JULY, 1980
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acoustics and noise control in canada

JUILLET, 1980
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l'acoustique et la lutte antibruit au canada

OUR CONTRIBUTORS AND REFEREES OVER THE LAST TWO YEARS:

))) Peter Alberti))) Don Allen))) John Bain))) Mohan Barman))) Ken Barron))) Alberto Behar))) Dee Benwell))) Susan Birnie))) David Bradbury))) Bill Bradley))) Tony Brammer))) Bren Brownlee))) Philip Dickinson))) Bob Donato))) Tony Embleton))) Stuart Eaton))) Gary Faulkner))) John Foreman))) Leslie Frank))) Pauline Fullerton))) Niki Gallo))) Rosemary Garsh))) Ed Granell))) Richard Guy))) Fred Hall))) Robin Halliwell))) John Hemingway))) John Jacobson))) Tim Kelsall))) Doug Kennedy))) Kathy Kono))) Frank Krammer))) Bob Leong))) John Manuel))) Heather Manzer))) George Menzies))) Greg Michel))) Bill Mongor))) Robin Morehouse))) Tom Northwood))) Moustafa Osman))) Geoff Perry))) Joe Piercy))) Robert Rackl))) Zieg Reif))) Les Russell))) Michael Seitz))) Edgar Shaw))) Cameron Sherry))) Tom Siddon))) Louis Strasberg))) David Sutton))) John Swallow))) Winston Sydenborgh))) Martin Taylor))) Tony Taylor))) Jean-Sylvain Tessier))) Jan Tiessinga))) Jim To))) Simon Tuckett))) Eric Welbourne))) Doug Whicker))) Marianne Wood)))

WE THANK YOU ALL

acoustics and noise control in canada

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BELL-NORTHERN CANCELS NOISE

Bell-Northern Research (BNR) is developing an active sound absorbing ear-insert device. Noise in the ear canal is reduced by broadcasting a noise signal of opposite magnitude, thereby "cancelling" much of the original noise.

BNR's device is called DENS, for Dynamic Ear-Insert Noise-Reduction System. It is funded by a $61,000 contract from the Canadian Defence and Civil Institute of Environmental Medicine in Toronto.

The principle of sound cancellation is simple to grasp, but implementing it is not. The ear canal is one of only a limited number of noise situations in which implementation is at present contemplatable. Even so, BNR's team had to overcome severe difficulties in signal processing, since phase control in the feedback circuit of these devices must be maintained across a wide frequency range and yet the device must be small enough to fit in the ear. We understand that much of the necessary miniaturization work still lies ahead.

The developed DENS will resemble a hearing aid, and use not much more power. If its promise is maintained, it could constitute a significant advance in noise control technique. The successful application of this principle to other noise control areas could be even more interesting.

ARCTIC SONAR CHARTING

Readers who have noticed, in recent issues, a flurry of research contract awards for Arctic sonar devices may be interested in some of their applications.

One such project, under a contract of $321,500 awarded by the Dept. of Fisheries and Oceans to Marinav Corporation of Ottawa, pinpoints underwater obstructions by a new application of through-the-ice sonar.

The current underwater survey technique, where ice is present, involves drilling holes through the ice before taking sonar readings. A series of these holes and depth readings leads to a grid-pattern depth chart. The Marinav system still requires a hole in the ice. However, the sonar transducer is so shaped and so deployed that it leads to a continuous depth picture. This successfully eliminates a danger of the traditional grid-pattern hydrography, which is its failure to detect obstructions which lie between sounding points. These obstructions include "pingoes," which are ice and earth mounds rising from the ocean bottom and posing a serious navigation hazard.

The Marinav system has been successfully tested off Nova Scotia. It is next scheduled for cold weather testing in the Resolute Bay area using tracked vehicles. The new device will assist in harbour development in northern waters, which is essential to support Arctic resource development.

ICA MEETS IN AUSTRALIA

The International Congress on Acoustics meets July 9-16 in Sydney, Australia. A number of other acoustical meetings are also being held in Australia in July including the I.S.O. and I.E.C. Technical Committee meetings on acoustics standards. We hope to report on these meetings in a future issue.

ASA IN LOS ANGELES

The Acoustical Society of America will hold its 100th Meeting at the Los Angeles Hilton, November 17-21, 1980. Abstracts (original and three copies) should be sent by August 4 to Dean Richard Stern, UCLA School of Engineering and Applied Science, 6426 Boelter Hall, Los Angeles, California 90024.

ULTRASONICS INTERNATIONAL 81

Ultrasonics International 81 is scheduled for June 30-July 2, 1981 at the Metropole Convention Centre, Brighton, England. The organizers invite enquiries: Dr. Z. Novak, UI81, P. O. Box 63, Westbury House, Bury Street, Guildford, Surrey GU2 5BH, England.

11th AICB IN BULGARIA

The International Noise Abatement Association will hold its 11th Congress in Varna, Bulgaria from October 7-11, 1980. There will be simultaneous translations into four languages.

Continued on page 4

FULL-PAGE ABSTRACTS FOR
"ACOUSTICS & NOISE CONTROL IN CANADA"

Your Name
We don't need your title
But your full mailing address
(including postal code) is required.

This page is an informal way of announcing new, full-page abstracts which "Acoustics & Noise Control in Canada" will be publishing.

Those members presenting papers at the Annual Meeting are encouraged to submit their papers for publication by the journal. Where papers are not available, however, the new full-page abstract provides an easy way for you to inform Canadians about what you are doing . . . in a form that gives your oral presentation some permanence. These abstracts will also be citable in your work and on your resumé.

Full-page abstracts will not be limited to Annual Meeting speakers. Consider them also a vehicle for reporting what you do at other times. We want "Acoustics & Noise Control in Canada" to carry a greater diversity of interesting material.

We will accept nearly any abstract that is clearly and comprehensively informative. Results as well as conclusions are encouraged. These criteria dictate more than just 50-100 words. A full-page of single-spaced typescript (400-500 words) will usually be required. Small figures and tables, and/or references, can be substituted for some of the text, however.

Please prepare your full-page abstracts as much as possible according to the format exhibited above. Send them to the Editor (address on inside front cover of this issue) as soon as you can.

The journal is ready when you are.

ACOUSTICS WEEK IN MONTREAL

Constellation Hotel, 3407 Peel St., Montreal H3A 1W7

CANADIAN ACOUSTICAL ASSOCIATION ANNUAL SYMPOSIUM

October 22-23, 1980

CALL FOR PAPERS

Papers on all aspects of acoustics are invited (including underwater acoustics and vibration).

o Astracts of 100 words or less, for publication in the symposium programme, to be mailed by August 1, 1980, to Cameron Sherry, Domtar Inc., 2001 University Street, Montreal H3A 2A6.

o An optional full-page (~450 words) synopsis may also be submitted for publication in "Acoustics and Noise Control in Canada." Mail to Editor - address on inside front cover of this issue.

FOR FURTHER INFORMATION AND REGISTRATION DETAILS, contact C. W. Bradley, William Bradley & Associates, 3550 Ridgewood Ave., Montreal, Quebec H3V 1C2, Tel: (514) 735-3846.

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Division of Physics

Non-Ionizing Radiation Section
Radiation Protection Bureau

Seminar on Occupational Exposure to Noise and Vibration - Effects, Measurement and Control

OCTOBER 20-21, 1980 — AT MONTREAL, QUEBEC

DESIGNED for all concerned with occupational health and safety, industrial hygienists, engineers and acousticians. SEMINAR FEE — $60.00

FOR FURTHER INFORMATION contact . . .
Mrs. D. A. Benwell, Room 233, Environmental Health Centre,
Tunney's Pasture, Ottawa, Ont. K1A 0L2 — Tel. (613) 995-9801

CANADIAN STANDARDS ASSOCIATION ANNUAL GENERAL MEETING

October 24, 1980

IMPORTANT! Register with hotel now. Preferential room rates are not guaranteed after August 15, 1980.

The programme is already published, and details of its contents may be obtained by contacting the Editor. To attend the conference, write: Noise Abatement Committee in Bulgaria, 1000 Sofia - Rakovski Street 108 or Telex 22185 NTS BG.

NANCO

The National Association of Noise Control Officials (NANCO) has started a membership drive. Membership is open to everyone, but active voting membership is restricted to officials who administer or implement environmental noise control laws.

The monthly publication, "Vibrations," keeps members informed. For details, please contact NANCO at P. O. Box 2618, Fort Walton Beach, Florida 32549. International Associate Members are welcomed.

HUGH JONES AT DALHOUSIE

Dr. Hugh W. Jones, a past president of the CAA, has been appointed Professor and Director of the Engineering-Physics Section of the Department of Physics, Dalhousie University, Halifax. He goes to this new post from the University of Calgary, where he was a Professor of Physics, and Adjunct Professor of Engineering, and where he headed the university acoustics group. He also has had experience in the U. S. and U. K.

Hugh brings to his new position a versatile acoustics expertise which encompasses acoustical imaging and holography, architectural and environmental acoustics, and R&D into receivers for faster ultrasonic scanning. CAA members will wish him well in his new post.

NEW RESEARCH CONTRACTS

To Eastern Marine Service Ltd., Musquodoboit Harbour, N. S., $2,265 for "Fabrication of a two bladed propellor for cavitation noise research." Awarded by the Dept. of National Defence.

To Aercoustics Engineering Ltd., Rexdale, Ontario, $24,449 for "Noise climate predictions for selected Canadian Forces Bases." Awarded by the Dept. of National Defence.

To CTF Systems Inc., Port Coquitlam, B. C., $112,416 for "Development, fabrication and testing of an ultrasonic NDT probe for the corrosion determination of navy boiler superheater tubes - phase IVb." Awarded by the Dept. of National Defence.

To Welding Institute of Canada, Oakville, Ontario, $16,566 for "Design, fabrication and testing of an ultrasonic scanner capable of measuring the depth of a fatigue crack at the toe of a longitudinal weld in a crude oil pipeline." Awarded by the Dept. of Energy, Mines and Resources.

To William Tennant Ltd., Victoria, B. C., $17,497 for a "Study of voice activated learning (VAL) and control systems." Awarded by the National Research Council.

To University of Guelph, Ontario (Dr. D. Ramprashad), $19,006 for "Comparative morphometric study of the inner ear - phase II." Awarded by the Dept. of National Defence.

To MPB Technologies Inc., Ste-Anne-de-Bellevue, Quebec, $95,967 for "Development of a signal processing system for low frequency hydrophones." Awarded by the Dept. of National Defence.

To University of Toronto, Ontario (Dr. V. Ristic), $28,210 for a "Study of signal processing techniques and fabrication of an acousto-optical receiver." Awarded by the Dept. of National Defence.

To University of Toronto, Ontario (Dr. I. I. Glass), $118,617 for "Determination of the effects of sonic booms with application to Canadian requirements." Awarded by the Dept. of Transport.

To L. J. Hutchison, Orleans, Ontario, $29,004 for "Development of a signal processor for acousto-optic receiver output data." Awarded by the Dept. of National Defence.

REPORT ON THE TORONTO CHAPTER, CANADIAN ACOUSTICAL ASSOCIATION, TECHNICAL MEETING HELD AT ONTARIO HYDRO HEADQUARTERS BUILDING, TORONTO, ON THE EVENING OF MAY 12, 1980.

The Toronto Chapter recently held its first technical meeting in Toronto.

We were lucky to be able to arrange an impressive list of technical speakers from various research establishments in the United Kingdom.

More than 40 chapter members attended a lively and varied evening during which five papers were presented.

Graham Rood, Ph.D. and John Chillery, Ph.D., two researchers at the Royal Aircraft Establishment, Farnborough, presented papers entitled "Research Projects of the Human Engineering Division within the Royal Aircraft Establishment" and "Earmuff Headband Force Measurements".

Doctor Rood's paper gave an overview of the various projects dealing with the ergonomic, environmental and health aspects of human engineering in modern military aircraft. Subjects touched on included whole body vibration, cockpit design, modern avionics and in-flight physiological studies.

Doctor Chillery's paper dealt with the work carried out in development of standards and test methods for the evaluation of hearing protectors. In particular, he outlined the development of various pieces of apparatus to determine the value of earmuff headband force and its variation with time under effects of aging and fatigue.

Both papers provided an interesting insight into the many topics coming under the "umbrella" of a Human Engineering Research Group.

A short coffee break followed which gave members an opportunity to mingle and discuss the preceding papers.

The evening resumed with Doctor Alan Martin presenting a brief, but informative, overview of the very wide range of acoustical and vibration research projects carried out at the Institute of Sound and Vibration Research, University of Southampton, in his paper -

"Scope of Current Research projects at the I S V R".

Topics covered included aspects of Automotive Engineering, Audiology, Fluid and Structural Dynamics, Industrial Noise Control and Noise Consultancy.

Doctor Peter Wilkins' paper "Non Speech Auditory Communciations" turned out to be one of the highlights of the evening. It dealt with the many complex and paradoxical problems that had been encountered in the development of audible signals for the "Pelican" pedestrian crossing system. The Pelican system is a traffic signal controlled pedestrian crossing featuring visual cues for children and audible phase indicators for the blind.

Experience has shown that existing signalling systems are both annoying to local residents and confusing and sometimes hazardous for the blind people they are intended to help. A great deal of research is being done to develop more informative, directional and pleasant signalling sounds to overcome the present shortcomings.

Doctor Wilkins' paper was presented in a lively and humorous manner and concluded with a taped demonstration of some of the new "Super sounds" they had developed.

The final presentation of the evening dealt with "Aspects of Industrial Hearing Conservation in the United Kingdom" and was presented by Steve Karmy, M.Sc., lecturer in audiology at the I S V R.

After outlining a brief history of the development of Industrial Noise Legislation in the United Kingdom, Steve went on to discuss the place of industrial audiometry and screening as part of the hearing conservation programme.

He outlined some of the problems of the widespread application of audiometric screening programmes and discussed the results of some of his case studies including the use of computer based audiometric data reduction techniques to assist in the interpretation of the mass of data obtained.

