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AUDIO TRANSDUCER RESEARCH

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Georgia Institute of Technology

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Audio Transducer	Piezoresistive Device	Transducer
Contact Microphone	Piezotransistor	Transistor Microphone
Microphone	Semiconductor Microphone	
Piezoresistance	Stress Sensor	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Audio transducers based on the piezoresistive and stressed-transistor principles have been investigated for possible use in future tactical communications systems—the goal being to develop small, light-weight, hands-free microphones that can operate satisfactorily in a high noise environment. The study has focussed on contact-type devices coupled more or less directly with the surface of the head or neck. Initial "mapping" tests of the relative availability of speech spectral power at nine such pickup sites gave highest rankings to Throat and Cheek locations. The Cheek site was considered preferable beacuse

of its apparently minimal frequency-compensation requirements and its amena-
bility to microphone positioning with a conventional boom mount.

Piezotransistor devices incorporating a diaphragm/needle stress-concentra-
ting arrangement were tested as contact microphones in both air-coupled and
elastomer-coated configurations. Miniature units developed at Georgia Tech
(1/8 inch or less in diameter) had to be closely coupled with the skin to achieve
adequate signal-to-noise ratios, and eventually proved to be too susceptible to
damage from accidental stress overloads occurring in the course of routine
placement against the skin. A larger (1/2-inch diameter) commercially available
piezotransistor pressure transducer, designed with a protective screen and
minimum-volume air coupling, was found to give the best performance. This unit
was fitted with a boom-mounting adapter and ambient noise shield for delivery to
ECOM as one of the required "exploratory development model" transducers. Beam-
lead transistors were specially investigated for possible advantages in con-
structing lower-profile contact devices based on a cantilever-beam flexure-
stressing arrangement. However, the sensitivity achieved by this approach was
found to be much less than that obtainable with the better-established "indenter"
technique.

Several batches of piezoresistive design elements were fabricated in the
microelectronic processing facilities at Georgia Tech using 10-mil thick wafers
of p-type boron-doped silicon. These were incorporated into a variety of experi-
mental contact microphone assemblies and subjected to simplified screening tests
for promising "signal-to-noise" and "voice-to-ambient discrimination" ratings.
The "exploratory development model" of this type of transducer that was
selected for delivery to ECOM has a 0.8-inch diameter diaphragm but is much
shallower in profile (about 0.4 inch) than the experimental piezotransistor
model.

The two exploratory development transducer models were laboratory tested
for their relative frequency responsiveness to phonetically balanced speech and
to high-level ambient noise, using time-averaged power spectrum analysis in 1/3-
octave bands. These measurements indicated that the two units were generally
comparable in speech-to-ambient discrimination capabilities, both at the pre-
ferred Cheek site and also at the Throat. In a more limited comparison test
with an M-87 lip microphone, the piezotransistor unit exhibited a slight
advantage in ability to reject ambient noise frequencies above about 2 kHz
(an objectionable part of the "Chinook" spectrum). However, both experimental
transducers appeared otherwise inferior to the M-87.

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ADDENDUM to Georgia Tech Semiannual Technical Report on
Contract DAAB07-73-0238, "Audio Transducer Research,"
Report No. ECOM-0238-1, dated February 1974.

Please make the following additions to Page 35 of the preceding
Semiannual Technical Report on this contract, as identified above:

1) Insert an asterisk at the end of the third paragraph under
   Section 4-3, so that the last line reads "resistance device.*"

2) Cut out the footnote material printed below and affix it near
   the bottom of page 35.

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*The diaphragm of the "T1" telephone transmitter is about 1-3/8 inches in
diameter as compared to nominally 3/8 inch for the active area of the
transistor transducer—representing a ratio of approximately 13.5:1 in
effective diaphragm areas. Assuming that the diaphragm acts as a whole in
integrating acoustic pressure and transmitting force to the sensing
element, then for a given voice signal the output voltages from the two
transducers (measured with respect to a common self-noise level) should be
in the same proportion as the areas—all other factors being equal. That
is to say, on the basis of diaphragm area alone, the signal-to-noise
ratio of the piezoresistive unit would have been expected to exceed that
of the transistor transducer by 20 log 13.5 or approximately 22.6 dB.
Actually, the internal cantilever-beam arrangement used in the former
device was found to give it an additional advantage of at least 2:1 in
stress-concentrating action, so that the difference in signal-to-noise
ratios should have been more like 28.6 dB in favor of the piezoresistive
unit. Since the observed difference was only 12 dB, it seems reasonable
to infer that the transistor type transducer is intrinsically more
sensitive (i.e., "has an inherently higher signal-to-noise ratio") than
the piezoresistive type transducer. (The above calculation of course
tacitly assumes that the observed self-noise of either type of transducer
is predominantly due to its semiconductor sensing element and any noise
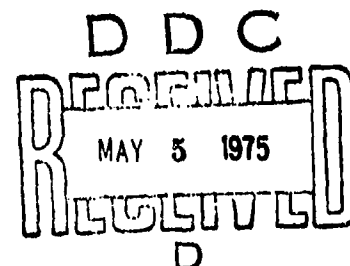effect associated with diaphragm size is relatively insignificant.)

AUDIO TRANSDUCER RESEARCH

Final Technical Report

29 June 1973 - 31 December 1974

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I. INTRODUCTION

1-1. Statement of the Problem and Objectives

Military vehicles such as tanks, armored personnel carriers, and helicopters generate very high ambient noise levels, which degrade the performance capabilities of microphones and other audio accessories. A requirement therefore exists for new techniques, innovative approaches, and advances in the state-of-the-art of audio transducers aimed at improving future tactical communication systems. The ultimate goal is to develop small (low-visibility), light weight, hands-free microphones that can operate satisfactorily in both quiet and high-noise field environments.

The purpose of the present study has been to determine the potential applicability to the above problem of direct-contact or air-coupled audio pickup devices based on the piezoresistance and piezotransistor principles. Of most immediate interest was the possibility of demonstrating acceptable speech transmission in the presence of 115 dB ambient noise of the type encountered on board the CH-47 "Chinook" helicopter.

1-2. Approach to the Problem

The following specific objectives were proposed for this study.

(1) Determine optimum sites for audio transducer location about the head and neck on the basis of the quality of speech transmission achievable with the aid of electronic spectrum shaping and noise rejection measures, while taking into account such factors as long-term wearer comfort, economy, and practicality of the required equipment for use under typical military conditions.

(2) Conduct an evaluation of state-of-the-art piezotransistor devices for the above purpose, including detailed investigation of the silicon beam-lead transistor, and develop for ECOM use a working prototype audio transducer model based on the piezotransistor principle which indicates the level of performance attainable with this type of device in comparison to the M-87.

(3) Conduct a similar evaluation of state-of-the-art piezoresistive devices for the above purpose, and deliver to ECOM a working prototype audio transducer model based on this principle which likewise indicates the level of performance attainable with such devices in comparison to the M-87.

Circuitry provided with the two required "exploratory development models" would include excitation or biasing controls, transducer temperature compensation (if necessary), appropriate electronic shaping of the frequency spectrum for optimum speech transmission, and suitable output voltage and impedance levels to permit operation of the transducers with military intercommunication systems.

The report which follows describes the work performed and results achieved in the main task areas identified above.

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1-3. Basic Definitions and Terminology

The expressions "contact microphone" and "air-coupled noise-cancelling microphone" are often used to distinguish between such devices as the Throat Microphone and the Lip Microphone. The basic difference, of course, is that one type of device is intended to pick up voice vibrations available through the skin while the other is designed to sense airborne sound pressure waves emanating from the mouth. Since the present study has been aimed primarily at optimizing speech transmission from pickup sites on the head and neck, it will by definition be concerned almost exclusively with devices operating in "contact" with the skin.

There is, however, a need to distinguish between cases to which the transducer diaphragm is placed more-or-less directly against the skin and those in which it is mounted so as to couple acoustically with the skin through a column or pocket of air. In the material which follows we use the term air-coupled to denote specifically this latter type of "contact" microphone operation. For the more general designation of a microphone operating in "open air" we employ the term air-pathway (or air-path).

A less ambiguous situation exists where we have used the expressions rubber-coupled, Silastic-coupled, or (more generally) elastomer-coupled to indicate that some other relatively compressible material has been applied between the microphone diaphragm and the speech pickup site. Such treatment might be appropriate for any or all of the following reasons: to prevent possible corrosive action on the metal diaphragm by skin exudates; to reduce the likelihood of damage to the basic sensing element through excessive contact pressure; and to provide a better acoustical impedance match between the relatively low-compliance transducer diaphragm and the much softer skin and subdermal sound transmission medium.

II. EVALUATION OF SPEECH PICKUP FROM HEAD AND NECK SITES

2-1. Basic Methodology

The test apparatus and procedures employed on this project for comparative evaluation of speech pickup sites and experimental transducer performance have been described in considerable detail in the Semiannual Technical Report (ECOM-0238-1). A system block diagram of the primary instrumental method used is shown in Figure 2.1 below. This method provides for the recording of speech (and/or ambient noise) response signals from a given "test microphone" at a specified pickup site on a subject, and simultaneously from a "reference microphone" of known characteristics at a standard location relative to the subject. The two recorded signals are then analyzed sequentially for their average power spectral density characteristics.*

Figure 2.2 shows typical results from the foregoing test process using 1/3-octave band analysis of a 20-second sample of phonetically balanced speech. Curve (A) represents the "reference spectrum" for the test speech as recorded through a standard microphone with essentially flat response (the General Radio 1565A sound level meter set on "C"-weighting scale) located 18 inches in front of the subject.** Curve (B) represents the "detected spectrum" as recorded in this case from an experimental transistor microphone placed against the subject's cheek. Since the acoustic vibrations coupled into the test microphone through contact with the skin cannot readily be expressed in terms of airborne sound pressure level, and since the amplification factor of the microphone preamp and subsequent electronics system is quite arbitrary, the output spectrum levels have here been normalized with respect to system "self noise" in the 1-kHz band. Curve (C) indicates how this inherent noise (measured in the absence of any acoustical test signal) varies over the frequency range of interest.

2-2. Derived Data

As discussed in Section 2-2 of the Semiannual Technical Report, the spectrum levels detected by an experimental microphone at a given pickup site (e.g., Curve B of Fig. 2.2 below) may be "corrected" for the variation in average spectral content of the speech sample itself (Curve A)

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*
Figure 2.1 in this report differs slightly from the version presented in the Semiannual Report in that (i) a spectrum-shaping Filter as well as an Attenuator is now shown at the output of the Test Microphone Preamp, and (ii) the previous "Octave-Band Filter" block in the playback equipment chain has been relabeled "Adjustable Filter" to account for the fact that 1/3-octave band analysis (using the Krohn-Hite 3100 unit) was performed during later phases of the study.

