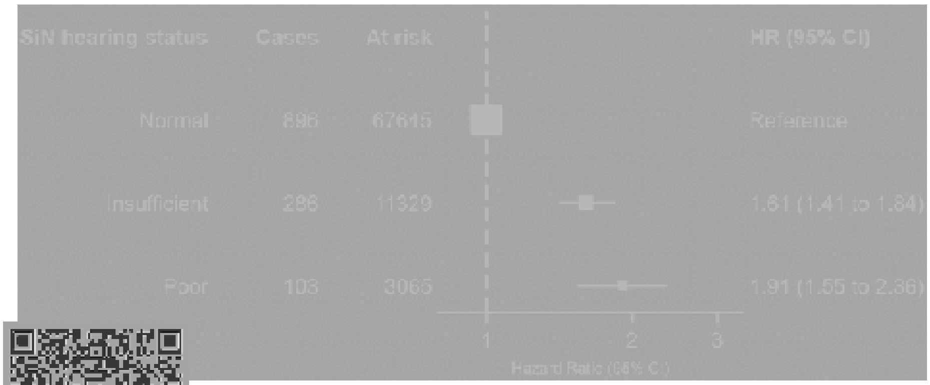
Reversing hearing loss with regenerative therapy

A new regenerative therapy uses small molecules to program progenitor cells derived from stem cells in the inner ear to grow new hair cells within the cochlear and restore hearing.

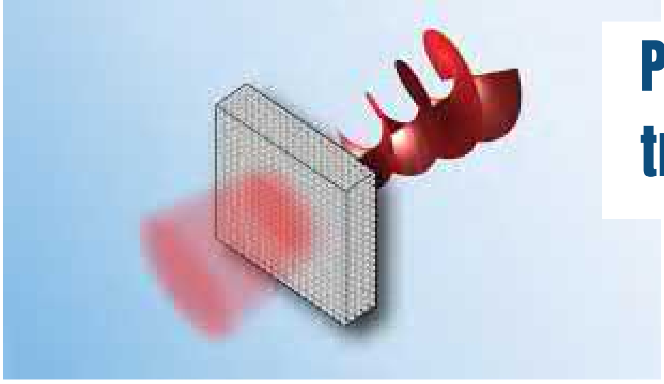
https://.com/regenerative-therapy-hearing-loss-20278/



People who struggle to hear conversations in noisy rooms are almost TWICE as likely to develop dementia



https://www.dailymail.co.uk/sciencetech/article-9810057/Struggling-hear-conversations-noisy-room-increases-dementia-risk.htm



Physicists discover special transverse sound wave

The absence of shear force in the air, or fluids, is the reason why sound is a longitudinal wave. A research team at City University of Hong Kong discovered a new type of sound wave: the airborne sound wave vibrates transversely and carries both spin and orbital angular momentum like light does.

Quantum optical microphone works even better than a regular one

By detecting tiny movements of particles of light, a quantum microphone has recorded human speech that is easier to understand than if it is captured by an equivalent classical version.

https://www.newscientist.com/article/2325051-quantum-microphone-works-even-better-than-a-regular-one/

'Students can't hear': Principal joins calls for road safety, noise improvements along stretch of Taranaki state highway

A petition has been launched to have the speed limit through a Taranaki township reduced to improve safety and reduce road noise, which is so bad the nearby school can't open its windows – breaking Covid-19 advice.

https://www.stuff.co.nz/taranaki-daily-news/news/127698657/students-cant-hear-principal-joins-calls-for-road-safety-noise-improvements-along-stretch-of-taranaki-state-highway

Larry John Elliott - Eulogy

ASNZ Member 1983 to 2018

Larry was born on the 22nd of September 1947. After a few years in Christchurch, Larry grew up on Auckland's North Shore.

Larry attended Westlake Boys High School. In his teenage years he played in a school band called "The Romfords" with friends Peter Calvert and Graham Horne. He played electric guitar, and owned a pre–CBS Fender Strat, that both his son Grant and his grandson Toby are gutted he sold to pay for some wedding photos.

In 1966 Larry secured a position with New Zealand Broadcasting Corporation at Radio 1XN in Whangarei as a sound technician. It was in Whangarei where he met Colleen Murphy. He used to regularly go to the record store Beggs to buy 45s where Colleen worked, but one day got the chance to accompany her on the guitar when she was recording a vocal track at the 1XN studio, as the booked guitar player was sick. He must have played well because 2 years later in 1968 they were married at the Whangarei Methodist Church and remained together for 54 years.

Around the same time, they got married, Larry got a new job in Auckland as a member of the floor crew for AKTV2 studios in Auckland, and quickly moved into the sound department. Following this tenure, he moved to Mascot Studios in 1970 and notably was finishing an all-night recording session with singer Larry Morris up until the police arrived and arrested Morris at 5:55am. In 1972 he moved to Stebbings Recording Studio in Jervois Road, recording many well-known NZ artists of the late 60s and early 70s. In the same year their son Grant was born, and in fact Larry was mastering a session of "Sunshine Through a Prism" by Susanne Lynch and had to leave early to go and meet him. Those were different days.

In 1973 their first daughter Donna was born and in the mid 70s Larry headed back to TV ending up as head of sound for TVNZ. During that time, he headed up the sound team for The Royal Variety Concert during Queen Elizabeth's visit in 1977, the visit of Pope John Paul II in 1981 and the Commonwealth Games in 1994. In 1980 his second daughter, Amanda was born.

Larry had a strong Christian faith which began in 1967 through his friendship with Wayne Hughes and unsurprisingly turned his sound engineering skills to worship music. Not long after, Larry & Colleen joined Queen Street Assembly of God that met in the Auckland Town Hall where Bruce was Head of Music. Larry quickly became involved in the sound team and has been associated with sound and worship teams ever since, including recording albums and training workshops. Following Queen Street, the family attended Takapuna AOG headed by Wayne Hughes and after than moved to Auckland City Elim, joining his friend Bruce again.

In the early 1980s Queen St AOG started a building programme for their auditorium at Beaumont Street and Larry was asked to design the Sound System. It was on this project that he met Sir Harold Marshall and Chris Day who were designing the acoustics of the venue. This led to a 37 year partnership between Larry and Marshall Day Acoustics (more to come from Chris Day).

In the early 2000s Larry was invited to teach Sound at the University of Auckland where he taught for several years. Larry was always proud of the students he had and continued to follow many of their achievements once they had completed their studies.

In 2016 Larry was diagnosed with prostate cancer which was removed however 6 months later in March 2017 he was diagnosed with myelodysplasia, a form of blood cancer which he bravely fought for 5 years with regular chemotherapy sessions every 4-6 weeks. The Family are extremely grateful to the staff at North Shore Hospital for helping get those extra years with him.

In his spare time, he continued to pursue his recording passions through the Auckland Choral Society of which Colleen has been a member since 1999 and who he had been recording since 2001. This work lead to him setting up Vivante, through which he recorded many orchestral concerts, ensembles and choirs. In May this year, Larry was made an honourary lifetime member of Auckland Choral Society, the only non-singing member ever to have received this honour.

In June 2022 Larry's diagnosis changed from myelodysplasia to acute myeloid leukaemia and on the 22nd of August 2022 Larry went to be with his Lord and saviour. He passed away peacefully in his daughter Donna's arms who had only made it back from the UK 24 hours earlier.

Tribute

by Christopher Day, 29 August 2022

I worked with Larry at Marshall Day Acoustics for almost 40 years and during that time developed a deep respect for him professionally. We also became close friends.

I visited Larry 3 weeks ago with my long-time colleague Keith Ballagh. He was completely lucid and as sharp as ever. He was sitting up in bed and we had a wonderful talk about our time working together. He spoke about the love he had for his family and how proud Colleen and he were of Grant, Donna and Amanda. He even managed to crack a couple of his slightly ironic jokes about his medical condition.

Some of you may not know much about Larry's professional career – so a brief summary

When I met Larry in 1979, he was already a highly successful sound mixer and recording engineer at TVNZ, Radio New Zealand and Stebbings recording studios. However, he was very keen to get involved with sound system design and in 1982 he took the brave decision to change careers and join Harold Marshall and me at Marshall Day Acoustics. I say brave because MDA was only 9 months old and there was no guaranteed work-flow. He was effectively a founding member of Marshall Day and part of the extended company family.

Larry very quickly became a world leader and pioneer in the field of sound system design. He was highly regarded by the acoustic and theatre design industry. The US loudspeaker manufacturer Altec Lansing, flew Larry to the USA and other locations around the world to lead electro-acoustic training seminars. Larry designed the sound system for the MCG in Melbourne, the Shah Alam Stadium in Malaysia and virtually every major venue in New Zealand.

Pete Fearnside, the founder of Marshall Day in Australia, said that Larry had a "no Bull" approach to electro-acoustic design and that his training sessions made an 'incomprehensible subject', easy to understand.

Larry was highly intelligent and an early adopter of technology. In 1981 he introduced me to the HP41c programmable hand-held calculator. It had a magnetic card reader and a printer - Larry loved it and taught me how to programme it. Larry was also an 'Apple guy' and became my Mac help-line.

He was the first person I knew to use voice recognition software - you know, computer dictation. He used a programme called Dragon. One day he was dictating a letter to a client and he finished it off, "Yours faithfully, Larry Elliott". The computer typed "Yours faithfully, Hairy Elephant". Luckily Larry spotted it before sending it off to the client. This had a wonderful double twist as, Larry had the memory of an elephant. Keith and I would always go to Larry about things in the past, which he could recall with remarkable detail.

Larry remained a highly sort after recording engineer in his spare time. He did countless hours of unpaid recording work for amateur groups including Auckland Choral Society, the Mt Albert Methodist Choir and the Auckland Youth Choir.

He was also the sound man for the Marshall Day rock and roll band - one of the most famous acts he has had the fortune to mix for. This was actually a bit of an ordeal for him as he didn't very much care for our music. Nevertheless, he did it and just made suitably disparaging remarks about the music.

To our elder son Simon, Larry was - "Larry the Lion". Whenever Simon came into the office in the early years, aged 3 to 5, Larry would hide behind the bars of the banister and roar like a lion. Initially Simon was suitably scared but after that he would always ask for Larry the Lion. Simon still refers to him as "Larry the Lion".

Our other son Andy was interested in loudspeaker design for the back of his mates' cars. Larry helped him get started designing and building 'doof doof' speakers. I wasn't quite so grateful to Larry when the manufacturing of those mammoth subs took over my garage and I couldn't get my car in.

My heart goes out to you Colleen - how amazing you have been through Larry's long illness. Two months ago, when the whole family was staying with you, you all got COVID - and Larry also got pneumonia - what a nightmare. But what wonderful love and support you have provided him through all this.

1983 NZ Acoustical Society Conference- Christchurch

Chris Day, Larry Elliott, Joanne Valentine, Stuart Camp

Larry was one of our real characters at Marshall Day. He was a significant part of our culture and knowledge base. He helped weave the fabric that is Marshall Day. He will be missed by all at Marshall Day and especially by me.

Last Monday I sent an email around the firm to let everyone know of Larry's death. I received lovely replies from all over the world with lots of kind words about Larry. I have collated them into a booklet for Colleen and the family along with some photos of Larry at work.

Thank you, Colleen, Grant, Donna and Amanda for the opportunity to pay tribute to my friend Larry - a stalwart at Marshall Day and a thoroughly good and decent man.

FEATURES

3D room acoustic measurements with low cost equipment

Malcolm Dunn

Marshall Day Acoustics, Auckland, New Zealand

Abstract

Measuring 3D Room Impulse Responses (3DRIR) provides significantly more information about a room than can be captured with standard omni-directional measurement system. However generally the use of this technology has been limited to auditoria and other specialist spaces due to the cost of the specialist equipment and the time required for the measurements. This paper describes how battery powered consumer grade equipment can be utilised to create effective 3DRIRs faster and cheaper than existing industry standard systems. The advantages as well as limitations are discussed.

1. Introduction

The methods for the measurement of room acoustic parameters are outlined in ISO 3382-1:2009. Measurements conforming to this standard have traditionally been undertaken with an omnidirectional microphone and dodecahedron loudspeaker. An additional figure-of-8 microphone has been used when Lateral fraction (JLF) or similar metrics are required. Modern measurement systems generally utilise a swept-sine or MLS measurement signal in accordance with ISO 18233:2006.

More recently, compact microphone arrays have been used to enable more detailed directional information to be captured. As well as enabling typical ISO 3382-1:2009 parameters to be measured, these compact arrays enable capture of full 3DIRs. The most common form of array consists of 4 cardioid microphones in a tetrahedral pattern. The signal captured by these microphones, as A-format, is converted into the more commonly used ambisonic B-format. The B-format 3D impulse responses can be processed to provide information on the direction of sound arrival (Protheroe, Guillemin, 2013) and can also be utilised to provide realistic 3D auralisations. The compact arrays can also generate figure-of-8 patterns that can be utilised to measure Lateral Fraction (JLF). By using the same array for both the omni and figure-of-8 pattern, error introduced in the calibration of different microphones can be avoided (Protheroe, Day, 2015).

ISO 3382-1:2009 requires the use of an ‘omnidirectional’ speaker. Most measurement systems use a dodecahedron shaped loudspeaker with individual wide range drivers per facet. A typical measurement grade dodecahedron would have an overall diameter of 350 mm and drivers of diameter 130 mm. The power amplifier can be separate or located within the loudspeaker. The system is generally mains powered with a weight of approximately 10 kg.

1.1. Limitations of the current system for common use

For a compact microphone array to provide accurate directional information the signal from each direction must be very evenly matched. This requires accurate calibration of microphone capsules and also very precise gain matching of the microphone channels. In practice a preamplifier with digitally controlled gains is required to enable accurate matching. To avoid the need for 4 separate microphone cables, conversion boxes that send analog audio through ethernet cables can be used. Alternatively, an audio-over-IP system such as Dante can be used.

