

An experimental study of the acoustic impedance characteristics of human hair

Bradley E. Treeby,^{a)} Jie Pan, and Roshun M. Paurobally

Centre for Acoustics, Dynamics and Vibration, School of Mechanical Engineering, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia

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Previous analytical and empirical studies of the human auditory system have shown that the cues used for localization are modified by the inclusion of nonrigid scattering surfaces (clothing, hair etc). This paper presents an investigation into the acoustic impedance properties of human hair. The legitimacy of a locally reactive surface assumption is investigated, and an appropriate boundary condition is formulated to account for the physiological composition of a human head with hair. This utilizes an equivalent impedance parameter to allow the scattering boundary to be defined at a reference plane coincident with the inner rigid surface of the head. Experimental examination of a representative synthetic hair material at oblique incidence is used to show that a locally reactive surface assumption is legitimate. Additional experimental analysis of a simple scattering problem illustrates that the equivalent impedance must be used in favor of the traditional surface impedance to yield physically correct pressure magnitudes. The equivalent acoustic impedance properties of a representative range of human hair samples are discussed, including trends with sample thickness, fiber diameter, bulk density, and mass. © 2007 Acoustical Society of America.

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I. INTRODUCTION

Below 3–4 kHz, the acoustic scattering characteristics of the human head match well with those of simple geometric shapes. As a result, sphere scattering models are commonly used to account for the principle features of human auditory localization cues over these frequencies. The traditional use of such models assumes that the head surface is completely rigid in nature.^{1,2} However, the surface impedance of the head affects both the binaural localization cues,³ and the head-related transfer function (HRTF).^{4–6} Given the appropriate impedance data, recent mathematical treatments of the sphere scattering problem facilitate an anthropometric investigation into the contribution of hair to the auditory percept.⁷ However, the acoustic properties of human hair are not well documented. While normal absorption coefficients for a small number of hair samples at arbitrary bulk densities have been presented,⁸ this is not sufficient to extrapolate the required trends or variability in impedance values representative of typical human subjects. Other investigations have been interested in the characteristics only at higher frequencies, for example in response to ultrasound.⁹ Additionally, no substantial discussion or investigation has been presented to address the validity of a locally reactive assumption for a covering of human hair. Measurements of the impedance of other fibrous materials at oblique incidence show that such materials can exhibit considerable properties of extended reaction, particularly at low frequencies.^{10,11}

This paper investigates the legitimacy of a locally reactive surface assumption and formulates a boundary condition

appropriate to examine the acoustic characteristics of a human head with hair. This is validated through impedance measurement at oblique incidence and simple sphere scattering experiments. The acoustic impedance characteristics of a representative range of human hair samples are then investigated. Changes in impedance with sample thickness, fiber diameter, bulk density, and mass are discussed.

The physical properties and distribution of human hair (terminal scalp hair) typically vary with both ethnicity and hair color. The mean diameter of individual Caucasian hair fibers is around 72 μm with an ellipticity factor (ratio of maximum to minimum diameter) of 1.5.¹² Asian hair is generally thicker and rounder (77 μm and 1.28) and African hair thinner and flatter (66 μm and 1.84), although there is considerable variability within the groups, particularly for Caucasians.^{12,13} Additional deviations are also evident along individual hair fiber lengths.¹⁴ On average the human scalp contains between 175 and 300 hair fibers per square centimeter,^{15,16} with a fiber density of approximately 1320–1340 kg/m^3 .^{15,17} These parameters allow a realistic range for the bulk density of human hair to be approximated. If the hair is assumed to stand perpendicular to the scalp surface, the bulk porosity is in the range of 98.5–99.5% and the bulk density 10–20 kg/m^3 . This alignment is realistic for short straight hair styled upwards. As the vertical hair is slanted back towards the scalp tangent, the hairs stack and the bulk density increases. Taking a parallelepiped segment of hair, as the hair is slanted the volume is scaled with angle ($\cos \theta$). Assuming that the segment retains a realistic finite volume, if the hair is sloped 75° from the scalp normal the bulk density range is increased to 40–80 kg/m^3 (94–97% bulk porosity). While the alignment of hair is more complex than this, and there are a multitude of fiber, distribution, and stylistic varia-

^{a)}Author to whom correspondence should be addressed. Electronic mail: treebs@mech.uwa.edu.au

tions that will change the overall bulk density, this provides a pragmatic approximation of the range. In comparison, sheep wool (also a largely keratin fiber) has a fiber diameter of 20–30 μm , a fiber density of 1320 kg/m^3 , and bulk densities in the range of 30–40 kg/m^3 .^{15,18,19}

Modeling the acoustical properties of fibrous materials has received considerable attention over the last several decades, particularly in relation to the mineral fibers utilized for sound absorption. These models are generally either derived from empirical power law relations,^{20–22} or detailed acoustic knowledge of the material microstructure.^{23,24} The ability of these models to accurately account for the acoustic properties of materials is reliant on the match between the fiber alignment evident in the material structure, and the geometry and interactions assumed in the model formulation (frequently parallel fibers). In relation to the fibrous materials that are generally of interest to acousticians, human hair has relatively unique bulk structural composition. The hairs are anchored to the scalp in a uniform patterned arrangement, and then depending on their length either stand at least partially upright (short hair) or stack towards the rear or sides of the head depending on hairstyle (long hair). Material models that can account for the acoustic characteristics of isotropic or layered anisotropic fine-fiber materials such as mineral wools cannot necessarily be extrapolated to account for the properties of hair. In addition to variations in bulk structural composition, the diameter of individual hair fibers is significantly larger than many acoustic materials previously investigated. Consequently, the current work does not attempt to evaluate the suitability of fiber models for predicting the acoustic properties of human hair. However, the material parameters and experimental results presented facilitate such an analysis should it be of interest to future researchers.

II. HUMAN HAIR AS A LOCALLY REACTIVE BOUNDARY

A. Use of equivalent impedance

The solution of a scattering problem in an unbounded medium is reliant on the knowledge of the boundary conditions that exist between the scattering bodies and their surrounds. These boundary conditions are typically expressed in terms of normal acoustic impedance, the complex ratio of surface pressure to the velocity normal to the surface.²⁵ The velocity is produced either by the flow of the surrounding fluid through porous surface openings, or by motion of the surface boundary itself.²⁶ The impedance is dependent on the detailed properties and structure of the material which are assumed to be time invariant. If a material is acoustically “rigid,” the surface impedance is much greater than that of the surrounding fluid. Consequently, the normal velocity at the boundary surface is approximately zero. Conversely, if a material is acoustically “soft” (or pressure released), the surface impedance is much less than that of the surrounding fluid and the total pressure on the surface is approximately zero. Physically, the real component of the impedance is associated with a damping force and corresponds to a net dissipation of energy. The imaginary part embodies the stiffness

and inertia of the surface and dictates the lag of the surface displacement behind the forcing pressure oscillation.