**
The distance to the reference microphone was originally chosen to be 6 inches, with the idea of ensuring strong signal levels and minimal loss of high-frequency speech components. When it became evident that these were not critical considerations the distance was changed to 18 inches in order to allow the subject to make minor head movements without significantly affecting the levels measured.
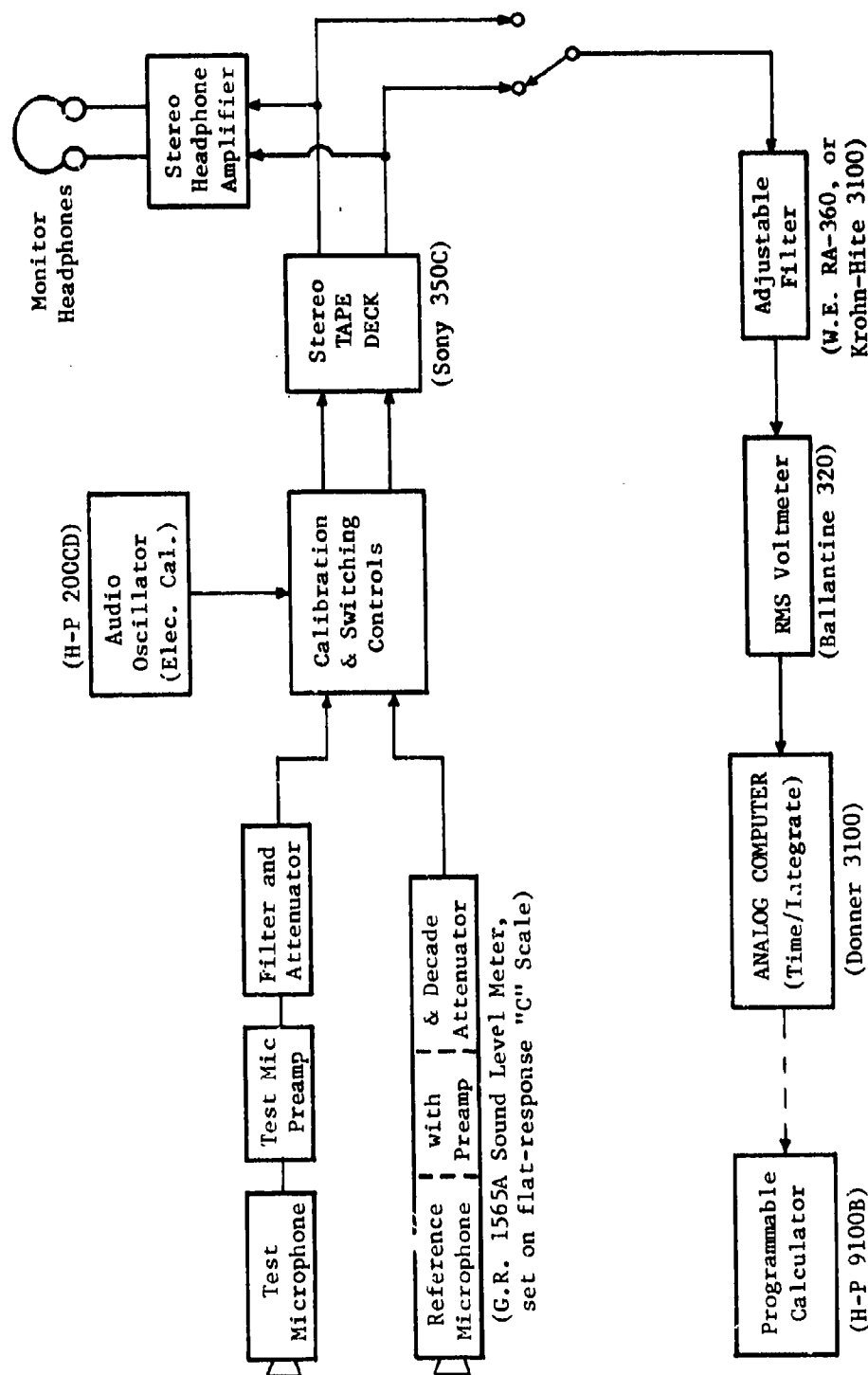
Fig. 2.1: Block diagram of instrument. on for audio transducer tests.
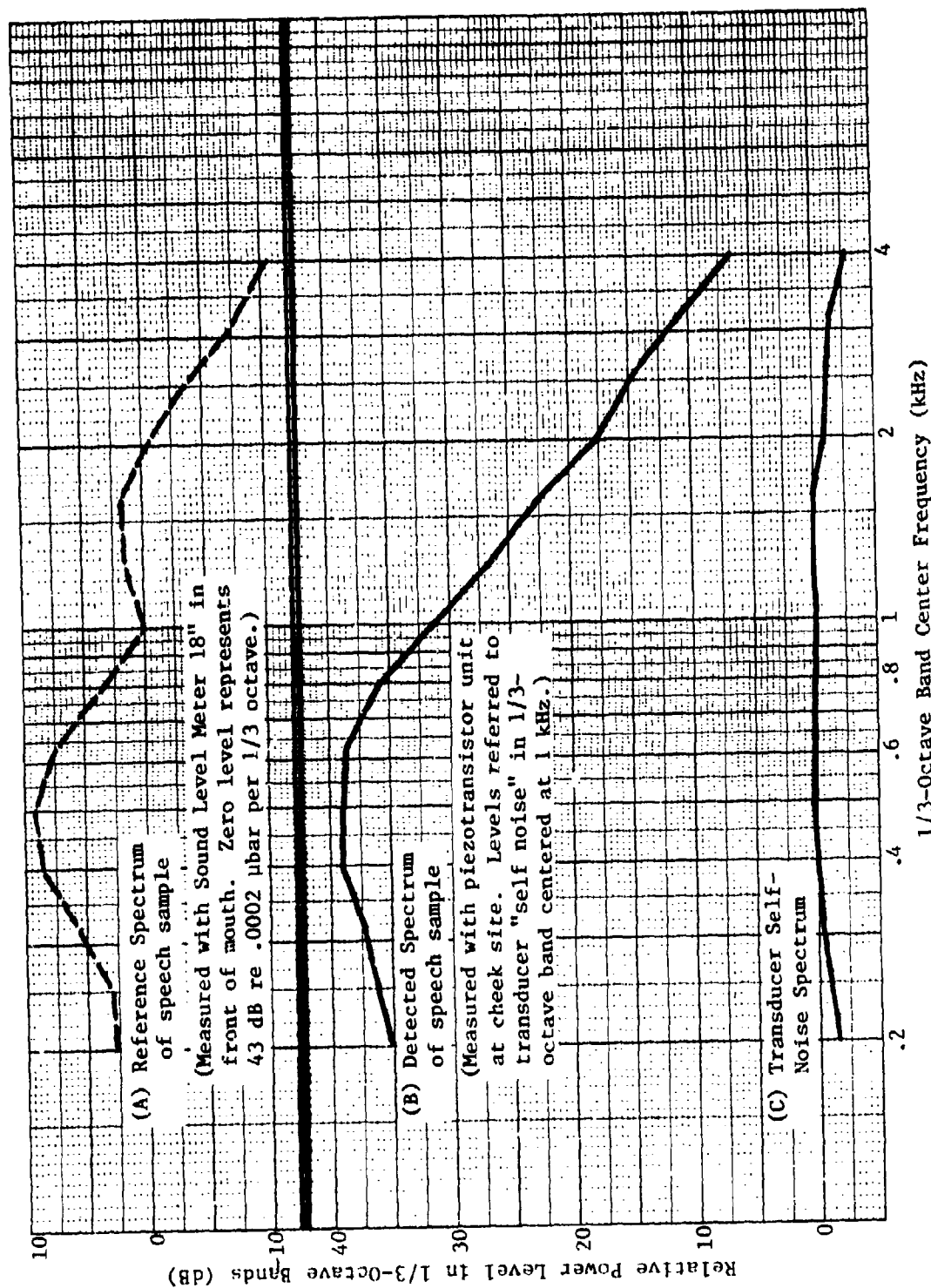
Fig. 2.2: Illustrating average power spectrum measurements used to evaluate speech pickup sites and transducer performance.

(A) Reference Spectrum of speech sample

(Measured with Sound Level Meter 18" in front of mouth. Zero level represents 43 dB re .0002 μbar per 1/3 octave.)

(B) Detected Spectrum of speech sample

(Measured with piezotransistor unit at cheek site. Levels referred to transducer "self noise" in 1/3-octave band centered at 1 kHz.)

(C) Transducer Self-Noise Spectrum

1/3-Octave Band Center Frequency (kHz)

Relative Power Level in 1/3-Octave Bands (dB)

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by a simple dB subtraction process. The result represents the response which would have been measured for the experimental microphone at the given location if the average sound spectrum delivered from the vocal tract to the reference microphone were "flat" instead of "speech-shaped." The term "spectral response" (or "relative spectral response") was previously applied to this derived frequency characteristic of a particular transducer/site combination.

In order to examine sound transmissibility properties more nearly specific to the speech pickup site itself, one may further subtract from the above-defined spectral response function the frequency calibration characteristic of the test transducer used. The term "spectral transmission factor" was previously applied to this type of difference function and discussed at some length in Section 2-4 of the Semiannual Report. Figure 2.3 below shows the principal results obtained in mapping such spectral transmission factors at various pickup sites about the head and neck.

2-3. Microphone Site Selection

The test transducer used to develop the data of Figure 2.3 was an Altec type 677B lavalier microphone. It was equipped with an aluminum adapter ring for air-coupling with the skin (in the manner of a stetho-scope bell) to pick up speech sounds from the various surface sites in-vestigated on the neck and head.* An auxiliary rubber coupling tube was added to this adapter for purposes of detecting speech vibrations via the ear canal. The "ear cup" measurement utilized an unmodified microphone unit mounted in one side of a standard H-158/AIC headset from which the normal earphone and connector had been removed. A separate frequency calibration determination was made for each of these configurations of the Altec 677B microphone and was used in deriving the appropriate spectral transmission factors shown.

The curves of Figure 2.3 collectively indicate the relative avail-ability of speech spectral power at different potential audio transducer locations about the head and neck. The curves individually suggest the degree of frequency compensation required to restore "fidelity" to signals picked up from any given site. Thus, on the basis of signal strength alone, it appeared that the Throat site should be given primary consideration. However, the Cheek site offered a significantly simpler frequency-compensation requirement (as indicated by the dashed -6 dB/octave line in Figure 2.3). In addition, it was felt that a contact microphone of the type envisioned on this project might be operationally more acceptable if it could be attached to a standard helmet fixture, such as the upper half of an M-87 microphone boom. The Cheek site was therefore placed first on the list of prospective locations for an experimental piezo-transistor or piezoresistive contact microphone.

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* The so-called Skull sites (ns) included: s1- Top of Head, s2- Bone Behind Ear, s3- Forehead, and s4- Cheekbone. Anatomical specifications for transducer emplacement at each of the sites considered are given in Section 2-3 of the Semiannual Technical Report.
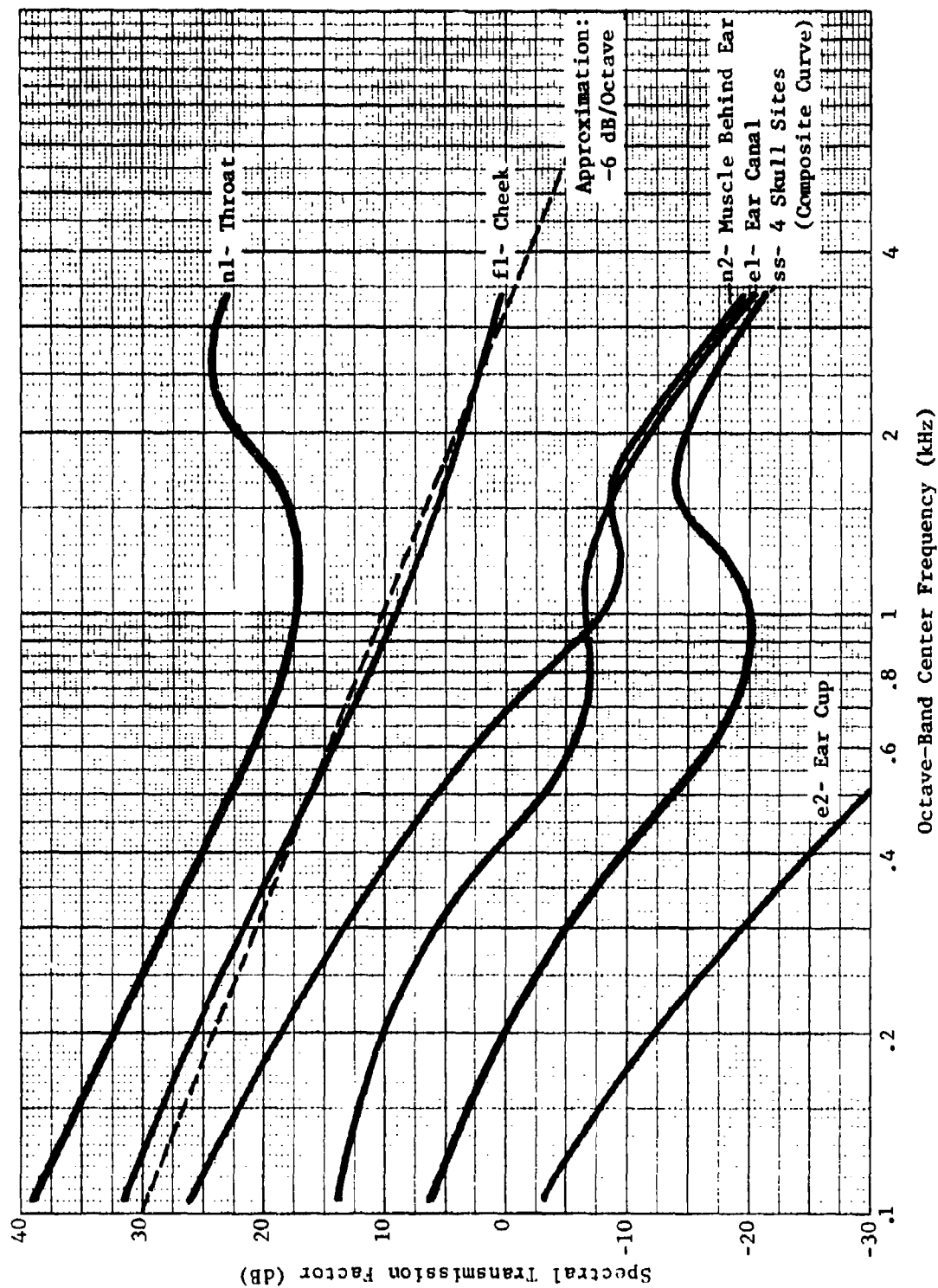
Fig. 2.3: Relative transmissibility of speech frequencies at various pickup sites about the head and neck. (From Fig. 2.8 in Semiannual Technical Report.)

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III. SIMPLIFIED SCREENING TESTS FOR EXPERIMENTAL TRANSDUCERS

The test procedure described in Chapter II in essence compares the "frequency responsiveness" of an experimental audio transducer at a given speech pickup site with that of an ideal microphone arrangement on an <u>average power</u> basis alone. The method provides no information concerning either <u>phase distortion</u> or <u>amplitude nonlinearity</u> phenomena that may be associated with the transmission of speech spectral components via potentially complex body-tissue pathways from the vocal tract as a whole to a localized vibration detecting pickup device somewhere on the head or neck. Speech intelligibility could be severely degraded by such factors (particularly when noise is present) and must ultimately be assessed in terms of overall audio system performance evaluated by listener teams under realistic simulated or operational field conditions.

In view of the fact that the spectrum analysis procedure of Chapter II provides a necessary but not sufficient performance-ranking criterion for experimental speech pickup units, a less time-consuming type of test was devised to allow rapid preliminary screening of the numerous trial designs involved in developing candidate piezotransistor and piezoresistive transducer models for delivery to the sponsor. This simplified screening procedure was described under Section 3-3 of the Semiannual Technical Report, but will be further expounded and justified in the present chapter.

3-1. Rationale and Procedure

Curve (A) of Figure 2.2 above presented a typical average power spectrum for phonetically balanced speech as measured in 1/3-octave bands using the reference microphone and instrumentation system specified in Figure 2.1. Curve (A) of Figure 3.1 below shows the results of analyzing several such test speech samples on a true power spectral density basis—i.e., with the individual band average-power readings corrected for the specific frequency interval involved. Curve (B) of Figure 3.1 indicates that a somewhat comparable distribution of spectral components is obtained when the same test subject sustains for a few seconds the simple vowel sound ă (as in "bat") at a visually self-monitored "standard" voice level (nominally 84 dB overall, as read on the sound level meter located 18" in front of his mouth.)

