4aPPa1. Mechano-acoustical measurement and modelling of the outer and middle ear

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Mechano-acoustical measurement and modelling have evolved together. Most early measurements of the behaviour of the outer and middle ear produced either spatial averages or single-point observations, which were amenable to modelling with uniform transmission lines and lumped circuits. A major step forward was the measurement of displacement patterns on the eardrum, which called for the use of finite-element models. Other major experimental steps forward included measuring spatial sound-pressure distributions, 3-D displacement patterns and intracochlear pressures. Use of the finite-element method made it desirable to obtain detailed 3-D shape measurements, which were made much easier by the introduction of magnetic-resonance microscopy and X-ray microCT. The finite-element method has also made it possible to exploit measurements of material properties, and several different approaches have been used recently for making such measurements. The greatest challenges may be in dealing with very small dimensions and non-linear visco-elastic behaviour. There is a need for more and better 3-D multipoint vibration measurements, and for material-property measurements that are more localized and that span a broader frequency range. Important directions for modelling include better use of available shape and material-property data, more attention to experimental animals and to variability, and better integration with cochlear models.
INTRODUCTION

Measurement and modelling of the mechanical and acoustical behaviour of the outer and middle ear have evolved together over the years. Most early measurements produced either spatial averages, such as acoustical input impedance and admittance, or single-point observations of displacement or velocity. Such measurements are amenable to modelling by means of uniform transmission lines and of lumped circuits based on an analogy between electrical circuits and mechano-acoustical systems. Multi-point measurements of spatial patterns, however, have inspired the use of distributed modelling techniques such as the finite-element method and the related boundary-element method. This in turn has called for better 3-D shape measurements and more detailed measurements of material properties.

Funnell et al. (2012, Sect. 3) presented a general overview of possible approaches to modelling (qualitative vs. quantitative, analytical vs. numerical, non-parametric vs. parametric, black-box vs. white-box, lumped-parameter vs. distributed-parameter, etc.) and discussed the principles of two-port models, circuit models and finite-element models in some detail. This paper very briefly and selectively reviews previous measurement and modelling work on the outer and middle ear and discusses future directions.

MEASUREMENT AND MODELLING

Head and Pinna

The earliest measurements of the acoustical effects of the head and pinna were perceptual. The stimuli were often artificially manipulated amplitudes and phases – for example, a tuning fork and tubes for the former and a device based on an electric motor, toothed wheels and two magnets for the latter (Stewart, 1920a, 1920b). However, not all combinations of intensity and phase differences correspond to physically possible sound-source locations (Hartley and Fry, 1921).

Firestone (1930) measured sound pressures at the position corresponding to the eardrum, for different actual source locations, using a head-and-body dummy on a roof; he used ‘many’ different azimuth angles in the horizontal plane. Wiener and Ross (1946) made measurements for three source locations in the horizontal plane, with human subjects, and also observed the effect of cupping the hand over the pinna. They measured at the entrance to the ear canal, half-way along the canal, and in front of the eardrum. They concluded that the eardrum/entrance pressure ratio did not depend on source location, so subsequent measurements were made only at the canal entrance (Wiener, 1947). Shaw and Teranishi (1968) made measurements in a realistic replica ear for multiple source locations in both azimuth and elevation. Burkhard and Sachs (1975) developed the still-popular KEMAR mannequin, which has realistic geometries for the torso, head and pinna; the ear canal and middle ear were based on the coupler designed by Zwislocki (1970, 1971) for earphone calibration.

As discussed by Gilkey and Anderson (1997, p. xv), making measurements ‘with real sources arrayed in space around the subject was often difficult, time-consuming, and expensive’. Wightman and Kistler (1989) reported measurements for 10 subjects and 144 source locations, and these measurements were subsequently used widely to simulate different source locations by means of headphones (Gilkey and Anderson, 1997, p. xvi).

