Heat generated by ultrasound in an absorbing medium

T. J. Cavicchi and W. D. O'Brien, Jr.
Bioacoustics Research Laboratory, Department of Electrical Engineering, University of Illinois, 1406 West Green Street, Urbana, Illinois 61801

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Nyborg's [J. Acoust. Soc. Am. **70**, 310–312 (1981)] derivation of heat generation density has been examined. An alternative approach has been developed to yield the same expression by assuming a complex wavenumber with the linear acoustic equations.

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Nyborg (1981) presented an elegant derivation for the time-averaged rate of heat generation per unit volume by a continuous sound field at any point p to be

$$\langle q_v \rangle = \alpha p_0^2/\rho_0 c_0 \tag{1}$$

where α is the sound amplitude absorption coefficient in a medium for which the shear viscosity is zero, p_0 is the sound pressure amplitude at P, and ρ_0 and c_0 are the density and sound velocity of the medium, respectively. In deriving Eq. (1), the general expression for $\langle q_v \rangle$ was assumed as

$$\langle q_v \rangle = -\nabla \cdot \langle p\mathbf{u} \rangle, \tag{2}$$

where $\langle p\mathbf{u} \rangle$ is the sound intensity vector, p is the instantaneous sound pressure, and $\mathbf{u}$ is the instantaneous particle velocity vector. The pressure and velocity vector are related by Euler's linear, inviscid force equation

$$\nabla p = -\rho \frac{\partial \mathbf{u}}{\partial t}, \tag{3}$$

which is valid at small amplitudes. Equation (2) can be expanded to

$$\langle q_v \rangle = -\langle \nabla \cdot (p\mathbf{u}) \rangle \tag{4a}$$

$$= -\langle p\nabla \cdot \mathbf{u} + \nabla p \cdot \mathbf{u} \rangle \tag{4b}$$

$$= -\langle p\nabla \cdot \mathbf{u} \rangle - \langle \nabla p \cdot \mathbf{u} \rangle, \tag{4c}$$

to yield

$$\langle q_v \rangle = -\langle p\nabla \cdot \mathbf{u} \rangle, \tag{5}$$

because, for a time harmonically varying sound field ∇p and $\mathbf{u}$ are in quadrature [according to Eq. (3)] and thus the time-averaged value of their inner product is zero.

At this point in the derivation, Nyborg (1981) introduced the dilatation ($\nabla \cdot \mathbf{u} = \dot{\theta}$), the fractional increment in volume, and the complex compressibility to derive Eq. (1). An alternative approach does not introduce explicitly dilatation or compressibility; rather Eq. (1) is derived by introducing the complex wavenumber

$$\mathbf{k} = k_0 - j\alpha = \omega/\mathbf{c}, \tag{6}$$

where $\mathbf{c}$ denotes a complex speed of sound and k_0 is the usual real-valued wavenumber. The concepts of dilatation and compressibility are assumed; however, they do not appear explicitly in the following discussion.

From the equation of conservation of mass for a homogeneous medium ($\nabla \rho = 0$)

$$\frac{\partial \rho}{\partial t} + \rho_0 \nabla \cdot \mathbf{u} = 0 \tag{7}$$

and from the linearized equation of state

$$p = \mathbf{c}^2(\rho - \rho_0), \tag{8}$$

the divergence of the velocity vector can be found by differentiating Eq. (8) with respect to time and substituting into Eq. (7):

$$\nabla \cdot \mathbf{u} = -\frac{1}{\rho_0 \mathbf{c}^2} \frac{\partial p}{\partial t} \tag{9a}$$

$$= -\frac{j\omega p}{\rho_0 \mathbf{c}^2}. \tag{9b}$$

Substituting Eq. (9b) into Eq. (5) yields

$$\langle q_v \rangle = \tfrac{1}{2} \operatorname{Re}[p(j\omega p/\rho_0 \mathbf{c}^2)^*], \tag{10}$$

where this step is possible because the time average is taken of a product of two terms with the same frequency but not necessarily the same phase.