The apparent repeatability of these two types of test signal was considered surprisingly good—particularly since most of the runs represented were made on different days (several of them widely separated in time), with the subject exhibiting significant variations in voice quality and pitch. Although the "instantaneous" spectrum associated with the vowel "ă" only moderately resembles the time-averaged spectrum of the 20-second "Rainbow" speech sample, the similarity was found to be closer than for any other easily reproducible utterance. Accordingly, the "84-dB ă" was adopted as a standard voice signal for the preliminary transducer screening tests described below.

Frequency in KiloHertz

Spectrum Level in dB re .0002 μbar/Hz at 18" in front of mouth

(B) Sustained ă, as in "bat" (nominally 84 dB overall level at 18" from mouth)

(A) "Rainbow" passage sample: (20-second segment read at comfortable voice level)

"When the sunlight strikes raindrops in the air, they act like a prism and form a rainbow. The rainbow is a division of white light into many beautiful colors. These take the the shape of a long round arch, with its path high above, and its two ends apparently beyond the horizon."

Range of Values

3-Run Average
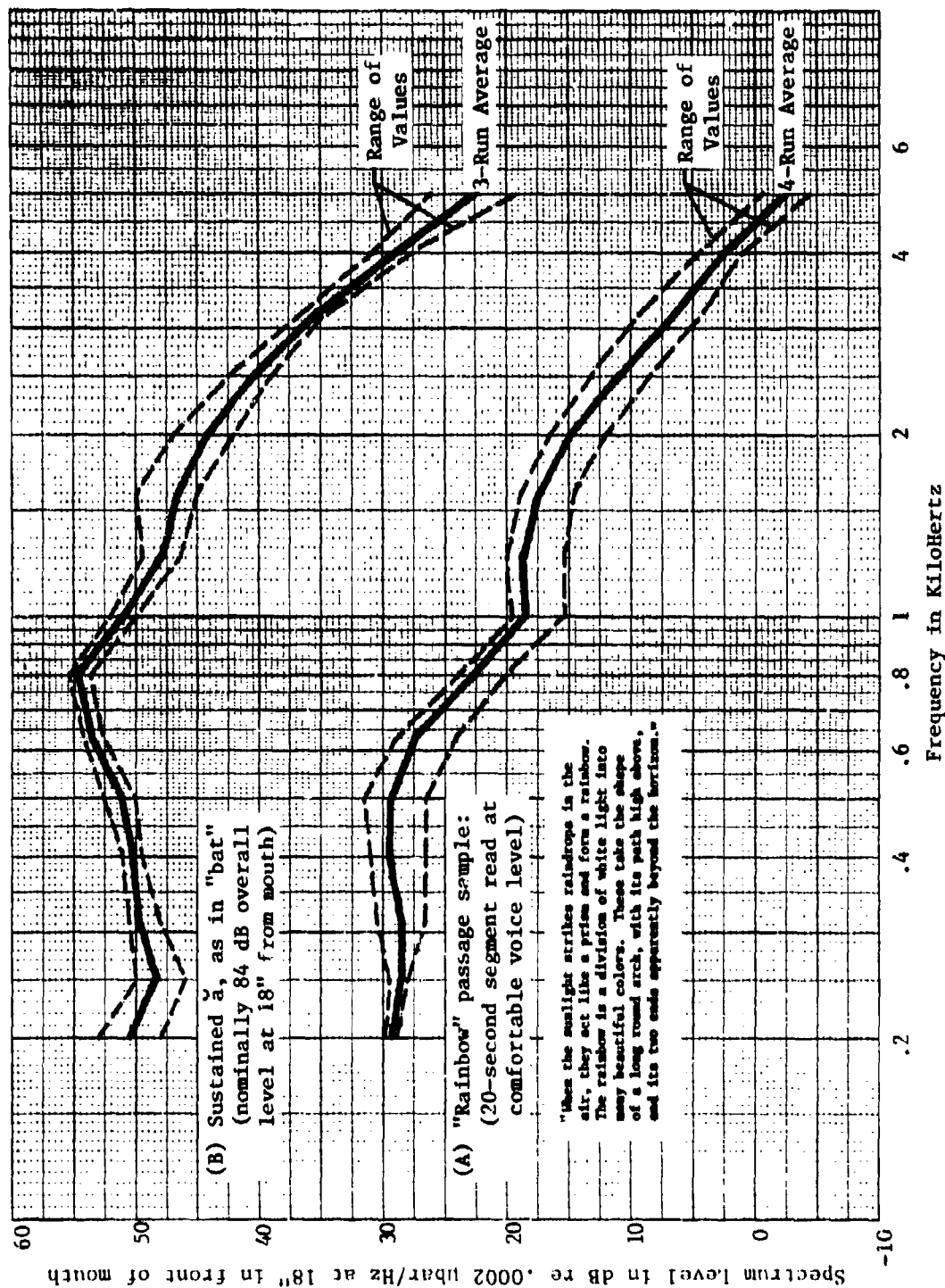
Range of Values

4-Run Average

Fig. 3.1: Spectral characteristics of standardized speech sample (A) and sustained vowel sound (B) used for testing experimental transducers. (Single-subject repeatability data.)

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The tests were conducted using appropriate portions of the instrumentation system diagrammed in Figure 2.1, and under conditions similar to those originally established for evaluating speech pickup sites. As indicated earlier, the Cheek site was adopted as the preferred location for both types of experimental contact microphone being developed on this project.

With the particular device to be tested either boom-mounted or hand-held in position, the subject proceeded to generate a steady "ä" sound long enough for the equipment operator to obtain an output reading from the RMS voltmeter. A few trial utterances usually sufficed to establish the proper degree of ventilatory effort and control so that sound pressure levels close to 84 dB could be readily produced by the subject at the standard distance of 18" from his mouth.* In general, however, the subject noted the exact level existing at the time the operator read the voltmeter, and the voltage reading was then corrected to correspond to the "standard" voice test level of 84 dB.

The next step in the screening procedure was to obtain a voltage reading representing the "self noise" (intrinsic electrical noise) of the device being tested. This was done with the subject silent but all other conditions (contact position, gain controls, etc.) the same as in the preceding voice measurement. The decibel ratio of these voltages associated with the standardized voice test signal and the system self noise has been designated the <u>Signal-to-Noise Test Rating</u> (S/N) and appears as one criterion for ranking the various experimental devices discussed in Sections 3-2 and 3-3 below. This particular rating serves primarily as a figure of merit for transducer operation in "quiet" environments; the higher the S/N Rating, the less noticeable or objectionable should be the transducer's background noise level.

In order to estimate the relative susceptibility of the different experimental transducer designs to ambient noise interference, separate test measurements were made using loudspeaker-generated noise fields with spectral characteristics of the form shown in Figure 3.2.** Spectrum (A)—a rather poor approximation to "white noise"—was produced at the test subject's location in the audiometric chamber by driving the loudspeaker system from the output of a General Radio type 1390B Random Noise Generator. Spectrum (B) was produced in the same way from a tape reproduction (furnished by ECOM) of noise recorded in the cabin of a CH-47 "Chinook" helicopter at an overall sound pressure level of 115 dB.

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*For this purpose the General Radio type 1565A Sound Level Meter was placed on a stand facing the subject, who periodically checked the mouth-to-microphone distance with an 18" ruler. (The sound level meter was operated on "C"-weighting and "Fast"-response settings.)
**Bass-reflex cabinets with 12-inch heavy-duty speakers were symmetrically positioned about three feet from the test subject and driven in parallel by a McIntosh 50-watt amplifier (model 50-W-2).
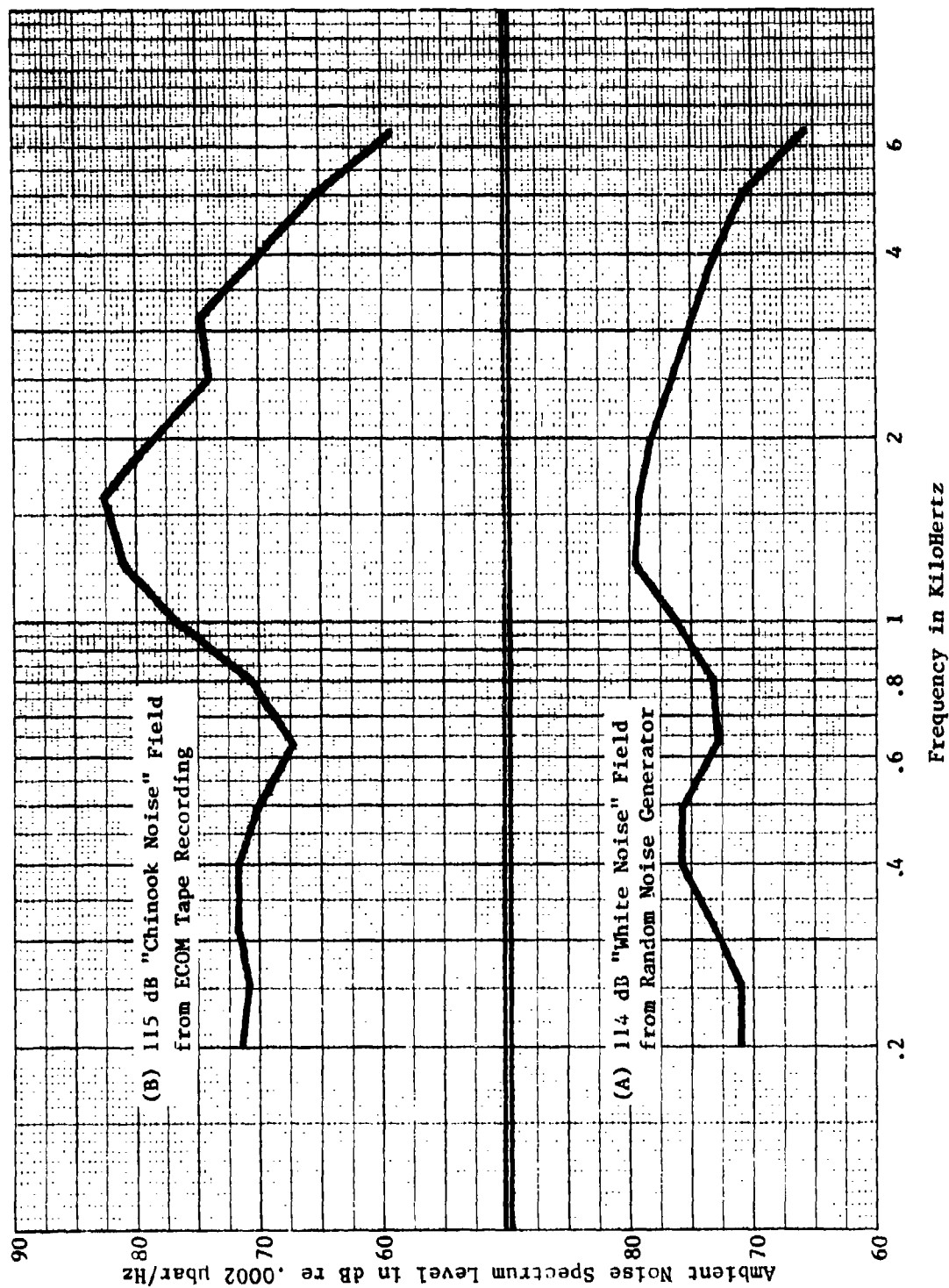
Fig. 3.2: Spectral characteristics of high-level noise fields used for ambient-susceptibility testing of experimental transducers.

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In the routine screening procedure that was finally adopted, the subject held the sound level meter in the vicinity of the transducer being tested while the equipment operator adjusted the loudspeaker amplifier gain so as to establish an ambient noise level of 114 dB at that point. (The 114-dB level was adopted as "standard" for purposes of this test, regardless of whether the source was "white" or "Chinook" noise.) With all other conditions and controls the same as in the preceding S/N test, the operator then read the voltage produced at the output of the transducer measurement system due to ambient noise pickup. This reading was next diminished by 30 dB so as to represent a theoretical ambient noise level of 84 dB—that is, a level numerically equal to the standardized voice test level. The final step was to take the decibel ratio of the voltage associated with the 84-dB voice sound to the voltage associated with an 84-dB ambient noise field. This decibel equivalent has been designated the <u>Voice-to-Ambient Discrimination Index</u> (V/A) and appears as a second criterion for ranking the various experimental devices discussed in Sections 3-2 and 3-3 below.*

The main reason for devising the foregoing S/N and V/A tests was to (hopefully) identify at an early stage those experimental transducer design trends which might provide superior speech-pickup and ambient-rejection capabilities over the range of audio frequencies considered most essential to voice communication in the field. It was therefore decided that all screening tests should be conducted with the transducer preamp output spectrum limited to a common pass-band extending from nominally 300 to 3,000 Hz. Since the spectral transmission factor curves of Figure 2.3 had indicated that frequency compensation of +6 dB/octave would be needed at the cheek site, a dual-function filter box was constructed which provided the optional band-limited "flat" and "pre-emphasis" characteristics shown in Figure 3.3.

Although obviously not ideal, the functional approximations depicted in Figure 3.3 were considered adequate for the basic comparison type tests contemplated. The primary intent was to determine whether performance ratings in any given case might be improved by <u>some</u> degree of pre-emphasis, or whether the natural frequency-transfer characteristics of the particular transducer with its coupling arrangement at the specified speech pickup site were in fact preferable. The filter box was therefore designed using readily available parts in as simple and compact a form as possible. (The actual unit constructed may be seen in Figure 4.3 of Chapter IV below.)

