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Voice Communication by Ultrasonic Excitation of a Ship's Hull
A Summary of the Acoustic Problems and Solutions

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The Naval Research Laboratory has designed and built ultrasonic transducer and mounting clamps. They have been used for trial evaluations of a voice communication system that uses ultrasonic excitation of a ship's hull. Successful distances of transmissions to date have reached 250 ft. With sufficient input power, no limit in distance is foreseen if the transmission path is correctly chosen.

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VOICE COMMUNICATION BY ULTRASONIC EXCITATION
OF A SHIP'S HULL
A SUMMARY OF THE ACOUSTIC PROBLEMS AND SOLUTIONS

INTRODUCTION

During battle at sea, damage inflicted on the hull or superstructure of a ship by aerial, surface, or undersea attack could so seriously impair the ship's communication systems that personnel would be exposed to extreme danger through loss of personal contact and control. To preclude this possibility, a last-resort communication system based on ultrasonic excitation of hull structures is proposed that could carry voice messages between distant points on the ship.

Communication of data with steady state signals by ultrasonics aboard ship was initially undertaken by the Naval Weapons Center, China Lake, CA, [1,2]. The concept, broadened to provide voice communication, was further development by the Naval Research Laboratory, [3-5].

In all these efforts actual implementation was constrained by narrow specifications. These specifications required a portable communications apparatus to serve at the transmitting end and a fixed or portable apparatus at the receiving end. Transmission was to be possible at any (correctly) selected location and reception was to occur in the nearest damage control locker or central damage control compartment. Transmission paths were designated to be the main ribbing, stringers, and bulkheads of the ship's hull and the ship's external steel casing. (Keywords: [illegible] hardening; ultrasonic [illegible])

These constraints severely limited possible design approaches.

DESIGN PARAMETERS OF THE COMMUNICATION SYSTEM

The basic components of the ultrasonic-link communications system actually developed are

- the electrical power source,
- the microphone and its associated electronic transmitting circuitry,
- the ultrasonic transmitter transducer,
- the ultrasonic receiver transducer,
- the receiving electrical circuit, and
- the loudspeaker.

Manuscript approved December 15, 1987.

Each of these components are assemblies of subcomponents. They are described as follows:

- The electrical energy source is a battery pack.
- The electronic transmitting circuitry comprises a voltage-controlled oscillator, a microphone, a modulator, and a high-power amplifier.
- The ultrasonic transmitter comprises a piezoceramic transducer, a matching coupler, and an attachment clamp.
- The receiving electrical circuit comprises an amplifier, a demodulator, and a loudspeaker.

In this report the design of the acoustic components is described. The electrical circuitry will be described in a separate report.

Design of Acoustic Components

The basic design considerations of the acoustic transducers are the frequency band over which carrier frequencies are to be selectable, choice of the piezoceramic mode of vibration, the driving power available, and choice of resonant or nonresonant operation.

These considerations, as they apply to transmitters and receivers, are:

- The frequency band of operation was requested initially to allow 14 channels of communication, each 3 kHz wide, or 42 kHz total. In the current apparatus, the lowest carrier frequency is 28 kHz. This choice was made to avoid noise background caused by ship operation and to reduce as much as possible the scattering of the ultrasound by multibranch structural paths. The upper carrier frequency resulting from this choice is ~70 to 73 kHz.
- The longitudinal piezoceramic mode of vibration was selected, and both transmitter and receiver are designed as cylindrical stacks. This choice is recommended because of simplicity of structure, availability of modeling, high power potential, ease of mounting and generation of waveforms with minimum attenuation over long paths. Geometric proportions have been selected to give maximum power on transmission and optimum response on reception. The transmitter consists of a piezoceramic driver stack of disks with holes, ~2 in. outside diameter and 3/4 in. thick total. The transmitter has a matching coupler of the same diameter, with selectable length depending on matching requirements. The receiver transducer is a piezoceramic stack of disks with holes, ~1 in. outside diameter and 1-1/2 in. length.
- The transmitter power is specified to be available in the amount of 50 W, although experience shows that much less power is needed for the shorter (<200 ft) paths.
- The frequency operating points of the transmitter, designated initially as "broadband," is on the rising characteristic (stiffness controlled section) of the main thickness resonance (at 83 kHz). Although smooth in air testing, this characteristic becomes extremely rough when the transducer is mounted on the beam because of standing wave fields in the beam itself.

