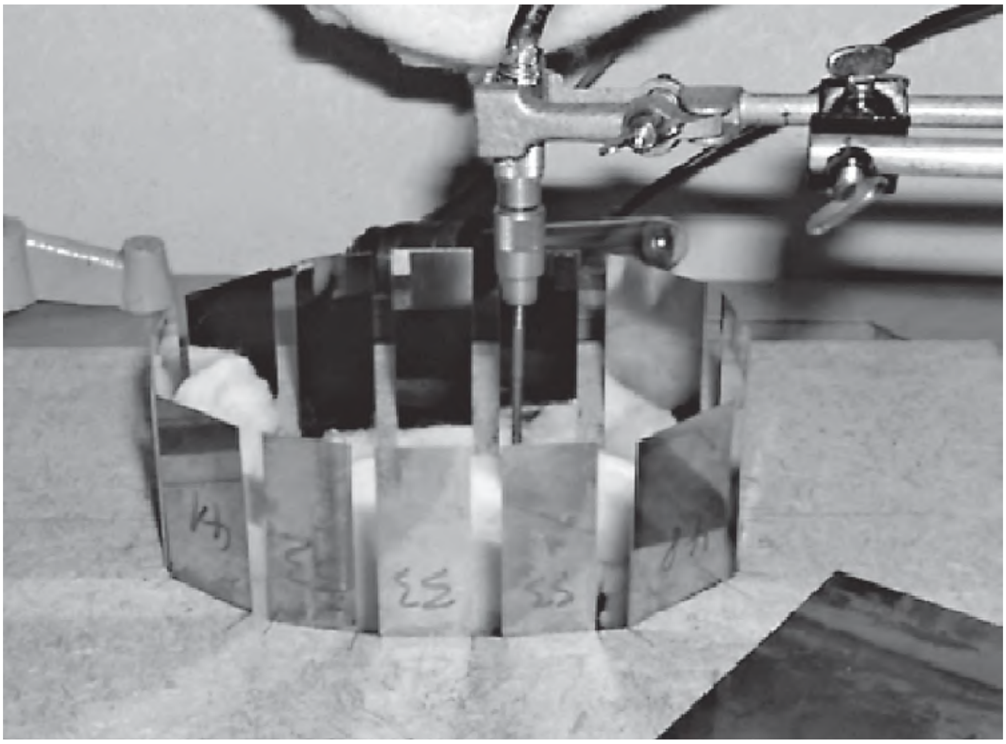
New Zealand Acoustics

Volume 27, 2014 / #3



3rd Quarter

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New Zealand Acoustics

Volume 27, 2014 3rd Quarter

Features

Regulars

Cover Image: First model of the auditorium of the Christchurch Town Hall

Source: Harold Marshall

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Contributions to the Journal are encouraged, and may be sent directly to the Editor either by email, or by post c/o the Acoustical Society of New Zealand Incorporated, PO Box 1181, Auckland.

From the President and Editor

From the President

Dear Members,

Spring has sprung and we're well and truly into the latter part of 2014. Me, I don't believe it. I'm sure that this is all part of some epic daydream... and meanwhile my body is slumbering peacefully in a hammock under a tree somewhere in February 2014.

I simply can't believe how quickly this year has gone. But then it's about this time of the calendar that everyone starts saying such things (probably prompted by seeing the first of the xmas decorations appear in shop windows!) so I'll quit harping on about it like everyone else, and talk about something more interesting... like acoustics!

Welcome to the third journal of 2014, and the sophomore effort for our new co-editors. I know that by now they'll be into the swing of things, and be whittling down their journo skills to a fine point.

I was pleased to see the inclusion of the new regular section in the last journal – recent environment court decision from RMA.net. I'm sure that will be a useful resource for many of you.

While I'm singing the praises of ASNZ initiatives, I'd like to point out that our CRAI (café and restaurant acoustic index) is going from strength to strength with interest popping up from all over the place. It was featured in the NZ Herald in May, we've received interest from groups overseas to adopt/expand on the idea, and I was told at a recent industry event that "it's brilliant" and asked "how can we progress it and get it out there!?" Remember to keep it ticking over by filling in a rating form for any and every dining experience you have! The more ratings we have the more valuable a resource it becomes, and as always a list of rated venues can be found in the latter pages of this Journal.

Now down to business, and to the main

topic I wanted to raise in this issue – Modern Learning Environments or MLEs. They are part of an initiative introduced by the Ministry of Education in 2010. The initiative aims to embrace "new technologies and building materials to allow for new, vibrant and well connected learning spaces" and is incorporated in the Ministry's 10 year property plan process and 5 year funding

Publication Dates and Deadlines

New Zealand Acoustics is published quarterly in March, June, September, and December.

The Deadline for material for inclusion in the journal is 1st of each publication month, although long articles should ideally be received at least 4 weeks prior to this.

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agreement. Details can be found on the minedu.govt.nz website. Practically speaking, it means that classrooms in new schools are being designed to a new set of objectives, and old classrooms are gradually being upgraded to achieve the same objectives. Sounds great… but eagle-eyed readers may have noticed that the initiative includes the term "well-connected learning spaces". Does this mean that the Ministry is now promoting a renaissance of the dreaded open-plan classroom concept?

Well, yes… and no. Or at least… this time it's different. There seems to be a clear understanding in the Ministry that the open-plan classroom 'experiments' of the 1970s were, on the whole, a dismal failure. Teaching multiple classes, using traditional teaching methods, in a large room with no walls was and is still a bad idea.

But, I've come to understand that as long as a few crucial acoustic principles are incorporated, and (perhaps most importantly of all) the school management and teaching staff understand that these new spaces can't be used in a traditional manner… then these modern spaces can be really dynamic and enjoyable places for our kids to learn. It can be a difficult balance to achieve, and may require some fine tuning to room design &/or the way in which it is used, but importantly, it can work. I'd be interested to hear your thoughts. There are enough MLE schools out there now for the general public (of which ASNZ members are admittedly a subset) to have formed an opinion. Let's hear it.

On a lighter note, I'd like to acknowledge that 15th September 2014 was Leo Beranek's 100th birthday! Along with most of the international acoustics community, ASNZ extended its congratulations to Dr. Beranek on that auspicious day.

Enjoy this issue. It's packed with great stuff including a paper from the venerable Sir Harold Marshall (who incidentally shares a birthday with Dr. Beranek. Happy Birthday Sir Harold!)… and I hope to see many of you at our November conference in Christchurch. The organising committee is doing a wonderful job!

Yours faithfully,

James Whitlock

Editor's Column

Dear Readers and Members,

This is a buper issue for content, we have a paper by Sir Harold Marshall who is recognised both nationally and internationally for his contribution to concert hall acoustic design in specific his seminal work on the importance of lateral reflections. Sir Harold has been involved with many well known projects worldwide including the *Guangzhous* Opera House and *Philharmonie de Paris* to name but a few. Sir Harold's paper is based on preserving the Acoustical Design of the Christchurch Town Hall with respect to recording its acoustical history. The paper was written at a time following the February 2011 Christchurch earthquake when significant damage was sustained and the future of the building was unknown. We now know that this very important piece on New Zealand architectural history is now going to be conserved and the Town Hall is to become part of a wider Performing Art Precinct as part of the Christchurch City rebuild. This paper is a must read for all acousticians young and old.

The paper by Protheroe and Guillemin on '3D impulse response measurements of spaces using inexpensive microphone arrays' is a very interesting read for all you audio engineers and building acousticians, thoroughly recommended.

If fan noise is your thing then take the time to read the intersting paper on an investigation of the effect of uneven blade spacing on the tonal noise generated by a mixed flow fan.

The last paper is all about determination and verification of speech intelligibility from sound systems in tunnels. Tunnels are hostile envrionments at the best of times and making sure annoucements are heard clearly takes careful design.

This issue also incudes some regulars; RMA Net as and a 5-minute brain teaser prepared by Dr George Dodd from Auckland University and ourselves.

Finally in this issue we wish to take the time to thank both our employers for their support as without such support we would not be able to prepare each issue.

Lindsay and Wyatt ¶

journal@acoustics.org

The acoustical design of the Christchurch town hall

Harold Marshall

Marshall Day Acoustics Ltd., P O Box 5811, Wellesley Str. 1141, Auckland, New Zealand

harold.marshall@marshallday.co.nz

Abstract

The Christchurch Town Hall (New Zealand) was opened on September 30 1972. Disastrous earthquakes hit Christchurch in September 2010 and February 2011. Most of the CBD and the historic buildings were destroyed or damaged by the February event, including much of the Town Hall complex. The City Council in November 2012, resolved to restore the entire building but at the time of writing there remains uncertainty. The intention of this paper is to put on record the history of the Christchurch Town Hall design in case it does not survive the political after-shocks of the earthquakes. With the building's future now in jeopardy it seems appropriate to set out the process that led to this unique design, acknowledge the many contributors, outline its research base, the innovations in predictive technology employed, the evaluation of its acoustical properties and the learning that flowed from it.

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1. Introduction

The design of the Christchurch Town Hall auditorium is inseparable from the discovery of the importance of lateral reflected sound in concert hall preference. Indeed the Christchurch project provided the problem statement, the hypothesis, testing and its initial application in a major symphony hall all in the space of five years between 1967 and 1972. In this paper I hope to give an account of this process.

2. Backround

Christchurch, the second largest city in New Zealand, pop c 250,000, (in 1965) had long needed a Town Hall. Such buildings in Australia and New Zealand were the principal cities' public auditoriums, rather than the seat of the city administration though some combined that function as well. There had been such a venue in the previous century but it was destroyed by fire in April 1873.

Prosperity had come to Dunedin and Auckland initially through the gold rushes of Central Otago and Coromandel respectively and their prosperity allowed them to build Town Halls, seating about 2000-3000 patrons in the classical tradition, and including a large pipe-organ. The prosperity of Wellington arose from its standing as Capital city with the commerce that attracted, and its Town hall was of a similar model. Seldom has a region, its Councils and its citizens been so united in desiring a public building, as Christchurch was in desiring a Town Hall.

2.1. The competition

An architectural competition was announced under the auspices of the NZ Institute of Architects [1], in July 1965. Only architects registered in NZ were permitted to enter. The first stage was to close on 31st January 1966. My role was as acoustical advisor to the competition Chairman, Mr. Ron Muston, then President of the NZIA. At the same time I was preparing to go to the UK to the newly formed Institute of Sound and Vibration Research at Southampton University, on Sabbatical leave from the University of Auckland, to complete my PhD. This was no small undertaking with a young family of 4 boys, with ages from almost one year to 7 so perhaps it is not surprising that I agreed without much discussion to provide an acoustical report on the 5 or 6 shortlisted designs at the end of Stage 1, prior to the second stage. That was to close on May 31st. In December we boarded the Shaw Saville liner "Southern Cross" and sailed to Southampton. Fifty eight entries were submitted in Stage 1.

2.2. At Southampton University

My project at Southampton had little to do with concert hall design [2]. I had long been intrigued by the enhanced annoyance that reverberation causes for the same level of intruding noise. My project was to find an objective measure using pupil dilation as a measure of CNS load. I was barely settled into the ISVR when a large role of drawings for the five short-listed schemes arrived by air from NZ, with the request that I furnish my acoustical reports by cable within two weeks.

As I looked through the competing designs I realized that there was nothing to guide me about preference for the sound these plans and sections would produce. When I undertook to write about each six months earlier I had in mind to draw heavily on Dr. Beranek's masterly work "Music Acoustics and Architecture" [3] which had seemed to me to tie up all the uncertainties around the design of music rooms. It is a matter of history that by 1966 the conclusions in this book–apparently represented in the design of the NY Philharmonic Hall–were subject to serious questions. At that time the conventional wisdom was that only a narrow "shoe-box" could produce the excellence the competition sought and there was no narrow shoebox amongst the short-listed room shapes (Figure 1).

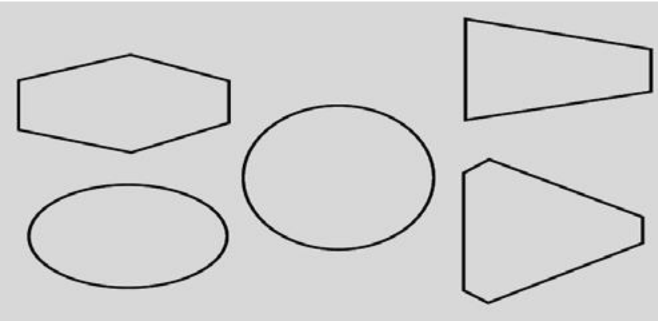

Figure 1. Short-listed room shapes

2.3. A visit to the Royal Festival Hall

While pondering this problem and feeling the truth of Dr Johnson's "If a man knows he is to be hanged in a fortnight, it concentrates his mind wonderfully," we went up to London for a concert in the Royal Festival Hall. As I listened I realised that there was only frontal sound–the lateral reverberation was inaudible. That started me on the hunt for a reason for this experience and led to a draft of my paper "A note on the importance of Room Cross-section in concert halls" [4].

2.4. Work in Germany

My supervisor and editor of the new and prestigious Journal of Sound and Vibration, Philip Doak, directed me to recent work in Germany which reflected the 60's change in emphasis from the Physics of sound in rooms to measurements in the psychophysics of what people hear.

Measurements at that time were primarily on the absolute threshold of perceptibility–*die Absolute Wahrnehmbarkeitschwelle*, abbreviated to AWS–of reflections in a variety of circumstances. Initially these were of speech signals [5] and showed the dependence of audibility of reflections on the relative direction of the direct sound and the reflection(s). That suggested to me a mechanism for the masking of lateral reflections. At that time I could find only one measurement for the threshold of a music reflection. That was in a BBC research report by Somerville, Gilford, Spring and Negus6 and was for a single reflection of music at 10ms delay. (That paper was subsequently published in the Journal of Sound and Vibration [6]).

2.5. Miles Warren visit to the UK and Europe

I wrote my reports on the five designs, including the new hypothesis, and sent them off. Entry Number 16 an elliptical room, was selected, and shortly thereafter, Miles Warren, the successful architect arrived to visit halls in Europe with me and to discuss the implications of the lateral reflection idea for his design. I was able to convince him of the reality of the effect, assisted by hearing Haydn's "Creation" on successive nights in both the Royal Festival Hall and in the Concertgebouw in Amsterdam. His visit turned into a design workshop with W. A. Allen (Bill) and his partners Engineering Design Consultants (EDC) London (see the next paragraph and Figure 2). In this the idea for the arrangement of reflectors in Christchurch TH was proposed. The architects were receptive because their design had already foreseen such large reflectors.

Meanwhile I had been appointed to a teaching position in the new School of Architecture, which opened in the University of Western Australia in 1967. I felt unable to continue as consultant for the Christchurch TH while settling into a new country and a new job. I asked Bill Allen to take it over for me and he agreed except that EDC would be the executive consultants. I agreed to retain only a "watching brief" for the project and set about writing up my PhD.

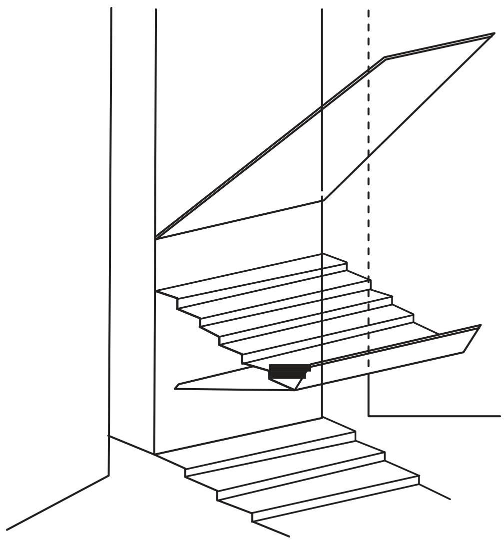

Figure 2. Sketch of reflector system

Meanwhile at Prof. Doak's suggestion I sent the draft of my paper to Professor Erwin Meyer, Director of the Third Physics Institute in Goettingen. He promptly invited me to Goettingen to discuss it. There, in addition to Prof. Meyer, I met Drs. Burgtorf, Kuttruff, Dieter Gottlob and several others. They referred me to a paper by Dr. Peter Schubert in the DDR which would not appear in the West for another two years [7]. It showed the AWS for reflections of a variety of music types, out to delays of 200ms. I want to acknowledge here the collegiality I encountered amongst the colleagues at Goettingen, their enthusiasm for the fresh idea I had proposed and

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the practical assistance they gave; even to making the first physical model of the Christchurch design, to demonstrate the reality of focusing in the ellipse. With the encouragement of Professor Doak, I submitted my paper, completed my experimental work and submitted my thesis now including the lateral reflection hypothesis. Late in 1967 this was examined and accepted, and I moved with my family to Western Australia in time for the start of the Autumn term in February 1968.

