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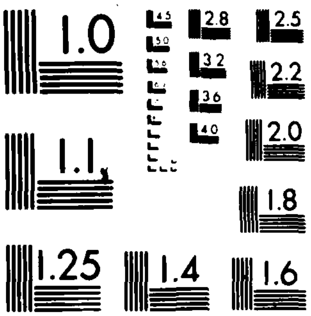

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AD A139476

DTIC ACCESSION NUMBER

II

LEVEL

I

INVENTORY

Annual Rpt., 19 Oct. '78 - Apr. '80

Teas, D.C.,

DOCUMENT IDENTIFICATION

Contract DAMD17-78-C-8067

Apr. '80

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Research and Development of a Cochlear Microphonic Response to Low-Frequency Noise

Annual Report

D.C. Teas, R.E. Hill, D.F. Dolan, J.P. Walton

April 1980

Supported by

US ARMY MEDICAL RESEARCH AND DEVELOPMENT COMMAND
Fort Detrick, Frederick, Maryland 21701

Contract No. DAMD17-78-C-8067

Institute for Advanced Study of the Communication Processes
University of Florida
Gainsville, Florida 32611

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)

RESEARCH AND DEVELOPMENT OF A COCHLEAR MICROPHONIC RESPONSE TO LOW-FREQUENCY NOISE

5. TYPE OF REPORT & PERIOD COVERED

Annual - October 19, 1978 - April 1980

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)

D. C. Teas, Ph.D.

8. CONTRACT OR GRANT NUMBER(s)

DAMD17-78-C-8067

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Institute for Advanced Study of the Communication Processes, University of Florida
Gainesville, Florida 32611

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

62773A.3E162773A819.00.02

11. CONTROLLING OFFICE NAME AND ADDRESS

US Army Medical Research and Development Command
Fort Detrick, Frederick, Maryland 21701

12. REPORT DATE

April 1980

13. NUMBER OF PAGES

46

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)

15. SECURITY CLASS. (of this report)

Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

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

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SUMMARY

An interim report of the status of our study on the effects of high-intensity, low-frequency noise is presented. A method has been implemented in which Discrete Fourier Transforms are computed from samples of two analogue waveforms. One source represents input to a system, the other represents the system output. The input spectrum, output spectrum and cross-spectrum are computed. The transfer function is calculated by dividing the averaged cross-spectrum by the averaged input spectrum. Limitations of the method in application to the Cochlear Microphonic are illustrated and the suitability of the method for characterizing the external auditory canal is demonstrated.

Foreword

In conducting the research described in this report, the investigator(s) adhered to the "Guide for Laboratory Animal Facilities and Care," as promulgated by the Committee on the Guide for Laboratory Animal, Resources, National Academy of Sciences-National Research Council.

Appendix A

1. Abstracts of papers MM1 and MM2, presented at Acoustical Society of America, Atlanta, GA, Spring, 1980.
2. Figures and text, MM1.
3. Figures and text, MM2.

The tasks targeted in the initial contract period for DAMD17-78-C-8067 have been developed and the experimental results examined in two papers presented at the 99th Meeting of the Acoustical Society of America in Atlanta, GA, 21-25 April, 1980. The figures and text are enclosed here along with copies of the abstracts for the two papers (JASA, Suppl, 67, Spring, 1980). The salient features from our conclusions will be described.

The use of Discrete Fourier Transforms (DFTs) from two sources, representing input and output and taken simultaneously, is a powerful method of analysis for linear systems which have a wide frequency response. Our procedure for deriving the transfer function incorporates the cross-spectrum which reduces the effect of uncorrelated noise, a difficult problem in physiological experiments. The procedure works well for measuring the transfer function of the external auditory canal, a system which can be driven with a broad band of noise and which shows resonant peaks in its output.

The application of the procedure to the Cochlear Microphonic (CM) encountered some basic limitations which were difficult to recognize; the basis for these limitations lies in the properties of the cochlea. The cochlear system can be described as a series of low-pass filters with high-frequency limits which decrease from the base to the apex of the cochlear coils. At any location along this system, there will be one frequency region for which cochlear output will be at a maximum. The range of input (signal) intensity over which the voltage within the most sensitive frequency region remains linear (undistorted) is about 30-40 dB. Above this intensity the output is non-linear, i.e., distortion develops.