The dodecahedron speaker is moderately heavy and requires power and a signal input. Because the source speaker is generally moved less than the microphone and is more difficult to move, it is common for the controlling computer and interface to be closest to the source. In large spaces this arrangement effectively necessitates a 2-person measurement operation. One person controls the measurements and moves the source speaker. The other person moves the microphone between receiver positions.

The above set-up works well for large performing arts spaces where the accuracy of the measurements is of prime importance. However, because the cost of equipment and the significant time required to undertake measurements, it is often not used in smaller spaces such as classrooms, meeting rooms, lecture theatres and studios. It is the author's experience that using 3D measurements in these spaces can be very useful in diagnosing issues that would not be seen in a traditional omnidirectional reverberation time measurements. An example would be a classroom with lots of ceiling absorption but minimal wall treatment. With a 3D measurement of the space it would be possible to see how sound reflecting between walls was creating a '2D field' and resulting in a much longer RT than would be expected based on the overall absorption.

In 2020, Marshall day Acoustics were approached by the Ministry of Education to develop a system to measure the room acoustic performance of a large number of classrooms within New Zealand. The system needed to be cost effective, portable and easy to use. The results of the measurements were to be used to identify need for remedial treatment. From our experience, using a 3D measurement rather than a traditional omni measurement would provide more information about the room and potentially reduce the need for additional site visits. However, using professional grade measurement equipment would be too expensive and impractical. This project provided the impetus to investigate the use of semi-professional and consumer equipment as part of a measurement system.

2. Advances in available technology

2.1. Widespread adoption of ambisonic format

As Virtual Reality (VR) and other mixed reality technology have become more common, ambisonic audio has become the standard format for sound within mixed reality content. This has meant that ambisonics equipment that was once only produced in small quantities for a specialist niche market is now being produced for the mainstream professional and semi-professional market. Ambisonic microphones are being produced by large manufacturers such as Sennheiser, Zoom and Rode. Interfaces are being produced that have 'ambisonics mode' or similar than ensures all gains are set equally. Some interfaces now include A-format to B-format conversion to simplify the user experience. Combined microphone and interface units are also becoming common with units available from Zylia, Zoom, MinDSP and Voyage Audio.

2.2. Small portable loudspeakers

Loudspeaker and battery technology has also significantly improved recently. Small portable "Bluetooth speakers" have become very common. The audio quality of such speakers vary considerably but the higher quality models produce a relatively balanced frequency response with an impressive sound output. Such speakers are battery powered and can operate for hours between charges. These loudspeaker systems are generally not designed for traditional stereo listening. Rather they are designed to provide a wide distribution of sound from a single point. This 'omni-directionality' is an advantage for acoustic measurements.

2.3. Widespread adoption of ambisonic format

Wireless transmission of audio is common in the live music and broadcast sectors but has not commonly been used for acoustic measurements. High quality lossless transmitters and receivers are available, however their typical cost and complexity means they are often not practical for acoustics use. There are further complexities if signals must be accurately time aligned, as is the case with ambisonic microphone signals.

Consumer grade wireless audio-over-Bluetooth devices have also significantly increased in popularity. However, Bluetooth systems are typically designed for only short range (<10 m) and the processing introduced to reduce bandwidth and latency results in an appreciable reduction in audio quality.

The increasing popularity of video recording for on-line content however has seen the introduction of low cost wireless systems for the semi-professional market that utilize 2.4 GHz transmission with minimal audio quality reduction.

3. COMPONENTS OF A LOW COST 3DRIR SYSTEM

Using the new technology available, as discussed in section 2, the following system was trialled.

3.1. Microphone and audio interface

The Zoom H3-VR is a semi-professional grade unit that includes both a tetrahedral mic array and USB interface with in-built A-format to B-format conversion. Designed to capture ambisonic audio in conjunction with a 360 camera it offers a significant number of features (Zoom, 2018) at a very affordable price (approximately $500 NZD).

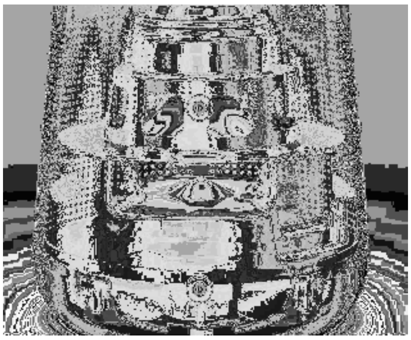
Source (Zoomcorp.com)

Figure 1: Zoom H3-VR

3.2. Loudspeaker

The Bose Revolve+ is an example of high quality consumer grade 'Bluetooth speaker'. This unit uses a single full range driver that is facing down and dual passive radiators (bose.co.nz). The sides of the unit are perforated to enable the sound to radiate in all directions. This design creates a very uniform distribution of sound in horizontal plane. The small size of the unit (18.4 cm H x 10.5 cm W x 10.5 cm D) also enables relatively uniform distribution in the vertical plane. The battery life is up to 16 hours (Bose.co.nz).

Source (Bose, 2021)
Figure 2: Bose Revolve+



Source (Bose, 2021)
Figure 3: Revolve+ loudspeaker internal cut-away

3.3. Wireless system

The Rode Wireless Go ($329 NZD) was chosen to enable wireless transmission. This system uses the 2.4 G Hz band to transmit “broadcast grade audio”(Rode, 2021) with a range of up to 70 m.

Source (Rode, 2021)
Figure 4: Rode Wireless Go

4. Performance testing

Testing of the individual components and overall system were undertaken as outlined below. The purpose of these tests was not to provide comprehensive performance data but to confirm the potential suitability of the equipment for practical use.

4.1. Directional accuracy of microphone and audio interface

Impulse response measurements were made over 360 degrees at 15 degree intervals in the anechoic chamber at the University of Auckland. There was some equipment in the chamber when the tests were undertaken but this is not expected to significantly affect results.

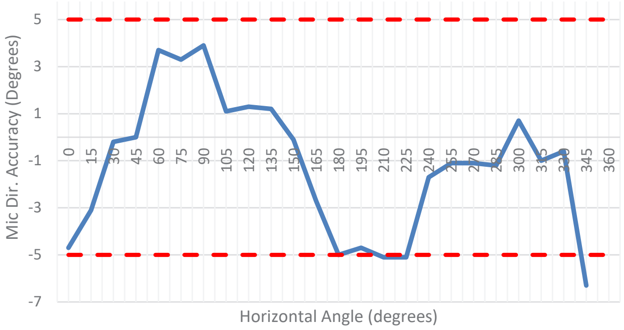


Figure 5: Directional accuracy of the system

The results show an accuracy of approximately +/- 5 degrees. This is similar to what is achieved with a fully calibrated professional grade system (Protheroe, Guillemin, 2013). Overall this indicates that the microphone capsules and preamplifiers in the interface are sufficiently well balanced and conversion to B-format provided by the H3-VR is effective.

4.2. Sound radiation of the loudspeaker

Pink noise was played through the Bose Revolve+ loudspeaker and the sound levels were measured at 30 degree intervals within the University of Auckland anechoic chamber. The results below show the variation in level with direction both horizontally and vertically. The level is compared to information from the data sheet of a standard measurement dodecahedron which conforms to ISO 3382-1 (Lange, 2013). Overall the Bose speaker performs well and the variation with direction is similar to a standard measurement speaker in the horizontal plane for all frequencies. In the vertical plane, the variation at high frequencies is slightly greater than a more spherical speaker but the tests indicate the variation is still within suitable tolerance.

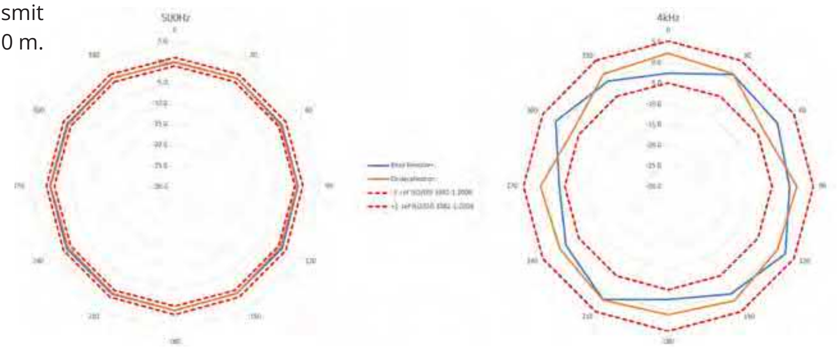


Figure 6 and 7: 500 Hz and 4kHz horizontal radiation of the Bose Revolve+

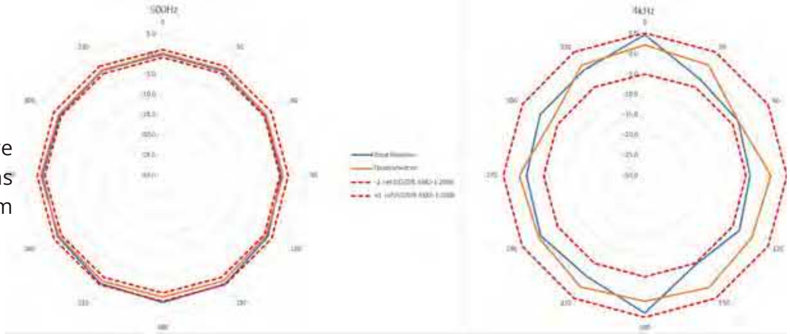


Figure 7 and 8: 500 Hz and 4kHz vertical radiation of the Bose Revolve+

4.3. Overall frequency response

The Rode Wireless Go system does not provide a flat frequency response (Rode, 2021). The system includes a high pass filter that that is, according to communication with Rode, “voiced for use with the Lav GO and a human voice”. This filtering cannot be prevented. The attenuation at low frequncies unnecessarily limits the low frequency performance of the system and other wireless systems are being investigated.

However, as shown Fig 9, the overall frequency response of the system, measured in the University of Auckland Anechoic chamber, is still relatively good and the performance is relatively flat over the key measurement range of 125 Hz to 4 kHz.

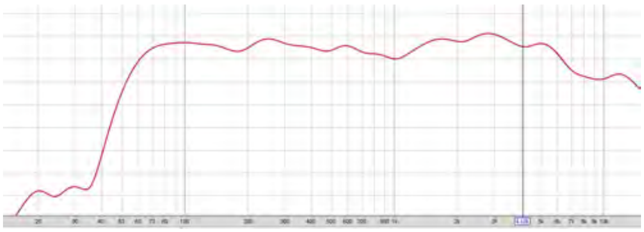


Figure 9: Frequency response of overall system (1/3 octave smoothed)

4.4. Practical Testing

Commissioning measurements were recently undertaken in a 900 seat performing arts auditorium. Measurements were undertaken using the standard Iris system and the trial system outlined in this paper.

Figure 10: System in use at a performing arts auditorium

This room was chosen to test the the ability of the system to provide sufficient excitation level in a large space and to confirm the wireless audio provided adequate transmission over extended distances.

Overall the trial system performed very well. The decay range was well above the recommend 45 dB in all octave bands from 250 Hz – 8 kHz.. The decay range was between 40 - 45 dB at 125 Hz in the most distant positions. The wireless audio link was effective even at positions at the rear of the auditorium (approx. 25 m).

The noise levels in the auditorium were relatively low (NC 25). The decay range would be lower in a similar sized room with higher background noise levels. However, the test indicated that the excitation signal would be loud enough to excite a wide variety of real spaces.

5. Conclusions

Following the body of the paper, a small and portable room acoustic measurement system has been put together from readily available consumer and semi-professional equipment.

The system enables 3D room acoustic measurement to be made more quickly and less expensively that traditional systems.

The equipment has not yet been tested for compliance with ISO standards. However initial tests and measurements indicate that the system provides comparable results to compliant systems.

Acknowledgements

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Designing and 3D printing the ultimate saxophone reed

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Abstract

The main objective of this project was to manufacture saxophone reeds using additive manufacturing. Reeds are traditionally made from a cane plant called Arundo Donax, which is an anisotropic material. An experiment was designed to determine the frequency response function of the reed when constrained similarly to a reed on a saxophone.

A finite element analysis (FEA) model was developed to model the experiment and calculate the modal frequencies. The model was verified using the results of the laser vibrometer experiment. The FEA model was used to study how the material properties affect the modal frequencies. Longitudinal Young's modulus and longitudinal-transverse shear modulus were highly significant, as was reed geometry.

A series of reeds were fabricated using additive manufacturing. Playable reeds were produced by adjusting the reed geometry. They were also fabricated by inserting aluminium and steel into the reed to increase the longitudinal stiffness. Most of the playable reeds did not have good sound quality. This was correlated with a dominant first mode. The modal frequencies were also lower than that of cane. A reed with steel needles inserted into the reed heart had a similar frequency response to existing synthetic reed products. This reed was subjectively assessed to have good sound quality. Evidence was found that suggests for a reed to have good sound quality, it should have a high degree of anisotropy. Good sound quality can be achieved by inserting steel needles into the heart of the reed.

1. Introduction

A saxophone is a reed instrument and a member of the woodwind family. A reed is a small piece of material that is clamped to the mouthpiece, leaving a small opening. The reed vibrates to cause an oscillating pressure wave inside the body of the saxophone. This standing wave of pressure produces sound.

Saxophone reeds have traditionally been made from a sugar cane plant called Arundo Donax. This is an isotropic material with stiffness aligned with the grain being far superior to the other two directions. There are some shortcomings of the cane reeds. The reed required moistening to be played properly, which gradually breaks down its structure, rendering the reed unplayable. The reed tip is also very thin and can be snapped easily. Additionally, the cane plant does not always grow uniformly, leading to inconsistencies in the reeds. These inconsistencies are often undetectable until played, leading to brand new boxes of reeds having several unplayable reeds.