3. Confirmations

It may be worthwhile here to recall my description of the "premium quality of sound" reproduced from the "Note" [4].

3.1 Identification of the quality

To aid in the identification of the quality sought, it is observed that: (a), as a property of the *sound*, it is related to the loudness attributes; (b), as a property of the *hall*, it carries the idea of special responsiveness to the music; (c), for the *listener*, it generates a sense of envelopment in the sound and of direct involvement with it [5] in much the same way that an observed is aware of his involvement with a room he is in.

There has followed some 40 years of on-going research, refining the measures: separating aspects of global terms such as "Spatial responsiveness" (Marshall) [8], "Spatial Impression" (Barron) [9] and "Räumlichkeit" (Kuhl) [10] into "Apparent Source Width (AWS) (Morimoto and Maekawa) [11] Envelopment (Bradley and Soulodre) [12] and the introduction of a raft of Inter-aural Cross Correlation (IACC) measures as an alternative to the lateral energy fraction, Lf, Barron and I proposed (Schroeder, Gottlob and Siebrasse [13], Ando [14], and Beranek [15]). These are a small but representative selection of the relevant research.

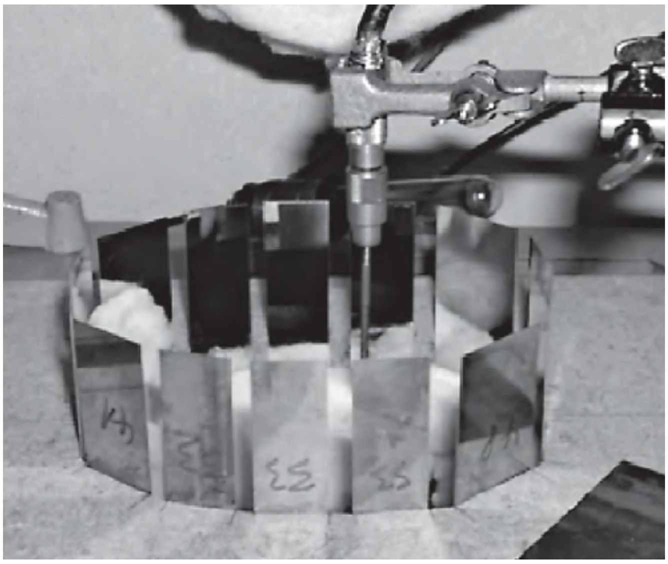

Figure 3. First model of the auditorium

4. In Western Australia

In WA, I received an establishment grant from the University and another from the Australian Research Grants committee which enabled me to set up a laboratory to pursue this question. The importance of these grants is gratefully acknowledged. In 1970 I was joined by Mike Barron who was completing his PhD, and we worked together on the research, until the opening of the Town Hall in October 1972 where he made the acoustic commissioning measurements.

4.1. Re-engagement with the Town Hall project

With research and teaching well established in WA (and because of the reluctance of Engineering Design Consultants to travel), the architects asked me to take up the executive role in the acoustical design. The principal result of EDC's work had been an increase in volume of the main auditorium following the predictions of the classical RT formulae, noise control, and optical reflection distribution studies for the main reflectors.

I reviewed the shape of the reflectors, found them ineffective and suggested the dihedral form for surfaces opposite the stage. The audible effect of this change (contrasting a single overhead reflection with a pair of lateral reflections oriented as if from adjacent dihedral surfaces) was demonstrated to the architects in a simulation recorded in the anechoic room. They were convinced sufficiently to make this change. The architects had produced their own 1:48 (1/4"=1') scale model which they sent to WA for me to study.

4.2. Testing for the audibility of lateral reflections

It had been argued that the mechanism by which lateral reflections could be masked depended on the reduction in intensity of the direct sound and reflections which grazed the audience; (after Schultz and Watters [16]). That resulted in the potential inaudibility of lateral reflections if these were preceded by an energetic ceiling or frontal reflection, on a path remote from the seating planes. This analysis was described in detail in a paper in the Architectural Science Review [17], and subsequently was included by Dr. Tom. Northwood in Volume 10 of Benchmark papers in acoustics, (Dowden, Hutchinson - Ross Inc. New York).

That approach was the basis for the testing of the model; estimating the strength of the respective reflections from the attenuations found in [16], and measuring the arrival times in the physical model using a spark source and a storage oscilloscope. It proved to be impossibly difficult. T.B Ardagh, already a graduate in both science and architecture, undertook Master of Building Science program in 1970.

For his thesis he chose to write the software for a digital study of echo and audibility of the lateral reflections in concert halls. Of course the subject hall was the Christchurch Town Hall design [18].

With computer power at everyone's fingertips these days we forget what a feat this was in 1970. The program was run on a PDP6 ex NASA computer and took all night for a single source position. It was certainly the first such application in our hemisphere and possibly in the world. T. B. Ardagh deserves special mention for his ground-breaking work.

Echoes were located and treated.

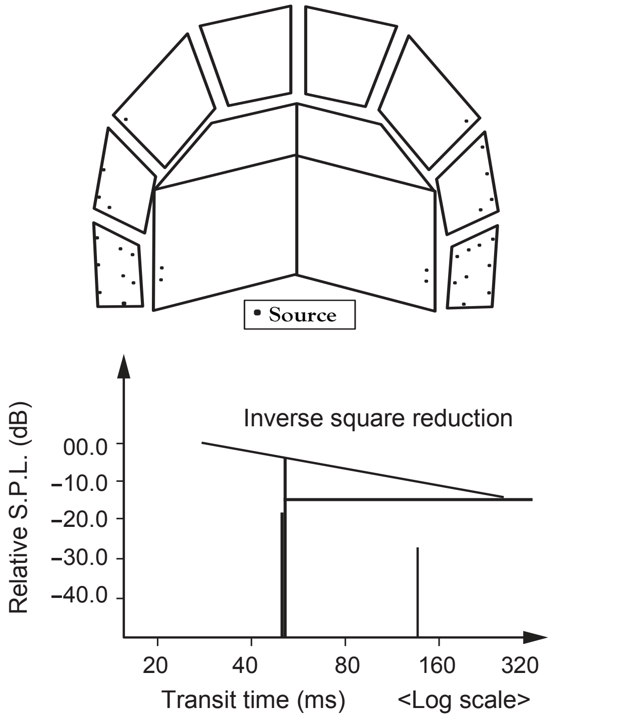

Figure 4. Two illustrations from [19]. On top is a plot of seats failing the lateral reflection audibility, on the bottom is the computed echogram for the chosen seat (marked interactively with a X). Only every third seat was tested and the hall side walls were adjusted to correct these seats.

4.3. Occam's Razor

While there is no doubt that in some cases the precedence of the ceiling reflection masked the side reflections, in the general case the precedence was not an issue. Barron showed conclusively that the ratio of lateral to frontal reflected sound energy was sufficient to describe all the subjective results. On this basis Barron devised the "lateral fraction" Lf as an objective measure for the spatial impression. This he measured with the "Gated Integrating Energy Meter" he designed and a Neumann SM69 studio microphone [19][20].

5. Commissioning

There was no opportunity for "tuning" the Hall as later became fashionable for concert halls. The official opening was on September 30 1972. For two or three days earlier we had access to make measurements - sometimes at night, as cleaning and finishing work was still in progress. On one of these days an invited audience arrived for occupied RT measurements (about 2000 people). The acoustic source was to be a 45 calibre pistol ex WW1, and I needed to warn the patrons to cover their ears. I found I could address this large audience without the sound system - which was still being installed. With an RT in excess of 2 seconds, speech clarity should have been poor. Subsequently this effect was quantified as described in [18].

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At the time of making these measurements, Dr George Dodd [21], University of Auckland, Acoustics Testing Service, pointed out that in effect we had clearly separated the early reflected sound field from the reverberant field. This separation both accounted for the high clarity, and I realized that it opened the possibility for large uncompromised multiple use spaces – arguably the most significant result to come from this design. Indeed the Programme Acoustique for the new Philharmonie de Paris [22] contains several essential passages, which might well have been a description of the Christchurch Town Hall acoustics [23].

Prior to the opening concert, balance between choir and orchestra was corrected with concealed reflecting panels which remained in place until the installation of the Rieger organ in 1997. Thereafter they were not needed. There were sundry other minor changes over the years.

At the opening concert the orchestra reported some difficulty with ensemble and that led to ongoing research [24] and measurement of the necessary and sufficient acoustical conditions for orchestral ensemble. A direct result was that the over-stage reflector and stage lighting framework (which had been omitted for cost and time reasons prior to the opening), was designed modeled, and installed by 1977.

6. Conclusions

Over some 38 years the Town Hall building had become a loved architectural treasure in Christchurch. It barely showed its age because of the architectural skills devoted to its creation. It received both the NZIA Gold Medal in 1973 and an Enduring Architecture award in 2000. Its acoustics have been acclaimed by such luminaries as Leonard Bernstein, Dame Kiri Te Kanawa, Yehudi Menhuin and Bryn Terfyl. I have outlined the process by which its acoustic design arose from the initial imperative to ensure the audibility of lateral reflected sound. I have recounted some unforeseen consequences of its unique form, which led in the subsequent decades to so much excellent research and learning. It may well be that the comparative isolation from the cultural inertia of both Europe and North America enabled the bold steps the architects were willing to embrace in the form of this room. Be that as it may, the intimacy, clarity yet full reverberance that the room produces remains one of the most exciting symphonic sounds in the world.

All that changed on February 22, 2011. The second earthquake destroyed the heart of Christchurch. The Town Hall building was damaged but is reparable; indeed the City Council has unanimously agreed to restore it in its entirety.

There is a counter-imperative however not unlike that that informed Rotterdam after WWII – the chance to have a brave new city [25], for which a concept plan now exists. The Town Hall could easily be included in this concept plan, given the will to do so. It would indeed be ironic if, when the *Philharmonie de Paris* opens next year, the Christchurch Town Hall has gone.

Acknowledgements

My presence at ISRA 2013 is supported by a grant from the organisers and a further grant from Marshall Day Acoustics Ltd. and this support is gratefully acknowledged. My wife Shirley has, as always, supported my efforts; there is another story underlying this one in which she is the principal.

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25. Should you wish to write in support of this restoration, as many did to the City Council with such effect, please address your letter to: *gerry.brownlee@parliament.govt.nz*

rma net

It has been a quiet couple of months in the Courts for acoustic and vibration issues. The following is a brief summary of a recent Environment Court decision relating to the validity of a gun club's Certificate of Compliance in light of subsequent subdivision nearby, together with some details on a significant case which will soon be going to a further hearing in the Environment Court involving Palmerston North City Council and New Zealand Windfarms Limited. Full decisions and further information can be found on the RMA Net website at www.rma.net

In the Enviromental Court

WAIMAKARIRI DISTRICT COUNCIL - Applicant

NORTH CANTERBURY CLAY TARGET ASSOCIATION - Respondent

[2014] NZEnvC 114, 24p, [88] paras, 23 May 2014

Summary of Facts

In 1995 the North Canterbury Clay Target Association (the Association) was granted resource consent for 13 shoot meetings and 13 practices per annum at a shooting facility at 269 Boundary Road, Cust. In 2007 the Association requested a Certificate of Compliance to increase its activity to 52 meetings and practices per annum. The application was accompanied by a noise assessment report which maintained that the noise at the then nearest dwelling complied with the permitted activity noise limits of the Waimakariri District Plan and as such the activity was a permitted activity under the Rural Zone rules. The Council granted the certificate in 2008, but subsequent lifestyle block subdivision closer to the facility resulted in complaints and the Council applied for declarations that the shooting activities were not permitted under the Plan and the Certificate of Compliance should not have been granted.

The Council held that the sound levels of gunfire associated with the activities were unable to be measured under Rule 31.11.1.1 in accordance with the provisions of NZS 6801:1991 and NZS 6802.1991. As such by reason of the application of the Plan Rules 21.1 and 31.11, the specified activities were not permitted but fell to be considered as a discretionary activity (restricted). The interpretation of the Rules was discussed along with the difficulty of assessing gunfire noise under NZS 6802.1991. The Court held that the original noise assessment was based on the correct interpretation of the Rules, noise measurement was in accordance with the Standards, and highest emitted current and predicted noise levels did comply with the noise limits. As such the Court found that Rule requirements were met and the evidence demonstrated that the Activity, as it was and was predicted to be, complied with Rules.

The Court then went on to discuss what the Certificate of Compliance authorised and considered that Rule 31.11.1.2 continued to apply to an activity in the face of changing factual circumstances over time (such as the establishment of dwellings closer to the noise source of an activity). In terms of the application of Rule 31.1.1.2 the Court held it was irrelevant that a dwelling did not exist at the time the Association requested its Certificate of Compliance. Overall the Court found against the Council on its interpretation of the Rules but declined to make declarations, finding it sufficient to inform parties of its views on how Rule 31.11.1.2 should be interpreted.

Court held

On the date of issue of the Certificate of Compliance the activity was a permitted activity under the Waimakariri District Plan. Costs reserved

Future Decision

Most members would be aware of the Te Rere Hau windfarm in the rural hinterland east of Palmerston North owned by New Zealand Windfarms Limited (NZ Windfarms). There have been on going Court proceedings since 2012 relating to debate over compliance of turbine noise with the consent conditions. We are currently awaiting a further decision of the Environment Court on the interpretation of the consent conditions and some further disputed declaration applications about monitoring and compliance which had previously been adjourned for further technical study. Hopefully in the next issue we can report the outcome of this hearing, in the meantime below is a brief summary of the proceedings to date with comments made by Judge Newhook at a recent Consent Conditions Roadshow where he used the NZ Windfarms case as an example of problems that can occur when drafting consent conditions of a technical nature.

Proceedings against NZ Windfarms were initiated in 2012 after the Council had received numerous complaints from neighbours when the windfarm was two thirds built. In decision [2012] NZEnvC 133 the Court agreed with the Council that the acoustic information supplied by NZ Windfarms in its noise impact assessment report (IAR) was inaccurate with the turbines producing considerably more sound power than the prototype, as well as producing Special Audible Characteristics which were not predicted. Accordingly the Court found the Council was entitled to review the noise consent conditions. Further debate centered on a question of whether there was inconsistency amongst three conditions of consent and if so which would prevail. Condition 1 was a general condition found in many resource consents requiring conformity with the application documentation - that is, the windfarm being constructed and operated in accordance with the information contained therein, including plans, drawings and certain "additional information". The other conditions (4 & 5 in this case) set specific standards as to allowable noise levels received at certain sensitive residential locations nearby, and monitoring requirements. The Environment Court held that NZ Windfarms was bound by both its own predictions in its IAR as well as the specific noise standards in its consent.

In 2013 NZ Windfarms successfully appealed to the High Court ([2013] NZHC 1504) who did not consider that NZ Windfarm's IAR predictions were intended to go to scope but related to how predicted noise levels would be achieved. However, subsequently the Council appealed this decision on two questions of law;

1) Whether Condition 1 of the consent applied to either or both, the noise generating characteristics and performance of the turbines, and the noise effects at receiver locations;
2) Whether it was lawful for the High Court rather than the Environment Court to determine if the windfarm was constructed, operated and maintained in compliance with Condition 1.