The receiver is designed to resonate in the first longitudinal mode at 28 kHz (in air) and operates over a frequency band 28 to 53 kHz on the falling characteristic of response (inertial controlled section).

Matching Waveguide for the Transmitter

The transmitter is viewed as a transducer mechanically tapping a finite length, elastically distributed (steel beam) waveguide. Since the tap location is random and the carrier frequency is selectable, the load seen by the transducer can vary within wide limits. It can also be highly reactive, with both elastic or inertial impedances potentially present. This loading condition requires a matching section in the form of a cylindrical (or conical) waveguide that must be inserted between the piezoceramic driver and the hull load. For matching mechanical resistance, the area of contact between the face of the matching section and the beam is varied. For matching reactive impedance, the length of the matching section is varied. Both procedures are effective over small bandwidths but become less effective over large spans of frequency operation.

Methods of Mounting Transducers on Hull Structures

It was initially specified that the portable apparatus transducers be mountable at randomly selectable locations, using simple tools, in a time duration of a minute or less. This requirement poses severe constraints on mounting fixtures. The final mount to date (used with success) is a clamp for flange mounting that consists of two plates, one flat, one crimped on an edge, assembled to grip the flange between them, and tightened on the location with two bolts. A second clamp, designed for hull or bulkhead mounting is designed but has not yet been fabricated. Figure 4 shows clamping structures.

ACOUSTIC TRANSDUCERS USED IN TRIAL EVALUATION

Figure 1 shows the transmitter. Figure 2 shows the receiver. Details of these structures are found in Refs. 3 through 5. Figure 3 shows the flange clamp mount used in the trial evaluation.

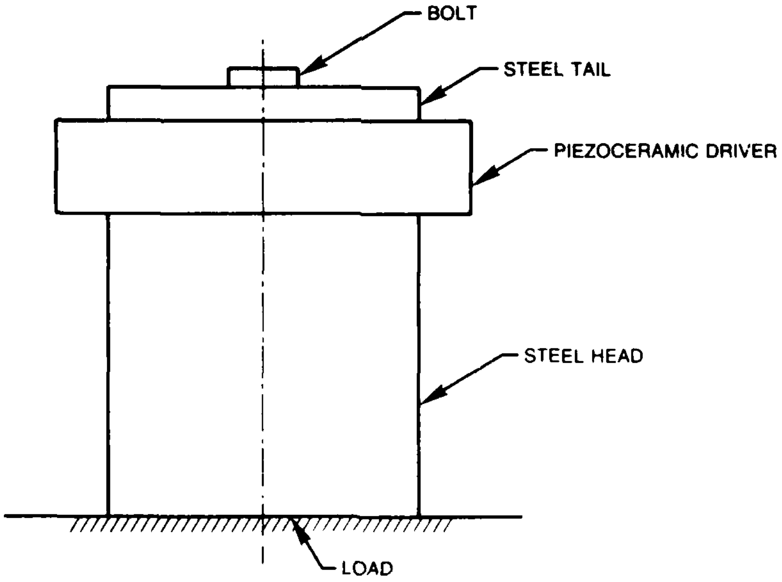

Fig. 1 — Ultrasonic transmitter (full scale)

Figure 4 shows the clamp design for use on the outer hull and bulkheads. It consists of a flange clamp that serves as one anchor of a telescoping section and a hinged mounting plate tightening by bolts that serves as the second anchor. Tightened the bolts squeezes the hinged mounting plate against the hull or bulkhead.

