Acoustics Australia

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Chaos in Acoustics **Condition Monitoring** **Timbre Assessment**

Acoustics Australia

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This will be the final change for some time.

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Business Manager

Acoustics Australia

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COVER . . . Example of a strange attractor as described in the article "Nonlinearity and Chaos in Acoustics" by Fletcher et al.

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LYNWOOD 6155

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Student $36

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Publications Officer
Australian Acoustical Society
15 Taylors Road, DURAL 2158

NEWS

ACT

November Meeting

On 1 November, **Dr Bob Perrin** from the Dept of Physics, Loughborough University of Technology, UK, and Consultant to J Taylor & Co, Bellfounders, spoke on "Why Bells Sound the Way They Do". Over 20 attended the talk, including some from the local bell ringers group.

Bob explained that bell-founding remains a *Black Art* despite efforts by himself and his colleagues, over a period of 20 years, as scientific consultants to the largest remaining practitioners in Britain. He described some of the surviving medieval practices and introduced the quaint jargon of the industry.

The geometries of various modern bells were discussed together with their normal modes of vibration and hence their musical qualities. Comparisons were made with the characteristics of hand bells. Recordings of English church bells being tolled and change-rung were included plus, for comparison, Russian church bells being rung in their local style.

February Meeting

On 20 February a group of 18 toured the Civil Aviation Authority Laboratories which have only recently been completed. **Colin Gray,** the Manager of the Measurement Laboratory, gave a short explanation of the range of investigations undertaken which have included sonic boom measurements, noise certification tests and follow up of complaints.

The group was then taken on a tour of the various areas and Colin was assisted by **Bob Lam,** who conducted one group. The storage and retrieval of data are vitally important to a calibration laboratory, so this information is filed in the Data Storage Room which is located adjacent to the Data Analysis Room. Here the procedure for digital storage of the acoustic data for an aircraft flyover and subsequent determination of the descriptors, EPNL, etc, was explained. The reverberation time of the room, which can be used for tests on the intelligibility of signals, can be changed by the placement of curtains and floor covering. A tape which highlighted the difficulties in understanding speech with a translation error of approx 300 Hz and for an AM transmission with high background noise was played. The Anechoic Chamber, with internal dimensions of the order of 3.5 m, is available for investigations requiring such a controlled acoustic environment. The other areas visited included the screened RF Room, the Electrical and Acoustic Calibration Rooms as well as the Electrical and Acoustic Standards Rooms.

The group was then taken to the special acoustic room in the Communications Laboratory of the Department of Transport and Communications. **Max Peace** explained the use of the room for testing broadcast systems. **Eric Taylor,** who was consultant for the acoustic design of the room, summarised the criteria for which the room was designed and described the various types of absorbers which were used to obtain the required reverberation time over the frequency range.

The tour was most interesting and showed the range of work undertaken by the staff at the Laboratory. Over half of the group enjoyed a Thai Banquet at a nearby restaurant after the meeting.

Marion Burgess

NSW

November Meeting

The Technical Meeting on 23 November 1989 was held at the National Acoustics Laboratories, Chatswood, and took the form of a Symposium on the recent Worksafe Publication "Discussion Paper with Options for a National Standard on Occupational Noise, and Draft National Code of Practice". It preceded the Annual General Meeting of the Society. About 40 people representing industry, research, consultants and occupational health workers attended the Symposium which had speakers from the various groups involved with preparation of the document. President of the AAS, **Bob Boyce,** who was a member of the working party preparing the document, explained the method in which it was prepared and those involved.

A representative of Worksafe further explained the tripartite arrangement of government, employers and union representatives in the committee working on occupational noise and the background of the document. The eventual aim is for regulations under the various State Occupational Health and Safety Acts to specify approved codes of Practice as the required method of hearing conservation in Industry.

A representative of the Standards Association of Australia presented their view that the regulations should not include technical details such as methods of measurement and assessment, those should be the role of standards and the regulations specify limits or levels to be achieved.

Following the speakers there followed a lively discussion with many of those attending participating. Items discussed included such things as:

- Over 50% of the workforce involved in noisy industries are employed in businesses with less than 50 employees and these businesses usually do not have the resources to implement a hearing conservation program.
- Statistics from court cases on workers' compensation for noise-induced hearing loss suggest that either there are many people susceptible to hearing loss at sound levels less than 90 dB(A) or the existing regulations are not being implemented as required.
- Management needs to enforce wearing of hearing protection more than currently occurs.
- What is the effect of different weighting times of instruments given that the current 90 dB(A) limit for eight hours was developed from studies made some decades ago using analogue meters with "slow" response.
- There is a confusion in the document of level versus dose versus exposure. The requirement to use competent technical people to assess sound levels was not noted in the document.
- Workers' compensation for hearing loss is not currently a high priority item because it is not a lost time injury. The costs should be compared with costs of other workers' compensation losses.
- There is a problem in using audiometric test results as a feedback tool for hearing conservation programs and determining individual susceptibility as the Unions hold that they are medical records and can't identify those individuals with hearing loss to an employer.
- Some larger employers have implemented hearing conservation programs and regular audiometric testing but they need the support of unions in getting employees to wear hearing protection in high noise level areas.

Eric LePage of NAL commented that research is showing there is a variation in the function of the ear for impact noise and continuous noise. There is evidence of damage to hair cells being caused at impact levels of 129 dBL. Audiometric testing does not indicate the actual performance of the ear and there can be a loss of performance without it showing on an audiogram. There is a need to measure the susceptibility of individuals to hearing damage so that they can be encouraged to take care and wear hearing protection when appropriate — NAL is currently working on a test method for this assessment of individual susceptibility.

The symposium was followed by the Annual General Meeting of the Australian Acoustical Society.

Colin Tickell

* * *

Coming Events

Don Woolford will be presenting a technical meeting for the NSW Division in late April on hearing impairment to performance of music.

* * *

The NSW Division wishes to announce its Excellence in Acoustics Awards 1990 to be presented at a special function later this year. The Awards inaugurated in 1988 were established to promote and stimulate the pursuit of excellence in the broad and exciting field of acoustics. By now all members of the Society should have received a brochure outlining details of the Awards and featuring details of the 1988 Awards winners and highly commended entries. All those wishing to enter should hurry as confirmation is required in writing by Monday, 30th April. The closing date for submission of entries is Monday, July 2nd. For further information and correspondence enquiries should be directed to Science Centre Foundation, Private Bag No 1, Darlinghurst NSW 2010. Phone: (02) 331 6920.

Andrew Zeinik.

QUEENSLAND

September Meeting and AGM

Mr Daniel Fournier presented an enlightening talk on the "Sound Recording Studios" of the Queensland Conservation of Music preceding the Annual General Meeting of the Division on 29 September 1989. The meeting was attended by 22 members and friends who enjoyed the talk by Mr Fournier, who is a Senior Lecturer in Music Technology.

December Technical Meetings

On 6 December approximately 18 attended a technical discussion meeting. The topics included reverberation chambers and impedance tubes and the discussions were led by **Ron Rumble, Warren Renew** and **Assoc Prof Bob Hooker.**

A social meeting was held at the home of **Bob** and **Joyce Hooker** as a completion of the year's activities. Over 20 guests enjoyed the convivial and relaxed atmosphere associated with wining, dining, chatting and even swimming.

WESTPAC IV Planning

The planning for **WESTPAC IV** is proceeding and information on the Conference and Call for Papers will be issued shortly. The Conference will be held at Griffith University, Brisbane, 26-28 November 1991. The Queensland Division of the Society, in conjunction with the Queensland State Government, Department of the Environment, is coordinating this Conference.

Warren Middleton

VICTORIA

November Meeting

The November meeting of the Victoria Division was held at the ABC Radio Studios, Lonsdale Street, Melbourne. **Donald Woolford** addressed the meeting on the subject "ACOUSTICS — the Basis of Sound Broadcasting and Recording". Donald is a senior professional engineer with the ABC in Sydney and spoke on the importance of psychoacoustics in broadcasting.

The AM broadcasting system is an extremely limited system with approximately 5 dB dynamic range and a severely restricted frequency range. The frequency range on the best car radio system seldom extends beyond 2.5 kHz.

The recording engineer must adjust the sound to enhance the listener's perception of the sound he is hearing from the receiver. Two different systems are used by the ABC in Melbourne, 3AR (Radio National) uses a compeller or compressor/expander system while 3LO uses the Optimod System. The Optimod optimises the sound over six octaves. The engineer basically "flies by the seat of his pants" using his experience to set the equipment to what he believes is the best result for the listener. The difference between the two systems can be heard between 6 and 7 pm when "PM" is broadcast on both stations. The difference is substantial.

Donald's talk was followed by a demonstration by Ross Smith of some recordings with and without the Optimod system.

Those who thought they would tune to FM to hear full sound will be disappointed. The ABC found soon after beginning broadcasting on FM that either the quieter passages of music were being lost in the background sound around most receivers or the louder parts blasted the listener out of the room. To overcome this problem some optimisation had to be introduced.

End of Year Function

The end of year function of the Victoria Division was held at Monash University. **Robin Alfredson** addressed the group on the design of pipe organs before giving a short recital on the organ in the Monash Religious Centre. Robin chose a variety of music to demonstrate the acoustics of the organ.

The recital was followed by dinner at the University Club. A pleasant evening was enjoyed by all present.

Student Awards

The **H Vivian Taylor Memorial Prize** for excellence in studies in the field of acoustics has been awarded to a student at each of the three participating institutions. The recipients are: Cornelius Huybregts from Royal Melbourne Institute of Technology, Jason Grant from Chisholm Institute of Technology and Donna Bennetts from Monash University.

Each of the recipients will receive a cash prize of $150, one year's student membership to the Society and a certificate.

Mike Snell

Call for Papers

1990 International Conference on Spoken Language Processing, 18-22 November, 1990, KOBE, JAPAN.

This will be the first international conference on spoken language processing by both humans and machines covering broad aspects from basic research to applications. It will be held at the International Conference Centre in Kobe, Japan. Abstracts of proposed papers must be received before 30 April 1990.

Further details: Secretariat, ICSLP-90, c/- Simul International Inc, Kowa Building No 9, 1-8-10 Akasaka, Minato-ku, Tokyo, 107 Japan.

Council Activities

The 43rd and 44th meetings of Council were held in Sydney on 23rd and 24th November 1989 respectively. The 43rd meeting was presided over by Mr R Boyce who had completed two years as President of the Society following five years as General Secretary. Office bearers for 1990 including the *new President, Dr S E Samuels* were elected at the 44th meeting.

- **Membership**

At the time of the Council meeting, Society membership was 396 which is higher than it has been for several years. Applications rose by 33 per cent and 32 new members were admitted. The Council Standing Committee on Membership chaired by *Mr Ken Cook* and assisted by *Mr Bill Davern* and *Dr John Davey* elevated 18 applicants to Member grade, one to Affiliate grade and four to Student grade during the year. Fifteen members were removed from the Register for various reasons.

- **Student Membership**

In response to a submission from the Victoria Division, Council recommended Divisions encourage students to join the Society by offering *free membership* particularly to full time undergraduates.

- **Retired Members**

Council considered a suggestion from the NSW Division that the annual subscription for retired members be reduced to the amount paid by Student members. Since the Articles of Association give authority only to the Divisions to do this, council recommended they reduce the subscription as suggested on application from individual members.

- **Fellows**

Council was disappointed that there had been no further elevations to Fellow grade. It would like to see Divisions active in developing new proposals.

- **1990 Budget**

Council is expecting to spend approxiately $30,000 during the financial year 1989-1990. This is a little over $3,000 more than the previous year and includes increased allowances for travel ($5,100) and expenditure on printing the Directory ($1,920) and Articles of Association ($1,500) and the Presidents Prize for the best annual conference paper ($1,000).

Estimated expenditure on the production of Acoustics Australia ($9,000), secretarial services ($7,700) and other recurring items (subscriptions to FASTS and IINCE $2,000, insurance $400 and registered office fees and accountancy $1,000), remain almost the same as in the previous year. It is worthy of note that the cost of producing Acoustics Australia has not varied significantly over several years. The main reasons for this are due to the editors and particularly to the more cost effective service provided by the printers for which the Society is extremely grateful.

- **Annual Subscriptions**

Council has increased annual membership subscriptions for 1990 to —

Fellow and Members — $61
Affiliates and Subscribers — $49
Students — $36.

These increases are slightly less than the CPI weighted average of the eight capital cities of 7.6 per cent for 1988-1989.

- **Technical Video Library**

Council strongly supported a proposal from the Queensland Division to establish a library of video tapes of a technical nature. It is expected that such a library would give members easier access to technical talks, displays of acoustical designs etc. The Queensland Division has been asked to commence work on the project.

- **Research and Education**

During the year the Society forwarded a submission to the Committee to Review Higher Education Research Policy.

The future of acoustics in the Faculty of Architecture at the University of NSW came under review following the retirement of Associate Professor Anita Lawrence from teaching. Council made strong representations in support of continuation of courses in acoustics.

- **History of Acoustics**

Dr Ferg Fricke has written to Council suggesting that the experiences and memories of people who have retired from acoustics should be recorded before they are lost. Council supported the idea and is considering the necessary action and funding.

- **Ties and Scarves**

All Divisions will have ties and scarves displaying the Society logo for sale in April this year.

Ray Piesse
General Secretary.

Association of Noise Control Engineering

Companies throughout Australia engaged in noise control engineering have united together and formed the Association of Noise Control Engineering.

On 17 March 1989 **Mr Geoff Barnes** of Acoustical Design convened the inaugural meeting attended by representatives from noise control companies. Geoff spoke on the many benefits to be gained by an Association of Member Companies. Companies pledged their support and proceeded to elect the following committee:

President: Geoff Barnes
Vice-President: Warwick Smith
Secretary: Keith Porter
Treasurer: Frank Muscroft
Publicity Officer: Keith Porter

The Association's objectives are:

(a) To assist in developing a high standard of technical excellence throughout the industry.
(b) to assist in maintaining professional integrity by its members to safeguard the interests of their clients and the public.
(c) To institute a Code of Ethics and to support those members acting in accordance with the Code.
(d) Development of Community, Government and Industry awareness of the noise control engineering profession.
(e) To create a united voice on issues affecting the noise control industry.
(f) Keeping members informed on new technologies, standards and regulations.
(g) To make tertiary institutions aware of the needs of the industry and to encourage and foster tertiary students into our profession.

Companies involved in the business of noise control engineering and/or the supply of goods and services to the industry and wishing to become members or associate members may obtain further information by writing to:

The Secretary
Association of Noise Control Engineering
PO Box 14
Moorabbin, Vic 3189

INTER-NOISE 90

INTER-NOISE 90, the 1990 International Conference on Noise Control Engineering, will be held on 13-15 August 1990 at the Chalmers University of Technology in Gothenburg, Sweden. Gothenburg is situated on the beautiful west coast of Sweden. The city is centrally located in Scandinavia at about equal distances from Copenhagen, Oslo and Stockholm, and is Sweden's industrial centre. With good meeting facilities, special hotel arrangements and an exciting social program, Gothenburg is an ideal place for the INTER-NOISE 90 conference.

INTER-NOISE 90 is the 19th in a series of international conferences on noise control engineering that have been held world-wide since 1972. The theme of INTER-NOISE 90 is "Science for Silence". The conference is sponsored by the Institute of Noise Control Engineering and is being organised by the Swedish Acoustical Society.

Tor Kihlman of Chalmers University of Technology is the General Chairman and Hans Jonasson of the Swedish National Testing Institute is the Technical Program Chairman. Mendel Kleiner of Chalmers University is the Secretary-General.

A major equipment, materials and instrument exhibition will be held in conjunction with INTER-NOISE 90. The exhibition will include acoustical materials and devices for noise control as well as noise control instruments such as sound level meters, noise monitoring equipment, sound intensity apparatus, acoustical signal processing systems and equipment for active noise control. There will also be an exhibition of silent products and quiet workplaces.

Several specialised noise control symposia will be held before the conference and summaries will be presented as papers at the conference.