The High Court granted the Council leave to appeal noting it was satisfied that there were seriously arguable questions of law which were of wider importance especially in the context of the local community in the receiving environment ([2013] NZHC 2654).

Since that time further technical measurements have been undertaken which has resulted in further disputes about the meaning of conditions 4 and 5 and whether conditions require data that best approximates the windfarm when all wind turbines generators are operating, or when there is a range of operating conditions being employed. Other questions concerned whether "near field assessment" or "far field assessment" should be the basis for assessment of Special Audible Characteristics. As such the next decision should make for some interesting reading and possibly some strong directors for future windfarm development in relation to consenting matters. Judge Newhook's final comment was that the case highlighted that great care was required not only in technical analysis but also in consent condition drafting of a technical nature.

3D impulse response measurements of spaces using an inexpensive microphone array

Daniel Protheroe[1] and Bernard Guillemin[2]

[1] Marshall Day Acoustics Ltd., P O Box 5811, Wellesley Str. 1141, Auckland, New Zealand

daniel.protheroe@marshallday.co.nz

[2] Department of Electrical and Computer Engineering, Faculty of Engineering, The University of Auckland

Private Bag 92019, Auckland Mail Centre

bj.guillemin@auckland.ac.nz

Abstract

The acoustical characteristics of a room are traditionally determined using omnidirectional impulse response measurements, yielding information about sound reflections in terms of magnitude and time, but not direction. However, the direction of reflections is often important, and thus the need for a practical, low cost measurement system for determining this. In this paper we present the performance of a low cost measurement system utilising an inexpensive microphone array, namely the Core Sound TetraMic, for the determination of 3D room impulse responses. These can then be visualised, for example, as a "hedgehog pattern". Experiments undertaken in an anechoic chamber indicate that the accuracy of directional estimation of this system is in the region of ±7.5°

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1. Introduction

In the field of room acoustics the measurement and visualisation of room impulse responses is of great interest. Room impulse responses are traditionally measured using an omnidirectional receiver. Sound reflections can therefore be analysed in terms of magnitude and time, but not direction. A 3D impulse response measurement system is required for the complete analysis of a sound field in terms of magnitude, time and direction of reflections. It then becomes possible, for example, to relate sound reflections to the physical features of the room, observe the directional distribution of early and late sound energy, as well as identify surfaces causing problematic reflections.

Several researchers have made 3D impulse response measurements, for example Abdou and Guy [1], Merimaa et al. [2], Fukushima et al. [3], Ohta et al. [4], Tervo et al. [5], and Bassuet [6]. However, their measurement systems often use proprietary, expensive or relatively impractical hardware. Further, details of the necessary calibration routines, as well as their practical limitations, are often not readily available. The consequence of this is that their use is essentially limited to the researchers who developed them.

In this work we propose a 3D impulse response measurement system which uses low cost, commercially available hardware, namely the Core Sound TetraMic microphone array [7], and investigate its performance. The necessary calibration routines for the TetraMic are software based and come supplied by the manufacturer. The subsequent processing routines leading to a fully directional analysis and visualisation of a sound field are relatively straightforward to implement and are presented in this paper. The system should be highly accessible to practitioners in the acoustics arena, as well as being relatively simple to operate in a real-world environment.

This paper is structured as follows. In Section 2 sound intensity theory is presented. Our measurement system is discussed in detail in Section 3, followed by some experimental results of the system in an anechoic chamber and a real room in Section 4. Our conclusions follow in Section 5.

2. Sound Intensity Theory

The system resolves magnitude and direction of reflections using a sound intensity technique. Sound intensity, **I**, at a position in a sound field is defined as the product of instantaneous sound pressure $p(t)$ and the instantaneous 3D particle velocity vector $\mathbf{u}(t)$ at that location:

$$\mathbf{I} = \overline{p(t)\mathbf{u}(t)}$$

where the average is made over a suitable length of time.

One approach for measuring sound intensity is with a B-format microphone which comprises a coincident array of transducers which can measure pressure and particle velocity in three dimensions.

3. Measurement System Overview

The major functional blocks of the measurement system

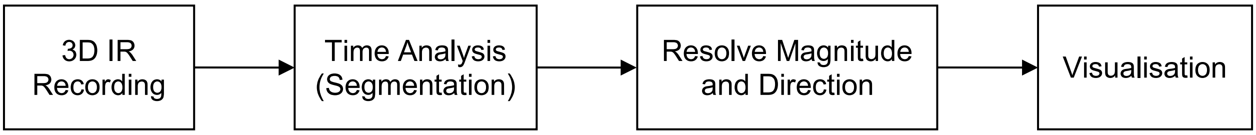

Figure 1. Major functional blocks of the measurement system

are shown in Figure 1. First, the 3D impulse response is recorded at a position in the room. The resulting signals are segmented into short time windows of interest, and for each the time averaged sound intensity is estimated, producing a series of 3D vectors which describe arriving sound energy in terms of magnitude, direction and time. Finally, these vectors are visualised as 2D or 3D "hedgehog patterns".

3.1 3D Impulse Response Recording

Capturing a room's intensity impulse response in 3D in B-format presents us with the challenge of arranging a pressure sensor and three orthogonal velocity sensors at the same point in space. One practical method to capture B-format, developed by Gerzon [8] in the 1970s, uses a tetrahedral microphone array of cardioid capsules. The outputs of this A-format array are summed and filtered to obtain the equivalent B-format signals. Our measurement system utilises a Core Sound TetraMic which is a relatively inexpensive and commercially available A-format microphone array. The manufacturer calibrates each device and supplies this data, as well as A-format to B-format conversion routines, in the form of software.

3.2 Time Analysis

The pressure signal from the B-format room impulse responses is analysed in time to identify important events including the direct sound, early reflections and any problematic echoes. The transition time between the early reflection period and late reverberation is also determined. This information guides a segmentation process whereby the B-format impulse response is divided into segments, with each segment ideally encapsulating an event. This is necessary because the direct sound and reflections are not delta functions but have dispersed energy. This is as a result of band-limited and non-flat frequency responses inherent in the measurement system and the room under test, as discussed in Section 3.4.

3.2.1 Direct Sound and Early Reflections

The magnitude, direction and timing of early reflections are important in concert hall acoustics and should ideally be analysed individually. Figure 2 shows the results of the segmentation process applied to the early part of a pressure impulse response signal. The shaded areas correspond to rectangular windows which encapsulate the direct sound (first shaded section) and three prominent early reflections (later shaded sectiond). This process could be conducted manually based on visual inspection, or automated through a peak-picking or arrival detection algorithm [9] [10] an example of which is discussed in Section 3.5.

3.2.2 Late Reverberation

After the so-called transition time [11], from the end of the early reflection period to the onset of the late reverberation period, it is no longer possible to consider reflections individually, and there is no value – from the point of view of the subjective sound – in doing so. In this region of the room response the signal is segmented

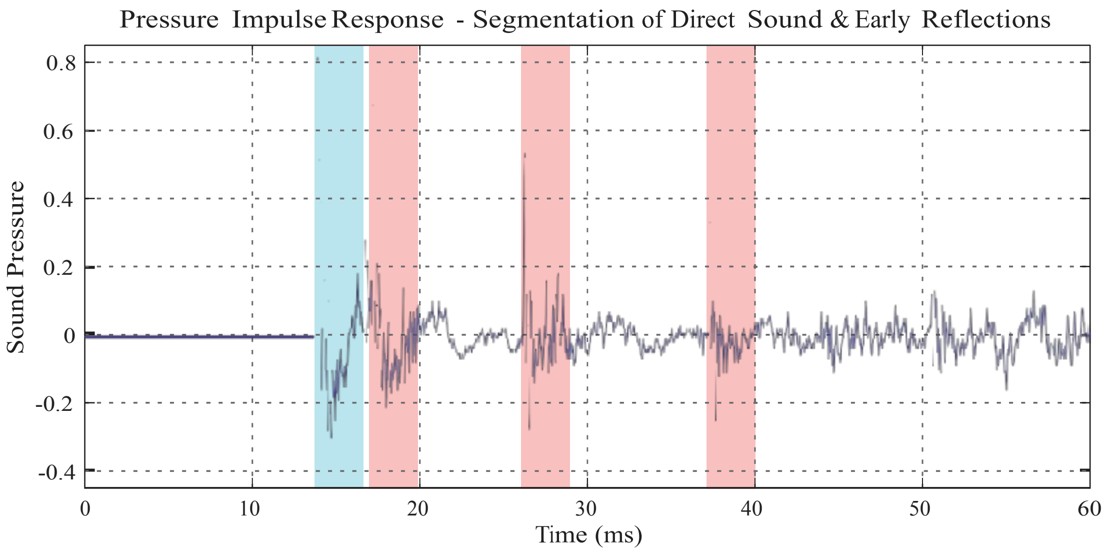

Figure 2. A pressure impulse response showing the segmentation of the direct sound (first shaded section) and early reflections (later shaded sections)

into a series of equal length, non-overlapping rectangular windows. The magnitudes and directions found from these windows will indicate the diffuse nature of the field.

3.2.3 Window Duration

For both the early reflection and later periods, the window durations used should be equal in order to accurately compare magnitudes within a non-steady-state signal, but it is not necessarily obvious what window length (nor the precise window function) will be optimal. Our experience so far suggests that a window length based on the duration of the direct sound is suitable. This ensures good timing resolution, but will be at the expense of some low frequency information in the resulting analysis. A longer window is more likely to encapsulate more than one reflection in the early period.

3.3 Determination of Magnitude & Direction

Magnitude and direction is estimated for each of the time segments according to the following process. For each segment sound intensity is determined in the X, Y and Z directions. The time averaged intensity for the i^{th} segment S_i in the X direction is given by:

$$I_{S_i,X} = \frac{1}{N}\sum_{n=0}^{N-1} I_X[S_{i,TOA}+n] = \frac{1}{N}\sum_{n=0}^{N-1} p[S_{i,TOA}+n]u_X[S_{i,TOA}+n]$$

where $S_{i,TOA}$ is its time of arrival and N its length (both in samples), $p[n]$ is the pressure signal, and $u_X[n]$ is the velocity signal in the X direction. Similar calculations are performed in the Y and Z directions resulting in the vector:

$$\mathbf{I}_{S_i} = \begin{bmatrix} I_{S_i,X} \\ I_{S_i,Y} \\ I_{S_i,Z} \end{bmatrix}$$

The length and direction of $\mathbf{I}_{S_i}$ correspond to the estimates of magnitude and direction, respectively, of the sound in segment S_i.

The pressure and velocity signals may also be filtered if particular frequency bands are of interest. It is recommended that signals are windowed first before filtering to avoid filter delay problems. Each window should be sufficiently zero padded to include energy delayed by the filters [12].

As will be discussed in Section 4.1, the individual transducers of a TetraMic do not appear to act as coincident in space for frequencies above about 5 kHz. This introduces error in the direction estimation process, but this can be avoided by filtering. In a broadband analysis, direction should be estimated from B-format segments which have been processed through a low pass filter with a cut-off frequency of 5 kHz. However, the sound intensity magnitudes should be estimated from the unfiltered signals.

3.4 Impact of Non-Ideal Frequency Responses

In the example shown in Figure 2, the direct sound and early reflections are well separated in time. However, in many situations this is not the case, and identifying individual events in the early reflection period can be challenging. The imperfect (i.e. non-flat) frequency responses inherent in the measurement system and the reflecting surfaces in the room will cause energy to smear out in time. For example, the impulse response of a dodecahedron loudspeaker, a source often used in room acoustic measurements, is shown in Figure 3. Clearly this deviates significantly from a delta function, as therefore will be the case for any resulting reflections that arise. This smearing of energy makes it difficult to identify individual early reflections, especially when these are overlapping. One approach of potential help in identifying reflections in this case has been suggested by Lee [13].

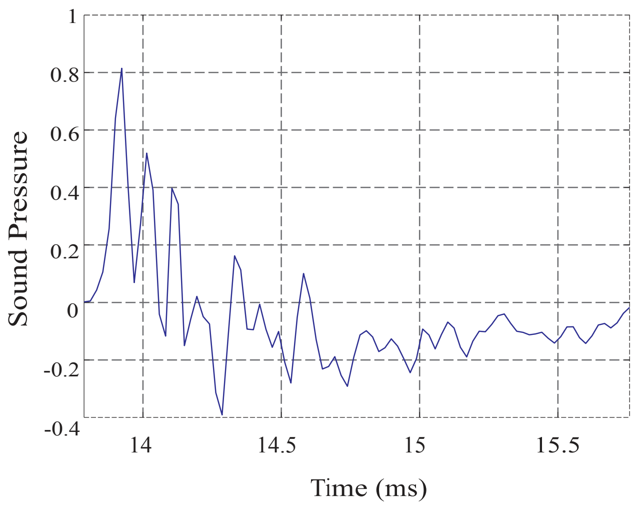

Figure 3. Impulse response of a dodecahedron speaker

3.5 Lee's Correlation Technique

This assumes that each early reflection is a relatively undistorted version of the direct sound. The idea is to cross-correlate the entire impulse response signal with the windowed direct sound.

Let $p[n]$ be the sampled pressure waveform and $p_{Direct}[n]$ be the segment identified as the direct sound, zero padded to equal the length of $p[n]$. The cross correlation between $p_{Direct}[n]$ and $p[n]$ is given by:

$$R_{pp_{Direct}}[m] = \sum_{n=0}^{N-1} p[n+m]p_{Direct}[n]$$

where N is the length of $p[n]$.

Provided that the early reflections exhibit a high degree of similarity with the direct sound, $R_{ppDirect}[m]$ should exhibit large, positively valued peaks at each arrival. Figure 4(a) shows a hypothetical impulse response consisting of a direct

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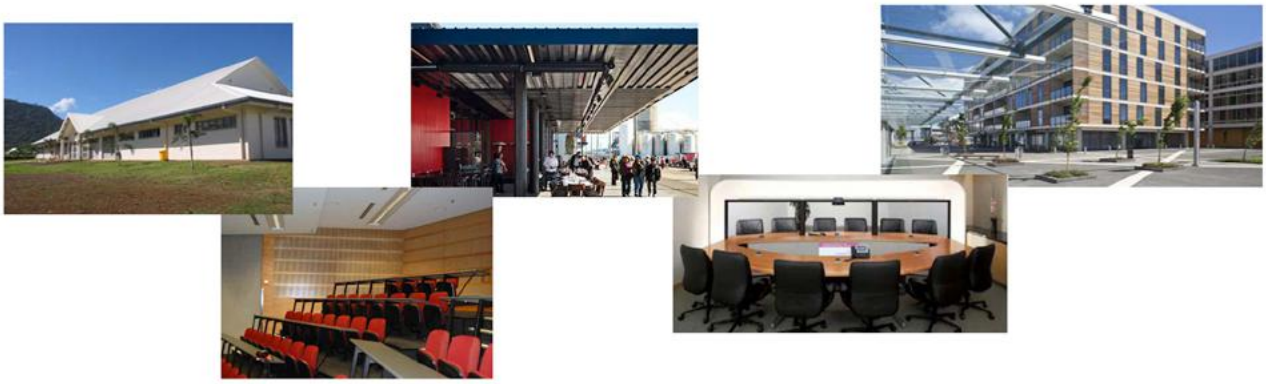
Conference Programme