A broadband input signal contains frequencies within the most sensitive region and also, frequencies below that region but which can fall within the (low-) passband for that cochlear location. As input intensity increases the output (CM) in these lower frequency regions reach a linear segment of their intensity function and, if intensity is increased further, they, too, enter a distortion region.

As the intensity of a broadband input is increased from low to high, therefore, the transfer function and the coherence function must be used together to characterize the properties of the one cochlear location from which the CM is recorded. At low intensities the transfer function will describe the operation of the system in a valid way only in its most sensitive frequency range, since the coherence function will show a value of 1.0 only within this range. As intensity increases, the CM in the most sensitive frequency region will begin to distort and the coherence function will tend toward zero. Simultaneously the input at frequencies below the most sensitive region will enter the (low-) passband region of the CM, the transfer function will now indicate a valid description in this adjacent lower frequency region as shown by the coherence function approaching a value of 1.0. With still further intensity increases the CM output in this region will distort, coherence will tend toward zero, etc.

Thus, the "system transfer function" is itself a function of input signal intensity when the signal is broadband noise. The value of the coherence function can be 0 because of two reasons, distortion or low signal/noise ratio. Without special tailoring of the input noise band, one cannot obtain a broadband reference condition that can be used as a basis for contrast with the effects produced by high-intensity, low-frequency noise. Although a firm baseline is not available, the effects of the low-frequency noise in the CM can still be determined by the method.

The data we have generated on the CM are illustrated by the figures in paper MM2 (Appendix). Paper MM1 represents data describing the transfer functions for the external auditory canals of four species. Some shortcomings in stimulus generation are apparent from the input spectra shown in paper MM2. We were unable to generate 65 Hz noise bands with sufficient intensity to test the hypothesis that distortion produces high frequency components within the 2 kHz frequency region. Because of this we used 250 Hz noise bands. The distortion we detected in those experiments occurred at multiples of the upper cut-off frequency of the input spectrum. Funds for additional instrumentation are included in the extension of the proposal to improve our signal generating capabilities in order to produce a valid test of the original hypothesis.

Because of the limitations of the CM, as discussed above, it seems clear that the method, as applied to the Cochlear Microphonic is highly suitable for measuring the CM spectrum from one location but not suitable for determining the location along the cochlear partition from which spectral components might originate. There are other differences between the behavioral experiments in which the phenomenon was defined and the physiological experiments in which we are measuring the CM spectrum and caution should be used when assuming that the two sets of experiments are parallel. In the physiological experiments anesthesia must be used and the animal is maintained in a headholder. In the anesthetized state the middle ear muscles are not active, while in the behavioral experiments they were capable of activity. In the behavioral experiments the sound field was carefully developed to deliver sufficient power, in the free-field, to reach 120 dB SPL. Because of restrictions of space a carefully calibrated sound field was not possible in the initial period of the contract. Some improvement is expected from the speakers and power amplifier to be ordered during the extension.

FRIDAY MORNING, 25 APRIL 1980 ANSLEY ROOM, 9:00 A.M. TO 12:00 NOON

Session MM. Physiological Acoustics III: General (Poster Session)

James H. Patterson, Jr., Chairman

U.S. Army Aeromedical Research Laboratory, P.O. Box 577, Fort Rucker, Alabama 36362

Contributed Papers

MM1. Acoustic properties of the external auditory canal in chinchilla, guinea pig, cat, and man. D. C. Teas (Department of Psychology, University of Florida, Gainesville FL 32611), R. E. Hill [Institute for Advanced Study of Communication Processes (IASCP) University of Florida, Gainesville FL 32611], D. F. Dolan, J. P. Walton (Department of Speech, and IASCP, University of Florida, Gainesville, FL 32611), J. H. Patterson, and C. K. Burdick (U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL 36360)

The acoustic pressures produced by a band of noise were measured at the entrance to the auditory canal and near the tympanum. The stimuli was produced by a TDH-39 earphone activated by a noise band tailored to produce an approximately flat spectrum between 0.1 and about 4 kHz at the entrance to the ear canal. A computer program calculated the output power spectra, the signal/noise, the cross-power spectrum, the transfer function, the coherence function, and the phase between the input and output power spectra. The transfer function in each animal shows an upper frequency peak, the location of which varies with the apparent volume of the canal, being highest for the guinea pig and lowest for man. The magnitude of the resonance is largest for the cat and smallest for the guinea pig. [Supported in part by DAMD 17-78C-8067 and NSF-77-16907.]