The marathon meeting ended just before ten o'clock. It was a tribute both to the interesting papers and the quality of speakers, and to the fortitude of the listeners, that very few members left before the concluding remarks and vote of thanks presented by Tony Taylor of Ontario Hydro.

It was a long and busy evening, but it was felt that the opportunity to present such a variety of topics and expertise was not to be missed.

We would like to extend our thanks to our speakers for devoting their evening to us and presenting us with so much food for thought.

The large attendance and the perseverance of our audience attested to the interest and enjoyment of the proceedings.

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NEXT MEETING

The Toronto Chapter will not meet during the Summer. The next meeting is being scheduled for September, when it is hoped to have a leading consultant in Architectural Acoustics discussing the development of the new Massey Hall concert auditorium in Toronto. This will be our major meeting of the fall series. Further details will be released as soon as arrangements are finalised.

Tel: 416 - 791 - 1642. Greg Michel.

ACOUSTICAL CONSULTANT REGISTRATION

I would like to discuss a question I first raised at the last Annual Meeting of the C.A.A. The question was this: "How do the acoustical consultants present at this meeting feel about their accreditation by a committee of C.A.A. members?"

As a reviewer of noise impact studies, I am sometimes asked to recommend a competent consultant. However I cannot make a recommendation without compromising my impartial position. At the same time, some consultants advertise their membership in the C.A.A. to prospective clients which can lend unwarranted weight to their claim for expertise.

I raise the question of accreditation because I feel that all parties concerned, i.e., client, consultant and reviewer, might benefit.

The problem of accreditation of acoustical consultants has been recognised elsewhere. For example, NIOSH Technical Report 70-117 on industrial noise control says: "Once you have decided to obtain a consultant, how do you proceed? You should first be warned that currently there is no legal bar to anyone offering services as an "acoustical consultant." Consequently, it is up to you to avoid those who are unsuitable because of lack of training or experience, as well as simple venality or greed." NIOSH then refers clients to two U. S. organizations interested in the qualifications of their membership: the Institute of Noise Control Engineering (INCE) and the National Council of Acoustical Consultants (NCAC). The client is also provided with a list of guideline questions to ask candidate consultants to aid in selection. The questions cover education (in acoustics), experience, professional affiliations, and special capabilities (in acoustics etc.).

At the time I first raised my question, the (then) President of the C.A.A., Dr. C. W. Bradley, pointed out that under the C.A.A.'s constitution as a non-profit organization it was legally unable to perform this function. Another consultant, Mr. J. Coulter, remarked that provincial Professional Engineering Associations are empowered to perform such accreditation - at the request of their membership. But, as far as I am aware, none of the provincial Professional Engineering Associations recognises acoustical engineering as a specialist field.

However, INCE is also non-profit making and INCE accepts into membership only those applicants who have passed suitable examinations. The route to membership has recently been revised (see Noise/News, Sept.-Oct., 1979). General membership requirements involve successful completion of the two-hour INCE Fundamentals Examination (evidence of registration as a professional engineer may be submitted in lieu of this examination). Registration as a professional engineer in some other specialist field, however, is insufficient to qualify for full membership, for which candidates must still pass the eight-hour INCE Professional Examination on the practice of noise control engineering.

NCAC's purpose in listing qualified noise consultants is similar to that of any other profession:

> "to preserve and protect the public welfare by discouraging unclear, inaccurate or unproven representations concerning acoustical products, materials and services."

That such aims have not yet been fully realised in the U. S. is evident from a recent editorial in "Sound and Vibration" (Oct. 1979).

The above concerns exist in Canada too, and I believe that professionals should recognise that the public ought not to be left to take "pot luck" from listings in the Yellow Pages. Now that the C.A.A. has "come of age," I feel it should assume the responsibility of offering accreditation to suitably qualified acoustical consultants even if this means a change in its constitution, and that acoustical consultants themselves should demand official recognition of their professional status in their specialist field. This opinion is, of course, mine and not that of my employer, and I'm writing to stimulate discussion among C.A.A. members.

S. H. Eaton
Noise Pollution Control Section
Environment Ontario

(We understand Stuart Eaton is now with the Workers' Compensation Board of British Columbia. - Ed.)

1979 RAYLEIGH MEDAL LECTURE:

THE ELUSIVE CONNECTION

E.A.G. SHAW

DIVISION OF PHYSICS, NATIONAL RESEARCH COUNCIL, OTTAWA, CANADA

This lecture was presented during the Annual Meeting of the Institute of Acoustics at The University of Southampton, England 10 April 1979. It will appear in the next issue of the *Proceedings of the Institute of Acoustics* and is reprinted in *Acoustics and Noise Control in Canada* with the kind permission of the President and Governing Board of the Institute.

THE ELUSIVE CONNECTION

E.A.G. SHAW

DIVISION OF PHYSICS, NATIONAL RESEARCH COUNCIL, OTTAWA, CANADA

In his monograph Electroacoustics, F.V. HUNT (1954) described the carbon microphone as "the only 'bad connection' tolerated in the telephone system". This whimsical comment was, of course, inspired by the unique electrical properties of that remarkable transducer. A broader view, encompassing the acoustical as well as the electrical elements of the system, would surely compel us to recognize the earphone, another essential element of the telephone system, as a connection of equally questionable quality. It was indeed this doubtful connection, lying at the heart of audiometric measurements, which first prompted my colleagues and I in Ottawa to enquire about the acoustics of the external ear many years ago (SHAW and THIESSEN, 1962, SHAW and TERANISHI, 1968). It seemed then, as now, that despite the remarkable advances in electromechanical transduction since the days of Alexander Graham Bell, the coupling between earphones and ears still rested on a very flimsy acoustical foundation. We soon found that there were questions concerning the external ear which were larger than the technological artifacts that had started us on our journey and it is to these larger questions that my title refers. The "elusive connection", then, is associated with the external ear but really embraces the entire transmission path between the sound source, which may be near the ear or in the far field, and the oval window of the cochlea which is the input terminal of the inner ear. The questions which arise fall under at least five headings:

(i) Anatomy and function: How does the external ear work? What are the functions of its various components? How is it coupled to the middle ear? What parameters best define its performance?
(ii) Reception efficiency: How well does the external ear collect sound energy? How well is that energy transmitted to the inner ear?
(iii) Sound localization: To what extent are we able to localize sound sources away from the horizontal plane especially sources lying in the symmetry plane of the head? What localization tasks can we perform with a single ear? What are the relevant auditory cues?
(iv) Space perception: Under what circumstances and how well do we externalize sound when listening under artificial conditions such as those arising with earphones?
(v) Measurement techniques: How should we specify and measure acoustic stimuli?

As we shall see, some of these questions were raised more than one hundred years ago but still lack precise answers.

Though he was by no means the first to study localization, Rayleigh made significant contributions to the subject giving special attention to the lateralization of sound brought about by interaural differences of phase and intensity (RAYLEIGH, 1877, 1909). He also experimented with monaural localization (RAYLEIGH, 1877, 1882) and was aware that some subjects could in some circumstances discriminate between front and back source positions, a task requiring auditory cues not available from a pair of monopole receivers on a rigid sphere. Such discrimination, he argued, must surely be associated with an alteration in the quality of sound, especially high frequency sound, mediated by the external ears (RAYLEIGH, 1907). This view, the Klang or timbre theory of sound localization, was widely held in the last century and has had much support over the years. THOMPSON (1883) expressed the matter as follows:

> "The ear has been trained from childhood to associate certain differences in the quality of sounds (arising from differences in the relative intensities of some of the partial tones that may be present) with definite direction, and relying on these associated experiences, judgments are drawn concerning sensations of sounds whose direction is otherwise unknown..."

Mach, like Rayleigh, emphasized the importance of high frequency sounds as indicators of direction and argued that their timbre was affected by the pinna acting as a resonator. He noted, significantly, that the wavelengths of audible sounds were too great to allow reflection from surfaces as small as the folds of the pinna. (See BUTLER, 1975; MACH, 1959.) This very idea was however, adopted by PETRI (1932) and developed quite recently by BATTEAU (1967) in a long paper published in the Proceedings of the Royal Society. According to this view, sound waves reflected from various parts of the concha arrive at the eardrum with direction-dependent time delays and are sorted out later by a hypothetical inverse transformation process performed by the inner ear or nervous system.

One of the few decisive experiments of the early period is due to BLOCH (1893) who showed that the ability to localize sources in the median plane of the head was severely impaired when the upper parts of the pinnae were filled with wadding and the lobules taped to the skull. This experimental evidence came along not many years after Darwin had concluded that the various folds and prominences within the human pinna are merely rudiments which in lower mammals provide structural support for holding the pinna erect (BUTLER, 1975).

Let us now turn our attention to the ear as a physical system. As we shall see, the information which has been gathered in recent years gives us a fresh appreciation of the progress made in earlier days, sheds new light on old problems and is complementary to some of the recent work in psychoacoustics.

Figure 1 shows various parts of the external ear referred to later. Notice that the canal proper opens into a wide shallow cavity, the concha, which is partially divided into two parts, the cavum and the cymba, by the crus helias. The cymba in turn is linked to another shallow cavity, the fossa. For convenience the structures surrounding the concha are collectively described as the pinna flange or pinna extension.

Figure 2 shows the average free-field response of the human ear at the eardrum in the azimuthal plane. This self-consistent family of curves, which is based on measurements made in a dozen laboratories around the world, sets out clearly some major characteristics of the human ear. We see that the primary resonance of the external ear is at approximately 2.6 kHz not at 4 kHz as frequently stated. At this frequency, the sound pressure level at the eardrum is much greater than that of the incident field: approximately 17 dB greater than the free field level at 0° azimuth (frontal incidence) and 21 dB at 60°. Even in the shadow zone there is appreciable pressure gain. Beyond the peak, a strong resonance due to the concha sustains the response for almost one octave. Notice also the difference in response between 45° and 135° azimuth which amounts to 11 dB at 4.5 kHz. This lack of front-back symmetry, which is due to diffraction by the pinna extension, is sufficient to change substantially the timbre of sound received from a broad-band source as it moves through the lateral sector.

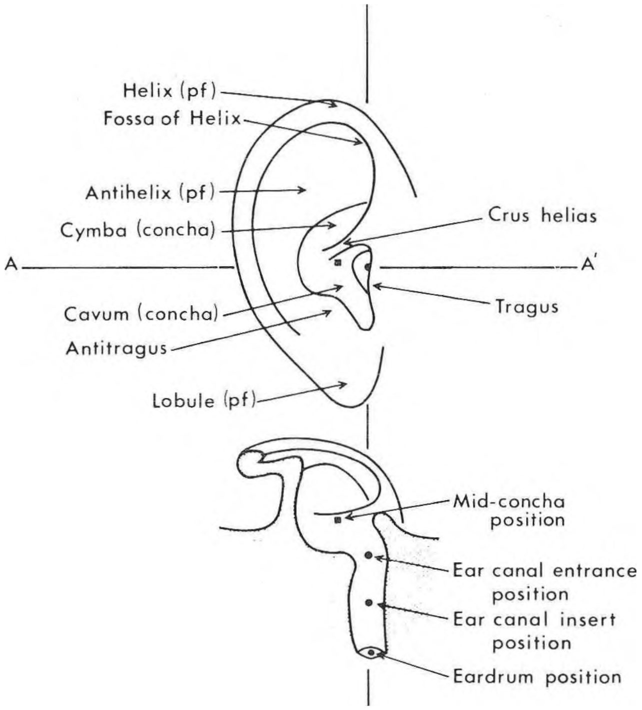


Fig. 1. Descriptive diagram of external ear and horizontal cross section at AA' showing functional components: pinna flange (helix, antihelix, lobule, etc.), fossa, concha (cymba, cavum, crus helias) and ear canal proper. After SHAW (1974b).

Several major characteristics of the human external ear can be readily demonstrated in simple physical models as shown in Fig. 3. In the first stage of development (Panel A) the concha is represented by a simple broad open cylinder whose dimensions have been chosen to bring it into resonance at approximately 4.5 kHz as in the average human ear under comparable conditions. Notice that the response is almost independent of source position up to approximately 6 kHz. In Panel B a rectangular plate has been added to represent the pinna extension. The resonance is now more strongly excited when the source is in front of the ear but hardly excited at all when the source is to the rear. In Panel C a long narrow cylinder has been added to represent the