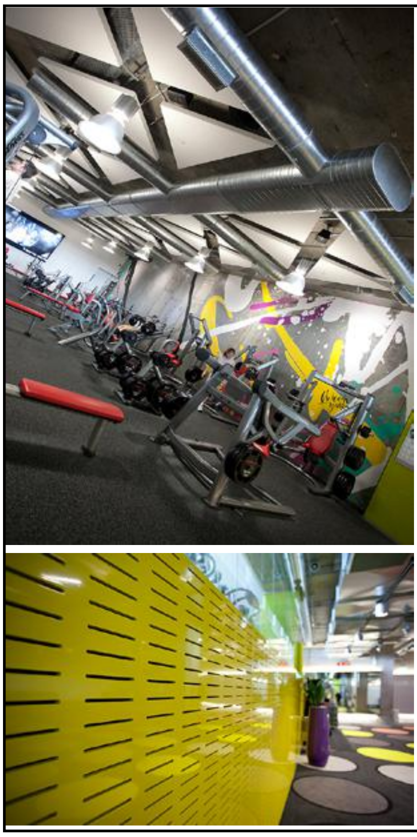
MONDAY 24th NOVEMBER 2014		
9.45 am	Registration opens	
10.00 am	Morning tea and Trade Show	
10.45 am	Conference welcome and sponsor address	
11.00 am	Technical Session 1:	
	Brett Giddens	*Hospitality in a transitional rebuild environment*
	Stuart Camp	*Entertainment noise rules in a vibrant city*
	Chris Day	*Noise and community complaint - is there correlation?*
	Peter Ibbotson	*Island acoustics*
12.30 pm	Lunch and Trade Show	
1.30 pm	Technical Session 2:	
	James Block	*Ferrymead bridge replacement project - construction vibration*
	Robbie Blakelock	*Modelling buildings to predict barrier effects for roads*
	Malcolm Hunt	*Transportation noise & vibration effects - best practice for district plan reverse sensitivity measures*
	Aaron Hudson	*Managing state highway reverse sensitivity effects*
3.00 pm	Afternoon tea	
3.20 pm	The Acoustical Society of New Zealand AGM	
4.00 pm	Garden City Tour	
6.00 pm	Happy Hour (venue TBC)	
7.30 pm	Conference Dinner (venue TBC)	

The programme is correct at time of printing; however the Conference Organising Committee reserves the right to amend any component as necessary

TUESDAY 25th NOVEMBER 2014		
8.45 am	Registration opens	
9.00 am	Technical Session 3:	
	Louise Carroll	*Is communicating to your potential a human right?*
	Sahan Wasala	*Numerical simulation and aeroacoustic noise modelling of the CART-2 wind turbine*
	John Bull	*Determining tonal audibility in large data sets*
	Stuart Bradley	*Where does background atmospheric acoustic noise come from?*
10.30 am	Morning tea and Trade Show	
11.00 am	Technical Session 4:	
	Michelle Wessing	*New Zealand's participation in international standards*
	Neil Jepsen	*The development of a remote noise monitor using the cellular network*
	Mathew Legg	*Non-destructive assessment of wood properties in tree stems using acoustic imaging*
	Gian Schmid	*A test report from ATS*
	Alex Campbell	*Design, installation and testing of a spring isolated outdoor roof top basketball court*
12.50 pm	Lunch and Trade Show	
1.50 pm	Technical Session 5:	
	Eric Wester	*Indefinite metamaterials for low frequency sound absorption*
	Jonathan Mountfort	*Configuration of material and its effect on acoustic performance*
	Yoshimasa Sakurai	*Forgotten linear behaviours in the sound field*
	George Dodd	*Measuring Ln without a tapping machine?*
3.30 pm	Conference closed	

Venue: Waimakariri Room, Novotel Christchurch Cathedral Square Hotel, Christchurch
For more information and to register now visit: www.asnzconference.com





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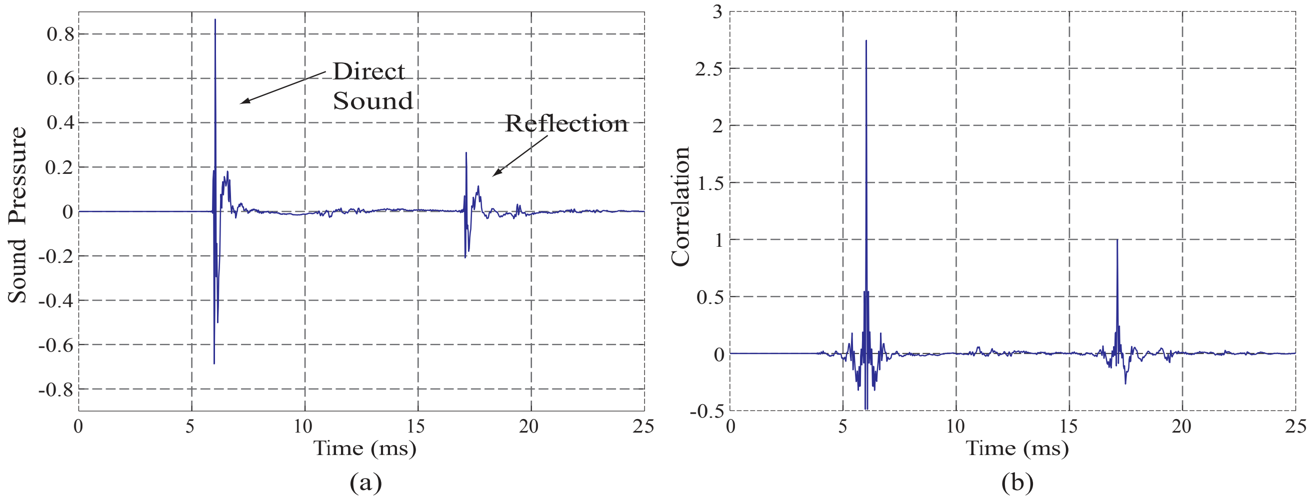

Figure 4. (a) Pressure impulse response showing the direct sound and a reflection, (b) Cross correlation of the impulse response with the direct sound segment

sound and one reflection. Figure 4(b) shows the resulting cross correlation function (note that the correlation delay has been shifted in time) with single, positive peaks at the position of the direct sound and reflection.

The correlation technique may be applied in 3D, also suggested by Lee [13]. The three particle velocity impulse responses are correlated with $p_{Direct}[n]$:

$$\mathbf{R}_{pp_{Direct}}[m] = \sum_{n=0}^{N-1} \mathbf{u}[n+m]p_{Direct}[n]$$

where $\mathbf{R}_{pp_{Direct}}$ is a 3D vector quantity and $\mathbf{u}[n]$ is the instantaneous 3D particle velocity vector.

This correlation function is effectively the sliding time-averaged sound intensity. In an analysis of the early reflection period, arrival times may be estimated by locating the peaks in $R_{ppDirect}[m]$. The value of each peak, in each of the X, Y and Z signals of $\mathbf{R}_{upDirect}[m]$, forms a 3D vector which points in the direction of the incoming arrival. Magnitude information will be incorrect, as the direct sound part of the pressure signal is used instead of the actual pressure. This alternative method of resolving direction may be particularly valuable in situations where reflections are overlapping in time, an example of which is shown in Section 4.2. The B-format impulse responses should be filtered to remove high frequency non-coincidence effects before calculating $\mathbf{R}_{upDirect}[m]$. A linear phase filter is recommended so that $\mathbf{R}_{upDirect}[m]$ can be time aligned with $R_{ppDirect}[m]$ after filtering.

3.6 Visualisation of 3D Impulse Response

The method presented here for viewing the sound intensity vectors generates a 2D or 3D "hedgehog" image in a similar style to Thiele's "Igel"[14] and Bassuet's [6] 3D impulse response visualisation. An example is shown in Figure 5. Each sound intensity vector or segment is represented by a single line, plotted on a 3D Cartesian diagram with respect to the measurement position (i.e. the origin). The length of each line corresponds to the relative sound intensity level (dB) normalised to the direct sound magnitude, and its direction is the estimated direction of incoming energy flow. The time information is represented by colour, as described by the key in Figure 5. The direct sound is coloured light green and thicker than the other vectors. The dynamic range is restricted to 40 dB. The clarity of the presentation can be enhanced by rotating the view. A 2D hedgehog pattern is useful for relating the sound intensity data to plans of the room, as shown in Section 4.3.

4. Experimental Results and Discussion

In this section we present the results from two experiments to demonstrate the performance of the system in an anechoic chamber, and then the results of measurements conducted in a real room (the Auckland Town Hall auditorium). Farina's exponential sine sweep technique [15] was used to excite the rooms, and recordings were conducted at 24 bit resolution and a sampling rate of 44.1 kHz.

4.1 Investigation of Directional Accuracy

Some of our preliminary experiments indicated that the angular estimation error present in the system was a function of direction. Thus this error was investigated for arrivals in the horizontal plane. In the anechoic chamber the source, a Tapco S5 studio monitor, was setup 1.6 m from the TetraMic mounted on a turntable, as shown in Figure 6. A total of 72 impulse response measurements were taken in 5° azimuth increments of the turntable from 0° to 360° (θ_D), and for each, the azimuth of the direct sound was estimated (θ^*_D).

The resulting broadband azimuth estimation error;

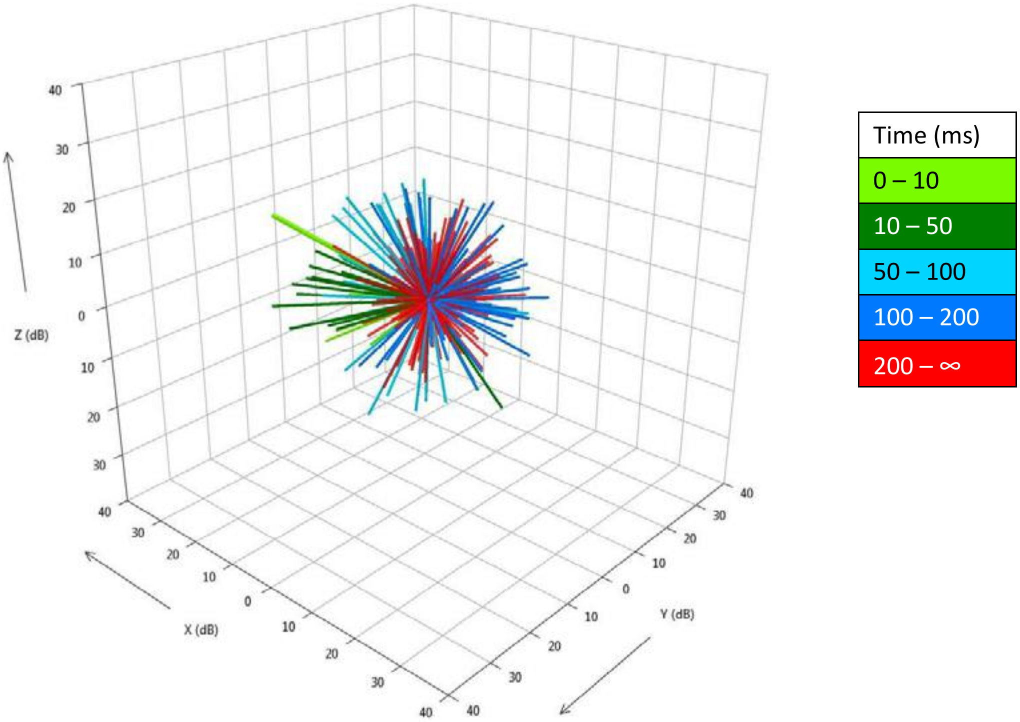

Figure 5. 3D sound intensity vectors visualised as a "hedgehog pattern"

$\theta_E = \theta^*_D - \theta_D$, is shown plotted in dashed in Figure 7. An average error of 5° was subtracted from θ_E before plotting the diagram. This offset implies a slight rotational misalignment of the TetraMic in the physical setup. The maximum error (without filtering) was ±18.8°. The smoothness and repeating pattern of this error function suggests it can be corrected for. Two causes for this error are likely to be the non-coincidence for high frequencies, and physical alignment errors in the experimental setup.

At high frequencies above about 5 kHz the TetraMic begins to no longer appear coincident, distorting the B-format polar patterns and thus introducing directional error. This error should be predictable and correctable, but further investigation is required in order to determine how this might be done. A simpler approach is to filter out this high frequency data. The angular error, after applying such a non-coincidence filter, is shown by the red trace in Figure 7. In this case, a Butterworth low pass filter with a cut-off frequency of 5 kHz was used. The maximum error after filtering is ±7.5°, which represents a substantial improvement over the unfiltered results.

Errors in the physical setup of this experiment would have also contributed to this error. For example, the TetraMic was unintentionally slightly lower in height than the

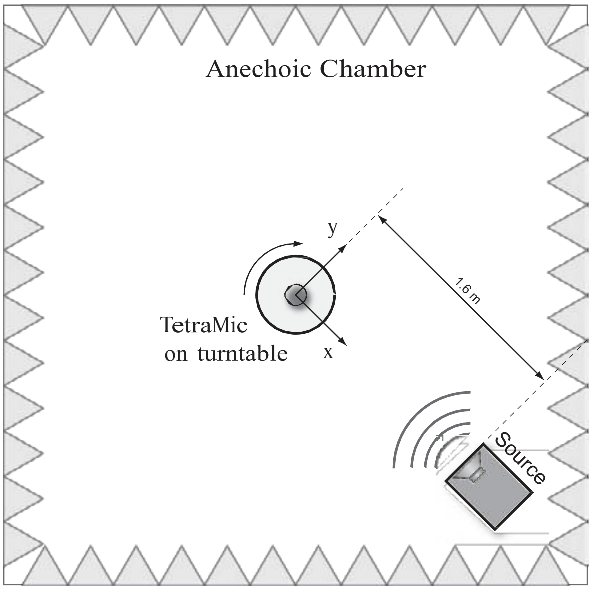

Figure 6. Experimental setup in the anechoic chamber for investigating directional accuracy in the horizontal plane

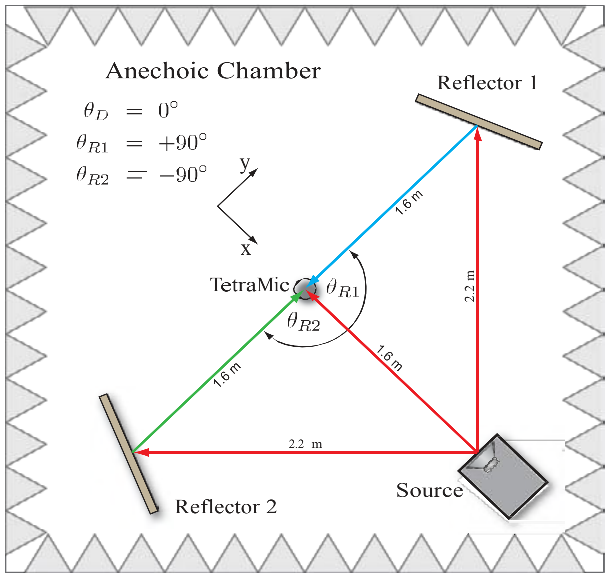

Figure 8. Setup for the overlapping reflections experiment

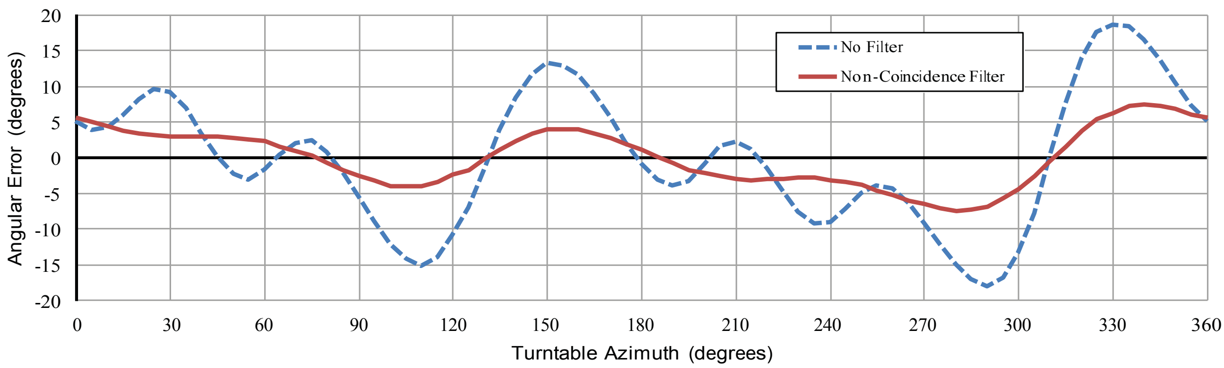

Figure 7. Azimuth error for unfiltered signals (dashed) & signals filtered with a non-coincidence filter (solid)

centre of the source and azimuth estimation is dependent on the elevation angle. This could be partly responsible for the cyclic shape of the error. Further, the source was not a true point source but a loudspeaker enclosure consisting of two separated drivers. The TetraMic was also displaced slightly in the horizontal plane as it was rotated. Careful alignment would be expected to reduce the errors for horizontally arriving sound.