In addition to measurements at various locations along the canal, Shaw and Teranishi (1968) also reported transverse spatial sound-pressure distributions based on measurements at multiple locations within the concha of the replica ear. They modelled their results using physical models with varying degrees of geometric simplification (Teranishi and Shaw, 1968).

Early mathematical models treated the head as a rigid sphere (e.g., Stewart, 1911; Hartley and Fry, 1921). Attempting to model more or less realistic geometries, Weinrich (1984; cited by Kahana, 2000) used the finite-difference method for the pinna and the boundary-element method for the head, but had ‘limited success’. Later the boundary-element method was used with much more realistic geometries obtained with laser scanners (Katz, 2001a, 2001b; Kahana and Nelson, 2006, 2007).

External Ear Canal

Early measurements of sound pressures in the external ear canal were taken at just one or two locations (e.g., Wiener and Ross, 1946). Lawton (1979; cited by Stinson et al., 1982) made measurements at up to ten locations along the canal, enough to be able to reconstruct standing-wave patterns, and then Lawton and Stinson (1986)
measured at about twice as many locations. Khanna and Stinson (1985) measured at a number of locations not only along the canal but also across the face of the eardrum, thus beginning to address the issue of transverse acoustical modes.

The simplest model of the canal, valid for the lowest frequencies, is a simple rigid-walled cavity. A model often used for higher frequencies is a rigid-walled circular cylinder with its ends perpendicular to its axis. To account for variations in the cross-sectional area along the canal, the one-dimensional horn equation of Webster (1919) can be used (Hudde, 1983; Stinson, 1985). Khanna and Stinson (1985) modified the horn equation to handle the curvature of the canal, and later extended their model to account for the non-rigidity of the eardrum (Stinson and Khanna, 1989). Rabbitt and Holmes (1988) used an asymptotic analytical approach that included the transverse modes of the canal and its interaction with the eardrum. Rabbitt (1990) reviewed a range of approaches to modelling the coupling between the canal and the eardrum. Rabbitt and Friedrich (1991) extended their analytical approach with a numerical method to handle realistic canal geometries and, among other results, illustrated the effects (usually neglected) of introducing a microphone probe tube into the canal. Stinson and Daigle (2005) compared the horn-equation approach for the canal with the use of the boundary-element method (related to the finite-element method) which permits calculation of the transverse variations of the sound pressure. See Funnell et al. (2013, Sect. 7.5.2) for a more detailed review and more recent references.

Middle Ear

In addition to measurements of outer-ear and middle-ear acoustical input impedance and admittance (e.g., Zwislocki, 1957), some early eardrum vibration measurements provided information about the spatial vibration pattern of the eardrum, at least at low frequencies. As discussed in a previous review (Funnell and Laszlo, 1982), most such research found that the displacements of the manubrium were smaller than the displacements of the surrounding pars tensa, but thinking about eardrum vibrations was dominated for many years by the interpretation by Békésy of his own measurements, namely, that ‘the whole eardrum except the extreme periphery vibrates as a stiff surface along with the manubrium’.

These early measurements were rather crude and ambiguous. A major step forward was the quantitative measurement of displacement patterns on the eardrum by Khanna and Tonndorf (1972) using time-averaged holographic laser interferometry. (Shortly thereafter, Dancer et al. (1975) used double-exposure pulsed holoigraphy for measuring the response of the eardrum to transients.) These measurements very clearly showed that the eardrum did not vibrate like a rigid plate at low frequencies, and also demonstrated increasingly complex spatial patterns at higher frequencies. Such measurements pushed circuit models beyond their comfort zone and called for the use of finite-element models, with their ability to represent distributed behaviour.

Another major step forward was the measurement of complex ossicular displacement patterns by Decraemer et al. (1991b), and subsequent 3-D measurements of ossicular vibrations (Decraemer et al., 1994) emphasized even more the complexity of the behaviour of the middle ear. The measurement of intracochlear pressures by Olson (1998) was an important step toward linking the phenomena of the middle ear to those of the inner ear.