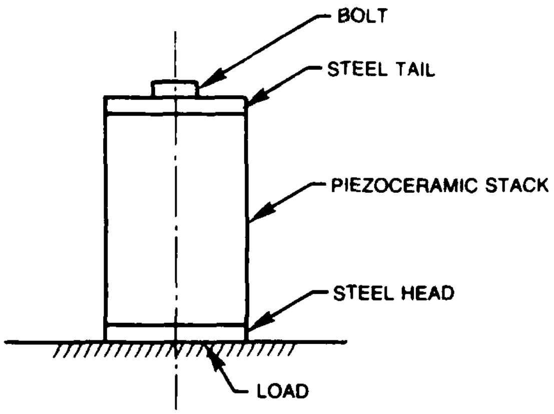

Fig. 2 — Ultrasonic receiver NB4 (full scale)

Fig. 3 — Flange clamp with transducers

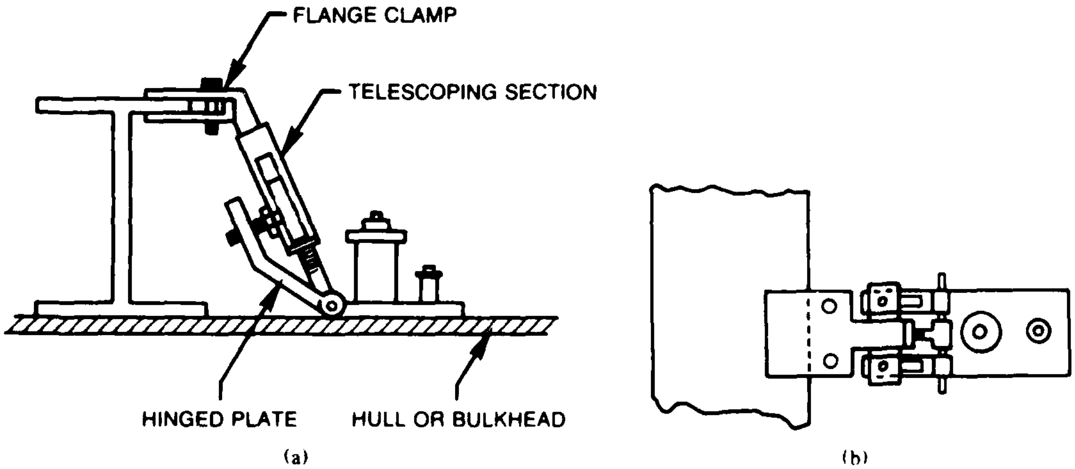

Fig. 4 — Hull or bulkhead clamp

RESULTS OF TRIAL EVALUATIONS

Trial voice transmission through the hulls of the USS *Forrestal* and the USS *Saratoga* gave intelligible voice communication by ultrasonics over distances up to 100 ft. Trials on a steel building beam at the Naval Research Laboratory were successful over a distance of 187 ft. Trials abroad the USS *Barry* docked at the Washington Navy Yard, Anacostia, DC gave intelligible transmission over a distance of 250 ft via a main stringer welded to the ship's hull below deck.

Details of these trials are found in Refs. 3 through 5 and in additional reports, available from the author on request. Typical test runs shown in the Appendix.

TRANSMISSION BANDWIDTH AND SIGNAL PROCESSING

The transducers used in the voice transmission test and evaluation have well-defined frequency responses when measured in unloaded (i.e., air) state. However, when loaded by the steel structures of a ship's hull and driven over the frequency range that was implemented (28 to 53 kHz) these frequency responses are greatly altered in two ways: (a) resonances (if any) are shifted in frequency because of the heavy inertial and elastic loads, the shifts sometimes being as much as 6 kHz between loaded and unloaded states, and (b) bands of frequencies over which transmissions are successful become randomized in position (this means that, depending on the local steel structures being energized, a multiplicity of transmission bands occurs at different frequencies and with different bandwidths).