The complex velocity from Eq. (6) is substituted into Eq. (10b) and reorganized to yield

$$\langle q_v \rangle = \frac{1}{2} \operatorname{Re}\left[p\left(\frac{2\alpha k_0 + j(k_0^2 - \alpha^2)}{\rho_0 \omega} p\right)^*\right]. \tag{11}$$

To simplify Eq. (11), the complex sound pressure p can be represented by its real and imaginary components as

$$p = p_1 + jp_2, \tag{12}$$

where of course p_1 and p_2 are real. Substituting Eq. (12) into Eq. (11), combining the real and imaginary components and operating upon the resultant expression with the Re operator yields

$$\langle q_v \rangle = \tfrac{1}{2}[(2\alpha k_0/\rho_0 \omega)(p_1^2 + p_2^2)], \tag{13}$$

which simplifies to

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$$\langle q_v \rangle = (\alpha/\rho_0 c_0) p\, p^*, \tag{14}$$

where $k_0 = \omega/c_0$ has been used. Equation (14) is essentially the same as Nyborg's (1981) expression shown in Eq. (1). Like Nyborg's derivation, the only restrictions introduced were the linearization of the force equation [Eq. (3)] and of the equation of state [Eq. (8)] and the assumption that the medium is homogenous and free of shear viscosity.

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Nyborg, W. L. (1981). "Heat Generation by Ultrasound in a Relaxing Medium," J. Acoust. Soc. Am. **70**, 310–312.

Place-of-articulation information in the closure voicing of plosives

William J. Barry

Institut für Phonetik, Universität Kiel, Olshausenstrasse 40, 23 Kiel, West Germany

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Two experiments are presented which examine whether the voice bar in [b] and [d] contains information relevant to the identity of the stop consonant and the following vowel. The results indicate that listeners can exploit consonantal place-of-articulation information contained in the voice bars. The ability of the subjects to ascertain the identity of the vowel following the voice bar was extremely limited, even after a training period; the confusions again point to the influence of consonantal place-of-articulation information.

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INTRODUCTION

A short-term absence of acoustic energy in the speech signal is an important perceptual cue for a stop consonant. The duration of that signal pause can be critical for the perception of the stop as phonologically "voiced" or "voiceless" (Lisker, 1957; Slis and Cohen, 1969), shorter closures cueing "voiced" and longer ones "voiceless" plosives. VC- and CV-formant transitions signal place of articulation, but if the closure in recorded utterances is shortened beyond a critical limit, the place-of-articulation information can be overridden by the extremely short closure information. Port (1977, 1979) reported the perceptual switch from "rapid" to "ratted" (with intervocal flap), and Dorman *et al.* (1979) observed that under certain conditions dual-stop clusters were perceived as single stops when the closure was shortened.

The presence of periodic energy during a stop closure contributes to the perception of a "voiced" stop. However, vocal tract differences resulting from place of stop articulation and from coarticulation with the following vowel result in spectral differences for the closure voicing. In a reaction time study (Barry, 1984), in which stimulus identity was maintained independent of the voice bar, the *sensitivity* of listeners to such differences is indicated. The present experiments examine the *exploitability* of the information for phoneme identification when other (supporting) cues have been removed. Some preliminary experimental evidence is presented which points to closure voicing containing information that can be used to identify place of articulation.

I. STIMULI AND EXPERIMENTAL PROCEDURE

The author, a native speaker of British English and fluent in German, recorded the nonsense syllables [bi, bu, ba, di, du, da] with prevoicing, which is optional in German, and the vowel [e] with a falling pitch and approximately equal length and loudness. The syllables were accepted as neutral German realizations, and the vowel was accepted as a naming of the orthographic vowel ⟨e⟩. The recordings were digitized at a sampling rate of 10 kHz and segmented and spliced with the Kiel speech signal processor (SSP; see Schäfer, 1982, for details). Segmentation marks were placed at the zero crossings of the first and last regular voice period in the voice bars and of the first full period and last recognizable period of [e]. The vowel was 340 ms and the voice bars varied from 110–170 ms in length.

Two sets of stimuli were produced: (1) Five repetitions of the six voice bars in random order, with a 5-s interstimulus interval. (2) Five repetitions of the six voice bars immediately followed by the vowel [e], resulting in a series of quasisyllabic stimuli. These were also in random order and with the same interstimulus interval as in set 1. The first series aimed to elicit responses as to the identity of the missing vowel. The second series provided a syllabic base for a consonant identification task with no place-of-articulation information other than the spectral differences contained in the voice bar. The vowel [e] was chosen after preliminary listening had indicated that the vowel was least prejudicial to either /b/ or /d/ judgments.