The analytic investigation of the contribution of hair to the auditory percept requires knowledge of these boundary characteristics, and their trends with representative modifications in hair diameter, thickness, and bulk density. Of particular interest to the current problem is whether the hair covering can be considered to be locally reactive. This requires that the motion of the surface at any position is dependent only on the incident acoustic pressure at that position, and is impartial to the pressure distribution over the remaining surface. The angle of refraction through the material is thus close to zero (the tangential component of the velocity is much less than the normal component) and the normal acoustic impedance is independent of the angle of wave incidence.²⁷ Note the reflection coefficient (and hence absorption coefficient) retains a characteristic dependence on the incidence angle, even for a locally reactive material.²⁵

Human hair as a sparse acoustic material in isolation cannot legitimately be assumed to be locally reactive. It has a high porosity and low bulk density and consequently the fluid velocity in nonradial directions cannot be reasonably neglected. However, human hair in context has a relatively unique bulk composition. The hairs are anchored to the scalp in a uniform patterned arrangement and form only a thin layer over the acoustically rigid head. Of the surface boundary formulations utilized for reflection and scattering problems, two are available for consideration. First, if the surface can be considered locally reactive, the relationship between the pressure and radial velocity at any location on the surface is entirely determined by the normal acoustic impedance at that position. The solution for the scattered wave can then be formulated using knowledge of these surface characteristics considering only the exterior sound field. Alternatively, if the scatterer is constructed from a homogenous material or fluid that is extensively reactive, the solution for the scattered wave can be formulated using the density and compressibility of the interior material. Morse and Ingard²⁵ give a thorough treatment of both of these problems for spherical scatterers. For a penetrable sphere with inhomogeneous material parameters that remain spherically symmetric (i.e., the density and compressibility are only a function of radial distance), a similar integral formulation can also be formed.²⁸

Given that the composition of interest approximates to a rigid sphere with a thin hemispherical covering of hair, the problem appears to correspond more closely to the assumptions of a locally reactive boundary than those of a penetrable sphere. While this may be a logical selection given the available boundary conditions, the assumption of a locally reactive surface does raise several other interesting questions. First, the traditional boundary formulation requires the surface impedance of the absorbent material. For a sparse fibrous material like hair, the location of this *surface reference plane* is not well defined or even necessarily immobile. Second, if a nonuniform impedance distribution is assumed, all impedance values must then be defined relative to this same surface reference plane [as shown in Fig. 1(a)]. Considering that the hair layer is atop the rigid head (in this case a sphere), this requires the impedance of the rigid sur-

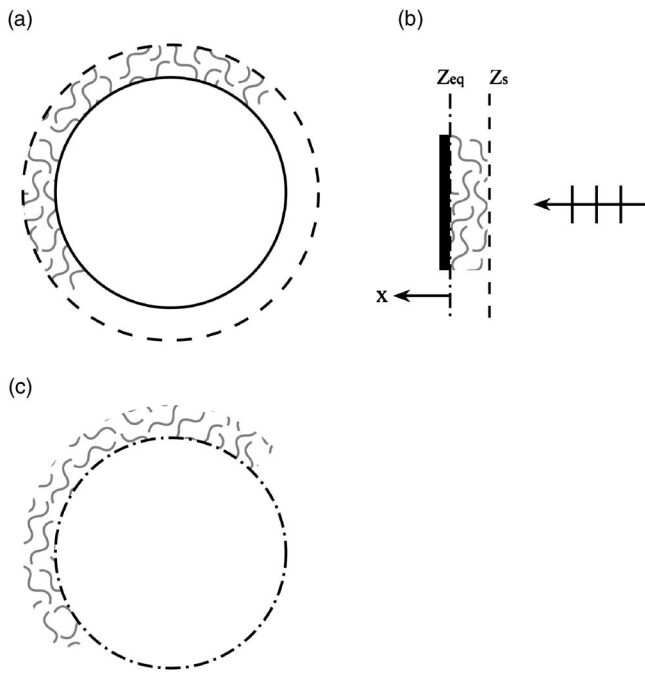


FIG. 1. (a) The traditional impedance formulation which requires the impedance of the rigid surface at an external reference plane. (b) The relationship between the equivalent and traditional impedance surface reference planes. (c) Reformulated scattering boundary condition using the equivalent impedance defined at the inner surface.

face to be defined at a reference plane exterior to the physical surface. For higher dimensional problems, the use of the normal surface impedance is no longer adequate to describe the characteristics of the material. This is because it is not legitimate to neglect the particle velocity in tangential directions. To correctly define the impedance would thus require three orthogonal components. Finally, as the formulation only accounts for wave motion exterior to the scattering surface, it is not valid to then examine the required pressure characteristics on the interior rigid surface which are obviously “inside” the defined surface reference plane.

Rather than reformulate the problem using a more complex composite boundary or to consider the impedance in three dimension, it is more convenient to define an *equivalent impedance* of the fibrous absorbent covering. This will be defined at a surface reference plane coincident with the interior rigid boundary, and formulated to adequately account for the absorption characteristics of the layer for all angles of incidence. Using the one-dimensional normal reflection problem for plane wave incidence (i.e., the impedance tube problem), the equivalent impedance Z_{eq} is computed by translating the traditional surface impedance Z_s to the new surface reference plane [see Fig. 1(b)]. Assuming a harmonic time component of the form $e^{-i\omega t}$, for a material of thickness ℓ this relationship is given by

$$\zeta_{eq} = \frac{(\zeta_s + 1) + (\zeta_s - 1)e^{-ik_0 2\ell}}{(\zeta_s + 1) - (\zeta_s - 1)e^{-ik_0 2\ell}}. \quad (1)$$

Here k_0 is the wave number in the propagation medium external to the material, and the specific acoustic impedance ζ is related to the normal acoustic impedance Z by the characteristic impedance $\rho_0 c_0$ of the external propagation medium

$$\zeta = \frac{Z}{\rho_0 c_0}. \quad (2)$$

Although the surface reference plane is defined coincident with the interior rigid boundary, the equivalent impedance defined here does not represent the impedance of this rigid surface in isolation. Rather, it continues to encapsulate the acoustic impedance properties of the material layer backed by the rigid boundary, the difference being in the nonconventional reference plane in which the impedance is defined. For the one-dimensional problem, it is straightforward to show that Z_s and Z_{eq} yield identical reflection (and absorption) coefficients. The solution for the time harmonic pressure (in one dimension) is thus independent of the reference plane in which the surface impedance is defined. It is important to note that the equivalent impedance values utilized throughout this paper can easily be converted to traditional surface impedance values using Eq. (1) and the thickness of the sample holder utilized for the impedance measurement. Likewise, any relevant surface impedance data that exist in the literature can be converted to equivalent impedance if the sample thickness is known.