An apparent solution to these issues is synthetic reeds. However, synthetic reeds have a reputation for sounding 'plastic' and overly harsh. For the cheaper ones, this may be accuracy. More expensive synthetic reeds, however, arguably sound as good as cane reeds, but at a cost of over $50 they are outside the price range of many players. Cane reeds typically cost between $5 and $10. A latent gap in the market would be filled if quality synthetic reeds were developed at low cost, or if players could easily manufacture their own reeds through accessible manufacturing technologies.

2. Literature Review

2.1 How a saxophone works

A saxophone is a reed instrument, meaning that it has a small piece of material, the reed, that vibrates against the mouthpiece, altering the airflow into the saxophone.

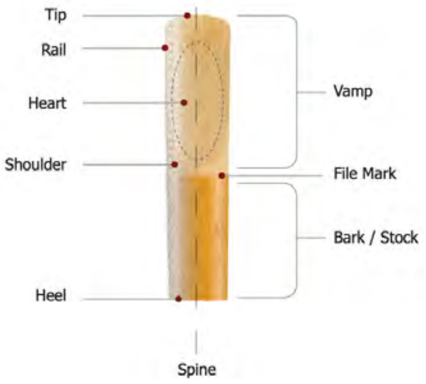


Figure 1: saxophone reed and mouthpiece setup

Oscillations occur inside the saxophone, of both pressure and flow. Standing pressure waves occur inside the saxophone. Some of the energy of these waves is dissipated in the form of sound, with the pitch corresponding to the frequency of the oscillations. The wavelength of the frequencies is dependent on the effective length of the saxophone pipe, which is controlled by the keys. The reed is not vibrating at its own natural frequency, but rather the frequency of the sound being produced, determined by the fingering controlling the effective pipe length of the saxophone.

The vibration of the reed controls the flow of air into the mouthpiece, as its oscillations correspond to an oscillating area for air to flow through. The range of airflow volumes depends on the pressure difference between the player's mouth and the saxophone mouthpiece. If this difference gets too large, the reed is forced shut, and flow goes to zero, causing the saxophone to stop producing sound. The stiffness of the reed is very important, as a reed that is too flexible easily closes against the mouthpiece, and one too stiff will struggle to produce oscillations.

2.2 Existing synthetic products

There are many existing synthetic reeds, ranging in cost and quality. The most prominent brands include Legere, ForestOne, and Fibracell. Numerous professional players have stated that they don't mind or even prefer synthetic reeds. For example, 'there is a notion out there that Synthetic sounds bad, and that is just not true' (The Music Room, 2017). In addition, synthetic reeds have a much longer lifetime than cane reeds (Mulder, 2015). The synthetic reeds are more consistent with greater longevity, but the high price limits a player's ability to develop a feel for what type of reed they prefer to play, as buying many different models is financially unfeasible.

3. Vibration Theory

The reed and clamp setup can be assumed to have some similarity to a cantilever beam in bending vibration, as well as a shaft in torsional vibration.

From literature, it is known that a saxophone reed has a combination of flexural modes (bending vibration) and torsional modes (torsional vibration) (Taillard et al., 2012). It is assumed that the reed can be modelled as a combination of a beam in bending vibration and a shaft in torsional vibration. Therefore, if the geometry and boundary conditions are kept consistent, the modal frequencies are dependent on Young's modulus, the shear modulus and the density of the material. The reed and clamp setup can be assumed to have some similarity to a cantilever beam in bending vibration, as well as a shaft in torsional vibration.

The receptance of a damped SDOF system is proportional to the inverse of stiffness. The reed on a saxophone is predominantly undergoing bending vibration, due to the nature of the excitation. The excitation is powered by pressure acting on either side of the reed, which produces a vertical force. For a cantilever beam, the effective stiffness is

$$K = \frac{3EI}{L^3} \qquad (1)$$

The playability of the reed depends on this effective stiffness. Two equally playable reeds of different materials are likely to have very similar effective stiffnesses.

4. Laser Vibrometer Experiment

4.1 Test setup

An experiment was designed to determine the frequency response of a reed under similar boundary conditions to when played.

A clamping system was designed to replicate the effect of attaching the reed to the mouthpiece with the ligature. The reed is placed between an upper and lower clamp, which bolt together to compress the spine of the reed, with the vamp and tip of the reed left free. The bottom clamp piece bolts onto a shaker, which vertically excites the clamp and reed. The clamping pieces had a cutout in the shape of the reed stock to ensure that each reed was constrained identically. The shaker used was the Ling V406 Permanent Magnet Shaker. It has a usable frequency range of 0 to 11kHz. (HBK, n.d.) To measure the reed excitation the Polytec PDV-100 portable digital vibrometer was used. This is a single point laser vibrometer with a frequency range of 0.5Hz to 22kHz. (Polytec, n.d.) This vibrometer was used to measure the response of the reed at both the middle of the tip and the corner of the tip. We used a Roland Octa-Capture Hi-Speed USB Audio Interface to control the shaker and measure the laser vibrometer signal from the computer. The software REW was used to control the USB audio interface.

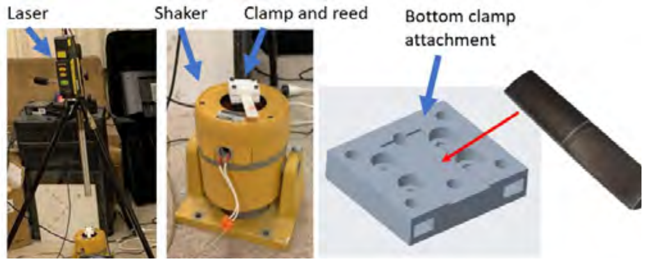


Figure 2: Reed clamping setup attached to shaker with laser point on reed

The reed was excited over a frequency range of 20 to 20,000 Hz and the frequency response function (FRF) was recorded.

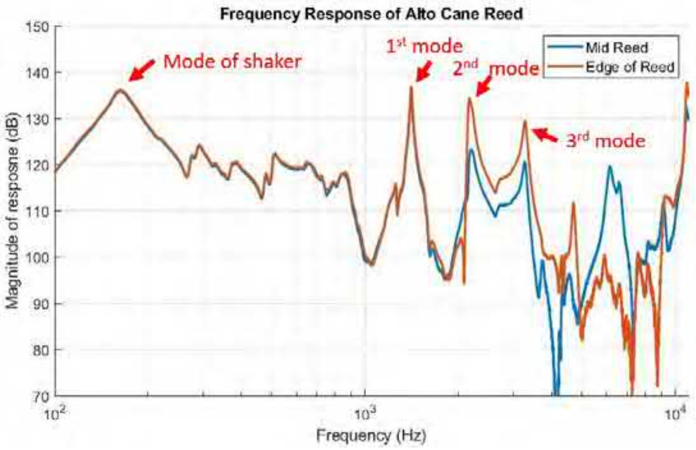


Figure 3: Example frequency response

Figure 3 shows the frequency response of an alto cane reed. The mode of the shaker is present in all reed measurements and must be discounted. The first mode will be the first significant peak after that. There are three key pieces of information that can be obtained for each mode:

- Frequency of mode
- Amplitude of mode
- Loss factor of mode

The loss factor can be calculated using the peak value method.

4.2 Limitations

The frequency response of the shaker is not flat. This does not change the frequency of the modes, but it does affect their amplitudes. This is something that must be considered when analysing the amplitudes of the modes. The excitation of the shaker is purely vertical. This means that the torsional modes are often not easily visible using this experiment. No inferences should be made from the amplitude of the torsional modes.

5. Finite Element Analysis of Reed Vibration

An FEA model of the experiment setup was developed. The model allowed for quick assessment of reed material and geometry choices without having to fabricate the reed. We chose to use ANSYS to do a modal analysis of the reed. A modal analysis calculates the frequency and shape of each mode but does not calculate the amplitude.

5.1 Model setup

The reed geometry was imported, and the clamped surfaces were set as fixed constraints. This mimics the clamped setup in the experiment. The clamp is assumed to be rigid.

5.1.1 Coordinate system

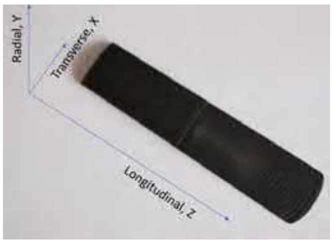


Figure 4: reed coordinate system used in the model

5.2 Model verification

Multiple reed geometries and materials were used to verify the model. Most of the reeds had average errors of 5% from the experimental data. The exception was the aluminium reed, which was used as an extreme case of longitudinal stiffness and was not a playable reed. The reed did not adhere well to the geometry file, so the reed profile was measured, resulting in possible minor errors.

We can be reasonably confident that the model will provide the approximate values of a wide range of reed designs that are being considered for printing.

6. Statistical Model

A statistical analysis was conducted to attempt to define a model to describe the modal frequencies as a function of the mechanical properties of the reed.

6.1 Sensitivity analysis

A 'one at a time' sensitivity analysis was conducted to determine which mechanical properties had an impact on the modal frequencies of the reed. For each of the variables considered, the variable was increased by 10% from the base case, and the percentage change for each of the first five modal frequencies was recorded. The analysis found that only Young's modulus in the Z direction, shear modulus in the XY direction and density cause significant changes to modal frequencies. Young's modulus in the Y direction was also considered for the statistical study as it had a minor effect. Poisson's ratio was not considered because it has been assumed to be a consequence of the other properties.

There is a clear mathematical relationship between the material density and all modal frequencies, with the frequency being proportional to the square root of 1 over density. Since it is well defined, density was not considered in the statistical study.

6.2 Multiple regression analysis

The maximum and minimum values for each of the three properties of interest were defined. The values were used to randomly generate values to be put into the FEA model. Young's modulus in the X direction was given the same value as Young's modulus in the Y direction. All three values of shear modulus were set as equal.

60 sets of variables were randomly generated and input into the FEA model. The modal frequencies were calculated and recorded. These values were used to conduct a multiple regression study of the modal frequencies to find a relationship between frequencies and mechanical properties. Statistically significant relationships were determined between each of the first 5 modal frequencies and the three properties of interest.

The model predicts the following relationship between modal frequency and material properties:

$$F_n = \sqrt{\frac{\rho_{nylon}}{\rho}} \times (A_n + B_n \times \sqrt{E_y} + C_n \times \sqrt{E_z} + D_n \times \sqrt{G_{yz}})$$

where E_y and E_z are Young's modulus in transverse and longitudinal directions respectively, G_{yz} is the shear modulus in the transverse – longitudinal direction and A_n, B_n, C_n, D_n are constants for each mode number, n. Values for the constants are shown in Table 1.

Table 1: values for constants for each mode number

	Mode Number, n				
	1	2	3	4	5
A_n	-12.07	7.17	-201.96	65.56	21.39
B_n	-1.412	0	0	12.371	0
C_n	9.654	5.091	20.018	10.225	13.282
D_n	2.08	25.325	12.151	30.95	45.506

Table 2: Percentage difference between FEA predictions and statistical model predictions

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Average % Difference	0.9	0.4	2.9	2.2	0.6
Maximum % Difference	3.0	1.6	11.7	13.7	3.0

Table 2 shows the average and maximum percentage disparities between the values determined with the FEA model and the values determined by the statistical mode. The statistical model is very accurate for the 1st, 2nd and 5th modes, with a moderate degree of accuracy for the 3rd and 4th modes.

6.3 Limitations

This statistical model provides a useful method of quickly calculating the modal frequencies for a given set of material properties. However, this model only works if the geometry remains constant. Any change to the geometry changes the frequencies and render the study unusable for frequency predictions.

7. Manufacture of Reeds

Alto reeds were the primary focus of the manufacturing efforts, as only an alto saxophone was available to test reeds on. Given results pertain to alto saxophone reeds.

7.1 FDM printer

In alignment with our objectives, we designed reeds that could be produced using FDM 3D printing. Two FDM printers were used in this project. A Creality Ender3 printer was predominantly used. This is a budget 3D printer costing around $350 (1-day, 2020). Since one of the primary aims of the project is to cheaply manufacture synthetic reeds, it is desirable that a cheap and accessible printer is used. Since the reeds printed were to have maximised anisotropy, the printer parameters were adjusted so that the print direction was the same for all layers. This was to mimic the cane structure by making the printed plastic have a grain.

7.2 PLA

PLA is one of the most common types of 3D print plastic. It has a very high print success rate and experiences minimal warping. A reed was modelled using the cross-sectional measurements of an alto reed, designed to be as similar in geometry as possible to the cane reed. We printed this using PLA. As expected, the reed was too soft to play, due to Young's modulus of PLA being far inferior to cane. By adjusting the heart and tip thickness, a playable reed was fabricated. However, the timbre was very harsh. As seen in Table 4, the modal frequencies are much lower than cane. The reed also has much lower damping than the cane and commercial synthetic reeds (Table 4).

7.3 Carbon prepreg PLA

We obtained a material that had strands of carbon fibre prepregnated in PLA. This material was expected to have a higher Young's modulus than regular PLA and would have greater anisotropy when the print directions were aligned. When the dimensionally accurate reed geometry was printed, once again, the reed was too soft to play. However, by increasing the thickness of the heart, a playable reed was fabricated. As seen in Table 4, the modal frequencies are much lower than that of cane. The loss factors are also much lower. This reed provides evidence that the modal frequencies do not have to be similar to cane for the reed to be playable.

7.4 Aluminium tabs

We hypothesised that a playable reed with the same geometry of a cane reed would have a similar frequency response from the laser vibrometer experiment. A reed of the same geometry was fabricated by pausing the print and inserting 0.1mm thick aluminium tabs into voids. The tabs were glued in place using two-part epoxy. The prints were then resumed. This resulted in playable reeds. The timbre of the reed was harsh, although less so than the previous prints. The laser vibrometer experiment revealed the modal frequencies to once again be lower than cane, although the loss factors were similar. We theorised that the frequencies were more dependent on the stiffness of the heart than the reed tip.

