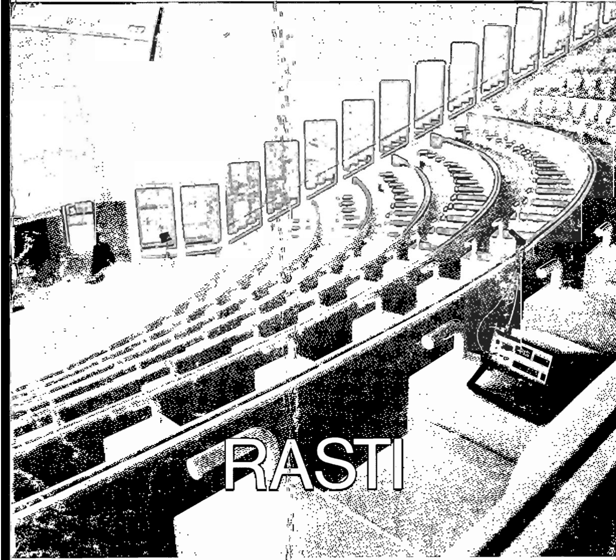
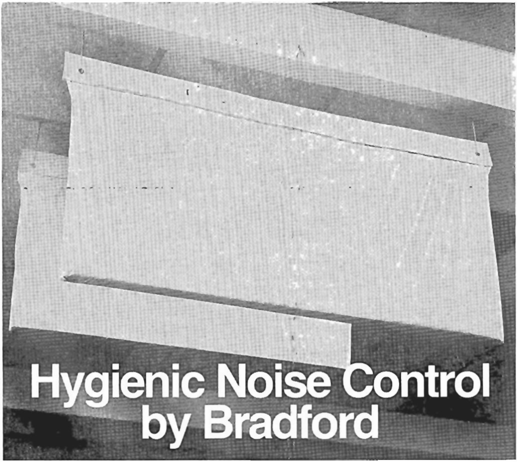
Acoustics Australia

Vol. 14 No. 2 | August, 1986 | AUSTRALIAN ACOUSTICAL SOCIETY



RASTI



Acoustics Australia

Subscription Rates
Surface Mail: 1 year A$33;
2 years A$59.50; 3 years A$86.50.
Airmail: 1 year A$45; 2 years A$71.50;
3 years A$98.50.

Address all correspondence to:
The Chief Editor
C/- School of Physics
The University of New South Wales
P.O. Box 1, Kensington, N.S.W. 2033

Acoustics Australia is published by the
Australian Acoustical Society
(Incorporated in N.S.W.)
35-43 Clarence Street, Sydney,
N.S.W. 2000, Australia.

Responsibility for the contents of articles rests upon the authors not the Australian Acoustical Society.

Articles may be reproduced in full provided adequate reference is quoted.

Printed by
Cronulla Printing Co. Pty. Ltd.,
16 Cronulla Street, Cronulla 2230.
(02) 523 5954.

ISSN 0814-6039

Vol. 14 No. 2 August 1986

CONTENTS —

Page

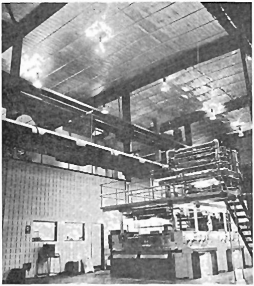
ARTICLES

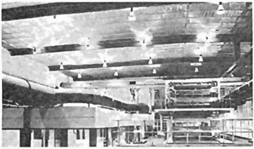
REPORT

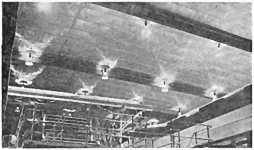
FRONT COVER — **RASTI — A Rapid Measure of Speech Intelligibility**
THE B & K 3361 SYSTEM

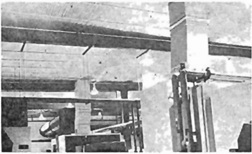
The quality of speech transmission is of paramount importance in any situation in which a speaker addresses an audience. Poor speech transmission in a room, theatre, auditorium, or outdoor public address system leads to reduced speech intelligibility.

B & K's new Speech Transmission Meter 3361 enables objective measurement of speech intelligibility in auditoria, churches, theatres, schools, etc. It can be used in localities with or without speech reinforcement systems and can also be used in the testing of Public Address systems in airports, railway stations, etc. For further details contact Bruel & Kjaer Aust. Pty. Ltd. (02) 736-1755.









The Western Mail, W.A. reduces noise levels with a RIPPLESOUND ceiling system

Newspaper offices can be very noisy places, particularly in the areas where printing presses are operating. So, in planning the new press building for The Western Mail in Canningvale, W.A., the design team and the acoustic consultants selected RIPPLE SOUND as an attractive ceiling lining system with proven effectiveness in absorbing unwanted noise. RIPPLE SOUND also has the virtue of being light in weight, and is easily installed.

In addition to its ability to absorb sound, RIPPLE SOUND also provides **efficient thermal insulation** and **maximum reflection** of natural light. It is a maintenance-free surface.

The RIPPLE SOUND Ceiling System comprises corrugated, perforated aluminium with polyethylene and bulk insulation above.

DESIGN & CONSTRUCTION: INTERSTRUCT Pty. Ltd.,
in association with Charles A.H. Abbott and L. D'Alessandro
Acoustic Consultants: Vipac Pty. Ltd.

RIPPLE SOUND

manufactured and installed by

RENHURST PTY. LTD. (Incorporated in Victoria)
A SUBSIDIARY OF JAMES HARDIE INDUSTRIES LIMITED
Incorporated in N.S.W.

Renhurst Pty. Ltd
Faigh St., Mulgrave, Vic. 3170.

Please send me Test details ☐ & literature ☐
about RIPPLE SOUND

Name...
Company..
Address ....
....Post Code..........

or phone

Melb.	560 3055
Syd.	709 6022
Bris.	265 7777
Adel.	252 2111
Perth.	451 5666

[illegible]

AUSTRALIAN NEWS —

NEW SOUTH WALES

April Technical Meeting

In recognition of a resurgence in the development of new acoustical products, and to encourage a closer relationship between suppliers (mainly Sustaining Members) and users (the general membership), a new type of meeting was held at the Crows Nest Club on 23rd April, 1986. The format was that a selected group of suppliers covering a broad spectrum of acoustics would briefly outline their products or views, and more detailed follow-up would occur between interested parties later. Six presentations were made:—

Cliff Winters of Bruel and Kjaer dealt with the historical development of acoustical instrumentation, going through the classical cycle of simple concepts becoming more complex while reducing in size and weight, but coming back to simplicity to satisfy demand.

Athol Patch of Cemac (Doors Division) continued the historical theme, referring to the earlier almost ad-hoc design of doors which did not reproduce their performance when installed on the job. This required the overcoming of deficiencies in five basic areas, ranging from design rationalisation and more realistic test procedures, to education of consultants, architects, tradesmen and particularly builders. He drew a parallel with the firedoor situation where similar efforts have led to performance guaranteed for years after installation.

Bill Mansell of Chadwick Industries gave a brief outline of a range of specialised products developed to overcome acoustical deficiencies found in traditional methods of building construction, with particular application to entertainment spaces and other large complexes.

Bill Richmond of Plastyne Products also provided a fine set of samples of their items and described the areas in which they were used. As with earlier speakers he showed how manufacturers must take into account many other criteria related to health, safety, etc., when developing new acoustical materials.

Geoff Pascoe of K. H. Stramit Pty. Ltd. continued the theme of illustrating the way in which their products are developed to meet a range of requirements, including mechanical, thermal, etc., as well as combining acoustical absorption and insulation.

Finally **Tom Crehan** of Auralguard & Bilsom Australia gave an historical summary of hearing protector development, and demonstrated two new earmuffs developed to combine with other safety equipment. He demonstrated also a programmable calculator that could be used to calculate accurately the dBA level experienced within 10 or up to 24 earmuffs of which the octave-band attenuation data had been pre-inserted into the calculator memory.

The meeting was preceded by an excellent informal dinner attended by 32 people, with about another 10 coming for the technical meeting. Both demontrators and audience had a socially agreeable and informative night.

QUEENSLAND

March Meeting

At the Extraordinary General Meeting of the Queensland Division of Australian Acoustical Society held on 11 March, 1986, the President of the Society, **Mr Graeme Harding,** presented an address dealing with the history, structure, aims and functioning of the Society.

Graeme pointed out that moves which led to the formation of the Society were begun in Sydney in May 1964 by Peter Knowland and H. Vivian Taylor. Interest was sought from others working in the field of acoustics in both Sydney and Melbourne. He traced the history of the Society through several name changes and drafts of the Society's constitution until the Society was incorporated as a company in April 1971.

Graeme then spoke on *Paradoxes in Acoustics* which included:—

- Why audiometric booths don't perform
- Why traffic noise intrusion is independent of glazing thickness
- Why your children have the television so loud
- Why solid brick houses are quieter than brick veneer houses

When he was field testing an audiometric booth in an industrial environment several years ago, he found that the performance of the booth was markedly inferior to the laboratory test results. It was not until he had made several checks on the construction and performance of the booth and the walls of the room in which it was housed that it became apparent that the siting of the booth in the room had a direct bearing on the sound isolation achieved. That is, the booth when placed as it was in a corner of the room was no longer totally within the diffuse sound field of the room but was, in fact, generating a highly reverberant sound field along two of its four sides.

By reference to transmission loss curves for window glass as a function of thickness, Graeme illustrated that thickness has little bearing on the sound isolation performance of single glazing for traffic noise. Some good-humoured debate ensued, however, regarding the spectral distribution of traffic noise in rainy Melbourne (where Mr. Harding has his practice) with that in Queensland!

To illustrate his next topic, the President showed how normal residential dwelling construction and layout does not provide adequate internal noise attenuation to allow the conflicting noise/listening requirements of parents and their children to co-exist. Elaborating further he showed how generally people require a certain minimum signal to noise ratio for good listening conditions, especially for music. Conversely, comfortable speech can be conducted only up to a particular background noise level. When internal wall and door constructions can not provide adequate isolation between rooms where children are listening comfortably to music and their parents are holding a discussion, conflict arises.

In his final topic, Mr. Harding drew upon personal experience to show that although it may be expected that the limiting factor in the sound isolation performance of a brick wall would tend to be the windows, other less obvious factors are present. In particular, modern building techniques are such that it is suspected that acoustical "weakness" exist through the eaves, tiles and above the windows of brick veneer homes, which make them noisier than older double brick houses wih the same glass area.

June Technical Meeting

On 11 June **John Cole** from the Fluid Dynamic's Group, Engineering Investigation Section, of the Queensland Electricity Commission spoke on a Practical Investigation into the Low Frequency (42 Hz) Noise recorded in a 275 MW Pulverised Coal-Fired Boiler.

On site measurement of a low frequency revealed a problem in the rear pass of a boiler at Gladstone Power Station. Further on-site measurement showed this to be the result of flow-induced vibrations exciting a cavity natural frequency. In order to resolve the problem it was decided to construct a scale model and to test out various de-resonating baffle arrangements. This technical talk covered some of the on-site work and modelling that was done, and included a video of some stages of the model testing.

SOUTH AUSTRALIA

March Technical Meeting

On 12 March **Professor Richard Lyon** of M.I.T. spoke on *Structure Borne Noise in Ships.* He gave a brief review of statistical energy analysis (S.E.A.), based on acoustical reciprocity and discussed the implications for noise transmission. Some recent calculations and measurements on a model of a ship engine mounting structure were described with particular attention to the relative roles of in-plane and flexural vibration on noise and transmission.

VICTORIA

April Technical Meeting

This meeting was held on 3 April at the Telecom Research Laboratories at Clayton. A brief overview of the latest developments in telecommunications and the associated acoustic problems was presented by **Eric Koop.** This was followed by a guided tour of the laboratories.

May Technical Meeting

On 29 May two speakers gave talks on the general topic of *Ultrasonic Techniques in Medicine.* **Ron McCartney** from Applied Physics at RMIT spoke on the development of instrumentation in ultrasonic applications. The second speaker was **Trudi Martin** from the Ultrasound Dept. at the Royal Children's Hospital and she spoke on the practical uses of ultrasound in medicine.

WESTERN AUSTRALIA

June Technical Meeting

On 19 June **Profesor P. Davies,** foundation member of the Institute of Sound and Vibration at Southampton spoke on *Vehicle Noise and Silencing.* Following a general review of the significant vehicle noise sources, a more comprehensive description was given of piston engine inlet and exhaust noise and its control. Specific illustrations were drawn from the United Kingdom Quiet Heavy Vehicle Project.

Reference Guide

The Australian Insulation Reference Guide has been released recently by Bradford Insulation. The first copy was received by Senator Gareth Evans, Federal Minister for Resources and Energy, at the recent launching.

The Guide has over 200 pages and is divided into 12 sections. These include: Unit Measurement and Conversion Tables; Fundamentals of Heat Transfer — Useful Equations; Tables of Calculated Rates of Heat Loss for Flat Surfaces and Pipes; Thermal Properties of Selected Solids, Liquids and Gases (including Steam); Design Criteria for Insulation Systems and Relevant Properties of Common Insulation Materials; Economic Thickness of Insulation; Insulation for Air Handling Systems; Cryogenic Insulation; Building Insulation; Acoustics and Noise Control; Insulation for Fire Protection (Industrial, Building and Marine Applications); and Standard Insulation Specifications.

Technical Drawing Seminars

During 1984 and 1985, the Standards Association of Australia published a revision of the Australian standard for technical drawing, AS 1100, which rationalized and amalgamated the 13 parts of the previous edition into five parts. SAA now recognizes the need for further restructuring to more adequately pursue the intent of providing a common language for all initiators and users of technical drawings.

To attract the maximum input from all relevant professions and industries, SAA is conducting 1 day seminars during September in Perth, Adelaide, Melbourne and Sydney — specifically aimed at engineers, architects, draughtsmen, teachers and lecturers, quantity surveyors, and representatives of building authorities and instrumentalities. The seminars will look at possible future developments in drawing, with an emphasis on establishing general principles for such aspects as dimensioning and tolerancing, and consideration of standards for computer aided drafting (CAD).

Enquiries should be directed to the Seminar Secretaries at SAA offices in each State.

Exchange Programmes

The Australian Academy of Science and the Australian Academy of Technological Sciences operate an exchange programme with the Royal Society. Applicants should propose a specific activity or a joint research project which has been developed in consultation with a host scientist in the United Kingdom. Proposals will be assessed on their scientific and/or technological merit. The host scientist or institution in the United Kingdom must be appropriate to the objective of the proposal, and the length of the visit must be suitable for conducting the proposed research. Finally, the expected outcome of the visit should be of value to Australian science.

Visits may be long-term (six months or more) for extended research or short-term (not less than two weeks). Support will not be given when the primary purpose of a visit is to attend a conference. Successful applicants will receive from the Academies a grant-in-aid which will cover the cost of a return excursion air fare to the United Kingdom and contribute to his or her living and travel costs within the United Kingdom. The contribution towards living costs will not normally exceed full allowance for a period of six weeks. Participants staying longer than six weeks will be expected to supplement their allowance from other sources.

Details: International Exchanges Officer
Australian Academy of Science
Canberra, A.C.T. 2601
G.P.O. Box 783

PEOPLE —

Duncan Gray, who was the General Secretary of the Society for many years, is the Hon. National Executive Director of the organisation called "Better Hearing Australia". This organisation was previously called the "Australian Association for Better Hearing".

* * *

Will Tonisson has left National Acoustic Laboratories to establish his own hearing testing consultancy up on Brisbane's specialist's row, Wickham Terrace. Will will be filling a long neglected gap in the private hearing health field.

* * *

Mark Simpson has joined Winders, Barlow and Morrison after seven years in the real estate business in Adelaide.