MM2. Spectrum of the CM produced by high-intensity, low-frequency noise bands in the chinchilla. D. C. Teas (Department of Psychology, University of Florida, Gainesville FL 32611), R. E. Hill [Institute for Advanced Study of the Communication Processes (IASCP) University of Florida, Gainesville FL 32611], D. F. Dolan and J. P. Walton (IASCP and Department of Speech, University of Florida, Gainesville, FL 32611), and J. H. Patterson and C. K. Burdick (U.S. Army Aeromedical Research Laboratory, Ft. Rucker, AL 36360)

High-intensity, low-frequency octave band noise in the free field has been reported to produce permanent threshold shift at 2 kHz in chinchillas [Burdick, Patterson, Mozo, and Camp, J. Acoust. Soc. Am. 64, 458 (1978)]. We have delivered 100- and 250-Hz low-pass noise to the chinchilla with intact pinna but open bulla and have measured the spectrum of the CM recorded with electrodes in turn I and turn II. SPL's were measured at the pinna. The output of the microphone was led to channel 1 of an A/D converter. The CM was led to channel 2. The inputs to the A/D's were adjusted to the same rms level to minimize digital noise. A computer program calculated FFT's and produced several calculations from them (see previous abstract). At SPL's below 100 dB, the output spectrum (CM) is similar to the input spectrum (microphone). Above 100 dB the output spectrum contains frequencies above the passband of the input spectrum. The coherence function indicates that the high-frequency output is not present in the input power spectrum. [Supported in part by DAMD17-78C-8067 and NSF 77-16907.]

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MM1

ACOUSTIC PROPERTIES OF EXTERNAL AUDITORY CANALS

D. C. TEAS, R. E. HILL, D. F. DOLAN, J. P. WALTON
UNIVERSITY OF FLORIDA GAINESVILLE, FLORIDA

AND

J. H. PATTERSON, C.H. BURDICK
U.S. ARMY AEROMEDICAL RESEARCH LABORATORY, FT. RUCKER, AL.

The external auditory system (pinna, concha, auditory canal) provides a pathway for transmission of acoustic information to the middle and inner ear. Because the shapes of the external structures vary across animals, the filter characteristics of the external systems should also vary. A procedure which yields simultaneous power spectra from two sources has been used to evaluate the acoustic pathways in four different species used for auditory research. The method is also appropriate for measuring the effects of alterations in the system, as occur for open and closed bulla.

The analogue voltages representing the acoustic pressures measured with two microphones ("input" and "output") are led to A/D converters. The voltage is sampled at 12.5 kHz in each channel (25 kHz sampling rate). The digitized data are corrected for alternating sampling times in each channel. Three power spectra are computed: Input, Output, and Cross for each segment, or Epoch of the ongoing waveforms. The Output spectrum is determined by the input to the system, the transfer function of the system and uncorrelated noise. The transfer function (XFR) is estimated by dividing the resultant averaged Cross spectrum by the averaged Input spectrum. At locations in the spectra where the noise is small with respect to the input power, the validity of XFR is high; where the noise is relatively large with respect to the input power, XFR is not an accurate measure of system properties. The Coherence Function (COH) describes this relation and is also computed by the program

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The XFR between a probe microphone deep in the external auditory canal of the chinchilla with Bulla Closed shows a resonance peak about 2.5 kHz with an anti-resonance about 2.9 kHz. For Bulla Open the resonance occurs at about 3.1 kHz and the anti-resonance at about 3.5 kHz.

Features of the power spectra at frequencies near 4 kHz can vary among animals.

The analogue voltage is read in Epochs which are initiated by a trigger pulse. The digitized data can be saved on floppy disks for later processing. In this study 10 Epochs could be obtained in about 20 sec, thus reducing the time required for obtaining data. The digitizing rate is a limiting feature - our data are valid up to a frequency of about 5 kHz.

