Acoustic Streaming as a Mechanism in the Treatment of Suspensions

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activity. This second region, where the difference tone become more prominent as the intensity was increased, corresponded to the location of maximal microphonic elicited by a pure tone whose frequency was the same as that of the difference tone. These results further confirm that distortion of the cochlear microphonic is a two-stage process. [Work supported by the National Institute of Neurological Diseases and Stroke.]

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4:35

Z11. Combination Tones on a Nonlinear Cochlear Model. J. L. STEWART, *Santa Rita Technology, Inc., Santa Clara, California 95050.*—A linear electric circuit model for motions of the basilar membrane was modified by introducing nonlinear diode elements so as to represent mechanical displacements that occur more readily in one direction than in the other. The specific nonlinear site or structure in the cochlea is not necessarily represented by the model; it may be some part of the organ of Corti, it may result from rigidity of scalae walls, and/or it may arise from fluid streaming near the oval window. Patterns on linear and nonlinear ears are compared for two specific tone combinations, the simple difference tone $f_1 - f_2$, and the more complex $2f_1 - f_2$ case. At least three explanations for perception of these difference tones, with and without presence of a third exploring tone, can be offered. Waveforms for clicks and voiced and unvoiced speech sounds are also presented, and similar phenomena are observed. In general, strongly augmented activity occurs in the apical part of the cochlea when nonlinearities exist, and for the $2f_1 - f_2$ component, an unusual pattern also occurs in the region most responsive to f_2.

THURSDAY, 23 APRIL 1970 — VERNON ROOM, 2:00 P.M.

Session WAA. Workshop: Noise Control in the Home

ROBERT W. BENSON, *Chairman*

2:00

Discussion led by the Chairman

THURSDAY, 23 APRIL 1970 — GARDEN ROOM, 2:00 P.M.

Session BB. Physical Acoustics II

M. GREENSPAN, *Chairman*

Contributed Papers (12 minutes)

2:00

BB1. Acoustic Fountain Effect. U. INGARD AND JAMES A. ROSS, JR., *Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.*—An intense standing sound wave along the free surface of a liquid produces a static deformation of the surface and in certain cases stationary fountains. This phenomenon has been known for a long time [V. Dvorak, Ann. Physik **7**, 42 (1876)]. We have measured the acoustic threshold of fountain formation in different liquids and propose an explanation for this instability. [This work was supported by the ONR, under contract.]

2:15

BB2. Effect of Acoustic Streaming on Diffusional Mass Transfer. H. S. FOGLER AND KASPER LUND, *Division of Chemical Engineering, University of Michigan, Ann Arbor, Michigan 48104.*—Upon the passage of an acoustic wave through a duct, one can form time-independent vortices. This phenomenon, which is commonly called acoustic streaming, can enhance mass transport by superimposing a convective transport on a diffusive transport. The differential mass transport equation was coupled with the second-order time-independent acoustic streaming equations in a rectangular duct and solved by a finite difference technique. A frequency range of 5–800 kcps in liquids and gasses was investigated for different acoustic and physical parameters such as first-order velocity amplitude, diffusivity, viscosity, duct height, and length. Preliminary results show increases in the mass flux of up to at least 120% above the normal diffusive transport. Possible applications to membranes, catalysts, and drying will be discussed along with a complete physical and mathematical description of the phenomena.

2:30

BB3. Acoustic Streaming as a Mechanism in the Treatment of Suspensions. JAMES A. ROONEY, *University of Vermont, Burlington, Vermont 05401.*—Hydrodynamical shearing of droplets occurs when sufficiently high-velocity gradients exist [F. D. Rumscheidt and S. G. Mason, J. Colloid Sci. **16**, 238–245 (1961)]. Theory for acoustic microstreaming near a gas bubble indicates that large velocity gradients can exist in the boundary layer. Comparison of such gradients with hydrodynamic theory leads to the prediction that acoustic streaming can be an important mechanism in the disruption of suspensions. For example hydrodynamic theory predicts that a velocity gradient of 2.5×10^4 sec^{-1} existing in a fluid with *a* viscosity of 20 cP is sufficient to shear a droplet of radius 10 μ and a surface tension of 10 dyn/cm. A velocity gradient of this magnitude exists near a resonant 20-kHz bubble oscillating with an amplitude of 20 μ. Under suitable experimental conditions, such amplitudes can be achieved using a single controlled oscillating bubble. Data obtained from such an arrangement substantiate aspects of the theory. [This investigation was supported by a National Institutes of Health Fellowship.]

2:45

BB4. Tensile Strength of Superheated Liquids. Robert E. Apfel, *Acoustics Research Laboratory, Pierce Hall, Harvard University, Cambridge, Massachusetts 02138.*—A novel technique has been developed for studying the properties of liquids under conditions that are not ordinarily accessible. This technique involves the use of an acoustic standing wave field established in a column of one liquid in order to trap an immiscible droplet of another liquid. In this experiment, an ether droplet suspended in glycerine was superheated and acoustically stressed until the combination produced an explosive liquid-to-vapor phase transition. The measured trade off between tensile stress and superheat, as causes of this vapor cavity formation are in gratifying agreement with the theory of nucleation in pure liquids. [This work supported by the Office of Naval Research.]