* * *

Recent graduands with M.Sc.(Acoustics) from the University of N.S.W. are **Athol Day** (Day Design), **John MacPherson** (Louis A. Challis & Assoc.) and **Ray Wilson** (who has returned to Melbourne).

* * *

Move to A.C.T. 1: **Leigh Kenna** has left the National Acoustic Laboratories in Sydney to take up a position in the Department of Aviation and will be based in Canberra.

Move to A.C.T. 2: **Marion Burgess** moved to Canberra in June (her husband has been transferred). She will be commuting to Sydney until the end of this academic year and is not certain what the future holds.

After considerable delays, the **National Acoustic Laboratories** and the **Ultrasonics Institute** moved from their location in the historic part of Sydney in May. The new address is 126 Greville Street, Chatswood 2067. The new phone numbers are (02) 412 6800 for N.A.L. and (02) 412 6000 for U.I. (Telex AA21655 and FAX 412 6999).

* * *

Dick Langford has recently moved from Tasmania to Perth. In his new position with the W.A. Dept. of Conservation and Environment he will be fully occupied with noise control issues; his major brief being to establish a co-ordinated traffic management programme for Perth.

* * *

In a letter received by Anita Lawrence from Poland, **Jaroslaw Rosinski** of the Institute of Mechanics and Vibroacoustics AGH in Krakow states that he would like to work in Australia for a few years. If anyone has a need for a worker in the field of mechanics or vibration acoustics, please contact Anita Lawrence or the Chief Editor at the University of New South Wales.

* * *

Our consulting editor **Dr. Neville Fletcher** has recently been elected a Fellow of the Acoustical Society of America "for research in musical and biological acoustics". Our sincere congratulations go to Neville for being granted this recognition of his outstanding contributions to acoustics. He now joins the small group of Australian acousticians who have been similarly honoured by the American society.

New Members

● Admissions

We have pleasure in welcoming the following who have been admitted to the grade of **Subscriber** while awaiting grading by the Council Standing Committee on Membership.

Victoria

Mr. M. W. Coates, Mr. A. Ligthart, Mr. Ng Say Teong.

● Graded

We welcome the following new members whose gradings have now been approved.

Subscriber

Victoria

Mr. B. N. Gearing.

Western Australia

Mr. B. W. Bickford, Mr. P. C. Marshall, Mr. L. J. Storer.

Member

New South Wales

Dr. N. E. Holmes.

Queensland

Mr. W. C. Middleton.

Western Australia

Mr. G. E. Woods, Mr. D. W. N. Young.

COMMUNITY NOISE CONFERENCE 1-3 OCTOBER, 1986, TOOWOOMBA

Co-Sponsors:

- The Queensland Division of Noise Abatement and Air Pollution Control
- The Australian Acoustical Society

As Chairman of the Organising Committee, I wish to extend to all A.A.S. members and other interested persons, a special invitation to the 1986 **Toowoomba Conference** which is also serving as the Annual Conference of the Australian Acoustical Society.

The Conference, which is being held at the Darling Downs Institute of Advanced Education, Toowoomba, 1-3 October, 1986, is the first of its kind in Australia and is promoting a multi-discipline approach to noise management.

Three keynote speakers have confirmed their participation. They are **Mr. Louis Sutherland,** Deputy Director and Principal Scientist, Wyle Research, California; **Mr. Walma Van der Molen,** Amsterdam City Council; and **Professor Arline Bronzaft,** Department of Psychology, City University of New York. Mr. Sutherland will be speaking on *Formulation and Application of Community Noise Assessment Procedures,* Mr. Walma Van der Molen will deliver his keynote address on *Planning for Noise Control,* and Professor Bronzaft will discuss *The Effects of Noise on People.*

An exhibition of acoustical equipment, instruments, products and literature will be run conjointly with the Conference. Further information may be obtained from **Mr. Ron Windebank,** CMA Foam Group, P.O. Box 532, Strathpine, Qld. 4500. Phone (07) 205 0222.

Conference Registration Books are now available and can be obtained from **Mrs. N. Eddington,** Division of Noise Abatement and Air Pollution Control, 64-70 Mary Street, Brisbane, Qld. 4000. Phone (07) 224 7698 or 224 4157.

Prior to the Conference, a public education programme in the form of a Quiet Community Project is being organised in Toowoomba by the Toowoomba City Council in conjunction with the Division of Noise Abatement and Air Pollution Control, Police and the Department of Education. The Project is designed to complement the Conference theme with a practical public relations exercise in effective noise management.

I do trust that you will be able to join us in Toowoomba and participate in what promises to be a very worthwhile forum on the management of noise.

Dr. G. J. Cleary
Chairman
Organising Committee

★ ★ ★

Feeling Sound

British scientists have developed a device that enables the profoundly deaf to "feel and see" noise around them.

"It can be worn like a wristwatch by children and adults, and gives a deaf person awareness of sound through vibration and a flashing screen", said Mr. **Mike Martin,** the head of scientific and technical services for the Royal National Institute for the Deaf.

He said the device "produces strong vibrations on the wearer's wrist when sounds reach a certain volume".

Deaf people using the device could "identify different sounds such as people talking and the telephone ringing".

Powered by rechargeable battery and incorporating a small vibrator, the device took 10 years to develop and costs about $190.

Mr. Martin quoted one blind woman as saying the device was a "revolution" in her life because it enabled her to identify important sounds, such as her kettle boiling.

(The Australian, 24 May 1986)

Bells, Their Design And Tuning

Hervey Bagot
Bagot Bellfoundries
Box 421
North Adelaide SA 5006

ABSTRACT: The tuned bell is an apparently simple instrument whose complete description, however, embraces music, acoustics, mathematics, and also metallurgy. These fields are briefly touched upon in this article, and some points of interest are discussed: Modes of vibration, how the bell "works", and manufacture of bells. In recent years important advances have been made in our understanding of the bell, and modern computers have facilitated rational design.

INTRODUCTION

It is my intention in this article to touch upon a few topics, concerning the bell, to illustrate the interest that can be stimulated by such an apparently simple musical object. The bell is a device with a long history in human affairs, in nearly all cultures. However, I shall confine myself to the modern metallic bell as we know it in European society.

Since the bell must be struck it belongs to the category of percussion instruments. Because its own mass produces the sound it is classified as an idiophone, a group of instruments which includes gongs and xylophone bars. A single bell emits only one sound, inherent in the character of the particular bell. That sound may be acoustically complex, but in musical use it can represent only one note. If several musical notes are required then a separate bell must be used for each note.

Bells may be either fixed rigidly in a stand or on beams (as for chimes or carillons), or mounted in a suitable strong frame for swinging (as for peals). A hammer or clapper, of a certain mass, is the element that brings the bell to give out its sound. The rhythm of the sound of several bells in concert may derive from physical determinants such as the swing time of the clappers or the swing of the bells themselves. Swinging bells, also, give a lively character to their music by virtue of the moving sound fields.

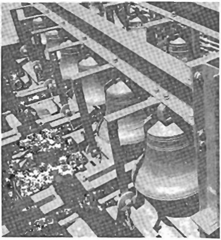


Figure 1: Some of the bells of the Sydney University carillon. This carillon consists of 54 bells, spanning a musical range of just over four octaves (strike note frequencies 206 to 4385 Hz; diameters approx. 1900 mm down to approx. 200 mm; masses approx. 4300 kg down to approx. 10 kg). (Photo: The University of Sydney)

At the outset it may be interesting to point to some bells in Australia. Quite well known are the carillons at the University of Sydney (Figure 1) and in Canberra. Both are large carillons of over 50 bells and of considerable weight of metal. Today carillon bells can be tuned with very great accuracy, and the carillon is now one of the grandest of all musical instruments, with scope comparable to that of the cathedral organ. By definition a carillon extends from two chromatic octaves (25 bells) upwards. The bells are sounded from a baton keyboard through mechanical connections to the bell clappers.

Swinging peals of bells are also to be found in Australia. Depending on the tradition (English or European) the bells are swung either full circle (±180°) or half circle (about ±90°). In Figure 2 is shown a bell from the European peal at Newcastle Anglican cathedral, six bells tuned in a pentatonic scale. The music consists of variations in the melody brought about by the differences in swing times of the bells.

In this article I shall touch upon the following topics: modes of vibration; how the bell works; and design, manufacture and tuning.

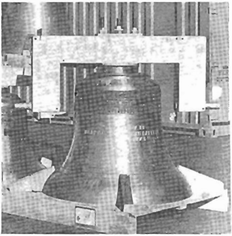


Figure 2: One bell from the electrically swung peal of six bells at Newcastle Cathedral, NSW (delivered 1977). This, the heaviest bell, has diameter 1010 mm, strike note g1 (392 Hz), and mass 640 kg. (Photo courtesy The Newcastle Morning Herald.)

MODES OF VIBRATION

Many physical measurements on bell harmonics and vibrations have been made, mostly since about 1890. At first only qualitative descriptions were available. With the advent of electronics much better measurements became possible. In the past 10 years group theory and finite element analysis have been used to make solid advances in our understanding of the bell, working from the need to classify the observed modes of vibration in a physically significant way.

The sound associated with a single mode of vibration is known, strictly, as a "partial tone". Such tones, or partials, may or may not be harmonic to each other. In principle there is an infinite number of modes, and tones, in any bell.

Just as a stretched string has modes related to the length of the string and its simple subdivisions, a bell's main modes are capable of rational description based on small integers. In Figure 3 is shown schematically the simplest mode that contains a nodal line in both azimuthal and axial directions. Figure 4 is a beautiful representation of the sound radiation from a bell stimulated to vibration in a single mode — complete with evidence of the phase changes occurring at nodal meridians.

The traditional system for classifying the vibrational modes of bells has been to specify the numbers of nodal meridians and nodal circles in the manner of a vibrating plate. The lowest mode, for instance, has four meridian nodes, so that alternate quarters of the bell move inward and outward. This is analogous to the 2,0 mode of a vibrating circular plate which has two nodal diameters.

Modern understanding of the bell started with the work of Lord Rayleigh in 1890 [2], who with simple aids (hammer, voice, organ pipe, and loaded tuning fork) stimulated some church bells into resonance in particular modes of vibration. He discovered the existence of nodal meridians and nodal circles in the bell body, mapping them with the aid of Helmholtz resonators. He found also an explanation for the acoustical "beating" in bells, proving that each mode examined by him was doubly degenerate — that is, each tone was indeed two tones (not usually coincident in frequency), created from identical pairs of vibration shapes with phase displacement relative to each other.

In a theoretical study in the same paper he likened the bell shape to certain mathematical shapes (hyperboloid of revolution, parts of cone) and found a proof for the existence of the nodal lines. At the time, however, he had to say that "the theory of the vibration of bells is of considerable difficulty", and "a complete theoretical investigation is indeed scarcely to be hoped for".

Much work has followed since 1890 at the hands of many investigators, both in mapping the modes of vibration of bells and in devising classification schemes. There is a rich litreature, but only a few of the most important papers need to be referred to here.

A.T. Jones in 1928 [3] located the first few important tones by audio beating against the variable output of a signal generator. Nodal lines were mapped by use of Helmholtz resonators. Concerning the work up to his time it seemed appropriate for him to say that "the vibrations of bells are not well understood. Even on so elementary a matter as the number and position of nodal lines the very meagre published values are not in satisfactory agreement". Jones' work consisted of clarifying the relation of vibration frequency to mode shape, but he made no rational classification. He also examined the interesting question of the strike note (see later).

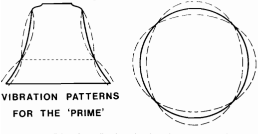


Figure 3: Radial surface vibrations for the prime, the second lowest mode in carillon bells, with one nodal circle and four nodal meridians.

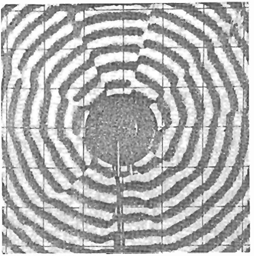


Figure 4: Visual representation of radial sound emanation from a bell vibrating with 10 nodal meridians, made by optical method. (From Schroeder [1])

F.G. Tyzzer [4] carried the matter significantly further with, this time, better continuous stimulation of various modes, selectively, using an electromagnetic exciter, and mapping of the surface vibrations using a kind of stethoscope. He classified graphically the relation of vibration frequency to number of nodal meridians and circles (see Figure 5).

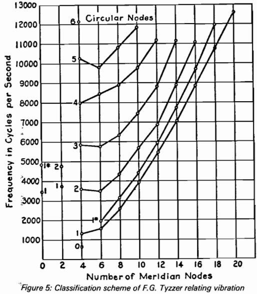


Figure 5: Classification scheme of F.G. Tyzzer relating vibration frequencies of a small (16 kg) bell to the numbers of nodal meridians and circles. (From Tyzzer [4])

Much other work was done about this time, and by 1954 it was indeed possible for Slaymaker and Meeker [5] to say that "there is a great wealth of published material on the characteristics of bell tones". Recording tapes, wave analysers, and multi-channel analysers had made this possible. These two authors now made high quality magnetic tape recordings of certain bells of American and European origin. In a useful analysis, they measured the relative tuning, relative tone amplitudes at the microphone position, and the decay rates of the various tones.

Grützmacher [6] in 1959 prepared a neat representation of the state of knowledge at that time — see Figure 6.

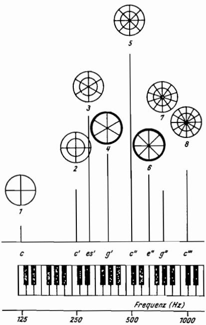


Figure 6: Relation of bell vibration modes to frequency and musical note, in a 2000 kg bronze bell with "strike note" middle C (c1) (261.6 Hz). The first eight modes, as shown, are the ones of greatest musical significance, and the lowest five are tuned directly by the founder. The mysterious strike note, not actually shown, is made to coincide with the second mode (see later). The relative strengths of the tones (sound pressures) are indicated in the vertical direction. The outermost circles, except where shown heavy, are merely the rim of the bell and not nodal circles. All modes shown here have 0 or 1 nodal circle, and from 4 to 12 nodal meridians. (After Grützmacher [6])

Further important work was published in 1965 by Grützmacher et al [7]. They made extensive measurements of the amplitude distribution all over the bell surface for a large number of singly excited tones. A classification scheme following the model of Tyzzer [4] was drawn up. They concerned themselves also with the dependence of sound pattern on mass, material, form, and strike of the clapper. Finally, they identified three energy loss mechanisms in the decay of any tone (internal friction in the bell metal; viscous damping at the bell surface; and radiation losses in the surrounding medium, linked also to the relation of sound wavelength to bell size).

By now the assembled empirical knowledge was good. It meant, amongst other things, that practical people such as bellfounders and consultants knew exactly where to look when analysing some strange new bell prior to reporting or tuning — safe in the knowledge that nothing was likely to be missed in listing say the first ten or twelve tones.

However, rational understanding of the bell was still lacking. The classifications of Tyzzer and Grützmacher et al were ad hoc only, and gave no real descriptive or prescriptive help. The reasons for the occurrence of many of the modes in degenerate pairs were not known. No realistic attempt at solving the problem of the bell theoretically had yet been made, and indeed the difficulties in setting up the eigenvalue equation for the system in detail are severe.

At this time R. Perrin of the Loughborough University of Technology (UK) brought group theoretical insights into the matter. He and T. Charnley started with flexural radial and axial vibration of rings, at both theoretical and experimental level [8, 9]. This work was followed by a series of papers reporting group theoretical studies on bells themselves and also some very careful physical measurements. Two papers are particularly important [10, 11]. In the first, the bell vibration modes were classified into families according to their behaviour under symmetry operations, a physically meaningful procedure for the bell which has axial (and other) symmetry. The families are characterised by the number of nodal meridians (axial symmetry), and not the number of nodal circles as in the scheme of Tyzzer [4]. Other theoretical insights were found also, explaining the "singlet" (as distinct from doublet) nature of the torsional and "breathing" modes, found at higher frequencies. As a practical benefit, the phenomenon of bell warble (splitting of doublets) appeared to find explanation in the slightly imperfect nature of the symmetries of real bells.