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* Appendix B illustrates the above measurements and indicates how the various readings are combined to obtain the desired S/N and V/A values. (The V/A determination just described differs somewhat in procedural detail from that originally presented under Subsection 3-3.2 of the Semiannual Technical Report, but will be found conceptually equivalent. It was ultimately decided to measure ambient susceptibility in all cases at the same high noise level (114 dB) in order to (a) approximate maximal environmental stress conditions and (b) avoid possible nonlinear responses to an arbitrarily adjusted ambient noise level.)
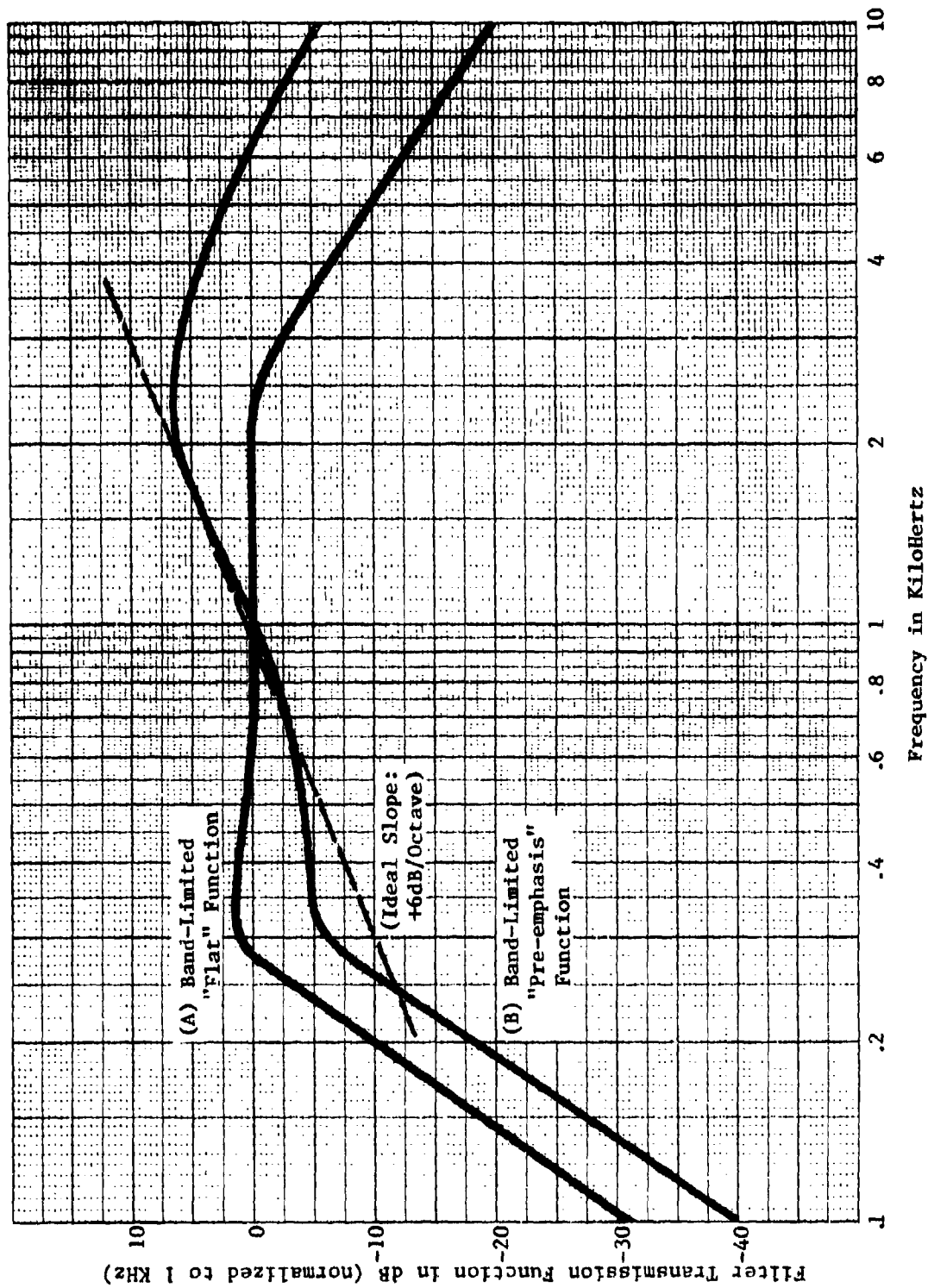
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Fig. 3.3: Frequency attenuation characteristics of Dual–Function Filter Box used in screening tests on experimental transducer units.

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3-2. Piezotransistor Transducer Selection

Most of the investigative effort involved in selecting the best piezotransistor transducer for evaluation as an experimental contact microphone has been previously documented in Chapter III of the Semiannual Technical Report on this project. Table II therein presented preliminary S/N and V/A readings for the three most promising transistor transducer units available—namely, the Georgia Tech built XT-18-5 (about 1/8" overall diameter, with Silastic coating to protect its .08"D sensing diaphragm); the Stolab model PTL2M04 (about 1/2" overall diameter, with Silastic coat to protect a .19"D sensing diaphragm); and the Stolab model PTM2M03 (dimensions similar to preceding unit, but with plastic screen over diaphragm providing a low-volume air-coupled configuration).

One indication from the above-referenced screening tests was that the XT-18-5 and PTM2M03 would be significantly better than the PTL2M04 in rejecting ambient noise (8 dB greater V/A). Figure 3.4 below shows data obtained from a supplementary series of measurements designed to check this conclusion—with obviously good qualitative corroboration.

The Signal-to-Noise Test Ratings observed in the aforementioned screening tests placed the XT-18-5 some 12-16 dB below the two larger-diameter Stolab units. This difference was, of course, immediately evident in the background noise levels perceived during comparative listening tests with the three transducers under quiet room conditions.

On the basis of the evidence just reviewed, it appeared that the PTM2M03 would be the best unit to choose for further experimental studies of piezotransistor transducer performance. This decision was reinforced by the sudden catastrophic failure of XT-18-5 during routine placement on the skin, and the realization that all such direct-contact diaphragm models (even though coated with an elastomer) would be too susceptible to accidental stress overload in normal field use.

The PTM2M03 was eventually fitted with a boom-mounting adapter and ambient-noise shield, and is shown in this form in Figure 4.1 of Chapter IV below.

As was discussed in Section 3-4 of the Semiannual Technical Report, beam-lead transistors had received special attention on this project through experiments designed to exploit their mechanical adaptability to a cantilever-beam mounting arrangement. In such an arrangement, stress could be applied to the transistor by bending action rather than by localized compression with an "indenter" device. If this type of transducer action proved feasible, it would permit construction of piezotransistor microphones with much lower profiles than had heretofore been achieved using the well-established diaphragm/needle configuration. Unfortunately, although the beam-lead transistors which were tested did exhibit some response to stressing in the flexural mode, the sensitivity obtained by this means was far below that associated with the indenter technique. In view of this result and the need to pursue evaluation efforts on other, more promising transducer types, further work with beam-lead transistors was considered unwarranted under the present project.
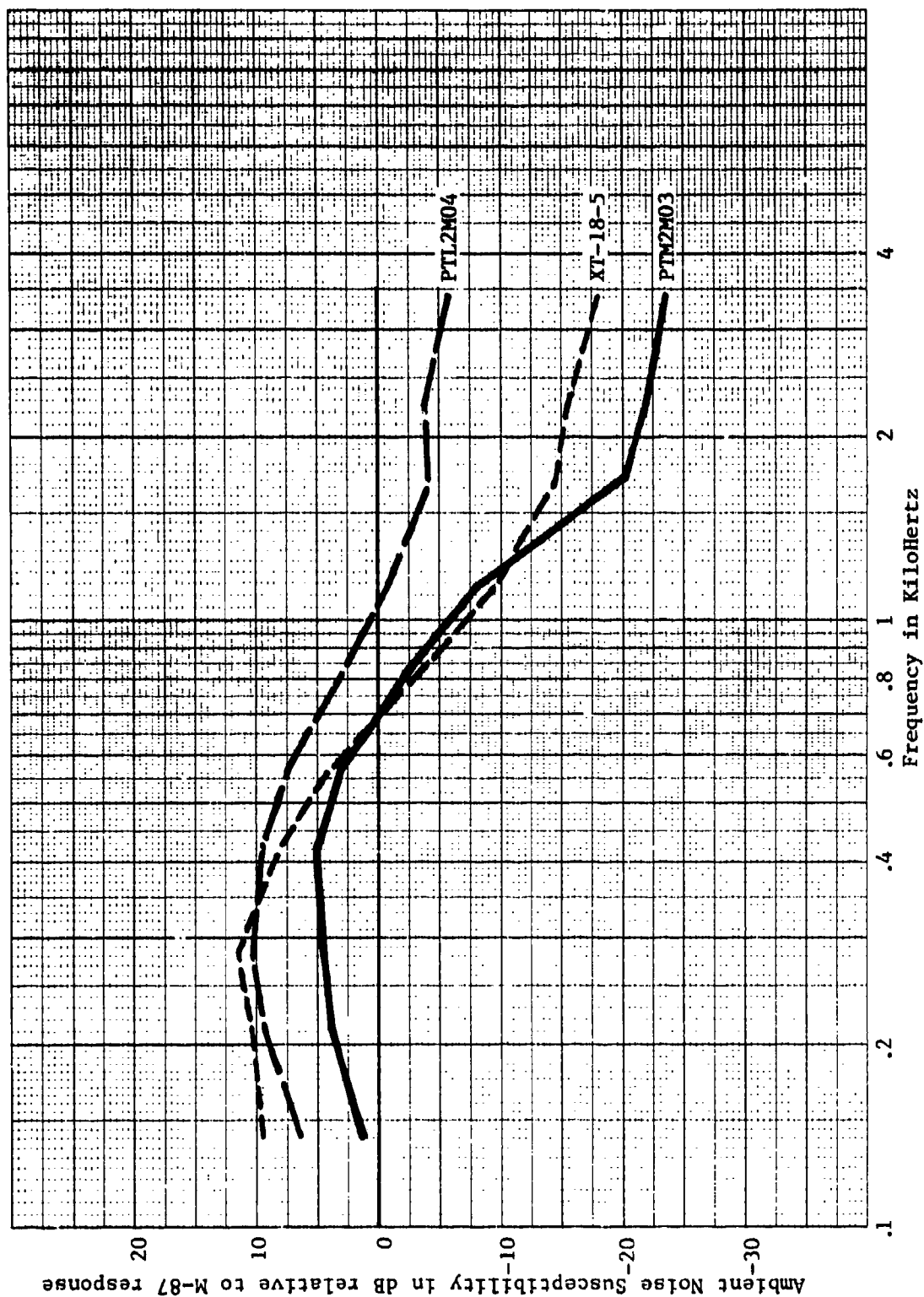
Fig. 3.4: Ambient noise susceptibility of experimental transistor transducers at cheek position in comparison to M-87 at lip position. (Difference in spectral responses to 114-dB "white" noise after gains adjusted for equal responses to same voice signal in 300-3000 Hz band.)

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3-3. Piezoresistive Transducer Selection

Background information on semiconductor strain gages and a description of initial efforts to develop piezoresistive transducers for this project have been previously documented in Chapter IV of the Semiannual Technical Report. Techniques were subsequently worked out for producing batches of special piezoresistive sensing elements in the microelectronic processing facilities at Georgia Tech. Appendix A describes the basic sensor configuration and transducer assembly designs that were adopted, leading to development of the experimental piezo-resistive contact microphone "C-3"—shown in Figure 4.2 of Chapter IV below.

The main difference between the transducer design illustrated in Figure A.2 of Appendix A and the contact microphone configuration of Figure 4.2 lies in the diaphragm size. It was found that the original experimental units, incorporating a 0.2-inch diameter diaphragm bonded to a modified TO-46 header cap (as depicted in Figure A.2), gave Signal-to-Noise Test Ratings far below those obtained with the previously described experimental piezotransistor transducers. In the design shown in Figure 4.2, the basic piezoresistive sensor assembly (Figure A.1) was mounted through a hole in the center of a 0.8-inch diameter disc-like aluminum shell. The shell was made with a thin circumferential lip for attaching the diaphragm, and with a rear "hub" (about 1/4" deep by 1/2" in diameter) for securing the sensor and supporting the whole unit from a standard lip-microphone boom.

A fourfold increase in diaphragm diameter would theoretically pro-duce a sixteenfold increase in effective contact area for sound-pressure pickup from the skin. This, in turn, would create 16 times as much force on the piezoresistive stress sensor and hence 16 times as much output voltage for the same acoustic signal. That is to say, the transducer sensitivity should be 24 dB greater with the larger diaphragm, and so should the Signal-to-Noise Test Rating. The general validity of this expectation is confirmed by the typical experimental results tabulated below. (Two sets of readings are shown to illustrate the normal variability of the data with different placements of the trans-ducer against the cheek.)

ILLUSTRATING EFFECT OF DIAPHRAGM SIZE ON SIGNAL-TO-NOISE TEST RATING (S/N) AND VOICE-TO-AMBIENT DISCRIMINATION INDEX (V/A) FOR PIEZORESIS-TIVE TRANSDUCERS AT THE CHEEK, USING FLAT AND PRE-EMPHASIS FILTERING

Experimental Piezoresistive Transducer Unit	Flat Filter		Pre-emphasis Filter	
	S/N (dB)	V/A (dB)	S/N (dB)	V/A (dB)
B-2 (0.2"D diaphragm)	15	33	12	28
	20	33	15	31
C-3 (0.8"D diaphragm)	39	45	38	36
	40	45	39	39
Difference in Ratings	19-25	12	23-27	5-11

The S/N Test Ratings for the two piezoresistive transducer designs are seen to be essentially independent of the filter characteristic used in the measurement. The Voice-to-Ambient Discrimination Index, on the other hand, is somewhat greater when measured with the Flat function (Figure 3.3A) than when measured with the Pre-emphasis function (Figure 3.3B). However, the indicated degree of improvement in going from the 0.2-inch to the 0.8-inch diameter diaphragm appears comparable for the two cases.

The V/A data tabulated above were obtained using the 114-dB "white noise" field shown in Figure 3.2(A). It was found that the "Chinook noise" field of Figure 3.2(B) gave virtually identical results.