This experiment presented the error for horizontally arriving sound, but in reality this should be examined in all directions. Additional investigation and modeling may lead to further improvements in the overall accuracy of the measurement system.

4.2 Overlapping Reflections

An experiment was carried out to investigate the effect of two overlapping reflections arriving from different directions, and whether or not their original directions could be estimated acceptably accurately. Again this was undertaken in the anechoic chamber (see Figure. 8). The positions of the source (Tapco S5) and TetraMic were the same as in the previous experiment. The positive X direction of the TetraMic was directed towards the source. Two reflectors of identical dimensions were arranged symmetrically about the TetraMic to generate two equal and opposite sound reflections.

The recorded impulse response for this arrangement is shown in Figure 9(a). As expected, it appears that only one reflection is present and thus it is concluded that the two reflections are highly overlapped. The estimated azimuth for these combined reflections is 136°.

When analysed using Lee's correlation technique, the part of the correlation function $R_{ppDirect}[m]$ relating to the reflections yields two distinct peaks as shown in Figure 9(b). From analysing the corresponding peaks in $\mathbf{R}_{upDirect}[m]$, the estimated azimuth of the first peak was -93° and the second peak was 93°, from which it can be concluded that the reflection resulting from Reflector 2 arrived slightly before Reflector 1. So in this case, even though these reflections were highly overlapped, their azimuths were resolved relatively accurately. There is,

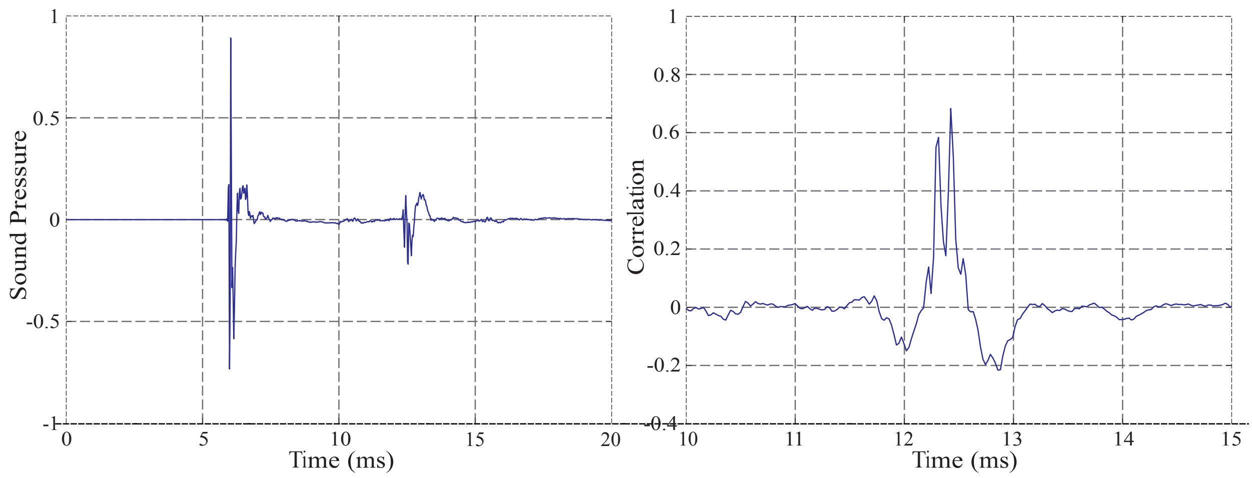

Figure 9. (a) Pressure impulse response of the overlapping reflections experiment, (b) Part of the cross-correlation signal showing two reflection peaks

however, no clear way of estimating the magnitude of each reflection in this case.

It would thus seem appropriate to use this correlation technique to identify the time and direction of arrivals in the early reflection period where reflections might be overlapping. However, it has been our experience that the usefulness of this technique is limited in a real world environment. Often the cross correlation signal would look equally as confusing as the original impulse response, and the significance of each peak would not be clear. One issue is that the impulse response of a dodecahedron speaker varies with direction. Correlating signals with a template radiated from only one direction of the source will therefore be erroneous. Another important issue is the band-limited responses of reflecting surfaces in the room which can cause significant time smearing of energy in the early reflection period.

Further work to improve the robustness of the correlation technique is required. Other methods to assist with identification of arrivals in an impulse response should also be investigated. Sturm and Defrance [9], and Defrance et al. [11], developed an arrival detection technique based on matching pursuit. This is similar to the correlation technique presented here, but with some additional steps. Usher [10] presented a technique based on a kurtosis analysis. Tervo et al. [5] suggested detecting reflections based on spherical variance.

When the impulse response in the early reflection period is not sufficiently clear to allow aligning of windows with individual reflections, this period can be segmented into a series of equal length rectangular windows, similar to the analysis of the late reverberation period (see Section 3.2.2). Segments will not correspond to individual reflections, but a series of segments in the early period should reliably indicate how energy is directionally distributed. This technique is also very simple to automate. The impulse response measurements presented in the next section were analysed in this way.

4.3 Measurements in a Concert Hall

The measurement system was used to obtain 3D impulse responses in the Great Hall of the Auckland Town Hall, a traditional shoebox concert hall which seats about 1500 people across three levels. The source, a dodecahedron loudspeaker, was placed at the centre of the stage, approximately 2 metres back from the front and at a height of 1.5 m above the stage floor. The receiver positions, shown in Figure 10, have the resulting hedgehog diagrams overlaid. The TetraMic was placed at listener head height, i.e. 1.2 m above the floor.

At each position, a 30 second sweep signal was used to excite the room. The impulse responses were segmented into a series of 2 ms rectangular windows following the onset of the direct sound. In each of the resulting broadband hedgehog diagrams, the direct sound segment is assigned a magnitude of 40 dB, and the magnitudes of the subsequent sound intensity vectors are referenced to this level. As a result, magnitude information cannot easily be compared between different hedgehog diagrams. The detected reflections have been grouped into several bands of time as shown by the different colours in Figure 10.

Considering the hedgehog diagram at receiver position R1, in the stalls, the thicker light green line, pointing to the source, is the direct sound intensity vector. The other light green lines may be related to direct sound arriving from other drivers in the dodecahedron loudspeaker, or floor reflections. The next interval of time, dark green, corresponds to the early reflection period. The directions of most vectors in this interval imply laterally reflected energy from the side walls. As time progresses (light blue to red) the sound intensity vectors gradually become more uniformly distributed about the measurement position, indicating the sound field is becoming diffuse.

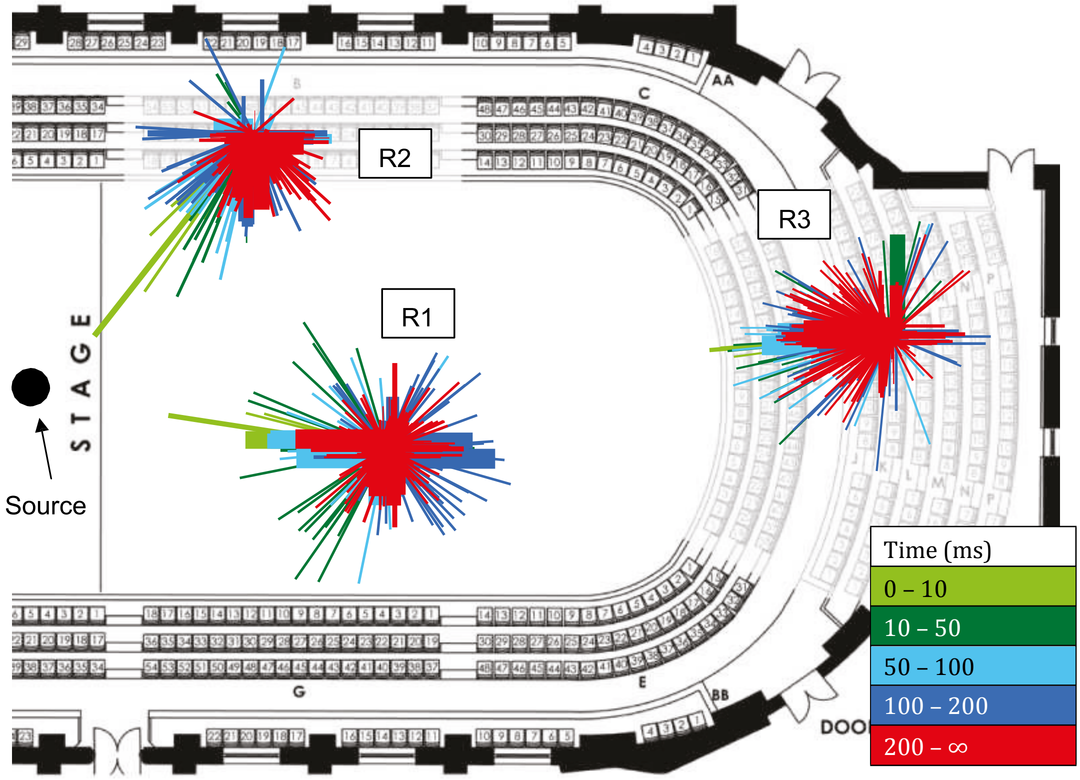

Figure 10. 2D hedgehog patterns for three receiver positions in the stalls and balcony levels of the Great Hall

At position R2, in the balcony level, the direct sound is quite prominent, followed by some early energy in a similar direction to the direct sound. The sound field doesn't become as diffuse as in position R1, indicated by the lack of sound intensity vectors in the top half of the hedgehog. This is consistent with having rear shielding and absorption from the raked padded seats located in this seating area, and the large area of curtains along the balcony walls.

Position R3, also in the balcony, is relatively far from the source and is overshadowed by the ceiling of the second balcony. As a result we see the length of the direct sound vector is similar to those of the reflection vectors. This indicates a smaller direct to reverberant ratio compared to the other positions. As with position R2, the steep raked seating behind R3 absorbs a significant amount of energy in these directions.

These results are well in agreement with what is expected from the form and contents of the room, and the hedgehog style of visualisation is, we feel, an effective way of comparing the acoustical properties at the different seating positions.

5 Conclusions

This paper has overviewed a technique for measuring and visualising 3D impulse responses of rooms using inexpensive and commercially available hardware, specifically the Core Sound TetraMic. The measurement system was tested in an anechoic chamber to assess its practical limitations, and it was found that directional accuracies in the horizontal plane are in the range of ±7.5°. A technique based on cross-correlation was also described to assist with discriminating arrivals in the early reflection period, but improvements to the robustness of this technique are required. Finally, the measurement system was demonstrated in a real space, the Auckland Town Hall auditorium, and the resulting visualisations show detail which is well matched to the physical environment.

Acknowledgements

The authors would like to acknowledge the invaluable assistance of Gian Schmid and George Dodd of the Acoustics Centre at The University of Auckland, as well as Len Moskowitz, Richard Lee and David McGriffy of Core Sound.

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An investigation of the effect of uneven blade spacing on the tonal noise generated by a mixed flow fan

Ludovic Desvard, Jeremy Hurault, Muhammad Affendi Bin, Mohamed Zamzam and Ash Symes

Dyson Ltd, Aeroacoustic Research Team, Tetbury Hill, Malmesbury, SN16 0RP, United Kingdom

Abstract

The current study investigates the flow performance and sound quality for a standard and an alternative compressor design for use in a Dyson desk fan. The alternative compressor has an uneven blade spacing to spread the associated energy of a single blade passing frequency to several frequencies in order to improve sound quality. The flow performance and acoustic signature for the two designs are compared both as a standalone compressor and installed in product. A dedicated sound preference model was developed to objectively evaluate the acoustic signature of both designs. This methodology can be used to help optimise compressor design in terms of user preference.

Originally published in FAN 2012, the International conference on Fan noise, technology and numerical methods

Introduction

This research was undertaken to improve the acoustic performance of the AM01 Dyson bladeless desk fan during the product development stage. Figure 1 illustrates the patented technology [1]. A mixed flow compressor in the base of the product forces air into the circular 'amplifier' section. A thin stream of air exits the amplifier through a 1mm annular gap and the initial flow rate is amplified by entrainment of the surrounding air.

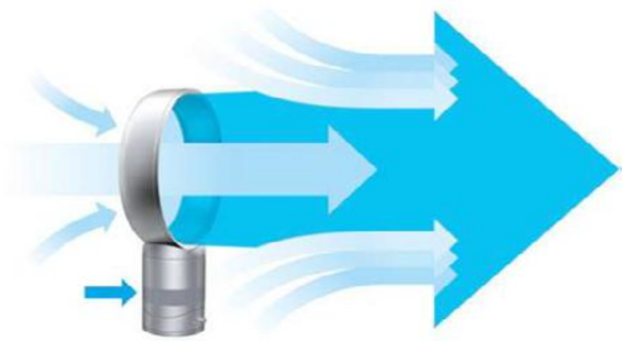

Figure 1. Illustration of the Air Multiplier™ (AM01) technology

The mixed flow compressor is the predominant source of noise from the product and the most significant component of this noise is aerodynamic related. Of particular interest to the current study, are the tones induced by the blade passing frequency which can be identified in the acoustic signature of the product.

The generation of tonal noise induced by a rotor has been widely studied [2, 3] and it has been stated that the aerodynamic noise is mostly induced by the wake of each blade interacting with the stator and also the non homogeneity of the inlet flow affecting blade loading.

Human perception of this tonal noise is considered to be undesirable and to this end, its study has been of interest to the automotive and the aircraft industries [4-6]. One proposed solution to this problem and the one investigated in this paper is to unevenly space the blades of the compressor about the centre of rotation, in order to spread the single, large tone induced by the blade passing frequency into several reduced tones to improve overall sound quality. The novelty of the current study was to demonstrate this as a potential solution in the context of a domestic appliance.

The issue of sound quality has been raised for radial fans [4] and axial propellers [5]. In both studies, the overall sound pressure level in dB or dB(A) and the magnitude of the tones were the important metrics used to evaluate sound quality following changes to the blade design. A different method of evaluation is presented in the current study using psychoacoustic metrics as a more thorough and relevant means to describe changes in sound quality.

In the current study, a simple model highlighting the motivation for uneven blade spacing is described. An alternative compressor design is realised and the flow performance and acoustic signature for both compressor designs are measured experimentally as standalone units and as integrated components of AM01. Finally, the sound quality evaluation methodology using psychoacoustic metrics is described and the results of a validated human preference model are presented to allow for an objective comparison of sound quality between the two designs.

Experimental Setup

Measuring the performance of the compressor

The compressors were measured using the dedicated set-up shown in Figure 2. In accordance with the in-duct sound power measurement standard [7], two ½ inch

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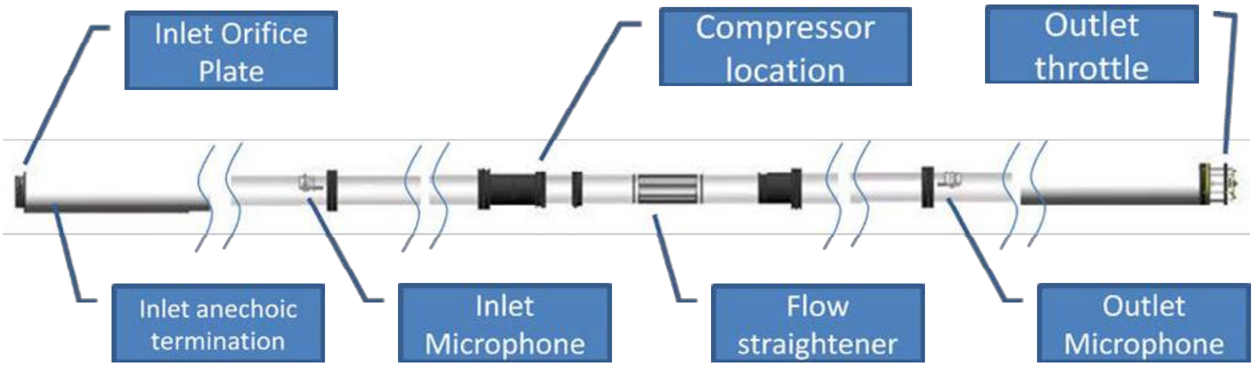


Figure 2. Aero-acoustic set-up

microphones (B&K 4189) were fitted in the inlet and outlet measurement ducts. These microphones were fitted with nose cones as turbulent noise suppression devices. Note that sampling tubes were not required as the mean flow velocity was sufficiently low (2 m/s). In order to minimise the turbulent noise at the microphone location, an anti-swirl device and an airfoil shaped microphone holder were used. The anechoic termination performance was checked by determining the sound pressure reflection coefficient. Aerodynamic performance curves and global efficiency curves were measured at constant rotational speed according to the performance standard for fans [8].