Thus, with portable systems tapping into steel structures at arbitrary locations in the hull, no fixed predetermined bands of transmission can be guaranteed. However, in every actual testing of equipment, many such bands have been found to exist. This strongly affects the nature of communication signals that can be transmitted and processed. Voice communication has been found to be always possible by simple sampling of available bands. However, communication of digitalized data is possible only by narrowly selecting the processing method. Clearly, no signal processing of digitized data based on tracking of phase (i.e., coherent processing) can be successful in hull-communications systems. This is because of the arbitrariness of phase and amplitude of the load at the point where the transducer is mounted on the hull structure and similar phase and amplitude arbitrariness of the transmission path. Because of limitations of the transducer/hull transmission path, processing based on signal energy measured above a threshold, with frequency diversity, is the only digital processing possible. In addition, the rate at which digitized data can be transmitted must be understood to be severely limited by the inertial/elastic responses of the transducer/hull complex at the chosen frequencies. Low data rates, however, can be compensated for by use of condensed message coding or, alternatively, by voice-delivered encrypted messages.

MODELING

Various models are available. The simplest approach to modeling is based on reflection of plane-wave pulses at boundaries in one-dimensional propagation. Reflection coefficients between differing acoustic materials are calculated from respective characteristic impedances. A more complex model and one frequently used, is that of Mason [6]. Again, it is a one-dimensional model that specifically neglects two-dimensional diffraction effects. It includes an ideal electromechanical transformer that decouples the electrical from the mechanical branches of the equivalent circuit. The model has been improved by the inclusion of backing and matching sections. Using the Mason model for design choices caused by parameter variations often leads to ambiguous results. A clearer approach in which prediction is made easier is provided by the Krimholtz, Leedom, and Matthaei (KLM) model [7]. In this model the acoustic properties are based on a transmission line analogy, and the electrical properties are lumped. The KLM model is suitable for predicting impedance, insertion loss, pulse shaping, and their variations with frequency.

The model actually used by NRL in designing the ultrasonic transducers incorporates a cascade or T-sections comprising a backing, a piezoceramic driver, and matching section and loads. Calculations were done exclusively with signals in the steady state. In its entirety it is a modified Mason-type model, suitable for voice signalling. Signalling digitalized data imposes different modeling requirements. A program was planned but not implemented to develop and use the KLM model, which is more suited to pulse transmission.

CONCLUSION

A system for ultrasonic communication of the human voice through the steel welded hulls of ships that expends 1 to 50 W electrical power has proved successful.

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Appendix

FREQUENCY RESPONSE TESTS

The "standard" NRL transmitter, consisting of the piezoceramic driver described in the text having a .25-in. steel tail and a 2.5-in. cylindrical steel head, was tested for frequency response. Figures A1 through A4 are typical of many test runs. Other tests are reported in the cited references.

Transmission tests with this transmitter and the receiver previously noted were taken in quantity. Figure A4 is a typical example of transmitting response compared to beam noise.

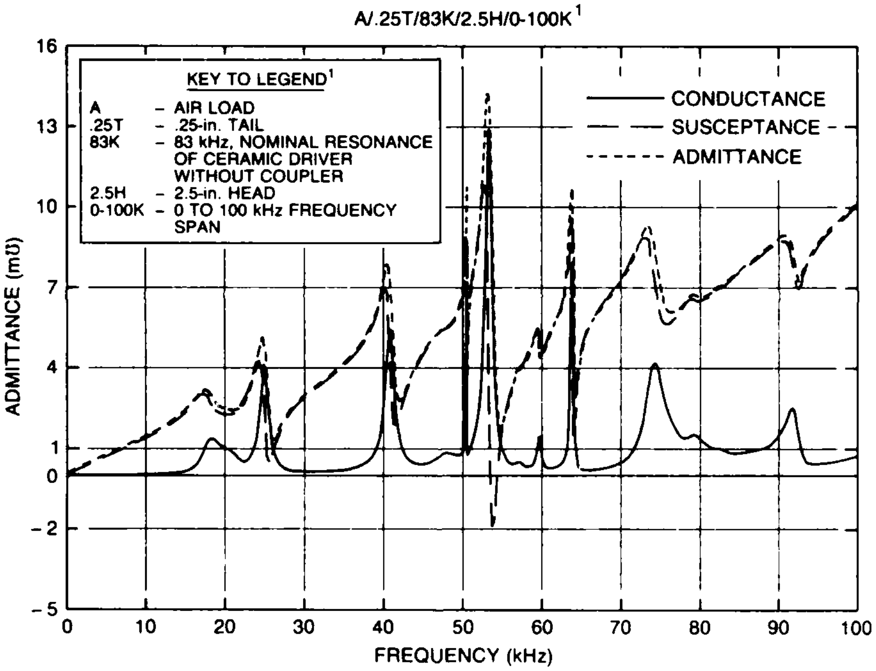

Fig. A1 — Unloaded admittance vs frequency (0 to 100 kHz)