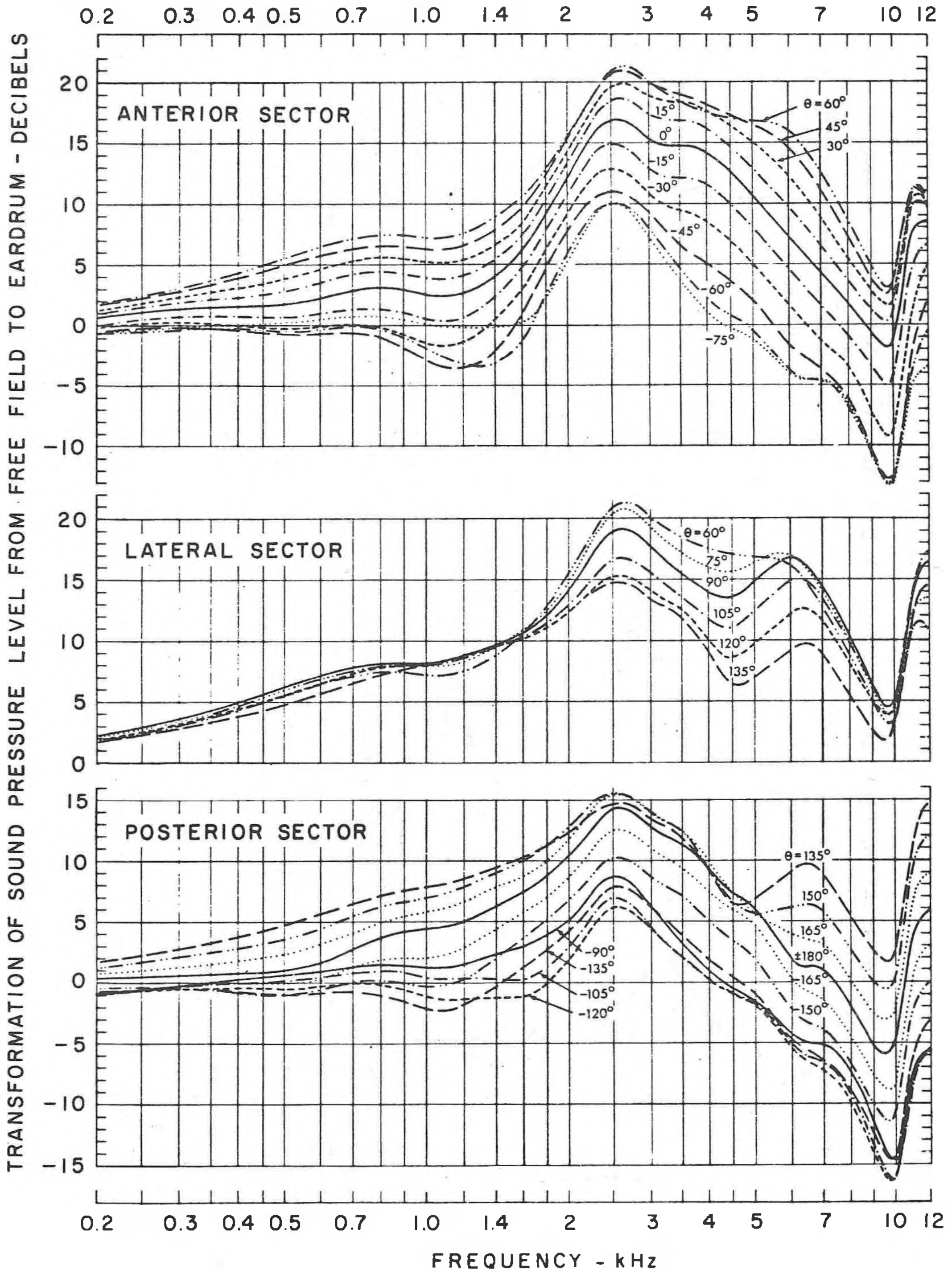


Fig. 2. Average transformation of sound pressure level from free field to human eardrum as a function of frequency at 24 angles of incidence in the horizontal plane. This family of curves was fitted to a pool of data covering a total of 100 subjects measured in 12 separate studies over a 40 year period. After SHAW (1974c).

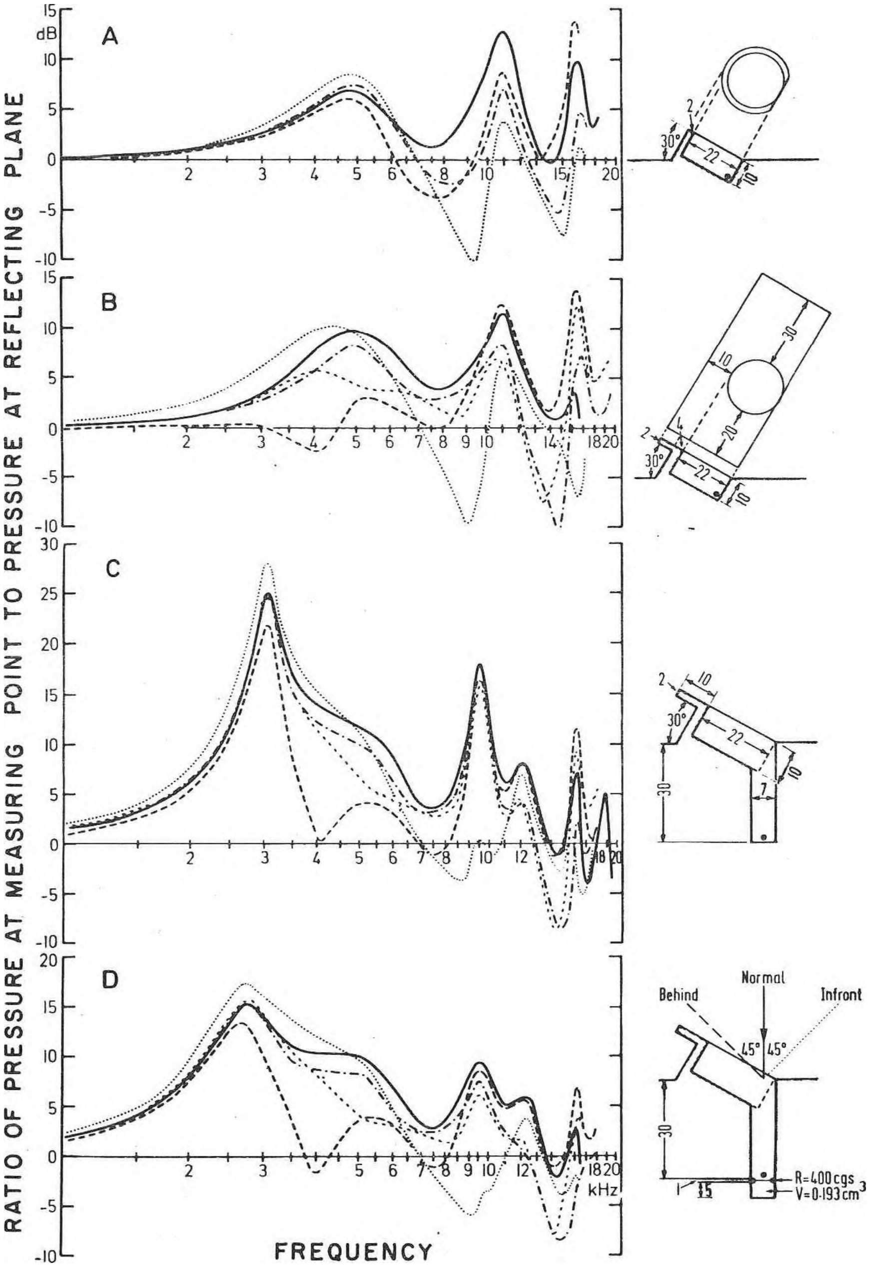


Fig. 3. Response of simple model of human ear, at four stages of development, excited by point source: with normal incidence (solid line), with source 45° in front (dotted), behind (long dash), above (dot-dash) and below (short dash). Three source positions are indicated in Panel D. Dimensions of model in millimetres. After TERANISHI and SHAW (1968), SHAW (1975).

ear canal proper. This introduces new degrees of freedom and hence additional resonances especially a new fundamental resonance at approximately 3 kHz. Finally, as shown in Panel D, the hard wall at the end of the second cylinder has been replaced by a simple acoustical network to simulate the absorption of sound at the eardrum. This model with four component parts matches the behaviour of real human ears very well up to 5 kHz but fails, as we shall see, at higher frequencies.

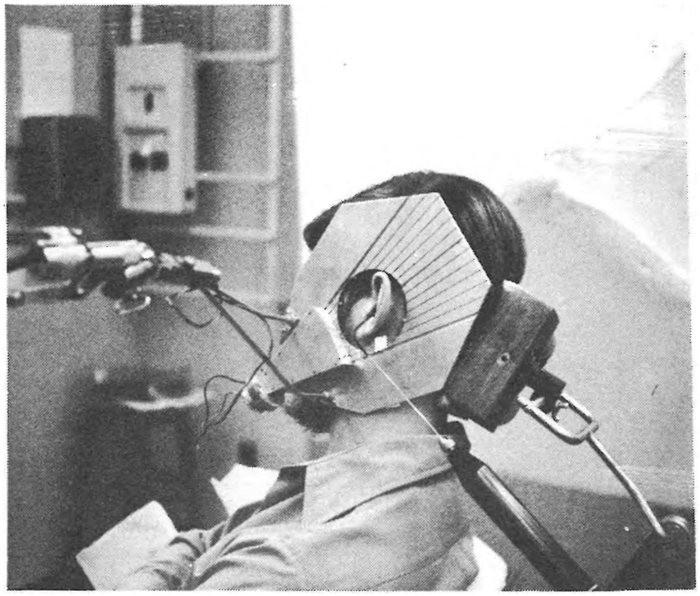


Fig. 4. Measurement of blocked-meatus response using a probe microphone (lower right) and a special source designed to generate well-defined progressive waves at grazing incidence. From SHAW (1974a, 1975).

To obtain precise information at the higher frequencies it is necessary to study the ear in isolation. The progressive wave source shown in Fig. 4 has been designed to operate sufficiently near to the ear that head diffraction effects are virtually eliminated while maintaining just enough clearance to prevent significant interaction between source and ear. This special source produces clean progressive waves at grazing incidence the direction of which, with respect to the ear, can be varied by changing the source orientation in the circumaural plane. The response of the ear is measured with a probe microphone whose orifice is located at the centre of a carefully fitted plug filling the ear canal entrance. At frequencies up to 10 kHz or more the polar diagram of the ear when measured under this blocked-meatus condition has been found to be almost identical with that measured at the eardrum position.

The blocked-meatus response curves for a single subject are shown in the upper panel of Fig. 5. As can be seen, there are astonishingly large variations in response with angle of incidence at frequencies greater than 5 kHz: rarely

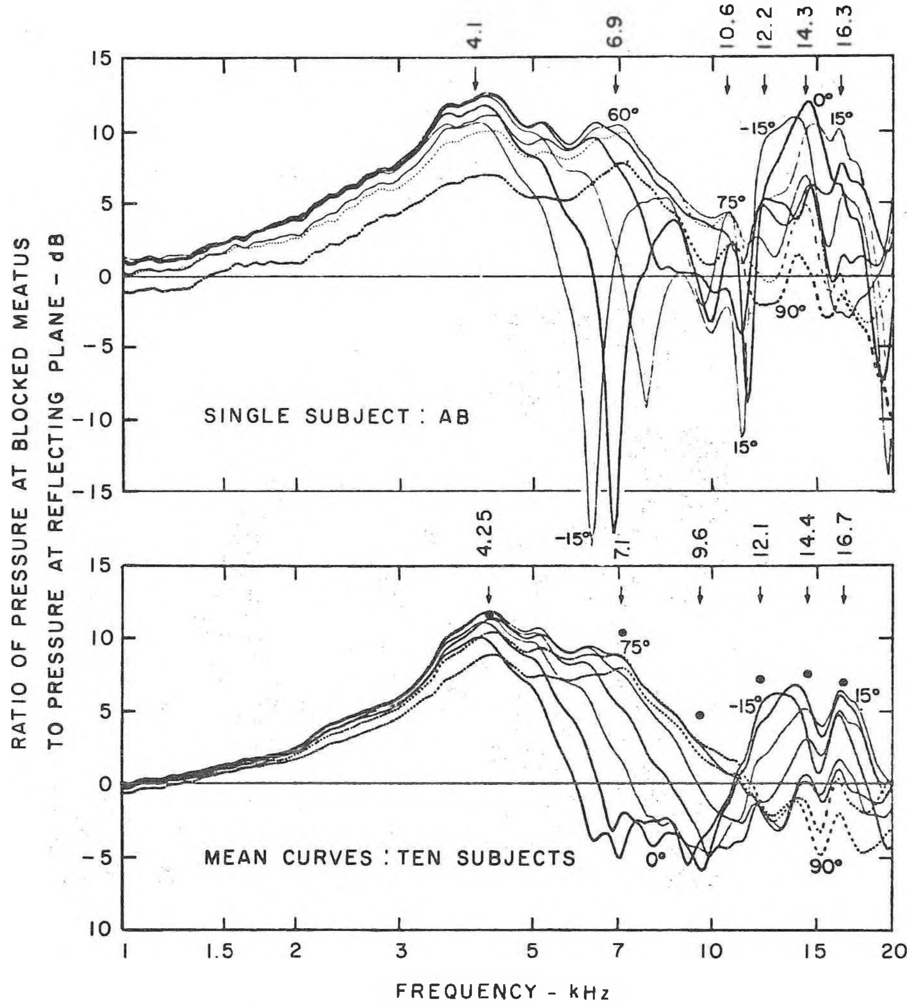


Fig. 5. Upper panel: Blocked-meatus response curves for single subject at eight angles of incidence (-15° to 90°). Source is in front of ear at 0°, above at 90°. Lower panel: Mean curves for group of ten subjects. Arrows indicate mode frequencies. After SHAW (1974a, 1975).

less than 10 dB and at some frequencies as great as 25 dB. Each ear has its own characteristic family of curves but different ears also have much in common as shown in the lower panel of Fig. 5. This family of curves was obtained by averaging the data for ten subjects, a procedure which eliminates idiosyncracies such as the deep minima but enhances those features which are common. Notice that with sound waves approaching from above - angles of incidences between 60° and 90° - the average response remains strong between 6 and 9 kHz but is weak between 11 and 16 kHz. With frontal incidence, however, - angles of incidence between -15° and +15° - the situation is reversed: the excitation is weak between 6 and 9 kHz but strong between 11 and 16 kHz.

THE ELUSIVE CONNECTION

Let us digress for a moment to mention the highly original work by BLAUERT (1969). When he presented his subjects with 1/3 - octave bands of noise produced by sources in five different symmetrical configurations he found, as would be expected, that the sound was always localized in the median plane. Contrary to expectation, however, the perceived direction was found to depend not on the source configuration but on the frequency of the noise band. Moreover, at each frequency, the perceived direction tended to coincide with that at which the acoustical response of the ear was at a maximum. It is reassuring to note that Blauert's observations are generally in harmony with the data presented in Figs. 2 and 5. For example, the 8 kHz band was most often localized above the head. Also, in retrospect, it appears that Blauert's work is strongly supported by a contemporaneous study of "in-head localization" (TOOLE, 1969). Finally one should mention the experiments of FISHER and FREEDMAN (1968) who showed that their subjects could localize quite well with artificial pinnae coupled to their ear canals but performed more accurately with their own pinnae. This observation is in qualitative agreement with the degree of similarity between ears indicated in Fig. 5.