Middle-ear models have taken the form of analytical models (e.g., Esser, 1947; Rabbitt and Holmes, 1986), circuit models (e.g., Zwislocki, 1957), finite-element models (e.g., Funnell and Laszlo, 1978), and various alternatives and hybrids (e.g., Shera and Zweig, 1991; Eiber and Kauf, 1994). See Funnell et al. (2013, Sects. 7.5.3-7.5.7) for a review of past modelling of the middle-ear air cavities, eardrum and ossicular chain; of coupling to the cochlea; and of non-linear middle-ear phenomena.

SHAPE MEASUREMENTS

Just as the measurement of spatial patterns led to the development of distributed models (analytical, finite-element, etc.), the capabilities of those models made it increasingly desirable to obtain accurate and detailed 3-D shape measurements. Early methods for measuring 3-D shapes included moiré topography, notably by Khanna and Tonndorf (1975a, 1975b) and later by Decraemer et al. (1991a); serial-section histology (e.g., Funnell and Funnell, 1988); and measurements on moulds, with a mechanical probe (Stinson and Lawton, 1989) or by sectioning, photographing and digitizing (Rabbitt and Friedrich, 1991). The subsequent introduction of magnetic-resonance microscopy for the middle ear (Henson et al., 1994) was a major advance, followed quickly by the use of X-ray microCT (Vogel and Schmitt, 1998; Decraemer and Khanna, 1999). The use of orthogonal-plane fluorescence optical sectioning (OPFOS) was demonstrated by Voie et al. (1993; Voie, 2002) and recently improved by Buytaert et al. (2011); it provides very high-quality images but requires a great deal of tissue processing.
MATERIAL PROPERTIES

Use of the finite-element method has also made it possible to really exploit measurements of material properties. For many years the only middle-ear material-property measurements were for the eardrum (Békésy, 1949; Kirikae, 1960; Decraemer et al., 1980; Wada et al., 1996), but in the past few years several different approaches have been used for such measurements (e.g., Cheng and Gan, 2007; Cheng et al., 2007; Luo et al., 2009; Soons et al., 2010; Zhang and Gan, 2010; Aernouts et al., 2010; Aernouts and Dirckx, 2012). Most of these measurements have been for the eardrum, but a few attempts have been made to measure the properties of the other soft-tissue components of the middle ear. The greatest challenges may be in dealing with the very small dimensions and in characterizing non-linear visco-elastic behaviour.

DISCUSSION

There is a need for more and better 3-D multi-point vibration measurements with high spatial resolution, both on the eardrum and on the ossicles, and for material-property measurements that are more localized and that span a broader range of frequencies. Important directions for modelling include better use of what shape and material-property data are available, more attention to experimental animals and to variability, and better integration with cochlear models.

The range of frequencies of interest in ear research has broadened over the years, from very low frequencies to speech frequencies, to the higher frequencies required for certain kinds of localization, to non-human communication frequencies, to the highest frequencies localized at the base of the basilar membrane in experimental animals. The higher frequencies greatly increase the complexity both of the acoustic fields and of the mechanical responses, making both experiment and modelling much more difficult.

Zwislocki (2002, p. x) stated that ‘the history of auditory research is full of examples of unrealistic mathematical and conceptural models that ignore existing experimental evidence and contradict fundamental physical laws’. Chizeck et al. (2009) stated that ‘most mathematical models published in peer-reviewed journals are not reproducible: they contain the authors’ errors of commission and omission, augmented by the errors introduced by editors and typesetters. Therefore, an exactly reproducible model is a rarity’. Moreover, the availability of increasingly sophisticated modelling software, and of numerical software in general, seems to make it easier and easier to do inappropriate things. Similar concerns apply also to experimental work, so considerable caution is required on both fronts.

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REFERENCES