The group theoretical approach found a crucial test, however, in some work on a highly eccentric bell especially fabricated for the purpose [11]. According to the group theoretical arguments [10], all the doublets should now be split, by large amounts owing to the large eccentricity. Surprisingly, the splittings were found to be very small, being less than 0.2% of frequency in the measured values of the usual first five tones. The authors concluded that group theory is here for some reason an inadequate tool to handle the situation fully, despite the other insights gained from its use.

HOW THE BELL WORKS

The scene is now set for the emergence of what must be considered the true explanation of the bell's tonal pattern — i.e. of the relative position of the tones in the modern bell. Figure 7 shows the tonal pattern commonly accepted and used today, and it is the equivalent in staff notation of the lowest five tones in Figure 6. It largely applied, indeed, with variations, from about 1400 onwards, when the bell arrived at the shape regarded now as modern. In the "modern" scheme the tones have internal harmony, and have frequency ratios 1:2:2.4:3:4 (alternatively, 5:10:12:15:20; or, 1/12, 1/6, 1/5, 1/4, 1/3). The tone with ratio 2.4 to the base tone is the so-called "minor third" tone, which gives the bell a certain character.

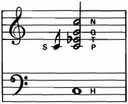
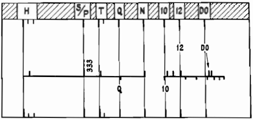



Figure 7: Modern five-point tuning scheme for cast bronze carillon bells, normalised to note C. The "strike note" (S), at middle C, is the short-lived black note shown at left. The other components are the characteristic minor third (or tierce, T), perfect fifth (or quint, Q), octave (or "nominal", N), and the long-lived "hum" (H).



ST JAMES' O.C., MELBOURNE — TENOR BELL, 700 KG IN E

Figure 8: Frequency relationships of the first 17 modes in a century-old, 700 kg bell at St James' Old Cathedral, Melbourne, with a "strike note" approximately E, 333 Hz. The tones are represented by grid marks on a horizontal logarithmic scale in the centre of the diagram. The musically significant tones are identified as: H = hum, S = strike note, P = prime (often, as in this case, coincident with the strike note), T = tierce, Q = quint, N = nominal, 10 = tenth, 12 = twelfth, DO = double octave.

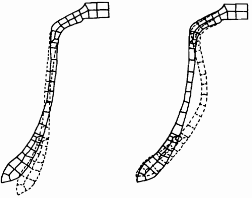


Figure 9: Vertical section through a bell vibrating in a ring-driven (left) and a shell-driven (right) mode. Cells show typical subdivision of the profile for the purposes of finite element analysis. (After Perrin and Charnley [13])

As a practical illustration, in Figure 8 are shown the author's measurements on a 19th century bell in Melbourne, depicted on a logarithmic scale as in Figure 6, and with (amongst others) the identifications as introduced in Figure 7. The first 17 tones were recorded. Judged by modern standards the lowest mode frequency is just over one semi-tone (6%) too high (it "should" be coincident with the fine vertical line under "H"), and the bell cannot be tuned to bring this tone down without affecting others — the mismatch is, empirically, too great. An important observation in analyses such as these is that the quint, tenth, and others (shown plotted *below* the horizontal line) have maximum vibration amplitude in the *waist* of the bell, not at the mouth as for the other main tones, and this observation is very significant as will be seen later.

Bellfounders had learnt by experience that certain of the tones appeared to be related to each other when it came to tuning. One could not usually alter any one tone to the general exclusion of others, though one main "family" of tones seemed to be to some extent independent of a second family. The two families are indeed precisely those that have vibrations largely at the mouth and those that have vibrations largely in the waist.

Perrin and co-workers [12] have now proposed a new type of classificaiton scheme, after work involving finite element calculations and an extensive set of measurements (more than 130 tones) on a single church bell of mass 214 kg, mouth diameter 702 mm, height 566 mm. In the classification, modes are either "ring driven" or "shell driven", depending on whether the greater radial vibration amplitude is near the mouth or in the waist of the bell (see Figure 9).

In the work, accurate measurements of the geometry of the bell were made and used as the basis for the finite element calculation of the normal modes. The finite element method considers a structure of complex shape as being made up of elements of simpler shape. Expressions for the dynamic behaviour of each element are obtained, and an enforcement of displacement continuity across the element boundaries results in an expression for the behaviour of the whole structure observed at certain sampling points. A suitable computer program was used, and separate runs made for each choice of the number of nodal meridians.

The work has now been reported at length [13]. For a given number of nodal meridians there is always one partial tone which corresponds to the heavy ring at the rim of the bell (known as the "soundbow") going into its inextensional radial motion and driving the rest of the bell. The lowest three modes of this "ring driven" type are the "hum", "tierce", and "nominal", i.e. the first, third, and fifth tones in a normal bell (see Figures 6 and 7). This fact is of significance for the history of bell shaping, as will shortly be seen.

Other tones are essentially all driven by the "bell minus soundbow" system which one may describe as the "shell". These partials are thus "shell driven", with the heavy rim ring (soundbow) remaining roughly at rest and supplying a nodal circle at or near the rim. The first two "shell driven" modes are the "prime" and the "quint". The first five partials may thus be set out as follows (see also Figure 10):

Partial No.	Name	Frequency Ratio	Vibration Type
1	Hum	1	Ring
2	Prime	2	Shell
3	Tierce	2.4	Ring
4	Quint	3	Shell
5	Nominal	4	Ring

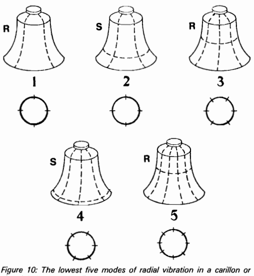


Figure 10: The lowest five modes of radial vibration in a carillon or church bell, corresponding to the five tones that are always tuned. These lowest modes are alternately ring-driven (R) and shell-driven (S). The dashed lines indicate the approximate locations of the nodal circles and meridians. (After T.D. Rossing, private communication 1981).

The improved nature of the classification scheme should now be clear. When to this is added the bellfounders' experience that partials 1, 3, and 5 tend to "tune" together on the tuning machine (as do partials 2 and 4, but in a different region of the bell), it becomes clearer why bells have developed their present shape. That is to say, fortuitous changes to the ratio of bell height to bell diameter, for instance, seem to have been the mechanism for (serendipitous) improvement in the harmonic quality of large cast bronze bells since about 1400. Also, the crucial role of the soundbow has become clear.

Some explanation of the so-called "strike note" of bells should now be made. This note is the usual descriptor for a bell, locating it amongst others of a set. Some curious facts emerge, however: (1) it is not the lowest tone in the bell, (2) it is a psycho-acoustical tone and has no physical existence in the bell (it cannot be made to beat with any other bell tone or any audio signal). In Figure 7 it is the black note, marked S, to the left of the other tones. In Figure 8 it is the dashed mark at 333 Hz, residing above the horizontal axis and coincident with the prime. It may, however, be non-coincident with the prime, as in many bells made before 1900, causing in some cases a discordant effect. In bells of less than about 50 kg mass it may not be heard at all, and in bells of deeper tone than about middle C (261.6 Hz, 2000 kg bell mass), there may indeed be a secondary strike note also, higher in frequency and rather undesirable.

Strike notes are now accepted to be "residues", i.e. subjective constructs of the human ear and brain, depending for their formation on higher tones including the nominal which is one octave higher [14]. The present author's own experiments with a tape recording of a bell provide an illustration. The bell's strike note had frequency 358 Hz (approx. 700 kg bell). Tests were done as follows.

(1) A low-pass filter passed tones below 500 Hz and rejected those above. The strike note could not now be heard, and the listener discerned only a tonal mix based on the hum note.

(2) A high-pass filter passed tones above 500 Hz, rejecting those below. The strike note came through loud and clear, at 358 Hz.

(3) A band-reject filter cut out tones around 716 Hz (only), the level of the "nominal". The strike note vanished.

These results show that the strike note does not exist as a single independent tone in the sound of the bell. It cannot be filtered out by applying a filter around the measured strike-note frequency. It is created in the human auditory system from higher tones, amongst which the nominal is an essential element.

DESIGN, MANUFACTURE, AND TUNING

The modern carillon or church bell has evolved in its shape in the somewhat fortuitous manner already alluded to. In principle, however, radical new departures ought to be possible in this computer age. Indeed the year 1985 saw the production in The Netherlands of a bell with significantly different tonality (see below).

The large financial commitment to particular shapes (in pattern costs and tuning know-how) understandably has made bellfounders conservative, though, when it comes to experimentation. One German bellfounder has over time built up no less than 18 different series of profile templates, for ranges of bells in four different tonalities, covering three chromatic octaves (37 notes), altogether a very large number of patterns.

Such is the pace of recent change, however, that one Dutch bellfounder now regularly creates such traditional profiles on an X-Y plotter, driven in accordance with design rules processed in a computer program — and from time to time creates special profiles to match tonalities of, for example, certain medieval bells to which newly cast bells are to be added to extend a range of notes. The computed drawings are then copied in sheet metal to make the profile templates.

However created, the bellfounder's templates are the basic tools for the manufacture of a bell, for instance through the successive stages of wooden and aluminium alloy patterns (see Figure 11). With the aluminium pattern the foundry mould for the eventual cast bronze bell is made.

In all design work the bellfounder follows similarity rules when creating the bells of a range. Halving the linear size makes a bell with twice the frequency in all tones (and one-eighth the mass). In practice, however, the smaller bells are usually thickened and enlarged a little in order to create a better balance of sound power against the larger bells (thickening raises all tones; increasing bell diameter and height lowers them).

In principle a bell of say note middle C (261.6 Hz) can be made any size. Practical considerations over the centuries have, however, dictated that the usual mass for such a bell should be about 2 tonnes (primarily, one would think, for adequate sound power over a distance). Table 1 shows an abridged list of details for a typical set of 14 carillon bells cast in bronze (the usual metal):

Table 1:
Abridged list of details for a typical set of carillon bells cast in bronze

Note*	Strike-note frequency (Hz)	Bell mouth diameter (mm)	Bell mass (kg)
g0	196.0	2110	5400
a0	220.0	1880	4000
b0	246.9	1680	2800
c1	261.6	1580	2400
cis1	277.2	1490	2100
d1	293.7	1410	1600
e1	329.6	1270	1150
f1	349.2	1180	1050
fis1	370.0	1120	850
g1	392.0	1060	680
a1	440	940	480
b1	493.9	840	345
c2	523.3	790	280
d2	587.3	700	200

* European notation: c1 = middle C; cis = C-sharp; fis = F-sharp

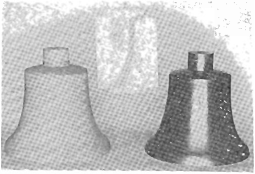


Figure 11: Stages in the production of cast bronze bells, using the method of solid patterns — aluminium templates (centre); wooden pattern (left); cast aluminium alloy pattern (right).

Metals other than bronze have been used in the past, notably a silicon-brass and also steel, for reasons either of economy or of acute metal shortage. It is perhaps interesting to compare the results of using various metals, as in Table 2, where all bells are supposedly A bells (440 Hz) and of similar profiles. The differences in size, for the same note, are due to the different metal densities and elastic moduli.

Table 2:
Data for A bells (440 Hz) of similar profiles but of different metals

Metal	**Mouth diameter (mm)**	**Mass (kg)**
Aluminium	1300	450
Brass	860	330
Lead	320	35
Zinc	990	480
Steel	1350	1400
Silicon brass	950	460
Bell bronze (80Cu/20Sn)	900	430

Of course, some of the metals are impractical owing to gross damping of vibrations. Only the last, the traditional bell bronze, has come through the centuries and earned its place on grounds of excellent strength, hardness, corrosion resistance, and low internal friction.

The copper-tin alloy composition (metal ratio) is not in itself critical. It is, however, usually standardised at about 80Cu/20Sn (weight percentages), at which value the internal friction is low. It could indeed vary from 18% to 24% tin, as is sometimes done, though in such cases the founder has to be careful to allow for the variation in tone frequencies as a function of tin content.

A word can be said here about the casting process itself. The mould is made in two parts from a wet loam, or other material — one mould for the outer shape of the bell and one for the inner. If the method of solid patterns is used then the moulder pours the moulding material both around and inside the pattern, in two separate stages. If, however, the moulding is to be done direct from the profile templates (as is often done) then each template is used to "sweep" a shape in moulding material built up by a more painstaking method. The difference between the two methods relates to cost, convenience, and tradition.

After drying of the moulds the metal can be poured, at about 1050°C, into the space between inner and outer. Upon cooling of the metal, which may take days, the moulds are broken and the new bell recovered.

After removal from the mould, the new bell must now be cleaned of superfluous moulding material and then tested for tonal structure prior to tuning. Such testing is done by active stimulation of tones, using electromagnetic exciters or loaded, variable tuning forks. The founder then must devise the correct tuning program, by either empirical means or by electronic computer, for correction of the bell to the specified values of tone frequencies. Bells are usually cast so that their tunable notes are perhaps 2% higher in frequency than specification. Metal then is turned from appropriate parts of the inner surface until the five lowest tones are correct. The cutting locations are known to tuners skilled in the art. Figure 12 shows schematically the bellfounders' understanding of the tunability of the lowest five tones.

For carillons (where several bells may be sounded simultaneously) the tuning tolerances may be as small as 1 Hz absolute in all the five tones. For certain other purposes, however (such as swinging peals), the tolerances may be larger.

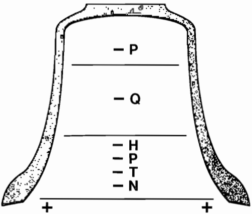


Figure 12: Generalised tuning sensitivity characteristic of a carillon bell, for cuts made on the inside surface. H = hum, P = prime, T = tierce, Q = quint, N = nominal. At the mouth (+) all tones (except the quint) may be raised very slightly by cuts there. Other cuts inside the bell lower the tones, and as can be seen most tones are tuned in a region not far from the mouth. However, the quint is tuned only at the centre, and the prime may be tuned almost independently near the head of the bell.

It may be interesting to conclude with a look into the future, with a mention of the new "major third" bell (see Figure 13). This was successfully achieved in The Netherlands in 1985 as a culmination of several years of mathematical studies on bells at the Department of Mechanical Engineering, Eindhoven University of Technology.

Finite element studies by van Asperen [15] had led to a satisfactory mathematical model for the bell, even including a numerical simulation of the "tuning graphics" (the bellfounders' hitherto rather secret formulae for tuning) and of the tuning process itself. Importantly, he showed that the conventional "minor third" bell could *not* be tuned into a "major third" bell, without unacceptable deflection of the other acoustically important tones. Maas [16] then developed a mathematics of variations upon the existing model. He showed that the traditional minor third bell (as in Figures 1 and 2 of the present paper) apparently had to be distorted. What we see in Figure 13 is the result of this research, in which the quest for the major third bell was taken up as a structural optimisation problem [17]!

There is no saying, now, what other harmonious tonalities in bells might not be achieved in the future.

REFERENCES

1 H.J. Schroeder, "Optische Schallfelddarstellung mit Phasen- und Amplitudenaufzeichnung." Acustica *13*, 92-108 (1963).

2 Lord Rayleigh, "On bells." Philosophical Magazine *29*, No. 176, 1-17 (1890).

3 A.T. Jones, "The vibration of bells." Physical Review *31*, 1092-1102 (1928).

4 F.G. Tyzzer, "Characteristics of bell vibrations." Journal of the Franklin Institute *210*, 55-66 (1930).

5 F.H. Slaymaker and W.F. Meeker, "Measurements of the tonal characteristics of carillon bells." Journal of the Acoustical Society of America *26*, 515-22 (1954).