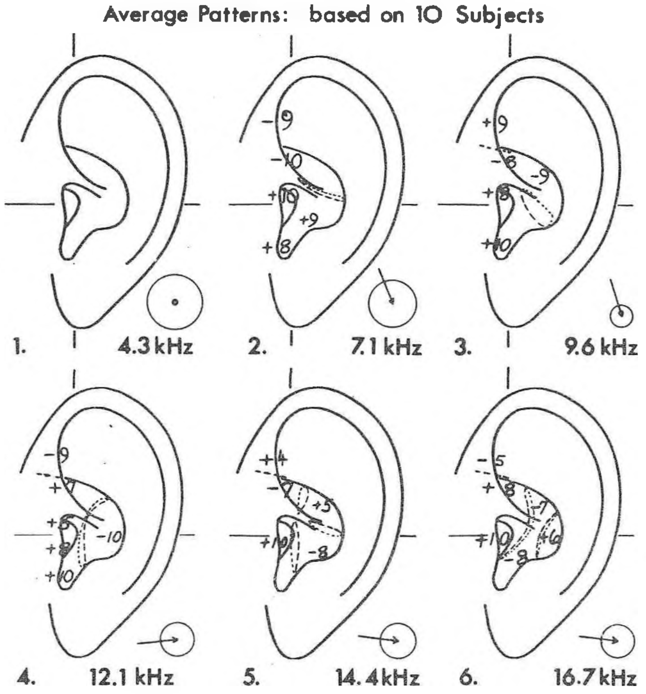


Fig. 6. Average pressure distributions and resonance frequencies of six modes measured with ear canal closed at entrance. Circles indicate relative degrees of excitation. Arrows show directions of maximum response. After SHAW (1974a).

The central feature of the human pinna is its network of cavities whose dimensions are comparable with the wavelength of sound at high audible frequencies. It seems natural then to propose the eigenmodes of the system as the key to its acoustical function recognizing, however, that these modes may be broadly tuned and therefore hard to separate experimentally since the concha is open to the sound field. The overlapping of the tuning curves does indeed make resolution difficult in some cases but it has been found that sufficient separation can generally be achieved if full advantage is taken of differences in directionality. The essential characteristics of six modes under blocked-meatus conditions are shown in Fig. 6. The first mode at 4.3 kHz is a simple depth resonance with uniform pressure across the base of the concha. The other modes are mainly transverse. The second mode at 7.1 kHz and the third at 9.6 kHz are best excited at 75° elevation but the second is more strongly coupled to the sound field than the third. Notice that the pressure distributions of modes 2 and 3 are similar apart from the sign of the pressure in the fossa: they form a doublet. Modes 4, 5 and 6 also form a group since all three are strongly excited from the front.

Once we have identified the eigenmodes of an acoustical system we can broaden our understanding of the system by constructing models which are acoustically similar but dissimilar in other respects. In Fig. 7 we compare a simple model (Panel A) in which only one mode has been tuned with a more refined model (Panel B) which has just sufficient complexity to produce five modes with approximately the same mode frequencies, pressure distributions, directionality and excitation as the average human ear. As the first refinement, we replace the cylindrical cavity by one that is rectangular in form. The first order transverse modes are then resolved in the frequency domain and aligned with the major and minor axes of the cavity as seems to be required by the directionalities of the modes. Tuning the first horizontal mode (Mode 4 in Fig. 6) is readily accomplished by adjusting the breadth of the cavity. When we attempt to tune the first vertical mode, however, we quickly discover that any reasonable choice of cavity length gives a resonance frequency which is much too high. To bring the frequency down it is necessary to follow nature by introducing a horizontal barrier (the crus helias) which diverts the airflow towards the rear of the cavity thereby increasing its effective length. Finally we require a resonant channel (the fossa) to produce an additional degree of freedom and hence two modes (Modes 2 and 3 in Fig. 6) where there would otherwise be only one.

To complete our refined model we must add a representation of the ear canal and a terminating impedance which simulates the load presented by the human eardrum as shown in Fig. 7, Panel C. Notice that there are now eight resonances between 2.6 and 15.7 kHz where there were only five before. Mach would surely see this as strong support for his view that the pinna served as a resonator for high frequency sounds. The grouping of modes with similar directionality is equally striking: It suggests perhaps that specific roles are associated with each of three frequency bands: Lateral discrimination linked with the 2-6 kHz band (see Fig. 2), the detection of sources above the head linked with the 6-10 kHz band, and the detection of sources in front of the head linked with the 12-16 kHz bands. Here, then, is a physical basis for large systematic variations in the timbre of broad-band sources moving over and around the head. And there is agreement with ROFFLER and BUTLER's experimental finding

(1968) that "to localize sounds in the median sagittal plane requires that the sounds be complex and that they contain frequencies of 7000 Hz and above." One should also mention the recent studies of GARDNER and GARDNER (1973). These authors, improving upon the technique of pinna modification initiated by Bloch, found that localization accuracy progressively deteriorated as the cavities of the pinna were filled with a rubber compound. Even the scapha (the channel at the rear of the pinna extension) was found to have a minor effect on the accuracy of localization in the median plane.

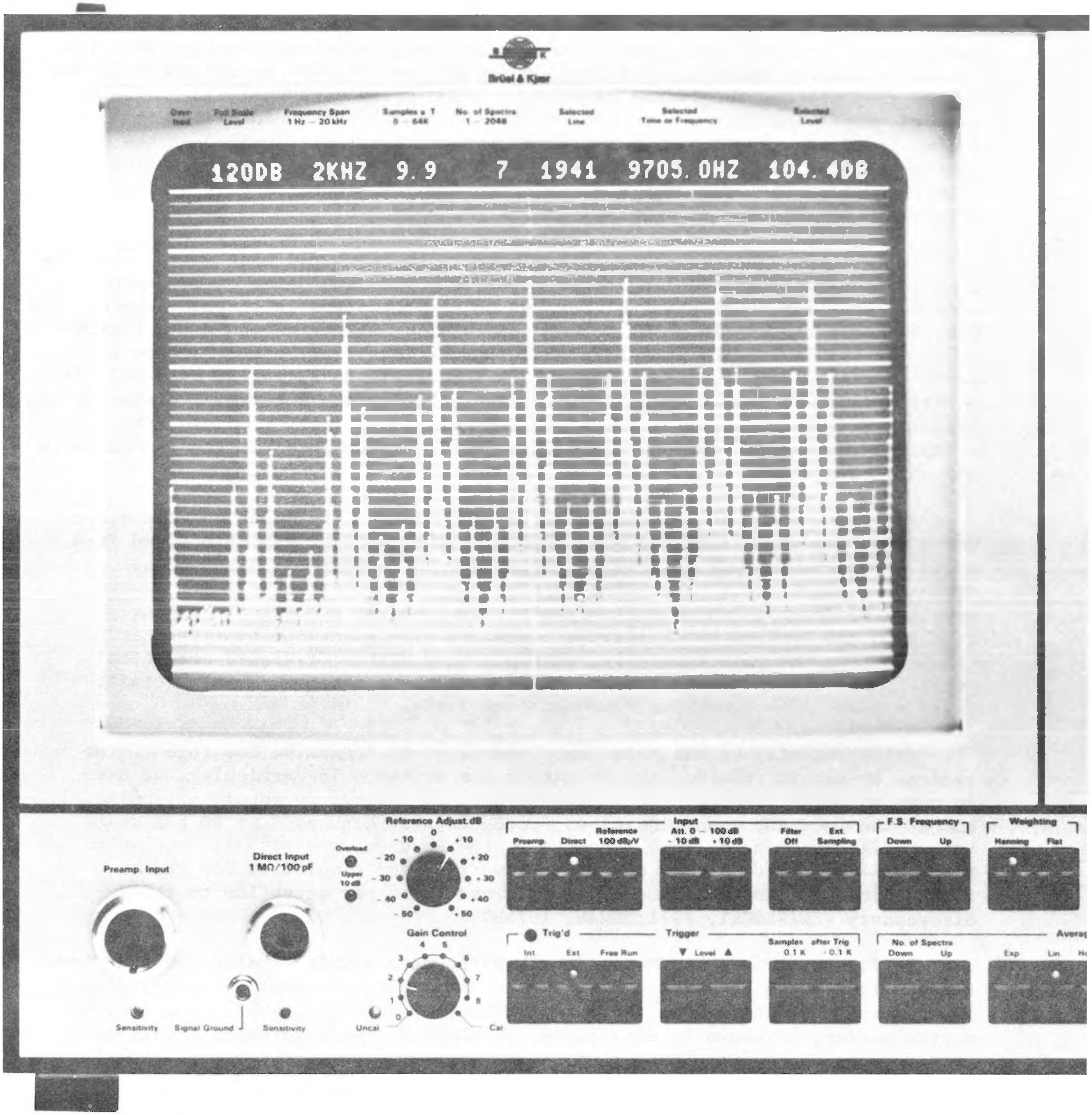
It is tempting to conclude this chapter with the broad observation that the timbre theory of localization is now supported by an abundance of evidence, both psychophysical and physical but, as so often happens in science, there are pieces of the puzzle which do not quite fit. Just three years ago SEARLE et al (1976), having analyzed a large number of localization experiments in terms of statistical decision theory, concluded that localization cues related to differences in characteristics between the two ears - interaural pinna-disparity - were stronger than the monaural cues. If their findings are accepted, then the second century of research on sound localization is evidently off to a good start.

The small bones of the middle ear - the malleus, the incus and the stapes - which link the eardrum to the oval window of the cochlea, are maintained in a state of equilibrium by an array of ligaments and muscles. This somewhat variable connection is part of an impedance matching device, a lever system coupling two pistons which differ greatly in area and acoustical loading. Thanks to the work of ONCHI (1961), MØLLER (1961), ZWISLOCKI (1962) and others during the past twenty years we now have highly developed acoustical networks describing the operation of the middle ear in considerable detail. These appear to work well up to about 1 or 2 kHz.

Quite recently it has been found necessary to reexamine the role of the eardrum itself in relation to the middle-ear system. In particular, we have to come to terms with the fact that the eardrum appears to absorb approximately 50% of the incident sound energy at frequencies as high as 8 to 10 kHz which is much larger than would be expected if the eardrum were rigidly coupled to the middle ear. It was the development work on ear simulators for the calibration of insert earphones which forced us to pay attention to this discrepancy (ZWISLOCKI, 1971; SHAW, 1974b).

It is now clear that the eardrum behaves as a simple elastic shell at low frequencies (FUNNELL, 1975) but breaks up into isolated zones vibrating almost independently as the frequency rises (TONNDORF and KHANNA, 1972). As a first approximation, as shown in Fig. 8, we can think of the eardrum as a pair of pistons, one approximately four times as large in area as the other, tightly coupled up to 1 or 2 kHz but operating independently at the higher frequencies. It is the smaller piston which is directly connected to the malleus and, hence, this alone which drives the ossicular chain at high frequencies. To represent such behaviour in an acoustical network we must introduce an ideal transformer which is switched out of operation at high frequencies by a frequency-dependent impedance. In effect, the middle ear transformation ratio is reduced at high frequencies and a substantial fraction of the input energy never reaches the ossicular chain. It must also be assumed that the larger piston,

Continued on page 22



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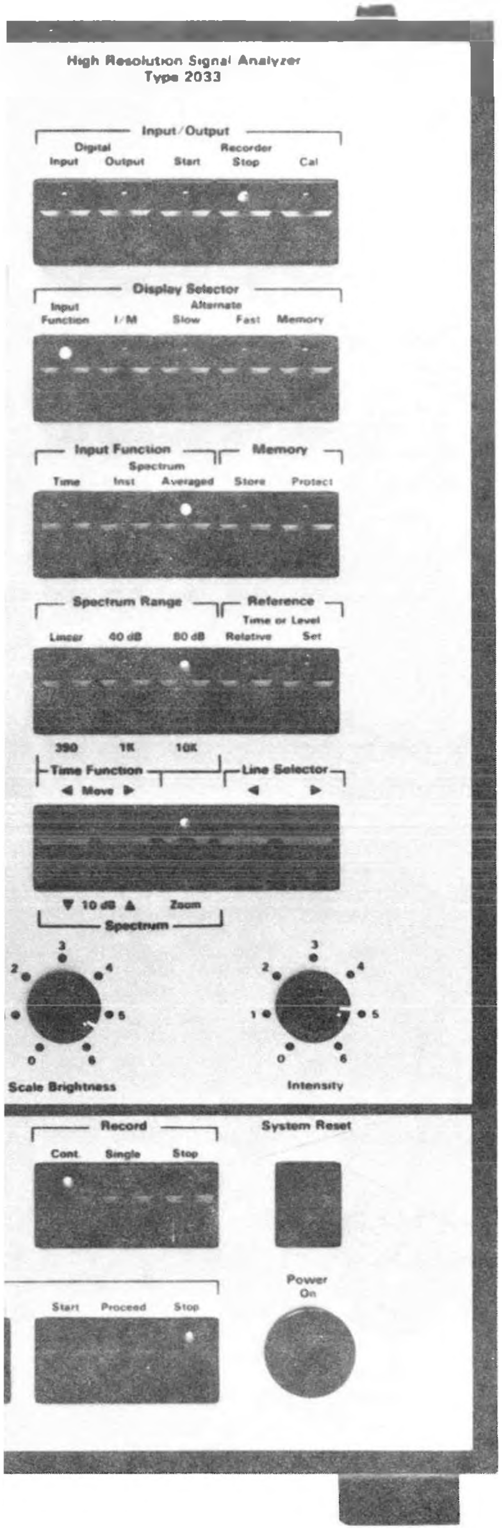