3:00

BB5. Dynamics of Vapor-Filled Cavities. E. A. Neppiras and R. D. Finch, *Department of Mechanical Engineering, University of Houston, Houston, Texas 77004.*—A theoretical study has been made of the dynamics of vapor-filled cavities using linear approximations and taking into account evaporation and condensation and the thermal transport properties of the liquid. Results for stiffness, damping, and resonance frequency have been obtained for the liquids helium, nitrogen, and water. Results of experiments carried out at frequencies around 10 kHz are discussed in the light of the theory. [This work was supported by NSF grant.]

3:15

BB6. Finite and Small Amplitude Underwater Gas Bubble Oscillations Compared. David Epstein, *State University of New York Maritime College, Bronx, New York 10465.*—Bubble oscillation is well described by the nonlinear Keller–Kolodner equation. Although compressibility effects, which strongly influence the motion, are considered, analysis starts with incompressible approximation. The key parameter is p_1/p_0, the ambient/bubble pressure ratio. This ranges from zero to unity; near the lower limit finite amplitude pulsations occur; near the upper, simple harmonic motion ensues. The equation determining the maximum and minimum bubble radii, with p_1/p_0 as parameter, is graphed; these endpoints coalesce at a level where $p_1/p_0=1$. Further, taking compressibility into account, at each depth the endpoints also converge to an equilibrium radius. $\bar{T}$ has a simple power law dependence on p_1/p_0; this is generally not true for the finite amplitude period T_1. The curves for $\bar{T}$ and T_1, as calculated from the Willis formula, cross; hence the actual T_1 vs depth may be inferred. The shape of the bubble radius vs time curve changes from pulsation to simple oscillation with depth; this is asymptotically correct at any level, since $T_1 \rightarrow \bar{T}$.

3:30

BB7. Rectified Diffusion under Adiabatic Conditions. H. S. Fogler and V. K. Verma, *Division of Chemical Engineering, University of Michigan, Ann Arbor, Michigan 48104.*—The theoretically predicted bubble growth rate for rectified diffusion under isothermal conditions is much lower than the rate found experimentally by Eller [J. Acoust. Soc. Amer. **46**, 1246 (1969)]. The assumption of isothermal condition can only be justified for infinite thermal diffusivity. For real gas bubbles, however, the thermal condition lies between the isothermal and adiabatic limits. Our analysis was undertaken to establish the adiabatic limit. Contrary to the case of isothermal collapse, wherein the increased pressure (hence the surface concentration) can only result in an outwards diffusional flux, the solubility inversion effect for gases can cause first inwards and then outwards diffusional flux during the same phase of adiabatic collapse. In particular, when the heat of solution, ΔH_0, of the gas is less than $-(\nu BT_0)/(\nu-1)$, where $\nu = C_p/C_v$, and B is the gas constant, the diffusional flux changes direction as mentioned above at

$$\frac{R}{R_0}=\left[\left(\frac{\nu}{\nu-1}\right)\left(\frac{BT_0}{-\Delta H_0}\right)\right]^{\frac{1}{3(\nu-1)}}.$$

This flux reversal can cause the bubble to grow much faster than in the isothermal case.

3:45

BB8. Singular Perturbation in Acoustic Cavitation. L. A. Skinner, *Department of Mathematics, University of Wisconsin, Milwaukee, Wisconsin 53201.*—Approximate solution of a model ordinary differential equation problem illustrates essential ideas in a new approach to acoustic cavitation theory. Rectified diffusion bubble growth through resonance size has been analyzed for the first time. This is a singular perturbation problem. The asymptotic expansion appropriate for the thin boundary layer of concentration oscillation effects is not uniformly valid. Details of the resonance domain, which is characterized by relatively rapid growth, are discussed. This work is based on a previous paper dealing with cavitation threshold [J. Acoust. Soc. Amer. **47**, 327–331 (1960)].

4:00

BB9. Expansion Time of an Underwater Cylindrical Gas Bubble. R. A. Wentzell, *University of Waterloo, Waterloo, Ontario,* and R. Adlington, *Defence Research Establishment Atlantic, Dartmouth, Nova Scotia.*—The collapse time of an infinitely long cylindrical cavity under constant pressure is determined. A bubble period–depth relation is determined analogous to the Willis formula for the spherical case. An underwater line charge explosion of known energy is treated as an adiabatic gas and a time equation for expansion from its initial radius to equilibrium is developed. To avoid the difficulties inherent in the cylindrical case due to the potential becoming infinite, the problem is treated as an initial value problem. Experimental results using 90-in. line charges at various depths verify the bubble period–depth relationship. [This work was supported by the DRB, under contract.]

4:15

BB10. Interaction of Sound with Sound in Water in the Presence of a Solid Surface. Joie Pierce Jones and Robert T. Beyer, *Department of Physics, Brown University, Providence, Rhode Island 02912.*—Recent experiments involving the scattering of sound by sound have produced negative results for the case of noncollinear beams. When two perpendicularly intersecting finite-amplitude sources (frequencies of 7 and 5 MHz, pressure ampltiudes of 4.5 and 1.8 atm, respectively, at the center of the interaction region) were allowed to interact in water, no scattering at the sum and difference frequencies was observed although pressure levels of 0.07 dyn/cm^2 could be measured with a 10 dB S/N ratio. However, scattering has been observed for the same case when solid objects, such as rigid cylinders, are placed in the interaction region. It appears that diffraction of the