IV. EVALUATION OF EXPLORATORY DEVELOPMENT TRANSDUCER MODELS

The experimental piezotransistor and piezoresistive transducers selected for delivery to ECOM as required "Exploratory Development Models" under this project are depicted in Figures 4.1 and 4.2. The associated preamplifiers appear in Figure 4.3, along with the dual-function filter box which was built for preliminary screening tests (see Chapter III) and included with the delivered items for possible further evaluation under field conditions.

Laboratory test data obtained on the above two transducers and preamps are presented in the graphical material which follows. For convenience, the piezotransistor transducer model will be regularly referred to herein as the "MO3" unit (an abbreviation for Stolab model PTM2MO3, the basic sensing device used in this experimental contact microphone). The piezoresistive transducer model will likewise be regularly referred to herein as the "C-3" unit (a Georgia Tech designation indicating from which batch of silicon sensing elements it was fabricated).

4-1. Laboratory Performance Tests

Comparative performance tests of the two selected transducers were carried out using the apparatus and procedures previously described in Chapter II for evaluating speech pickup sites on the head and neck. The basic power spectrum analysis data developed from each test run have been illustrated in Figure 2.2. Those are, in fact, the actual results obtained for the MO3 unit in the Cheek position, with the subject reading the "Rainbow passage" sample (exhibited in Figure 3.1) at a comfortable volume and pace. As noted in the accompanying discussion, the difference between curves (A) and (B) of Figure 2.2 represents the response which would have been measured for the particular transducer/site combination if the average sound spectrum generated had been "flat" instead of "speech-shaped." This difference—termed the relative spectral response—appears as the solid curve in Figure 4.4A below. The dashed curve represents a similarly normalized characteristic for ambient noise pickup by the same transducer at the same site. Figure 4.4B displays the decibel difference (ratio) of these two response characteristics, serving as a convenient generalized indicator of speech-to-ambient discrimination capability.

Figure 4.5 shows corresponding sets of performance data for the piezoresistive transducer C-3 at the Cheek site, while Figures 4.6 and 4.7 present like results obtained with the two experimental units at the Throat location. The speech/ambient discrimination characteristics from all four cases are reproduced for comparative evaluation purposes in Figure 4.8. Since the data represent single runs on only one test subject, strong conclusions cannot be drawn concerning the relative merits of the two transducer types. The C-3 unit is evidently superior below about 1 kHz, but the MO3 appears to have an edge in the upper frequency range—where, for example, most of the "Chinook" noise power is concentrated.
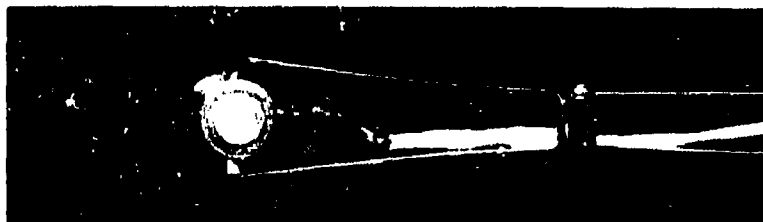
18

Fig. 4.1: Exploratory Development Model of Transistor
Transducer for use as air-coupled contact microphone.
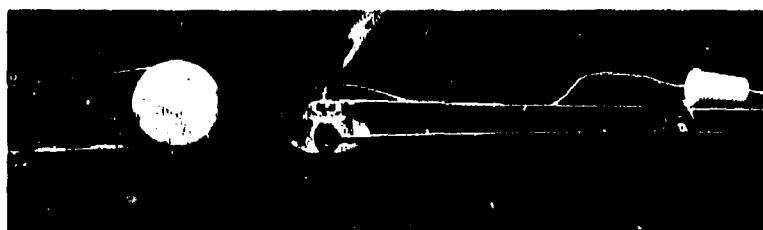(Stolab type PTM2M03 in boom-mounted acoustic shield.)

Fig. 4.2: Exploratory Development Model of Piezoresistive
Transducer for use as direct-coupled contact microphone.
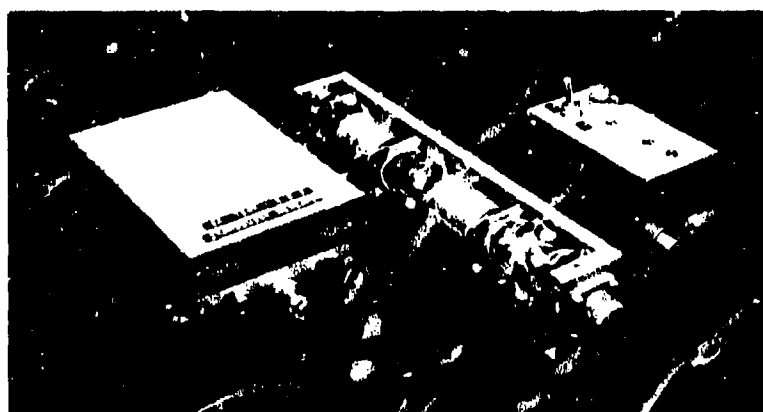(Georgia Tech unit "C-3"; 0.8-inch diameter diaphragm.)

Fig. 4.3: Electronic circuitry for use with Exploratory
Development Transducer Models. (left) Preamplifier for
transistor microphone; (center) Preamplifier for piezo-
resistive microphone; (right) Filter Box providing band-
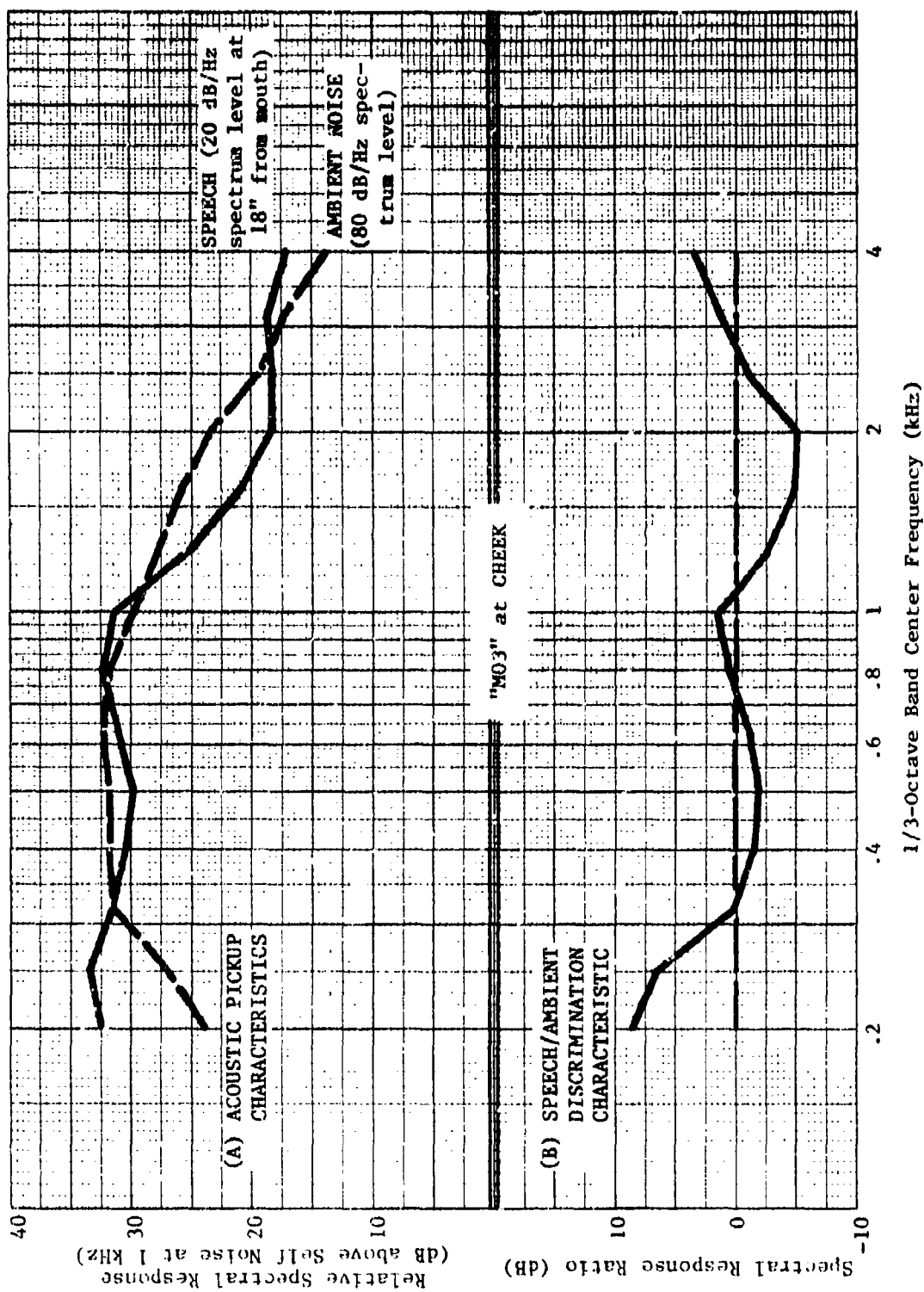limited flat and pre-emphasis characteristics (Fig. 3.3).

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Fig. 4.4: Laboratory performance characteristics of Piezotransistor transducer "M03" in Cheek position. (Tests made with speech spectrum as in Fig. 3.1A and ambient noise spectrum as in Fig. 3.2A.)
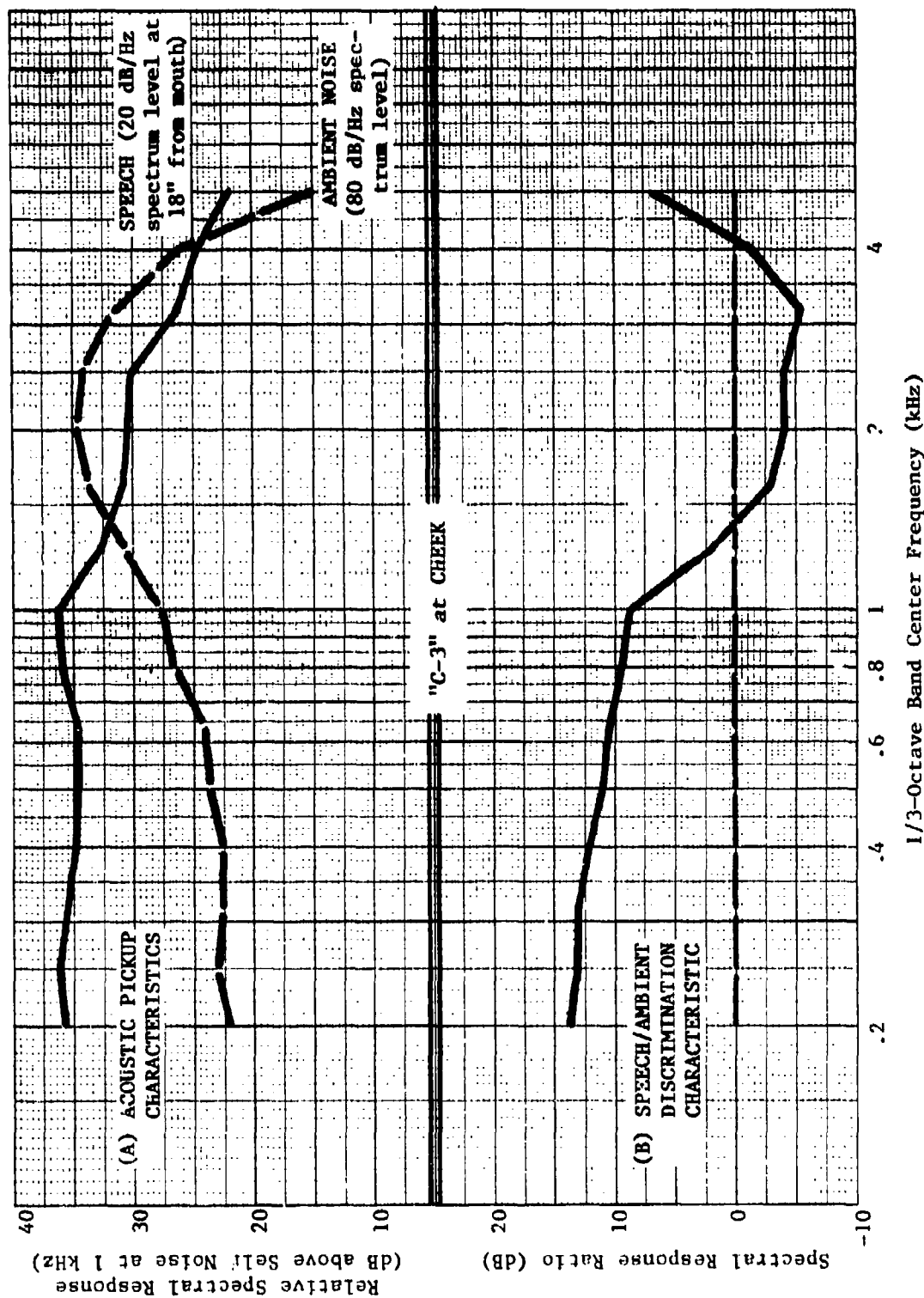
20

Fig. 4.5: Laboratory performance characteristics of Piezoresistive transducer "C-3" in Cheek position. (Tests made using speech spectrum as in Fig. 3.1A and ambient noise spectrum as in Fig. 3.2A.)