6 M. Grützmacher, "Das Teiltonspektrum einer Glocke." Gravesaner Blätter *4*, 124-8 (1959).

7 M. Grützmacher, W. Kallenbach, and E. Nellessen, "Akustische Untersuchungen an Kirchenglocken." Acustica *16*, 34-45 (1965/66).

8 T. Charnley and R. Perrin, "Characteristic frequencies of a symmetrically loaded ring." Acustica *25*, 240-6 (1971).

9 T. Charnley and R. Perrin, "Perturbation studies with a thin circular ring." Aucstica *28*, 139-46 (1973).

10 R. Perrin and T. Charnley, "Group theory and the bell." Journal of Sound and Vibration *31*, 411-18 (1973).

11 T. Charnley and R. Perrin, "Studies with an eccentric bell." Journal of Sound and Vibration *58*, 517-25 (1978).

12 J. de Pont, R. Perrin, and T. Charnley, "Normal modes of church bells." Paper K-7.5 presented at 10th International Congress on Acoustics, Sydney 1980.

13 R. Perrin and T. Charnley, "Normal modes of the modern English church bell." Journal of Sound and Vibration *90*, 20-49 (1983).

14 G. Bruhn, "Uber die Hörbarkeit von Glockenschlagtönen. Untersuchungen zum Residualtonproblem." Kölner Beiträge zur Musikforschung, Bd 90 (Gustav Bosse Verlag, Regensburg, 1980), 194 pp.

15 F.G.J. van Asperen, "Het optimaliseren van de eigenfrequenties van axiaal-symmetrische constructies, toegepast op een luid- of carillon-klok." ("Optimisation of eigenfrequencies of axial-symmetric figures, with application to the bell.") Report WFW 84-012, Eindhoven University of Technology (1984), 150 pp. (in Dutch).

16 P. Maas, "Onderzoek naar de geometrie van een grote-terts klok." ("Investigation into the geometry for a major-third bell.") Report WFW 85.027, Eindhoven University of Technology (1985), 150 pp. (in Dutch).

17 B. Schoofs, F. van Asperen, P. Maas, and A. Lehr, "Experimental design theory and structural optimisation; design of a major-third church bell." Paper presented at C.A.M.P. 1985 Congress, Berlin, 24-27 September 1985.

Figure 13: Probably the world's first true "major third" bell, produced in 1985 by the Royal Eijsbouts bell foundry, The Netherlands (bell diameter approx. 1000 mm, mass approx. 600 kg). (Photo courtesy Royal Eijsbouts)

* * *

LETTERS —

Types of Articles Published

As my previous letter to Acoustics Australia, on membership of the AAS, provoked some useful comments and actions I would like to air another issue. I would like to suggest that Acoustics Australia gives less emphasis to research papers and more emphasis to articles of interest to practitioners.

If one looks through the membership list of the Australian Acoustical Society one finds that academics and researchers form a small proportion of the membership. While research papers are of potential interest to all members I think Acoustic Australia should be including more review articles, practical application articles and articles on business development, accounting, etc., to help those members who are consultants and in small businesses.

I realize the one big difficulty with this suggestion is getting the articles. Maybe the Acoustical Society could seek articles from outside the acoustics fraternity. Such articles exist in "Sound and Vibration" and "Sound and Video Contractor" from the U.S.A. and doubtless there are other journals that could be approached for the right to reproduce material.

The above comments should in no way be taken as a criticism of Acoustics Australia: it is a wonderful journal and its publication is the most important thing the Society does. However, membership and member wishes and expectations are, I suspect, changing and it is perhaps time that members expressed their views.

Fergus Fricke

Dept. Architectural Science
University of Sydney
15 June, 1986

Editors' Comments

The Editors agree with Ferg Fricke that the biggest difficulty in obtaining more general and practical articles is the problem of persuading busy consultants and acousticians to put pen to paper. We are now receiving an increasing percentage of unsolicited articles but these mainly come from members in professional institutions whose livelihood depends on their ability to communicate and publish their work.

As expressed in editorials in August 1982 and April 1985 we would like to receive more short reports or technical notes from members dealing with their current activities. Those we have published have been well received but have all been specifically requested. In the meantime let us have your views on Ferg Fricke's letter: Should we print more practical articles? Do you prefer review articles? Should we reprint articles from other journals and so on? Without feedback we are working in the dark.

Howard Pollard and Marion Burgess

Introducing . . . **SOUND-SORB**

by . . . **STRAMIT**

STRAMIT BOARD or EASIWALL faced with pre-finished perforated vinyl-clad semi-rigid fibreglass – providing –

Roof/Ceiling & wall constructions tested to perform in excess of **STC 49** whilst also having **NRC 0.70**

K. H. STRAMIT LIMITED
A National Company using 100% Australian products

SYDNEY (02) 631 5222
CANBERRA (062) 80 5921
MELBOURNE (03) 329 7611

WOODTEX
LIGHTWEIGHT WOODWOOL BUILDING SLABS

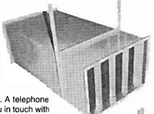
At Peace... We know noise.

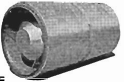
PEACE ENGINEERING has specialised exclusively in the field of engineered noise control products for well over 10 years.

In that time we have developed a vast range of products to cater for most types of noise problems.

We are ready to share that knowledge with you. A telephone call to our office or one of our agents will put you in touch with someone who will discuss your problem and if necessary provide an obligation free, written quotation.

Custom built press enclosures, control rooms, pulsation snubbers, fan and blower silencers, return air vents, acoustic louvres — no matter what your requirements, we have the products when it comes to noise control.





PEACE NOISE CONTROL EQUIPMENT

PEACE ENGINEERING PTY. LTD. 2/20 MARIGOLD STREET, REVESBY 2212 (02) 772 4857, 772 4858, 774 1595

TP 1,929

The Acoustics of the Recorder

John Martin
11 Cromer Street
Sunnybank Hills Qld 4109

ABSTRACT: The current interest in making and playing historical reproductions of recorders has led to an interest in the underlying acoustical principles. In this paper the basic acoustics connected with the recorder's sound production mechanism, bore and finger holes are outlined, and used to shed light on various aspects of the instrument's construction and playing technique.

INTRODUCTION

To many readers mention of the word "recorder" will conjure up visions of massed primary school children fumbling their way through "Turn On The Sun". They will wonder why the acoustics of such an instrument are of any interest, believing that it is (as Danny Kaye once said of the oboe) "an ill wind that nobody blows good".

There is of course more to the story than this, as recent tours by performing groups such as Sour Cream, Quadro Hotteterre, and the Orchestra of the Eighteenth Century remind us. The recorder had a long history from its development during the middle ages up to the late eighteenth century when it went into a temporary decline due to changing fashions in musical taste. It was revived at the beginning of the present century along with the viols, lute and harpsichord as a medium for exploring the riches of the early music repertoire — a kind of "museum curator" in other words. It has also gained an extensive contemporary repertoire as composers have discovered it: firstly as just another melody instrument, battling it out with a piano accompaniment; more recently as an instrument in its own right, especially suited to the special effects called for in "avant garde" music.

The recorder is in fact not one instrument but a whole family, with members ranging in length from a few centimetres to over two metres. Figure 1 shows a typical consort of recorders. From the left, and with their lowest notes in brackets, the instruments are the great bass (C3), bass (F3), tenor (C4 = middle C), treble (or alto) (F4), descant (or soprano) (C5), sopranino (F5), and garkleinflötlein (C6). Most of the instruments have a range of over two octaves.

The recorder's role in playing Early Music is still its main appeal for professionals and advanced amateurs. The quest for "authenticity" in performance has led to the production of instruments copied from or based on surviving historical models, and to a close study of playing techniques as set out in early treatises. However, just copying without understanding is unsatisfactory, so we will look at the acoustics of the recorder with the aim of elucidating particular points of construction or technique. Some of the features of the recorder are extremely subtle, and will probably slip through our nets, but at least we will be able to cover the basics.

Acoustically, the recorder is closely related to the flute and organ flue pipe, and shares certain features with them. All three instruments have a common sound production mechanism, but whereas the flautist can exercise wide control of tone and dynamics by altering the relative position of his mouth and the flute, in the recorder and organ pipe this is fixed by the maker.

Figure 1: A consort of recorders. From left: great bass, bass, tenor, treble, descant, sopranino and garkleinflötlein. Measurement reference is 30 cm long.

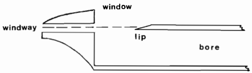


Figure 2: Schematic diagram of sound-producing parts of recorder.

Whereas each organ pipe is designed to play only one note at a fixed level, the recorder shares with the flute the ability to play a wide range of notes by opening holes along the length of the instrument, and to alter the qualities of each note by varying breath pressure. There has been a considerable amount of research into this sound production mechanism, dating back to the nineteenth century work of Rayleigh and Helmholtz. Specific research into the recorder did not commence until von Lüpke's work of 1940 [1] and has continued sporadically since. The remainder of this article draws on this published research, and on additional work carried out by the author.

SOUND PRODUCTION

The appropriate parts of the recorder involved in sound production are shown in Figure 2. (The bore and fingerholes will be considered later.) The player blows air into the windway at the top of the instrument. This forms a jet of air which emerges and travels across the window to the lip. If we consider a note to be already sounding, then the standing wave in the bore causes a flow of air in and out of the window. This tends to carry the jet with it as it emerges from the windway, and produces a wave on the jet which travels along it at about half the central jet speed, and growing in magnitude. The jet tip then sweeps back and forth across the lip, so that the jet itself blows alternately into and out of the bore. Providing that the correct phase relationship between the driving force so produced and the standing wave in the bore exists, the sound continues.

When the player blows harder the jet speed increases. This advances the phase of the jet tip relative to the standing wave in the bore and has the effect of raising the frequency of the oscillation. The opposite effect occurs when the player blows more softly. The optimum jet speed allows approximately half a wavelength along the jet [2].

We have assumed above that only one frequency is present, determined by a resonance of the bore. In fact the bore will have a number of resonances, which may or may not be harmonically related. Additionally, the profile of the jet will have an important effect, but let us suppose for the moment that it has a constant velocity across a finite width (a "top hat" profile). Then as long as the lip remains within the jet width as the jet moves back and forth, the system can be considered as linear: that is, any frequency present in the bore standing wave will produce a wave along the jet and a corresponding component of the force which the jet applies back on the standing wave, and each frequency will behave independently of the others. In this case the sound could contain inharmonically related components.

This linear situation vanishes when we remove our two assumptions about jet behaviour, so that a non-uniform profile or a jet which swings completely inside and outside the lip will cause non-linear behaviour. One of the features of the linear case outlined above is that any component which is increasing in amplitude at any instant continues to do so indefinitely. In practice this cannot happen due to the finite width of the jet. Also in practice, the jet profile is not uniform, but rather the velocity decreases on either side of a central maximum. Fletcher [3] has shown that under the usual conditions of a bore with resonances which are almost harmonically related, coupling between the modes results in a steady state sound of harmonically related frequencies.

Now even if there were a single frequency present in the bore standing wave the resultant sinusoidal movement of the jet tip in the non-linear case would produce a "source function" containing that frequency and its harmonics. Thus the position of the lip with respect to the jet has an effect on the harmonic content of the sound [4]. For instance, if the lip were placed centrally in the undisturbed jet, we would expect all even harmonics to be absent from the source function, and thus greatly reduced in the radiated sound. As the lip is moved away from this central position (in either direction) the intensity of the second harmonic in particular increases rapidly. In fact, in well-made recorders the lip is usually placed nearly in line with the innermost wall of the windway. The resultant increase in second harmonic produces a richer sound, and also has the desirable property of reducing the rate at which the note frequency increases as the jet speed increases. This gives the player a wider range of pressures over which he can blow to produce changes in intensity and tone, without going markedly sharp or flat.

The distance from the windway exit to the lip (the "cut-up") is one of the factors determined by the recorder maker. Increasing the cut-up means that the jet speed must be increased if the waves on the jet are to cross the window in the same time, thus preserving the required phase relationships. This increase in jet speed may be accompanied by an increase in sound intensity, but also means that the player's breath is used up more quickly, affecting the phrasing of the music. Also to be taken into account are: the change in size of the window which affects the bore resonances; the spreading of the jet; and so on.

For each note across the recorder's compass the condition of roughly half a wavelength along the jet must be maintained. For higher notes this requires the player to blow harder, with a consequent increase in sound level. This imbalance between the high and low notes of the recorder can be reduced to a certain degree by designing the instrument to have its higher notes naturally slightly sharp: in order to be played in tune, they must be played somewhat softer.

The fixed geometry of the sound-producing parts of the recorder limits the ways in which the player can add expression to the notes played. One resource available is to use vibrato, in which the blowing pressure and hence jet speed are repetitively increased and decreased, at about five hertz. This produces a corresponding change in the frequency and level of the note, but as the various harmonics change by differing amounts the most useful result of this is a varying change in tone, useful in adding life to an otherwise monotonous sound.

The player also has control over how the note begins, and the resulting attack transient is known to be very important to the overall perception of the subsequent sound. When a player begins a note the jet blows more or less rapidly across to the lip, according to the blowing pressure used and the way in which the air is released by the tongue [5]. In the case of a jet which attains its final velocity immediately it starts, the initial frequencies produced will be the resonant frequencies of the bore, and as the transverse displacement of the jet becomes larger, the increasing non-linear interaction between the jet and bore will cause these frequencies to move into a harmonic relationship and to reach steady amplitudes. If however the jet is started faster than its final value then the second mode may well be favoured over the fundamental until the jet speed falls, giving a different attack to the note. Recorder players probably seldom actually think of what is happening to the jet velocity, but the required control of breath and tongue is contained in syllables such as "te-te-te" or "de-de-de", or with faster notes "de-ge-de-ge", etc.

A note once begun may take about fifty cycles to settle into its steady state, and we find that this is fairly independent of the instrument size. This means of course that the smaller recorders are quicker to speak than the larger sizes, a fact reflected in the florid writing for the sopranino by Vivaldi and Handel.

We have said above that the ideal condition for a note to sound is if a half wavelength is present along the jet, as this provides the appropriate phase relationship for maximum sound regeneration. If the jet velocity is increased then this condition will be deviated from, until there is a quarter wavelength, at which stage no regeneration occurs. (Actually this will occur somewhat earlier, due to the losses from sound radiation and wall friction which have to be replaced.) However the same increase in jet velocity may have made regeneration of some higher mode favourable, and this note will then sound. The note overblows.

Often there is a definite sudden transition from one note to the other, but sometimes we find that there is a range of jet speeds in which both notes sound together, and that the two notes are not harmonically related. In this case the coupling between the modes is very weak, and instead of locking into a harmonic relationship, they (and their harmonics) interact to produce a rich "multiphonic" including sum and difference frequencies. An easy multiphonic to produce is to cover all the holes except for the middle finger of the lower hand: the multiphonic occurs over quite a wide range of breath pressures. Multiphonics were not used in the early repertoire of the recorder (or at least were never written down!) but have become a common effect in contemporary writing.

Some other "special effects" of modern compositions are produced by varying the flow of air into the windway. "Flutter tonguing" (produced by rolling the letter R) produces a rapid alternation in the jet speed, and again the non-linear sound process forms sum and difference frequencies. Sometimes beginners accidentally hum while playing, but as a controlled technique this is also called for by modern composers. Again the humming and played frequencies interact through the non-linear sound production. This technique does have some historic validity: Mersenne [6] mentions that it is possible for one player to perform a sonata, by playing the melody while humming the bass. Perhaps we can be thankful that this has never caught on!.

Among recorder players a point of continuing debate is whether the shape of the player's mouth has any significant effect on the recorder sound [7, 8]. The fact that there is any debate at all indicates that any effects that are present must be small. Obviously, the flow of air through the mouth can be impeded, by clenching the teeth for instance, and this can introduce noise into the note, but that is not the point at issue here. Rather the question is whether the shape of the mouth can change the harmonic content of the note. The mouth and windway together form a Helmholtz resonator and, by varying the mouth volume, can be brought into tune with one or other of the sound components. These can be heard quite clearly if the player wears ear protectors, and even without them the player can learn to hear the small changes in harmonic content. Presumably this sound travels directly to his ears through the Eustachian tubes. However the effects are not nearly so apparent to any other listener. The small coupling between the mouth-windway and the bore may shift the bore resonances slightly if the mouth resonance falls near one of them, and this may alter slightly the willingness of some notes to overblow.