Figure 5: Aluminium tab reed and mid-print when aluminium is added

7.5 Needle reed

Using the geometry of the playable carbon filled PLA model, a reed was printed with small holes running from the heel to midway through the vamp. Five 0.5mm thick stainless-steel sewing needles of 37mm length were inserted into the holes and glued in place using epoxy.

Figure 6: Reed with 5 needles and CAD assembly

The timbre of this reed was substantially smoother than without the needles. A vibrational analysis revealed that the modal frequencies had increased significantly, to values very similar to other synthetic reeds. The FEA model predicted no significant difference between the 37mm length needles used and needles extending to the reed heel. The loss factors of this reed were significantly higher than the equivalent reed without needles (Table 3).The epoxy used to glue the needles in place likely added damping to the reed.

Table 3: Loss factor of first 3 modes

	5 needle	Legere	Forestone	Fibracell	Alto3M	Nylon	PLA	CarbonFill	AluminiumTabs	TPU
Loss Factor 1	0.042	0.074	0.047	0.027	0.015	0.012	0.014	0.015	0.022	0.035
Loss Factor 2	0.030	0.063	0.051	0.048	0.045	0.010	0.014	0.017	0.027	0.050
Loss Factor 3	0.024	0.044	0.054	0.030	0.032	0.013	0.015	0.017	0.032	0.052

Table 4: First three modal frequencies of various reeds

	5 needle	Legere	Forestone	Fibracell	Alto3M	Nylon	PLA	CarbonFill	AluminiumTabs	TPU
Mode 1 (Hz)	824	988	833	812	1408	412	618	651	573	540
Mode 2 (Hz)	1736	2473	2335	2517	2201	1187	1500	1598	1387	1252
Mode 3 (Hz)	3194	4599	4615	3648	3269	2795	2973	3257	2218	3417

8. Subjective Reed Assessment

8.1 Untrained listener blind test

A series of blind tests were conducted to subjectively assess the reeds being played. Four recordings of reeds being played were taken. The recordings were of a cane reed, the ForestOne synthetic reed, our 'needle' reed, and a recording of the needle reed poorly played. The poor recording was played correctly but softly, which meant it sounded more timid than the other recordings. The recordings were played to 19 participants, none of whom had significant musical training. Two clips were played to the participants. The participants were asked to choose which reed recording sounded better.

The ForestOne recording was assessed to sound better than each of the other recordings, including cane. However, when the cane recording followed by the needle recording were played, the needle reed was assessed as better. When the poor recording of the needle reed was compared to the Forest One recording, all participants chose Forest One. This shows that how the song is played has more of an impact on subjective assessment than the reed characteristics itself.

8.2 Trained listener blind test

Two expert players of wind instruments assessed the reed recordings. One player was a saxophonist and the other played the oboe, which is another reed instrument. In this case 5 recordings were given: a cane reed, synthetic reeds Legere and ForestOne, and a PLA reed of ours as well as the needle reed. The recordings were assessed by apparent ease of playing, fluidity of sound, and lack of harshness. Their rankings are given in Table 5.

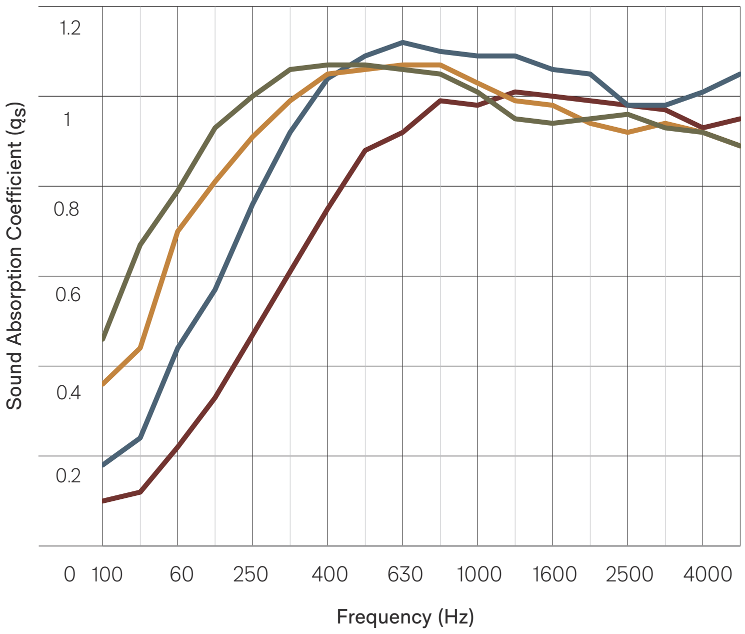
Table 5- expert rankings of reed recordings

	Legere	Cane	ForestOne	Needle	PLA
Oboist Ranking	3=	3=	1	2	5
Saxophonist Ranking	3	2	1	4	5

8.3 Testing limitations

The untrained participants struggled to distinguish between recordings and were not certain as to which recording sounded better. For example, if Participant 1 ranked Recording A above Recording B, and Recording B above Recording C, logically Recording A should be ranked above Recording C. However, this was not always the case. The Needle reed performed worse against ForestOne than the cane reed but was assessed to be better when compared directly to cane. This is not logical and shows that the participants were inconsistent with their assessments. This gives evidence to the theory that most untrained listeners struggle to distinguish between different reeds.

The metrics ease of playing and fluidity of sound consider how the reed was played rather than the timbre of the reed itself. This means that the recordings were assessed mainly on the playability of the reed. Every saxophone player has a preference for reed hardness. Ideally, each reed played should have the same hardness and ease of playability, but this was inevitably not the case. However, each reed was comfortably playable, so the hardness of each reed will fall into my playability range.


1.2
1
0.8
0.6
0.4
0.2
Sound Absorption Coefficient (αs)
0
100
60
250
400
630
1000
1600
2500
4000
Frequency (Hz)

9. Discussion

Numerous playable reeds were fabricated, but only a limited selection subjectively sounded good. We considered the frequency response of all playable reeds to see if any differences could be observed between good and bad sounding reeds.

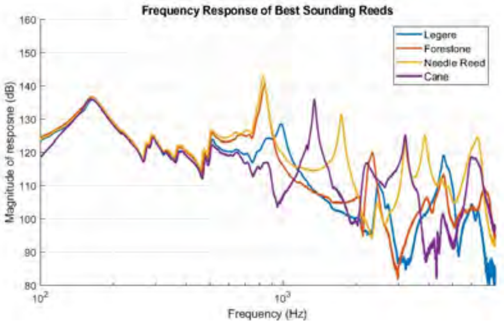


Figure 7: FRF plot of best sounding reeds

There were three clear differences that were observed. First, the fundamental frequency of the good sounding reeds was always above 800Hz. Second, almost all the bad sounding reeds had a very dominant first mode, in terms of amplitude in the frequency response. This dominant first mode was not present in the good sounding reeds.

Finally, the good sounding reeds all had a similar level of damping, whilst the bad sounding reeds had much lower damping.

9.1 Loss factors

The loss factors of the first three modes of a selection of playable reeds were calculated. It can be seen in Table 3 that the PLA reed has substantially lower loss factors, meaning less damping is present. It is possible that the damping of the reed mitigates the harshness when played.

9.2 Effect of dominant 1st mode

Almost all bad sounding reeds have a very dominant fundamental mode, with the first mode amplitude being far superior to subsequent mode amplitudes. It is likely that this frequency dominates the harmonic response, resulting in the sound produced when playing having only a limited number of significant harmonics. This will produce a harsh timbre.

The good sounding reeds do not have this dominant fundamental frequency. The harmonic response will have a broad range of significant frequencies and will have a softer and more mellow sound.

9.3 Theories

9.3.1 Young's modulus ratio

Inserting needles into the heart of the reed increased the modal frequencies and decreased the dominance of the first mode. This can clearly be seen in Figure 8. We theorise that the decreased dominance of the first mode is due to a high ratio of longitudinal to transverse Young's modulus, or greater anisotropy. By inserting needles into the reed it is effectively increasing the longitudinal Young's modulus while keeping the transverse Young's modulus roughly the same. There are some mathematical theories that support this hypothesis.

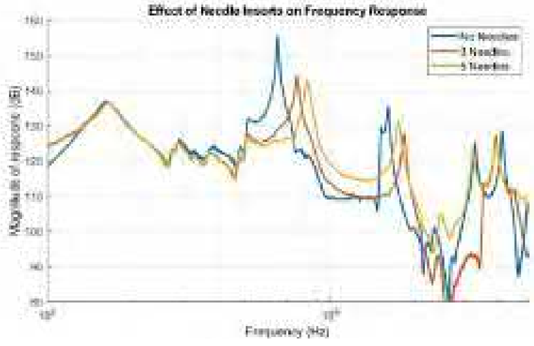


Figure 8: effect on increased longitudinal Young's modulus

Stiffening a structure is a form of vibration treatment that decreases the modal amplitudes. It increases the lowest natural frequency and changes all natural frequencies. However, in this case, the first mode is the most significantly affected. According to the STATISTICAL MODEL, the first mode is predominantly controlled by the longitudinal Young's modulus. The subsequent modes less dependent on longitudinal Young's modulus as they are significantly controlled by shear modulus also.

This extends to the effective stiffness of each mode. For the first mode, an increase of longitudinal Young's modulus results in an increase in effective modal stiffness. For subsequent modes, the increase of effective modal stiffness is not as significant, due to a weaker dependence on longitudinal Young's modulus. Therefore, increasing the ratio of longitudinal to transverse Young's modulus results in stiffness increasing for the first mode more than for any subsequent mode. The amplitude of the first mode decreases by more than the other modes, resulting in a less dominant first mode in the frequency response.

9.3.2 Shaker flatness

The decreased dominance of the first mode could be caused by the unevenness of the shaker. If the fundamental frequency increases to a dip in the shaker response, it will appear to decrease in dominance. However, if the location of the dips does not change with a reed inserted into the clamp, this is not the case. Figure 9shows the frequency response plots from Figure 8 if the clamp flatness graph is subtracted. This is not a good way to calibrate the experiment as the results are very messy. However, they still show that the dominance of the first mode decreases when additional needles are added.

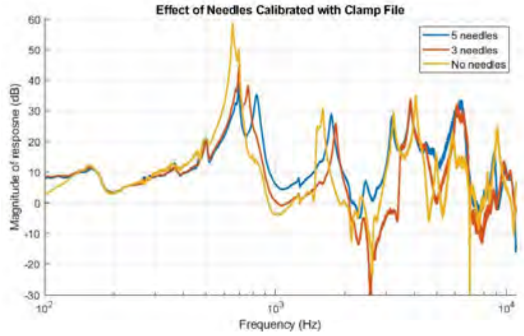


Figure 9: reed responses when calibrated with clamp response

10. Conclusions

- Synthetic saxophone reeds that are playable and have good sound quality were produced. The best example of this is the carbon-filled PLA reed with needles inserted. This reed was assessed to be playable by the player, as well as trained and untrained listeners. The untrained ears struggled to distinguish this reed from other synthetic and cane reeds.
- Quality sounding synthetic saxophone reeds can be fabricated using low priced FDM printers. Some steps are required post-print to insert and glue the needles, but the reed can manufactured cheaply, so long as a 3D printer is available.
- Reed playability is dependent primarily on the stiffness of the reed. No evidence was found that the modes need to be of specific frequency or amplitude for the reed to be playable.
- The amplitude of the first mode affects sound quality. A dominant first mode results in poor sound quality. Increasing the anisotropy of the material used decreased the dominance of the first mode. Increased anisotropy through increased longitudinal Young's modulus resulted in a higher fundamental frequency, although this is thought to be consequential.

- Links were found between damping of the reed and sound quality, for playable reeds. No evidence has been found that damping level is the only requirement for good sound quality.

11. Future work

One area for future research in this project is to investigate the effect of reed damping and develop a way to print reeds with an ideal amount of damping.

Different materials could be used to fabricate the reed. Inserting needles into a reed made from softer material could have potential, as this would result in a higher level of anisotropy.

Other work could include working to print reeds consistently so that the player can be confident that two reeds printed with the same method will play the same. This could be taken even further, with the player able to choose the characteristics of the reed before printing it. Work could be done to quantify the strength and timbre of the printed reeds to make these properties customisable.

Acknowledgements

I would first like to thank Dr Andrew Hall and Dr George Dodd for supervising this project. They were both always helpful and had good advice and made an effort to continue giving guidance when the project work had to be done at home.

Gian Schmid was very helpful as the lab technician. He was very patient when showing us how to use the equipment and helpful when we needed assistance.

Gratitude must be extended to Professor Olaf Diegel and his team for always being enthusiastic about letting us print reeds off at his Newmarket workshop. These prints were essential to the project.

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Developing A New Generation of Acoustic Ceiling Tile Utilising A Holistic Approach

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Abstract

Designing Quality Learning Spaces: Acoustics Ver 3.0 December 2020 (DQLS) sets out the acoustic requirements for education spaces in New Zealand Schools. In schools, a number of acoustic requirements are addressed using a suspended ceiling with 1200x600mm acoustic ceiling tiles in a metal grid, The DQLS mandates maximum reverberation times and suggests that ceiling tiles meet a minimum NRC of 0.85. In addition, the roof/ceiling system is required to reduce rain noise and external environmental noise. In many cases this requires that the ceiling tile has both high absorption and high transmission loss properties. These two acoustic demands require a tile to be both porous and to have relatively high surface mass weight.

This paper focusses specifically on ceiling tiles that absorb and attenuate simultaneously and looks at the wider implications of using such a tile; namely hygrothermal and non-structural seismic consequences. It discusses the improvements made to an existing commercially available acoustic tile to create a product that meets DQLS acoustic requirements while addressing the wider design implications that come with the placement of ceiling tiles. This design has a Patent Pending.