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AMBIENT NOISE
(80 dB/Hz spec-
trum level)

SPEECH (20 dBHz
spectrum level at
18" from mouth)

"M03" at THROAT

(A) ACOUSTIC PICKUP
CHARACTERISTICS

(B) SPEECH/AMBIENT
DISCRIMINATION
CHARACTERISTIC

1/3-Octave Band Center Frequency (kHz)

.2   .4   .6   .8   1   2   4

Relative Spectral Response
(dB above Self Noise at 1 kHz)

30   20   10   0
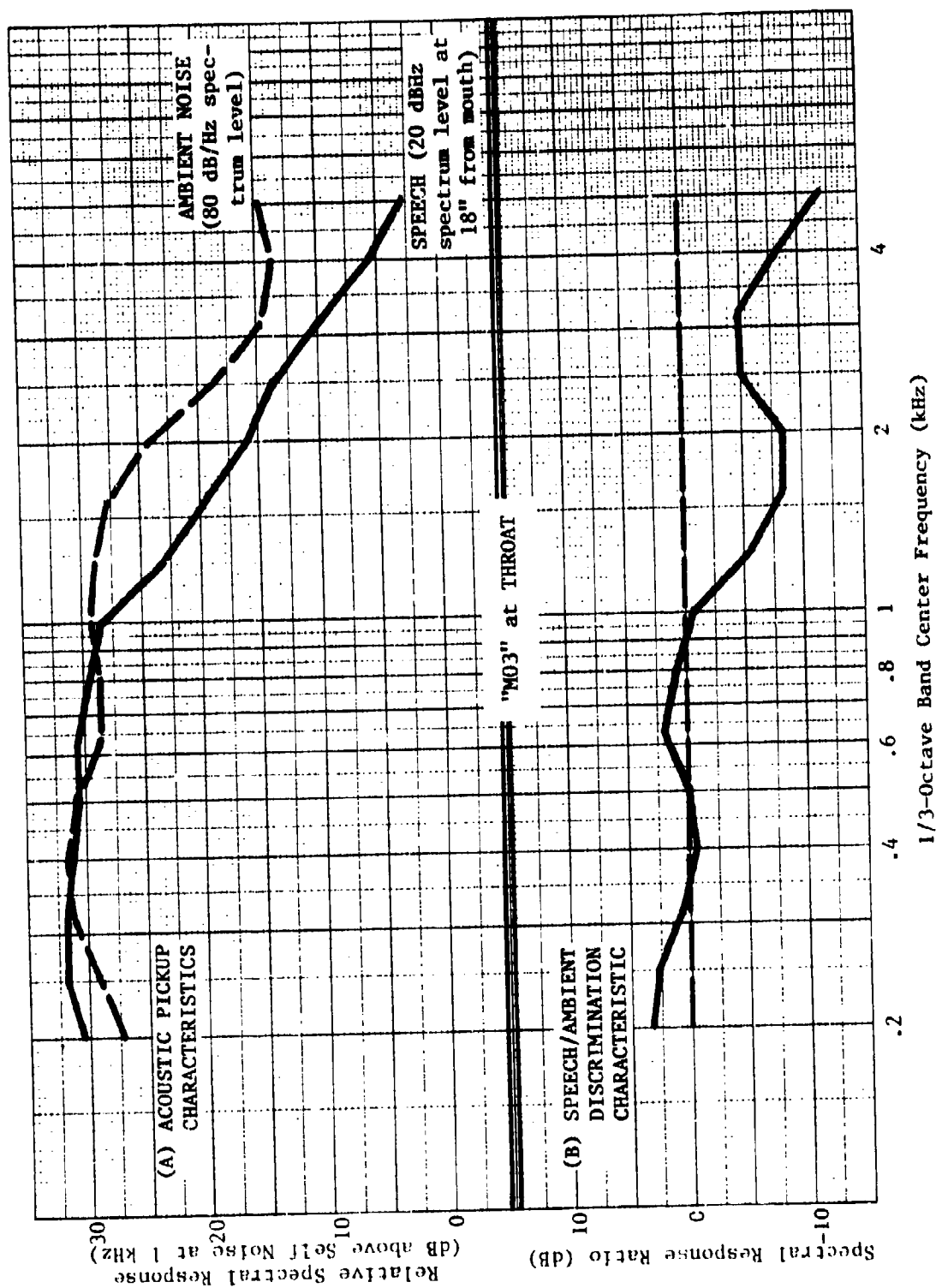
Spectral Response Ratio (dB)

10   0   -10

Fig. 4.6: Laboratory performance characteristics of Piezotransistor transducer "M03" in Throat position.
(Tests made with speech spectrum as in Fig. 3.1A and ambient noise spectrum as in Fig. 3.2A.)
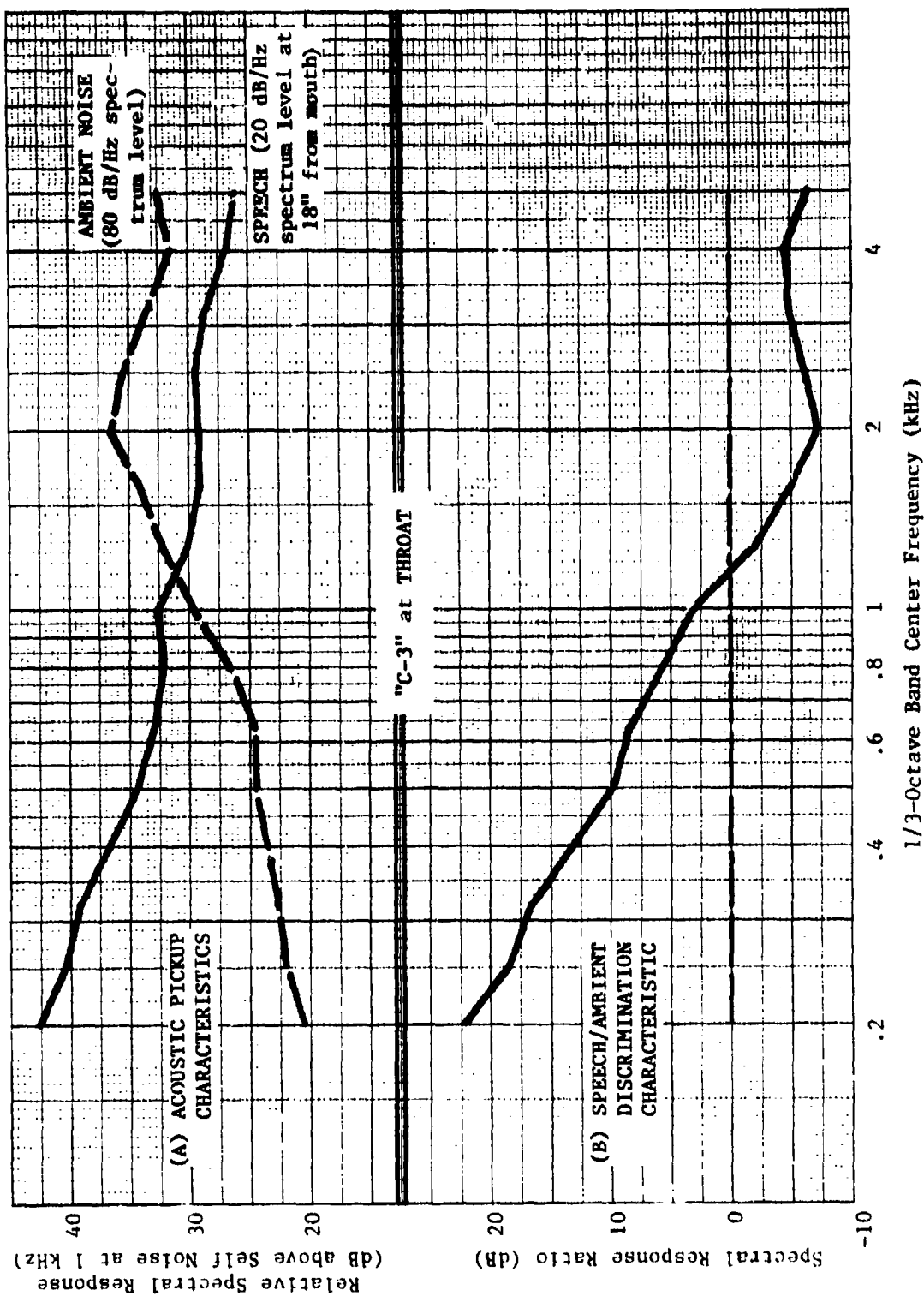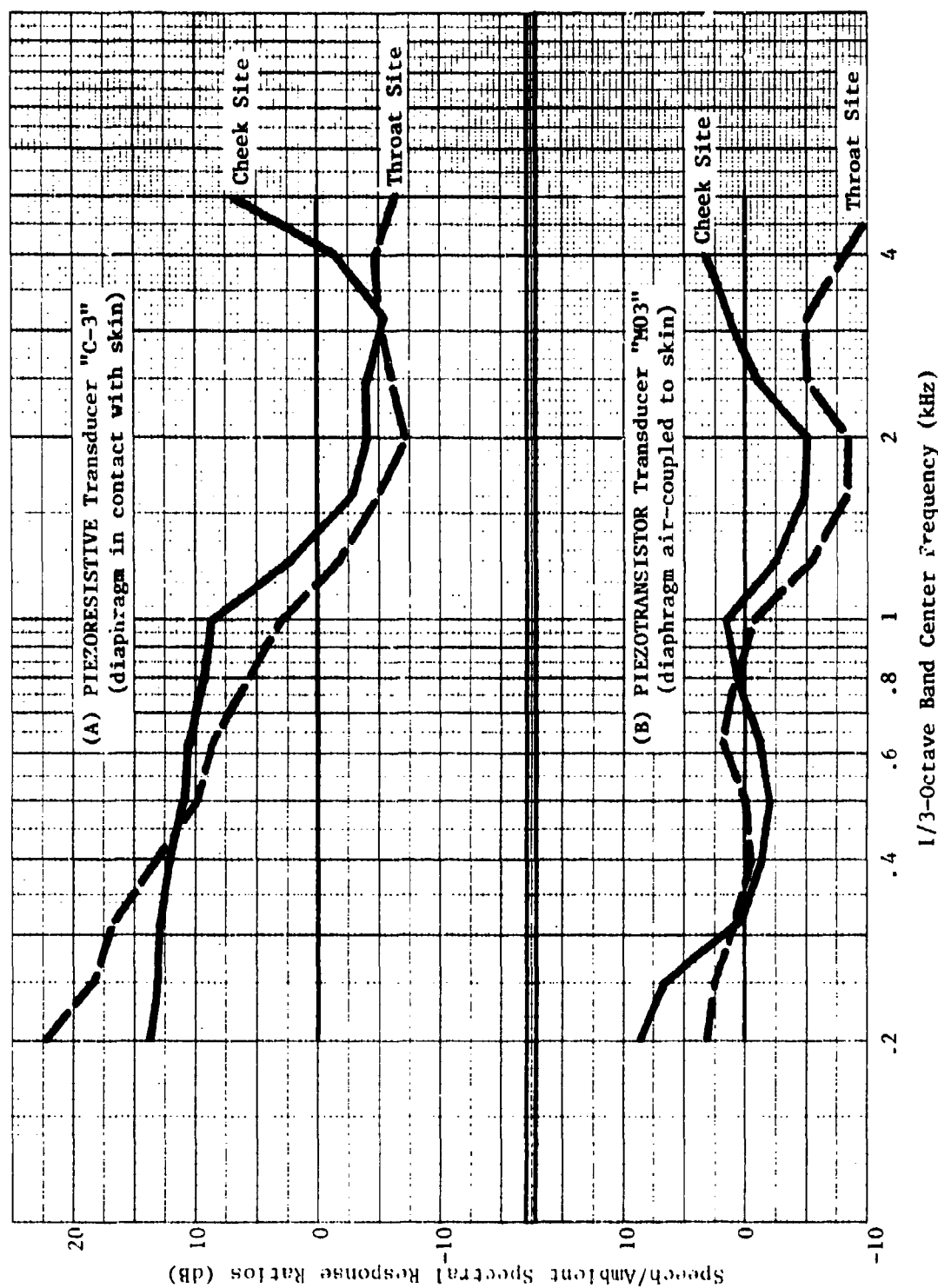
22

Fig. 4.7: Laboratory performance characteristics of Piezoresistive transducer "C-3" in Throat position. (Tests made with speech spectrum as in Fig. 3.1A and ambient noise spectrum as in Fig. 3.2A.)

23

Fig. 4.8: Comparison of speech/ambient discrimination characteristics for Exploratory Development Model transducers at Cheek and Throat sites. (From Figs. 4.4-4.7)

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Additional tests were conducted to compare the two experimental transducers with a standard M-87 lip microphone. In this case, the simpler vowel sound described in Chapter III (Figure 3.1B) was used to provide a spectrum of speech frequencies—corrected, as before, by the recorded signals from the sound level meter. Figure 4.9 below shows (A) relative spectral responses of the M-87 to both voice and ambient noise, and (B) the associated difference function indicating the M-87's generalized voice-to-ambient discrimination characteristics. Equivalent test data were generated for the MO3 and C-3 units, but at the Cheek site only. The resulting normalized acoustic pickup characteristics were similar to those shown in Figures 4.4 and 4.5 (obtained using the 20-second speech sample) and are not reproduced in that form here. Instead, the final voice-to-ambient discrimination characteristic of each experimental unit is shown plotted in Figure 4.10 relative to that of the M-87 lip microphone (viewed as a standard of comparison). This picture indicates a slight advantage on the part of the MO3 unit to reject ambient noise frequencies above about 2 kHz (an objectionable part of the "Chinook" spectrum). However, both experimental transducers appear otherwise somewhat inferior to the M-87.

4-2. Additional Considerations

As suggested in the introduction to Chapter III, the foregoing method of evaluating experimental transducers—by power spectral analysis of their average responses to separate voice and noise pickup tests—omits many important factors which must enter into the ultimate criterion of performance, namely speech intelligibility under true field conditions. In anticipation of a possible visit to Fort Rucker to assess first-hand some of the operational problems in communication from helicopters, the following additional test observations were made in the project laboratory at Georgia Tech.