Measuring the performance of the Air Multiplier™ product

Two types of measurement were performed. The first was a standard sound power level measurement taken in a semi-anechoic chamber, as shown in Figure 3(a), in accordance with the standard [9]. Ten microphones were placed in a two meter hemisphere and the desk fan was

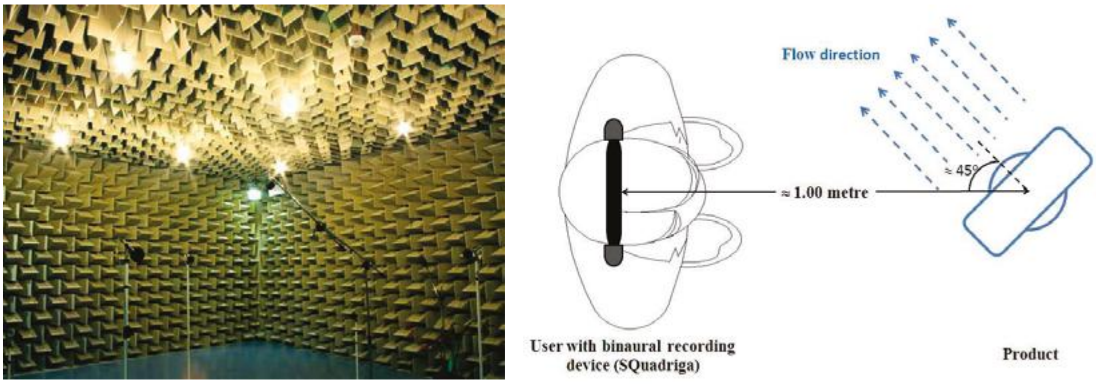


Figure 3. (a) Semi-anechoic chamber and (b) binaural recording set-up

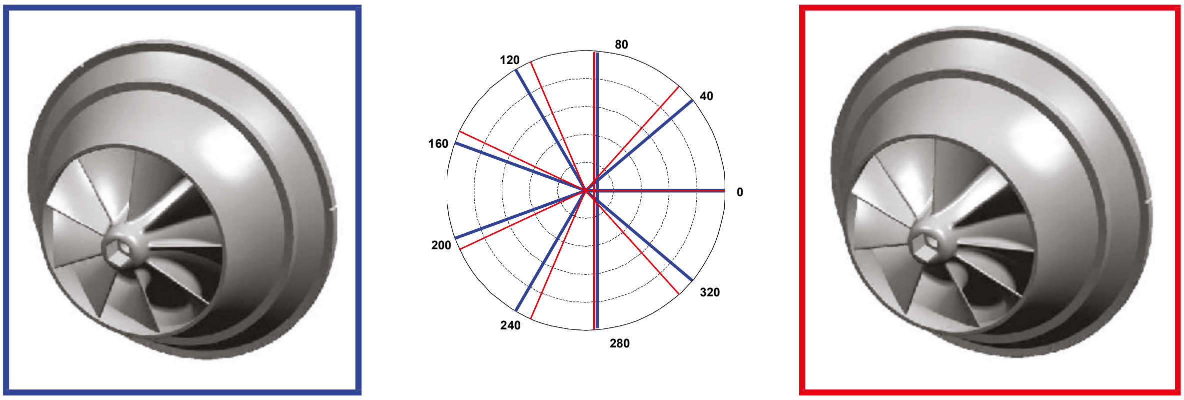


Figure 4. Two different impeller designs, symmetric (blue) and asymmetric (red)

located at its centre.

The second measurement was used for determining sound quality. The sound of the desk fan was recorded using a binaural recording device worn by an auditor. The desk fan was again placed in the semi anechoic chamber and the listener was positioned relative to the desk fan to represent typical usage, as shown in Figure 3(b).

Alternative Design Investigation

Description of the design

Two different designs of impeller have been investigated. The first design, which is termed 'symmetric' for the purpose of this study, is a mixed flow shrouded impeller with 9 evenly spaced, identical blades. The second impeller, termed 'asymmetric' has identical hub, shroud and blade profiles as the first but the nine blades are unevenly spaced. The circumferential offset of the blades in the asymmetric design was governed by a sinusoidal variation of up to 8 degrees from the position of the blades in the symmetric design. This design modification kept the centre of mass at the rotational centre of the impeller.

Figure 4 illustrates the difference between the two designs. Measurements using the methodologies outlined in the previous section highlight the difference in flow performance and in acoustic signature of the standalone compressors and also when installed in product. The two designs were prototyped from nylon using a selective laser sintering process (SLS).

Motivation for the asymmetric design

The signature of the blade pass frequency induced by an evenly spaced blade impeller is well understood and can be described as a pure tone. This tone will sit exactly at the frequency f_{BP} as shown in the following equation (Eq.1):

$$f_{BP} = N \times \varpi_{RPM}/60 \qquad (1)$$

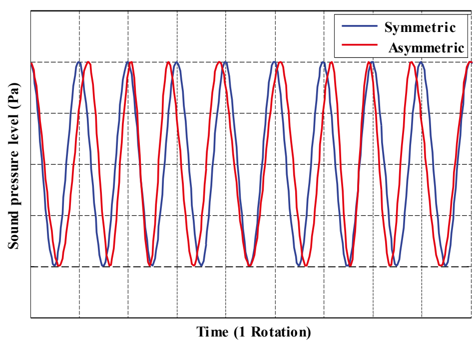
Where, N is the number of blades and ϖ_{RPM} is the rotational speed expressed in number of revolutions per minute. The time domain signature of a pure tone is a sinusoid and it is possible to generate an altered time signal which takes into account the blade asymmetry, as shown in Figure 5(a).

Performing a Fast Fourier Transform (FFT) results in the spectrum presented in the Figure 5(b). From this, the asymmetric design should provide a sound pressure reduction of 25% for the 9th harmonic and may also generate other harmonics including the 2nd, 5th, 7th, 11th, 13th and 14th.

The acoustic signature of both designs can be put simply as follows:

- The symmetric design gives a single strong tone.
- The asymmetric design gives several reduced tones

Before investigating the users' acoustic preference between the two designs when installed in the product, it was necessary to ensure that the compressor flow



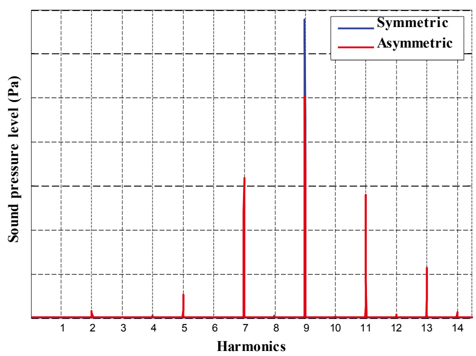


Figure 5. Blade passing induced signal in (a) time domain & (b) frequency domain for a 9 bladed design

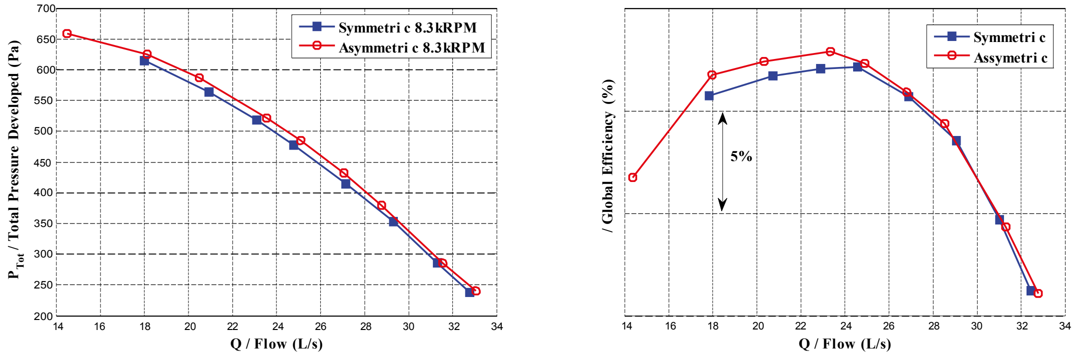


Figure 6. (a) Performance curves and (b) efficiency curves of compressors

characteristics were similar and if the anticipated acoustic signatures could be measured experimentally. Therefore, compressor measurements were carried out prior to product integration.

Compressor measurements

The difference between the two compressors is illustrated by the performance curves presented in Figure 6(a). For the same rotational speed, the total pressure developed ΔP_{Tot} was compared against the flow rate Q in litres per second (l/s). For a given flow rate, the asymmetric compressor developed approximately 10Pa more pressure than the symmetric design.

It is also interesting to define the point of maximum global efficiency for these compressors. Note that the efficiency η can be calculated from the following expression (Eq.2):

$$\eta = (Q \times \Delta P_{Tot} \times 10^{-3})/W_{Elect} \quad (2)$$

where W_{Elect} is the electrical input power in Watts.

From Figure 6(b), the point of maximum global efficiency occurs at approximately 24 l/s for both compressors.

Generally, despite these small differences which are likely to be due to hand assembly tolerances, the compressor performance curves are very similar.

The primary goal of the asymmetric design was to improve the acoustic signature of the compressor unit. Initially, the sound power level for both designs was measured. The asymmetric compressor showed a reduction of less than 1dB(A) in the overall sound power, as shown in Figure 7. Note that the flow rate corresponding to the minimum sound power level is offset from that for the peak global efficiency.

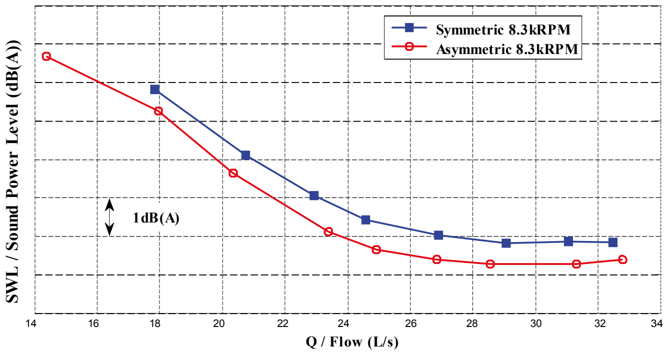
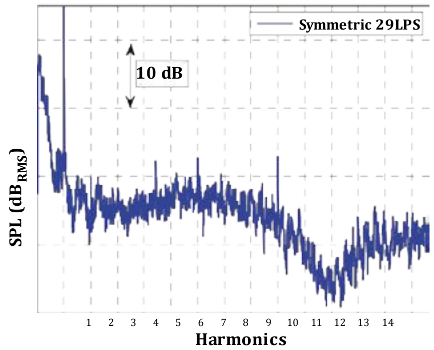


Figure 7. Sound power level of compressors

The aero-acoustic test differentiated between the inlet and the outlet acoustic signatures. However, to evaluate the overall acoustic signature, the inlet and outlet signatures were combined. As the current study was primarily driven by acoustic performance, the measurements were taken at 29l/s corresponding to the minimum sound power level for both compressors. The acoustic spectrums are presented in Figure 8.

For the asymmetric design, the predicted attenuation of the 9th harmonic is not apparent. As expected, the only



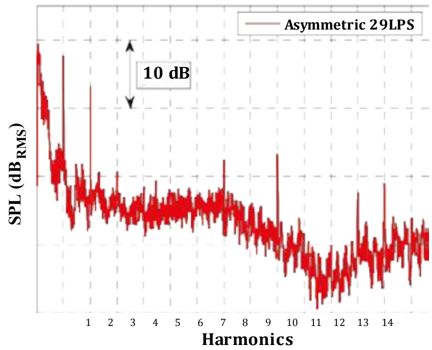


Figure 8. Compressor acoustic signatures of the symmetric design (left) & the asymmetric one (right)

harmonic observed from the symmetric design is the 9th, whereas the asymmetric design gives rise to the 2nd, 7th, 9th and 13th harmonics. However, not all of the expected harmonics are apparent, possibly masked by the broad band noise. The 6th harmonic of the symmetric design and the 12th harmonic of the asymmetric design are known to be induced by the dc brushless motor.

For both configurations the fundamental is induced by the imbalance of the impeller. This tone is transmitted through the structure and will be mostly damped in product as the compressor is soft mounted. The next step in the study was to understand the implications of these two designs when installed in product.

In product measurements

Due to motor manufacturing variability, the rotational speeds for the symmetric and asymmetric compressor units were not identical and were measured as 8220rpm and 8340rpm, respectively. The fan law (Eq.3) can be used to calculate the flow rate Q and the pressure rise ΔP developed by both designs for measured rotational speed ϖ_2 if their values are known at ϖ_1. Since the impellers were characterized prior to compressor assembly, corrected values of Q and ΔP can be determined for the compressors.

$$\frac{\omega_1}{\omega_2} = \frac{Q_{\omega_1}}{Q_{\omega_2}} = \sqrt{\frac{\Delta P_{\omega_1}}{\Delta P_{\omega_2}}} \quad (3)$$

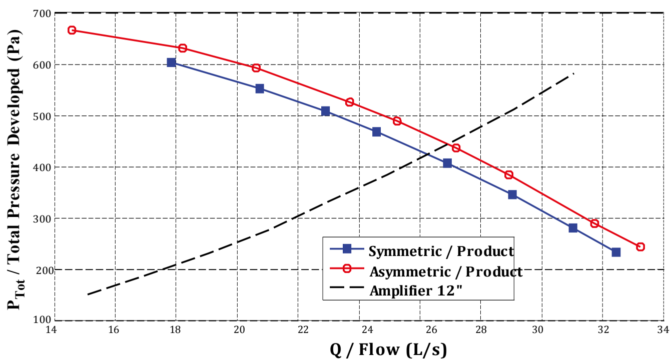


Figure 9. In product performance curve and restriction curve of the amplifier

The Figure 9 shows the corrected performance curves together with the restriction curve of the desk fan amplifier section. Assuming negligible losses arising from the product inlet, the flow rates were 26.2L/s and 26.9L/s for the symmetric and asymmetric designs, respectively. As way of confirmation, the same flow rates were also inferred from measurement of the pressure in the amplifier.

The sound power level for the symmetric and asymmetric designs was measured in a semi-anechoic chamber as previously described and the asymmetric design was quieter by 0.6 dB(A).

The acoustic signature for each compressor unit when installed in product was investigated by performing a binaural recording as previously described. Figure 10 shows the acoustic spectrum for the left ear recording for both compressor designs (the same conclusions can be drawn from the right ear).

Firstly, by comparing the signatures of the compressors shown in Figure 8, to those installed in product shown in Figure 10, it is apparent that the fundamental has been significantly damped. Secondly, comparing both designs in Figure 10, the 9th harmonic is 6.5 dB lower for the asymmetric design. Finally, all the expected tones, except the 5th harmonic, are apparent in the asymmetric design signature. It is interesting to note that the order of the tones in terms of magnitude for the asymmetric design installed in product is different for that for the compressor, shown in Figure 8. This difference is likely to be due to the transfer function of the amplifier.