1. Introduction

There are a plethora of activities that come together to form good architecture and the finer points of each activity is often the domain of experts in each field. The challenge is to approach product design with the understanding that solving one facet (in this case, an acoustic one) will have wider implications on other aspects of the internal environment.

Therefore, this paper, although talking about acoustic research, will also focus on hygrothermal and non-structural seismic requirements of suspended ceilings.

A holistic approach is essential, and no single internal environmental quality factor should be altered without assessing its effect on all the others. This is because they interact with one another.(DQLS Ver 3. 2020, pg 9).

1.1 Acoustic Requirements For Education Spaces In New Zealand

New Zealand's Ministry of Education (MOE) has developed a range of documents to provide technical requirements that assist architects, designers, and engineers in creating quality learning environments that are fit for purpose. These are known as the *Designing Quality Learning Spaces* (DQLS) series and set out the requirements for the main internal environmental quality factors: acoustics, lighting and visual comfort, indoor air quality and thermal comfort.

In *DQLS: Acoustics, Ver 3.0*,(released December 2020), section 2.2.5. *Helpful tips and rules of thumb* (DQLS, pg. 23) advises designers to treat the whole ceiling with a highly absorptive product (NRC 0.85 or higher). A ceiling tile with a high level of absorption is essential in education spaces, especially with the current education model that favours Innovative Learning Environments (ILEs)[1]. Although it calls for a high NRC, the desired reverberation time varies depending on the type of space. For instance a learning space in a Primary School smaller than 300m^2, breakout spaces, meeting rooms and offices require a reverberation time between 0.4 - 0.5 seconds, whereas circulation spaces and music spaces are required to be between 0.5 - 0.8 seconds. In addition, the roof/ceiling system is required to reduce rain noise and external environmental noise and this noise spectrum requires ceilings to have high transmission loss properties.

For Sound Absorption a single number quantifier is often used. These are either an NRC (Noise Reduction Coefficient) or αw (Weighted sound absorption coefficient): A highly absorbent product can be defined as NRC 0.80 – 1.00.

For transmission loss in ceilings, a single number quantifier is typically used. These are either CAC (Ceiling Attenuation Class) or $D_{n,c,W}$ (normalised ceiling attenuation weighting): High transmission loss performance be defined as CAC/ $D_{n,c,W}$ 40 upwards

To achieve these two acoustic requirements simultaneously, requires a ceiling to be both porous and to have relatively high surface mass weight. In education projects, they are typically addressed either with a plasterboard ceiling with acoustic absorption below, or using a suspended ceiling encompassing both performance criteria, as 1200x600 mm tiles in a metal ceiling grid.

This paper focusses specifically on ceiling tiles and the improvement made to an existing commercially available model. The previous model was a thick glasswool tile for absorption, backed by a layer of plasterboard to provide attenuation. The research and development sought to create a ceiling tile that meets MOE/DQLS acoustic requirements while addressing the wider design implications that come with the placement of ceiling tiles, namely non-structural seismic and hygrothermal performance. The research and development and subsequent acoustic testing was conducted in early 2020 at Canterbury Acoustic Testing Laboratories.

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[1] *An innovative environment (ILE) is one that can evolve and adapt as educational practices evolve and change – thus remaining future focused. It is generally a larger space housing multiple class-bases.*

1.2 Non-Structural Seismic Requirements For Suspended Ceiling Tiles

Predominantly suspended ceiling tiles that have a combination of high absorption and high surface mass are heavy; weighing 11 kg/m^2 or more (this equates to a 1200x600 mm tile weight of 8kg). According to NZS1170.5 (NZ Earthquake Actions) any un-tethered non-structural product above floor level that has the ability to fall (in this case a ceiling tile) is considered a hazard to human life if it weighs 7.5 kg or more, regardless of the height it may fall during a seismic event. Therefore, a ceiling tile with a weight of 8 kg is not acceptable. AS/NZS2785:2020 (Suspended Ceilings – Design and Installation Standard) requires that anything suspended weighing over 7.5kg is fixed with a tether and fixed to the main structure to prevent the object from falling more than 100 mm (AS/NZS2785:2020 pg. 32). A clipped tile is not considered to be an effective tether.

The thought of a heavy tile falling in an education space is clearly unacceptable. Furthermore, heavier tiles result in a higher ceiling mass, which affects the amount of seismic force that is experienced across the system. This in turn, directly influences the amount of seismic restraint that the ceiling requires. In other words, heavier tiles require more back bracing. This results in added cost and can lead to coordination issues as different trades fight for space in the plenum.

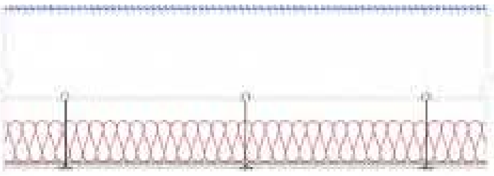
1.3 Hygrothermal Performance

The term 'hygrothermal' refers to the movement of heat and moisture through buildings. Consideration of hygrothermal performance is very important in schools especially when considering roof/ceiling systems because children produce a high vapour load. Poor design can lead to condensation forming in the roof, ceiling or plenum space. This condensation can cause varying degrees of damaging effects, such as reduced indoor air quality, thermal discomfort, odour, microbial and mould spread, and building materials' deterioration.

1.4 Roofs Systems For School Buildings

The *DQLS: Acoustics ver.3 (2020)* outlines three approved design solutions for roofs. These focus primarily on the mitigation of rain noise in areas of high, medium, and low rainfall intensity. The approved solutions in the latest DQLS version are all warm roof systems, where the thermal insulation layer is in the form of a rigid or flexible panel of the roof build-up. A warm roof system is the MOE's preferred roof type for learning spaces due to the benefit in thermal and hygrothermal performance (DQLS, 2020).

Prior to prioritising warm roofs, the traditional way of constructing roofs in schools was to install insulation between the rafters or above the suspended ceiling. However, these methods can lead to condensation forming on the underside of the roof deck. (See Figure 1 and Figure 2). The build-up of moisture in these types of traditional roof systems ideally require a ventilated system. However, ventilating a roof system is unreliable and prone to failure.



Source (Rooflogic, 2020)
Figure 1: Detail of one type of traditional roof and ceiling. Insulation is placed above acoustic ceiling tile creating a thermal layer at suspended ceiling height with high R-value below a ventilated steel roof.

Source (Rooflogic, 2020)
Figure 2: The traditional roof construction as seen in Figure 1 in practice. Condensation and black mould have formed in ceiling plenum of a school that is less than 2 years old. Futhermore, steel fixings have started to rust.

With warm roofs the need for roof space ventilation is eliminated. The ceiling space is on the warm side of the insulation and the insulation layer is above a vapour barrier. The dew point temperature (the temperature at which water vapour in the air condenses as water) is on the exterior side of the insulation, so condensation in the ceiling plenum is unlikely to occur.

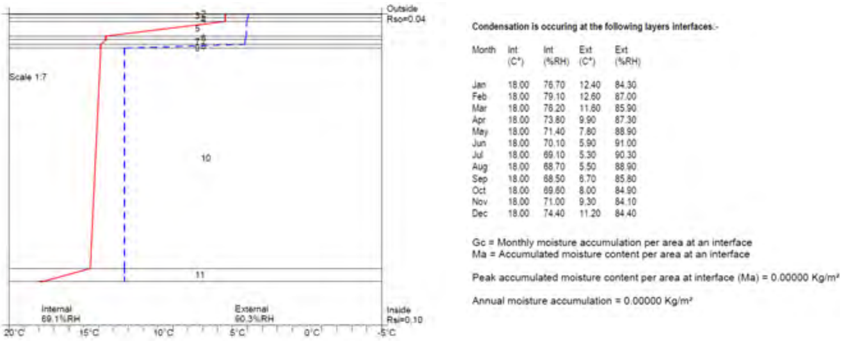
Furthermore, warm roofs have significant benefits over traditional roofs because energy efficiency is improved and this in turn means that heating and ventilation costs are reduced.

1.5 Acoustic Ceiling Tiles Below Warm Roof Systems

Although warm roof systems greatly improve hygrothermal performance, acoustic tiles with high R-values can still lead to condensation forming in the ceiling plenum or in the layers of the roof assembly. There are numerous examples of newer schools in New Zealand with warm roof systems, where moisture and mould issues are prevalent are caused by the incorrect placement of high-value thermal insulation at ceiling height (Rooflogic on site investigations for MOE, 2013-2020).

The calculations below demonstrate a hypothetical classroom in Wellington with a warm roof system and two different ceiling tiles below. The modelling scenarios calculate hygrothermal performance and use the original plasterboard backed tile (with an R-value of R1.4 m^{2}K/W) and compares this to a ceiling tile with an R-value of R0.7 m^{2}K/W.

Please note that these calculations will vary depending on the project location and local climate; climactic conditions vary greatly along the length of New Zealand. Wellington is an example of a fairly temperate climate without too many hot/cold extremes in the context of New Zealand and therefore the potential condensation issue caused by a high R-value tile can be much worse in other parts of the country and it will better in others.



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Condensation is occuring at the following layers interfaces:-

Month   Int     Int     Ext     Ext
        (C°)    (%RH)   (C°)    (%RH)

Jan     18.00   76.70   12.40   84.30
Feb     18.00   79.10   12.60   87.00
Mar     18.00   76.20   11.60   85.90
Apr     18.00   73.80   9.90    87.30
May     18.00   71.40   7.80    88.90
Jun     18.00   70.10   5.90    91.00
Jul     18.00   69.10   5.30    90.30
Aug     18.00   68.70   5.50    88.90
Sep     18.00   68.50   6.70    85.80
Oct     18.00   69.60   8.00    84.90
Nov     18.00   71.00   9.30    84.10
Dec     18.00   74.40   11.20   84.40

Gc = Monthly moisture accumulation per area at an interface
Ma = Accumulated moisture content per area at an interface