As the equivalent impedance encapsulates only the properties of the material for normal incidence, its use for higher-dimensional problems is only valid provided that its value does not significantly change with incidence angle. This is examined experimentally in Sec. II B. For a sphere with a nonuniform boundary, the definition of equivalent impedance now allows the scattering boundary to be defined on the interior surface of the sphere as shown in Fig. 1(c). The use of this equivalent impedance parameter in conjunction with a locally reactive surface boundary offers computational advantages over more complex boundary conditions. The pressure and velocity on the boundary can now be related simply by the impedance of the surface material, rather than the maintenance of a pressure and velocity continuity across the boundary considering the wave motion inside the scattering object.

B. Measurement of acoustic impedance at oblique incidence

To examine the validity of a locally reactive surface assumption, the acoustic properties of human hair at oblique incidence were experimentally examined using a representative synthetic fibrous material. The properties of this material are shown in Table I (sample SH 01), and a large scale sample is visible in Fig. 2. The material was constructed with individual fibers attached at one end to a thin fabric backing with an approximate bulk density of 30 kg/m^3 . The material was initially selected as it had similar fiber diameter and bulk density characteristics to human hair, and then later verified to have comparable impedance properties. Reference measurements were made of the material using the two microphone impedance tube technique following the experimental procedure outlined by the ISO 10534-2 standard.²⁹ The impedance tube utilized had a circular internal cross section 60 mm in diameter, with a removable pipe section containing a movable rigid piston to allow sample placement. The working frequency range of the tube was 375–3000 Hz. Samples

TABLE I. The color, texture, treatment (N – natural, C – colored), curvature (s – straight, w – wavy, c – curly), diameter, and length of the human hair (HH) and synthetic hair (SH) samples.

Sample	Color	Texture	Treatment	Curvature	Mean diameter [μm]	Mean length [mm]
HH 01	Light brown	Thick	N	w	104	60
HH 02	Blonde	Medium	C	c	64	90
HH 03	Dark brown	Medium	C	s	77	60
HH 04	Dark blonde	Thick	N	s	75	40
HH 05	Light brown	Medium	N	c	80	50
HH 06	Light blonde	Fine	N	w	80	80
HH 07	Dark blonde	Medium	N	w	80	140
HH 08	Dark blonde	Fine	N	c	75	120
HH 09	Medium blonde	Medium	N	c	89	150
HH 10	Dark blonde	Medium	C	s	95	160
HH 11	Dark blonde	Medium	C	w	74	140
HH 12	Dark brown	Thick	N	c	85	70
SH 01	Medium brown	Fine	N	s	55	50

were held within a 40-mm-deep sample holder with a frontal termination made from an open wire grid. Two other smaller holders (20 and 10 mm in depth) were also constructed for additional tests. While the material had hair fibers up to 60 mm in length, the natural arrangement and pile of the bulk material meant that the samples were not significantly deformed when placed in the holder. The microphone separation and termination distances were calibrated by repeating multiple no sample tests with and without each of the sample holders (removing and replacing the microphones between each test). The distances were then calculated using the position of the first pole and first zero of the inter-microphone frequency response function and the speed of sound in the tube, averaged across the appropriate tests. The thin grid covering of the sample holders was shown to have a negligible effect on the measured parameters by repeating tests both with and without the grid present. The resulting surface impedance of the synthetic hair material measured in the impedance tube is shown in Fig. 3(a).

The measurement of normal acoustic impedance at oblique incidence has been of historical interest and a variety of test methodologies have previously been discussed.^{10,30,31} The development of two microphone *in situ* measurement techniques has allowed this measurement to be simplified



FIG. 2. (Color online) Experimental setup for the measurement of normal acoustic impedance at oblique incidence using a spherical sound source. The synthetic hair material is shown with a random fiber alignment.

significantly, and mathematical formulations using both plane and spherical waves have been proposed.^{11,32,33} The

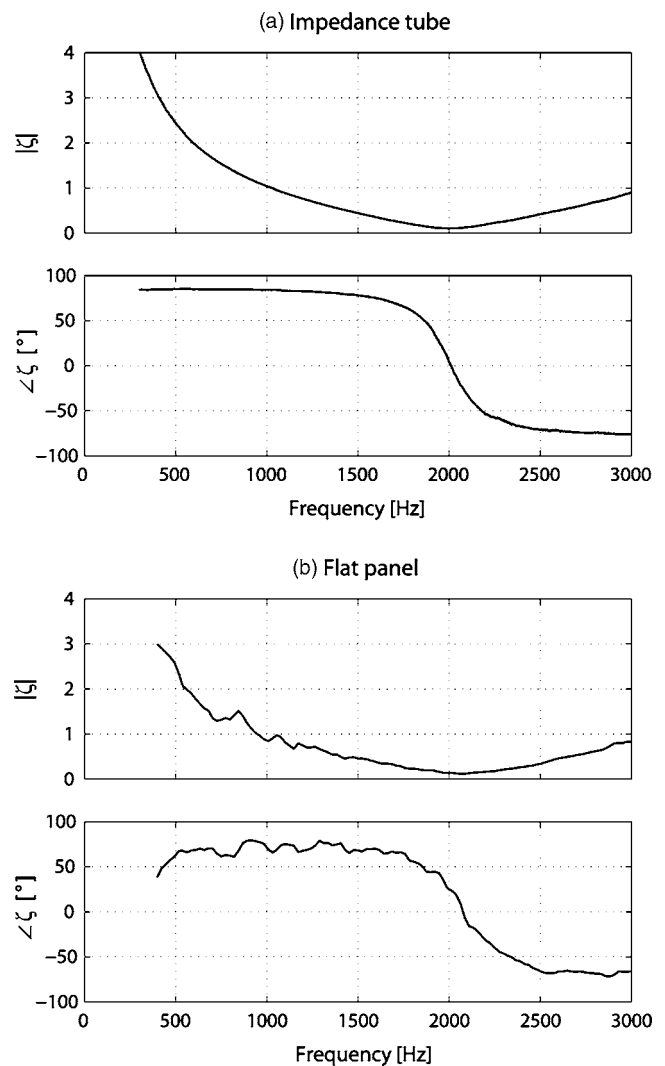


FIG. 3. Comparison of the specific normal surface impedance of the synthetic hair material for a random fiber alignment and a sample thickness of 40 mm. (a) Results from impedance tube tests. (b) Results from flat panel tests in free field using a microphone spacing of 15 mm and a surface offset of 63 mm.