In this study one A/D input was the voltage from a 1/2 in. B&K microphone near a TDH-39 earphone placed close to the pinna, and the other was from a second 1/2 in. microphone with a probe tube inserted into the canal. The stimulus was a broadband noise, pre-emphasized with additional low-pass noise to help flatten the input spectrum.

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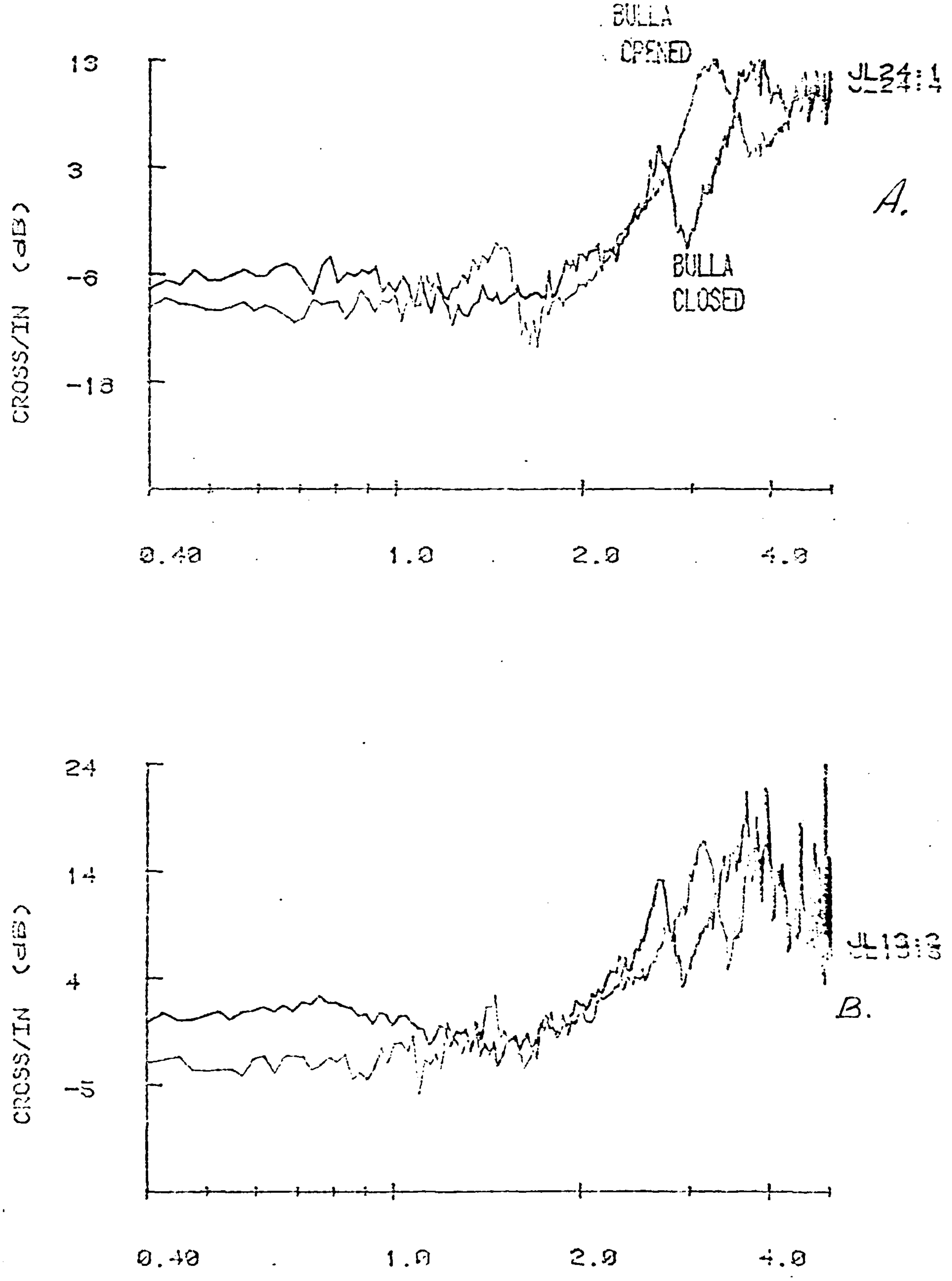
Fig 1