Peak accumulated moisture content per area at interface (Ma) = 0.00000 Kg/m²

Annual moisture accumulation = 0.00000 Kg/m²
```

Source (JPA Software, Rooflogic, 2020)
Figure 3: Hygrothermal calculations showing a Rooflogic warm roof system and a ceiling tile with an R-value of R0.7m^{2}K/W below.

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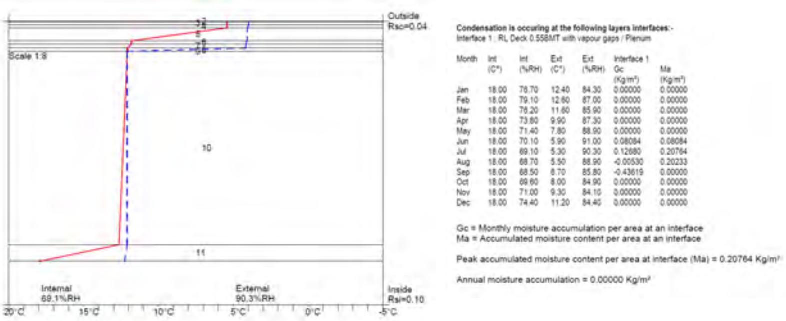


Condensation is occuring at the following layers interfaces:-
Interface 1 : RL Deck 0.558MT with vapour gaps / Plenum

Month	Int (C°)	Int (%RH)	Ext (C°)	Ext (%RH)	Interface 1 Gc (Kg/m²)	Ma (Kg/m²)
Jan	18.00	76.70	12.40	84.30	0.00000	0.00000
Feb	18.00	79.10	12.60	87.00	0.00000	0.00000
Mar	18.00	76.20	11.60	85.90	0.00000	0.00000
Apr	18.00	73.60	9.90	87.30	0.00000	0.00000
May	18.00	71.40	7.80	88.90	0.00000	0.00000
Jun	18.00	70.10	5.90	91.00	0.08084	0.08084
Jul	18.00	69.10	5.30	90.30	0.12680	0.20764
Aug	18.00	68.70	5.50	88.90	-0.00530	0.20233
Sep	18.00	68.50	6.70	85.80	-0.43619	0.00000
Oct	18.00	69.60	8.00	84.90	0.00000	0.00000
Nov	18.00	71.00	9.30	84.10	0.00000	0.00000
Dec	18.00	74.40	11.20	84.40	0.00000	0.00000

Gc = Monthly moisture accumulation per area at an interface
Ma = Accumulated moisture content per area at an interface

Peak accumulated moisture content per area at interface (Ma) = 0.20764 Kg/m²

Annual moisture accumulation = 0.00000 Kg/m²

Source (JPA Software, Rooflogic, 2020)
Figure 4: Hygrothermal calculations showing a Rooflogic warm roof system and a ceiling tile with an R-value of R1.4m²K/W below. (Please note, when the Blue and Red line touch, there is a potential condensation issue as confirmed in the calculations).

The calculations shown in figures 3 & 4 above demonstrate that the R1.4 tile can cause condensation issues during the winter months in Wellington. There is no moisture accumulation at all with the R.0.7m²K/W tile option shown below an identical warm roof construction with identical climactic parameters. Since this example is in Wellington, with this type of construction we would expect less condensation issues in Northern New Zealand but more down South.

1.6 Solution Required

As demonstrated above, while the existing plasterboard backed ceiling tiles achieved acoustic requirements set out in the DQLS, these tiles failed to meet the wider design implications that come with the placement of ceiling tiles.

A new type of ceiling tile was required to resolve the issues identified with seismic and hygrothermal performance. This tile needs to meet the acoustic requirements of educational building (in particular in reference to the DQLS) while achieving a lower weight to satisfy seismic constraints and low R –value to satisfy hygrothermal performance criteria.

2. A new ceiling tile: Development process

2.1 Required Parameters

2.1.1 Sound absorption

Internal noise control requires the ceiling tile to provide a level of sound absorption to help absorb at least some of the noise generated within a room and to reduce the reverberation time.

There are several mechanisms controlling the performance of a porous absorber, such as suspended ceiling tiles, they are:

- Viscous dissipation (flow resistance) through the structure of a porous absorber
- Elastic frame absorption
- Boundary conditions
- Thickness

By varying any one of these parameters, the products' acoustic performance can either be reduced or increased.

2.1.2 Transmission loss

The first variable which is normally considered when designing for sound transmission loss is the mass of the panel per unit area. An increase in transmission loss is expected with increasing mass because the heavier the panel, the less it vibrates in response to incident sound waves and hence the less sound energy it transmits.

However, considering the installation method, at a certain point, the suspended ceiling grid becomes the weakest link and therefore more mass in the ceiling tiles does not lead to an improvement in sound transmission across the system. Previous testing has shown this point to be at around CAC 46.

2.2 Materials Used To Create Absorptive Ceiling Tile With Mass Layer

2.2.1 Summary of ceiling tile performance requirements

The tile improvement process started with a range of aims and performance criteria that needed to be met. These performance criteria are summarised as follows:

Table 1: Summary of ceiling tile performance criteria

Aim	
Sound absorption	>NRC 0.85
Transmission loss	>CAC:40
R-Value	< R0.7 m²K/W
Weight	<8kg/m²

It was determined that, based on the conflicting material choices best suited to the acoustic requirements that the most appropriate method would be to stick two products together and create a hybrid tile. The hybrid allows one layer to provide the absorption and one to provide the transmission loss performance. This was in line with the existing plasterboard backed tile. However, in this improved tile, the absorption portion needed to provide a lower overall R-value, and the product chosen for transmission loss needed to be lighter for seismic reasons.

To develop a hybrid/combo tile the following products were selected:

- Glass wool fibre has high sound absorption properties, this material faces into the rooms. The thickness and density of the tile was varied until the required recommended MOE DQLS design criteria NRC was achieved.
- A mineral fibre ceiling tile is placed on the back of the glass wool fibre tile to increase the sound transmission loss, CAC. This product is less dense than plasterboard (and therefore less heavy) but commonly used to control sound transmission. The R-value is lower than plasterboard also. The thickness and density of the tile is selected based on the CAC required by the DQLS design criteria.

However, in addition to the choice of base materials, there are a number of parameters that can be considered in the development of a tile that can have an effect on the overall acoustic performance.

2.3 Investigating Alternative Methods Of Creating A Composite Tile

To create a hybrid/combo tile that is practical to use and easy to install the two tiles must be fixed together. However, a rigid adhesive constrains and stiffens the tiles reducing the combined tiles' sound absorption performance (Latimer, Michael. Testing procedures, February 2020). The alteration of potential fixing method to create hybrid tiles was identified as the leading solution in achieving the required further reduction in weight, R-value and tile thickness. This aspect was therefore thoroughly investigated and researched.

As expected - and subsequently confirmed through the research programme - a loose laid combination of tiles (one on top of the other without any fixing methods) performs the best for sound absorption. This is because the tiles are unconstrained, preserving the elastic frame absorption and boundary conditions, allowing the tile to vibrate freely when excited by a sound wave. Thereby dissipating sound energy into latent heat energy.

To limit the attachment points for the new tile design or order to define an air cavity between the layers to allow as much free vibration as possible, spot and perimeter gluing options were explored and tested for sound absorption. It was found that although spot gluing did improve performance significantly when compared to fully bonded tiles, perimeter gluing the tiles only, performed the best due to the reduced bonding area. This method of adhering the tiles achieved an NRC of 0.85 with 19mm of glasswool. In comparison, the previous model of ceiling tile required 40mm of glasswool below plasterboard to achieve the same sound absorption performance. A reduction of 21mm is a significant reduction in glasswool which leads to a significant reduction in R-value.

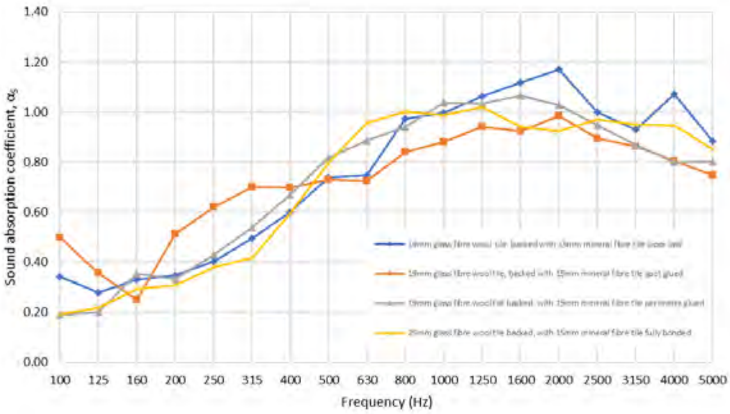
To further allow the tiles to vibrate as freely as possible, flexible adhesive was chosen to allow for movement between the tiles produced by incident sound waves.

The following table and graph show the comparison between fixing methods:

Table 2: Comparison Between Tile Fixing Methods across One Band Octave Frequencies (Hz)

Frequency Hz	19mm glass fibre wool tile, backed with 15mm mineral fibre tile loose laid	19mm glass fibre wool tile, backed with 15mm mineral fibre tile spot glued	19mm glass fibre wool tile backed, with 15mm mineral fibre tile perimeter glued	25mm glass fibre wool tile backed, with 15mm mineral fibre tile fully bonded
100	0.34	0.50	0.19	0.19
125	0.28	0.36	0.20	0.22
160	0.33	0.25	0.35	0.29
200	0.35	0.51	0.33	0.31
250	0.40	0.62	0.43	0.38
315	0.50	0.70	0.54	0.42
400	0.60	0.70	0.67	0.59
500	0.74	0.73	0.82	0.80
630	0.75	0.72	0.89	0.96
800	0.97	0.84	0.94	1.00
1000	1.00	0.88	1.04	0.99
1250	1.06	0.94	1.03	1.02
1600	1.12	0.92	1.07	0.94
2000	1.17	0.98	1.03	0.92
2500	1.00	0.89	0.95	0.97
3150	0.93	0.86	0.87	0.95
4000	1.07	0.80	0.80	0.95
5000	0.88	0.75	0.80	0.85
NRC	**0.85**	**0.80**	**0.85**	**0.75**
αw	**0.85**	**0.80**	**0.85**	**0.65**

Source (Latimer, 2020)



Source (Latimer, 2020)

Figure 5: Comparison of Sound Absorption Performance Between Hybrid Tile Fixing Methods

and not bonded at all, but this performance was almost matched by the perimeter glued tile. Both these tiles achieve an NRC and αw of 0.85. A comparative tile with 25mm of glasswool (an extra 6mm) fully bonded (with flexible adhesive) only achieved an NRC of 0.75 and αw of 0.65. The gluing method clearly affects performance.

2.4 Sound Transmission Loss (CAC) Performance Of New Perimeter-Bonded Hybrid Tile

As previously stated, a tile that has a high NRC will usually have a low CAC.

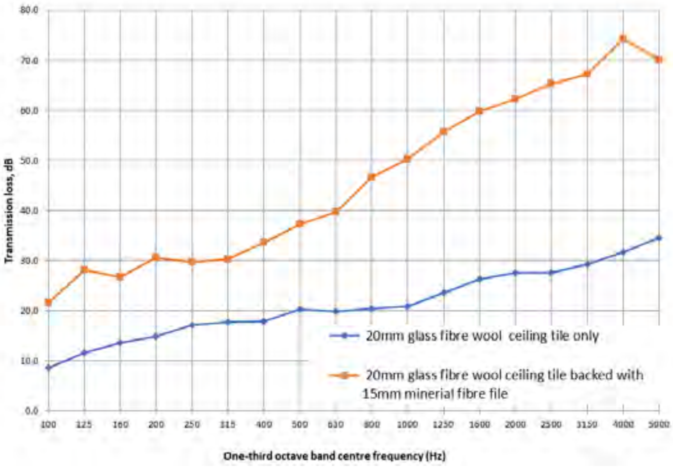
The addition of a mineral fibre tile to the back of the glass fibre wool tile will lift the CAC, due to the increase in weight per m^2. This increase in performance is due to the well understood mass law.

Table 3 and figure 6 below shows the CAC performance of a 20mm glass wool tile only, and 20mm glasswool with the addition of the mineral tile behind.

Table 3: The transition loss performance of a 20mm glass wool layer alone and of a tile comprising a 20mm glass wool layer that is periphery bonded to a 15mm mineral fibre backing layer and having an air cavity between the layers.

Frequency Hz	Glass fibre wool layer only	Tile of glass fibre wool layer backed with mineral fibre layer and air cavity between
100	8.6	21.6
125	11.6	28.2
160	13.6	26.8
200	14.9	30.6
250	17.2	29.8
315	17.8	30.2
400	17.9	33.5
500	20.3	37.3
630	19.9	39.8
Frequency Hz	Glass fibre wool layer only	Tile of glass fibre wool layer backed with mineral fibre layer and air cavity between
800	20.5	46.7
1000	20.9	50.3
1250	23.6	55.8
1600	26.3	59.8
2000	27.6	62.3
2500	27.6	65.2
3150	29.3	67.3
4000	31.8	74.3
5000	34.6	70.2
CAC	**23**	**42**

Source (Latimer, 2020)



Source (Latimer, 2020)

Figure 6: CAC Performance of a Glasswool Tile Only, Compared to the same tile Perimeter-Bonded to 15mm Mineral Fibre Tile Behind.

It was found that the sound transmission loss of the glass fibre wool and mineral fibre layered tile with air cavity between (CAC 42) was significantly superior to that of the glass fibre wool layer alone (CAC 23).

Conclusion

A tile comprising a glass fibre wool layer flexibly glued to a mineral fibre layer around the periphery of the tile to define an air cavity between layers provides a high sound absorption (NRC of 0.85) and a high transmission loss (CAC of 42). Where the glass fibre wool layer is about 19 mm or 20 mm thick and the mineral fibre layer is about 15 mm thick, the resulting tile is equal to or less than 35 mm thick. The reduction of the glasswool component and the removal of plasterboard provides much lower thermal insulation (R-value). The resulting weight of the tile is between about 7 kgm^{2} – 7.5kg/m^{2}, which falls within the current weight limitations for suspended ceiling tiles set out by the New Zealand Earthquake Standard.

The hybrid tile reduces the weight of the previous commercially available model by 30% and achieves an R-value of R 0.7 while meeting acoustic absorption and attenuation requirements stipulated by the DQLS. This design has a Patent Pending.

Acknowledgements

The author wishes to thank Mike Latimer at Canterbury Acoustic Testing Laboratories for the information on testing procedures and encouragement to submit this paper. She would also like to thank Dave Edkins and Graham Tennent from Rooflogic for their help in explaining Hygrothermal performance. She would also like to thank Rooflogic for supplying the graphs and photographs.

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Occupant behaviour regarding opening windows and alternative ventilation systems in real use

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Abstract