A separate international tyre/road noise conference will be held in Gothenburg during the week preceding INTER-NOISE 90.

Further information from: INTER-NOISE 90, Chalmers University of Technology, S-41296 Gothenburg, Sweden. Tel: INT 4631722211, Fax INT 4631722212.

FASTS Meeting

The Federation of Australian Scientific and Technological Societies (FASTS) Council, AGM and Policy Forum Meetings were held on 1 November 1989 at the National Science and Technology Centre, Canberra. About 60 attended despite transport difficulties.

In FASTS the member Societies are grouped, with each group having one Board member. The AAS is in the Physical Sciences Group along with the Astronomical Society, Society of Crystallographers, Microscopical Society, Optical Society, Institute of Physics, Solar Physics Association and the Society for Electron Microscopy. The new Board member for this group is **Prof Ron MacDonald** from the University of Newcastle and nominated by the Australian Institute of Physics.

The new President for FASTS is **Prof Tony Wicken** from University of NSW and the two Vice-Presidents are **Judy Hammond** and **Angela Delves.**

The retiring President, Frank Larkins, summarised the achievements of FASTS over the last two years. He stated that FASTS has been instrumental in putting science and technology back on the political agenda but now the challenge is to maintain the momentum into the future. While there have been many contributions by FASTS, in the form of press releases, delegations to government submissions to committees of enquiry and services to member societies the following are considered achievements in which FASTS played a major role:

- the establishment of the Prime Minister's Science Council.
- a comprehensive Science and Technology policy passed by the ACTU at its September 1989 Congress.
- a National Career Fellowship Scheme aimed at holding younger experienced researchers in Australia.
- improvements in Commonwealth Post-Graduate Awards both in the number available and in the size of the stipends.
- a comprehensive report on teacher education in Mathematics and Science.
- a strengthening of the role of active researchers in S&T policy development in the Australian Research Council.
- FASTS has lobbied for the retention of the 150% tax incentive for R&D.
- FASTS has consistently raised the issues in school education in mathematics, science and technology by providing opportunities for public statements.

Following the Treasurer's report, which stated that the finances are in a stable although tight situation, the policy forum commenced. The first three topics addressed were government S&T policy, industry policy and public sector research agencies. Each topic led to lively discussion and suggestions for the involvement of FASTS over the coming years. It was agreed by all that both the government and industry desperately needed to have a long-term view to science, technology and research. After lunch the two topics for the policy forum were school education and tertiary entry then tertiary education and careers. The perceived lack of a clearly defined career structure for researchers was considered to be an important reason for the reduction in good quality students undertaking Science courses.

Marion Burgess

People

NEW MEMBERS

New Members

- **Interim 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.

New South Wales
Mr J C Gray (ACT), Mr Wu Qunli.

Victoria
Mr D M Edwards.

- **Graded**

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

Affiliate

South Australia
Mr D L Hywood.

Victoria
Mr J Vestergaard.

Student

New South Wales
Mr J Alekna, Mr C McKeith.

Subscriber

New South Wales
Mr G A Haigh.

Victoria
Mr P Barker.

Member

New South Wales
Mr G S J Glazier.

Victoria
Dr K S Jraiw.

* * *

Congratulations to **Dr Neville Fletcher AM** for being awarded Member of the Order of Australia (AM) in the Australia Day Honours List. The award was made for Neville's "service to science particularly in applied science". The President and members of the Australian Acoustical Society join in congratulating Neville for a fitting award for a distinguished career in science.

* * *

Anita Lawrence has retired from her position as Associate Professor in the School of the Built Environment at the University of NSW. She will still be in contact with the academic world as a Visiting Professor to the Faculty of Architecture. The first activity for her retirement is a long sea journey followed by travel in UK and Europe.

* * *

On 1 July 1989 the parent company of the Vipac Group changed from a private company to become an Unlisted Public Company. The new name for the company is **Vipac Engineers & Scientists.**

* * *

More News on page 31

Nonlinearity and Chaos in Acoustics

Neville Fletcher*, Robert Perrin† and Katherine Legge‡
Acoustics and Vibration Centre
Australian Defence Force Academy
Campbell, ACT 2601

ABSTRACT: A brief survey is given of the nature of nonlinearity and the transition to chaotic behaviour in vibrating systems of interest in acoustics. Chaotic behaviour is illustrated by considering the response of a circular plate or thin axisymmetric shell excited sinusoidally at its centre. Chaos sets in at an unexpectedly small amplitude and leads to large excitation of non-driven modes. Some practical implications are considered.

1. INTRODUCTION

If there is one development in basic understanding that, over the past ten years, has had greater impact than any other on the way we look at physical phenomena, then it is the theory of nonlinear and chaotic phenomena. Along with its associates, catastrophe theory and fractal geometry, it is one of the most exciting areas of research today in a whole range of classical areas of study such as mathematics, mechanics, acoustics and fluid dynamics, and it is beginning to penetrate into the world of quantum phenomena. There was a special section on acoustic chaos at the 13th ICA in 1989, a major conference on more general aspects of chaos was held in Sydney early this year, and we even read about the subject in the weekend newspapers!

It is not possible, in an article as short as this, to give any extensive discussion of either chaos theory or its implications. What we have tried to do, therefore, is to give an outline of the basic background, and to illustrate it with some examples from our own experience of the chaotic behaviour of a vibrating panel. Not only is this potentially simple enough to understand in detail — though we are as yet a good way from such understanding — but it has important applications in the real world of acoustics and vibrations. For those who wish to delve deeper, we recommend the popular non-technical book by Gleick [1] and the extensive set of more technical papers edited by Cvitanovic [2]. There have also been numerous articles on chaos and fractal geometry in the pages of Scientific American.

2. NONLINEARITY

A physical system is linear if its response amplitude is proportional to the stimulus amplitude, all other things being kept constant. A simple linear spring (extension proportional to applied force) is a familiar example, but linearity is assumed in mechanics (force ∝ acceleration) and in electric phenomena (Ohm's law). Predictions of system behaviour based on such linear assumptions generally work well provided we do not depart too far from equilibrium, but for extreme cases a linear theory is inadequate — springs unwind, beams buckle, resistors get hot.

In acoustics and ordinary vibration applications we are generally in a domain where linear theory is adequate, though there are exceptions for such things as the sound production mechanism of musical instruments [3]. Nonlinearity is more noticeable when the pressure amplitude of a sound wave becomes appreciable in comparison with normal atmospheric pressure, say greater than 10 kPa or about 174 dB, as in an explosion or a lightning flash or the passage of an aircraft at supersonic speed. Then the temperature of the air in the pressure crests rises significantly relative to that in the troughs, which falls similarly. Because sound travels more quickly at higher temperatures, this leads to distortion of the pressure wave to an N-shaped shock wave.

The nonlinearity with which we shall be concerned here, however, is of a much less extreme variety, and concerns only the gradual stiffening of various types of springs as their deflection is increased. This is illustrated in Figure 1. This sort of behaviour is found in many ordinary springs, and also in the sideways deflection of plates, in which a tension force builds up to assist the stiffness arising from simple bending. If f is the distorting force and x the spring deflection, then this type of behaviour can be written

$$f = ax + bx^3 \qquad (1)$$

where a is the normal spring stiffness and b/a measures the severity of the nonlinearity. There are, of course, many more complex forms of nonlinearity than that shown in equation (1); the deflection of a slightly dished plate, for example, requires the addition of a term in x^2.

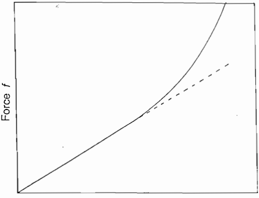

Figure 1: Behaviour of a stiffening spring, as in equation (1).

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† *Permanent address:* Department of Physics, Loughborough University of Technology, Loughborough, Leicestershire, England

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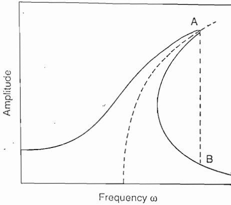

Figure 2: Nonlinear resonance curve, as described by equation (3) with $\alpha = 0$.

If we think of the motion of a simple loaded spring with stiffness given by (1), acted on by a sinusoidal force f sin ωt, then this motion is described by the equation

$$m\ddot{x} + r\dot{x} + ax + bx^3 = f \sin \omega t \quad (2)$$

where m is the loading mass and r is the viscous damping. Dots signify differentiation with respect to time, so that $\dot{x}$ is velocity and $\ddot{x}$ is acceleration. If we plot the amplitude response of this system as the frequency ω is varied, then we get the distorted resonance curve shown in Figure 2, the small-amplitude resonance frequency being $\omega_0 = (a/m)^{1/2}$. The amount of distortion is proportional to the nonlinearity b/a. It is convenient to simplify equation (2) by dividing by m and changing the unit of time to $\tau \equiv \omega_0 t$ so that it can be written

$$\ddot{x} + k\dot{x} + x + \alpha x^2 + \beta x^3 = F \sin \Omega\tau \quad (3)$$

where $k = r/m\omega_0$, $\beta = b/a$, $F = f/a$, and $\Omega = \omega/\omega_0$ is the ratio of the driving frequency to the small-amplitude resonance frequency. A quadratic term αx^2 has been added for generality. The parameter k is called the damping coefficient and is the reciprocal of the quality factor Q. Equation (3) is closely related to the Duffing equation, which has both the linear and quadratic terms omitted, so that the restoring force is simply βx^3. The Duffing equation is nonlinear at all amplitudes and has been extensively studied.

We can hear the effects of this nonlinearity quite easily with a rather loose metal string on a musical instrument such as a guitar. If we pluck the string to large amplitude, rather than exciting it with a sinusoidal force, then its oscillation decays along the spine of the curve, shown as a broken line in Figure 2, and the sound dies away with a twang as the pitch falls. Experiments with sinusoidal excitation of such a metal string show that we can have a sudden fall in amplitude from point A to point B if we slowly increase the frequency ω while keeping the force f constant. This is an elementary example of a catastrophe — a large change in some physical result (the amplitude) for a very small change in the excitation (the frequency in this case) near a critical point A. Catastrophe theory deals with more general features of this sort of behaviour.

3. ORBITS AND ATTRACTORS

We are used to looking at oscillatory phenomena in two complementary ways — either we examine the waveform with an oscilloscope, or we look at the frequency spectrum using, for example, an FFT (Fast Fourier Transform) analyser. These two approaches, provided we record the phases of the spectral components, give us exactly the same information, and one representation can be derived from the other mathematically.

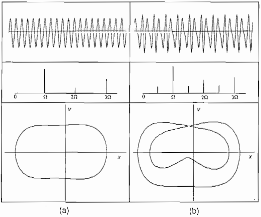

Figure 3: (a) Waveform, spectrum and orbit in phase space for a nearly sinusoidal solution of equation (3) corresponding to a slightly dished plate with $k = 0.02$, $\alpha = 0.3$, $\beta = 0.1$, $\Omega = 2$, $F = 12$; (b) bifurcation and generation of a subharmonic of order 2 for the same system with $F = 20$.

For discussions of chaotic behaviour, it turns out that a rather different representation is also useful. The time behaviour of a vibrating system can be described by giving the value of its displacement x at all times t, but it can also be described if we know the displacement x and the velocity $v = \dot{x}$, which is just the slope of the x(t) waveform, at every point. We can then describe the behaviour by plotting the motion of the point representing the system on a graph in which the axes are x and v. If the waveform is repetitive, then the curve in (x,v) space, which is called phase space, is a closed orbit which repeats itself in every cycle of the motion. This is illustrated in Figure 3a for a nearly sinusoidal wave, such as would arise from solution of a particular case of equation (3) at rather small amplitude. If the wave were exactly sinusoidal then the curve would be an ellipse. There is actually a value of the time parameter t or τ associated with every point on the orbit, and we will need to know this later.

A simple repetitive wave represents a steady state but, if we apply a sinusoidal force to a system, it takes an appreciable time to settle down. This approach to a steady state can be represented in phase space, as well as in the (x,t) time domain seen on an oscilloscope. Figure 4a shows what happens for an arbitrary starting condition — the initial orbit can begin anywhere in phase space, but it is "attracted" towards the final stable orbit and eventually coincides with it. The stable orbit is then called an attractor for this particular motion. If the exciting force is zero, then the attractor is simply the point $x = 0$, $v = 0$, as in Figure 4b.

To further simplify the presentation it is useful to employ a device introduced by the French mathematician Poincaré, and hence called a Poincaré section. The easiest way to think of this is to recognise that we are dealing with a system driven by a regular sinusoidal force, according to equation (3). The time scale is thus fixed by this external force, and we can imagine taking a flash photograph of the phase space just once in each cycle, at a fixed phase of the external force, and plotting the position of the point representing the system response. Once we are on the stable orbit, this always shows up as a single point on the section, while the behaviour of the system in approaching the steady state shows up as a sequence of points steadily approaching this limit point.

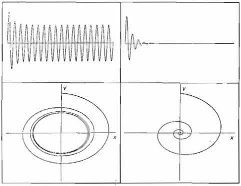

Figure 4: (a) Approach to the steady state, showing a periodic attractor orbit; (b) the same, showing a point attractor.

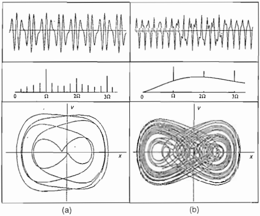

Figure 5: (a) Subharmonic splitting of order 5 for the system of Figure 3(a) with F = 12; (b) chaotic behaviour for the same system with Ω = 1, F = 23.

4. BIFURCATIONS AND STRANGE ATTRACTORS

All this is quite straightforward and introduces nothing unexpected. It is possible to calculate the approach of the system to its attractor by simply integrating the equation (3) from its given starting conditions. With a modern desk-top microcomputer this takes only a few seconds. However, playing around with such calculations soon turns up some very strange behaviour. Actually it was found first for even simpler equations, but the generalised Duffing equation (3) is most suited to our discussion here. The first thing to be discovered is that, for particular values of the relative frequency Ω and force amplitude F, the orbit doubles, or bifurcates. This shows up as a period doubling on the waveform display, a subharmonic of order 2 on the frequency spectrum, or a double orbit in phase space, as illustrated in Figure 3b. This phenomenon appears on the Poincaré section as two point attractors, which we have not bothered to illustrate.

Even this bifurcation behaviour is easy to accommodate among our usual ideas — it is simply the nonlinear driving of the mode at half the driving frequency, and occurs most easily when the driving frequency is about twice the free mode frequency. The other components in the spectrum in Figure 3b then simply arise as nonlinear distortion products. Rather surprisingly, however, an increase in the force amplitude or a decrease in the damping sometimes leads to further bifurcations, giving subharmonics of order 4, 8, and so on. Feigenbaum [2] has shown that this behaviour is governed by universal rules. For the particular equation we are studying, however, this does not appear to happen; if the force is increased outside a small range, then the system reverts to simple periodic behaviour. However, for other small ranges of frequency and force we find more complex behaviour such as 3rd or 5th order subharmonics. The fifth order case is illustrated in Figure 5a.

Further computer integration of the equations, however, shows up an entirely different and unexpected behaviour. For larger values of the driving force, the orbit simply never repeats! The orbits scribble over a large region of phase space when they are drawn in full as in Figure 5b, and the spectrum shows a large amount of wideband noise, with superposed peaks at the driving frequency and some of its harmonics or subharmonics. This behaviour is called chaotic — but it is

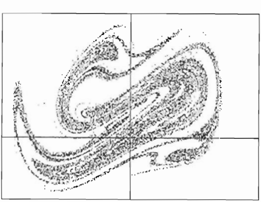

Figure 6: The strange attractor generated by the system of Figure 5(b).

deterministic chaos, in that it results from exact integration of the equation (3), and we get exactly the same result every time.