BORE AND FINGER HOLES

The resonances needed for the sound production are a property of the bore and the finger holes. Part of the art of recorder making involves adjusting the shape of the bore and the size and positions of the finger holes to produce notes of the required pitch, tone, stability, etc. As is well known, the resonant modes of an open cylindrical pipe (ignoring any end corrections) form a harmonic series, and each mode forms a standing wave in the tube with a (velocity) antinode at each end. Contracting the bore at an antinode lowers the resonant frequency, while contracting it at a node raises the frequency. The opposite applies when the bore is expanded. Thus it is possible to adjust the mode frequencies independently by varying the bore diameter in different places. For instance, the fundamental mode of an open tube has a node in the middle of the tube and an antinode at the ends, whereas the second mode has an antinode in the middle and at the ends. Contracting the bore at an end and in the middle would lower the frequency of the second mode while leaving the fundamental unchanged. We should note here that bore contractions do not affect the modes equally. For instance contracting one end of an open pipe flattens the fundamental to a greater extent than the scond mode. This situation occurs at the window, which acts as a contraction of the upper end of the bore.

Figure 3 shows two recorders based on different historical models. (Also included are extra barrels which allows the recorders to be played at different pitches.) The recorder on the right (based on a 16th century design [9]) has a cylindrical bore for most of its length, tapering outwards near the foot. This taper is designed to counteract the contracting effect of the window at the other end, so that when all holes are closed, the modes are harmonically related. Thus the same fingering serves for the bottom note and for the note two octaves above, with a few holes leaking to encourage the extra antinodes. The recorder on the left (based on an 18th century original, and closer in appearance to our modern recorders) has a bore which tapers from the head down to the foot, with the diameter almost halving in this distance. This bore then acts as if it were contracted at both ends, lowering the pitch of the fundamental relative to the upper modes, and leading to different fingerings

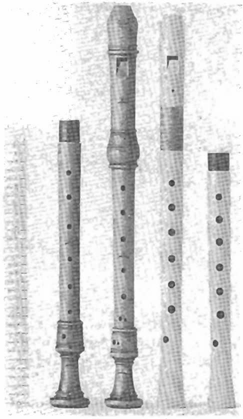


Figure 3: Recorders modelled after 18th century and 16th century originals. Maker: Fred Morgan. Measurement reference shows centimetres.

for the upper notes. The flattening effect of the tapering bore is seen in Figure 3: although the sounding length of both recorders is almost identical, the tapering one on the left sounds one tone lower than the other.

Figure 4 shows the difference in bore diameter for each recorder at the head and at the bottom end. The external flare of the 18th century recorder is seen to be decorative, not matched by the bore itself.

The bore does not taper uniformly, as seen in Figure 5. We do not know why the simple cylindrical instrument developed a tapering bore, but Morgan [10, 11] has conjectured that the impetus came from the design of the larger members of the consort. A tapering bore allows deeper instruments to be made which are somewhat shorter, and whose holes are smaller and closer together. This had the effect of throwing the simply-fingered high notes out of tune, but by modifying the rate of taper and changing these fingerings, the two-octave range was restored. The bore decreases steadily from the upper end of the lower, but it can also be thought of as deviating inside and outside a uniform cone. Thus a practical advantage of the tapering bore is apparent: it allows the maker to include local bore expansions and contractions using a single reamer, something which is of course not possible with a basically cylindrical bore.

The placing of the finger holes depends on a number of factors. They must be able to be covered by the fingers (!), and this constrains their size and position. Moving a hole up the bore will sharpen the note, while making the hole smaller will flatten the note. So to produce a note of the same pitch, an open hole may be moved upwards as long as it is reduced in size. However the upper modes will be flattened in relation to the fundamental, and this changes the tone and stability of the note. Another constraint on hole placing is the usual need for notes in the two registers to share similar fingerings.

It is common in good recorders to find the holes undercut: they are larger on the inside where they meet the bore than on the outside. This has the effect of making the hole acoustically larger, while retaining a small outside hole size. It also helps to smooth the bore, decreasing energy losses due to wall friction, which in turn helps to reduce the variation of frequency with blowing pressure on each note. Another device sometimes used is to slant holes so that they meet the bore and the outside at different positions. This is commonly used on tenor recorders where it is used to bring under the fingers holes which would otherwise be too far apart.

CONCLUSION

Many other early wind instruments were redesigned and festooned with keys to produce their modern orchestral counterparts, with even tone and loud sounds capable of reaching the back row of a concert hall. The recorder escaped this, but its simple uncluttered exterior nonetheless hides an instrument with many complex and subtle acoustical features.

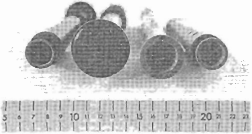


Figure 4: The recorders of Figure 3, viewed end on. Scale in centimetres.

In an introductory article such as this it has not been possible to do more than touch on some of the more obvious features, but a number of references are included below for the reader who would like to pursue the subject.

I would like to thank Dr Neville Fletcher for his generous help in guiding my studies into recorder acoustics. Thanks are also due to Helen Flight for taking the photographs.

REFERENCES

1 von Lüpke, A. (1940). "Untersuchungen an Blockflöten". Akust. Z., *5*, 39-46.
2 Fletcher, N.H. (1074). "Nonlinear interactions in organ flue pipes". J. Acoust. Soc. Am., *56*, 645-652.
3 Fletcher, N.H. (1978). "Mode locking in nonlinearly excited inharmonic musical oscillators". J. Acoust. Soc. Am., *64*, 1566-1569.
4 Fletcher, N.H. and Douglas, L.M. (1980). "Harmonic generation in organ pipes, recorders and flutes". J. Acoust. Soc. Am., *68*, 767-771.
5 Fletcher, N.H. (1976). "Transients in the speech of organ flue pipes — a theoretical study". Acustica, *34*, 224-233.
6 Mersenne, M. (1636). Harmonie universelle... Paris. Facsimile (1965) Paris: C.N.R.S.
7 Coltman, J.W. (1973). "Mouth resonance effects in the flute". J. Acoust. Soc. Am., *54*, 417-420.
8 Bak, N. (1969). "Pitch, temperature and blowing-pressure in recorder playing. Study of treble recorders". Acustica, *22*, 295-299.
9 Morgan, F. (1982). "Making recorders based on historical models". Early Music, *10*, 14-21.
10 Morgan, F. (1984). "Old recorders and new ones". The Recorder (Journal of the Victorian Recorder Guild), *1*, 12-16.
11 Morgan, F. (1984). "A recorder for the music of J.J. van Eyck". American Recorder, *25*, 47-49.

ADDITIONAL REFERENCES

Benade, A.H. (1960). "The Physics of Woodwinds". Sci. Am., *203*, 144-154.
Benade, A.H. and Gans, D.J. (1968). "Sound production in wind instruments". Ann. N.Y. Acad. Sci., *155*, 247-263.
Coltman, J.W. (1968). "Sounding mechanism of the flute and organ pipe". J. Acoust. Soc. Am., *44*, 983-992.
Elder, S.A. (1973). "On the mechanism of sound production in organ pipes". J. Acoust. Soc. Am., *54*, 1554-1564.
Fletcher, N.H. (1979). "Air flow and sound generation in musical wind instruments". Ann. Rev. Fluid Mech., *11*, 123-146.
Haynes, B. (1968). "The baroque recorder — a comparison with its modern counterpart". Recorder and Music, *2*, 364-368.
Herman, R. (1959). "Observations on the acoustical characteristics of the English flute". Am. J. Phys., *27*, 22-29.
Lyons, D.H. (1981). "Resonance frequencies of the recorder (English flute)". J. Acoust. Soc. Am., *70*, 1239-1247.
Marvin, B. (1972). "Recorders and English flutes in European collections". Galpin Soc. J., *25*, 30-57.
Morgan, F. (1981). "The recorder collection of Frans Brüggen". Tokyo: Zen-On.
Mühle, C. (1966). "Untersuchungen über die Resonanzeigenschaften der Blockflöte". Frankfurt am Main; Verlag Das Instrument.
Myers, H.W. (1980). "The practical acoustics of early woodwinds". Thesis for D.M.A., Stanford University. Ann Arbor: University Microfilms International.
Wogram, K. and Meyer, J. (1984). "Zur Intonation bei Blockflöten". Acustica, *55*, 137-146.

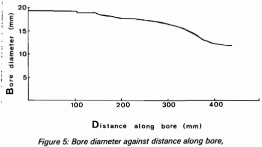


Figure 5: Bore diameter against distance along bore, for 18th century model recorder.

Vibration Geometry and Radiation Fields in Acoustic Guitars

Graham Caldersmith
20 Dryandra Street
O'Connor ACT 2601

ABSTRACT: Natural vibration modes of the acoustic guitar body are excited by the vibrating strings, and they generate radiation fields (monopole, dipole, tripole and multipole) characteristic of the mode geometries which interact in the space around the guitar. The multipole fields generated at frequencies above the monopole, dipole and tripole fields create a complex sound output the average profile of which reflects the structure and materials of the guitar. The musical qualities of the guitar can be described in terms of the special physical behaviour of this integrated resonator.

The popular notion of the violin as an instrument embodying a legacy of musical perfection from the Original Masters has ensured some general awareness of research into the physical behaviour of the violin, and has also ensured perennial rediscoveries of "original violin making secrets", often, unfortunately, by practising scientists who have not recognised the dimensions of the excessive claims they have made. By contrast, research into acoustic guitar behaviour has (less conspicuously) made sober and substantial progress over the last two decades, providing a body of knowledge which has been practically communicated to guitar makers who, in turn, are applying scientific knowledge to the making of fine instruments. The established tradition of violin making has not allowed scientific knowledge such a ready influence, even though practical applications of substantial violin research have been widely published. [1, 2, 3]

The physical behaviour of the essentially flat-faced, structurally symmetrical guitar can be more directly understood than that of the arched, structurally asymmetrical violin. From its set of natural vibration modes, some of which are excited by resonance coupling processes, the guitar generates a corresponding set of radiation fields which interact in space and frequency in a way uniquely suited to its musical requirements.

STRUCTURE AND FUNCTION OF THE GUITAR

At this stage of its evolution, the acoustic guitar has become standardised in two principal forms: the lighter classical/flamenco (nylon string) form and the heavier folk/jazz (steel string) form, as depicted in Figure 1, with typical top bracing, the configuration of which remains the subject of continuing redesign. Each of the six strings (tuned in doubles in the twelve string guitar) "drive" the guitar top at the bridge location with periodic harmonic forces proportional to the vertical and transverse components of string vibration amplitude. We shall ignore the smaller periodic forces operating on the bridge in the string direction at double the string vibration frequencies due to the stretching of the string in its excursions about rest position. Vibration of the plucked string is a well-studied phenomenon [4, 5], and it suffices to say here that the decay rates of the string partial vibrations are partly determined by the rate of energy transmission to the guitar top through the bridge, a process whereby the vibrations of the harmonic drivers, the guitar strings, are influenced by the vibrations of the guitar body, the latter being the focus of this discussion.

When the top of a guitar vibrates, it does so in natural modes of vibration which respond optimally to a driving vibration at their resonance frequencies. These mode frequencies are determined by the characteristic geometries of top deformation undergone during cycles of vibration, as well as by the

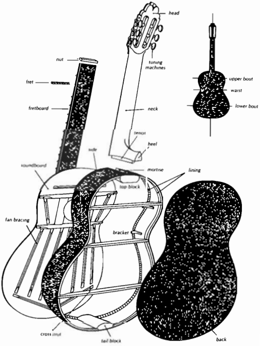


Figure 1: The traditional classical guitar structure. Top is usually of European Spruce or of Western Red Cedar, while back is of Brazilian or Indian Rosewood. The bracing design varies from one instrument model to another. (after I. Sloane)

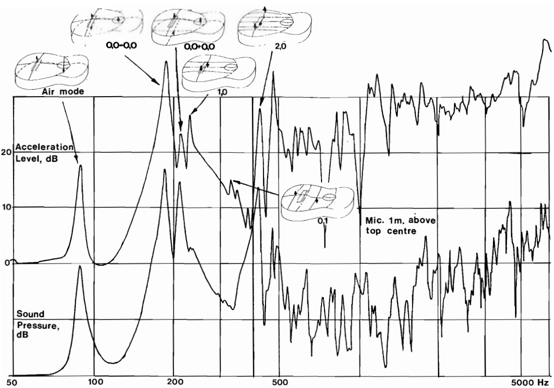


Figure 2: Frequency response curves produced by a guitar driven sinusoidally with constrant force at the bridge between the two top strings (E and B). The upper response curve (the "input") is that recorded by an accelerometer attached to the bridge just behind the driver: Acceleration Level. The lower response curve (the "output") is the sound pressure level recorded 1 m above top centre. The lower peaks are those of the resonances of modes identified and sketched near the peaks.

structure and materials of the guitar top. Figure 2 shows the deformation geometries of the lower classical guitar modes and corresponding resonance peaks in the frequency response curve produced by a pure tone force driving the guitar at the bridge. The modes are designated by the number of nodal lines aligned apporoximately along the top centreline and across it, given that for most top modes the top boundary is also nodal (in contrast to the violin).

(i) The Coupled Fundamental Guitar Modes

The 0,0 (fundamental) top mode resonates twice because it is coupled to the "air piston" in the sound hole through the elastic air volume enclosed within the guitar. The physics of this top fundamental coupling is similar to that of the bass reflex speaker enclosure, although the back e.m.f. moderating the speaker cone excursions at its resonances has no counterpart in the guitar problem, where the amplitude of the fundamental mode at resonance is limited by sound radiated, by near field viscous losses and internal wood losses. At the lowest resonance, the air piston and guitar top vibrate in antiphase, but the periodic volume flow generated by the air piston exceeds that generated by the fundamental top motion, so that a net volume flow results. Because this occurs at ~100 Hz when the sound wavelength is ~3 m compared to the rear guitar bout radius of ~0.3 m, the guitar produces essentially spherical sound waves at its lowest resonance, the so-called "air resonance".

At the upper resonance of this coupled pair, the air piston and guitar top vibrate in phase, this time with the periodic volume flow from the top fundamental mode predominating, but supplemented by the air piston's reflex motion. The sound wavelength at the upper top fundamental resonance (~200 Hz) is about 1.5 m, substantially larger than the guitar top radius, so that the sound field produced by this mode remains essentially spherical, although perturbations from spherical field geometry are observable.

Between these coupled resonances, the top fundamental amplitude passes through a minimum at the frequency of the helmholz cavity resonance, which is the frequency of natural vibration of the air piston against a rigidly enclosed air volume — which would occur were there no top or back resonances. However the air piston amplitude relative to the top fundamental amplitude peaks between resonances, so that periodic volume flow rate is maintained efficiently in the frequency interval between fundamental resonances, as the sound pressure response in Figure 2 shows. This reflex behaviour provides efficient sound generating capacity for the acoustic guitar in its lowest range.

Some guitar makers favour an extension of this reflex behaviour in which the back plate structure is adjusted so that the back fundamental mode couples to the top fundamental mode through the air volume. The effect of this "double reflex action" is shown in Figure 2, where the upper top fundamental resonance appears twice, in the lower case where the top and back move in antiphase relative to the surrounding air, reducing the net volume displaced during vibration cycles, and in the upper case where the top and back move in cophase relative to the surrounding air (i.e. in together and out together), increasing the net volume displaced during vibration cycles.