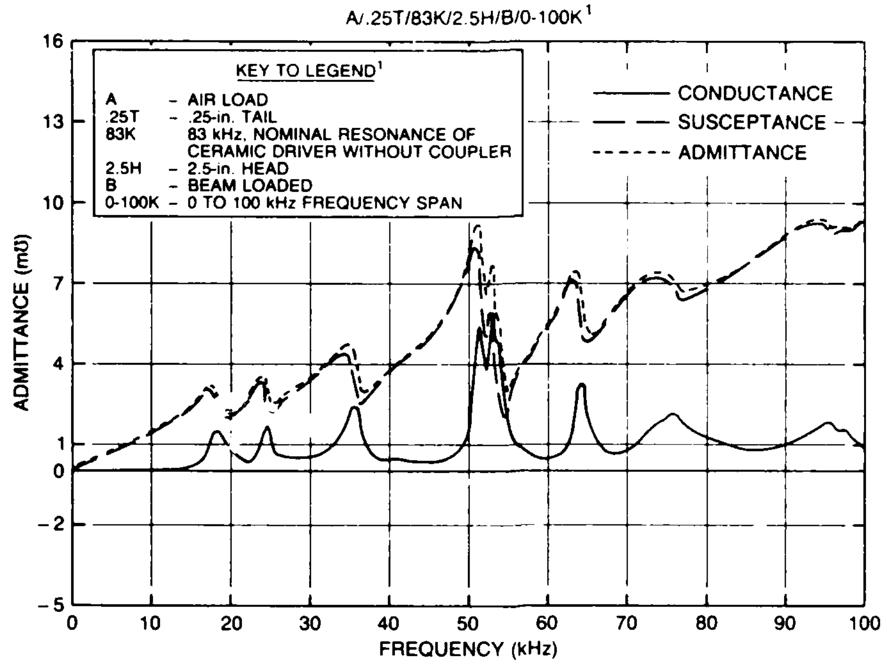

Fig. A2 — Loaded admittance vs frequency (0 to 100 kHz)