The beauty and unexpected structure of chaos appears when we examine the behaviour in the Poincaré section plane, plotting one point per orbit at a defined phase of the external force. After the initial transient has died down, the points on the section plane are not simply randomly placed, but all lie upon a complicated swirling figure of the type shown in Figure 6. It is clearly some sort of more complicated attractor for the chaotic motion and, with good reason, it is called a strange attractor. Its form is characteristic of the parameter values in the equation representing the physical system, together with the values of the external force amplitude and frequency. Transition to chaotic behaviour is again a catastrophic change — the system goes from a simple attractor to a chaotic attractor for a very small change in parameter values. In some cases there is a progression through sudden bifurcations of progressively higher order, as mentioned above.

If we watch the points, one per orbit, building up on the attractor, then we note that their placing is apparently random — though it is deterministically random in that the orbits can be calculated exactly. The essence of chaos, however, is that the exact sequence of orbits depends with the utmost sensitivity upon the initial conditions. For an ordinary attractor, two orbits or representative points that start off very close together remain close together, and indeed slowly approach one another. In a chaotic system, however, the points diverge exponentially, at least for a start, so that very soon their subsequent motion is quite uncorrelated. This behaviour in phase space and in its Poincaré section reflects what is occurring in real physical space — detailed behaviour is very sensitively dependent on initial conditions.

Examination of the geometry of strange attractors shows that they are much more complex objects even than they appear at first glance. The structure, indeed, remains equally complex if they are examined at higher and higher magnification — they are self-similar or fractal objects. Only a few attractors generated from differential equations have been examined in detail, but there is a wealth of beautiful pictorial information available on fractal objects, such as the Mandelbrot set, generated from simpler nonlinear algebraic equations [1,4,5].

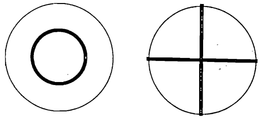

Figure 7: (0,1) and (2,0) modes of a freely suspended disc.

5. PHYSICAL EXAMPLES

Very many experimental studies of the occurrence of chaotic behaviour have been made for appropriate nonlinear systems. Many of the most convenient use electrical resonant circuits with nonlinear inductive elements, since these are easy to measure and are appropriately one dimensional, in the sense that the charge on the capacitor can be taken as the physical variable x, and the quantity $v = \dot{x}$ is then the current through the inductive element. More complex examples with larger numbers of variables abound.

Our experiments have concerned the vibration of a freely suspended metal plate, excited sinusoidally at its centre. The stiffness of the plate provides the linear part ax of the restoring force in (1), and the tension forces, which vary as the square of the amplitude and have a normal component additionally proportional to amplitude, provide the cubic restoring force term bx^3. The plate itself is an extended system and has an infinite number of normal vibration modes, but we can make an approximate separation of the motion so that each mode is described by a nonlinear equation of the form (3), with different value of the mode frequency ω_n, and with extra nonlinear terms linking the modes together. The mathematics is thus rather complicated and has not yet been explored in detail.

In the experiments, the plate was cut from steel sheet about 1 mm thick and had a diameter of about 40 cm. It was held vertically by light strings passing through holes near its edge, and was excited with a small B&K shaker attached to its centre. The displacement at any point could be measured with a B&K capacitive transducer — essentially the electrode of a condenser microphone with the plate forming the diaphragm — and the velocity by integrating the signal from a B&K subminiature accelerometer attached to the surface. Actually one could simply integrate this accelerometer signal once more to find the displacement, but a direct method has some advantages.

Exploration of the ordinary linear vibration modes showed that the two of lowest frequency were the (2,0) and (0,1) modes illustrated in Figure 7, the first number in the description giving the number of nodal diameters and the second the number of nodal circles. The (2,0) mode had a frequency of about 39 Hz and a Q value of 850 ($k \approx 0.001$) while the (0,1) mode had frequency 69 Hz and Q = 330 ($k \approx 0.003$). The (2,0) mode is actually a degenerate pair with the same frequency, the nodal lines of one being rotated by 45° relative to the other. The linear behaviour of these modes was quite unremarkable. The (0,1) mode was efficiently driven at the centre of the plate, but the (2,0) modes were nearly inactive, because their nodal lines cross there.

Interesting behaviour was found when the frequency was set at about 75 Hz, near to that of the (0,1) mode, and the driving force was increased. Quite suddenly, for an (0,1) amplitude of only a few tenths of a millimetre at the disc centre, the (2,0) mode became active at a frequency exactly half the driving frequency and reached an amplitude of about 1 mm at the disc edge. The orbit, as measured some distance from the disc centre, bifurcated, and a subharmonic of order 2 appeared on the FFT analyser. At a rather increased level of drive, giving an (0,1) mode amplitude of about 0.5 mm at the centre, the whole vibration became wildly chaotic in both modes, and the vibration amplitude at the disc edge exceeded 2 mm. Fortunately the low frequency and the small size of the disc meant that the radiated sound intensity was small! For other combinations of force and frequency near these values, subharmonics of other orders were observed, while if the shaker amplitude was increased much above that necessary for chaotic behaviour, the response again became simple.

One might be tempted to simply take this as a nice illustration of the general behaviour discussed above, except for one feature. This is that, while numerical integration of equation (3) leads one to expect a transition to chaos at an amplitude such that the nonlinear terms comfortably exceed the linear term ($\beta x^3 > 1$), the experimentally observed transition occurs for an amplitude nearly 10 times smaller, so that $\beta x^3 \sim 0.001$. The reason for this extreme sensitivity is not clear, but seems likely to be associated with the existence of two (or more) nonlinear modes, and the particular nature of the nonlinear coupling between them. It does not appear to be accounted for by the smaller damping of the experimental system. We discuss the significance of this behaviour in the final section.

Very similar behaviour was found for the case of an orchestral cymbal, which is essentially a shallow spherically-dished shell about 40 cm in diameter, and for a large Turkish gong, again a dished shell 50 cm in diameter and surrounded by a stiff conical flange [6]. The curvature of the shell adds a quadratic term αx^2 to equation (3). The conical flange on the gong reverses the frequency order of the two low-frequency modes of the gong and adds a nodal circle to (2,0), so that these modes are (0,1) at 96 Hz and (2,1) at about 180 Hz. There is also a mode (1,1) at 136 Hz, and many modes of higher frequency. The cymbal modes were not investigated in detail but, because of the high curvature of the shell, the (0,1) mode frequency was about 600 Hz.

For both these systems the behaviour when excited sinusoidally at the centre at a frequency close to that of the (0,1) mode was very similar to that of the simple plate. Subharmonics of various orders, particularly 2, 3 and 5, were observed, and the onset amplitude for chaotic behaviour was again of order 1 mm. The main difference was that, because of the higher frequencies involved, and the flange effectively baffling the gong, the radiated sound intensity was large, almost painfully so in the case of the cymbal! It was also noticeable that the timbre of the sound in the chaotic regime was very similar to that produced when the gong or cymbal was simply struck a heavy blow, as in normal playing.

6. CONCLUSION

It would be a mistake to regard nonlinear and chaotic behaviour as simply an interesting curiosity, for it has both profound basic significance and important practical consequences. The proliferation of current research literature attests to the former fact, and it is appropriate here to comment only briefly on the latter.

The behaviour of musical instruments such as gongs and cymbals is important to musicians, but is hardly seen as being significant in the larger world. It is often in musical instruments, however, that acoustic phenomena are most clearly exhibited, and for this reason their study can give valuable pointers in more practical fields. In this connection, it is perhaps the observation of chaotic behaviour and nonlinear mode coupling at force amplitudes several orders of magnitude smaller than expected from consideration of a simple Duffing equation that is most significant. Once chaotic behaviour has been initiated, the system then displays large vibration amplitudes in modes that might have been expected to be quiescent.

The most direct application of these ideas is to the vibration of panels, not necessarily of circular shape, under the influence of periodic exciting forces, generated for example by reciprocating machinery. If conditions are such that the response becomes chaotic, then panel amplitudes may greatly exceed those normally expected and may be in unexpected modes, leading to unpredicted and perhaps dangerous stresses on the structure. The same thing may apply to the flutter of panels under aerodynamic forces, where the initial vibration is to a large extent self-excited, rather than provided by an external force. Even the case of a plate or shell may be an unduly restricted model, for similar behaviour might well be expected of any extended system with multiple modes and appropriate nonlinearity. Certainly chaotic behaviour is a subject of which we will hear a great deal more in the future.

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Standards Australia

Mark Potocki
Executive Officer

Standards Australia, the peak standards writing body, has the responsibility for the development and publication of the variety of standards which have influence on the daily life of many Australians.

The Standards are prepared by a wide cross-section of the Australian community including numerous representatives of the Australian Acoustical Society.

By participating on the diverse Standards Australia Committee devoted to acoustics and vibration, they provide authoritative advice, counsel and the latest know-how in this vast and heterogenous field. On the other hand, their involvement with these Committees which represent a multitude of interests, from government and statutory authorities to manufacturers and users, provides them with the platform for the exchange of views and ideas as well as access to relevant knowledge from other disciplines.

The current international climate of standardization and Standards Australia's policy on the adoption of the international documents from the International Standards Organization (ISO) and the International Electrotechnical Committee (IEC) as a preferred way for publication of the Australian Standards, means members of the Committees have ready access to the information on the international work, plans and progress. Through Standards Australia which is the member body of both international organizations, Committee members have the opportunity to comment and vote on the new and revised international standards.

Committee members who participate in this international work facilitate adoption of the international documents in Australia, by their considerable input at the drafting stage. This has been documented in 1989 by adopting a number of the ISO and IEC documents and will be a major trend in 1990 and years to follow. This is particularly true with the product and test methods standards where there is an overwhelming commercial attraction in the ability to obtain reports and tests conducted in any of the EEC countries, USA, Japan and Australia, each having identical test procedures.

One of Standards Australia most important and efficient means of information about the new and revised standards and their implication on the society is through educational seminars. Seminars provide the public with the opportunity to update and further their knowledge. The latest developments are delivered by experts to a user audience ensuring that the information is clearly conveyed, illustrated and often demonstrated first hand.

The 1990 seminar program was launched in February. As part of Standards Australia commitment to improving quality and safety in Australian industry, our first series of seminars, "Hearing Conservation", was presented in Sydney, Perth and Melbourne. This series introduced the revised 1989 edition of Australian Standard AS 1269, Acoustics — Hearing Conservation.

Australian Standards Published in 1989

AS 1055 Acoustics — Description and measurement of environmental noise.
- Part 1: General procedures.
- Part 2: Application to specific situations.
- Part 3: Acquisition of data pertinent to land use.

AS 1127 Sound system equipment.
- Part 1: General (identical with IEC 268-1).
- Part 2: Explanation of general terms (identical with IEC 268-2).
- Part 8: Analogue audio disc records and reproducing equipment (identical with IEC 98).

AS 1269 Acoustics — Hearing conservation.

AS 3657 Acoustics — Expression of the subjective magnitude of sound or noise.
- Part 1: Pure tones, equal loudness contours (based on ISO 226).

AS 3650 Vibration and shock — Mechanical vibration and shock affecting humans — Vocabulary (in agreement with ISO 5805).

AS 3663 Acoustics and mechanical vibration — Definitions of fundamental quantities and their expression as levels in agreement with ISO 131).

AS 3671 Acoustics — Road traffic noise intrusion — Building siting and construction.

AS 3709 Vibration and shock—Balance quality of rotating bodies (identical with ISO 1940/1).

AS 3710 Vibration and shock — Balancing machines — Enclosures and other safety matters.

AS 3713 Acoustics — Industrial trucks — Noise measurement.

AS 3721 Vibration and shock — Balancing machines — Description and evaluation (identical with ISO 2953).

AS 3728 Vibration and shock — Resilient shaft couplings — Information to be supplied by users and manufacturers.

Australian Standards Scheduled for Publication in 1990

AS 1081 Acoustics — Measurement of airborne noise emitted by rotating electrical machinery.
- Part 1: Engineering method for free field conditions over a reflective plane (identical with ISO 1680/1).
- Part 2: Survey method (identical with ISO 1680/2).

AS 1127 Sound system equipment.
- Part 6: Amplifiers (identical with IEC 268-3).

AS 1259 Acoustics—Sound level meters.
- Part 1: Non-integrating (based on IEC 651).
- Part 2: Integrating-averaging (identical with IEC 804).

AS 2012 Acoustics — Measurement of airborne noise emitted by earthmoving machinery and agricultural tractors — Stationary test conditions.
- Part 1: Determination of compliance with limits for exterior noise (based on ISO 6393).
- Part 2: Operators position (based on ISO 6394).

AS 2670 Evaluation of human exposure to-whole-body vibration.
- Part 1: General requirements.
- Part 2: Continuous and shock induced vibration in buildings (1 to 80 Hz).
- Part 3: Evaluation of exposure to whole-body Z-axis vertical vibration in the frequency range 0.1 to 063 Hz.

AS 2991 Acoustics — Method for the determination of airborne noise emitted by household and similar electrical appliances.
- Part 2: Particular requirements for dishwashers (based on IEC 704 Part 2.3).

AS 3755 Acoustics — Measurement of airborne noise emitted by computer and business equipment (identical with ISO 7779).

AS 3756 Acoustics — High frequency noise measurement — Computer and business equipment (identical with ISO 9295).

AS 3757 Acoustics — Declared noise emission values — Computer and business equipment (identical with ISO 9296).

*AS XXXX Acoustics — Assessment of noise from helicopter landing sites.

*AS XXXX Mechanical vibration and shock — Guidelines for the overall evaluation of vibration in merchant ships.

*AS XXXX Measurement and reporting of local vibration data of ship structures and equipment.

*AS XXXX Measurement and reporting of shipboard vibration data.

(*Indicates no number yet assigned.)

Introduction to Condition Monitoring

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ABSTRACT: This paper is an overview of machine condition monitoring techniques based on vibration measurement and analysis. After a general discussion of the way in which a variety of faults manifest themselves in the vibration signal, the particular cases of gears and rolling element bearings are looked at in more detail. Finally, the different requirements for fault detection, diagnosis and trend analysis are discussed, along with the choice of appropriate transducers for the different situations.

1.0 INTRODUCTION

Condition monitoring forms the basis of "Predictive Maintenance", a system wherein machines are run as long as possible between shutdowns, i.e. repairs are carried out just prior to failure. This is obviously better than "run-to-break" systems where the actual failure usually increases consequential damage (and shutdown time) as well as posing a safety hazard, and time-based "preventive maintenance", where maintenance is carried out at fixed time intervals, based on the minimum time to failure (typically only one half or one third of the mean time to failure). However, predictive maintenance does require the employment of reliable condition monitoring techniques which give information about the current condition of machines while in operation. The development of such techniques has been considerable in the past twenty years or so.

There are two main ways of getting information from the inside to the outside of operating machines so as to monitor their internal condition. One is lubricant analysis, including spectrographic oil analysis (SOAP) and ferrography, microscopic analysis of ferromagnetic particles and other entrained debris carried by the lubricant. The other is by "mechanical signature analysis", primarily the analysis of vibration signals which also carry information about internal events to the outer casing (in much the same way as a doctor uses a stethoscope to interpret sounds inside the human body). This paper concentrates entirely on the uses of mechanical signature analysis for condition monitoring, while recognising that there are situations where oil analysis is an economical alternative, or even more frequently a useful supplement to these vibration-based techniques.

Experienced mechanics have long used the sounds of machines as a guide to their condition, but a more reliable indication is given by the vibrations measured at the bearings, where the dynamic forces are transmitted from the internal moving components to the stationary (and accessible) housing or frame of the machine. The vibrations contain basically the same information as the sound, but are more repeatable, more localised and less affected by background noise. Continuous monitoring, with permanently attached vibration transducers, is used on the most critical and valuable machines to shut them down in the event of sudden rapid failure, and thus avoid further consequential damage. However, with typical costs of several thousand dollars per channel, this is somewhat restricted, and it is more common to use a single transducer and analysis system to cover a large number of machines at intervals of typically one month. Using detailed analysis techniques, some of which are described below, it is often possible to detect incipient faults several months before they become serious, and thus plan repair work to give minimum disruption of production. It is also possible to diagnose the type and location of faults, and make predictions as to how much longer the machine can safely be operated, so that spare parts can be obtained in advance, and the repair work planned more efficiently. These three aspects, viz. fault detection, diagnosis and trend analysis will be examined in the following. First, however, the effect of a range of typical faults on the vibration signal will be described.