CHINCHILLA



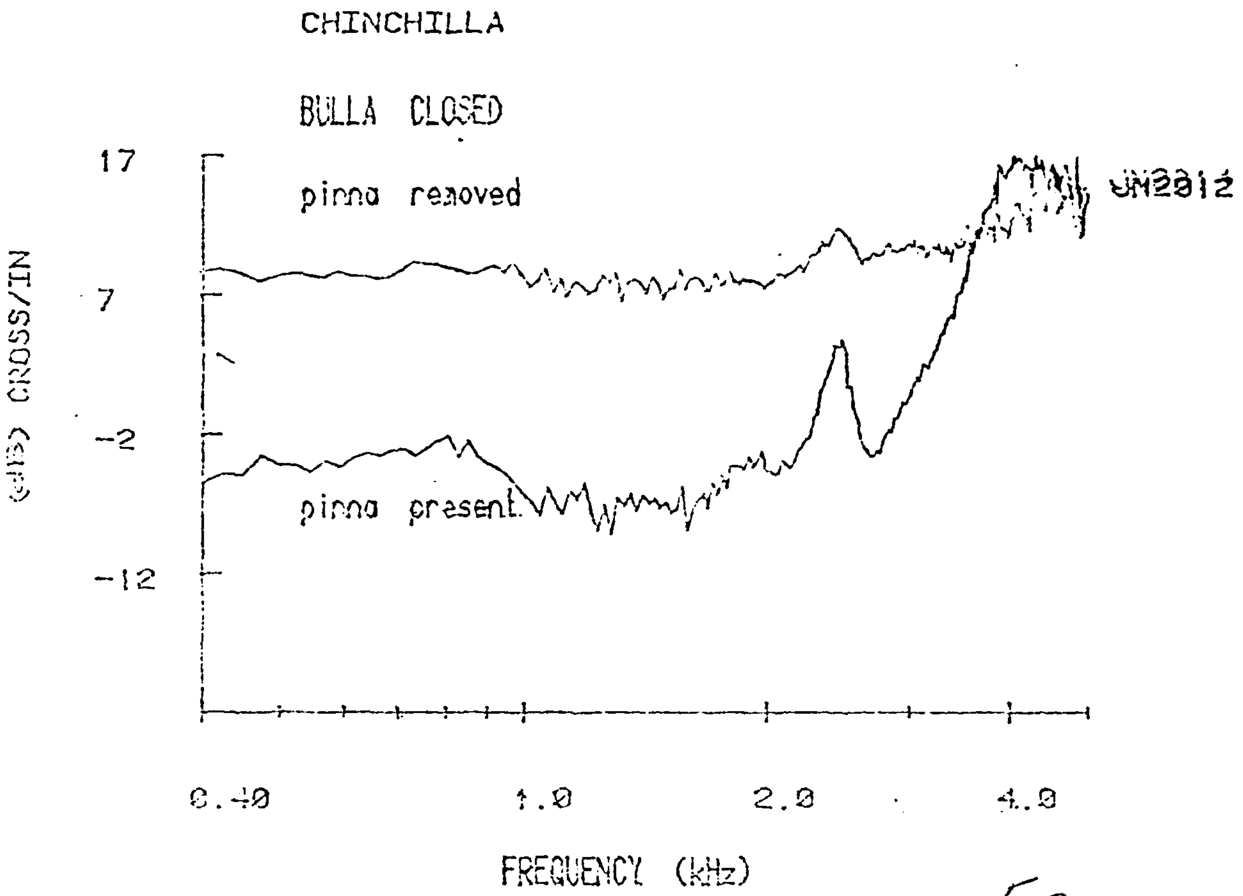

CHINCHILLA
BULLA CLOSED
pinna removed
pinna present
UN2012
(dB) CROSS/IN
17
7
-2
-12
0.40
1.0
2.0
4.0
FREQUENCY (kHz)

FIG 2

Fig 3

For Closed Bulla, the experimental conditions can result in static pressure increase in the bullar cavity. This static pressure condition is detectable in the probe tube measurements in the external auditory canal. However, changes in the probe tube tip position produce large variations in the measurements, particularly in the 2 to 4 kHz frequency region.