From these results, it is reasonable to conclude that the preferred compressor design would be asymmetric, providing better flow performance and lower overall sound power level. However, a sound quality investigation was necessary to understand the user preference of these different acoustic signatures.

Sound Quality Approach

A sound quality investigation was undertaken to establish an objective measure to describe the subjective preference of listeners. The outcome of this investigation provided a dedicated preference model for quantifying the acoustic

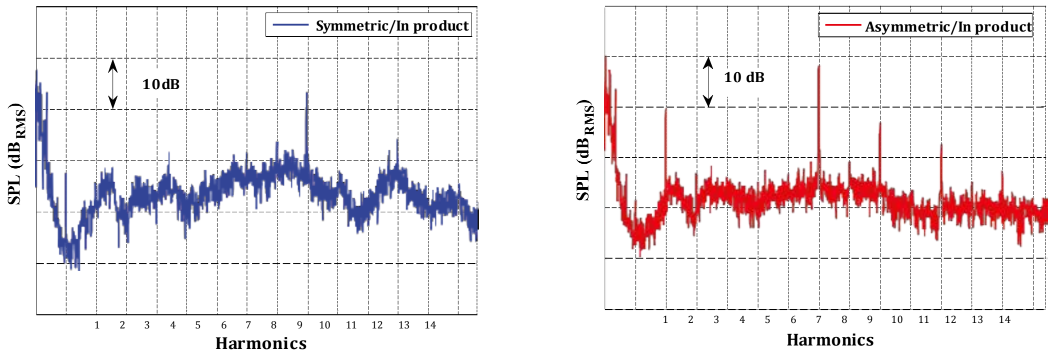


Figure 10. Left ear binaural recording

user preference for desk fans.

A schematic of the method employed is shown in Figure 11. Twenty eight (28) desk fan sound signatures were generated and objective psychoacoustic metrics computed from this time domain data. A total of 14 metrics were produced including those commonly used such as dB, dB(A), loudness, sharpness, tonality, roughness, and fluctuation strength.

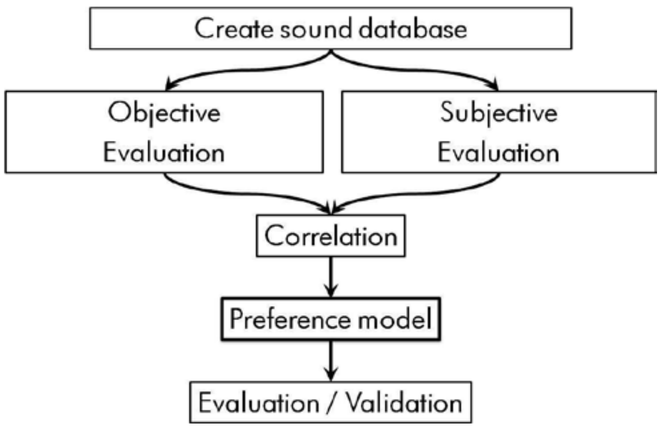


Figure 11: Methodology to define a preference model

Subjective measurements were elicited by conducting a perceptive test. During a test the listener was played multiple sound recordings and asked to rank them in order of preference. This gave rise to a 'preference index' with a value between 0 and 100 with 0 tending toward the least preference and 100 tending toward the greater preference for a particular sound recording. The perceptive test used to develop the current perception model included 10 sound recordings and 16 listeners. This number of listeners was sufficient for the preference model to converge whereby further listener tests yielded no significant change to the model.

The correlation between the objective sound quality metrics and the preference index was carried out using a least square linear regression method. Regressions with one and two parameters (metrics) were investigated.

The method generated multiple solutions to the preference model dependent upon the number of metrics considered. In order to pick the most relevant solution, three requirements for the solution were defined as follows:

- The coefficient of determination needed to be greater than 90%;
- The preference model needed to be statistically relevant; complying with the T-test and the F-test [10].

The model needed to be logical. For example, if the loudness of the recording decreased then it is logical that the preference index should increase. The preference model which best fit these requirements is defined by the following equation (Eq.4):

$$\text{Preference Index} = -\alpha \times \text{Loudness} - \beta \times \text{Tonality} + \gamma \qquad (4)$$

The coefficients α, β, and γ are positive constants. The Loudness is expressed in "sones" and computed according to the standard [11, 12] and the Tonality is expressed in "tu" [13].

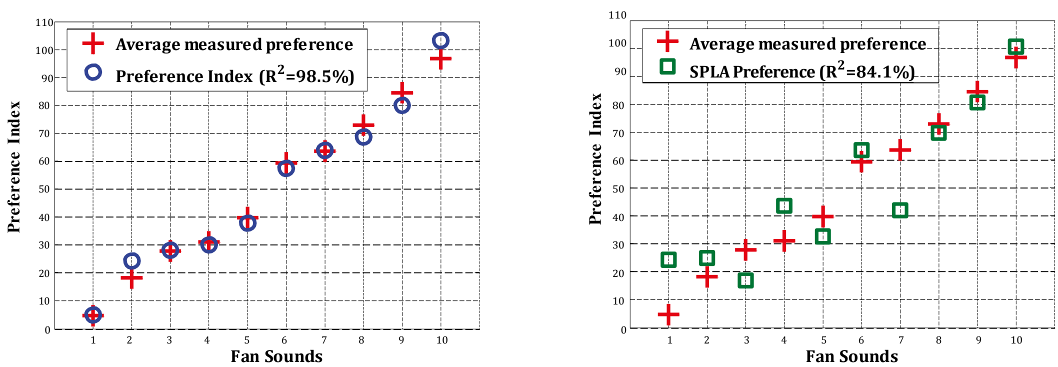


Figure 12. (a) Final preference model and (b) SPLA preference model

The coefficient of determination for this preference model is 98.5% and the correlation between this model and the subjective results is illustrated in the Figure 12(a).

For comparison, a simpler preference model using only the A-weighted sound pressure level (SPLA) is also presented in Figure 12(b) and the coefficient of determination for this preference model is 84.1%.

To evaluate the model, further perceptive tests were performed using 18 new fan recordings and 52 new listeners. The average correlation of the preference model as described in the equation (Eq.4) with the new subjective results was 86.1% whereas the preference model using only SPLA gave a correlation of 65.2%. From this, it is apparent that the model using loudness and tonality more accurately describes subjective preference than the model relying solely upon SPLA.

Applying the preference model to recordings made of the symmetric compressor installed in product gave a preference index of 20 whilst the asymmetric design in product gave a preference index of 6. Therefore, in terms of user perception, we can speculate that the symmetric design would actually be preferable to the asymmetric design.

Conclusion

Blade spacing asymmetry has been previously suggested as a potential solution to reduce the blade passing frequency induced tone in an effort to improve the sound quality of radial and axial compressors [4, 5]. The current study investigated the value of this concept when applied to a Dyson desk fan mixed flow compressor. To this end, the flow performance and the acoustic signature of a symmetric and an asymmetric design were compared as standalone compressor units and also when installed in product.

A dedicated sound quality preference model was defined to objectively evaluate the acoustic signature of both designs. It was interesting to note that, despite having a higher sound power level, the symmetric design gave rise to a higher preference index suggesting that the asymmetric design had made no improvement to sound quality.

The preference model, developed specifically for desk fans in the current study can be used as an important tool to further understand and optimise the asymmetric design concept.

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Five Minute Brain Teaser

1. What is this a photo of?

2. Is the medium absorption of sound energy greater in water or air at 1kHz?
3. What is the difference between sound power level and sound pressure?
4. Does adding two identical sound power levels give an increase of 3 dB or 6 dB?
5. What is the relation between loudness and decibels?
6. What is the relationship of dB to the phon and the sone?
7. Yes or No - can you convert from dB to phons?
8. Why do the sounds of two musical instruments always reinforce, and never cancel out?
9. What does STC an acronym for?
10. What is the difference between a Hemi Anechoic and Semi Anechoic Room?


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• TBA fire barriers • Intumex • Supalux
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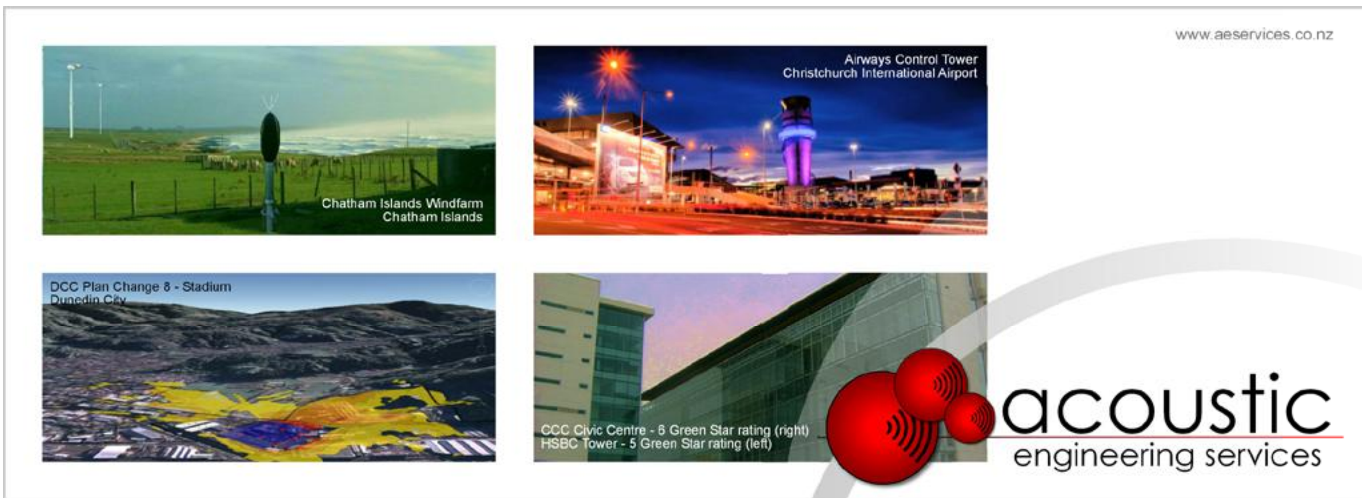

Acoustics Quiz Answers (Volume 27, No 2)

1. AKOUEIN – to hear
2. Vitruvius (Marcus Vitruvius Pollio)
3. Longitudinal
4. Overtones
5. Concerns the phenomenon of materials emitting acoustic waves when under load
6. The character of a sound other than its pitch which is determined primarily by its spectral composition
7. The contraction of the stapedius reflex muscle in the middle ear when sound levels exceed a certain value
8. Temporary Threshold Shift
9. The Reverberation Time of a space determined from the slope of the first 20 dB of the reverberation decay.
10. A capacitor microphone in which the required charge is stored permanently in a layer attached to the diaphragm
11. The raising of a speaker's voice when something blocks or masks the feedback of their own voice to their ears
12. The spectrum adaptation term (or C correction) applied to the weighted sound reduction of a construction to reflect its performance when insulating against a typical traffic noise spectrum
13. Quadratic Residue and Primitive Root diffusors.
14. A marine or under-water acoustician.

2014

16 - 19 November, Melbourne, Australia
Internoise 2014
www.internoise2014.org

24 - 25 November, Christchurch, New Zealand
ASNZ 2014 Biennial Conference
www.asnzconference.com

2015

18 - 22 May, Pittsburgh, USA
169th Meeting of the Acoustical Society of America
www.acousticalsociety.org

12 - 16 July, Brescia, Italy
22nd International Congress on Sound and Vibration (ICSV 22)
www.iiav.org

31 May - 3 June, Maastricht, Netherlands
Euronoise 2015
www.euracoustics.org/events/events-2015

9 - 12 August, San Francisco, USA
Inter-Noise 2015
http://internoise2015.com/

Recent Retirement

Dr Con Wassilieff recently retired after 25 years service to the New Zealand Acoustics Industry. Con who was a well liked acoustic consultant at MDA's Wellington Offices was well known and respected in the acoustics industry as an authority on building acoustics. After obtaining his Ph.D. in physics Con spent nine years as a scientist in the Acoustics and Vibration Section of the DSIR's Physics and Engineering Laboratory where Cons' work included development and operation of acoustical test facilities and equipment, research and acoustical consulting in general.

Con joined MDA in 1989 to run the MDA Wellington practice where he recently resided until June of this year when Con and his wife retired to beautiful Gisborne. Con has given a great deal of time to the acoustics industry including serving as a member of the technical committee revising the NZ Building Code for airborne and impact sound.

Con's friendly smile, witty comments and expertise in the field of acoustics will be missed across the entire acoustics industry.

Determination and verification of speech intelligibility from sound systems in tunnels

Robert Waddell

Bartons Sound Systems Ltd, PO Box 8821 Symonds Street, Auckland 1150

Abstract

Achieving reasonable speech intelligibility in a highly reverberant space is one of the more difficult problems encountered by a sound system designer. With the addition of high ambient noise and a demand for life-safety voice messages, vehicle road tunnels present a clear challenge. Improving speech intelligibility requires optimum type and placement of loudspeakers and acoustic modelling software is a required tool. Where knowledge of the acoustic properties of the materials used in the tunnel is known or can be determined, acoustic modelling provides an assurance of what will be heard. A road tunnel in Auckland New Zealand, AMETI Panmure Covered Box (PCB), is used as a test case where acoustic modelling has provided confidence in achieving high speech intelligibility and this has been confirmed through commissioning measurements..

An original Article

Introduction

Standards in New Zealand for emergency warning systems generally require pre-recorded voice messages [1]; there may be different messages for various stages of an emergency or for different locations within a site. Messages are generally preceded by warning tones and sometimes live voice messages may be used, for example a fireman's microphone. When the area where the message is played is highly reverberant like a maintenance depot, railway station or road tunnel, the intelligibility of the message becomes a prime consideration. The criteria for minimum intelligibility is defined in the standards that are commonly used [1] and the measurement of intelligibility can now be qualified. This is easily performed in real-time.

That leaves the sound system designer with the problem of designing a sound system that can reproduce pre-recorded and live speech messages with a received intelligibility in these reverberant spaces that satisfy the standard used. To get some idea of the intelligibility of a sound system before it is installed, acoustic modelling is a mandatory tool. This article describes some modelling tools and techniques that have been used to achieve a successful result for a combined road and pedestrian tunnel in Auckland New Zealand; the Auckland Manukau Eastern Transport Initiative Panmure Covered Box or AMETI PCB. Detailed test measurements during & after installation of the sound system have been used to validate the modelling process.

AMETI Tunnel

Part of the AMETI group of projects, the PCB tunnel is a combined vehicle and bicycle tunnel that reduces congestion and facilitates patronage of the new rail and bus station around Panmure area of Auckland. This tunnel is 220 metres long, 21 metres wide, averages 6.2 metres high and is of cut-and-cover construction.

The tunnel walls and roof are precast concrete, the base is mastic asphalt and as the tunnel has no fire deluge system, the concrete roof needs to be protected from fire damage with a mineral cladding system. Promatect H, a proprietary 20 mm thick mineral board suspended below the roof is used to achieve this. Bicycle lanes sit astride two opposing vehicle lanes and for this reason it was decided to equip the tunnel with an emergency sound system. The sound system, required to satisfy Fire evacuation standards, uses tone and pre-recorded speech but there is also provision for general purpose speech from a remote microphone mainly to aid public safety but also for prevention of crime and vandalism.

Initial design

The one small advantage that tunnels have over other large acoustic spaces is their high plan aspect ratio (length to width). The high aspect ratio would suit a single high power loudspeaker with a very narrow beam pattern that would provide sound for the entire tunnel. Unfortunately, air and boundary absorption preclude this approach in all but the shortest and narrowest tunnels but a variation of it is usable. A longitudinal array is an array where each loudspeaker is incrementally delayed along the length of the tunnel, the delay time relating to the loudspeaker spacing and velocity of sound in air.