Text of paper presented at Seminar on Condition Monitoring held by the Acoustics & Vibration Centre, Australian Defence Force Academy on 8 December 1989.

2.0 TYPICAL MACHINE VIBRATIONS

A change in the vibration signal not only indicates that a change in condition has occurred, but usually also points to the problem. The frequency or frequencies at which the change occurs can be tied to periodic events in the machine such as the rotating speed of shafts, and multiples of mains frequency in electrical machines.

Rotors can become unbalanced as a result of loss or erosion of components, uneven build-up of dust and/or fouling, or distortion. The unbalance force rotates at shaft speed, so the response is primarily at this frequency. Misalignment of shafts generally also gives a response at shaft speed and its low harmonics (i.e. multiples). Mechanical looseness, and other effects giving an impulse once per revolution generate a somewhat greater number of harmonics of the shaft speed, the number being larger the shorter the impulse.

High speed turbo-machines with plain bearings often run at speeds well above their "critical speed". These can exhibit vibrations at frequencies below shaft speed as a result of various non-linearities and instabilities. In the case of "oil whirl", for example, the shaft rides a wave of oil around the bearing at a frequency corresponding to the mean oil velocity, typically 42-48% of shaft speed. "Hysteresis whirl" is caused by hysteresis, or friction, between components on the rotor; it is initiated on passing through the critical speed, and the vibration remains at this frequency even as the shaft speed increases. Exact subharmonics of shaft speed, e.g. 1/2, 1/3 etc, can be caused by variations in stiffness such as looseness (softening spring) and "rubs", or contact between rotating and stationary components (hardening spring).

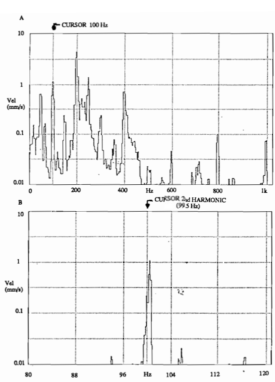

Figure 1: Use of a harmonic cursor to separate harmonics of shaft speed from those of mains frequency.
(A) Baseband spectrum from 2-pole induction motor with cursor showing a high level component at approximately 100 Hz.
(B) Zoom spectrum with harmonic cursor (adjusted on first and third harmonics of shaft speed) depicting second harmonic of shaft speed. This shows that the dominant component is at twice mains frequency and therefore of electrical, not mechanical origin.

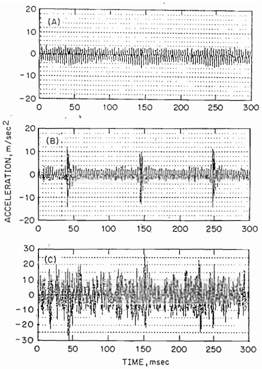

Figure 2: Use of signal enhancement in gear fault diagnosis.
(A) Enhanced signal (120 averages) for a gear in normal condition.
(B) Enhanced signal (120 averages) for a similar gear with a local fault.
(C) Section of raw signal corresponding to (B).

Most of the above symptoms can be recognised by a straightforward frequency analysis of the signal. This can now be done very efficiently using so-called FFT (fast Fourier transform) analysers, which convert sections of the time signal into the equivalent frequency spectra (i.e. distribution of the signal with frequency). Portable, battery-operated FFT analysers have become available in recent years. Their diagnostic capability is enhanced considerably when they have a finely tunable "harmonic cursor", highlighting the members of a particular harmonic family, thus allowing very accurate measurement of the fundamental frequency, and determining whether a particular spectral peak is related to one source or another. An example is the separation of the various harmonics of shaft speed from those of mains frequency in induction (i.e. asynchronous) electric motors (Figure 1)).

Other faults give more complex symptoms, of which two examples will be given, viz. gears and rolling element (i.e. anti-friction) bearings. Gears generate vibrations as a result of departures from the ideal tooth profiles. When new, these errors will be due partly to geometric manufacturing errors, and partly to tooth deflection under load (and in particular, variations in this as the load is supported by different numbers of teeth through the meshing cycle). Changes in the vibration signals measured under constant load normally indicate deterioration by wear and/or damage in service. Effects which are the same for each tooth pair e.g. uniform wear, show up as an increase in the first few harmonics of the toothmeshing frequency (i.e. number of teeth times rotational frequency). Differences between the teeth show up as changes in the other harmonics of the gear rotational speeds. Such localised and non-uniformly distributed faults can also often be detected in the time signals, in particular if these are enhanced by synchronous averaging (Figure 2). In this process, the time signals are averaged by overlaying them digitally in synchronism with a once-per-revolution timing pulse from the gear in question. As illustrated in Figure 2, this has the effect of enhancing that part of the signal which repeats periodically at the given rate, with respect to both noise and any effects with other periodicity (for example, the mating gear). This process can be repeated for each gear in turn.

Note that the only frequencies generated by the actions of gears are harmonics of the gear rotational speeds. This allows them to be separated from the effects of rolling element bearings with which they are often combined.

Figure 3 illustrates how vibrations typically are generated by local faults in rolling element bearings, giving a series of impulses (like the effect of periodic hammer blows) as the fault comes in contact with a load-bearing element. The characteristic bearing frequencies are given by the following formulae:

Fundamental train frequency (cage rotational speed)

$$FTF = (f_r/2)(1 - d/D) \quad (1)$$

Ball-pass frequency, outer race

$$BPFO = (nf_r/2)(1 - d/D) \quad (2)$$

Ball-pass frequency, inner race

$$BPFI = (nf_r/2)(1 + d/D) \quad (3)$$

Ball spin frequency

$$BSF = (f_rD/2d)[1 - (d/D)^2] \quad (4)$$

where f_r is the shaft speed, n is the number of rolling elements, and d and D are illustrated in Figure 3.

These formulae give only the repetition rates of the high frequency pulses generated by impacts with the fault. Each pulse is dominated by resonances excited by the impacts, and as illustrated in Figure 3, the whole pattern can be modulated by lower frequencies as the fault rotates in and out of the loaded zone. Note from equations (1) to (4) that the bearing characteristic frequencies in general are not harmonics of shaft speeds, which makes possible their separation from gear faults.

Many simpler techniques for diagnostics of antifriction bearings rely on detecting a "spiky" signal, with localised peaks much larger than the general RMS (root mean square) value of the signal. Often the spikiness is enhanced by filtering away all frequencies except a band around one of the resonances excited by the impacts. The most powerful technique, however, is "envelope analysis", where the envelope of the filtered signal is generated as illustrated in Figure 3, and then frequency analysed to reveal any ball-pass frequencies and modulation effects. This is much more reliable than the simpler techniques, which can respond to spikiness caused by other phenomena, for example, cavitation and turbulence in pumps. It can be shown that frequency analysis of the raw signal (as opposed to the envelope) does not necessarily reveal the pulse repetition frequencies (Figure 4).

3.0 FAULT DETECTION AND TREND ANALYSIS

Even though displacement is perhaps the vibration parameter most easily visualised, velocity is that best indicating condition, as reflected in many criteria such as the International Standard ISO2372. It can be shown that velocity is the parameter most closely related to stress, and for this reason the velocity spectrum tends to be flattest, so that changes at any frequency have a roughly uniform chance of affecting the overall vibration level. Some vibration criteria differ in detail as to what constitutes a severe vibration, but most are in agreement that equal changes in severity are represented by equal changes on a logarithmic scale (i.e. changes by a certain factor, or by a certain number of dB). They are also mostly in agreement that a change by 2:1 (6 dB) is significant, and a change by 10:1 (20 dB) is serious. These same principles can be applied as a starting point when evaluating changes in vibration spectra, which generally gives the earliest indication of a change in condition.

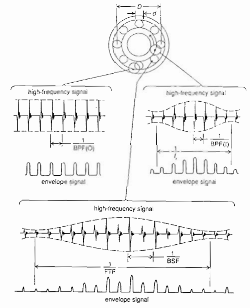

Figure 3: Typical vibration signals generated by local faults in rolling-element bearings. In the high-frequency signals, it is assumed that masking vibrations are filtered away. The envelope signals are produced by amplitude demodulation. Symbols are explained in the text.

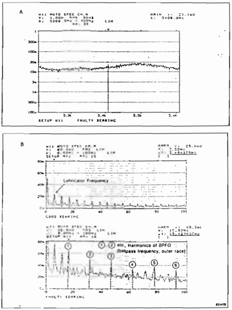

Figure 4: Envelope analysis applied to rolling element bearing diagnostics.
(A) Zoom spectrum for a faulty bearing in a frequency band where a 15 dB increase had occurred as a result of a fault (no discrete frequency information apparent).
(B) Envelope analysis for the same frequency band as in (A). Comparison of the same faulty bearing with a similar bearing in good condition. Envelope analysis reveals the influence of pneumatic lubricators in both cases, but additionally an outer race fault in the faulty bearing.

Trend analysis of the change with time should also most logically be of logarithmic values. Since it is not known in advance what changes will occur, it is of advantage to compare spectra covering a wide frequency range of perhaps 1000:1 (e.g. 10 Hz to 10 kHz) to cover all possibilities from 40% of shaft speed to harmonics of toothmeshing frequencies, and ringing frequencies excited by bearing faults.

Figure 5 shows an example of detection of a fault by spectrum comparison, and how trend analysis can be used to give an indication of how much longer the machine can safely be run. This example is taken from a Bruel and Kjaer Application Note on Condition Monitoring in a Canadian iron mine.

4.0 VIBRATION TRANSDUCERS

Mechanical vibration can be expressed in terms of displacement, velocity or acceleration, and transducers exist which give electrical signals proportional to each. The most common displacement transducers, proximity probes, actually measure relative displacement (between rotor and casing, or between a shaft and its bearing). This is quite a different parameter from the absolute vibration measured by seismic tranducers mounted on the housing and often gives additional information, in particular on machines with journal bearings. X-Y pairs of proximity transducers allow depiction of shaft orbits, including information about whether precession is forward or backward, diagnostic information which can not be obtained any other way. However, it should be realised that they have a limited dynamic range, and consequently, a frequency range limited to a few harmonic orders of shaft speed, since the shaft vibration expressed as displacement invariably falls off rapidly with frequency. As proximity probes have to be permanently installed, their main application is to permanent monitoring of key machines.

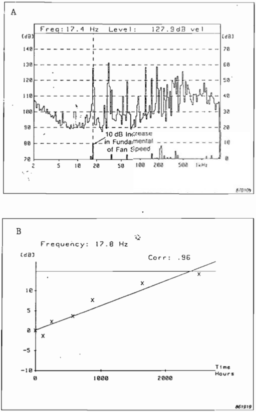

Figure 5: Example of fault detection and trend analysis of a fan vibration problem. (Courtesy Bruel and Kjaer).
(A) Upper spectrum: Fan vibration spectrum with cursor depicting shaft speed component. Lower spectrum: dB difference spectrum showing the amount by which this spectrum has increased over the original reference spectrum.
(B) Trend plot of the fan shaft speed component against running hours, showing a steady growth in unbalance.

As mentioned previously, velocity is the parameter which best represents the severity of casing vibrations, but what is not generally realised is that an accelerometer (which produces a signal proportional to acceleration) combined with an electronic integrator is technically the best velocity transducer. Velocity transducers, based on the motion of a seismically suspended magnet in a coil (or vice versa) typically have a frequency range limited to 10-1000 Hz, with dynamic range 60 dB, whereas a piezoelectric accelerometer typically has a frequency range of 1 Hz — 10 kHz and can be combined with an integrator to give velocity ranges 1 Hz — 1 kHz or 10 Hz — 10 kHz at the flick of a switch, with dynamic range between 60 and 120 dB. Velocity signals from an accelerometer generally give the best possibilities of detecting faults over a wide frequency range at the earliest possible time.

5.0 CONCLUSIONS

Mechanical signature analysis through vibration analysis provides a very powerful means of detecting, diagnosing and trending incipient faults in a machine. This facilitates predictive maintenance, where repair work is based on the monitored condition of operating machines.

The most economical systems for covering large numbers of machines would typically be based on the use of accelerometers together with FFT analysers for signal analysis, either directly in the field or via intermediate recording. The analyser data can be processed by computer (typically PCs) for automatic fault detection and semi automatic trend analysis. Automatic diagnosis is still some way off, but experienced diagnosticians make use of a number of techniques (often provided by the FFT analysers, or computer software) to diagnose faults at an early stage, and thus allow efficient planning of repair work and acquisition of spare parts.

Condition monitoring is still developing rapidly, but by virtue of its success in a wide range of industries, is now approaching maturity and general acceptance.

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Timbre Assessment

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ABSTRACT: The historical development of ideas relating to timbre are traced. Helmholtz' contributions, investigations using verbal scales and those employing multidimensional scaling are discussed. Emphasis is on determining the minimum number of factors (dimensions) required to represent timbre.

1. INTRODUCTION

A seemingly inevitable human characteristic is the predisposition to apply mental filters to all incoming and outgoing information. Despite their intended devotion to impartiality, those engaged in scientific endeavour are not immune to this process. The differing attitudes to musical sounds is an apt illustration of the point.

To a physicist a steady musical sound is a mechanical vibration that has a number of distinguishing characteristics: (1) the overall intensity (dependent on the acoustic power radiated by the musical instrument), (2) the frequency spectrum of the component tones, (3) the fundamental frequency of the spectral series (loosely called the pitch), (4) time-dependent aspects associated with the starting transient and the decay of the sound.

A psycho-acoustician's view of the same sound would be more concerned with the processing of the sound in the inner ear. The same basic characteristics would be described in terms of (1) loudness, related in a non-linear manner to intensity, (2) timbre, a complex multi-dimensional entity that describes the "quality" of the sound independent of loudness and pitch, (3) pitch, related non-linearly to frequency, (4) duration, which determines the relative importance of the starting transient, steady state and the decay.

A musician's view is different again. Musicians tend to talk in terms of groups of concepts, being more concerned with the overall effect and message conveyed by the sound than with the individual elements of sounds. Musicians speak of tone quality, volume, harmony, timbre, rhythm... for which they have clear definitions, as well as a wide range of other undefined terms such as warmth, fullness, density, singing tone, brightness, roundness, etc.

It is interesting to note that, as discussed so far, it would not be possible to distinguish by analysis a musical sound from the squealing of bus brakes, a locomotive whistle or other noise with tonal components. A more recently recognised essential component of a musical sound is its *microstructure*, that is, the variations in time of pitch, loudness and timbre. To qualify as a musical sound, a particular signal needs to have a definable pitch, a set of related partial tones (not necessarily harmonic), a characteristic starting transient and its own microstructure.

Many of the above concepts, such as loudness and pitch, are one-dimensional and, although far from simple, can be defined and measured. What can be done about timbre? Timbre is a multi-dimensional entity, that is, its assessment is dependent on many seemingly independent factors. Until recent times it was only possible to state what timbre was not. Most standardising bodies settle for a statement that "defines" timbre as a characteristic of a sound that is not-loudness and not-pitch. Physical scientists, in particular, find it very difficult to measure a not-quantity!

Musicians, acousticians and listeners generally are frequently required to make judgments of the quality of musical sounds (timbre) in relation to a violin, piano, organ, etc or a hall with poor acoustics. Usually, subjective decisions are made which rely heavily on the experience, preferences and, possibly, expectations of the person involved. Even external factors, such as the comfort of the seating or the colours of the decorations have been known to influence such judgments. There is therefore a challenge to explore the possibility of using analytical procedures that will provide a reliable measure for timbre. One complication is that listeners tend to judge sounds differently from performers who are influenced by the "feel" of their instrument and by its reputation.

Successes in coping with the analogous field of colour measurement suggest that it should be possible to quantify even an elusive topic such as timbre. The first stage is a recognition that there are at least three levels of analysis possible for musical sounds: physical, psychophysical and feature analysis. These levels correspond to: instrument-only analysis, allowance for the properties of the inner ear, and processing by the brain. Feature analysis leads to a number of useful measures including the quantitative specification of both starting transients and steady state timbre. Part A of this article will survey various approaches that have been made to specify timbre. In Part B experimental techniques that lead to quantitative measures for timbre will be discussed.