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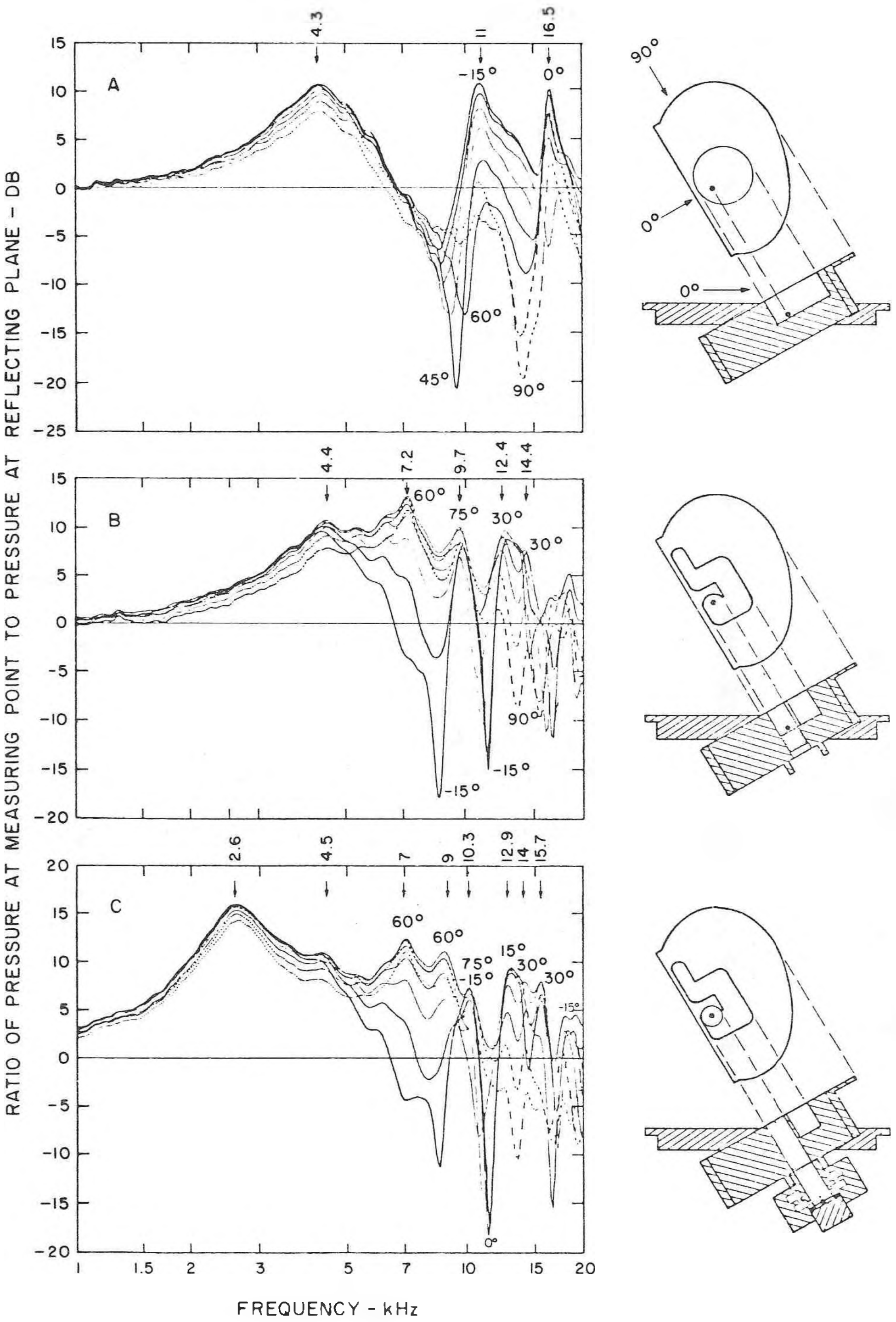

Fig. 7. Response of model ear at three stages of development when excited by progressive-wave source. Arrows indicate mode frequencies. Source is in front of ear at 0°, above at 90°. Panel A: Cylindrical concha. Panel B: Refined concha. Panel C: Refined concha, cylindrical canal and eardrum impedance simulator. After SHAW (1979b).

representing the isolated zones of the eardrum, is well damped at high frequencies by a mechanism which has yet to be determined.

How well is the ear matched to the sound field? To answer this question WEVER and LAWRENCE (1954) compared the characteristic impedance (ρc) of air with that of water making allowance for the impedance transforming function of the middle ear. Implicit in this approach is the assumption that one is dealing with a system whose dimensions are much greater than the wavelength of sound in each of the two media, an assumption which is clearly unjustifiable in the present case (see SCHUBERT, 1978; KILLION and DALLOS, 1979). Another approach, which leads to a rather precise answer, is by way of the acoustical reciprocity principle which was shaped, in part, by RAYLEIGH (1973, 1976). By performing a mental experiment in which the external ear is first a receiver and then a transmitter we can express the power absorbed by the ear, when immersed in a diffuse sound field, essentially in terms of two impedances (SHAW, 1976). These are the load impedance, that is to say the eardrum impedance, and the impedance looking outward from the load, predominantly the radiation impedance. (Where there are appreciable radiation losses the response is multiplied by a radiation efficiency factor which for the human ear is probably greater than 80% at most frequencies.) We cannot of course measure the radiation impedance of real human ears but we can make such measurements on models and replicas using an impedance tube. We can go a stage further and express the performance of the ear as a sound collector in terms of its absorption cross section, the parameter universally used in radiation theory. For the ear, the absorption cross section in a diffuse sound field can be defined as the size (cross sectional area) of the transparent sphere which, when placed in the same sound field, would intercept the same amount of power as the ear. Such measurements and calculations have been carried out for the model ear described earlier. The results are shown in Fig. 10.

Consider first the absorption cross section at the eardrum. According to the upper graph of Fig. 10, below 1 kHz the absorption cross section decreases rapidly with decreasing frequency and soon becomes exceedingly small. This is hardly surprising since three adverse factors come into operation in rapid succession. First, the external ear provides negligible pressure gain much below its principal resonance frequency which means, acoustically speaking, that the eardrum is simply a small piston mounted in a spherical surface. Second, the wavelength of sound, already large compared with the circumference of the piston, soon becomes large compared with that of the sphere. Third, the load carried by the piston is an impedance whose magnitude rises with decreasing frequency while its power factor falls. Above 1 kHz the situation is quite different. As shown in Fig. 10, at the principal resonance frequency of the external ear (∿2.6 kHz), the power absorbed at the eardrum is that which would pass through a sphere approximately 6 cm^2 in cross section (radius 1.3 cm) immersed in the same diffuse sound field. This is 40% of the limiting value. At higher frequencies, the absorption cross section declines in absolute value while passing through a series of minor peaks at the mode frequencies but always stays quite near the theoretical limit of $\lambda^2/4\pi$ imposed by radiation theory. In fact, at 9 kHz, the absorption cross section (1 cm^2) almost reaches that limit.

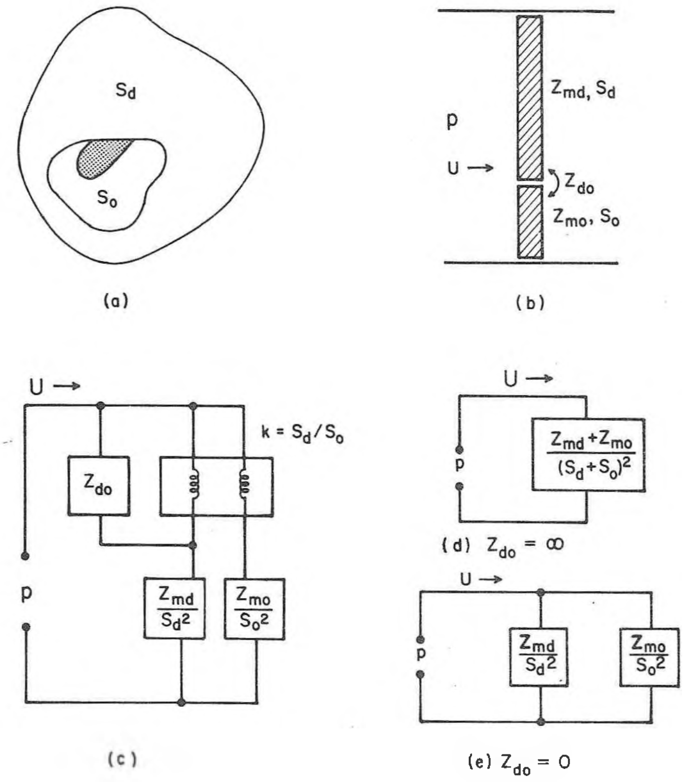

Fig. 8. Compound-eardrum concept: (a) S_o rigidly attached to malleus, S_d independent of S_o at high frequencies; (b) Rigid pistons S_d and S_o coupled by frequency-dependent impedance Z_{do}; (c) Network representation with ideal transformer; (d) Low frequency behaviour; (e) High-frequency behaviour. From SHAW (1977).

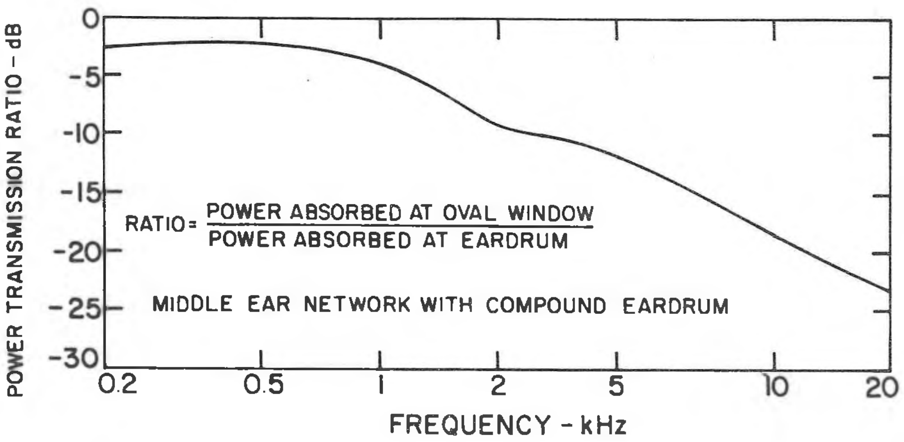

Fig. 9. Power transmission ratio of average human ear calculated from Zwislocki-style middle-ear network with compound-eardrum representation. From SHAW (1979a).

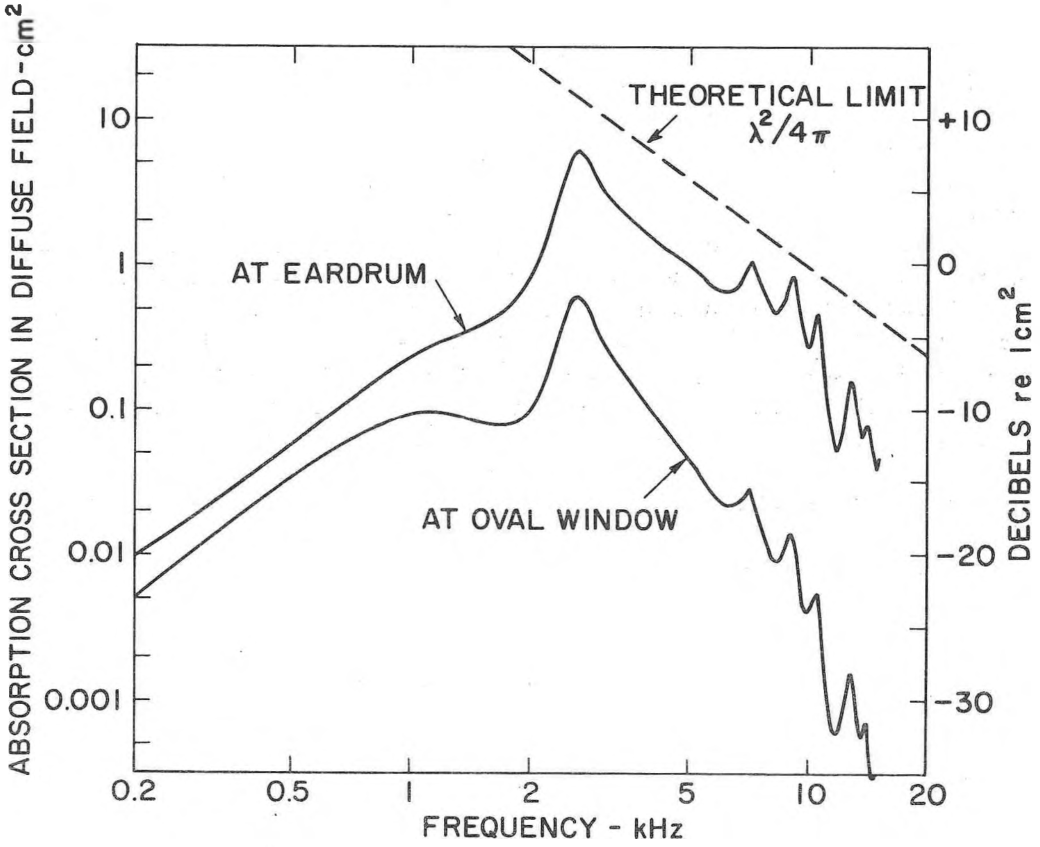

Fig. 10. Calculated absorption cross section of external ear physical model when terminated by middle-ear network with compound eardrum representation: (a) at eardrum, (b) at oval window of cochlea. From SHAW (1979a).

Viewed in isolation, the external ear is clearly an impressive sound collector at the higher frequencies. Unfortunately, as we have seen, only a small fraction of the high frequency energy reaching the eardrum appears to be transmitted to the oval window of the cochlea. Hence, if our understanding of eardrum and middle-ear function is correct, the inner ear receives barely 10% of the energy available from the sound field at the principal resonance frequency (∿2.6 kHz) and only 0.5% at 10 kHz.