Consequently the sound "output" per unit driving "input" is higher in the upper of these coupled resonances, and the adjustment of the back thickness and bracing to achieve a coupling level producing almost equal "output" peaks is a skilled procedure now being adopted by dedicated contemporary luthiers.

Cyclic compression and decompression of air surrounding the guitar due to net volume changes effected by the guitar's reflex or double reflex action in its lowest frequency range generates sound at wavelengths larger than the guitar dimensions, so that the guitar acts as a cyclic air pump in its lowest resonances. That is, the guitar is effectively an acoustic monopole in its lowest vibrational modes, the "pumping" modes.

(ii) The Dipole Modes and Tripole Mode

Above the frequencies of the pumping modes occur the two "dipole" modes, the cross dipole mode and the long dipole mode. The cross dipole mode is symmetrical about its central axial nodal line, and because air cycles back and forth between the antinodal poles without experiencing much compression when the wavelength is larger than the pole separation, this dipole mode is not an efficient sound generator. The bridge traverses the cross dipole nodal line and so the bass E and treble E strings (the lowest and the highest strings) may excite this mode strongly, the A and B strings less so and the D and G strings minimally. Typically the cross dipole mode resonates at ~300 Hz which is below the treble E string frequency of 330 Hz so that it is not excited strongly by the top string.

The long dipole mode is not symmetrical about its transverse nodal line, so that incomplete volume flow cancellation occurs between the poles moving in antiphase in this mode, which may therefore contribute some net volume flow to the acoustic field generated by the guitar in the dipole frequency range (250–400 Hz). However the long dipole nodal line is usually very close to the bridge, where the mode is driven, and the mode is therefore usually weakly excited.

So although the long and cross dipole guitar modes have claimed much attention from researchers and makers, not only are they poor radiators, but are weakly excited by the vibrating guitar strings, the exceptions being some overtones of the bass E and A strings and some fundamentals on the B string. These strings may deliver some of their precious plucked energy to the dipole modes but gain little sound production in return!

What is of more importance for the sound generating performance of the classical guitar is the appearance of the cross tripole mode typically a little above or below 500 Hz. Except in guitars with very heavy bridges which suppress the tripole amplitude at the string driving points, this mode is strongly excited by all strings, and because the two outer antinodal poles vibrate in antiphase with the centre pole and with greater amplitude, this mode is an efficient net volume pump and so radiates strongly, as the high sound pressure peak per unit driving amplitude indicates. When excited below its resonance frequency, the tripole mode pumps air in cophase with the fundamental mode(s) excited above resonance frequency, so that the net volume flow and hence sound output is maintained efficiently in this frequency range (20–500 Hz) above the coupled air piston — fundamental range (80–200 Hz). While the dipole radiation fields may superimpose on the net pumping field between fundamental and tripole resonances (200–500 Hz) with two radiation lobes in antiphase either transverse to or axial to the guitar (one lobe supplementing the pumping field, the other reducing it), the main radiation output from the guitar in its lower range (80–500 Hz) is due to a unique and efficient interaction between air piston, fundamental top (and back) mode(s) and the tripole mode. In some classical guitars the long dipole is excited significantly at the bridge, and produces a net volume flow from the predominant front pole, so that this mode supplements the monopole—tripole field below its resonance frequency (~400 Hz) and opposes it above.

We should note that the cross braced steel string guitar does not vibrate in a tripole mode, and the sound output generated by the top (and back) fundamental mode(s) decreases steadily above the fundamental resonance frequency into the next resonance regime. This is an important difference in physical behaviour reflecting traditionally estalished outlines and bracing designs for the classical and steel string guitars, the musical effects of which are discussed below.

(iii) The Higher Multipole Modes

At frequencies above 500 Hz, the guitar top vibrates in "multipole modes" with increasingly more antinodal poles, which radiate sound less efficiently than the pumping modes as long as the poles are separated by less than one sound wavelength in air. The sharp dip in the average sound output from the modes above the tripole mode indicates lower radiating efficiency of the multipole modes relative to that of the pumping modes. Each of the multipole modes generates a spatially complex field, which may overlap with the fields of one or more multipole modes adjacent in frequency, producing a radiation field that varies rapidly in space and in frequency. Fortunately, average trends in sound pressure level measured at any position around the guitar are clearly evident in the sound pressure frequency response (Figure 2). Since then acoustic power radiated from the guitar is proportional to driving point velocity, the difference between the sound pressure level and the driving point velocity level is a broad measure of the radiation efficiency of the guitar. Comparisons of average sound pressure per driving point velocity for different guitars afford useful estimates of relative radiation efficiencies.

Whereas the increase in driving velocity of, and sound output from guitar top modes above the tripole mode at 500 Hz to 5 kHz depends on the structure of the guitar and wood bending and twisting moduli, the decrease in driving velocity and sound output from above 5 kHz seems to depend on wood-bending and twisting damping rates. Hence the physical behaviour of the guitar is broadly determined by its dimensions and structure, and the frequency-dependent visco-elastic properties of the woods. Much of the character of individual instruments derives from small variations in the fairly standard structure, and from differing (coated) wood properties. That is why guitar makers pay so much attention to bracing heights, top thicknesses and bridge dimensions as well as to wood selection and finishing procedures, although their stated reasons for their chosen practices usually owe more to tradition and intuition than to the sort of analysis above. More recently communication and consultation between music-acoustic researchers and professional guitar makers has brought scientific knowledge and workbench practice into a lively partnership and the resulting design modifications are undergoing a complicated process of cultural selection.

MUSICAL QUALITIES AND PHYSICAL BEHAVIOUR

The response of the guitar to the driving forces exerted on the bridge by the vibrating strings is determined by the structure and materials of the guitar body, and the sound generated by the guitar's response in its family of natural modes will be perceived by guitarist and listeners and assessed for musical quality.

The dramatic variation in the guitar's response to string driving forces exciting the top at different frequencies would lead us to expect the guitar to be very uneven across lower range notes which occur in the frequency range of the lower, well-separated modes. In fact for notes on the lower four strings, some guitars are noticeably uneven, and mode resonances can be clearly identified in chromatic scales played through mode frequencies. The paradox is that this degree of unevenness does not seem to influence a judgement of musical quality strongly.

There are three main reasons why guitars do not sound as uneven as we would expect from the frequency response curves:

(i) Played notes excite the guitar with a whole series of partials and the total response averages out the strong resonance and weak antiresonance responses to individual partials of the notes. The general preponderance of lower partials in the plucked string makes it useful to study the guitar's response to the lowest three partials (fundamental, first and second overtones) of a range of plucked notes.

(ii) The maintenance of sound output between the air, top fundamental(s) and tripole resonances is an important factor in guitar behaviour which reduces excessive variation in the sound output levels produced by the lowest three partials of the lower range notes. Higher range notes excite the guitar at frequencies where resonances occur more closely in frequency and merge into a resonance continuum which affords a less erratic response to the driving vibrations.

(iii) Figure 3 shows the lower frequency response curve for a guitar with and without the strings damped. The degree of string partial coupling with the guitar modes depends on the proximity of the string partial frequency to the mode frequency, and this coupling effectively broadens the frequency range over which the guitar modes can respond to the string vibrations.

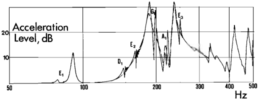


Figure 3: Frequency Responses of a sinusoidally driven guitar with strings damped (solid line) and with strings undamped (broken line). Interactions of string modes with guitar modes are evident when both occur at similar frequencies.

Figure 4 derives from the frequency response curve the relative strength of the three lowest partials of certain lower range notes played on a guitar having strong double reflex action. While the string fundamental output is high, the first and second overtone output is relatively low, and vice versa. So a weak fundamental is compensated by stronger first and second overtones, the frequency difference between which is, of course, the fundamental frequency, and is perceived as such even in the virtual absence of the fundamental in the radiated sound.

One outstanding exception to this compensatory resonance placement is the occurrence of the air and top fundamental resonances at an octave interval in guitars of various musical qualities. Then certain low range notes (often G, 98 Hz) will have a strong fundamental and first overtone content relative to other notes adjacent in frequency, creating a marked unevenness in playing response. Why this obvious unevenness does not seem to trouble many guitarists is not easily explained, since other guitarists pay close attention to the evenness of lower range notes in the instruments they play.

The spectral envelopes of the higher range notes vary over the note's duration according to the decay rates of the partials forming the envelopes, and they will reflect the characteristic response curve of any given guitar, a response curve which depends on the considered structure and materials the maker has invested in that guitar. While the radiated spectrum generated by the vibrating guitar body will vary in space around the guitar, the average output response curve will be represented to the listener in the reverberant sound field generated within the environment in which the guitar is heard. Indeed playing a guitar (or any acoustic instrument) in a non-reverberant environment such as the outdoors, misrepresents the character of the instrument, and thereby we infer the vital importance of architectural acoustics in the subjective assessment of any particular instrument: it is the subjective assessment which is, after all, the ultimate measure of musical quality. It is also likely that the perception of musical sound quality involves an averaging of tonal qualities over a range of played notes and so we invoke the discipline of psychoacoustics in the assessment of overall sound quality.

We find that those frequency bands which are important in human voice production and in speech recognition are also important in the quality of musical tone. In particular the human ear is most sensitive to sound in the 2–5 kHz band, and it is no coincidence that guitars and violins have a broad optimum in this frequency range where important differences between instruments can be identified. This factor in instrument tone can be practically demonstrated by playing a recording of solo guitar music through a graphic equaliser and varying the levels of different frequency bands while listening to the effects. Increasing the levels below 1 kHz makes the guitar sound "boomy" — strong in lower partials. Increasing levels between 1 kHz and 2 kHz makes the guitar sound nasal and "honky". Increasing the levels between 2 kHz and 5 kHz makes the guitar incisive and clear, while increasing the levels above

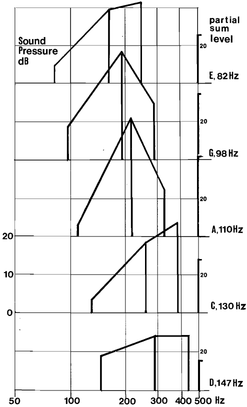


Figure 4: Relative strengths of three lowest partials in five lower range guitar notes. While the partial strengths vary dramatically, the sum of their sound pressures, shown at right (which is a rough index of guitar output) does not vary dramatically across the different notes. Sound pressure levels are taken as dB above background level.

5 kHz makes the guitar "edgy" and brittle. All of these terms describing musical quality convey subjective experiences and they may not have the same meaning for different listeners. Discussion of graphic equaliser variations amongst members of a listening group is an effective way to understand the musical effects of quantifiable changes in response curves.

Finally we recall that the average higher response profile depends on structural preferences and wood selection, and thus we may discuss variation of tonal properties in terms of guitar design and wood properties, thereby specifying a link between perceived musical quality and workbench procedure.

CONCLUSION

The guitar is a portable stringed musical instrument of simple but subtle configuration which has recently become almost universal in local and international musical traditions. The expansion in both classical and steel string guitar technique and composition this century has interacted with enormous energy in guitar making, and the quest for musical excellence has involved scientific study, featuring physical analysis which has tackled advanced problems in vibration of complex structures and the attendant sound radiation processes in different frequency regimes. Communication between scientists and guitar makers during recent decades has ensured the effectiveness of the analysis and continues as a vital part of an endeavour of excellence uniting musicianship, craft and science.

REFERENCES

1 Hutchins, C.M. "The Acoustics of Violin Plates", Sci. Am., Oct. 1981, 170-186.

2 Moral, J.A. and Jansson, E.V. "Input Admittance, Eigenmodes and Quality of Violins", Acustica *50*, (1982) 329-337.

3 Hutchins, C.M. "A History of Violin Research", J. Acoust. Soc. Am. *73 (5)* (1983), 1421-1440.

4 For Example: Morse, P.M. "Vibration and Sound", McGraw-Hill, 1948.

5 Fletcher, N.H. "Plucked Strings — A Review", Catgut Acoust. Soc., No. 26, (Nov. 1976).

Another ultrasonics application

One of the problems in the hot extrusion method for production of copper pipes is the *maintenance of concentricity of the shell.* Small variations in extrusion press alignment, billet temperature, die and container conditions, and stability of the central mandrel during extrusion, can all influence the quality of the extruded shell.

The aim of a collaborative project between Metal Manufacturers Ltd. and CSIRO Division of Applied Physics, Sydney was to devise a robust system that would pick up the beginnings of misalignment and provide information about the causes of the eccentricity. The prototype monitor built by **Dr. Don Price and colleagues** at the Division comprises three transducers, or probes, a multiplexer and a microcomputer. It is proving to be a most useful 'early warning device' giving readings of eccentricity to within 2 per cent while also indicating the location of the point of minimum wall thickness in the extruded tubing ('shell').

This device transmits ultrasonic pulses to the inner and outer walls of extruded shells and measures the times taken for echoes from the surfaces to be received. The time difference is proportional to the thickness of the wall. The accuracy of the eccentricity figure is limited mainly by the assumption that the two surfaces have circular cross-section, but is more than adequate for present purposes.

From CSIRO Industrial Research News No. 173.

Analysis of Guitar Top-Plate Modes

S. Marty

School of Electrical Engineering, University of Sydney, Australia 2006

B. F. Oreb and P. Hariharan

C.S.I.R.O. Division of Applied Physics, P.O. Box 218, Lindfield, Australia 2070

The design of the present-day classical acoustic guitar is essentially that developed by Antonio Torres in the mid-nineteenth century with only minor changes. Guitar construction has been, by and large, more of an art than a science, and it is only recently that studies have been undertaken to identify the objective criteria which determine the quality of an instrument. These have shown that the performance of a guitar is mainly dependent on the amplitude distribution and quality factors (Q) of the top-plate modes in the frequency range up to about 700 Hz (Christensen 1983). A scientific approach to the development of an improved instrument must therefore be based on measurement techniques which can give detailed information on these modes and permit assessing the effects of changes in construction.

Measurements of the frequency response were made by applying a mechanical impulse to the body of the instrument and performing a fast Fourier transform (FFT) on the acoustic time response (Boullosa, 1981). The impulse was applied by a small striker rod attached to an Advance vibrator type 6 which was excited with a single pulse from an I.E.C. F53A function generator. The acoustic signal from the guitar was picked up by an electret microphone placed directly in front of the bridge at a distance of 0.5 m and taken to a Nicolet 3091 digital oscilloscope with 12-bit resolution which sampled and stored the signal at 4000 points. The stored data were then transferred to a Sirius microcomputer which carried out a FFT on the data.

Measurements of the amplitude distribution in the top-plate modes were made by holographic interferometry (Jansson 1971, Richardson 1983). For these measurements the guitar was mounted vertically on a metal stand on the holographic table and excited by a B & K type MM 002 magnetic transducer coupled to a small mumetal disc attached to the soundboard at a suitable point. The resonant frequencies were located by recording a hologram of the guitar with no excitation and then observing on a TV monitor the real-time fringes corresponding to the various top-plate modes as the excitation frequency was varied. After optimizing the settings to excite the desired mode, a time-averaged hologram of that mode was recorded.

Figure 1 shows the time-averaged fringe patterns corresponding to six of the top-plate modes of a Ramirez guitar at resonant frequencies of 195, 292, 385, 537, 709 and 905 Hz respectively. As can be seen, the antinode of the fundamental top-plate mode is displaced laterally to the wing of the bridge due to the asymmetry of the internal bracing. While this has little or no effect on the acoustic output from this mode, it results in the other modes in the low- to mid-frequency range radiating quite strongly, resulting in a "warm" Spanish sound.

We have used these techniques to study a number of prototype guitars incorporating a new radial soundboard bracing pattern developed by one of the authors (S. M.). Other innovations studied were the use of a carbon fibre-balsa composite as the bracing material as well as a new design for the bridge. These changes have led to substantial improvements both in the acoustic output and the performance at high frequencies, resulting in an instrument which is very well suited to contrapuntal styles of music.