2. THE NATURE OF TIMBRE

The meaning of the term timbre has been debated for at least 100 years. There is still some uncertainty as to whether timbre applies only to the "steady" part of a sound or whether the attack (starting transient) should be included. The great pioneer of modern musical research, Helmholtz [1885], considered that timbre only applied to the steady state and that the attack was a separate phenomenon. Research on cell physiology (e.g. Moller [1983]) might be interpreted as supporting this view in that different groups of cells in the brain appear to be involved in the assessment of the attack and the steady state. Also, different times are required for these two tasks. To assess a steady sound (estimation of loudness, pitch, timbre) requires between 100 and 200 ms whereas changes in these quantities during the attack involve times of the order of 5-20 ms.

However, because of the brain's powers of cross-referencing and memory storage, there is good reason to suppose that the brain integrates its response to both parts of the sound. A picture is beginning to emerge that the many factors contributing to the concept of timbre are all recorded, presumably in independent, specialised parts of the brain, and then subjected to correlation with sets of similar factors stored in memory.

All possible factors are not always relevant to the identification of a particular sound. Many experiments have been conducted to determine the minimum number of factors required to assess timbre. Although most investigators are agreed that there is a close connection between estimates of timbre and the frequency spectrum of the sound, it is not entirely clear what features of the spectrum are used by the brain. Before discussing more recent investigations, it is interesting to trace the history of this connection.

2.1 Early Development of Ideas

PYTHAGORUS (287–212 BC) studied vibrating strings and observed that a series of partial tones of higher pitch were produced when the length of the string was subdivided into simple ratios. These tones corresponded with known musical intervals: a ratio of 1:2 with the octave, 1:3 with the fifth, 1:4 with the fourth, etc. The concept of frequency was not then known.

GALILEO (1564–1642) is generally credited with the discovery of the laws governing stretched strings. He was the first to associate pitch with frequency of vibration. Lindsay [1965] describes a remarkable experiment conducted by Galileo "in which he scraped a brass plate with an iron chisel and found that when a pure note of definite pitch was emitted the chisel cut the plate in a number of fine lines. When the pitch was high the lines were close together, while when the pitch was lower they were further apart. Galileo was actually able to tune two spinet strings with two of these scraping tones; when the musical interval between the string notes was judged by the ear to be a fifth, the number of lines produced in the corresponding scrapings in the same total time interval bore precisely the ratio 3:2".

MERSENNE (1588–1648) independently discovered the laws of stretched strings and was the first to measure frequency directly: he measured the frequency of vibration of a long string and from this inferred the frequency of a shorter one. He established the existence of a set of partial tones for a string and measured the frequencies of six of these tones. Mersenne wrote the first textbook on sound in 1636.

The realisation that the overall vibration of a string was a composite of all the partial tones was pointed out by SAUVEUR (1653–1716) in 1701 who was also the first to suggest the name *acoustics* for the science of sound. It was over 100 years later before FOURIER (1768–1830) devised his famous theorem, in 1822, which showed how a complex vibration could be broken down into a number of simple sinusoidal components (the partial tones).

2.2 Helmholtz' Contribution

Our current understanding of musical acoustics owes much to the extensive psychophysical investigations carried out by HELMHOLTZ (1821–1894). He recognised three essential characteristics of *steady* musical sounds: pitch, loudness and timbre. His experiments showed that there was a clear connection between timbre and the number and strength of the partial tones present. He associated timbre with steady musical sounds, thus excluding starting transients. He discussed with considerable insight the nature of transient sounds but then stated (Helmholtz [1885], p. 67): *"When we speak in what follows of musical quality of tone, we shall disregard these peculiarities of beginning and ending, and confine our attention to the peculiarities of the musical tone which continues uniformly".*

As with his predecessors, dating back to Pythagorus, the perfection of whole numbers dominated his thinking about musical sounds and he presumed that the partial tones of musical instruments were part of a harmonic series. Of course, the precision of measurement available, using a set of tuned Helmholtz resonators, was such that small deviations from whole number ratios (as occur with nearly all musical instruments) would not have been measurable. Helmholtz recognised that there were sounds having inharmonic partials, such as plates and bells, but he did not think that they should be classed as musical sounds.

Helmholtz stated the following general rules in relation to the perception of musical tones (Helmholtz [1885], p. 118):

(1) Simple Tones, like those of tuning forks applied to resonance chambers and wide stopped organ pipes, have a very soft, pleasant sound, free from all roughness, but wanting in power, and dull at low pitches.

(2) Musical Tones, which are accompanied by a moderately loud series of the lower partial tones, up to about the sixth partial, are more harmonious and musical. Compared with simple tones they are rich and splendid, while they are at the same time perfectly sweet and soft if the higher upper partials are absent. To these belong the musical tones produced by the pianoforte, open organ pipes, the softer piano tones of the human voice and of the French horn.

(3) If only the unevenly numbered partials are present (as in narrow stopped organ pipes, pianoforte strings struck in their middle points, and clarinets), the quality of tone is hollow, and, when a large number of such upper partials are present, nasal. When the prime tone predominates the quality of tone is rich; but when the prime tone is not sufficiently superior in strength to the upper partials, the quality of tone is poor. Thus the quality of tone in the wider open organ pipes is richer than that in the narrower; strings struck with pianoforte hammers give tones of a richer quality than when struck by a stick or plucked by the finger; the tones of reed pipes with suitable resonance chambers have a richer quality than those without resonance chambers.

(4) When partial tones higher than the sixth or seventh are very distinct, the quality of tone is cutting and rough... When their force is inconsiderable the higher upper partials do not essentially detract from the musical applicability of the compound tones; on the contrary, they are useful in giving character and expression to the music. The most important musical tones of this description are those of bowed instruments and of most reed pipes, oboe, bassoon, harmonium, and the human voice. The rough braying tones of brass instruments are extremely penetrating, and hence are better adapted to give the impression of great power than similar tones of a softer quality.

Helmholtz developed a model for hearing that was the forerunner for modern theories. After discussing the available experimental evidence concerning the basilar membrane, he wrote (Helmholtz [1885], p. 146): *If the tension in the direction of its length is infinitesimally small in comparison with the tension in the direction of the breadth, then the radial fibres of the basilar membrane may be approximately regarded as forming a system of stretched strings, and the membranous connection as only serving to give a fulcrum to the pressure of the fluid against these strings. In that case the laws of their motion would be the same as if every individual string moved independently of all the others, and obeyed, by itself, the influence of the periodically alternating pressure of the fluid of the labyrinth contained in the vestibule gallery.*

The equivalent strings are shorter and stiffer at the end nearest to the eardrum, longer and more elastic at the end furthest away. Thus, the basilar membrane acts as a frequency analyser being more sensitive to high frequencies near the eardrum and low frequencies further away. A sound containing a number of partial tones would cause the basilar membrane to resonate at a corresponding number of places. The modern concept of critical bandwidths, in which the basilar membrane is divided into 24 zones slightly less than 1/3 octave in width (Zwicker et al [1957]) is a refinement of Helmholtz' model. One major difference is that the energies of all partial tones falling within a particular critical band are integrated; only one composite tone is perceived.

Helmholtz developed a theory of dissonance that is still relevant and explained the effect of roughness as a rapid beating effect between two tones (Helmholtz [1885], p. 192):

Roughness vanishes when there are no beats, increases to a maximum for 33 beats, and then diminishes as the number of beats increases. The concept of roughness has now been extended (Terhardt [1974]) to include beating between two or more partial tones that lie in the same critical band. Thus, the rough sounds referred to by Helmholtz are those having many high-order partial tones with consequent beating effects in the higher critical bands. (For musical sounds, only the first 5 or 6 partial tones lie in separate critical bands. For the higher partials there will be two or more partials in each band.)

2.3 Verbal Prescriptions for Timbre

Despite extensive experimentation, Helmholtz was only able to specify timbre in terms of general terms such as sweet, pleasant, dull, sharp, rough, penetrating, etc. Over the following 100 years many investigations were conducted in order to find suitable verbal scales consisting of ranges defined by opposites derived from these words, such as dull-sharp. Even though musicians use a multitude of words to describe the various aspects of timbre, there is no general agreement as to the meaning to be ascribed to each word and often a given word is used to describe more than one characteristic.

PRATT AND DOAK [1976] investigated this aspect in an endeavour to find a rating scale for timbre. In a preliminary survey they determined that seven words were used most frequently by a panel of musicians to describe timbre: rich, mellow, colourful, brilliant, penetrating, bright and warm. From these words three psychophysical scales were chosen. In their main experiment, 21 subjects were asked to make judgments on six synthesised musical sounds using the three scales: Dull-Brilliant, Cold-Warm, Pure-Rich. In preparing the test sounds it was found that life-like musical tones could only be synthesised if the characteristic microstructure for each sound was included; otherwise the sound was immediately recognised as being artificial. With the reduction to three scales, a graphical presentation of the results became possible. Figure 1 shows a sample graph from their investigation and the scales used by the subjects in their evaluations.

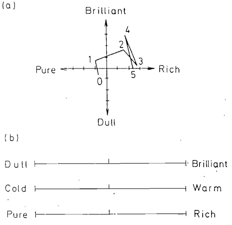

Figure 1:
(a) Graphical presentation of some of the test results obtained by one subject for six repetitions (marked 0 to 5) of one test signal. Six different sounds were repeated six times in Latin square order making 36 test signals for each listener.
(b) For each presentation the listener was asked to mark his/her estimate on each line for the three selected verbal scales.
(After Pratt and Doak 1976)

BISMARCK [1974] made a psychophysical study of 30 verbal scales in relation to judgments of 35 steady synthetic sounds of different spectral composition, equalised for loudness and pitch. Two groups, each of eight subjects took part, one group consisting of musicians and the other of non-musicians. Some of the scales investigated were soft-loud, weak-strong, dull-sharp, relaxed-tense, smooth-rough, thick-thin, clean-dirty, simple-complex, compact-scattered, etc. Applying factor analysis to the results showed that the timbres of the 35 sounds were almost completely rated using the four independent scales dull-sharp, compact-scattered, full-empty and colorful-colorless. Two of these were found to have the most significance in interpreting the experiments by the musicians' group: dull-sharp and compact-scattered. Bismarck called the first scale *sharpness* and the second *compactness*.

Compactness differentiates between complex sounds and noise but does not have a relevant measure. Sharpness was identified as a measure of the centroid of the loudness spectrum of the sound and has proven to be an important and useful timbre factor.

Sharpness (SH) is defined as

$$SH = \sum_{i}^{n} N_i m_i / \sum_{i}^{n} N_i \qquad (1)$$

where N_i is the band (critical or 1/3 octave) loudness in sones, m_i is the band number, n is the number of the highest band included. Standard 1/3 octave band numbers may be used giving a measure of SH on an absolute scale.

For the analysis of musical notes, it is more useful to define the *relative sharpness*, SH(rel), for which the band containing the fundamental of the note is labelled Band 1. A low value of SH(rel), e.g. 1.5, indicates a sound with strong fundamental and little harmonic development, whereas a value such as 6 would indicate a moderately bright sound containing many partial tones.

2.4 Non-verbal Techniques

The inherent limitations of verbal scaling methods are avoided by adopting a simplified comparison test in which the only decision expected of the subject is to determine whether a pair or a triad of test sounds are similar or dissimilar. A matrix of scores is assembled for all combinations of the test signals and then multidimensional analysis applied. This statistical procedure determines how many significant factors are involved in making the comparisons without any assumptions being necessary as to the nature of the factors. The physical identification of the factors is made from a knowledge of the sounds or is left to supplementary experiments or evidence.

Grey's Experiments

In a comprehensive series of experiments (Grey [1975], Grey [1977], Grey & Moorer [1977]) various aspects of timbre were investigated in an endeavour to find the most significant factors involved. Grey observed that the attack part of a sound is important for identification and for drawing attention to the sound; the steady state part is important in judging timbre; the presence of vibrato is found to aid identification; the decay part of a sound does not contribute significantly to the assessment of timbre since in most cases the decay heard is that of the room rather than the decay of the sound as it leaves the instrument.

Timbre thus involves both time and frequency elements. The *starting transient* plays an important role since it represents an abrupt change of state from previous sounds even if they come from the same instrument. Because of the short duration (between 5 and 350 ms for musical sounds) it seems likely that the brain responds to an overall transient pattern. Studies of musical transients suggest that a small number of significant features are involved in this recognition process. Grey identified three factors: the presence of early noise or inharmonic partials, the rise-times of the partial tones and the degree of synchronism in the growth of the partial tones. Pollard and Jansson [1982] added a fourth factor: dominant tones (modes) at specific times during a transient. During the following *steady state*, important characteristics are the instantaneous loudness spectrum and the degree of fluctuations in the loudness and frequency of the spectrum components.

Grey describes a series of comprehensive experiments involving 20 listeners using a set of 16 instrumental notes that were analysed and then reconstructed by a computer so that all characteristics of the sounds, such as duration, loudness and pitch were equalised, leaving timbre as the only variable.

Since the estimation of timbre involves many factors, none of which the listener may be consciously aware, it is necessary to employ procedures that limit the listener's task to simple comparisons. A group of sounds was presented to each listener in pairs. The listener was asked to rank each pair on a scale of similarity ranging from 1 to 30 with 3 ranges: 1-10 very dissimilar; 11-20 average level of similarity; 21-30 very similar. Multi-dimensional analysis was then applied to the experimental data to determine the number of significant factors used in the judgments. Analysis of the experiment, in terms of the variances for each factor compared with the total variance, showed that most of the results could be accounted for by three main factors. The identity of the factors is not revealed directly in this procedure: the experimenter has to determine these from a knowledge of the sounds used.

Grey concluded that the three factors could be interpreted as: (1) a factor related to the spectral energy distribution, later associated with sharpness, (2) the presence of low-amplitude, high-frequency energy in the initial attack segment (this could include noise and inharmonic tones), (3) synchronism in the transients of the higher partials, that is, whether the higher partials rise in level together at the beginning of the note or fall together at the end. Closely associated with synchronism is the level of spectral fluctuation in the tone with time.

One method of displaying the results is in the form of a three-dimensional diagram as in Figure 2. The test sounds are represented by cubes: the squares on the floor and wall are projections of the cubes onto those planes. Axis I can be interpreted in terms of the spectral energy distribution, the sounds with few harmonics are at the top and those with wider spectrum at the bottom. Axis II is related to synchronism. It also appears to group the sounds according to musical family with woodwinds, brass and strings forming three groups. Axis III is related to the amount of high frequency energy in the early part of the starting transient.

Plomp's Investigations

Plomp and Steeneken [1973] describe an experiment in which the relation between timbre and sound spectrum for selected steady sounds was studied at various locations in a diffuse sound field. In analysing the data using multidimensional analysis they found that the timbre judgments could be represented satisfactorily by three dimensions. They were not able to identify the dimensions but observed that there was good correlation between changes of timbre and changes in sound spectrum.

A similar experiment was conducted by Plomp [1979] using the steady state parts of a number of organ tones. Figure 3 shows a two-dimensional plot of the results where the vertical scale correlates with the extent of the spectrum of the sound: flute pipes have few harmonics, diapasons have a moderate number whereas reed pipes have many. It is not clear from this investigation what the horizontal scale represents — it could relate to synchronism.