In the initial design for the PCB tunnel, two rows of six loudspeakers were modelled with the two rows offset from the centreline of the tunnel by 7 metres. The loudspeakers mount to the underside of the ceiling at approximately 35 metre spacing along the tunnel with the starting pair directly under the north portal. The choice of loudspeakers is also quite straight-forward as there are only two types commonly available that satisfy tunnel use; DNH DUP40 and Duran AXYS AFB-260. Both feature high degrees of electrical and mechanical durability, 20 by 20 degree radiation patterns, suitable speech bandwidth and high output power. High electrical efficiency is achieved due to their use of compression drivers and long flare length horns. The AFB-260 was chosen for AMETI PCB mainly due its low profile and wider bandwidth.

Acoustic Modelling

As the PA system is required to be used as a life-safety system it has been designed from the ground up to comply with recognized standards [1] [2]. As well as electromechanical attributes such as fire survival cabling, back-up power supplies and fault logging, acoustic attributes also apply. These consist of the PA system having sufficient loudness to overcome maximum expected ambient noise or Signal to Noise ratio (S/N), as well as meeting a defined intelligibility criteria.

Maximum ambient noise levels in tunnels can be very high. Measurements of dynamic traffic sound levels inside other New Zealand road tunnels show sound levels within the range of 70 to 80dBA. The sound level of traffic noise during an emergency is unknown and we have allowed a 10dB margin above dynamic traffic measurements for this. AS 60849 requires that signal-to-noise ratio (S/N) be no less than 6dB with a maximum sound pressure level of 105dBA [1]. Using the speakers mentioned above it is relatively easy to produce A-weighted sound pressure levels in the range 95 to 100 dB inside the tunnel and S/N values of 6-10dB can easily be achieved.

Speech Transmission Index Public Address (STIPA) [2] is a recognized standard for intelligibility that can be predicted using modelling tools and measured in real time. For example; the AS 60849 Standard [1] requires that a PA system provide sound with a STIPA of at least 0.5 for speech where the content is unknown by the listeners. As the speech content is unknown to the listeners and we are required contractually to provide a compliant system, then STIPA of 0.5 becomes the design standard. AFMG's EASE AURA [3] software was used to predict STIPA over the listening plane (1.5 m above the road surface) of the tunnel. The hybrid deterministic and stochastic ray tracing methods employed by AURA [4] vastly reduce computational time compared to a soley deterministic approach. AURA additionally supports multi-processor PCs, further reducing computation time. As an example, the entire listening plane of PCB tunnel modelled using a 4x4 metre patch with all 12 loudspeakers active takes around 10 minutes on a 16 processor PC. But like all modelling techniques, any reliable output requires accurate inputs and the most difficult of these to obtain is the octave band absorption coefficients, α, for the surface materials. Absorption coefficients of common materials like concrete are easily obtained but sourcing these for the fire rated ceiling material proved more difficult.

Tunnel Ceiling

Reinforced concrete needs to be protected from heat damage from single and multiple fire events, and ablative coatings or panels are generally used to do this. To simplify cladding around the castellated roof beams a suspended ceiling clad with Promatect H mineral fibre board [5] was used. Promatect H is primarily a fire protection system and the manufacturers do not provide any acoustic specifications for their product. To progress the acoustic modelling we need to determine the absorption coefficient, ▯, for this material which comprises 37% of the entire tunnel volumetric area.

To determine the absorption coefficient of Promatect H, a reverse engineering technique was used. RT60 measurements were made in the centre of the tunnels after a considerable amount of ceiling had been installed. The unfinished ceiling was only at the portals so the RT60 measurements made in the centre was still considered representative. Multiple balloon pops were analysed on a NTI XL2 portable audio analyser and averaged to produce an RT60 plot (Figure 1).

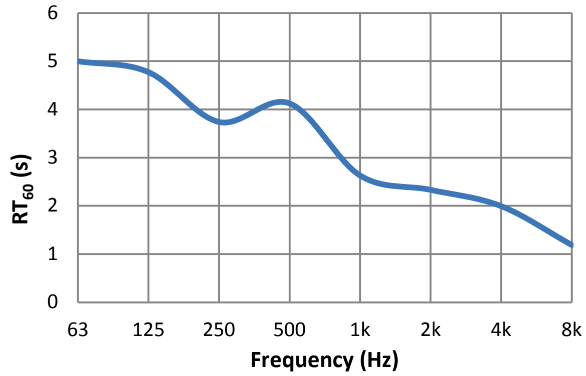

Figure 1. Average measured RT_{60} in centre of tunnel

Using the EASE "Optimize Reverberation Time" routine, it is then possible to adjust α for a dummy ceiling material to achieve the measured RT60 values. The dummy ceiling material with the calculated α can then be renamed and used in the model. It is also possible to generate α from samples using laboratory measurements although this is a relatively difficult process made more difficult if multiple layers or air gaps are used. Mathematical modelling techniques that can analyse multiple stacked acoustic materials such as AFMG SoundFlow [6] have proved to be a low cost and useful tool to do this. Figure 2 shows a SoundFlow prediction of the ceiling with Promatect H suspended 340 mm (on average) below the castellated concrete roof beams. From Figure 1, the reader may notice a reduction in measured RT60 at 250Hz, this dip directly relates to the air gap between the roof and the Promatect H mineral board. This is easily identified using SoundFlow software where a corresponding peak in α is shown in Figure 2. The air gap improves the overall α of the ceiling material reducing reverberation in a critical part of the

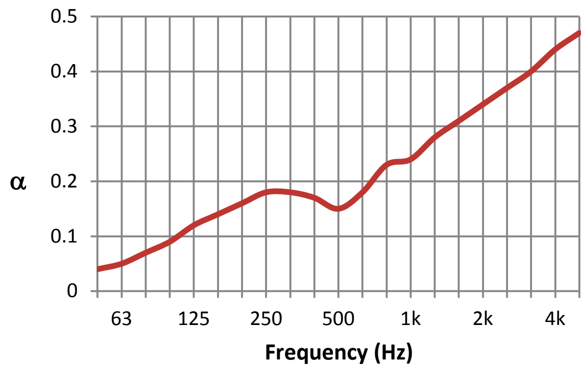

Figure 2. Estimated absorption Coefficient (α) of Promatect H (20 mm) suspended 340 mm below roof

voice spectrum thus improving the intelligibility of speech at any point inside the tunnel. The value of the Promatect H on the suspended ceiling derived from both EASE RT60 optimization and SoundFlow are nearly equal, <1% Standard deviation, across the 8 octave bands.

STIPA prediction and verification

The absorption coefficients for concrete walls and asphalt are from data tables and previous measurements; these are ($\alpha_{average}$) 0.04, 0.12 respectively. The portals are treated as pure absorbers i.e. α =1. These and the loudspeaker positions and corresponding delays were entered into the model and STIPA prediction using EASE AURA was performed. As STIPA predictions are highly sensitive to ambient noise, a noise file is required for use in any simulation. A pre-recorded file using measurements of traffic noise in a similar tunnel (Terrace Tunnel Wellington) was used as a noise file for the STIPA simulation. The average noise from each 1/3 octave band equals 70dB broadband for this file. The simulation showed that STIPA for the entire listening plane averaged 0.54 STIPA. This exceeded the design criteria and was useful when the initial loudspeaker locations were revised to accommodate vehicle height restrictions.

The relocation required that the two rows of speakers were moved above the pedestrian lanes and angled 10° towards the tunnel centreline. Remodelling showed that the STIPA criterion was still achieved thus avoiding the need for complex construction to recess the speakers above the ceiling. Figure 3 shows STIPA distribution from the revised loudspeaker mounting positions and Figure 8 shows predicted STIPA over the entire listening plane.

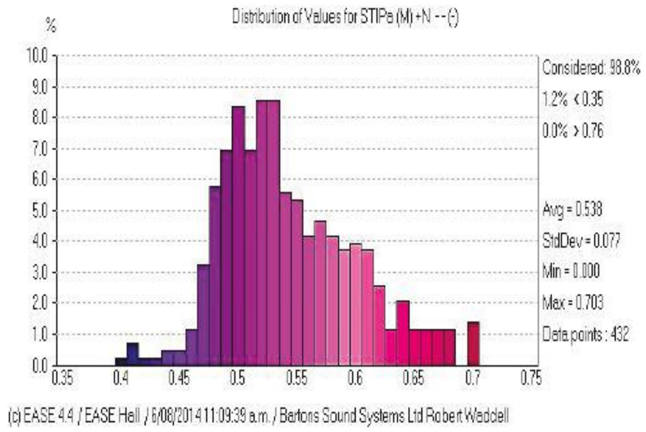

Figure 3. Predicted STIPA distribution across entire listening plane using revised loudspeaker positions. The colour scale also relates to Figures 5 and 7

One significant advantage of STIPA over any other method of determining intelligibility is that real-time measurements can be easily made. During commissioning, spot measurements made along the centreline of the tunnel using an NTI XL2 with STIPA option showed very close agreement with predicted STIPA. The agreement with modelled prediction was so close that it warranted a more detailed examination, as doing so would enhance the predictive ability of the modelling process. To do this, STIPA measurements were made on a 3m by 3m grid between speaker Right3 and Right4 and between the right tunnel wall and the centreline (Figure 4). The detailed test area is shown in Figure 4 and Figure 7.

Measured and predicted results are compared in Figures 5 and 6. Note that the bottom right corner, C4-R13 of each chart corresponds to a position directly under loudspeaker Right3 and C1-R1 corresponds to a position 4m in front of Right4 near the centreline of the tunnel. Although only a small area of the tunnel was examined, all 12 speakers are activated in both measured and modelled charts, this

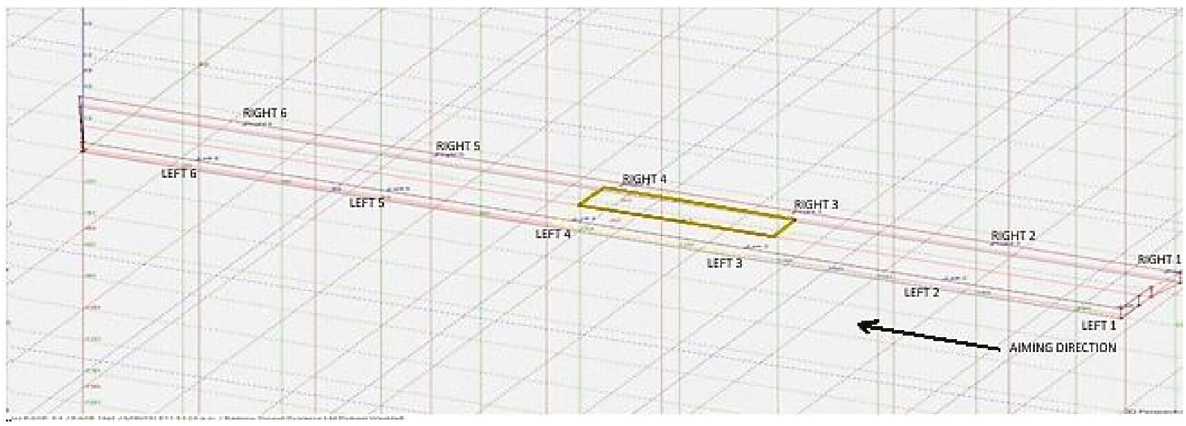

Figure 4. Iso view of the tunnel shows loudspeaker layout and the detailed test area (rectangular box)

being a necessary requirement for any STI prediction or measurement.

MEASURED	C1	C2	C3	C4
R1	0.56	0.57	0.58	0.55
R2	0.56	0.58	0.58	0.58
R3	0.57	0.59	0.59	0.59
R4	0.58	0.59	0.61	0.57
R5	0.59	0.61	0.58	0.58
R6	0.58	0.58	0.61	0.61
R7	0.56	0.59	0.65	0.62
R8	0.55	0.55	0.6	0.63
R9	0.52	0.55	0.62	0.65
R10	0.54	0.6	0.58	0.61
R11	0.52	0.56	0.57	0.62
R12	0.55	0.55	0.56	0.57
R13	0.57	0.56	0.57	0.57

MODELLED	C1	C2	C3	C4
R1	0.55	0.54	0.54	0.6
R2	0.53	0.53	0.56	0.56
R3	0.56	0.54	0.54	0.56
R4	0.55	0.55	0.56	0.55
R5	0.56	0.56	0.56	0.57
R6	0.53	0.54	0.56	0.61
R7	0.56	0.56	0.6	0.6
R8	0.54	0.56	0.6	0.63
R9	0.53	0.53	0.61	0.66
R10	0.52	0.51	0.55	0.64
R11	0.55	0.54	0.55	0.56
R12	0.52	0.52	0.54	0.59
R13	0.5	0.5	0.51	0.55

Figure 5. (a) Measured STIPA (b) Modelled STIPA

Although the comparison shows that the measured STIPA is actually slightly higher than the modelled STIPA, this is a result of low ambient noise when the measurements were made. The most important aspect of the detailed analysis is that STIPA follows the radiation pattern of loudspeaker Right3. This pattern equivalence indicates that there is excellent agreement between measured and modelled results. Figure 6 shows standard deviation in percentage for measured and modelled for each 3m patch; overall the STIPA standard deviation for the detailed test area is less than 1.5%.

	C1	C2	C3	C4
R1	0.7	2.1	2.8	3.5
R2	2.1	3.5	1.4	1.4
R3	0.7	3.5	3.5	2.1
R4	2.1	2.8	3.5	1.4
R5	2.1	3.5	1.4	0.7
R6	3.5	2.8	3.5	0.0
R7	0.0	2.1	3.5	1.4
R8	0.7	0.7	0.0	0.0
R9	0.7	1.4	0.7	0.7
R10	1.4	6.4	2.1	2.1
R11	2.1	1.4	1.4	4.2
R12	2.1	2.1	1.4	1.4
R13	4.9	4.2	4.2	1.4

Figure 6. Difference (Standard Deviation as %) between measured & predicted results

Conclusion

To comply with internationally recognized standards relating to life-safety systems, speech intelligibility needs to exceed a defined threshold for a large percentage of the listening area. For AS 60849 this is 0.5 STIPA or its equivalent on a Common Intelligibility Scale graph [1].

Longitudinal arrays of loudspeakers with incremental signal delays between sections are now the standard for sound systems in tunnels as they can increase intelligibility markedly over other speaker systems.

Sound absorbers are used to improve STIPA values. Almost every material used in a tunnel needs to be utilised as a sound absorber; this includes the concrete and asphalt even though their sound absorption coefficients may be very low. It is expected that the addition of fire protection coatings or cladding will improve STIPA and these materials will need to be tested to determine α. Quite often the sound absorbing properties of these materials can be enhanced by small modifications in their design or by the way they are installed.

Intelligibility can be easily predicted and measured using low cost software and measurement instrumentation. If a single material with unknown □ is used, this can be determined by RT60 measurements and may be confirmed with absorber modelling software. Verification of the model is a straight-forward task and allows confidence for modelling future projects.

Acknowledgments

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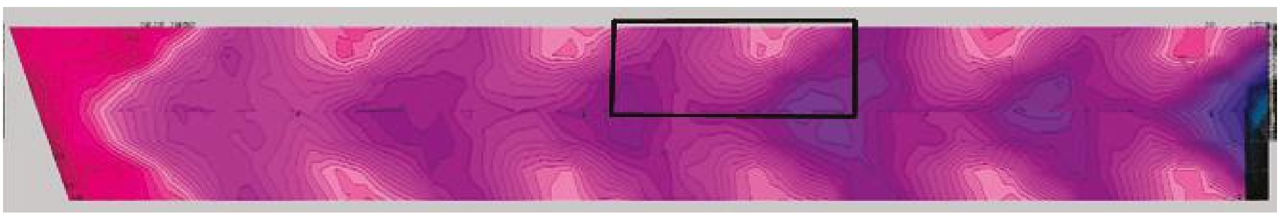

Figure 7. Shows PCB tunnel STIPA prediction on listening plane 1.5m above road and pedestrian level. The loudspeakers are pointing from right to left and are located approximately 4.7 m above the listening plane. In this figure, the 4m by 4m patches have been converted to contours. The rectangle shows the detailed test area.