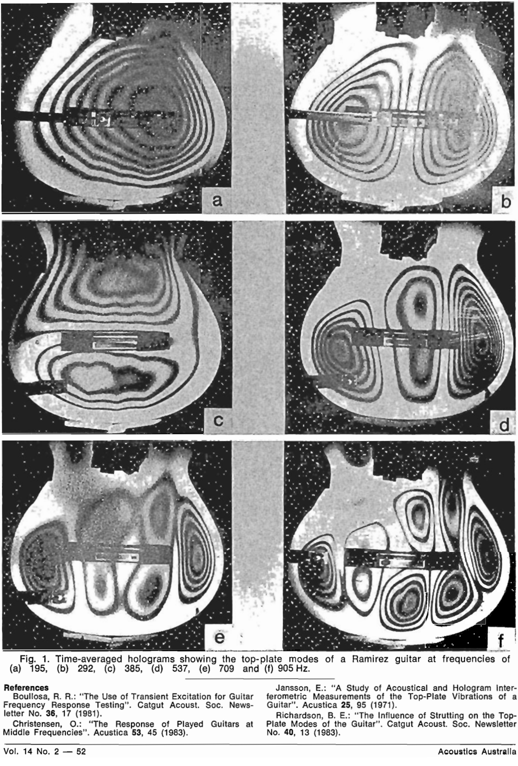


Fig. 1. Time-averaged holograms showing the top-plate modes of a Ramirez guitar at frequencies of (a) 195, (b) 292, (c) 385, (d) 537, (e) 709 and (f) 905 Hz.

References

Boullosa, R. R.: "The Use of Transient Excitation for Guitar Frequency Response Testing". Catgut Acoust. Soc. Newsletter No. **36**, 17 (1981).

Christensen, O.: "The Response of Played Guitars at Middle Frequencies". Acustica **53**, 45 (1983).

Jansson, E.: "A Study of Acoustical and Hologram Interferometric Measurements of the Top-Plate Vibrations of a Guitar". Acustica **25**, 95 (1971).

Richardson, B. E.: "The Influence of Strutting on the Top-Plate Modes of the Guitar". Catgut Acoust. Soc. Newsletter No. **40**, 13 (1983).

NEW PRODUCTS —

BRADFORD INSULATION

TUFF-SKIN BATTS

Tuff-Skin Fibreglass Partition Batts were specifically developed for speedy installation in steel framed partitions and internal walls. They are a random felted mat of flame attenuated glass fibres, bonded with a thermosetting resin. Tuff-Skin Fibreglass Partition Batts are especially stiffened and lightweight with high tensile strength, to make handling easy and to resist tearing.

Tuff-Skin Fibreglass Partition Batts have three excellent qualities which make them ideal for installation in partition and walls. Firstly, they provide acoustic insulation in internal walls and partitions. In tests Tuff-Skin Fibreglass Partition Batts were found to provide the kind of sound transmission reduction that is necessary between building elements. Tuff-Skin Fibreglass Partition Batts also provide good thermal insulation which is particularly important in areas where precise temperatures have to be maintained, such as computer rooms. They also have passed fire resistance tests with impressive results. When tested in accordance with AS1530 Part 3-1976, Tuff-Skin Fibreglass Partition Batts scored nil for ignitability, spread of flame, heat evolved and smoke developed, which is the best attainable rating.

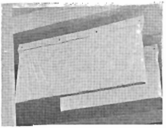
FLEX-SKIN

Flex-Skin is a revolutionary surface treatment, that increases Fibertex Rockwool's strength and handleability. It is a strong non-woven fabric which is resin bonded to Fibertex Rockwool flexible blankets. Flex-Skin is available as a standard feature on Fibertex-350, -450 and -650 Rockwool blankets and Fibertex-R4 and -R6 Ductliner with BMF, CF and PERF foil facings at no extra cost, and can be added to other Bradford insulation products for building, industrial, acoustic and air handling applications.

Flex-Skin is an important practical feature of Fibertex Rockwool because it supports the outer skin of the Rockwool blanket during installation as well as providing a smooth easy to handle surface. Flex-Skin is bonded to the bottom surface of faced ductliners giving them the additional tensile strength, rigidity and handleability often needed when handling large sheets of material. With the addition of Flex-Skin, faced ductliners are covered, providing smooth and easy to handle surfaces.

ACOUSTIC BAFFLE — 602

Fibretex Acoustic Baffles are manufactured from Rockwool fibres which are resin bonded to form a rigid batt. The batts are enclosed in a 30 micron white plastic film which is suspended from the ceiling by "S" hooks. Bradford Fibretex Acoustic Baffles are a simple solution for reverberation control in buildings because of their outstanding sound absorption characteristics.



The new Fibretex Acoustic Baffles are fully enclosed in a plastic film that can be wiped clean. They are also resistant to oil and moisture vapours making them ideal in buildings where hygiene and noise control are vital factors. They also have an attractive appearance which can be further enhanced by imaginative layout as they can be installed at various heights and spacings to build up any desired pattern.

Further information: Bradford Insulation Group, Carmel M. Carrigan (02) 332 3088.

BRUEL & KJAER

MACHINE HEALTH MONITORING SYSTEM

The Type 3542 is a semi-automatic system for condition monitoring on rotating machines. It monitors machine vibration levels and employs advanced spectrum-comparison techniques for the earliest possible detection of faults. When a fault is discovered, trend analysis techniques predict the time at which the fault will become critical. Maintenance procedures can then be planned ahead, so as to keep costly down time to a minimum. The System is extremely easy to use. Extensive help facilities are built in and the entire system is operated via a central terminal.

The Type 3542 Machine-Health Monitoring System comprises the following: Accelerometer Type 4391 (5 supplied), Calibration Exciter Type 4294, Portable Tape Recorder Type 7007, High Resolution Signal Analyzer Type 2033, Graphics Recorder Type 2313 fitted with Application Package BZ 7014, Digital Cassette Recorder Type 7400 and Visual Display Terminal Type 4718.

VOLT AND PHASE METERS

Bruel & Kjaer introduce two new instruments for electronic and electro-acoustic testing and measurement. The Type 2432 Voltmeter and the Type 2977 Phase Meter are versatile and easy-to-use instruments designed for stand-alone use with straightforward front panel control and for system use on the IEEE 488/IEC 625-1 interface bus. Both instruments feature unique facilities for eliminating ground loop interference, with carefully designed input circuits and with analogue circuits electrically isolated from the digital (interface) circuits.

VERSATILE SOUND LEVEL METER

Bruel & Kjaer's Precision Sound Level Meter Type 2235 is a versatile, comprehensively equipped IEC Type 1 instrument, suitable for general purpose measurements and a wide range of applications including building acoustics, audiometer calibration and frequency analyses. It measures sound pressure levels from 24 dB up to 130 dB, a range which can be extended to 150 dB with the addition of the 20 dB Attenuator Type ZF 0020.

The Type 2235 can measure the maximum or instantaneous sound pressure level with automatic (1 s) or manual reset in accordance with IEC and Japanese standards. Measurements can be made with RMS or Peak detector modes, with Slow, Fast or Impulse time weighting, and with A, C or Lin. frequency weighting. Measurements are displayed with 0,1 dB resolution on a digital display.

SINE TEST CONTROLLER

Bruel & Kjaer's Vibration Exciter Control Type 1050 is a technically advanced instrument for swept sine control of vibration exciter systems. The digitally controlled generator enables highly accurate resonance investigation with a frequency resolution to 1 mHz. Piezo-electric accelerometers and force transducers can be directly connected to the Type 1050 for control of any vibration measurement parameter, or for vibration measurement.

Further Information: Bruel & Kjaer, P.O. Box 120, Concord, N.S.W. 2137. Telephone (02) 736 1755.

BOOK REVIEWS ——

SPATIAL HEARING

Jens Blauert

(Translated by J. S. Allen)

MIT Press, Cambridge Mass., 1983. Review copy from Book & Film Services, P.O. Box 226, Artarmon, N.S.W. 2064. Price $93.50 (Aust.).

In the preface of his original volume, Blauert defines that the spatial attributes of auditory perceptions and the signals that accompany these attributes constitute the phenomenon of spatial hearing. What follows in the four chapters of this book is a unique review of the literature and experimental analysis which has occurred during the development of this broad subject.

Before presenting an outline of the structure of the book, it is worth noting that most of its content was originally published in German in 1974. The present volume was published in 1983 and contains an English translation of the original work (Chapters 1 to 3) and an additional chapter which summarises some of the contributions to the subject which have been made after 1972. It could fairly be said then that the book is not new. Nevertheless, as a review of all aspects of the subject's development, which includes work not before presented in English, this volume represents a fine text book, a reference source and essential reading for anyone with an interest in spatial hearing. The scope of the audience to which this book is directed is as broad as the subject and includes those with interests in psychology, psychophysics, physiology, medicine (especially otology and audiology), engineering, physics, musical analysis and architecture.

The organization of the major chapters (1 to 3) is entirely logical. The first chapter (Introduction) establishes the technical and experimental foundations upon which the later chapters are built. It defines auditory events, auditory space and methods of analysis, and concludes with a technical discussion of experimental procedures. The second chapter is concerned with the analysis of spatial hearing when the input to the ears is from a single sound source. An opening discussion of localization ability under these somewhat simple conditions is followed by an analytical description of the nature of the sound field at the two ears and the transfer functions of the external ear. The next two sections of the chapter are concerned with situations in which there is an identical input to the two ears (particularly directional hearing in the median plane) and when there are nonidentical inputs to the two ears. The latter section is concerned with the analysis of interaural time and intensity differences and the "trading" between these differences. The chapter concludes with a brief discussion of theories which include motion, visual, vestibular and tactile inputs in the percept of spatial hearing.

The third chapter of the book deals with spatial hearing in the more complex (but more realistic) situations in which there are multiple sources of sound or the sounds are generated in an enclosed space. The major impact of this chapter is in the analysis of stereophony. However, the more demanding concerns associated with room echoes, multiple sources of sound and the evidence for neuronal inhibition in these circumstances (the cocktail party) receive considerable attention. The fourth chapter, by the author's admission, is selective and presents a few, more recent contributions to the study of spatial hearing.

Overall, the text is concise and, although heavily analytical, it is easily read. There is also a wealth of original data presented in diagrams or summarised in extensive tables. The use of diagrams to aid in the description of stimulus conditions, recording techniques, analytical considerations and in the development of models is also a feature of the presentation. Another major strength of the book is the careful development of arguments from the evidence available and the exposition of a model or a definitive view. Briefly, on the negative side, minor lapses in translation or editing have allowed several instances where a word of Latin origin is incorrectly pluralized and reference is made to a Figure which is not in the book.

Finally, it should be stressed that this text is largely the juxtaposition of the analysis of sounds at the human head and human spatial perception of auditory stimuli of very different form and mode of presentation. As such, the book is essential reading for all those with interests in either of these areas, as well as for those with a neurophysiological bent who are interested in what occurs between these extremes.

—*Alan Pettigrew*

SOUND HEALTH

Steven Halpern and Louis Savary

Harper and Row, Sydney, 1985, 211 pp., paperback, ISBN: 07-3120672, A$9.95. Review copy from Book and Film Services, Unit 3B, Artarmon Industrial Estate, Artarmon 2064.

This is an unusual book dealing broadly with the subject of "sound therapy". Dr. Halpern is a well-known author and composer of music for relaxation; Dr. Savary is a lecturer and author of several books. The book contains a lot of useful information presented in non-technical language covering almost all aspects of sound and noise. The physical, psychological and medical aspects of sound are covered together with the use of sound in therapy and relaxation. The authors state that "it is our purpose in this book not only to raise awareness of the harmful sounds that we tolerate, wittingly or unwittingly, in our environment, but also to present a variety of ways to use relaxing and healing sounds".

Supporters of orthodoxy will no doubt object to the degree of speculation which follows some of the quotations from published work. Some of this does stretch credibility at times but we have to remember that everything is not known yet about sound and its effects on human beings. Legitimate speculation still has a place in scientific (and human) endeavour.

The sections dealing with music and its effects are most enlightening: the emotions generated by music, the choice of music for relaxation, the "wrong" music to accompany aerobic exercising, how a performer can project the inner meaning of music are some of the topics covered.

The final part of the book lists references to books, articles, records, cassettes, video tapes, etc. that are available on the subject.

Howard Pollard

NEW PUBLICATIONS —

The following publications have been received by the Society and are held, temporarily, in the Acoustics Laboratory, School of Physics, University of N.S.W. They are available for inspection or loan by members. Photocopies (not in contravention of copyright conditions) may be ordered by contacting Cronulla Secretarial Services on (03) 527-3173. A charge will be made for photocopying and postage.

JOURNALS

Canadian Acoustics V. 14 No. 1 Jan. 1986

Contents: **M. Morin,** Noise isolation standards in condominiums; **H. G. Pollard,** A proposal for sound testing prior to occupancy of multi-family dwellings.

V. 14 No. 2 Apr. 1986

Contents: **S. E. Semercigil, K. McLaughlan, N. Popplewell,** A non-contacting optical displacement transducer; **J. H. Rainer, G. Pernica;** Vertical dynamic forces from footsteps; **F. Ingerslev,** International co-operation in acoustics.

Applied Acoustics V. 19 Nos. 1, 2, 3 1986

Acta Acustica V. 11 No. 1 Jan 1986

(Text in Chinese, captions and summaries in English.)
Contents include **M. R. Schroeder,** Some new results of hearing research.

J. Aust. Assoc. Mus. Instr. Makers V. 5 Nos. 1, 2 1986

Contents include articles on violin making.

REPORTS

Quarterly Progress and Status Report

Dept. Speech Communication & Music Acoustics, Royal Institute of Technology, Stockholm.

Apr. 1986 *Contents:* **F. J. Lundin,** A study of speech intelligibility over a public address system; **M. Blomberg** et al, Some current projects at KTH related to speech recognition; **G. Plant,**

A single-transducer vibrotactile aid to lipreading; **G. Plant, A-M. Oster,** The effects of cochlea implantation on speech production — a case study; **G. Plant, K-E. Spens,** An experienced user of tactile information as a supplement to lipreading — an evaluation study; **N-E. Molin** et al, Parameters influencing eigenmodes of violin plates.

CSIRO Division of Building Research, P.O. Box 56, Highett 3190.
Progress of Research 1985-1986.

Institute of Sound and Vibration Research, University of Southampton — Technical Reports.
128 — **P. M. Clarkson,** The application of optimal control methods to the deconvolution of velocity meter signals.
129 — **J. Nedwell,** Acoustically compact transient sources for underwater measurement and calibration.
130 — **L. C. Chow, R. J. Pinnington,** On the prediction of loss factors due to squeeze film damping mechanisms.
131 — **R. C. N. Leung,** Power transmission of an idealised gearbox.

FILM

"The voice source as analysed by inverse filtering" — an instructional video tape by **J. Sundberg** et al.
This video tape demonstrates various aspects of phonation, as analysed by inverse filtering, a noninvasive, realtime method for studying the human voice source. Spoken comments in English; duration 19 min; available in various video formats.
Further details: The Music Acoustics Committee, Royal Academy of Music, Blasieholmstorg 8, S-111 48 Stockholm, Sweden.

Motor Vehicle and Traffic Noise Proceedings

The Proceedings of the 1985 Conference of the Australian Acoustical Society are now available for purchase. These Proceedings include the Keynote Paper by Dr. A. Alexandre, from the OECD, on "Strengthening Motor Vehicle Noise Abatement Policies". The other 28 contributed papers deal with the many aspects of traffic noise and the noise from different types of motor vehicles.

The cost of the Proceedings, including handling, packing and surface postage, is $35 (Aust.).

Orders and payments (to AAS NSW Division) should be sent to:

AAS 1985 Conference, AAS NSW Division, 35-43 Clarence Street, Sydney, NSW 2000

Golden Boomerang Award

Cochlear Pty. Ltd. one of the Nucleus group of Australian high-technology medical companies and makers of the cochlear implant developed by Professor Clark and Associates of Melbourne, was yesterday given the Golden Boomerang Award in recognition of its outstanding export performance.