My final vignette is inspired by a problem which caused confusion and consternation for three decades: the lack of agreement between psychoacoustic measurements with earphones and in the free field. It is now established beyond reasonable doubt that the elevated low-frequency hearing-threshold-levels measured with conventional earphones are contaminated by the masking effect of physiological noise generated when the ears are enclosed. This noise is most likely due to relative movement between the earphones and the head which is kept in vibration by the pump action of the heart and by general muscular activity. Above 1000 Hz the differences between the minimum audible field (MAF) and minimum audible pressure (MAP) can be readily explained by sound pressure transformations in the ear and around the head. Building on this knowledge and making use of various data which have become available in recent years, KILLION (1978) recently presented a revised estimate of the minimum audible pressure from 100 Hz to 10 kHz with tentative extensions at either end. (The minimum audible pressure, as defined by SIVIAN and WHITE in 1933, is the sound pressure level measured at the eardrum for a median normal subject at hearing threshold.) In Fig. 11 we approach the subject in a slightly different way. The solid curve and points are various experimentally determined average pure-tone hearing-threshold levels processed and translated into sound pressure levels at the eardrum so that they can be directly compared. As can be seen, there is reasonable agreement but some minor discrepancies remain which is hardly surprising considering the probable errors in the original measurements, the data processing and the translation procedures. We are, however, bound to ponder the significance of the peak in hearing threshold level at 2.6 kHz which is indicated in Fig. 11. If more sound pressure is, indeed, required at the eardrum to bring the median subject to threshold level at this peak than is required at frequencies on either side, then there must be a mechanism in the middle ear or beyond which, on average, counterbalances the principal resonance of the external ear.

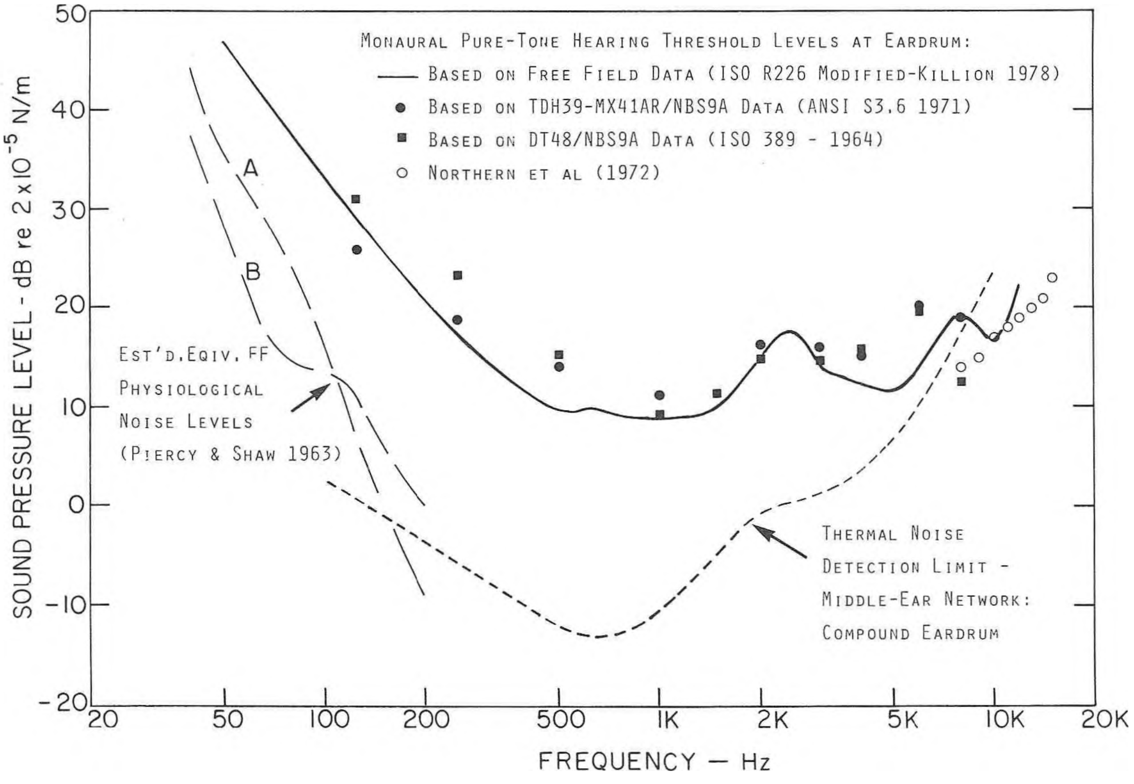

Fig. 11. Comparison of various standard values of monaural pure-tone hearing-threshold level presented as minimum audible pressure at the eardrum with estimated free-field physiological noise levels (broken lines) and calculated thermal-noise detection-limit (dotted lines). Transfer of free-field and earphone-coupler levels to eardrum position: according to KILLION (1978).

THE ELUSIVE CONNECTION

The reality of physiological noise generated within earphone enclosures was clearly demonstrated in two papers presented in 1962 (RUDMCSE, SHAW and PIERCY). As a corollary, it seemed likely that the head vibrations which generated noise within an enclosed ear should also set the middle ear into vibration, thus producing low-level masking even when the ear was open to the sound field. To estimate these noise levels a colleague and I set up a special measurement of the "occlusion effect". The results, which were presented at a meeting in 1963 (PIERCY and SHAW), are indicated by the broken lines at the left of Fig. 11. As can be seen, at 50 Hz the estimated third-octave band equivalent levels of physiological noise in the free field are not much lower than the hearing threshold levels which suggests that the sensitivity of the ear at very low frequencies may well be adapted to this built-in noise.

What can be said about the internal noise of the ear at higher frequencies? In 1948, DE VRIES concluded that "the Brownian movement of the inner ear is close to the threshold actually observed whereas the Brownian motion of the air at the eardrum is below the audible threshold." Now that we have acoustical networks to represent the human hearing system up to the oval window, we are in a position to calculate the thermal noise levels by applying the Nyquist noise generator theorem. The calculation confirms that most of the noise appearing at the oval window is associated with the input impedance to the cochlea not with the external ear. Knowing the integration time of the ear (GREEN and McKEY, 1959) we can then calculate the detection limit for pure tones in the presence of thermal noise. As shown by the dotted line in Fig. 11, this limit is nearly 20 dB below the observed median normal hearing threshold level at 500 Hz. At 5 kHz, however, the ear is evidently operating near the thermal limit. When the lines cross as they appear to do in the vicinity of 8 kHz, it is time to remind ourselves that such perfect agreement between theory and experiment is uncharacteristic of auditory acoustics and, therefore, to be viewed with the deepest suspicion! It seems safe to conclude that the last words on the external- and middle-ear systems have yet to be written and that the nature of the connection between the sound field and the inner ear will remain somewhat elusive for some time to come.

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A Comparison of Two Stationary Measurement Procedures for Truck Exterior Sound Levels

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Transport Canada

MEASUREMENT PROCEDURES that are intended to form the technical basis of vehicle exterior sound level regulations must satisfy a number of criteria that tend to conflict with each other. An efficient regulation requires, inter alia, that what is measured be highly correlated with the noise impact of the vehicle on the community. A regulation that is enforceable requires a highly repeatable measurement and a regulation that is actually to be enforced must necessary be based on a simple measurement procedure. This last requirement is particularly important for regulation of the sound levels of vehicles in service.

SAE Recommended Practice J366b must be rated highly on such criteria as a basis for regulating the sound emission of a heavy duty truck at its point of manufacture. Its merits have been recognised both by the United States Environmental Protection Agency and by Transport Canada in adopting it in all essentials as the basis of their respective regulations for new vehicles. However, a drive-by procedure, such as J366b, that requires a clear site of some 7000m^2 with ambient sound levels of no more than about 70 dBA is simply impractical as a basis for effective regulation of the sound emissions from heavy trucks in service.

At a slight cost in realism, the use of a test in which the vehicle remains stationary, such as SAE J1096, provides a useful simplification. However, a relatively quiet and rather extensive measurement site is still required by this procedure. Moreover, its use of a microphone located at 1.2m above the ground raises doubts about the repeatability of results on different sites, as noted by Piercy and Embleton (1)* among others. These considerations led to the development of Canadian Standards Association (CSA) Standard Z107.22, "Procedure for measurement of the maximum exterior sound level of stationary trucks with governed diesel engines". This procedure is notable for its use of a microphone located at 7.5m from the truck centreline and 80mm above the ground.

Although the federal government in Canada has no jurisdiction over the motor vehicle once it has entered service, it is nonetheless interested in having the effectiveness of its standards for the new vehicle maintained by appropriate provincial

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*Numbers in parentheses designate references listed at the end of the paper.

ABSTRACT

SAE RP J1096 and CSA Standard Z107.22 are compared in terms of their performance as predictors of pass-by sound levels measured in accordance with SAE RP J366b. The comparison is based on the results of tests on 60 diesel trucks covering a range of ages, sound levels and configurations. The CSA procedure is found to be at least as good a predictor of pass-by sound levels as RP J1096 and can be used on smaller and noisier sites. The results of some exploratory measurements of the effects of wind and temperature gradients on the repeatability of the two procedures are also presented and discussed.

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and municipal regulations. The Province of Ontario having indicated its intention to cite the new standard in its Model Municipal Noise Control By-Law (2), Transport Canada initiated the study described in the present paper. The primary purposes of the study were to evaluate the repeatability of measurements made using the new standard and to provide information on which a choice of maximum permitted sound level could be made for regulatory use of the CSA standard.

DESIGN OF THE STUDY

The basic approach selected was to compare the performance of CSA Z107.22 with that of SAE J1096 as a predictor of the sound levels measured according to SAE J366b. SAE J1096 was chosen as a standard of comparison since it was an existing alternative to the new standard and known to produce results in good agreement with SAE J366b. In addition, an exploratory study of the relative sensitivity of the two stationary measurement procedures to wind and temperature gradients was undertaken since it appeared possible that sound levels measured at 80mm above the ground might be significantly affected by refraction effects.

EQUIPMENT, PROCEDURES AND RESULTS

VEHICLES - A sample of 60 diesel-engined trucks was selected to cover the widest possible ranges of age, manufacture, size, configuration and state of maintenance. The oldest truck in the sample was built in 1958 while the newest was built in 1978 and still in chassis-cab form. The quietest truck recorded only 79.3 dBA while the noisiest produced 95.7 dBA in the measurements to SAE J366b. A sub-sample of 5 trucks was selected for the exploratory study of propagation effects to include various engine, exhaust and body configurations. Table A1 of the appendix to this paper contains a summary description of each of the vehicles.

MEASUREMENTS AND INSTRUMENTATION - All measurements were carried out on an extensive paved site at the intersection of two runways of a disused airfield. The surface was flat, level and relatively free of discontinuities, except for the joints between pavement slabs.

In all test procedures, simultaneous sound level readings were obtained from four sound level meters, two on each side of the truck. GenRad 1982 Precision Sound Level Meters equipped with 1/2 inch (13mm) random incidence microphones, digital read out to 0.1 dB and maximum hold circuits were used. The AC output from the sound level meters was recorded on a Bruel & Kjaer Model 7003 tape recorder to permit subsequent analysis and verification of the data. Each measurement was repeated a minimum of three times, even though the requirements of the relevant measurement procedure might have been met by the first two or three runs.

To compare the effects of wind and temperature gradients on the repeatability of the two stationary measurement procedures, the sub-sample of 5 trucks was tested on two separate occasions characterised by differing temperature profiles near the ground. It was hoped to find one occasion on which a strong negative lapse rate obtained and a second on which a temperature inversion existed. In fact the latter condition was not found during the period available for experimentation. The two temperature conditions therefore both correspond with negative lapse rates, one rather stronger than the other, as exemplified by Figure 2. The temperature profiles were measured by traversing a Wallac

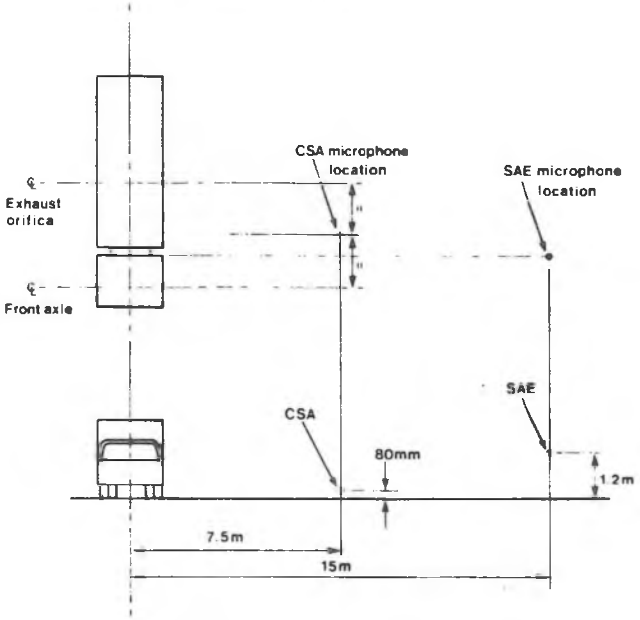

Fig. 1 - Microphone locations in SAE J1096 and CSA Z107.22

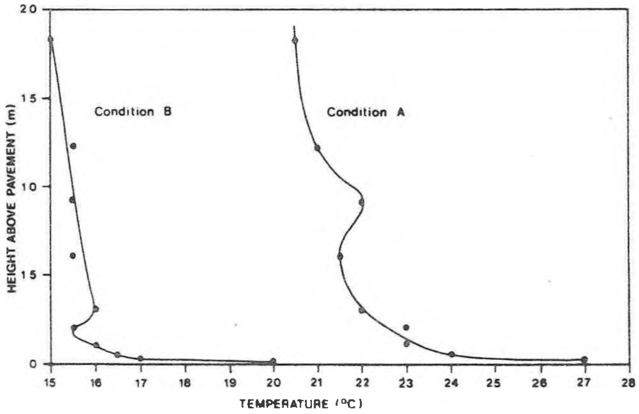

Fig. 2 - Typical temperature profiles (Truck #27)

GGA 23S thermoanemometer over a range of some 1.8m above the pavement, at intervals during the sound level measurements. Under both temperature conditions, the 5 trucks were oriented with their longitudinal centrelines perpendicular to the wind direction. Measurements were made first with one side exposed to the wind and then with the other, to provide four combinations of temperature profile and wind direction. The wind speed was approximately 4.5m/s at 1.2m above the pavement for both temperature profiles.