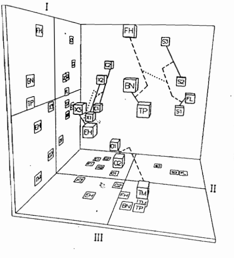

Figure 2: Diagram showing Grey's results for the timbre of 16 instrumental notes. (O1, O2 oboes; C1, C2 clarinets; TP trumpet; S1, S2, S3 strings; FL flute; X1, X2, X3 saxophones; EH English horn; FH French horn; BN bassoon.) The test sounds are represented by cubes: the squares on the floor and wall are projections of the cubes onto those planes. Axis I can be interpreted in terms of the spectral energy distribution, the sounds with few harmonics are at the top and those with wider spectrum at the bottom. Axis II is related to synchronism. It also appears to group the sounds according to musical family with woodwinds, brass and strings forming three groups. Axis III is related to the amount of high frequency energy in the early part of the starting transient. (After Grey 1977)

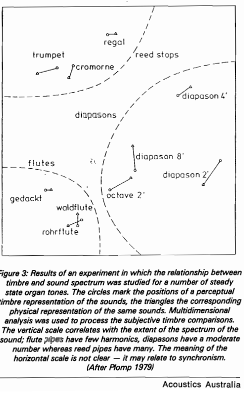

Figure 3: Results of an experiment in which the relationship between timbre and sound spectrum was studied for a number of steady state organ tones. The circles mark the positions of a perceptual timbre representation of the sounds, the triangles the corresponding physical representation of the same sounds. Multidimensional analysis was used to process the subjective timbre comparisons. The vertical scale correlates with the extent of the spectrum of the sound; flute pipes have few harmonics, diapasons have a moderate number whereas reed pipes have many. The meaning of the horizontal scale is not clear — it may relate to synchronism. (After Plomp 1979)

Plomp and De Laat [1984] studied the plenum spectrum (octave band analysis of the full diapason chorus) for 14 organs using multidimensional procedures. The five octave bands included in the measurements were treated as separate dimensions; application of principal-components analysis then reduced the number of significant dimensions to three. Dimension 1 was found to be largely determined by the overall level of the organ sounds; Dimension 2 was highly correlated with the slope of the spectra; Dimension 3 compared the centre octave with the lowest and highest ones. Application of the three new dimensions correlated well with subjective impressions of the full sounds of the organs.

3. CONCLUSIONS

Ever since the days of Pythagorus, whose understanding of the subject was exceptional for his time, there have been problems in defining and measuring musical sounds. Over 2000 years elapsed between the writings of Pythagorus and the next major contribution from Helmholtz.

Experimental methods based on the use of verbal scales have clarified the words used by musicians and have led to the identification of a significant quantitative measure — sharpness. Such methods, however, do not lead to a measurement system for timbre.

Traditional methodology in the physical sciences prefers to allow only one factor to change at a time, all others being held constant. With a complex phenomenon, such as timbre, multidimensional scaling allows for the identification of the number of significant factors involved even though the total number of variable factors is large. A conclusion of major significance from several investigators is that the many possible factors involved in timbre assessment can be reduced to three major factors: a multidimensional problem is thereby reduced to a three-dimensional problem. Unfortunately there is no general agreement as to the identification of the three most significant factors. Although agreeing on the magic number of three, different investigators have suggested different factors of which one always shows a dependence on the spectrum. It is quite possible that the other most-significant factors depend on the sounds used in the experiment.

In a subsequent article, some new experimental techniques will be discussed that lead to quantitative measurement and specification of timbre.

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Seminar on Condition Monitoring

A half day seminar on Condition Monitoring was held at the Australian Defence Force Academy (ADFA) on Friday, 8 December 1989. This seminar was organised by the Acoustics and Vibration Centre with the aim of providing a general overview of condition monitoring using vibration measurements. It was directed towards those who need to have an understanding of the principles and applications of condition monitoring, in particular those at management level.

There were thirty-seven participants, including those involved with the presentations. The seminar was opened by *Professor Duggins*, Head of the Department of Mechanical Engineering at ADFA. Professor Duggins outlined the establishment and the objectives of the Acoustics and Vibration Centre within the Department. *Lyle McLean*, from the Centre, was the Chairman for the seminar.

The keynote address was presented by *Bob Randall* from the School of Mechanical and Industrial Engineering at the University of NSW in Sydney. Bob explained the basic methods available for analysis of the vibration signals from machinery. He also gave examples of more complex analysis methods which are necessary to identify correctly some machine faults. While automatic diagnosis is still some way off, condition monitoring does allow efficient planning of repair work and maintenance. The quality of the data is important as is the training of operators.

The subsequent panel discussion included presentations from representatives from four companies. *Don Smith*, from Bruel and Kjaer, spoke on "Reliable fault detection without false alarms". He identified five important aspects for the measurement: frequency range, dynamic range, mounting of accelerometers, signal analysis and the correct interpretations of changes in spectra. *Peter Stapleton*, from Hewlett Packard, followed with a discussion of the advantages of dynamic signal analysers. This led to some discussion on the need for Standards in equipment. The next speaker was *John Morey*, from Tensor Systems, who described condition monitoring systems using portable data collectors utilising proximity probes and/or accelerometers. The PC based analysis system reduces the overall cost of the condition monitoring system. *Peter Osborne*, from Maintenance System Consolidated P/L, outlined the advantages and benefits of predictive systems with examples of typical applications.

While a number of issues were raised in the general discussion, an important one related to the estimate of the cost of a system. All the speakers agreed that, while the actual costs of the monitoring system depended on the scale of the project, the cost of equipment loss is likely to be very much greater. The problem is to get management to believe the potential benefits and savings of a complete condition monitoring system.

The general discussion continued during the light lunch. This was also a time for further demonstrations of the equipment and computer software available for assisting in the diagnosis of faults. The questionnaires returned by the participants were unanimous in stating that the seminar had been interesting and worthwhile.

—*Marion Burgess.*

John Ernest Benson, D.Sc.Eng., M.A.A.S.

On 2nd August 1989, Dr J E Benson, known affectionately to his friends as "Ern", passed away at the age of 78. His loss is felt by a wide circle of friends and colleagues, among them the electroacoustics community where he was continuing to contribute to our understanding, of loudspeakers especially, to the moment of his death. We are grateful to have had his friendship, encouragement and advice for so long, but our deep sense of personal loss is compounded with regret for what he might have achieved even further.

Ern Benson was born in 1911 and educated at Sydney Technical High School and Sydney University, graduating Bachelor of Science (BSc) in 1932 and Bachelor of Engineering (BE) with First Class Honours in 1934. Little engineering work being available then in the Great Depression, he took up a Teachers' College Scholarship and obtained a Diploma of Education (Dip Ed) from Sydney University. When a position became available at the end of 1934, he joined the Research Laboratories of Amalgamated Wireless Australasia (AWA) Ltd where he tested the carrier frequencies of MF broadcasting stations. When crystal control of these frequencies became mandatory, he specialised in the study of piezo-electric crystals. Ten published papers resulting from his work in this field led to a Master of Engineering (ME) degree from Sydney University, with First Class Honours and the University Medal, in 1945.

Ern's life was permeated by his Christian belief and his devotion to the Anglican Church, as a Sunday School teacher, a member of Synod and of the World Council of Churches. That devotion led him eventually to applying the art of electroacoustics to the service of the Church.

In 1939-40, with the assistance of his wife Mavis, he constructed an electric organ following the Hammond principle that had been patented in 1936, in which the tones are produced by steel wheels rotating under magnetic pickup coils. In 1944 he built for St Anne's Church, Ryde, NSW the first model of a new musical instrument, a keyboard operated carillon, in which sounds produced by tubular bells were amplified and radiated by loudspeakers from the bell tower. AWA commercialised the design and installed a number of chime carillons in churches throughout the country in the late forties.

From 1947, when AWA inaugurated a television section at its Ashfield plant, Ern was involved in television. In particular, his paper "A Survey of the Methods of Colorimetric Principles of Colour Television", in the Proc IRE (Aust) for July and August 1951, was a landmark, both for the novelty of the material it presented and for the clarity of its exposition. It became for at least one younger author a life-long model for writing a technical paper. He continued this involvement, with a number of clearly-presented demonstrations and lectures throughout the fifties and sixties.

In the late fifties Ernest had been involved in designing loudspeakers, in particular a stereophonic system for the large auditorium of Sydney Town Hall. In 1960, when AWA submitted a tender for Electroacoustics and Signalling Systems for the Sydney Opera House, which was then in the long process of being built, the fine performance of the Sydney Town Hall installation was a deciding factor in acceptance of AWA's tender by the Sydney Opera House Trust. When the Opera House opened in October 1973, the fidelity of reproduction of his electrically-tapered column loudspeakers was an outstanding feature and one of the contributions to the Opera House installation for which AWA as an organisation and Ern personally had received a Duke of Edinburgh prize for industrial design in 1972.

Ern published papers on the "Theory and Design of Loudspeaker Enclosures", in three parts in the Proc IREE Aust and the AWA Technical Review between 1969 and 1972. These were followed by "An Introduction to the Design of Filtered Loudspeaker Systems", first published in the AWA Technical Review in 1973, and reprinted in 1975 in the Proc IREE and Journal of the Audio Engineering Society, and followed again by more detailed work on loudspeaker systems incorporating electrical filters in the AWA Review in 1974 and 1975. These seven papers constitute some of the most important work published on loudspeaker design. Because of their wealth of detail, new insights and clarity of presentation, they are still repaying study fifteen to twenty years later. They constituted, along with his earlier work on piezo-electric crystals and television, the basis of an award of Doctor of Science in Engineering (D Sc Eng) by Sydney University in 1975.

Besides his highly innovative engineering work and his devotion to many aspects of the Anglican Church, Ern edited the AWA Technical Review for 27 years up to his retirement from AWA in 1975. From 1975 on, he continued to apply his expertise in electroacoustics to the design of loudspeakers for high quality sound reproduction, in homes and for a number of large buildings, halls and churches, including St Andrew's Cathedral in Sydney. He was also a consultant for loudspeaker design, incorporating his electrically-tapered columns, in the new national Parliament House in Canberra that was opened in October 1988.

He also took a keen interest in the work of Standards Australia (SA) on electroacoustics. He had chaired the relevant committe TE/24 (later TE/8), which complements TC84 of the International Electrotechnical Committee (IEC), from 1968 to 1980, and continued to make solid contributions to its work in setting Australian and international standards right up to the day of his death, always characterised by his usual care for detail and clarity of exposition.

Dr Benson was a Fellow of the Institution of Radio and Electronics Engineers Australia (IREE), the Institution of Engineers Australia (IE Aust), and a Member of the Audio Engineering Society Inc (AES) and the Australian Acoustical Society (AAS).

Those of us who knew him and worked with him are deeply aware of the contribution he has made to our lives, by his example, his encouragement, his diligence, his kindness, his generosity and his fund of wisdom on all matters, including electroacoustics. We are grateful for the great contributions he made to society during his life and cannot suppress a pang for the loss of contributions that he might still have made, was still making, when he passed from us.

Ern Benson is survived by his wife Mavis, whose support in all things he continually acknowledged, and their two sons Ronald Ernest and David John.

We will remember him gratefully as long as we have memory.

Neville Thiele
(reprinted from IREE Monitor).

REPORT

INTER-NOISE 89

NEWPORT BEACH, CALIFORNIA,
DECEMBER 4-6th 1989

Anita Lawrence
Chairman, Inter-Noise 91

Inter-Noise 89 was organised on behalf of the International Institute of Noise Control Engineering, I-INCE, by INCE-USA. The professionalism of the organisers was obvious, and to be expected, as until recently, Inter-Noise Conferences were held in the United States every second year, (with the growth of member countries, this has now been reduced to every third year).

The venue was the Newport Beach Marriott Hotel which was fully booked by the conference delegates. The location was very pleasant with an adjoining golf course, the nearby harbour with wall-to-wall luxury "yachts" and an extraordinary retailing development called "Fashion Island" just opposite!

The theme of the meeting was "Engineering for environmental noise control" and *Dr Leo Beranek* presented the opening plenary paper "Criteria for controlling noise and vibration" in which he gave an overview of many of the criteria in use for evaluating speech interference, environmental noise and human response to vibration and for estimating the risk of hearing damage. He proposed a "better unit" to measure the cumulative noise exposure of a person or population. The second distinguished lecture was presented by *Dr Jiri Tichy* on "Noise control applications of sound intensity".

The 260 contributed papers were printed in two volumes of proceedings and they were presented in six parallel sessions. (Despite the requirement to forward a registration fee with each contributed paper there were still a few "no-shows"). The topics ranged through noise sources, propagation, noise control (including several papers on active noise control), vibration and shock, transportation noise, the effects of noise, diagnostic and analysis techniques and legislation. The overwhelming number of participants were from the United States, although some 30 countries were represented altogether — there was a numerically disappointing delegation from Australia.

A very large technical exhibition was presented, with considerable emphasis on software developments for measurement, diagnostics and analysis.

A short reception was held on both Monday and Tuesday evenings, in the dramatic open-roofed atrium of the hotel. These were very pleasant occasions, enabling delegates to meet old friends and to make new ones.

The closing plenary session included the presentation of five excellence awards for students' contributed papers. Tor Kihlman, the Chairman of Inter-Noise 90 then invited all delegates to participate in the next conference to be held in Gothenburg, Sweden, August 13-15, 1990. The slides of the city and country were very attractive and the meeting itself, to be held at Chalmers University, should be very interesting. Technical visits are planned for the Thursday following the meeting and include the Volvo and Saab plants.

I hope very much that as many Australians as possible participate in the Gothenburg meeting and assist in encouraging delegates to attend Inter-Noise 91 in Sydney from December 2-4, 1991 — please make a note of the dates now and plan to present a paper, or at least to *participate* in Inter-Noise 91 and take the opportunity to meet your colleagues from all round the world and to discuss ideas and problems in noise control engineering with them!

BOOK REVIEWS

CONCERT SOUND AND LIGHTING SYSTEMS

J Vasey

Focal Press, USA, 1989, pp 178, ISBN O-240-51798-9.
Australian Distributor: Butterworths Pty Ltd, 271-273 Lane Cove Road, North Ryde, NSW 2113.
Price A$45.

Concert Sound and Lighting Systems, as John Vasey points out in his preface, was intended for the sound and equipment operator involved in large concert productions. It can be used as an effective introduction to the complications of assembling a large sound reinforcement system, but lacks the depth needed to gain any real understanding of the equipment operation.

However, for the uninitiated, the book does give an overview of reinforcement and, as was made clear, is not intended to replace or reduce the need for practical training. It is well set up as a reference text, with the inclusion of a good Glossary and Index. Some of the Appendices contain invaluable technical information to those wishing to work in this field but without the technical background.

There are a number of worrying technical errors in the text that may cause confusion but in general the book is easily readable and up-to-date with current techniques practised in large reinforcement sound systems.

Subjects covered include:

Sound Systems

- speaker systems
- power amplifiers
- Multicore systems
- mixing consoles and output drive systems
- effects units
- insert signal processors
- monitor systems
- microphones
- sound system setup.

Lighting Systems

- trusses and grids (lighting support structures)
- lamps, dimmer equipment, control cables and consoles
- intercom systems
- smoke machines
- lighting setup procedure.

This book is primarily set up for the large concert sound systems and does not attempt to address the typical middle range systems that are used by the average owner/ operator. Composite speaker systems (full audio frequency range speakers) and active processor systems (processors which compensate for the non ideal frequency/ phase response of the speakers) are not covered in the text at all.

The lighting section of the book is similarly treated in that large conthe case with sound reinforcement. cert systems are described although these practices are more easily applied to smaller systems than is This section does provide a good overview of lighting systems for concerts through to theatre applications with comprehensive colour filter media guides.

In conclusion the book provides a good overview of sound reinforcement and lighting systems. Fo, those who have had little experience in this field it can be useful as a reference to terms and techniques.

Glen Thurecht

* * *

Glen Thurecht is a Director of Applied Audio, a Canberra based company providing professional engineering and development of audio electronic equipment for use in commercial and broadcast applications. Glen is a qualified engineer with 15 years' experience in sound reinforcement.

SOUND INTENSITY

F J Fahy

Elsevier Applied Science, 1989, pp 274, Hard Cover,
ISBN 1 85166 319 3.
Australian Distributor: DA Books, PO Box 163, Mitcham, Vic 3132.
Price A$97.75.