The award was presented by the N.S.W. Export Development Group, in conjunction with the N.S.W. Chamber of Commerce, Austrade and sponsors, in Sydney. The prize replaces the 18-year-old Exporter of the Year Award.
(The Australian, 24 May 1986)

PUBLICATIONS BY AUSTRALIANS —

We are grateful to Richard Rosenberger, University of N.S.W., for this updating of publications by Australian authors. Within each year the listing is alphabetical by first author.

A Comparison of Three Speech Coding Strategies Using an Acoustic Model of a Cochlear Implant
B. J. BLAMEY, L. F. A. MARTIN, G. M. CLARK
Dept. of Otolaryngology, Univ. of Melb., The Royal Vic. Eye and Ear Hospital, 32 Gisborne Street, Vic. 3002
J. Acoust. Soc. Am. **77** (1), 209-217 (1985).

Response to a Reduction in Traffic Noise Exposure
A. L. BROWN, A. HALL, J. KYLELITTLE
School of Aust. Env. Studies, Griffith Univ., Nathan, Brisbane 4111
J. Sound. Vib. **98** (2), 235-246 (1985).

Reverberation Times in British Living Rooms
(1) M. A. BURGESS
(2) W. A. UTLEY
(1) School of Architecture, The Univ. of NSW, PO Box 1, Kensington 2033
(2) BRE, Building Res. Station, Garston, Watford WD2 7 JR, UK
Appl. Acoustics **8** 369-380 (1985).

The Use of Acoustic Pressure Measurements to Determine the Particle Motions Associated with the Low Order Acoustic Modes in Enclosures
K. P. BYRNE
School of Mech. & Ind. Eng., The Univ. of NSW, PO Box 1, Kensington, NSW 2033
J. Acoust. Soc. Am. **77** (2), 739-746 (1985).

Modal Filters in Rectangular Ducts
A. CABELLI, I. C. SHEPHERD, R. F. LA FONTAINE
CSIRO Div. of Energy Techn., Melbourne
J. Sound. Vib. **99** (2), 285-292 (1985).

Soil Impedance Measurements by an Acoustic Pulse Technique
C. G. DON, A. J. CRAMOND
Dept. of Appl. Phys., Chisholm Inst. of Techn., Vic. 3145
J. Acoust. Soc. Am. **77** (4), 1601-1609 (1985).

An Open Tube Technique for the Measurement of Acoustic Paramaters of Porous Absorbing Materials
J. I. DUNLOP
School of Phys., The Univ. of NSW, PO Box 1, Kensington 2033
J. Acoust. Soc. Am. **77** (6), 2173-2178 (1985).

The Future of Architectural Acoustics Research and Testing in Australia
F. FRICKE
Arch. Sci. Dept., Sydney Univ., Sydney 2006
Appl. Acoustics **18** (4), 283-292 (1985).

A Biological Chorus in Deep Water North-West of Australia
L. J. KELLY, D. J. KEWLEY, A. S. BURGESS
Dept. of Def. Weapons Syst. Res. Lab., Def. Res. Centre, Salisbury, SA 5108
J. Acoust. Soc. Am. **77** (2), 508-511 (1985).

Improved Computer Model of Direct-Radiator Loudspeaker
(1) I. C. SHEPHERD
(2) R. J. ALFREDSON
(1) CSIRO Div. of Energy Techn., PO Box 56, Highett, Vic. 3190
J. Audio Eng. Soc., **33** (5), 322-329 (1985).

News to I-INCE

The International Institute of Noise Control Engineering, of which the Australian Acoustical Society is a member, has recently requested information for their **Newsletter.** This is produced four times per year and they are seeking items of news on national laws and regulations, doctoral thesis work, current and future research projects and notes on research reports.

Send information to:
I-INCE Newsletter
Celest ijnenlaan 200D
B-3030 Heverlee-Leuven
Belgium

ADVERTISER INDEX

Bradford	ii
Bruel & Kjaer	Front cover
Chadwick	33
Davidson	55
Industrial Noise Control	32
Kell & Rigby	54
KH Stramit	42
Peace Engineering	42
Renhurst	30
Sound Attenuators	34

Readers are asked to mention this publication when replying to advertisements.

ADVERTISING RATES

Full page, black and white	$360
Full page, spot colour	$410
Half page, black and white	$235
Half page, spot colour	$285
Prepared insert, max. 4 pp.	$150
Column rate (for small ads) one-third p. width, per cm	$8

Special sizes

Page width, 5 cm high	$120
One-third p. width, 11 cm high	$90

Discount rates available for three consecutive ads and for sustaining members.

FUTURE EVENTS —

● Indicates an Australian Conference

1986

September 2-6, HUNGARY

6th FASE SYMPOSIUM.
"Subjective evaluation of objective acoustical phenomena."
Details: 6 FASE-Opt. Akuszt. Filmt., Anker-koz 1, H—1061, Budapest.

September 16-19, POLAND

XXXIII SEMINAR ON ACOUSTICS — CSA '86
Details: Zaklad Akustyki, Instytut Fizyki WSP, ul. Rejtana 16a, p. 228, 35 31C Rzeszow, Poland.

September 19-28, LONDON

ULTRASOUND SYMPOSIUM
Details: M. J. Ullman, Medical Seminars Int. Inc., 22135 Roscoe Blvd., Suite 104, Canoga Park, CA 91304, U.S.A.

● October 1-3, TOOWOOMBA

CONFERENCE ON COMMUNITY NOISE.
Details: Ms Nola Eddington, Division of Noise Abatement, 64-70 May Street, BRISBANE, Q. 4000.

October 7-9, THE HAGUE

2nd INTERNATIONAL SYMPOSIUM ON SHIPBOARD ACOUSTICS
Details: J. Buiten, Institute of Applied Physics TNO, P.O. Box 155, 2600 AD Delft, The Netheralnds.

October 7-10, BASEL

XIV AICB CONGRESS
Traffic Noise and Urban Planning
Details: Dr. W. Aecherli, Hirschenplatz 7, Luzern, Switzerland 6004.

● October 17-21, PERTH

16th ANNUAL MEETING OF AUST. SOC. FOR ULTRASOUND IN MEDICINE
Details: AUSM 16th Annual Meeting, P.O. Box 40, West Perth, W.A. 6005.

October 21-24, TOKYO

8th INTERNATIONAL ACOUSTIC EMISSION SYMPOSIUM.
Details: Prof. Dr. K. Yamaguchi, Institute of Industrial Science, University of Tokyo, 22.1 Roppongi-7, Minato-ku, TOKYO 106, JAPAN.

November 3-6, CZECHOSLOVAKIA

25th ACOUSTICAL CONFERENCE ON ULTRASOUND.
Details: House of Technology, Ing. Vani Skultetyho ul. 1 832 27 Bratislava.

November 17-19, WILLIAMSBURG, USA

ULTRASONICS SYMPOSIUM
Details: Inst. Elec. & Electronic Eng., Conference Cor-ordination, 345 E 47th St., New York, NY 10017, U.S.A.

December 8-12, CALIFORNIA

MEETING OF THE ACOUSTICAL SOCIETY OF AMERICA
Chairman: Alan H. Marsh, DyTec Engineering Inc., 5092 Tasman Drive, Huntington Beach, CA 92649, U.S.A.

December 8-12, HONG KONG

1st ASIAN PACIFIC CONFERENCE ON DEAFNESS
Details: Hong Kong Soc. of Deaf, 901 Duke of Windsor Social Serv. Bldg., 15 Hennessy Road, Hong Kong.

December 9-10, WEYMOUTH, U.K.

INTERN. CONF. ON FLUCTUATION PHENOMENA IN UNDERWATER ACOUSTICS
Details: Institute of Acoustics, 28 Chambers Street, Edinburgh, EH1 1HU.

1987

January 26-30, NEW ZEALAND

56th ANZAAS
"Science in a Changing Society".
Details: 56th ANZAAS, P.O. Box 5158, Palmerston North, New Zealand.

March 24-26, AACHEN

DAGA '87
Details: H. Kutruff, Inst. Technische Akustik der RWTH, Templergraben 55, D-5100 Aachen.

May 11-15, INDIANAPOLIS

MEETING OF ACOUSTICAL SOCIETY OF AMERICA
Details: Mrs. B. Goodfriend, A.S.A., 335 East 45th St., New York, NY 10017, U.S.A.

● May 20-27, MELBOURNE

MAINTENANCE ENGINEERING CONFERENCE 1987
"Effective Maintenance: the road to profit"
Details: Institution of Engineers, 11 National Circuit, Barton, A.C.T. 2600.

May 19-21, POLAND

INTERNATIONAL CONFERENCE.
"How to teach Acoustics."
Details: Prof. Dr. A. Sliwinski, University of Gdansk, Institute of Experimental Physics, 80 952 Gdansk, Wita Stwosza 57.

June 1-4, YUGOSLAVIA

XXXI ETAN CONFERENCE
Details: Prof. P. Pravica, Electrotechnical Faculty, Bulevar Revolucije 73, Belgrade, Yugoslavia 11000.

● June 17-19, BRISBANE

COMPUTING SYSTEMS CONFERENCE 1987
Details: Institution of Engineers, 11 National Circuit, Barton, A.C.T. 2600.

June 19, MADRID

ACOUSTICS AND OCEAN BOTTOM
Details: SEA - FASE 87, Calle Serrano, 144, Madrid 6, Spain.

June 23-25, LISBON

5th FASE CONGRESS
Details: SPA - FASE 87, Lab. Nac Engenharia Civil, Av. Brasil, 1799 Lisboa Codex, Portugal.

July, ANTWERP, BELGIUM

15-25, SUMMER SCHOOL ON INTERNAL FRICTION PROCESSES.
27-30, CONFERENCE ON INTERNAL FRICTION AND ULTRASONIC ATTENUATION IN SOLIDS.
Details: R. de Batist, S.C.K. — C.E.N., Boeretang 200, 2400 MOL, Belgium.

August 24-28, U.S.S.R.

11th INTER. SYMPOSIUM ON NON-LINEAR ACOUSTICS
Details: V. K. Kedrinskii, Lavrentyev Institute of Hydrodynamics, Lavrentyev Prospekt 15, 630090 Novosibirsk.

September 15-17, CHINA

INTER-NOISE 87
"Noise Control in Industry".
Details: Inter-Noise 87, 5 Zhonggvancun St., P.O. Box 2712, Beijing, China.

September, BIRMINGHAM, U.K.

CONFERENCE OF BRITISH SOCIETY OF AUDIOLOGY
Details: Mr. N. Bland, 14 Bryony Road, Weoley Hill, Birmingham B29 4BU.

November 16-20, MIAMI

MEETING OF ACOUSTICAL SOCIETY OF AMERICA
Details: Mrs. B. Goodfrend, A.S.A., 335 East 45th St., New York, NY 10017, U.S.A.

1988

May 16-20, SEATTLE

MEETING OF ACOUSTICAL SOCIETY OF AMERICA
Details: Mrs. B. Goodfriend, A.S.A., 335 East 45th St., New York, NY 10017, U.S.A.

August 21-25, STOCKHOLM

5th INTER. CONGRESS ON NOISE AS A PUBLIC HEALTH PROBLEM
Details: Noise '88, C/- Reso Congress Service, S-113 92 Stockholm.

August 29 - September 1, EDINBURGH

7th FASE SYMPOSIUM ON SPEECH
Details: Mrs. C. Mackenzie, I.O. Acoustics, 25 Chambers St., Edinburgh, EH1 1HU, Scotland.

AUSTRALIAN ACOUSTICAL SOCIETY

DIVISIONAL COMMITTEES

(* Indicates Councillor)

	New South Wales	*Victoria*	*South Australia*	*Western Australia*	*Queensland*
Chairman	Serge Hlistunov	Stephen Samuels*	David Bies*	Giafranco Rasile*	Robert Hooker*
Vice-Chairman	Peter Knowland	Jim Watson	Robert Boyce*	Peter Wilkins	Ronald Rumble
Secretary	Tony Hewett*	John Modra	Adrian Jones	Lynn Kirkham	Noela Eddington
Treasurer	John Mazlin	Geoff Barnes	Ken Martin	John Spillman	Will Tonisson
	Graeme Atkins	Sin Chan	John Lambert	Ian Bailey	A. Lex Brown
	Anita Lawrence*	Graeme Harding*	Max Lane	Pamela Gunn	A. Russ. Brown
	Ray Piesse	Robert Monteith	Peter Swift	Marie Kormendy	Fritz Kamst
	Jack Rose	David Rennison		Tibor Vass*	Warren Middleton
	Colin Tickell	Charles Rossiter		Peter Wilkins	Warren Renew*
	Andrew Zelnilc	John Upton		Graeme Yates	Ron Windebank

ADDRESSES: All correspondence on NATIONAL matters should be addressed to the General Secretary.
All correspondence on REGIONAL matters should be addressed to the appropriate Division Secretary.

General Secretary
A.A.S.—General Secretary
Science Centre
35 Clarence Street
Sydney, N.S.W. 2000

New South Wales
A.A.S.—N.S.W. Division
Science Centre
35 Clarence Street
Sydney, N.S.W. 2000

Victoria
A.A.S.—Victoria Division
National Science Centre
191 Royal Parade
Parkville, Vic. 3052

South Australia
A. D. Jones
Nat. Exhaust Ind.
29 Morrow Road
O'Sullivan Beach, S.A. 5166

Western Australia
L. Kirkham
Dept. Mech. Eng.
Univ. W.A.
Nedlands, W.A. 6009

Queensland
A.A.S.—Qld. Division
C/- Div. Noise Abatement
64-70 Mary Street
Brisbane, Qld. 4000

SUSTAINING MEMBERS

AQ-VIB DIVN. OF AQUA-COOL TOWERS PTY. LTD.
UNIT 7, 2 STANTON ROAD
SEVEN HILLS 2147

ASSOCIATION OF AUSTRALIAN ACOUSTICAL CONSULTANTS
C/- SCIENCE CENTRE
35 CLARENCE STREET
SYDNEY, N.S.W. 2000

AUSTRALIAN GYPSUM LTD.
G.P.O. BOX 4325
MELBOURNE 3001

BRADFORD INSULATION, C.S.R. LTD.
7-9 PERCY STREET
AUBURN 2144

BRUEL & KJAER (AUST.) PTY. LTD.
P.O. BOX 120
CONCORD 2137

CMA FOAM GROUP
1 HEATHCOTE ROAD
LIVERPOOL, N.S.W. 2170

THE CHADWICK GROUP
292 BURNS BAY ROAD
LANE COVE 2066

FOAMLITE AUSTRALIA PTY. LTD.
P.O. BOX 331
SUNNYBANK, QLD. 4109

INDUSTRIAL NOISE CONTROL PTY. LTD.
7 LEVANSWELL ROAD
MOORABBIN, VIC. 3189

JAMES HARDIE INDUSTRIES LTD.
G.P.O. BOX 3935
SYDNEY 2001

JOHN LYSAGHT (AUST.) LTD.
P.O. BOX 77
PORT KEMBLA, N.S.W. 2505

NAP SILENTFLO PTY. LTD.
P.O. BOX 173
CLAYTON, VIC. 3168

PEACE ENGINEERING PTY. LTD.
UNIT 2/20 MARIGOLD STREET
REVESBY, N.S.W. 2212

PITSTOCK PTY. LTD.
ACOUSTICS DIVISION
5-15 COTTAM AVENUE
BANKSTOWN, N.S.W. 2200

SOUND ATTENUATORS AUSTRALIA
P.O. BOX 269
DRUMMOYNE, N.S.W. 2047

SOUNDGUARD PTY. LTD.
P.O. BOX 246
RYDALMERE, N.S.W. 2116

K. H. STRAMIT LTD.
52 MANDOON ROAD
GIRRAWEEN 2145