experiments presented here follow this two-microphone methodology assuming a spherical incident wave. Figure 2 shows the experimental setup with a large sample of the synthetic hair attached to a $1.2 \times 1.2 \times 0.025$ m panel made from high density fiber board. The wooden material was shown to be approximately rigid over the frequency range of interest (absorption coefficient $\alpha < 0.08$). Both random (hair gently swept against pile direction) and parallel (hair swept with pile direction) fiber alignments were tested. For each test, two 1/4 in. microphones (BSWA Tech MPA416) were held perpendicular to the panel, with either a 15 or a 50 mm separation (see Li and Hodgson³³ for a diagram of the standard experimental configuration). For the two fiber alignments, the closest microphone was positioned within 10 mm of the effective frontal surface (63 mm from the rigid backing for the random fiber alignment, 32 mm for the parallel). This was to minimize errors associated with the assumption of a constant source angle relative to material surface and the microphones.³³ A source separation of 0.4 m was used and incidence angles from 90° (normal incidence) to 40° were tested. For each angle of incidence, impulse response measurements were obtained using maximum length sequences (MLS) produced by the Brüel & Kjær DIRAC software. A horn driver fitted with a 0.2 m cylindrical attachment (19 mm internal diameter) was used to provide a spherical incident wave. A MLS length of $2^{14} - 1$ (the shortest available sequence length) with ten averages and a sampling frequency of 96 kHz was used. The impulse responses were shortened to 2^{12} samples, windowed using a cosine-tapered (Tukey) window with a 25% taper ratio, and converted to the frequency domain using a 2^{12} point fast Fourier transform. To compensate for any phase mismatch between the microphones, all tests were repeated with the microphone positions reversed.

Comparative trends for the surface impedance at normal incidence (from 400 Hz) are shown in Fig. 3(b). The results shown correspond to a random hair alignment and a microphone spacing of 15 mm. To allow direct comparison with the impedance tube measurement, this assumes a surface reference plane that is offset 40 mm from the rigid backing (equal to the depth of the impedance tube sample holder used). While the results from the free-field flat panel test contain significantly more noise, the two measurements are essentially identical. This mutually validates both experimental procedures. The noise in the free-field panel tests, particularly at low frequencies, is attributable to the frequency limitations of the sound source used, the finite size of the material sample, and the imperfect nature of the anechoic test environment. The exact impedance values for both test methodologies are strongly dependent on the selection of the location of the surface reference plane. For the free-field panel tests this was extremely difficult to estimate. The corresponding changes in the real and imaginary components of the normal surface impedance with incidence angle are shown in Fig. 4. Again this assumes a surface reference plane that is offset 40 mm from the rigid backing. Contrary to the discussion by Li and Hodgson,³³ the results from either microphone separation yielded nearly identical results over the entire frequency range of interest. For the same surface ref-

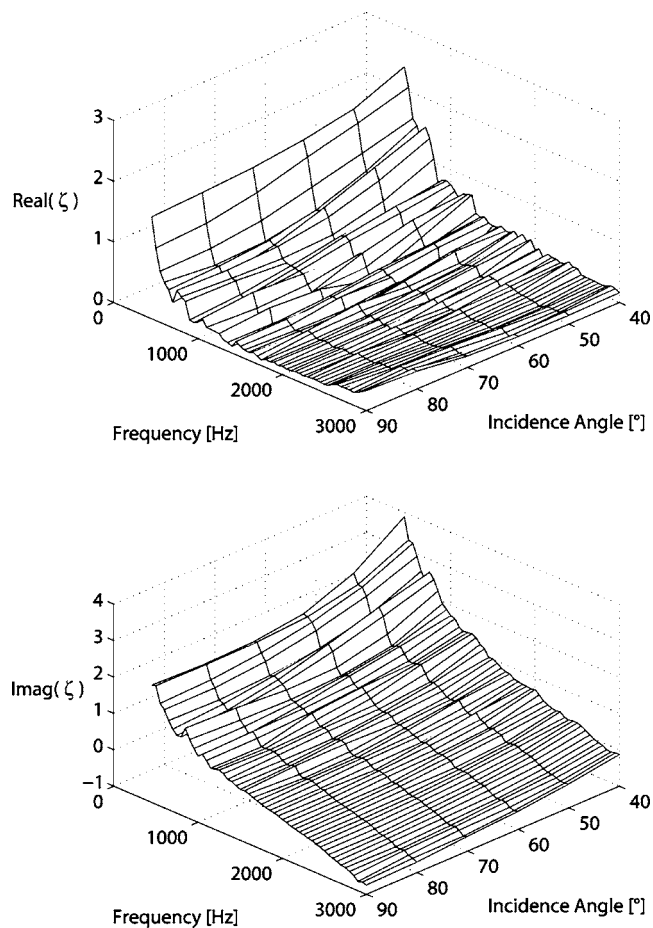


FIG. 4. Changes in the specific normal surface impedance of the synthetic hair material with incidence angle (real and imaginary components) for a random fiber alignment, a sample thickness of 40 mm, a microphone spacing of 15 mm, and a surface offset of 63 mm. Here 90° corresponds to normal incidence.

erence plane, the alignment of the fiber also had little effect, although a diminutive resonance was observable over a small frequency range for the parallel alignment tested. This resonance is due to the coupling between the motion of the air and the fibrous material.³⁴ As the bulk density is increased this becomes more significant, however, as tested the impedance properties are not strongly dependent on this alignment.