This book is the first and a very timely monograph on the theory and measurement of sound intensity, a subject which has seen extensive research and development in the eighties. The author himself is the pioneer in the field. He and J Y Chung independently published in 1977 the cross-spectral method of measuring sound intensity using two pressure microphones. The sound intensity technique is a very powerful technique which enables "in situ" measurements of the flow of energy in sound fields, a feat that is beyond the capability of conventional sound pressure measuring instrumentation. Commercial sound intensity measuring systems have been available since 1980.

The book is divided into nine chapters. The first four chapters cover the history and development of sound intensity measurements, the nature of sound and the behaviour of sound waves, the flow of energy in sound fields and the derivation of complex intensity. The principles of measuring sound intensity and the practical implementation with hardware have been carefully described in Chapters 5 and 6. The principles of applying sound intensity measurements in different areas are outlined in Chapter 7 followed by practical applications described in Chapter 8. The draft ISO DP/9614 for determination of the sound power levels of noise source by sound intensity measurement is also included in Chapter 8. The measurement of sound intensity in flow ducts, which is still very much under research and development, is covered in Chapter 9. There are 148 references quoted which a reader can refer to for further details.

While highlighting the advantages in using sound intensity measurements, the author has pointed out that the technique is not a magic wand that will give solutions in all situations. The understanding of the limitations of the technique and its accuracy, together with intelligent interpretation of the results, are the basic ingredients required for the successful application of the sound intensity technique. The author stated in the preface that his "principal purpose in writing this book has been to compile information about sound intensity and its measurement which is otherwise accessible only to those who have the time and energy to seek out and peruse the wide range of publications in which it appears". The author has certainly achieved his objective in producing a well written and understandable book on the subject. It is without doubt that, in the years to come, the sound intensity technique will be extensively used in most applications dealing with acoustics and noise control. This book will be very useful to both beginners and experts in the field of sound intensity measurements and will be a valuable addition to any library in the field of acoustics and noise control.

Joseph Lai

* * *

Joseph Lai is a Senior Lecturer in the Department of Mechanical Engineering at the Australian Defence Force Academy. He is the Director of the Acoustics and Vibration Centre, established within the Department, and has had considerable experience with sound intensity measurements.

ACOUSTICS AND THE BUILT ENVIRONMENT

Anita Lawrence

Elsevier Applied Science 1989,
pp 242, Hard Cover,
ISBN 1 85166 308 8.
Australian Distributor: DA Books, PO Box 163, Mitcham, Vic 3132.
Price A$93.25.

In the Preface of *Acoustics and the Built Environment*, Anita Lawrence states that: "It is therefore very important that the professionals involved with the design and construction of the 'built environment' should understand the principles of acoustics". This book attempts to provide the information necessary for this understanding.

The first chapter is on the theory of sound, characteristics of sound sources and the perception of sound and vibration. Chapters 2 and 3 form a pair. Chapter 2 provides information about noise sources in the community and the propagation of sound while Chapter 3 deals with planning considerations. Included are guidelines for assessing compatible land-use near each of the major sources of noise in the community, namely road traffic, aircraft, railways and industry. Chapter 4 is entitled "Room Acoustics" and is concerned with the design of rooms to ensure that the wanted sounds, such as speech and music, are kept in their most desirable form. Sound and vibration transmission through buildings and the methods for control are discussed in Chapter 5. The last chapter identifies the applications of the principles for specific building types. The main acoustic factors to be taken into account for 21 different building types are given, with cross references to the appropriate sections in the preceding chapters. It is perhaps this chapter which will be of most use to architects, designers and builders as it provides rapid access to information on the relevant aspects.

Those familiar with Lawrence's book *Architectural Acoustics* will recognise the similar style and layout. All chapters conclude with comprehensive reference lists which are essential in a book which attempts to cover such a wide range of topics. While the material in the text may be adequate in many circumstances there are often times when the source needs to be consulted or additional details found. These references are not just to other books, but in most cases are to journal articles and conference papers.

Anita's vast teaching experience is evident from the clear explanations of complex concepts. While equations are included in relevant sections, they are within the context of the text and unlikely to deter the non-mathematical reader. In relevant places there are worked examples, such as overall transmission loss for wall incorporating a window and noise attenuation for enclosure of roof/ceiling, wall and window. It is a pity that a different type style or layout was not used for the examples to identify them clearly from the main text.

In summary, this is a very comprehensive book which provides clear explanations of the important considerations relevant to the acoustic aspects of buildings. It achieves the aim of bridging the gap between the theory and the practical applications. It is a practical reference book for architects, planners and designers and for students in these areas. It also provides much useful information for those who specialise in the area of acoustics.

Marion Burgess

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Marion Burgess is currently a research officer at the Australian Defence Force Academy in Canberra but spent many years in the School of Architecture at NSW University where she was involved with teaching and research in collaboration with Anita Lawrence.

NONLINEAR OPTICS AND ACOUSTICS OF FLUIDS

F V Bunkin (Editor)

Nova Science Publishers, 1989,
pp 172, Hard Cover,
ISBN 0-941743-28-4.
Australian Distributor: DA Books, 11-13 Station Street, Mitcham, Vic 3132. Price A$69.50.

This book comprises three seemingly unconnected articles on nonlinear techniques in the study of fluids by three groups of Russian authors. There are, however, some interesting common threads apart from a common author (G A Lyakhov) in each section. Unfortunately, despite the title the book strings along the dedicated acoustician right till the end before touching on nonlinear acoustic interactions.

The first chapter describes the principles of distributed feedback lasers and their application to the study of fluids. DFB lasers spatially modulate the dielectric properties of the lasing medium, usually by creating a standing light wave in the medium from a separate pump laser. The lasing frequency and direction are then determined without the use of mirrors since the spatially modulated gain medium only supports modes with wave vectors that satisfy the Bragg condition.

The second (and longest) chapter is devoted to nonlinear optical processes in orientationally-ordered liquids, primarily liquid crystals (LCs).

The final chapter is devoted to the determination of the kinetic properties of liquids by nonlinear optical and acoustical means. The propagation of intense light in binary fluids is examined, and experiments have identified a self focusing mechanism due to light induced changes in the concentrations of the constituents (separate from purely thermal effects) near the critical stratification temperature. A theoretical treatment indicates that such experiments should also be possible using strong acoustic waves (10^2-10^3 W/cm^2), although generation of shock waves and strong background reflections are serious impediments to such studies. Acoustic self focusing due to thermal mechanisms, and the acoustic analogue of self-induced transparency (where the penetration of the beam increases with increasing power) have been observed. However, stimulated scattering effects such as modulation sidebands to the laser frequency in stimulated Brillouin scattering have yet to be seen (although they are predicted) for acoustic waves.

The book is mainly theoretical but is interspersed with practical estimates of the strength of the predicted phenomena. Unfortunately the use of diagrams is sparse, and is not helped by the retention of Russian script in some instances. The language gives the impression of translation by a non-native speaker or by a non-expert in the field so the jargon does not quite sound right, and the style is sometimes grandiose. The physics presented in this volume is however wide-ranging and interdisciplinary, so if you can bear with the presentation, it makes for some interesting reading.

Ken Baldwyn

Ken Baldwyn is a Research Fellow in the Laser Physics Centre, Research School of Physical Sciences at ANU. His field of research is the experimental investigation of nonlinear optical processes in atomic and molecular systems using tunable, high power pulsed dye lasers. These fundamental studies have applications to the generation of narrow-band, coherent vacuum ultraviolet radiation which is used in his laboratory to carry out high resolution spectroscopy of molecules of atmospheris interest.

NEW PRODUCTS

Bruel & Kjaer

IBM-compatible Intensity Mapping

Sound Intensity Program WT9378 is now available. It is an easy-to-use, versatile software package for the measurement and analysis of sound intensity or sound pressure data. It maps sound intensity, calculates sound power and ranks user-specified planar sectors in terms/order of sound power. The new feature, which sets it apart from its predecessors, is the calculation and mapping of the pressure-intensity index. In this way the nature of the sound field over a measurement surface is easily determined.

Sound Intensity Program WT9378 can be used with all Bruel & Kjaer intensity analyzers, for example, Real-Time Frequency Analyzer Type 2133. Measurements can be made in 1/1-, 1/3- and 1/12-octave bandwidths or in narrow bands, depending on which analyzer is being used.

The user-friendly, menu-driven program is written in Turbo Pascal and runs on an IBM® personal computer PS/2 series or AT using DOS version 3.0 or later.

Electroacoustic Test Systems

Electroacoustic Test Systems Types 9598, 9620 and 9621 are based on the new Electroacoustic Test Software Type 5301 for use with an IBM series PS/2 or AT Computer.

The systems are extremely versatile yet very simple to operate due to a menu-controlled user interface with different access levels and complete IEEE/IEC bus-control. They offer advanced postprocessing of measurements, extensive storage facilities and displays of measurement curves with flexible display formats. The flexible structure of the program allows measurements and processing to be set up in arbitrarily selected sets of frequencies.

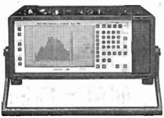
The Type 9598 System includes Sine/Noise Generator Type 1049 and is delivered with a bus-controlled compressor loop for very accurate acoustical measurements, eg, telephone measurements. The Type 9620 System includes Sine Generator Type 1051 and may be used for both acoustical and electrical measurements, eg, loudspeaker measurements. The Type 9621 System is similar to Type 9598 except that it uses Generator Type 1054. The versatility of these systems makes them suited for use in both development and quality-control applications, and a range of instruments and transducers from Bruel & Kjaer allows both systems to be expanded to specific applications.

Real Time Frequency Analyser

Weighing < 10 kg and with > 4 hours of operation from built-in rechargeable batteries, Bruel & Kjaer's NEW Real-time Frequency Analyzer Type 2143 is the ideal analyzer for acoustical and vibration measurements in the field and in the laboratory.

Type 2143 operates in real-time with bandwidths down to 1/24-octaves, and is able to read 1000 spectra per second into non-volatile memory, thus making it both an excellent analyzer and a powerful data-gathering device. The memory capacity in the standard unit is sufficient for 512 1/3-octave spectra.

The built-in PC/MS-DOS compatible



disk-drive makes it easy to store the measured data and can be used to transfer data to other equipment. Type 2143 is operated by means of user-interactive menus while a system of on-screen help pages enables even a novice user to realise the full potential of the analyzer in the field. Type 2143 has further control and data-processing possibilities via the IEEE-488 and RS 232C interfaces.

Force Transducer/Impact Hammer

The latest model in Bruel & Kjaer's force transducer line-up, the Type 8203, answers the call for smaller, lighter instruments suitable for dynamic and impact force measurements on delicate structures. Compact in size, the new transducer is constructed of titanium and steel (type AISI 303) for strength and to minimize the mass. It is supplied with a complete force testing package which comprises a stinger, accessories for impact testing and other accessories for ease of operation and versatility.

For impact testing, an impact hammer is easily assembled to be used for fast, accurate measurements with a minimum of interaction with the structure. The hammer can be used for the measurement of frequency response functions applied to modal analysis, quality control, mechanical impedance, etc. Impact testing has a lower signal-to-noise ratio than using an attached exciter. However, by using the time-weighting functions incorporated on a frequency analyzer such as the Bruel & Kjaer Dual Channel Analyzer Type 2032, this disadvantage is overcome.

For the application of an attached exciter, the kit provides stinger and attachment gadgets to decouple the exciter from the test structure, and thus minimize undesirable modifications of the dynamics of the structure. (The stinger also provides a mechanical protection fuse to guard against possible damage to exciter, transducer and test structure.) In addition to the measurement of frequency response functions, the transducer may also be used as a part of a feedback control loop, or for any other force measurements where quality and size are determining parameters.

New Applications Notes

Two new Application Notes from Bruel & Kjaer detail different approaches to vibration monitoring of the Pulp & Paper industry's critical paper-machines. Both approaches have led to detecting faults at a very early stage, and actual case-stories are fully documented.

A Case Study from the Alma Paper Mill concentrates on how a Canadian Paper Mill uses the Spectrum Comparison technique for detecting faults in rolling-element bearings. *A Case Study from the Kenogami Paper Mill* describes how another Canadian Mill uses Crest Factor techniques for screening the many bearings for possible faults, and Cepstrum Analysis for confirming the faults. The Cepstrum Analysis is also used for detecting worn felts and roll surface-defects, as a valid means for quality control.

Further information: Bruel & Kjaer, 24 Tepko Road, Terrey Hills, NSW 2084. Tel: (02) 450 2066.

Cirrus

Convertible Grade Sound Level Meter

The CRL 2.35A not only has the grade convertible L3M microphone system for its input, but also the full DP 15 system function interface. At the input socket a huge range of L3M microphone units its available, giving a measurement range from 10 to 160 dB in many different configurations and grades; while at the DP 15 analogue interface various plug-in units are available to perform a wide variety of measuring functions.

The concept of different plug-ins allows the purchase of an instrument to exactly the specification desired with the ability to change this specification at will. Amongst the functions available are Leq, Sound Exposure, Dose Measurement, Frequency Analysis, Vibration

Measurement, Digital Read-out and Speed Sensitive Measurements.

The main body of the CRL 2.35A features S(low), F(ast) and I(mpulse) time constants with "Hold" and "Automatic Memory" on all three response speeds together with "A" and "Lin" weightings. The basic instrument has ranges in 10 dB steps allowing full use of the wide dynamic span which can be extended down below 20 dB when an octave band filter is in use.

Automatic Safety Sign

While ear defenders can protect the worker against excessive noise, almost everyone dislikes wearing them as they can often cause discomfort and hinder communications. In many factories the noise level is only high for part of the time, so the ideal solution would be a sign which lit up ONLY when the 90 dB (or 85 dB) level was exceeded.

The Cirrus Research CRL 301HS Automatic Noise Alarm is such a sign which gives a visual warning of high noise levels. The display of the CRL 301HS has a blue and white logo which lights up when a pre-set noise level is exceeded, any level between 40 and 110 dB can be pre-set. On reaching the pre-set level, after an integrated delay period the CRL 301HS illuminates informing employees that ear protection should be worn. Throughout this "on" phase the light will switch off only when the short-term average noise level (Leq) is reduced to below the pre-set level.

If required, three microphones can be used to activate the CRL 301HS from the combined noise of a very wide area. Slave repeater signs can be added to the system, working from one base unit, giving extended visual coverage throughout a large factory area or even into the plant manager's office.

Further information: M B & K J Davidson, 17 Roberna Street, Moorabbin, Vic 3189. Tel: (03) 555 7277.

Peters

Screening Audiometers

The **AP27** Screening Audiometer, manufactured by ALFRED PETERS, provides a simple means of establishing an employee's hearing levels at an initial medical check and thereafter allows easy routine screening which will ensure early detection of any claims for hearing loss due to noise exposure.

The AP27 is fully portable and has eight frequencies doing from 250 Hz to 8 kHz, thus covering the recommendations of the International IEC recommendations, the American OSHA and also the UK Health and Safety Executive. These frequencies are at 19 hearing levels which range from —10 to + 80 dB in 5 dB increments, allowing excellent discrimination of small hearing differences.

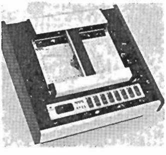
The AP27 is totally "user friendly", having simple, easy-to-use controls and a front panel indicator showing both the internal state of the battery and also the presence of a signal during the test procedure. In addition, a patient response button can be attached to allow the test to be carried out in silence and also to ensure that the patient does not "read" the tones from the operator's movements.

The earphones on the AP27 are the internationally standardised TDH 39 units and these can be fitted with noise reducing earmuffs — recommended if ambient background noise could interfere with the tests. Being fully portable, the AP27 is built into an attache case and can be run from batteries or from an AC supply.

* * *

The **AP25** complies with the IEC 645 specification for Class 4 instruments and conforms with electrical safety specification BS 5724 Part 1 (IEC601-1). It is primarily intended as a screening audiometer for industry but has obvious uses in any environment where large numbers of tests are required such as in schools, military forces, etc.