(a) A tape-recorded comparison was made between an M-87 lip microphone and the experimental MO3 and C-3 cheek-contact microphones using a standard speech sample delivered both in the quiet and in a simulated 115-dB Chinook-noise environment (see Figure 3.2B). Tape play-back listeners expressed varying opinions as to the quality of voice reproduction obtained with the three devices and the relative unpleasantness of the ambient noise interference. There appeared to be some improvement in "listenability" when the rather shrill sound from the M-87 was blended (electronically) with the more muffled output from the C-3 unit. Speech intelligibility in the high-noise condition was in general judged "poor" but not markedly different between devices.

(b) It had been suggested that under actual field conditions, such as in a helicopter cabin during takeoff or flight, vehicle vibrations transmitted via the body to a cheek-contact microphone might significantly degrade its performance. In order to test this hypothesis in the laboratory, a massage-type vibrator was operated at various points on the head and neck of a subject during speech tests with each microphone. There was no observable interference except when the vibrator touched the microphone boom support itself.
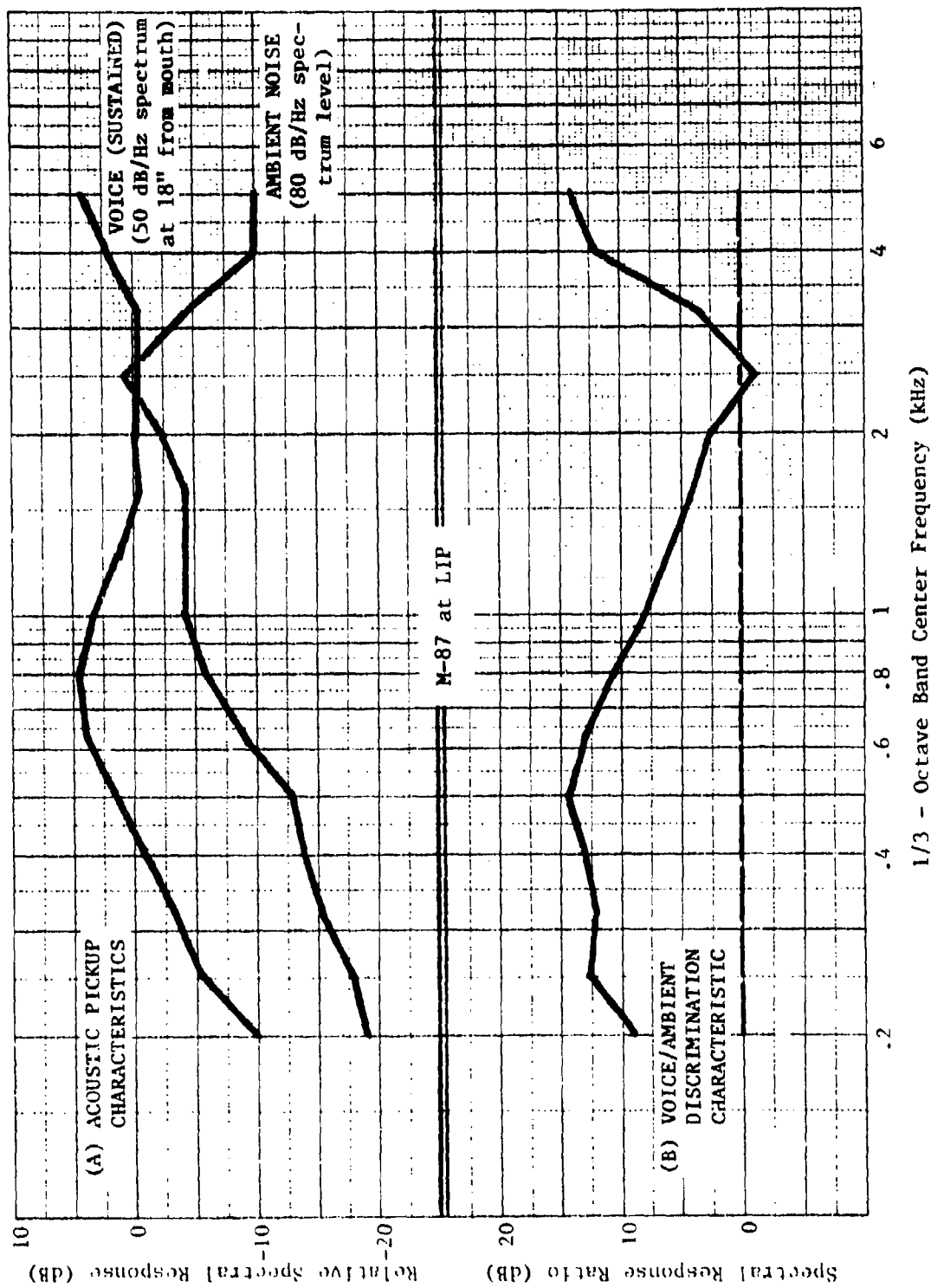
Fig. 4.9: Laboratory performance characteristics of M-87 microphone in normal Lip operating position. (Tests made with voice spectrum as in Fig. 3.1B and ambient noise spectrum as in Fig. 3.2A.)
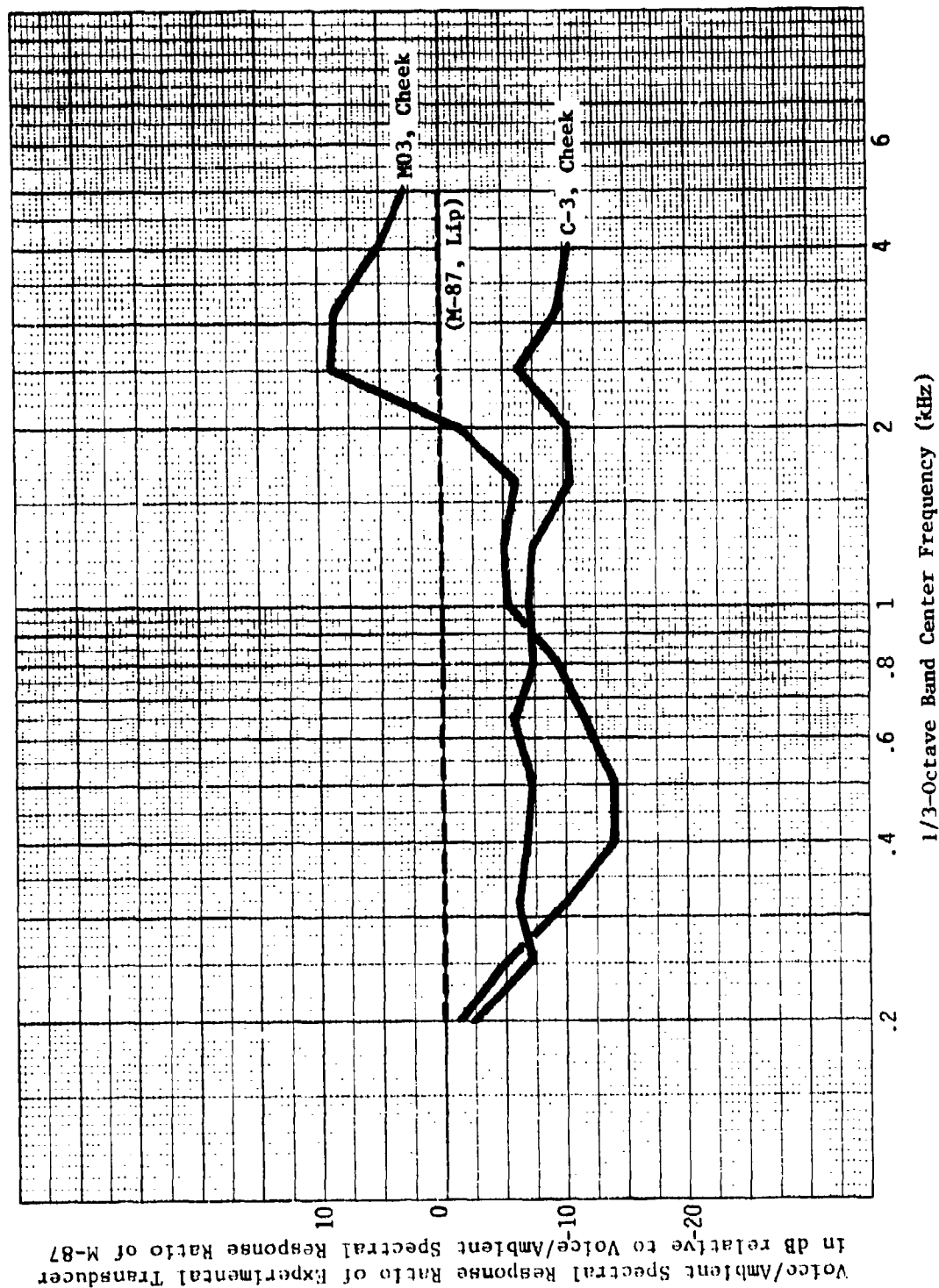
Fig. 4.10: Voice/ambient discrimination characteristics of Exploratory Development Model transducers at Cheek site relative to M-87 characteristics in normal Lip position (taken as baseline).

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V. CONCLUSIONS

1. Experimental piezotransistor and piezoresistive contact
    microphones (one each) have been furnished to ECOM
    which incorporate the best state-of-the-art designs that
    could be found or developed within the scope of effort
    available on this project.

2. Comparative evaluations based on power spectrum analysis
    of time-averaged responses to phonetically balanced
    speech, sustained vowel sounds, and continuous high-
    level ambient noise indicated that neither experimental
    device--operated as a cheek or throat microphone--
    would give as good performance as the existing M-87
    lip microphone.

Appendix A

PIEZORESISTIVE TRANSDUCER DEVELOPMENT

Figure A.1 illustrates the basic sensor assembly design adopted for piezoresistive transducer development on this project. A standard TO-46 gold-plated transistor header was used as a base for mounting the silicon piezoresistive sensing element. As indicated in the figure, the silicon element is centered on the header and is bonded, using a solder preform, to the top of an alumina standoff. Both top and bottom surfaces of the insulating standoff were gold-plated prior to attachment to the header and the silicon element. To provide electrical contacts to the silicon sensor, gold wires 0.7 mil in diameter were thermocompression-bonded between the contact areas of the silicon element and the header posts which serve as electrical feed-throughs. In addition to providing electrical isolation from the header, the standoff allows the silicon sensing element to protrude over the posts of the header for unobstructed contact with the diaphragm, as illustrated in Figure A.2.

After the header cap was machined to an appropriate height, it was resistance-welded to the base of the transistor header. Then the diaphragm was attached by the same method to the rim of the header cap, thus completing the transducer structure. Materials such as molybdenum, beryllium-copper, phosphor-bronze, Kovar, and stainless steel were tried for making diaphragms. Especially good results were obtained using Kovar as diaphragm material; molybdenum, on the other hand, appeared to be too ductile for the application. Diaphragm thickness was varied from 1 mil to approximately 3 mils in the experimental work.

In order to provide electrical isolation between the diaphragm and the contact on top of the sensor element, insulating epoxy was applied over the contact area prior to final assembly. Since this approach was not entirely satisfactory, a small alumina disc about 10 mils thick was used as a spacer between the sensor and the diaphragm.

As indicated in Figure A.2, external pressure on the diaphragm results in a force being applied to the piezoresistive sensor. Changes in the magnitude of this force cause resistance variations of the sensing element. These resistance changes are then converted into electrical signals which are amplified and appropriately filtered.

The material chosen for the construction of the piezoresistive sensors was p-type boron-doped silicon in the resistivity range of 8 to 10 ohm-cm. The silicon wafers from which the sensing elements were made had a thickness of 10 mils and were cut perpendicular to the longitudinal axis of the crystal which was oriented in the (111) direction. The purpose in this choice of crystallographic orientation was that the sensing elements be stressed in the (111) direction which, for p-type silicon, corresponds to a direction of largest piezoresistance effect.

