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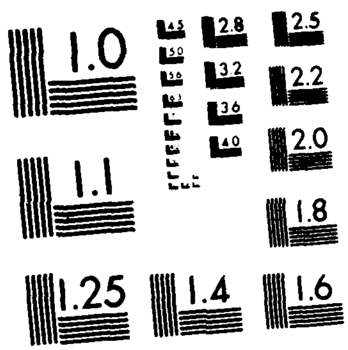

MICROCOPY RESOLUTION TEST CHART
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CONTRACT NUMBER N00014-86-C-0051 (ONR)

FINAL REPORT

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Research has been directed towards discovering novel nonlinear signal processing principles by studying the way in which the inner ear analyzes sound and encodes the information contained therein as neural impulses. These principles may be abstracted from the context of hearing and usefully applied to the analysis of any type of nonstationary signal containing both time and frequency information. Applications of this work to the recognition of speech in noisy environments and the classification of ocean sounds are expected.

A number of major issues have been resolved since the previous progress report and are reported on in the four enclosed papers to be published. Additional information describing aims and other results is contained in the previous progress report, a copy of which is enclosed. This work has also been supported by DARPA and NSA contracts, and a breakdown of progress assignable to each of the individual contracts will be furnished upon request.

The central research problem has been the characterization of the nonlinear mechanics of the inner ear and the elucidation of its role in signal processing. The mechanics of the inner ear at low sound pressure levels (levels of unvoiced speech) has been accurately characterized with the unexpected conclusion that the inner ear functions as an active nonlinear one-dimensional mechanical transmission line with negative feedback involving delay. The parameters defining the circuit elements vary gradually along the line. Each section of the line contains a negatively damped harmonic oscillator stabilized by the feedback of a force proportional to the displacement of the oscillator at a time in the past, where the time delay of the force is proportional to the oscillator's period.

Nonlinearities arise through the dependence of damping and feedback on oscillator displacement. The damping increases and the feedback strength decreases with increasing oscillator displacement. The precise functional form of these nonlinearities, which become important at higher sound pressure levels (levels of voiced speech), is currently under investigation. Preliminary results indicate that the nonlinearities provide the automatic gain control necessary for the analysis of speech whose components differ markedly in amplitude. The nonlinearities also appear to sharpen formants, making them easier to recognize in the presence of noise. Details are given in the enclosed paper, "The Mechanics of Hearing," which will be submitted to **Science** in response to its request for a "General Article" on hearing.

In the course of analyzing measurements of basilar membrane motion we have developed two novel and powerful methods of data smoothing and interpolation. Both methods combine measurements and a priori information to obtain the best estimate of the function being measured. In the enclosed paper "Constraints on Measurements of Causal or Minimum Phase Systems," the estimation is optimized by exploiting prior knowledge of the analyticity properties of causal functions; a second enclosed paper "Approximating Functions from Measured Values and Prior Knowledge" exploits the expected smoothness of functions arising in certain problems. The first paper has been accepted for publication in the **Journal of the Acoustical Society of America**, and the second paper will be submitted to **Nature**. Both papers have already found application in other fields. For example, the analyticity of scattering amplitudes found in high energy physics is being used to improve their measured values. In ionic crystal chemistry, the smoothness of partition coefficients as a function of ionic radius and charge is being used to determine their functional form and to study the processes by which ionic crystals incorporate impurities.

An experimental program to measure spontaneous and induced otoacoustic emissions in humans has also been initiated. These emissions result from the active nature of cochlear mechanics and provide a unique noninvasive window on the inner ear. Models of hearing, which predict the nature of these emissions, will be tested in these experiments. At the present time, otoacoustic emissions provide the only hope for studying the nonlinear mechanics of the inner ear in non-anesthetized humans.

The sound created in the inner ear must travel through the middle ear before it may be measured in the ear canal. In order to interpret otoacoustic emissions it is therefore necessary to understand the transmission properties of the middle ear. The enclosed paper "Transfer Matrices of the Human Middle Ear," which will be submitted to the **Journal of the Acoustical Society of America**, provides this understanding.

The machinery is now in place for a careful theoretical and experimental investigation of nonlinear cochlear mechanics and its implications for the recognition of speech and other nonstationary signals.

The last two sections of the enclosed previous "Progress Report" compare the linear analysis of sound by the peripheral auditory system with the linear analysis done by conventional filter banks, and also describe speech recognition and signal processing principles identified by our research in hearing.

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