As shown in Fig. 4, at low frequencies there is a noticeable dependence of the normal impedance on incidence angle, and the material cannot be considered entirely locally reacting. As frequency increases, the changes with incident angle are reduced. This is consistent with other oblique incident tests of fibrous materials,^{10,11,33} although a definitive acoustic explanation does not always accompany such results. For fibrous and porous materials, the acoustic impedance modalities necessitate a slightly different phenomenological explanation than other textbook acoustic interfaces. Such a description is given in detail by Ingard.²⁷ At very low frequencies, the physical structure of the material itself is able to vibrate and the acoustic impedance properties are dependent on the material's stiffness. The excitation and coupling of a limited number of structural wave modes within the material cause it to be extensively reactive (the excitation of the surface at one position will induce motion at other

locations). Similarly, at very high frequencies the air within the porous cavities will support wave motion similar to that in free space, and the surface impedance will again be extensively reactive. Between these extremities, the material frame is approximately rigid, and the friction force dominates both inertial or stiffness characteristics. In this circumstance, the wave motion in the material degenerates into a diffusive process, and the interior phase velocity is much smaller than that in the external propagation medium.²⁷ Consequently, the angle of refraction through the material is close to zero, and the normal acoustic impedance does not show a strong dependence on incidence angle.²³

Even if the phase velocity in the material is not substantially below that in the external propagation medium (i.e., the refraction angle within the material is not necessarily close to zero), for a thin porous layer with a rigid backing, the material may nonetheless be approximately locally reacting. If the stiffness and inertia of the material do not facilitate additional wave motion, the area of *extended influence* (i.e., the region over which the pressure oscillation at any position has influence) can still be considered to be relatively small. In this situation, the normal impedance will again not show a strong dependence on incidence angle (away from grazing incidence). For the synthetic hair material, it is likely that both a reduced internal phase velocity and the small thickness of the layer contribute to the diminished observable variance in the normal acoustic impedance with incidence angle over the higher frequencies shown in Fig. 4.

The impedance properties of the material layer at higher frequencies cannot be intrinsically inferred from those discussed at lower frequencies. Without access to detailed material properties and adequate material models, it is difficult to estimate exactly how the material will behave, particularly at frequencies significantly above the measured range. This is due to the multiplicity of acoustic characteristics that porous layers may exhibit.²⁷ Frequency and other limitations currently exist in both free-field and impedance tube measurement techniques, and consequently published results rarely exceed 5 or 6 kHz. While this range is sufficient for the current problem (sphere scattering models of the human head), further classification may be required to describe the acoustic impedance properties of human hair over the complete audible frequency range.

As the surface reference plane is translated towards the rigid backing (where the equivalent impedance is defined), the overall impedance magnitude is increased. Figure 5 illustrates the corresponding equivalent impedance of the synthetic hair material. Any remaining incongruity with incidence angle at low frequencies is now of less relevance, as the impedance magnitude over this range dictates a surface that is approximately rigid. Considering the frequency range of interest for scattering models used by binaural synthesis (typically below 3 kHz), a locally reactive surface boundary can now be considered a legitimate assumption. Although not formally tested, it is intuitively expected that higher density hair samples would illustrate similar characteristics. Conversely, for samples with a substantially increased material thickness (a large afro, for example), a locally reactive equivalent impedance parameter may no longer adequately

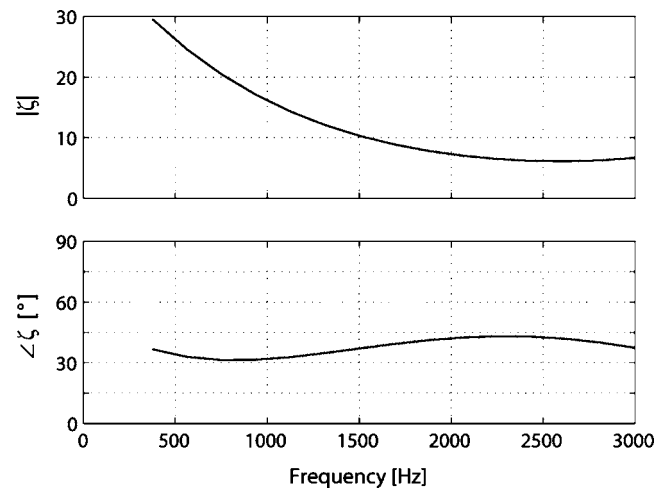


FIG. 5. Equivalent impedance of the synthetic hair material calculated using Eq. (1) and the surface impedance measured by the impedance tube shown in Fig. 3.

capture the acoustic properties of the layer, as a small area of extended influence no longer inherently exists.

C. Experimental validation of the use of equivalent impedance

To illustrate the legitimacy of using equivalent impedance for higher dimensional problems, the scattering of sound by a sphere with a uniformly distributed surface boundary will be briefly examined. The mathematical formulation of this problem is reviewed in many texts and is not repeated here, e.g., Ref. 3. Given a 0.124 m radius rigid sphere uniformly covered in the synthetic hair material, the pressure exterior to the surface can be calculated using the normal acoustic impedance. Figure 6 illustrates the resultant pressure magnitude at 1000 Hz along the anterior median axis adjacent to the sphere. The solid line corresponds to use of the equivalent impedance (shown in Fig. 5), and the dashed line the impedance defined at the traditional surface reference plane (shown in Fig. 3). To allow direct comparison, the results using the latter assume an enlarged sphere radius equal to the material thickness. Clearly the definition of the surface reference plane influences the analytical result.