The silicon sensing elements were made by the use of standard microelectronic methods including photomasking to define the top contact areas of the sensors. The individual sensors were obtained from the silicon wafer by etching away the silicon between the metal dots
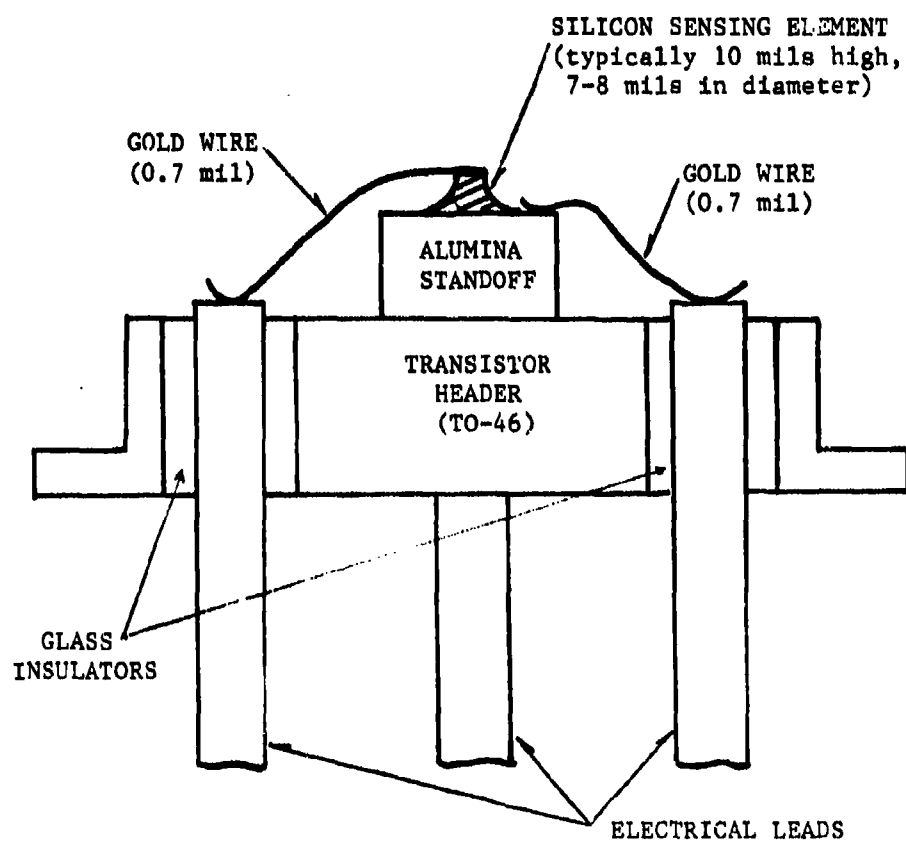
Fig. A.1:   Illustrating basic piezoresistive sensor assembly.
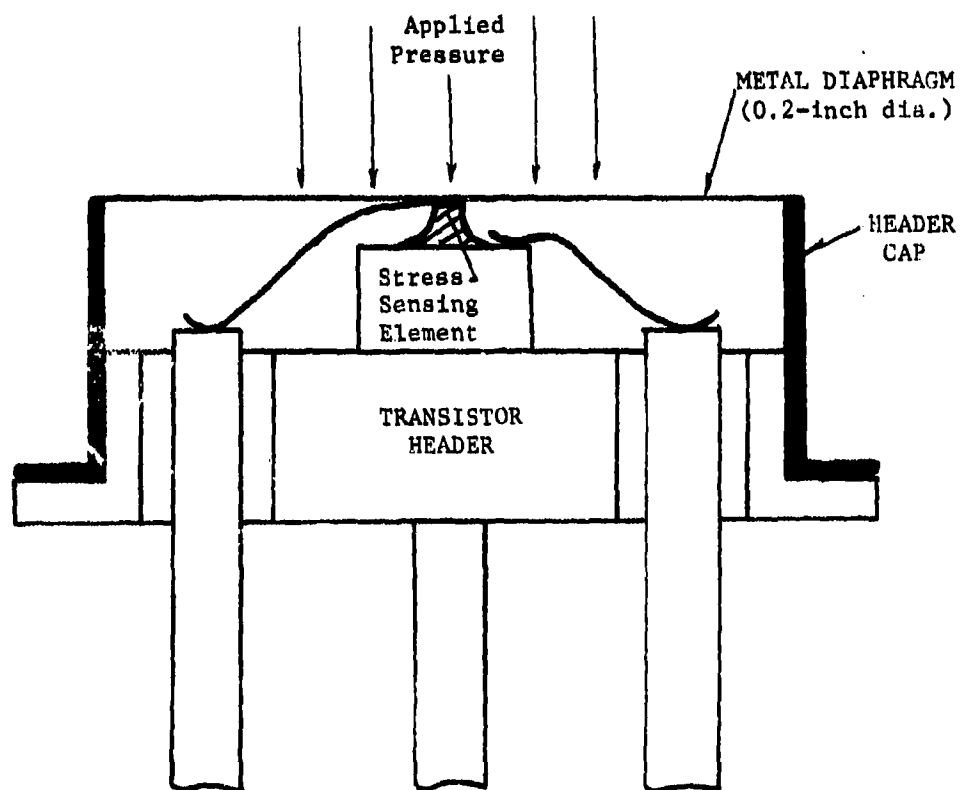
a2

Fig. A.2: Piezoresistive transducer assembly incorporating
diaphragm bonded to modified header cap.

which served as masks for each element. After separation of the individual elements, they were mounted in a package using eutectic solder.

Figure A.3 presents experimental data from a number of silicon piezoresistive elements showing how the electrical resistance changes with diameter of the top surface of the sensors. The dimensions of the sensors were controlled by chemical etching. The diameter of the piezoresistive sensor in the experimental transducer delivered to ECOM is approximately 7 mils.
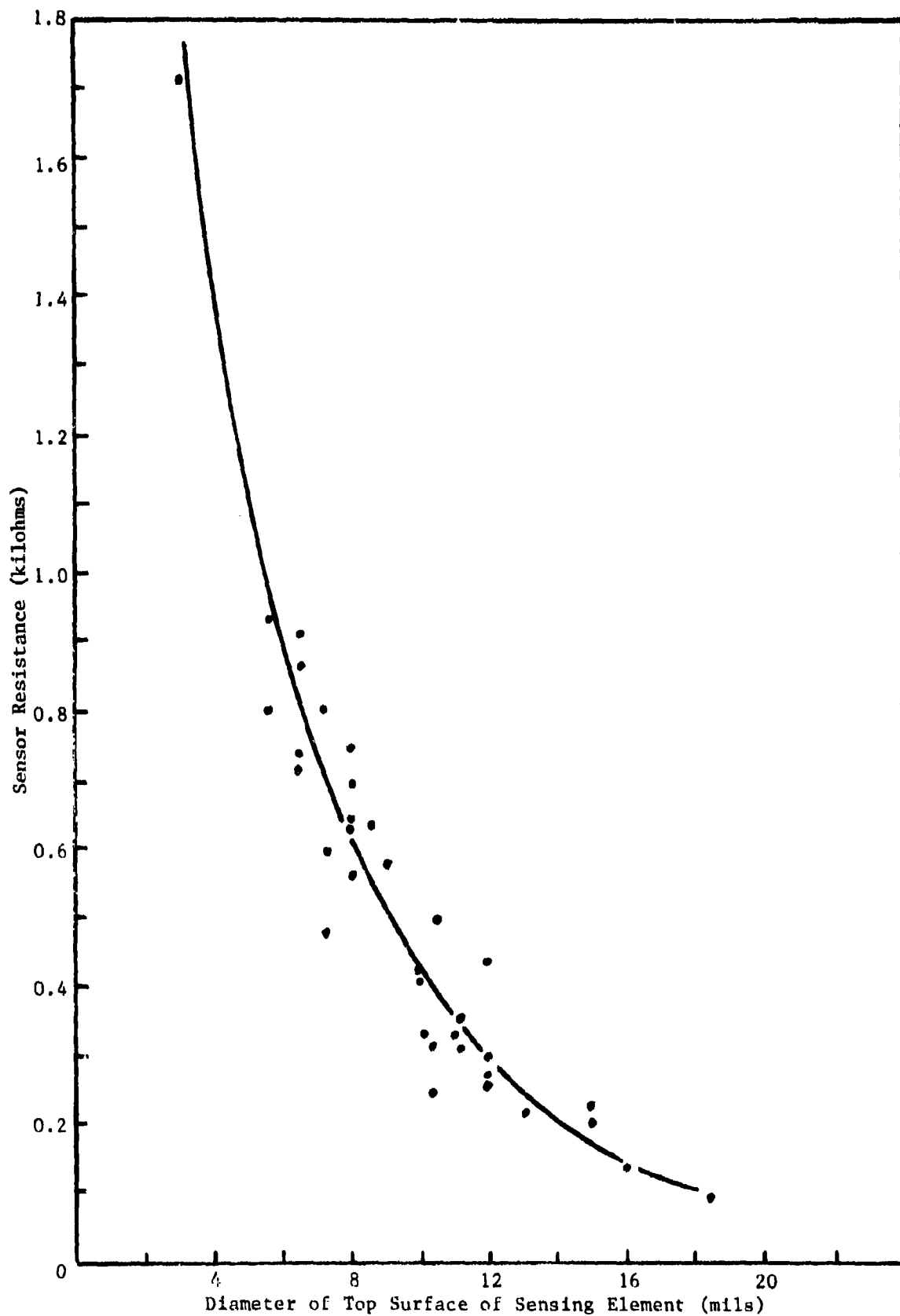
Fig. A.3: Variation of piezoresistive sensor resistance with element diameter.

a5

Appendix B

TRANSDUCER SCREENING TEST DEFINITIONS

Figure B.1 illustrates the test procedure described in Section 3-1 for preliminary screening of experimental transducer designs on this project. As indicated by steps (1), (2), and (3) in the figure, the procedure involves reading the output voltage from the test transducer and associated electronics under three standardized acoustic input conditions.

In step (1), the subject sustains the selected vowel sound "ä" at such amplitude as to produce a reading L_v of approximately 84 dB on the C-weighted sound level meter (SLM) located 18 inches in front of his mouth. The output voltage reading E_v obtained from the transducer being tested at the given pickup site (the Cheek) is taken with the circuit gain controls arbitrarily adjusted and then left unchanged during the remainder of the test. A corrected output voltage reading, E_v', corresponding to the "standard" delivered sound level of exactly 84 dB at 18", is found from the following equation (in decibel units):

$$\text{(B1)} \qquad 20 \log E_{v'} = 20 \log E_v - (L_v - 84) .$$

The conditions for step (2) of the test procedure are the same as for step (1) except that the subject now remains silent. Since the acoustic background in the test room is relatively quiet, the voltmeter reading E_0 represents mainly the inherent electrical noise of the measuring system as a whole—which, in turn, was found to be attributable almost exclusively to the "self noise" of the experimental transducer itself. The Signal-to-Noise Test Rating of the transducer, as defined in Section 3-1, is then given by the following equation:

$$\text{(B2)} \qquad S/N = 20 \log E_{v'} - 20 \log E_o .$$

The final step in the test procedure involves generating an ambient noise field such that the measured overall sound pressure level L_a in the immediate vicinity of the test transducer has the "standard" value of 114 dB. Under this condition the transducer produces an output voltage reading designated as E_a in Figure B.1(3). However, for purposes of assessing the transducer's relative responsiveness to speech signals versus ambient noise, this measured output is "corrected" to correspond to an ambient noise level of 84 dB (numerically equal to the standardized voice test level). The correction is included in the following formula for Voice-to-Ambient Discrimination Index (V/A) as defined in Section 3-1:

$$\text{(B3)} \qquad V/A = 20 \log E_{v'} - \{20 \log E_a - (114 - 84)\}$$

$$= 20 \log E_{v'} - 20 \log E_a + 30 .$$

(1) Response to voice signal.

18

SLM $L_v = 84$ dB

Preamp → RMS V/M → E_v

(2) Self-noise reading.

Preamp → RMS V/M → E_o

Loudspeaker

SLM

$L_a = 114$ dB

Power Amp.
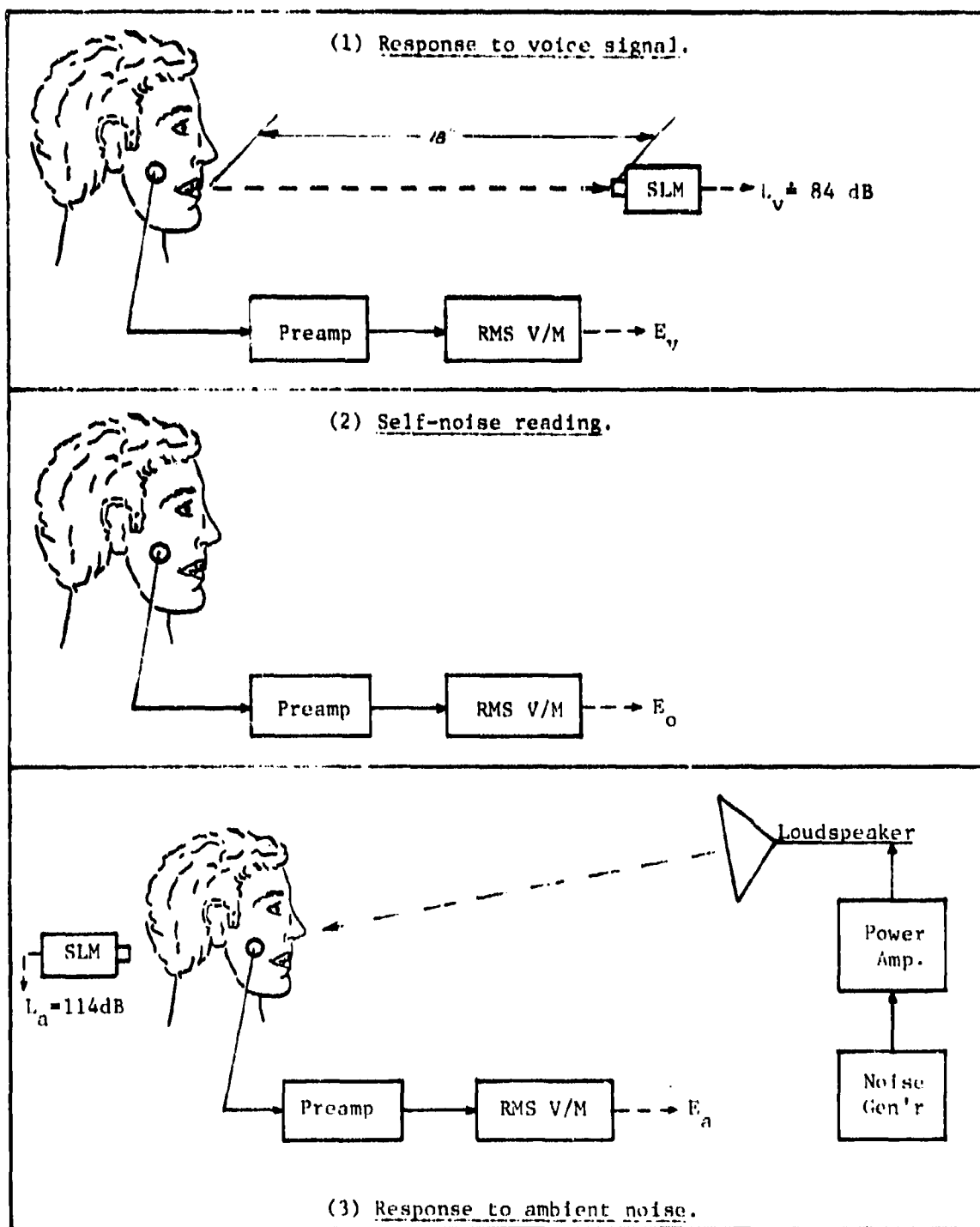
Noise Gen'r

Preamp → RMS V/M → E_a

(3) Response to ambient noise.

Fig. B.1: Illustrating transducer screening test measurements.