For automatic testing, the patient is provided with a push button and the operator merely explains the simple test procedure; this involves the patient listening to the various tones presented and pressing the button whilst the tone is audible and releasing the button when the tone is absent. The operator then presses "start" and the test begins. Responding to the signals, the pen travels across the audiogram chart tracing out a zig-zag of the threshold of hearing at all frequencies in each ear. In this way the patient "produces" his



own audiogram for both ears and the test-time is less than nine minutes.

With the option of automatic stepped or swept frequency facility the ALFRED PETERS AP285 makes early detection of hearing loss far easier. The unit is specially designed for industrial hearing conservation programmes and with electronic touch controls and a built-in XY pen recorder it requires minimum operator training.

Further information: M B & K J Davidson, 17 Roberna Street, Moorabbin, Vic 3189. Tel: (03) 555 7277.

VIPAC

Portable FFT Analyser

The new CF-250, made by Ono Sokki, is a portable FFT analyser developed for easy diagnosis of facilities and equipment at work site. The unit is a compact, lightweight attache case unit which can be operated using AC, DC or battery power suppleis.

The CF-250's vibration analysis functions include order ratio analysis for rotating machines and diagnostic func-

tions for roller bearings and gears, so it can be used as a portable diagnostic instrument. The CF-250 has built-in field balancing functions so it can be used as a portable balancer.

Other features include: a low-pass filter and envelope function, built-in large memory capacity, optional memory cards and a GP-IB interface.

Blast Monitoring Seismograph

Instantel Inc, the market leader in blast monitoring seismographs, has taken the most asked for features of the industry standard DS-477 and combined them with the best price in the industry. The result is the DS-277, a no nonsense full waveform recorder which provides immediate and accurate blast records.

The DS-277 requires only two steps to be followed. Turn the power *ON* and press *Start Monitor.* After the blast event has been recorded the results are documented on the plotter. Multiple copies can be generated in the field. Prior to monitoring, the *Setups* can be verified and/or changed using a LCD and tactile keyboard. These include trigger level and trigger source, record mode, record time and time and date.

Further information: Vipac Engineers & Scientists, 275 Normanby Road, Port Melbourne, Vic 3207. Tel: (03) 647 9700.

New Publications

The following publications have been received by the Society and are held temporarily in the Acoustics Laboratory, University of NSW where they are available for inspection or loan. Photocopies (not in contravention of copyright conditions) may be ordered from Cronulla Printing Co at cost: Tel (02) 523 5954; Fax (02) 523 9637.

JOURNALS

Applied Acoustics

Vol 28 Nos 2, 3

Vol 28 No 3 includes: Qualification of room diffusion for absorption measurements by **J L Davy, W A Davern** and **P Dubout.**

Australian Journal of Audiology

Vol 11 No 2, Nov 1989

Canadian Acoustics

Vol 17 No 4, Oct 1989

J Catgut Acoustical Society

Vol 1 No 4, Nov 1989

I-INCE Newsletters 54, 55

New Zealand Acoustics

Vol 2 No 3, Sep 1989

Vol 2 No 4, Dec 1989

Shock and Vibration Digest

Vol 21 Nos 10, 11, 12
Vol 22 No 1

REPORTS

ISVR Technical Reports

University of Southampton
No 180, July 1989, **M O Ene** and **D Anderton,** Diesel engine exhaust emissions, 9 pp.

No 173, March 1989, **C Y Chen and M J Griffin,** The application of a nonlinear least squares method to predicting seat transmissibility, 28 pp.

No 181, July 1989, **R S Ming, G J Stimpson, N Lalor,** A study of the vibrational trasmission through flanged joints, 41 pp.

No 183 September 1989, **P Vitiello, P A Nelson and M Petyt,** Numerical studies of the active control of sound transmission through partitions, 59 pp.

THESIS ABSTRACTS

The following abstracts describe recent successful research conducted in the Department of Architectural Science at the University of Sydney under the supervision of Dr Ferge Fricke.

Aspects of Outdoor Sound Propagation

Andrew Madry —PhD thesis

PhD thesis

Abstract . . .

The study of sound propagation close to the surface of the earth is important. People may be adversely affected by the presence of loud noise. Environmental considerations make it necessary to be able to predict the sound levels which would be produced by the introduction of noise sources. This thesis investigates a number of factors which influence outdoor sound propagation. The interaction of sound with the ground and atmosphere is also a useful tool that can be used to obtain information about properties which are difficult to measure directly.

Experiments are performed outdoors to compare measurements of sound attenuation over homogeneous ground surfaces with theory. The case of a ground surface with a discontinuity in impedance is investigated. An experimental technique is described which makes possible the measurement of the diffraction contribution from an impedance discontinuity in a laboratory model. A method to calculate the effect of diffraction from the discontinuity is derived using Kirchoff diffraction theory. The result is the same as a previously proposed method except that using this derivation it is possible to specify conditions for which the method should be accurate. A physical explanation for the ground wave helps to explain discrepancies of measurements with theory.

The effect of a sonic velocity gradient on propagation above a ground surface is studied. Measurements of sound attenuation are made in various atmospheric conditions at several locations. An integral method of calculating the effect of refraction on sound is used for comparison. In a refractive shadow zone the method is shown to give predictions which are in reasonable agreement with measurements. Methods such as ray theory are not valid in a refractive shadow zone. It is found to be possible to make predictions for the effect of non-linear sound speed gradients. However, no experimental evidence in accurately monitored atmospheric conditions is available for comparison. Limitations of the integral method in strong refractive conditions are pointed out.

Atmospheric turbulence is one of the least understood factors in outdoor sound propagation. Experiments are carried out to measure the fluctuations of sound levels in the presence of turbulence. Comparison of measurements is made with two theories of turbulence.

Outdoor measurements of sound levels in a refractive shadow do not agree with predictions made using accurate theory. Scattering of sound into the shadow zone by turbulence has been suggested as a possible explanation. Using signal processing techniques it is found to be possible to locate the region in space from which sound reaches a receiver. Experimental results indicate that scattering is a dominant mechanism in the case when a receiver is in a refractive shadow. Scattering is observed in an experiment away from the influence of the ground. The results suggest that certain large scale turbulence eddies affect propagation.

Simplified Methods of Measuring Reverberation Time

Chao Sun

MSc(Architecture) thesis

Abstract . . .

Two alternative methods of measuring reverberation time in the room have been developed and investigated.

A simplified method of measuring reverberation time is described, which uses a series of white noise or filtered white noise pulses to excite an enclosure. A sound level meter is used to measure the maximum and minimum sound levels during the pulse cycle. This method can be used for on-the-spot assessments of rooms with reverberation times greater than 1.0 second. The reverberation times measured by this method agree with those measured by standard methods within an accuracy of ±20%.

Using a subjective comparison method based on earlier work by Seraphim, the reverberation time is determined by aurally comparing the decay of sound in a room with a standard decaying signal from a tape recorder or other electronic device. Results of paired comparison tests are presented for different reverberation times and different techniques. The data shows that this comparison method is suitable for measuring reverberation times of less than 1.5 seconds. The reverberation times obtained by this method agree with those obtained by the standard method to within an accuracy of ±0.2 seconds.

The accuracy of both of these techniques is considered sufficient for most purposes. The methods allow architects and others to deal with acoustic problems with a minimum of equipment and instrumentation.

NEWS . . .

New Era Noise Barrier to be used for Sydney Freeway

The Roads and Traffic Authority of NSW will install Australia's first **Fanwall** noise barrier on a new stretch of highway that cuts through the Sydney suburb of Rhodes. The RTA had earlier purchased and removed a number of houses from what was a quiet back street to allow the new corridor to be built.

The Authority's engineers originally proposed to erect a timber sound barrier to protect neighbouring homes from road traffic noise. However, after timber was used on the new F3 freeway at Hornsby, they recognised a need to become more sensitive to public opinion. After wide-ranging evaluation of all of the systems currently available, the engineers then gave the residents of Rhodes the opportunity to make the final selection themselves. The majority chose Fanwall — a modular, concrete, free-standing system licensed to the Reinforced Earth group in Australia.

Concrete barriers have dominated the market in the United States since Congress enacted laws regulating noise emissions. Fanwall is widely used there on freeways and other installations. Reinforced Earth's Fanwall product manager, **Gary Power,** said that up to 10 dBA reduction in sound level had been achieved at Los Angeles International Airport, where it had been used both as a noise and a security barrier.

The barrier to be built at Rhodes will be 2.5 metres high and, because its installations can be staged, it will also help to protect local residents from equipment noise during the period the road is being constructed.

For further information: Gary Power, Reinforced Earth Pty Ltd, 26 Ridge Street, North Sydney, NSW 2060. Telephone (02) 922 2122, Facsimile (02) 957 3831.

Press release by courtesy of Harold Abrahams & Associates Pty Ltd, 8 Berry Street, North Sydney, NSW 2060.

Worksafe Australia Seeks Noise Information

If you work in, or manage, a noisy environment, the National Occupational Health and Safety Commission (Worksafe Australia) would like to hear from you.

The Commission has identified noise-induced hearing loss (NIHL) as a major workplace hazard, responsible for nearly 10,000 workers' compensation cases for industrial deafness a year, costing $70 million.

As part of its national strategy to prevent NIHL, Worksafe Australia is developing a national information program and is seeking information from workers and management for possible inclusion in associated publications.

Objectives of the strategy are to:

- Raise public awareness about NIHL.
- Focus industry attention on taking preventive action.
- Co-ordinate and provide information products.
- Stimulate and facilitate hearing conservation programs and services.

Information products to be published include case studies of noise control or hearing conservation successfully implemented in the workplace.

Worksafe Australia is particularly interested in hearing about initiatives including the following elements:

- Mechanisms to assess the extent of the noise problem.
- Initiatives aiming to reduce exposure or reduce noise levels at source.
- Practical examples of solutions used to reduce noise, such as machinery re-design.
- Noise policies and reports, including *Buy Quiet* guidelines.

Information should be sent to Worksafe Australia, GPO Box 58, Sydney 2001; or contact Dick Waugh on (02) 265 7580 or Justine Francis (02) 265 7578.

Changes at Richard Heggie Associates

The period from late 1989 to early February, 1990 has seen the arrival of four new staff members at acoustical consultants Richard Heggie Associates. They include *David Lindsey,* a physics graduate with several years experience in underwater acoustics and general acoustical consulting, *Geoff Bray* from Flakt Australia, a specialist in vibration of rotating machinery and machinery condition monitoring, and *Angela Jones,* recently graduated from the University of Western Sydney with a degree in Environmental Health. *Jodie Thwaite* also joined as receptionist and secretary, bringing her own chic style to the company's contact with the outside world.

During the same period, the company was saddened to lose a much valued employee, the bright and sparkly *Sue Ridler,* back to her native England. Sue contributed greatly to the growth of the practice over the past two years, and she will be missed by many in the Australian acoustics fraternity.

Growing demand in Queensland for acoustics, vibration and blasting services has also lead to Richard Heggie Associates opening a Brisbane office in mid February this year, headed by company director, *Dick Godson.* Apart from a broad range of general consulting work, the company has been engaged to conduct noise and vibration studies for a major tunnelling project in Brisbane; duplication of Queensland Rail's inner city rail tunnels.

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ADVERTISER INDEX

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

FUTURE EVENTS —

● Indicates an Australian Conference

1990

• April 19-20, PERTH
1990 AAS ANNUAL CONFERENCE
Interior Noise Climates.
Details: AAS 1990 Conference Secretary, PO Box 5077, Cloisters Square, Perth 6000. Tel: (09) 327 8818.

• May 1-3, SYDNEY
TACTILE AIDS, HEARING AIDS AND COCHLEAR IMPLANTS
Details: National Acoustics Laboratory, 126 Greville Street, Chatswood, NSW 2067.

May 21-25, PENNSYLVANIA
MEETING OF ACOUSTICAL SOCIETY OF AMERICA
Details: Murray Strasberg, ASA, 500 Sunnyside Blvd., Woodbury, New York 11797, USA.

June 6-8, BRIGHTON (UK)
16th CONGRESS OF A ICB
The Future for Noise Control — towards an interdisciplinary approach.
Details: Dr. iur. Willy Aecherli, Rechtsanwalt Hirschenplatz 7, CH-6004, Luzern, Switzerland.

June 19-23, LEUVEN
SYMPOSIUM ON PHYSICAL ACOUSTICS
Details: Prof Leroy, Katholieke Universiteit Leuven Campus Kortrijk, E-Sabbelaan, B-8500 Kortrijk, Belgium.

August 8-10, GOTHENBURG
INTERNATIONAL TIRE/ROAD NOISE CONFERENCE.
Details: Intern. Tire/Road Noise Conference, C/- Sandberg, Swedish Road and Traffic Research Institute, S-581 01 Linkoeping, Sweden.

August 13-15, GOTHENBURG
INTERNOISE 90
Dept Applied Ac, Chalmers University Technology, S-412 96 Goteborg, Sweden.

• September 18-20, MELBOURNE
VIBRATION & NOISE CONFERENCE
Details: L Koss, Dept Mech Eng, Monash University, Clayton, Melbourne, Vic, 3168.

October 9-11, LONDON
QUIET REVOLUTIONS
International Conference on Power Train and Vehicle Noise Refinement.
Details: Conference Dept C420, Institution Machanical Engineers, 1 Birdcage Walk, Westminster, London SW1H 9JJ.

• October 15-19, MELBOURNE
METROPOLIS '90
Details: Secretariat, 545 Royal Parade, Parkville, Vic 3052.

October 22-25, SENDAI
10th INTERNATIONAL ACOUSTIC EMISSION SYMPOSIUM
Details: Prof Niitsuna, Engineering, To hoku University, Aramaki aza Aoba, Sendai 980, Japan.

October 29-31, KUMAMOTO
INTERNATIONAL JOINT MEETING
Workshops on Acoustic Emission in Civil Engineering and Acoustic Emission and Rock Fracture Mechanics.
Details: Dr Ohtsu, Dept Civil & Env Engineering, Kumamoto University, Kurokami 2-39-1, Kumamoto 860, Japan.

November 18-22, KOBE
1990 INITERNATIONAL CONFERENCE ON SPOKEN LANGUAGE PROCESSING
The first international conference on spoken language processing by both humans and machines.
Details: Secretariat, ISCLP-90, c/-Simul International Inc. Kowa Building No 9, 1-8-10 Akasaka, Minato-ku, TOYKO 107 JAPAN.

November 26-30, SAN DIEGO
MEETING OF ACOUSTICAL SOCIETY OF AMERICA
Details: Fredrick Fisher, Marine Physical Lab, P-001, Scripps Institute Oceanography, Univ California, San Diego, La Jolla, CA 92093-0701, USA.

1991

May 5-9, BALTIMORE
MEETING OF ACOUSTICAL SOCIETY OF AMERICA
Details: Murray Strasberg, ASA, 500 Sunnyside Blvd., Woodbury, New York 11797, USA.

November 4-8, HOUSTON
MEETING OF ACOUSTICAL SOCIETY OF AMERICA
Details: Murray Strasberg, ASA, 500 Sunnyside Blvd., Woodbury, New York 11797, USA.

• November 26-28, BRISBANE
WESTERN PACIFIC REGIONAL ACOUSTICS CONFERENCE IV
Details: Unisearch Ltd, PO Box 1, Kensington, NSW 2033.

• December, SYDNEY
INTER-NOISE 91
Details: Unisearch Ltd, PO Box 1, Kensington, NSW 2033.

INFORMATION FOR CONTRIBUTORS

ARTICLES

Authors are requested to submit manuscripts with double-spaced typing. Normal maximum length is the equivalent of 18 pages of typing (5 printed pages) with due allowance for diagrams. Authors may be asked to pay the additional typsetting charges for articles in excess of this length.

Frequent headings and subheadings are desirable and an abstract of approx. 200 words should be included. Authors may provide a list of suggested keywords.

DIAGRAMS

Diagrams will normally be reduced to single column width (84 mm). It is important to ensure that lines and letters are thick enough to withstand any loss of definition caused by the reduction required. Captions for diagrams will be typeset and should comprise a complete description of the diagram including, if appropriate, comments on any distinctive features.

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