To validate which impedance surface reference plane yields the physically correct pressure values, the problem was examined experimentally within an anechoic chamber. A 0.124 m radius wooden sphere supported by a thin steel rod was uniformly covered by the synthetic hair material using a thin double-sided tape. The covering was tailored circumspectively to maintain the overall distribution of the hair (with a bulk density of approximately 30 kg/m^3), and so that it fitted neatly over the sphere surface without any significant deformation. Seven 1/2 in. microphones (BSWA Tech MA211) were positioned in an evenly spaced array along the anterior median axis as shown in the upper panel of Fig. 6. The pressure perturbation due to the presence of the sphere was then obtained by measuring the frequency response between the microphone array and the excitation source (white noise from a Brüel & Kjær HP1001 unidirectional sound source) both with and without the sphere. The source was positioned

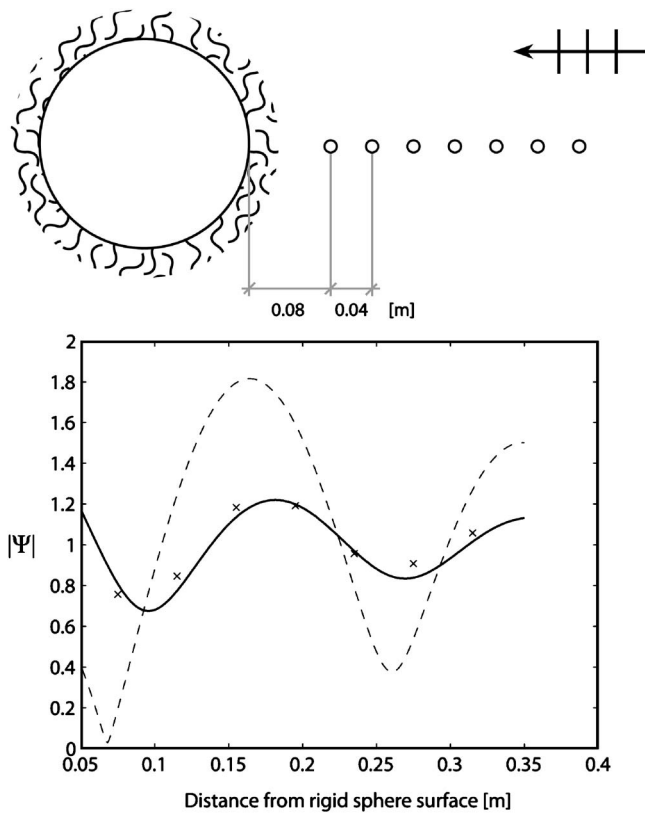


FIG. 6. The pressure magnitude $|\Psi|$ along the anterior median axis of a 0.124 m radius rigid sphere uniformly covered by a synthetic hair material, where Ψ is the spatially dependent component of the complex pressure. The upper panel illustrates the experimental setup showing the position of the evenly spaced array of seven microphones (circles). The incident wave approaches from the right and is assumed to be plane. The lower panel illustrates the experimental pressure magnitude at 1000 Hz (crosses), along with comparative analytic values using the equivalent impedance (solid line) and the traditional surface impedance (dotted line). The impedance characteristics used are shown in Figs. 5 and 3, respectively.

approximately 2.5 m from the sphere to allow plane wave propagation to develop. The measurements were captured and processed using the National Instruments LabVIEW software, and an eight-channel data acquisition card (National Instruments 4472B). Again both random (hair gently swept against pile direction) and parallel (hair swept with pile direction) fiber alignments were tested.

The pressure magnitudes at the seven microphone positions are illustrated by the crosses in Fig. 6. The results shown correspond to the test using a random hair alignment and match closely with the analytical results using the equivalent impedance. As with the oblique incidence tests the alignment of the hair had little effect on the measured pressure magnitudes. At other frequencies the experiment yielded analogous results. However, it should be noted that at significantly higher frequencies the spatial resolution of the microphones was not high enough to give an accurate comparison. For the current work it is sufficient to conclude that the use of the equivalent impedance yields legitimate analytical results. Experimental analysis of the sphere surface pressure (not discussed here) yielded the same supposition.

A similar scattering problem was examined by Cook and Chrzanowski³⁵ to determine the absorption coefficient of a cattle-hair felt. A series of rigid spheres covered with a layer

of the hair felt were placed within an anechoic chamber. Comparative results derived from a locally reactive sphere scattering model using the surface impedance of the hair felt deviated substantially from experimental results. The differences were attributed to the inadequacy of the boundary condition to account for the properties of the felt. Experimental results presented by Brungart³⁶ for the pressure adjacent to a rigid sphere uniformly covered with kapok (simulating hair) also differed substantially from analytical results. The analytical results were derived using measured values of the surface admittance assuming a locally reactive surface. The simulations using the kapok admittance (defined at the traditional surface reference plane) more closely resembled the characteristics of an infinitely soft sphere than those of a rigid sphere. This is consistent with the results presented in Fig. 6. The differences in Brungart's results were again attributed to the inadequacy of the measured surface impedance to account for the properties of the material.

III. NORMAL ACOUSTIC IMPEDANCE PROPERTIES OF HUMAN HAIR

A. Validation of measurement technique

As the formulation and validation of an appropriate impedance boundary is now complete, it is useful to examine the extent of equivalent impedance values experienced by a representative range of human hair samples. As it is not possible to easily measure hair impedance *in situ* from human subjects, the acoustic properties will again be examined using an impedance tube. The experimental results discussed in the preceding sections suggest that the impedance is not strongly dependent on the relative arrangement of the hair fibers. However, for these experiments the individual fibers remained attached to a fabric backing. Samples of human hair collected from hair cuttings are no longer constrained in such a manner. The consequence of this constraint on measured impedance values was examined using three samples of the synthetic hair material each attached directly to a rigid wooden backing with thin double-sided tape. The impedance properties of the material samples were measured, then the hair fibers cut from the backings and remeasured under the same conditions using a variety of fiber alignments. The mean (solid line) and range (dashed lines) of the measured impedance values are shown in Fig. 7(a). The variability is well within the expected range for multiple sample tests, and there is clearly not a strong dependence on the attachment of the material to the rear surface.

To examine the impedance trends of human hair, 12 samples of varying hair type and length were collected from cuttings from a salon. The properties of these samples are shown in Table I. The mean diameter was measured using a profile projector ($\pm 1 \mu\text{m}$) and three hair fibers selected at random from each sample (each fiber was measured at two different locations). The color, texture, treatment, and curvature were classified by the salon from which the samples were collected. The equivalent impedance variability across all samples for a density of 40 kg/m^3 and a sample thickness of 20 mm is shown in Fig. 7(b). Again, the results across all samples are reasonably consistent, particularly at high fre-