EXPERIMENTAL RESULTS - The results of the measurements made in accordance with SAE J366b, SAE J1096 and CSA Z107.22 on the sample of 60 trucks are summarised in Table A2. The averaging procedures specified in each of the respective procedures was applied to the basic sound level observations to arrive at the tabulated values. Thirty of the trucks were equipped with engine brakes so maximum sound levels observed during the deceleration phase of the SAE J366b procedure with engine brake engaged are shown separately for such vehicles.

Tables A3 and A4 contain, respectively, the results of measurements made according to SAE J1096 and CSA Z107.22 under 4 conditions of wind and temperature gradient. In these tables, the figures shown represent the average of the highest pair of readings that were within 1 dB of each other for a given side of the truck, temperature profile and wind direction. The highest pair within 1 dB was selected from all four nominally similar observations for the given location and conditions to provide a uniform basis for comparing the results from the two procedures.

ANALYSIS OF RESULTS

DISTRIBUTIONS - The sound levels of the 60 trucks measured in accordance with each of the three procedures were plotted on normal probability scales to facilitate comparison of their distributions. Figure 3 shows the results for SAE J366b when maxima resulting from engine brake operation are excluded. The straight line in the figure corresponds with the mean and standard deviation of the sample. Figures 4 and 5 show the equivalent results for SAE J1096 and CSA Z107.22 respectively.

In all cases it can be seen that the central 90 per cent of the data are fairly well represented by the normal distribution. The highest and lowest sound levels tend to depart from the linear trend of most of the data however, particularly for the two stationary procedures. The difference in slope between the line shown and the trend of the points in the central region indicates the contributions of the outlying results at each end of the distribution to the sample variance. The distributions are evidently sufficiently similar that linear regression techniques are appropriate for analysis.

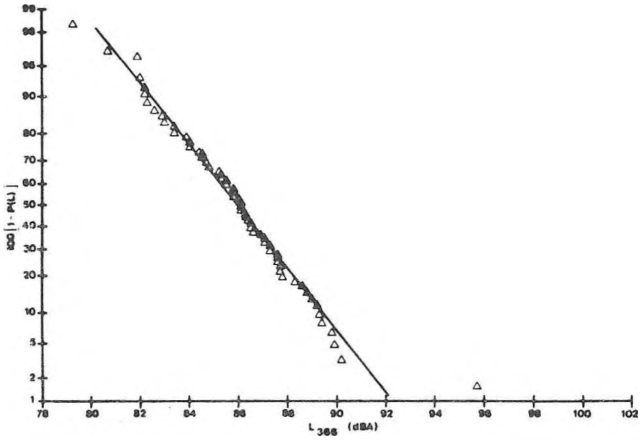

Fig. 3 - Cumulative distribution of results from SAE J366b, excluding engine brake maxima

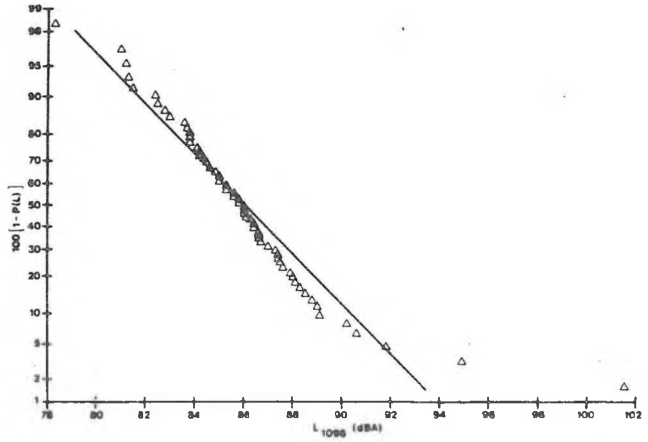

Fig. 4 - Cumulative distribution of results from SAE J1096

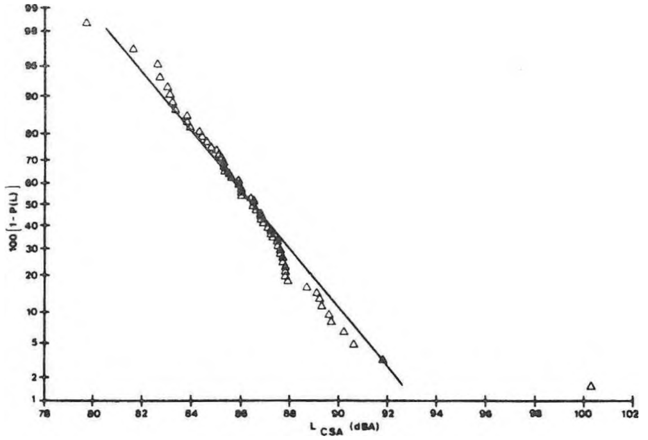

Fig. 5 - Cumulative distribution of results from CSA Z107.22

LINEAR REGRESSION ANALYSES - The sound levels of the 60 trucks measured in accordance with SAE J366b were then plotted against the levels measured in accordance either with SAE J1096 or with CSA Z107.22 and straight lines corresponding with the minimum mean square error in the SAE J366b levels were fitted. Figures 6 and 7 show the results of this procedure when maxima resulting from engine brake operation are excluded. Inclusion of maxima due to engine brake operation, which were produced by twelve of the thirty trucks so equipped, does not materially alter the correlation as can be seen from Table 1, in which the regression equations, standard errors and correlation coefficients are shown. Table 1 also includes such values for the regression of SAE J1096 sound levels on levels measured in accordance with CSA Z107.22.

It can be seen that the CSA procedure leads to standard errors that are slightly higher and correlation coefficients that are slightly lower than those resulting from the use of SAE J1096 as the predictor procedure for SAE J366b. The differences are not significant at the 95 per cent confidence level. The standard error and correlation coefficient for the regression of SAE J1096 on CSA Z107.22 are however significantly different from the corresponding values for the regressions of SAE J366b on CSA Z107.22.

DISTRIBUTIONS OF SOUND LEVEL DIFFERENCES - A slightly different method of comparing the predictive performance of the two stationary measurement procedures is to look at the variance of the difference between the sound level measured using J366b and that measured using each of the other two

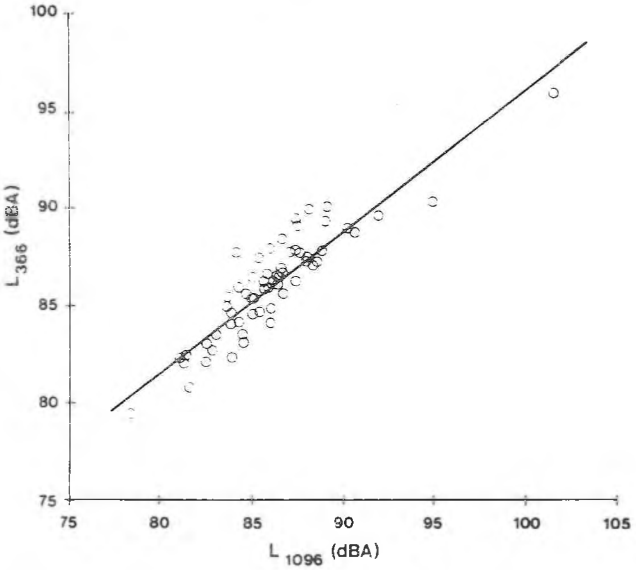

Fig. 6 - Linear regression of results from SAE J366b, excluding engine brake maxima, on results from SAE J1096

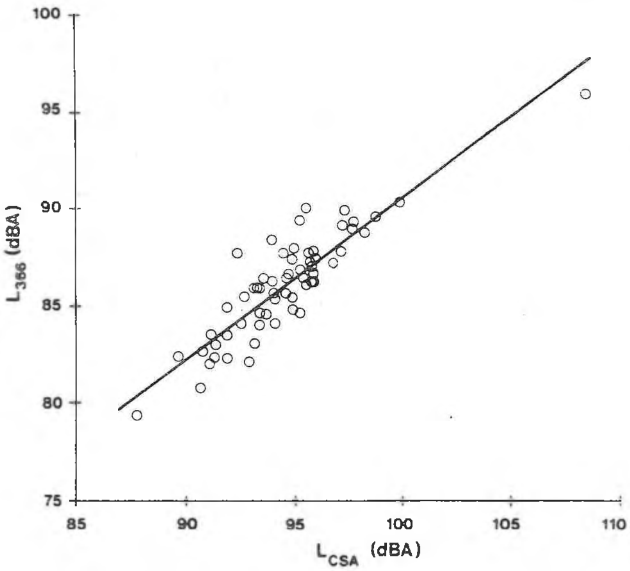

Fig. 7 - Linear regression of results from SAE J366b, excluding engine brake maxima, on results from CSA Z107.22

Table 1 - Comparison of Regression Equations (n=60)

Regression	Equation	Standard error, dBA	Correlation coefficient
J366b on J1096	$L_{366} = 24.0 + 0.721\ L_{1096}$	1.17	0.90
J366b on CSA	$L_{366} = 7.4 + 0.832\ L_{CSA}$	1.25	0.89
J366b* on J1096	$L_{366} = 15.1 + 0.827\ L_{1096}$	1.22	0.92
J366b* on CSA	$L_{366} = -4.3 + 0.959\ L_{CSA}$	1.29	0.91
J1096 on CSA	$L_{1096} = -20.1 + 1.12\ L_{CSA}$	0.97	0.96

*including maxima due to engine brake operation procedures. Table 2 shows the means and standard deviations of the difference distributions.

Table 2 - Distributions of Sound Level Differences (n=60)

Variate	Mean, dBA	Standard deviation, dBA
$L_{1096} - L_{366}$	0.08	1.51
$L_{CSA} - L_{366}$	8.51	1.34
$L_{1096} - L_{366}$*	-0.22	1.36
$L_{CSA} - L_{366}$*	8.21	1.30
$L_{CSA} - L_{1096}$	8.43	1.04

*including maxima due to engine brake operation

It is apparent that considering the difference distributions is equivalent to forcing a linear relation of unit slope between the two sound levels. Thus, for example, the second line of Table 2 is equivalent to:

$$L_{366} = -8.51 + L_{CSA} \pm 1.34 \text{ (dBA)}$$

Consideration of Table 2 shows that the difference distributions based on the CSA procedure have somewhat smaller standard deviations than those based on SAE J1096, although the differences are again not significant. The standard deviation of the differences in levels between J1096 and Z107.22 is however significantly smaller than that of the differences between J366b and Z107.22.

RUN-TO-RUN REPEATABILITY - To evaluate the run-to-run repeatability of each of the measurement procedures, the pooled variance of all observations for the noisier side of the vehicle was computed from the expression:

$$S^2 = \frac{\sum_{i=1}^{i=60} (m_i - 1) s_i^2}{\sum_{i=1}^{i=60} (m_i - 1)}$$

where m_i was the number of nominally identical runs (usually four) and s_i^2 the variance computed over those runs. Table 3 shows a comparison between the pooled standard deviations of the various measurement procedures. The differences between all pairs of standard deviations shown are significant at the 95 per cent confidence level, except for the two sets of data from J366b with and without engine brake maxima.

Table 3 - Pooled Standard Deviations of Observations

Measurement procedure	Pooled standard deviation, dBA
SAE J366b	0.67
SAE J366b*	0.74
SAE J1096	0.53
CSA Z107.22	0.46

*including maxima due to engine brake operation

EFFECTS OF WIND DIRECTION AND TEMPERATURE GRADIENT - Since the object of the exploratory study was to assess the magnitude of possible refraction effects on the sound levels measured in SAE J1096 and CSA Z107.22, analysis was directed to examining the largest differences in sound levels attributable to these environmental parameters.

For each of the two sides of the five trucks tested, the greatest differences in measured sound levels attributable to differences in wind direction and temperature profile were extracted by inspection of the results given in Tables A3 and A4. These greatest differences were then plotted as in Figures 8 and 9 and the mean values computed.

A comparison of these figures shows that the mean and variance of the results for the CSA procedure are somewhat greater than the equivalent figures for SAE J1096. In view of the small and arbitrary sample, the results were not further analysed in detail, except to note that the largest differences observed were not associated with any particular vehicle or configuration.

To obtain a general indication of the sensitivity of the results to refraction

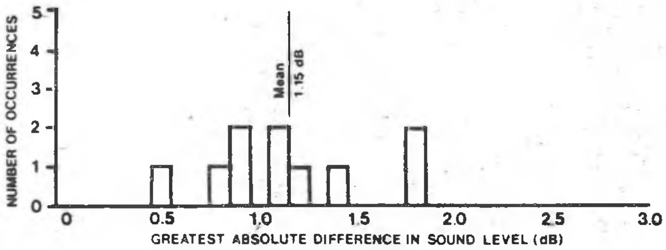

Fig. 8 - Histogram of greatest differences in results for SAE J1096 attributable to differences in wind direction and temperature profile

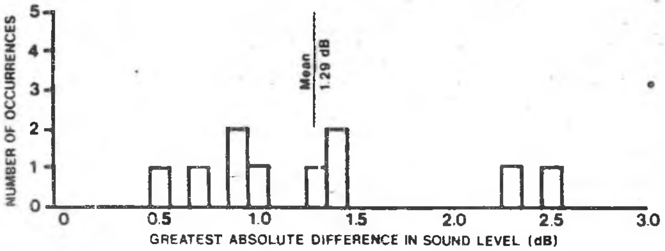

Fig. 9 - Histogram of greatest differences in results for CSA Z107.22 attributable to differences in wind direction and temperature profile

effects, specifically, the conditions were examined under which the greatest differences attributable to wind direction and temperature profile occurred. If refraction effects were predominantly responsible, then the greatest differences should have occurred most frequently when both wind direction and temperature profile differed, since the two influences would then have been additive. This analysis is presented in Table 4, where it can be seen that the greatest differences are distributed quite randomly among the three possible sets of conditions. Within the limited range of the present results, Table 4 thus implies that the repeatability of neither procedure is particularly affected by refraction effects.