Where new residential dwellings establish in an area with high noise levels, there is often a need for windows to be closed to achieve suitable internal noise levels. Since closing windows will have flow on effects on indoor air quality and thermal comfort, there is commonly a rule within a District Plan or Resource Consent for these developments requiring alternative ventilation. There is variation in how prescriptive these rules are, and the aspects covered. A literature review of current guidance and research relating to the use of ventilation systems was undertaken. As part of this review, several studies were found which examined occupant behaviour around window opening even when provided with a well performing alternative ventilation system. There were several factors such as user friendliness and control, energy consumption, cost to run and noise generated which were shown to impact how these systems were used on a day to day basis. While external high noise environments were not the focus of these studies, these factors are relevant in the context of alternative ventilation rules and general implications are discussed.

1. Introduction

Acoustic Engineering Services was engaged by Waka Kotahi NZ Transport Agency (NZTA) to undertake a review of ventilation specifications. This scope included a literature review of current guidance and research about the use of alternative ventilation systems, and a review of District Plan rules with ventilation requirements throughout the different regions of New Zealand.

This study is part of ongoing research by NZTA to help robustly determine appropriate performance requirements for mechanical heating, cooling and ventilation for homes in areas with elevated traffic noise levels, when windows need to be closed to achieve adequate sound insulation.

Since the scientific knowledge base in the area of thermal comfort and user perception of ventilation systems is relatively large, we focussed our review on residential activity and people's interactions with real buildings where possible. Several field studies were found which discussed how people interact with the ventilation systems in actual dwellings. Although not focussed on scenarios where there are high external noise levels, many of the factors discussed are expected to also be relevant when this is the case.

2. Factors influencing how people interact with alternative ventilation systems

2.1 Window opening behaviours

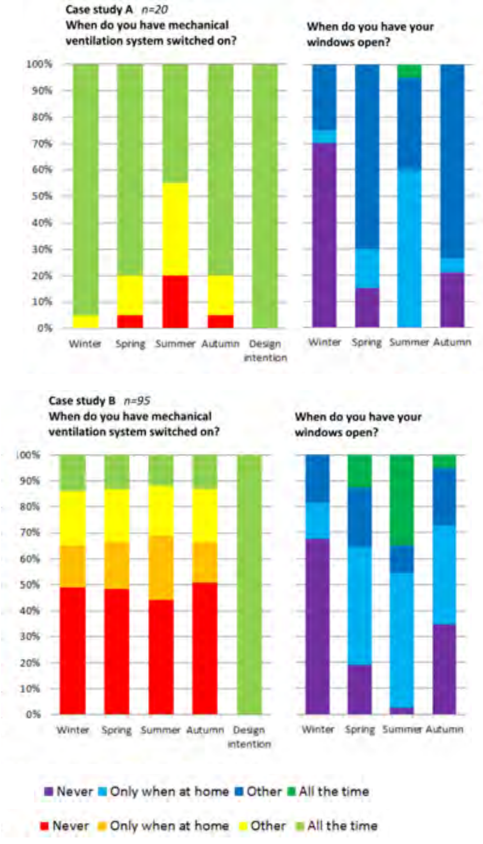
Studies relating to the use of alternative ventilation were commonly linked to investigation of people's window opening behaviour. The studies show that occupants often open windows for airing even when there is whole house alternative ventilation in place. While only discussed briefly in these studies, external noise is noted as a reason some occupants close windows, so it is likely that this behaviour may be moderated in scenarios where there are high external noise levels.

Hou, et al. carried out a field study in order to identify window opening patterns during heating season and its related factors in residential buildings in Tianjin, China during winter (Hou et al, 2017). Ten residences were monitored, seven with mechanical ventilation and three with natural ventilation. The study found that during winter occupants in bedrooms opened their windows almost as much within mechanically ventilated dwellings as for naturally ventilated dwellings. Average daily opening times were 65 minutes for mechanically ventilated houses and 66 minutes for naturally ventilated houses. Residents typically opened windows when there was no haze outdoors or when it was considered 'stuffy' indoors. In winter they close them for inclement weather and in summer they close windows for noise.

Dubrul found that the presence of an alternative ventilation system only had a very small effect on window opening behaviour, although interviews showed that occupants had little understanding of how the ventilation systems worked (Dubrul, 2018). External noise was identified as one reason why occupants may close windows (amongst many other reasons identified).

Lai, et al. monitored the use of opening windows in 46 Chinese apartments with natural and mechanical ventilation in a number of climate zones for a year (Lai et al, 2018). Lai found that on average, for dwellings equipped with mechanical ventilation the system operated for 7 hours per day, while windows were also open for 11 hours per day. As the climate became warmer, natural ventilation increased and mechanical ventilation decreased. This is a much longer duration of both open windows and mechanical ventilation operation than those found by Hou, et al., but represents the average of a whole year and many different climate zones rather than one location in winter.

Baborska-Narozny and Stevenson conducted a one year-long in-depth building performance evaluation of 40 households in two UK developments (Baborska-Narozny and Stevenson, 2015). One development had mechanical ventilation with heat recovery (Case A) and the other had mechanical extract ventilation (Case B). Figure 1 below shows the declared behaviour of occupants of two buildings – Case A with mechanical ventilation with heat recovery and Case B with mechanical extract ventilation.



Source (Baborska-Narozny and Stevenson, 2015)
Figure 1: Seasonal variation in declared ventilation behaviour

In Case A, the study demonstrated that the majority of households developed hybrid ventilation practices, relying on either mechanical or natural ventilation depending on the weather or time of day. External noise was identified as a reason for closing windows at night, and noise from the ventilation system was also identified as a reason for turning the system off. Reasons occupants gave for opening their windows included "'fresh air', audible connection with the outside (birds, leaves, social life), coping with excessive heat and habit" (Baborska-Narozny and Stevenson, 2015:8). Van Dongen analysed different types of ventilation ranging from 1-3 l/s (trickle vents) to 100 l/s (windows wide open) during a moderate Dutch winter (Van Dongen, 2007). Van Dongen demonstrated that ventilation behaviour is only partly related to the type of ventilation system. In 25% of main bedrooms a window is always open for ventilation, mostly in addition to alternative ventilation. At an external temperature of 19°C, apartment occupants aired living rooms for an average of 13 hours by opening the external doors. This reduced to seven hours when the temperature was 14°C and two hours when the temperature was 5°C (Dongen, 1990a: and Cornelissen, 2002 as cited in van Dongen, 2007). The number of hours that occupants ventilate decreases as the temperature decreases, however people still open their windows down to -5 °C.

Overall, the literature suggests that even if provided with an alternative mechanical ventilation system, many people will still open their windows. External environmental conditions such as noise, air quality and weather will affect the duration of opening but even in adverse conditions windows are opened by some occupants for short periods.

2.2 System control and understanding

Several studies identified that use of alternative ventilation systems is influenced by how easily the users can understand the systems, particularly with regard to operational controls and modes. The ability for control over aspects such as noise and airflow rate from the systems was also important.

One of the outcomes reported by Baborska-Narozny and Stevenson was that concerns about energy consumption from system use and the inability to check it led to anxiety and occupants opening windows for ventilation instead of using the system (Baborska-Narozny and Stevenson, 2015). Manuals were not helpful even when residents were technically capable. For both systems investigated in this study, the intended user control was limited to a manual boost switch. Main unit control panels or mains switches were hidden and not readily available to occupants – although some residents who discovered them actually found the control functions useful.

For the second system investigated (Case B with mechanical extract ventilation) a building use studies survey was undertaken. Out of 95 questionnaires returned, 19 inhabitants stated they did not have mechanical ventilation installed or did not know what it was. A further eight respondents left all ventilation related questions blank which may also suggest lack of awareness of the subject. Therefore, up to 30% of occupants lacked basic awareness of having the mechanical ventilation system. It is noted in the study that this may be an unintended result of having an aesthetic cover for the fan.

When Brown and Gorgolewski conducted post occupancy questionnaires for four high rise buildings in Canada, over half the resondants did not use their heat recovery ventilators due to acoustic dissatifaction, difficulty accessing filters, and lack of engagement with training materials (Brown and Gorgolewski, 2015).

The Acoustics Ventilation and Overheating Residential Design Guide provides evidence that "occupants will adjust mechanical ventilation systems to a level of noise that is tolerable, or disable it entirely" (Acoustics & Noise Consultants and Institute of Acoustics, 2020:22). The guide provides higher system noise criteria when systems are operating to prevent overheating conditions, typically under occupant control.

In 2015 the UK Ministry of Housing, Communities and Local

Government commissioned AECOM to undertake a study on new homes which had been built since the introduction of Approved Document F of the Building Regulations (AECOM & Ministry of Housing, Communities and Local Government 2019). The aim of the study was to validate the ventilation provisions of Approved Document F by examining the air quality of houses which had been constructed in accordance with the criteria.

Walk through inspections were conducted on 80 new dwellings across several developments in the UK, with the residents being interviewed. Of these homes, 55 were naturally ventilated (with trickle ventilation and intermittent extracts for key areas), and 25 were ventilated using a decentralised mechanical ventilation system. Following this, limited monitoring was conducted in 54 of the homes, with subsequent long-term detailed monitoring conducted for 10 homes.

The study was compromised because it found that only two of the naturally ventilated homes and one of the homes with decentralised mechanical ventilation were able to fully meet the requirements of Approved Document F with regard to extract fan flow rates and minimum trickle ventilator area.

The study notes reasons for the homes not meeting the minimum ventilation provisions included incorrect fan selections or poor installation of exhaust fans such as the wrong speed, or duct resistance settings. Aside from one development in Leeds, 50% or fewer homes met the requirements for trickle ventilation areas. Trickle ventilators were also installed in wet rooms, short circuiting the mechanical extracts. In two of the three developments sampled around one quarter of doors had undersized door undercuts to provide adequate make-up air to balance the mechanical extract system.

In close to half of the survey cases, bathroom and WC fans, or continuous fans associated with the decentralised mechanical ventilation system, had been turned off by the occupants due to noise concerns or misunderstandings about the intended purpose. The report refers to similar findings from a site verification study undertaken by Zero Carbon Hub where occupants had turned off ventilation systems because they were too noisy (Zero Carbon Hub, 2016). Reducing external noise ingress (i.e. traffic noise from a main road) was also described as a reason for closing trickle ventilation in one survey case.

Although 86% of occupants were aware of the presence of trickle ventilators and had a basic understanding of their use, in 29% of the homes the trickle vents were observed to be closed during the initial visit to the property. Additionally, due to the layout of rooms, many of the trickle vents were located behind curtains, and the study raises concerns about their effectiveness during the night-time period.

The above findings illustrate that human response to ventilation is a complex issue and that humans have a wide variety of requirements and behaviours. Nevertheless, the studies identified various commonly perceived shortcomings with mechanical ventilation systems. Common shortcomings identified by Dubrul (Dubrul, 1988), Baborska-Narozny and Stevenson (Baborska-Narozny and Stevenson, 2015), and Brown and Gorgolewski (Brown and Gorgolewski, 2015) include:

- No instructions to inhabitants and a resulting lack of understanding of the system (e.g. thermal bypass switch, boost control)
- No user control
- High noise particularly when going to sleep
- Severe draught
- High extra energy
- Insufficient ventilation rates
- Odour transfer (e.g. kitchen/bathroom to living)
- Systems not installed properly
- Insufficient maintenance, unclean, poor access (e.g. filters)

Conversely, factors that appear to contribute to acceptance of and a positive attitude towards a mechanical ventilation system are:

- Quality and directions
- Good performance
- Fulfilling expectationsUser-friendliness
- Integration with usual behaviour
- Increased sense of comfort, health and safety promoting
- Ease of installation, repair, maintenance and cleaning
- Aesthetics

Other findings were that any ventilation system installed should be able to cover a wide range of comfort levels and should be user controllable. To achieve thermal comfort often both the heating, cooling and ventilation system performance, as well as the user knowledge and awareness need to be improved.

Good education includes ensuring that inhabitants know why a system is installed and how to use it. Even better outcomes can be achieved when inhabitants are involved in design, as occupants' ventilation practices can be influenced during the process. A low setting is important to allow for a diurnal quiet period to aid sleeping and avoid noise 'nuisance' whilst maintaining indoor air quality (Baborska-Narozny and Stevenson, 2015). It is also noted that "the device needs to function as expected, 'growing pains' are decisive for use or not use" (van Dongen, 2007:22).

It has also been found that the rate of successful interaction with mechanical ventilation in dwellings can be significantly increased if the learning process is better supported and user's varied expectations are met in terms of control over the system.

2.3 Other priorities

The Acoustics Ventilation and Overheating Residential Design Guide references a study in London where 85% of planning applications requiring both noise and overheating assessments for consenting purposes relied on having windows closed for acoustic purposes while also needing windows to be openable to prevent overheating (Acoustics & Noise Consultants and Institute of Acoustics, 2020). This means that in high noise environments, when conditions which may cause overheating occur, occupants are forced to decide between acoustic and thermal comfort. During the daytime, the guide hypothesises that occupants may be willing to accept higher noise levels for a short time in order to achieve increased thermal comfort.

Lai, et al. found that residents prioritised their thermal comfort needs over healthy indoor air quality (Lai et al, 2018). However, when the temperature was acceptable, they were willing to spend money on mechanical ventilation to improve air quality. Dubrul found that while personal comfort was very important, low-middle income groups were more likely to change behaviour to save money (Dubrul, 1998).

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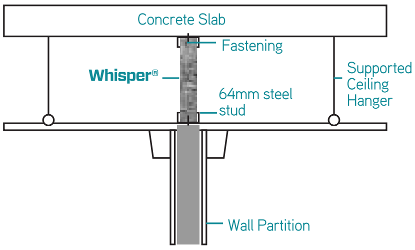
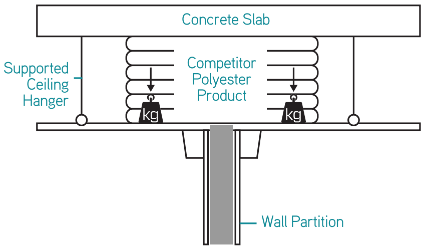
New Method



Old Method



Acoustic Ratings Whisper® 50mm

Transmission Loss

STC
15

Acoustic Absorption

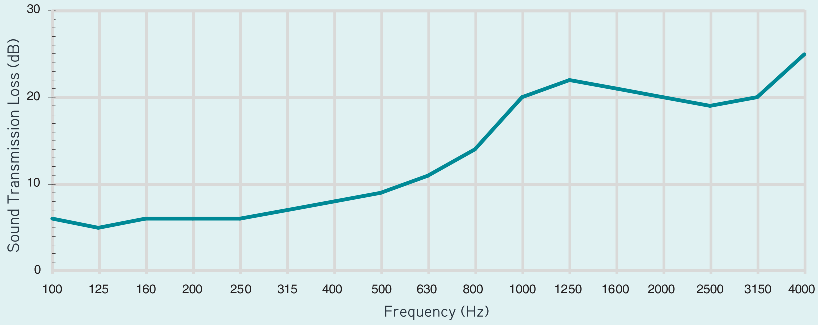
NRC
1

Ceiling Attenuation

CAC
30
Whisper as ceiling tile

CAC
36
Whisper ceiling tile, with plenum barrier

Whisper® 50mm Sound Transmission Loss



Frequency (Hz)	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	STC
Whisper® 50mm	6	5	6	6	6	7	8	9	11	14	20	22	21	20	19	20	25	30	15

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Another study performed in low to middle income housing in South Australia demonstrated that, due to the cost of using air-conditioning, people primarily tried to cool themselves through less expensive methods: by turning on fans, operating openings and drawing curtains and by changing their clothes (Soebarto and Bennetts, 2014, as cited in Rupp, Vasquez and Lambertsl, 2015).

Along with cost, environmental concerns may also lead to occupants turning off ventilation systems due to their energy consumption (real or perceived). This is also discussed by Baborska-Narozny and Stevenson as a reason for occupants developing hybrid ventilation practices (Baborska-Narozny and Stevenson, 2015).

Dubrul also demonstrated that "the older people are, the less they ventilate" (Dubrul, 1988:25). Conversely, elderly (along with educated, and renters) complain about "less ventilation than preferred". Occupants who smoke use more ventilation in living rooms. Households with respiratory diseases ventilate and air more than average and complain more about too warm conditions (van Dongen, 2007). Other studies show that there is no evidence that health issues motivate ventilation behaviour, except in households which contain asthmatics (Price and Sherman, 2008).

These studies illustrate that occupants of a dwelling have other priorities including thermal comfort and reducing running costs which influence how they will interact with an alternative ventilation system. Reducing external noise break-in will be considered against other factors in this heirachy.

3. Conclusions

The above studies show that there are many factors which affect the use of alternative ventilation on a day to day basis. It appears that occupants of dwellings will still open windows when there is the opportunity for various reasons, rather than rely primarily on alternative ventilation systems when installed. Even in adverse conditions windows are opened for short periods.

Locations with high external noise levels were not the focus of these studies and are expected to moderate this behaviour. However, in high noise situations where there may be less desire for occupants to open their windows, there appear to be opportunities for better outcomes (reduced exposure to high noise) through improved specification and design of alternative ventilation systems. Some key observations are:

There is good evidence that opportunities for control of the internal environment is an important factor in how people perceive it (for both air-conditioned and naturally ventilated buildings). This suggests that ventilation systems with an increased level of occupant control are preferable.

There is also good evidence that clear instructions on the use of a ventilation system, why it is installed and information about it's energy consumption would be beneficial and increase the likelihood of effective use.

High noise levels from the system itself was identified as a reason why systems were not used in many cases. A lower fan speed setting for night-time and reduced noise level to aid sleeping was noted as an important factor in some cases. During the daytime, occupants may be willing to accept higher noise levels for short durations in order to achieve increased thermal comfort.

This indicates that District Plan rules or Resource Consent conditions which include clear requirements for the noise emitted by any mechanical ventilation system are preferable. If these rules/conditions also have a requirement for a minimum number of control stages or allow the occupant to turn systems on and off individually, and control ventilation rates and associated noise levels incrementally across the range, this is likely to improve how often these systems are used.

Providing clear instructions about how to use an alternative ventilation system, why it is installed and information about its energy consumption is unlikely to be practical to implement through a rule or condition. Improved communication between developers, owners and occupants of their dwelling about the design intent of any installed systems, and opportunities for occupant control would likely be required to lead to improvements in both use of systems and user perception.

Acknowledgements

The authors would like to thank Waka Kotahi NZ Transport Agency for the opportunity to conduct and present this research, along with Dr Stephen Chiles for providing oversight and direction throughout the project.

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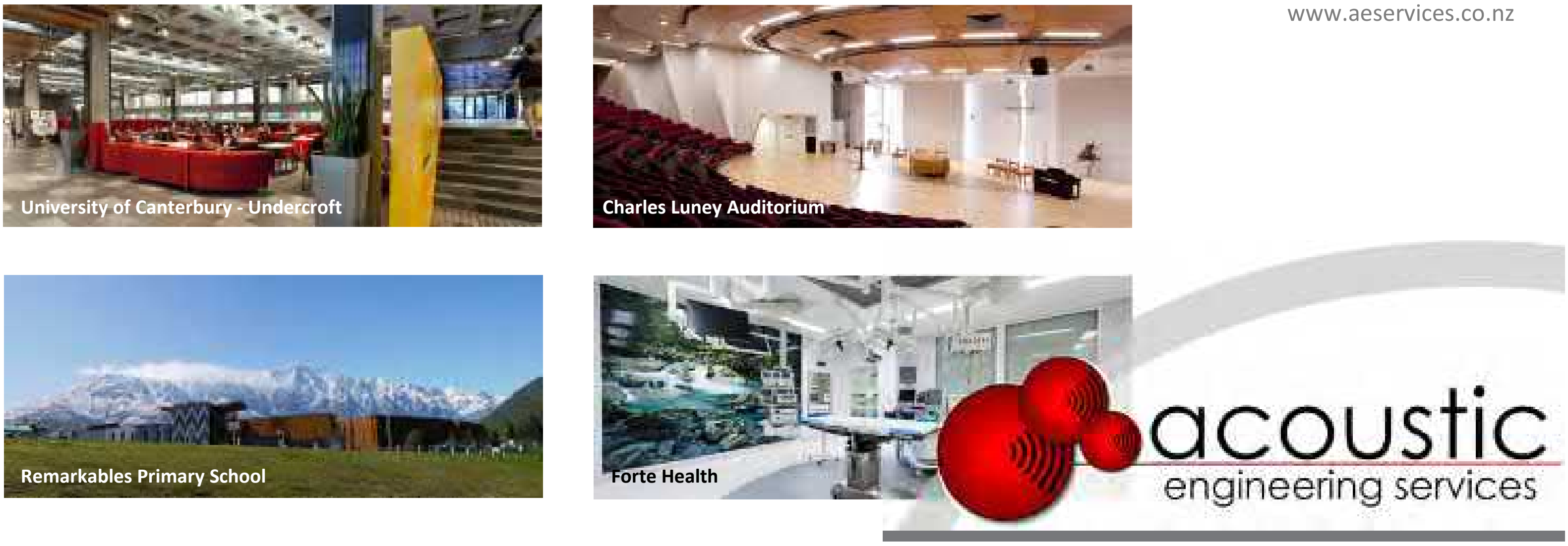
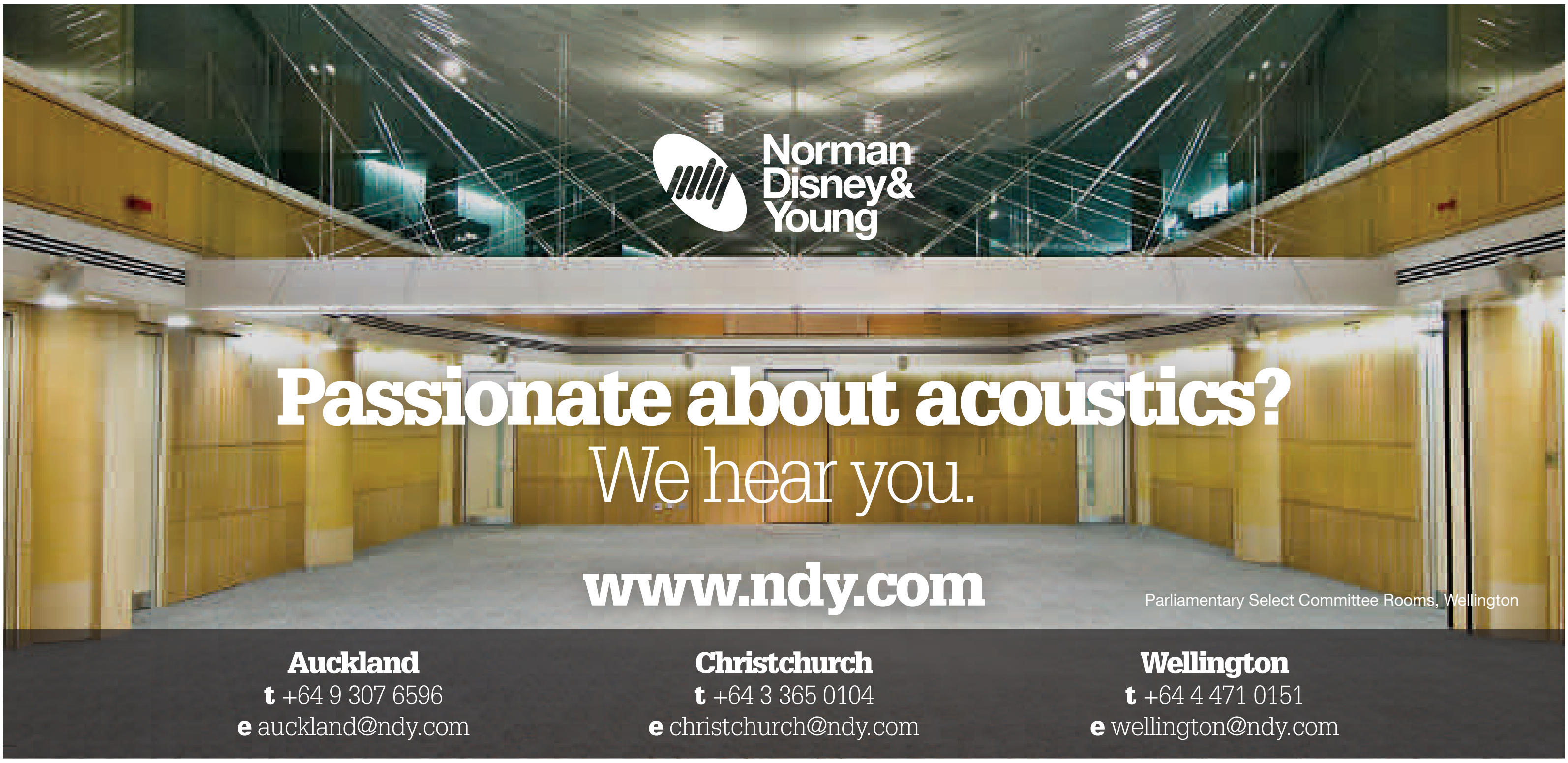




QUIZ

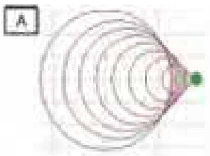
How sound is your acoustic knowledge?

1 **True or False?**
Sound waves are longitudinal waves.

2 A tuned trap designed to absorb a narrow frequency band is called?

A) Active trap
B) Diffusive trap
C) Helmholtz resonator
D) Resonant absorber

3 Which of the following represents a sound source moving at the speed of sound? (The green dot represents the sound source, and the brown circles represent sound waves)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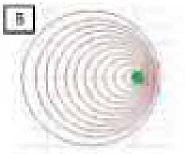
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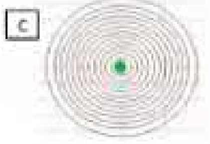
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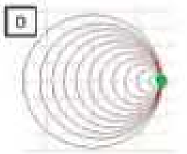
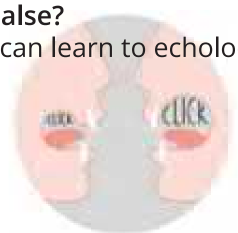
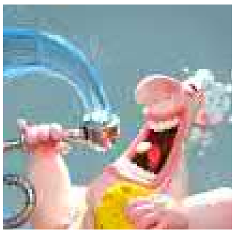

D

4 **True of False?**
Humans can learn to echolocate using tongue clicks.



5 **True or False?**
When you sing in the shower, the reflected sound waves combine with your original sound waves, which is an example of reverberation.



6 **True or False?**
Pythagoras noticed that some combinations of sounds seemed more beautiful than others and he found answers in terms of numerical ratios representing the harmonic overtone series on a stone.

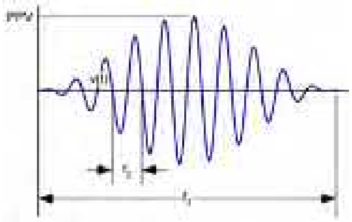
7 For school buildings in New Zealand, there is a technical design requirements document for classrooms to meet a proper level of acoustical performance. What is the name of this document?

8 **True or False?**
There is a National Environmental Standard (NES) for noise under the Resource Management Act?

Resource Management Act 1991

9 The joint Australia / New Zealand Standard, AS/NZS 1270:2002 Acoustics - Hearing Protectors, provides a rating value for hearing protectors. What is the name of this value?

10 The National Planning Standards (which aren't standards in the 'Standards New Zealand' sense) includes 'Noise and Vibration Metrics' that say, "Any plan rule to manage damage to structures from construction vibration must be consistent with the metrics for peak particle velocity (ppv) in ISO-4866:2010…". Why does this ISO standard use PPV and not acceleration (m/s^2)?



QUIZ ANSWERS

1. True, normally, but see the news item, ‘Physicists discovered special transverse sound wave’ on page 11.
2. D. Helmholtz resonator
3. D
4. True, see the news item ‘Humans can learn to 'echolocate' in just 10 weeks, experiment shows’, on page 10.
5. True. See the ‘The 40 Best Songs to Sing in the Shower'
6. False, but Pythagoras is considered the “Father of Harmonics”. He applied the principles of harmonics to everything from music, art, and architecture to running governments, raising a family, friendship, and personal development.
7. Designing Quality Learning Spaces – Acoustics (currently version 3, 2020
8. False, although there is provision for a noise NES, there is not one. There are a few NESs that include specific noise provisions, eg. Resource Management (National Environmental Standards for Plantation Forestry) Regulations 2017. It will be interesting to see whether the replacement legislation (due by the end of 2022) includes a noise standard.
9. SLC$_{80}$ (Sound Level Conversion 80). For a given value, it is expected to provide this level of protection for ≥ 80% of the population, when correctly fitted and maintained.
10. PPV is used because it is the most basic and direct parameter of a vibration event to connect with the stress increment in ground or a structure.

UPCOMING EVENTS

All event dates are current as at time of print.

ACOUSTICS 2022
JOINT NEW ZEALAND & AUSTRALIAN ACOUSTICAL SOCIETIES CONFERENCE
THE NATURE OF ACOUSTICS
31 OCT – 2 NOV 2022
TE PAPA, WELLINGTON, NEW ZEALAND

Joint New Zealand and Australian Acoustic Societies Conference
ACOUSTICS 2022 | 31 October – 2 November 2022 | Wellington | NZ

WORLD ACADEMY OF SCIENCE, ENGINEERING AND TECHNOLOGY

International Conference on Building Acoustics and Vibration (ICBAV 2022)
20 – 21 September 2022 | Toronto, Canada

ASA

183rd Meeting of the Acoustical Society of America
5 – 9 December 2022 | Nashville, Tennessee, USA

ICA 2022

24th International Congress on Acoustics (ICA 2022)
24-28 October 2022 | Gyeongju, Gyeongsangbuk-do, Republic of Korea

inter.noise
21-24 AUGUST
SCOTTISH EVENT CAMPUS
GLASGOW
2022

51st International Congress and Exposition on Noise Control Engineering
INTER-NOISE 2022 | August 21 – 24 2022 | Glasgow | Scotland