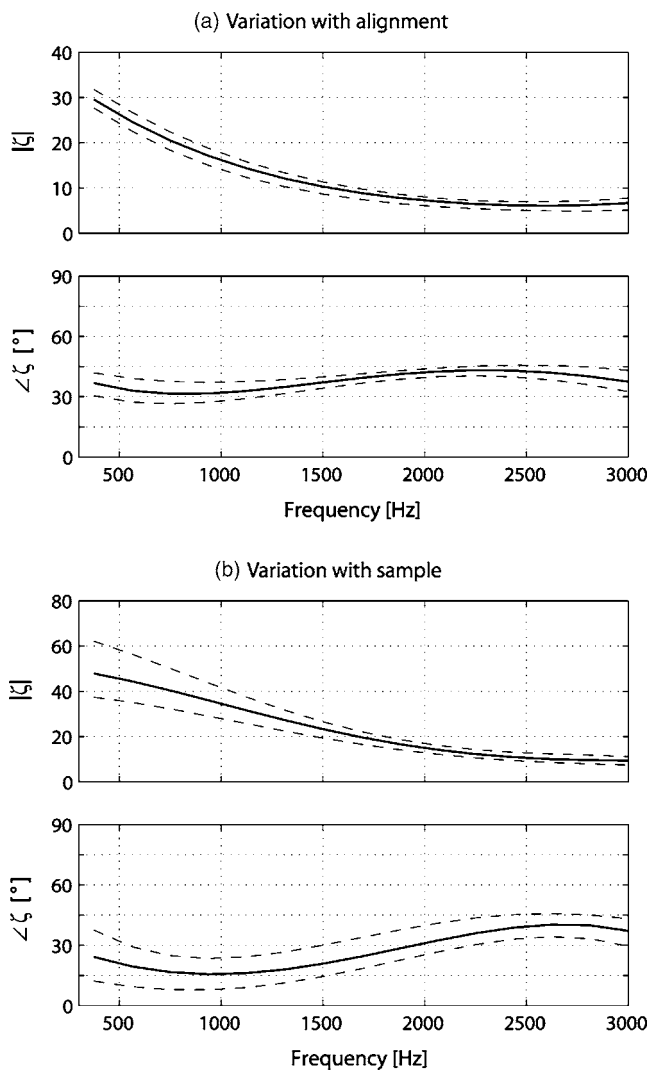


FIG. 7. (a) Variation in the equivalent impedance of the synthetic hair material with sample alignment. (b) Variation across all human hair samples for a sample density of 40 kg/m^3 and a sample holder thickness of 20 mm.

quencies where the material is absorptive. There is not a strong correlation between the spread of results and the properties of the individual hair samples. While it is generally expected that flow resistance and hence impedance will change with both bulk density and fiber diameter, for larger diameters this variability is considerably reduced.³⁷ The differences seen may be partly attributed to the difficulty in arranging the fibers homogeneously within the sample holder, particularly for longer samples. It is also interesting to note that there is significantly less observable variance in the traditional surface impedance computed from the same material tests.

At this point it is useful to briefly discuss the consequences of the choice of the harmonic time component (which is assumed here to be of the form $e^{-i\omega t}$). While this selection is arbitrary, care must be taken that it is rigorously maintained. Analytical problem formulations, impedance measurements, and any Fourier transforms or signal analysis techniques utilized must all exhibit the same dependence. Many presentations of impedance data do not state the form of the time component used. Likewise, the ISO two micro-

phone impedance tube standard²⁹ does not explicitly state which form it assumes in its analytical formulation. This is significant as this selection affects the physical interpretation of the impedance results. For a harmonic time component of the form $e^{-i\omega t}$, a positive reactance (positive impedance phase angle) corresponds to a stiffness-like response, and a negative reactance to a mass-like response. If $e^{i\omega t}$ is assumed, the impedance becomes its complex conjugate and the opposite is true.

B. Impedance trends

Considering that the impedance properties of the hair samples do not show a strong correlation with individual sample parameters, it is sufficient to investigate changes in equivalent impedance with sample density and thickness using a subset of these. Samples HH 01 through HH 04 were tested using the impedance technique previously described for a variety of bulk densities using three sample holders (10, 20, and 40 mm in depth). The corresponding impedance and absorption coefficient results are shown in Fig. 8. The plots of absorption coefficient (right panels) also illustrate the variability across the four tested samples (dashed lines). Figure 8(a) illustrates the variation with sample density using a constant sample holder thickness of 20 mm. These plots show the variance between people with a high natural bulk density of hair (i.e., a high number of hairs per cm^2) and those with a low bulk density. Obviously there is no theoretical minimum to this trend and it is not completely uncommon to see people without any scalp hair. In this situation a uniformly rigid boundary is an adequate approximation. The variance with sample thickness for a constant sample density of 40 kg/m^3 is shown in Fig. 8(b). These plots illustrate the effect of growing shorter hair outwards at an approximately constant bulk density. For people with longer hair, if the hair is not styled upright the individual fibers stack parallel and the impedance properties over the scalp remain reasonably impervious to hair growth. Figure 8(c) again shows the variance with sample thickness, this time for a constant sample mass. This is equal to the mass of the hair sample at 40 kg/m^3 held within the 20 mm sample holder. These plots illustrate the effect of compressing and separating the same quantity of hair fibers.

Examining the trends shown within Fig. 8, it is clear that the impedance properties scale with both sample density for constant thickness, and sample thickness for constant density. Increasing the bulk density reduces the impedance magnitude (and increases the absorption coefficient) while the impedance phase angle remains reasonably constant. Increasing the sample thickness also reduces the impedance magnitude, and additionally scales the impedance phase angle. The changes with thickness for constant mass are considerably less, but a decrease in impedance magnitude (and increase in absorption) is again seen with an increase in sample thickness. For all modifications the equivalent impedance retains a stiffness-like reactance, and the impedance phase angle remains largely within the range of $10\text{--}50^\circ$.

It is important to note that for the one-dimensional problem the choice of surface reference plane does not alter the