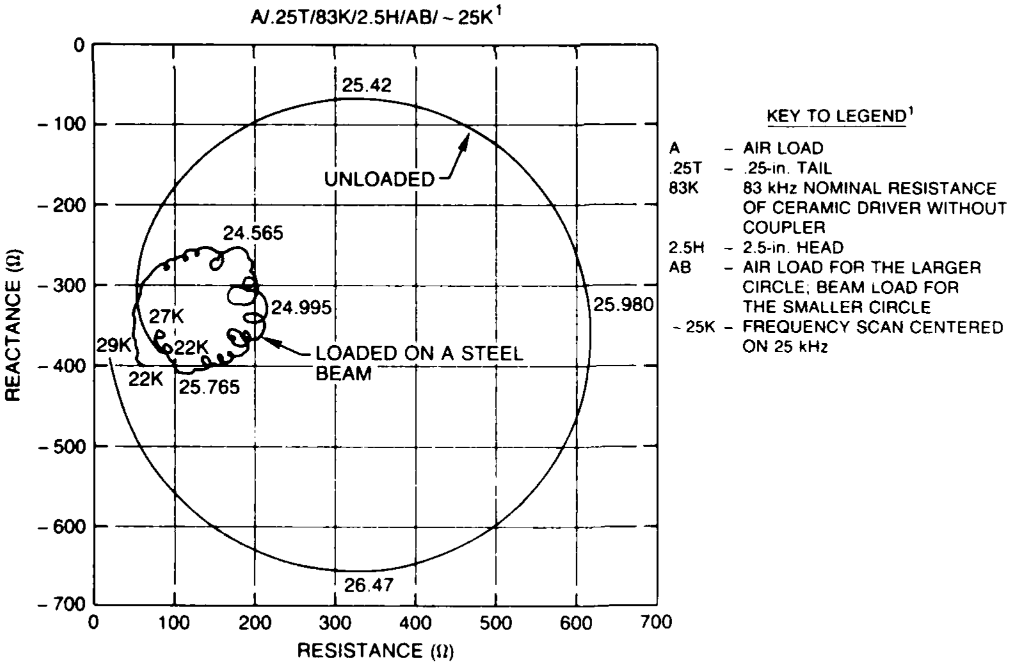

Fig. A3 — Reactance vs resistance plots at 25 kHz in unloaded and loaded state

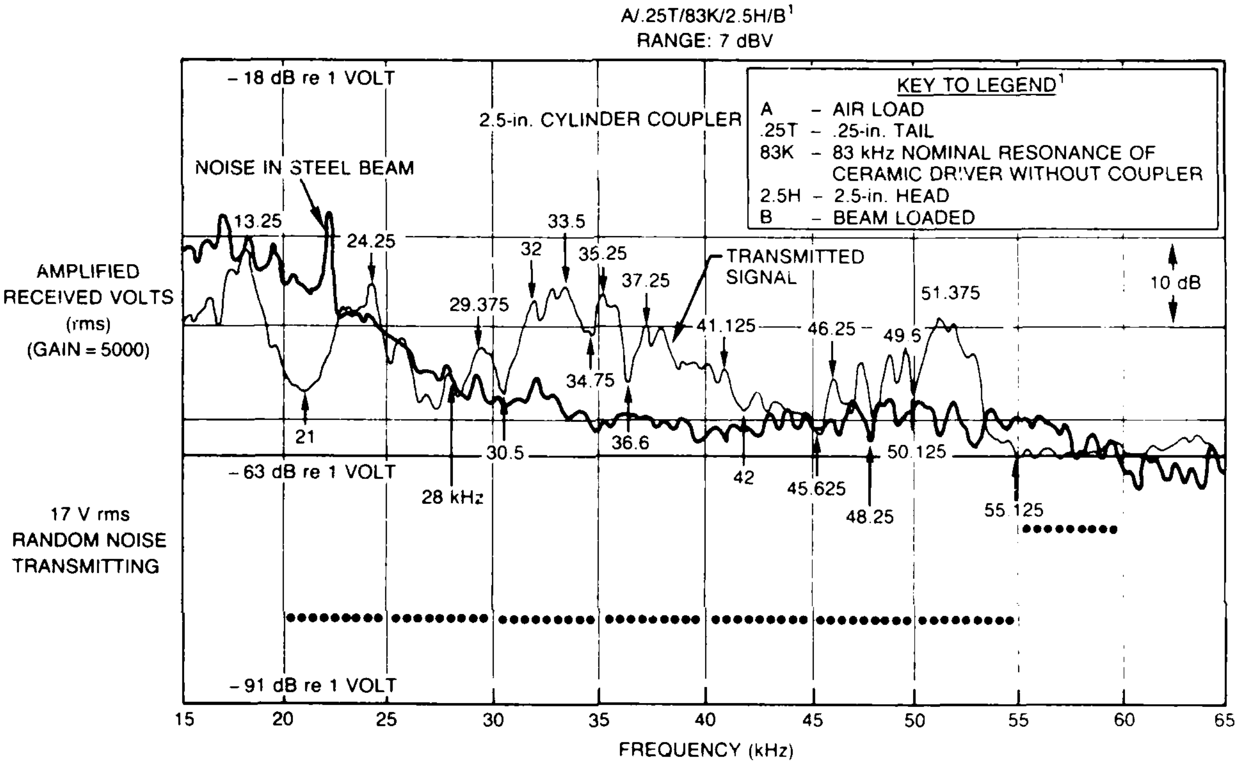

Fig. A4 — Received voltage vs frequency over the frequency range 15 to 65 kHz at 17 V rms random noise input, compared to beam noise. Receiver is the NB4 (see Fig. 2). Arrows indicate frequency in kHz.