Table 4 - Wind and Temperature Conditions associated with Greatest Differences in Sound Level for One Side of Truck

Measurement procedure	Temp. profile different	Wind dir. different	Both different	Total
SAE J1096	4	5	3	12*
CSA Z107.22	4	4	3	11*

*greatest difference replicated for Truck #57
**greatest difference duplicated for Truck #50

DISCUSSION OF RESULTS

CORRELATIONS BETWEEN PROCEDURES - The linear regression analyses and the comparisons of the difference distributions show in general that SAE J1096 and CSA Z107.22 are equally good predictors of the maximum exterior sound level measured by SAE J366b. On neither basis are statistically significant differences in the predictive performance of the two stationary procedures detectable.

CSA Z107.22 is however a somewhat better predictor of SAE J1096 results than it is of SAE J366b. This is consistent with the fact that the levels in the stationary tests are determined essentially by engine and exhaust, while during a pass-by, additional sources such as tires and transmission may contribute. That the observations in the stationary test were made simultaneously also enhances their correlation.

The mean differences among the sound levels measured in accordance with the three procedures for a given truck agree well with expectations. When maxima due to engine brake operation are excluded, the mean difference between SAE J1096 and SAE J366b is less than 0.1 dB. Under a similar exclusion, the mean difference between CSA Z107.22 and SAE J366b is some 8.5 dB. This may be compared with the increment of 9 dB that would be expected to result from the difference in microphone positions, if the truck were simply a point source of broadband noise.

RUN-TO-RUN REPEATABILITY - The significant differences in the run-to-run repeatability of the three measurement procedures are also broadly consistent with expectations based on a number of published studies. The higher repeatability of CSA Z107.22 in comparison with SAE J1096 is attributable principally to the shorter measurement distance and the consequently smaller effect of atmospheric turbulence on the properties of the transmission path (3, 4). That SAE J1096 is more repeatable than SAE J366b may be due to a number of factors. It is evidently more difficult to repeat the more complex pass-by procedure exactly, while the additional turbulence induced by motion of the vehicle tends to increase the variability in the properties of the transmission path between vehicle and microphone (4). In the present study, two runs for SAE J366b were made in each direction with respect to the site whereas all stationary measurements were carried out with the same vehicle orientation. Moreover the time to obtain four sets of measurements with the vehicle stationary was appreciably less than with the vehicle in motion. Relatively slow fluctuations in local environmental conditions may therefore have contributed more to the variability of the pass-by measurements than to the stationary measurements.

EFFECTS OF WIND AND TEMPERATURE GRADIENT - The very limited range of results obtained from the exploratory study does not justify conclusions of great generality. For example, if measurements had been made at higher wind speeds and during a temperature inversion, a systematic effect of wind direction and temperature profile might have been observed. The results obtained do however suggest that, within a typical range of test conditions, neither stationary measurement procedure is noticeably affected by refraction effects.

FURTHER WORK

The study described in the present paper has addressed only the correlations among, and repeatability of, three measurement procedures for a sample of vehicles tested at one site. A question of at least equal importance for regulatory purposes is the repeatability of measurements made on a given vehicle at several sites. Further work is therefore planned to compare the site-to-site repeatability of SAE J1096 and CSA Z107.22. In particular, it will be aimed at determining whether the theoretical advantage of CSA Z107.22, in using a microphone at ground level, is realised in practice.

CONCLUSIONS

The performance of SAE RP J1096 and CSA Standard Z107.22 as predictors of the maximum exterior sound level measured in accordance with SAE RP J366b has been compared for a sample of 60 diesel trucks. It is concluded that the CSA Standard is as good a predictor of the sound level during the pass-by test as is SAE J1096.

The run-to-run repeatability of the two stationary measurement procedures has also been compared and a small but statistically significant advantage to the CSA Standard has been demonstrated.

An exploratory study of the sensitivity of both SAE J1096 and CSA Z107.22 to refraction effects induced by wind and temperature profiles suggests that neither procedure is particularly affected.

ACKNOWLEDGMENTS

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APPENDIX

Table A1 - Description of Sample Vehicles

Truck No.	Year of Manufacture	Manufacturer and Model	Description	Engine
1	76	Mack RS600L	10 yd. Cement Mixer	Mack ENDT 676
2	78	Kenworth W924	Cab and Chassis	Cummins NTC 400
3	78	International S2500	Cab and Chassis	Cummins NTC 350
4	69	Kenworth W923	Tractor/Trailer	Cummins NHC 250
5	74	White Freight-liner WFT-6364	Flat Deck & Pup	Cummins NTC 350
6	78	White Western Star 4864-2	Tractor	Cummins NTC 350
7	78	Kenworth W924	Tractor	GM 8V 92TA
8	69	International 559444	Tractor/Trailer	Cummins NHC 250
9	71	GMC Astro 95	Tractor	GMC DH 9782
10	78	White Western Star	Tractor	GM 8V 92T
11	78	International Transtar 4300	Tractor	GM 8V 92T
12	74	International Fleetstar 2050	Dump Truck	GM 6V 53
13	70	Ford 8000	Dump Truck	GM 6V 53
14	78	Ford 9000 Custom	Dump Truck	Cummins NTC 350
15	69	Kenworth W925	Tractor/Trailer	Cummins NHC 250
16	78	Ford 9000	Tractor	GM 8V 92N
17	70	White Freight-liner WFT-8664T	Tractor/Trailer	GM 8V 71N
18	70	White Freight-liner WFT-8664T	Tractor/Trailer	GM 8V 71N

Table A1 - Description of Sample Vehicles (Continued)

Truck No.	Year of Manufacture	Manufacturer and Model	Description	Engine
19	76	White Freight-liner WFT-5164T	Tractor/Trailer	GM 8V 71N
20	69	Kenworth W923	Tractor/Trailer	Cummins NHC 250
21	76	White Freight-liner WFT-5164T	Tractor/Trailer	GM 8V 71N
22	76	White Freight-liner WFT-5164T	Tractor/Trailer	GM 8V 71N
23	76	International Transtar II COF 4070 B	Tractor/Trailer	GM 8V 71N
24	75	Kenworth Hustler	Commercial Refuse Packer	Cummins 555
25	75	International Cargostar 1950-13	Commercial Refuse Packer	GM 6V 53
26	76	International	Tractor	GM 671N
27	78	GMC MK 9782	Tractor	GM 8V 92TT
28	78	White Freight-liner WFC-12064T	Tractor/Trailer	Cummins NTC 400
29	76	Mack Cruiseliner	Tractor/Trailer	Mack 866
30	76	International Fleetstar 2070A	Tractor/Trailer	GM 6V 71
31	76	White Freight-liner WFT-6364T	Tractor/Trailer and Pup	GM 8V 92N
32	76	International Transtar II	Tractor/Trailer	GM 8V 92
33	76	International Fleetstar 2070A	Tractor/Trailer	GM 6V 71
34	76	White Freight-liner WFT-7564T	Tractor/Trailer	GM 8V 92N
35	58	Kenworth W923	Tractor/Trailer	Cummins NTC 350
36	76	International Cargostar 1950B	Domestic Refuse Packer	GM 6V 53
37	75	Kenworth Hustler H-2	Domestic Refuse Packer	GM 6172
38	75	Kenworth	Domestic Refuse Packer	GM 6V 53
39	77	White Freight-liner WFT-8664T	Tractor/Trailer	Cummins NTC 350
40	78	Hino LA 660	Cab and Chassis	Hino EH 100
41	77	GMC MK 9672	Tractor	GM 8V 92T
42	75	White Western Star	Tractor/Trailer	Cummins KT 450
43	76	White Freight-liner WFT-7564T	Tractor/Trailer and Pup	GM 8V 92N
44	75	White Freight-liner WFT 63644	Domestic Refuse Packer	GM 6171N
45	73	International Cargostar 1950A	Domestic Refuse Packer	GM 6V 53
46	74	Hayes	Flatdeck	GM 671N
47	76	Mack RS600L	10 yd. Cement Mixer	Mack ENDT 675
48	76	Mack RS600L	Cab and Chassis	Mack ENDTB 676
49	65	GMC DFWI-701	Tractor	GM 671
50	73	International Transtar 4300	Tractor	Cummins NT 230
51	71	International M623-50	10 yd. Cement Mixer	Caterpillar 3208
52	72	White Freight-liner	Tractor/Trailer	Cummins NTC 350
53	73	Ford 9000	Tractor	GM 671
54	78	Mack Cruiseliner	Tractor	GM 8V 92T
55	73	International Transtar COF 4070A	Tractor	Cummins NTC 350
56	71	International M623-50	10 yd. Cement Mixer	GM 6V 53
57	74	Hayes	Tractor	GM 671N
58	77	Scot A2HD	Dump Truck	GM 6V 53
59	69	Kenworth W923	Tractor	Cummins NH 250
60	77	Hino LB 660D	Van	Hino EH 300

Table A2 - Measured Sound Levels in dBA

	SAE J366b				
Truck No.	Accel'n	Decel'n	Engine Braking	SAE J1096	CSA Z107.22
1	83.8	84.8	-	83.7	91.9
2	85.5	84.0	84.0	86.7	94.0
3	79.3	77.2	-	78.3	87.7
4	87.7	85.2	87.1	87.4	95.8
5	89.8	87.4	88.2	88.1	97.3
6	85.8	83.4	86.2	85.8	93.0
7	84.0	82.5	82.4	84.2	92.4
8	89.3	87.8	87.8	87.4	95.2
9	87.3	86.9	87.1	88.0	95.9
10	82.2	80.3	82.4	83.8	91.8
11	86.1	85.0	-	86.1	93.9
12	89.2	84.4	-	39.0	97.7
13	88.8	83.6	-	90.2	97.6
14	87.1	84.9	-	87.9	95.6
15	86.5	83.8	88.6	86.6	95.8
16	84.5	80.9	-	85.3	95.1
17	95.7	88.2	99.0	101.5	108.3
18	89.4	84.7	94.2	91.8	98.6
19	85.8	83.5	86.3	84.2	93.3
20	86.5	85.2	86.9	85.8	94.6
21	86.3	85.2	86.1	86.4	94.5
22	87.3	83.5	86.6	85.3	94.8
23	85.2	82.0	82.7	85.0	94.0
24	86.9	83.8	-	88.3	95.7
25	84.4	83.4	-	85.0	93.6
26	87.8	82.1	-	86.0	94.9
27	82.3	80.8	-	81.3	89.6
28	83.0	81.4	84.2	84.5	93.1
29	81.0	81.9	82.2	81.2	91.0
30	87.7	83.1	-	88.8	97.1
31	84.0	82.3	85.1	86.0	94.0
32	83.9	80.7	84.1	83.8	93.3
33	85.8	82.6	-	85.6	93.2
34	84.5	81.7	-	83.8	93.3
35	84.7	82.8	87.9	86.0	94.8
36	85.3	84.4	-	84.9	94.8
37	86.8	86.3	-	86.6	95.2
38	87.2	87.6	-	87.6	95.6
39	88.3	86.5	87.6	86.6	93.9
40	87.6	86.1	-	87.0	94.4
41	83.4	80.6	82.6	84.4	91.1
42	89.9	89.4	89.6	89.1	95.5
43	86.1	82.6	85.7	87.3	95.8
44	86.3	83.4	-	85.0	93.5
45	82.6	80.8	-	82.8	90.7
46	88.6	86.0	-	90.6	98.2
47	84.2	85.3	-	83.6	92.6
48	80.7	79.0	80.2	81.5	90.6
49	86.1	82.2	-	85.6	95.7
50	83.4	79.8	-	83.0	91.8
51	82.9	82.1	-	82.5	91.3
52	86.0	83.9	83.9	86.4	95.5
53	86.4	83.5	-	86.3	95.3
54	82.2	79.8	81.9	81.0	91.2
55	89.0	86.1	86.2	87.5	97.2
56	85.3	85.5	-	84.6	94.5
57	87.1	82.4	-	88.5	96.7
58	90.2	86.9	-	94.9	99.8
59	87.6	83.9	86.7	84.1	92.3
60	82.0	81.7	-	82.4	92.8

Table A3 - Measured Sound Levels in dBA from SAE J1096 under Four Combinations of Wind and Temperature Profile

Truck #	Side of Truck	Temperature Condition A		Temperature Condition B	
		Upwind	Downwind	Upwind	Downwind
27	Left	84.3	84.2	84.8	85.0
	Right	84.3	84.5	83.6	84.1
40	Left	86.4	86.0	86.2	85.9
	Right	86.7	87.0	87.3	85.5
50	Left	83.8	83.7	83.5	84.4
	Right	84.8	83.7	84.0	84.0
57	Left	89.9	89.9	88.7	89.9
	Right	92.4	92.9	91.2	91.1
60	Left	82.9	82.2	81.8	82.1
	Right	82.3	82.3	83.1	81.7

Table A4 - Measured Sound Levels in dBA from CSA Z107.22 under Four Combinations of Wind and Temperature Profile

Truck #	Side of Truck	Temperature Condition A		Temperature Condition B	
		Upwind	Downwind	Upwind	Downwind
27	Left	91.6	92.6	92.2	91.8
	Right	91.3	91.7	91.6	91.8
40	Left	94.4	95.0	94.2	94.1
	Right	94.7	95.2	94.2	93.8
50	Left	91.3	92.7	91.4	93.8
	Right	92.1	92.1	93.0	93.5
57	Left	96.0	96.1	95.9	96.8
	Right	98.3	98.7	98.2	98.9
60	Left	89.9	92.2	90.4	91.4
	Right	90.9	91.8	90.6	90.5

Correction: 8 dB should be added to all sound levels in the abscissa of Figure 5.

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