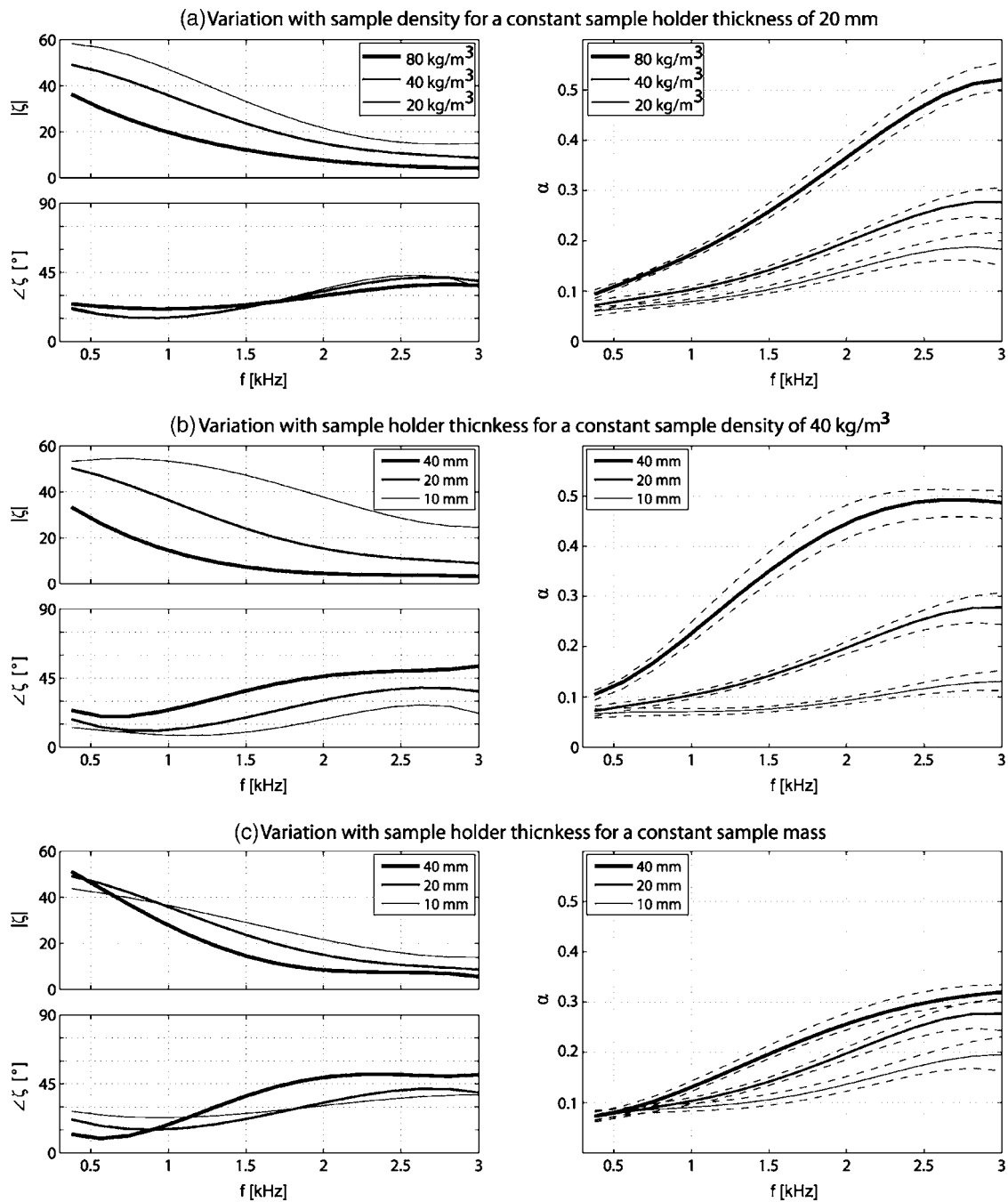


FIG. 8. Variation in equivalent impedance with (a) sample density for constant thickness, (b) sample thickness for constant density, and (c) sample thickness for constant mass (equivalent to a sample density of 40 kg/m^3 in a 20 mm sample holder).

solution for the time harmonic pressure, and the absorption coefficients provided are thus directly comparable with those from other studies. In this regard, for the limited number of tests at comparable densities, the results presented here show a good agreement with the absorption coefficients of hair provided by Katz.⁸

IV. SUMMARY AND DISCUSSION

Previous empirical studies of human auditory cues using mannequins, spheres, and boundary element methods have

shown that the addition of scalp hair introduces asymmetrical perturbations to the HRTF in the order of several dB.³⁻⁶ These features are also noticeable in human HRTF, although little is currently known about their perceptual significance. The traditional use of sphere scattering models to account for the broad acoustic properties of the human head assume the head surface is completely rigid. Consequently, these models cannot account for, or investigate, these features. However, recent treatment of the sphere scattering problem provides an analytical model to compute the scattering of sound by a sphere with a hemispherically divided surface boundary.⁷ Given the appropriate impedance data, this facilitates the in-

clusion of hair characteristics in spherical-head models, and additionally provides a method for the systematic investigation of its perceptual significance.

The current study provides the required acoustical impedance data for a pragmatic range of human hair characteristics. The legitimacy of a locally reactive surface assumption is investigated, and an appropriate boundary condition is formulated to account for the physiological composition of a human head with hair. This utilizes an equivalent impedance parameter to allow the scattering boundary to be defined at a reference plane coincident with the inner rigid surface of the head (in this case a sphere). Experimental analysis of a simple three-dimensional scattering problem illustrates that the equivalent impedance must be used in favor of the traditional surface impedance to yield physically correct pressure magnitudes. Experimental examination of the normal acoustic impedance of a representative synthetic hair material for oblique source incidence is used to show that a locally reactive boundary assumption is legitimate.

The equivalent acoustic impedance properties of a representative range of human hair samples are presented. Increasing either the bulk density or the sample thickness reduces the impedance magnitude (and increases the absorption coefficient). Increasing the sample thickness for constant mass also decreases the impedance magnitude, but to a much lesser extent. For all modifications the equivalent impedance retains a stiffness-like reactance, with the impedance phase angle in the order of 10–50°. Increasing the sample thickness produces a relative increase in the impedance phase angle. A robust correlation between the spread of results and the properties of the individual hair samples is not exhibited. Additionally, there is not a strong dependence on the relative alignment of the hair sample. The latter is confirmed by experimental results from flat-panel tests for oblique source incidence, and examination of the pressure in the proximal region around a single sphere. The absorption coefficients presented show a good general agreement with the limited other data available in the literature.

The formulation of the equivalent impedance allows the legitimate use of a locally reactive boundary for a sphere with a nonuniform boundary condition, particularly if the properties on the inner surface are required (as is the case for binaural synthesis). This formulation, however, is not consistent with typical treatments of reflection or scattering problems which generally utilize only the normal surface impedance defined at an external surface reference plane. More complex multilayered nonuniform penetrable boundaries may yield a more accurate description of the wave processes within the material layer. However, for the current problem the use of the equivalent impedance provides an adequate description of the material boundaries of interest. The comparative limits of this assumption, and the relevance of this formulation to other materials or scattering problems is outside the scope of this paper. However, a comprehensive analytic investigation into this problem may form an area of interesting further study.

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