CHINCHILLA

FIG. 3

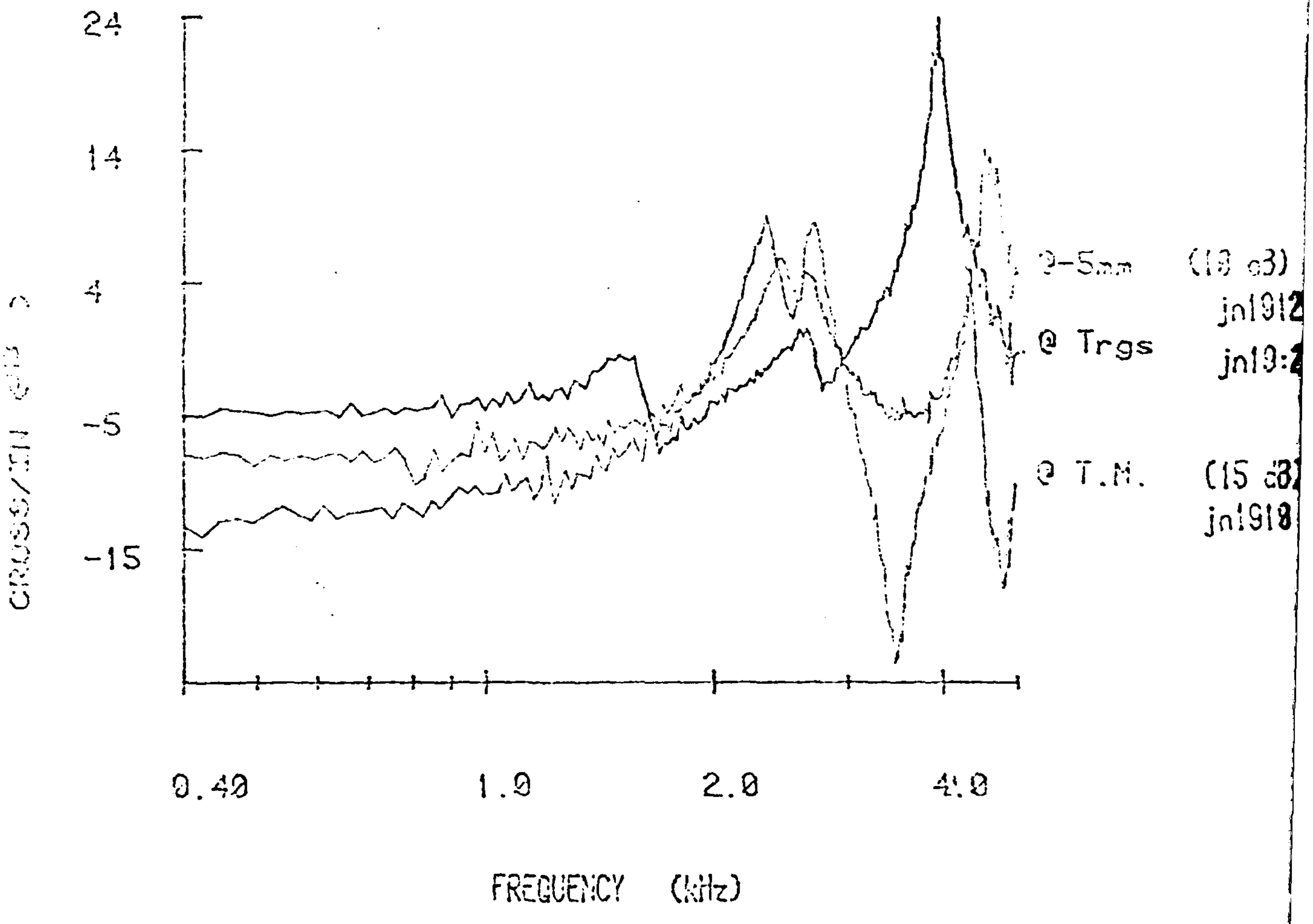
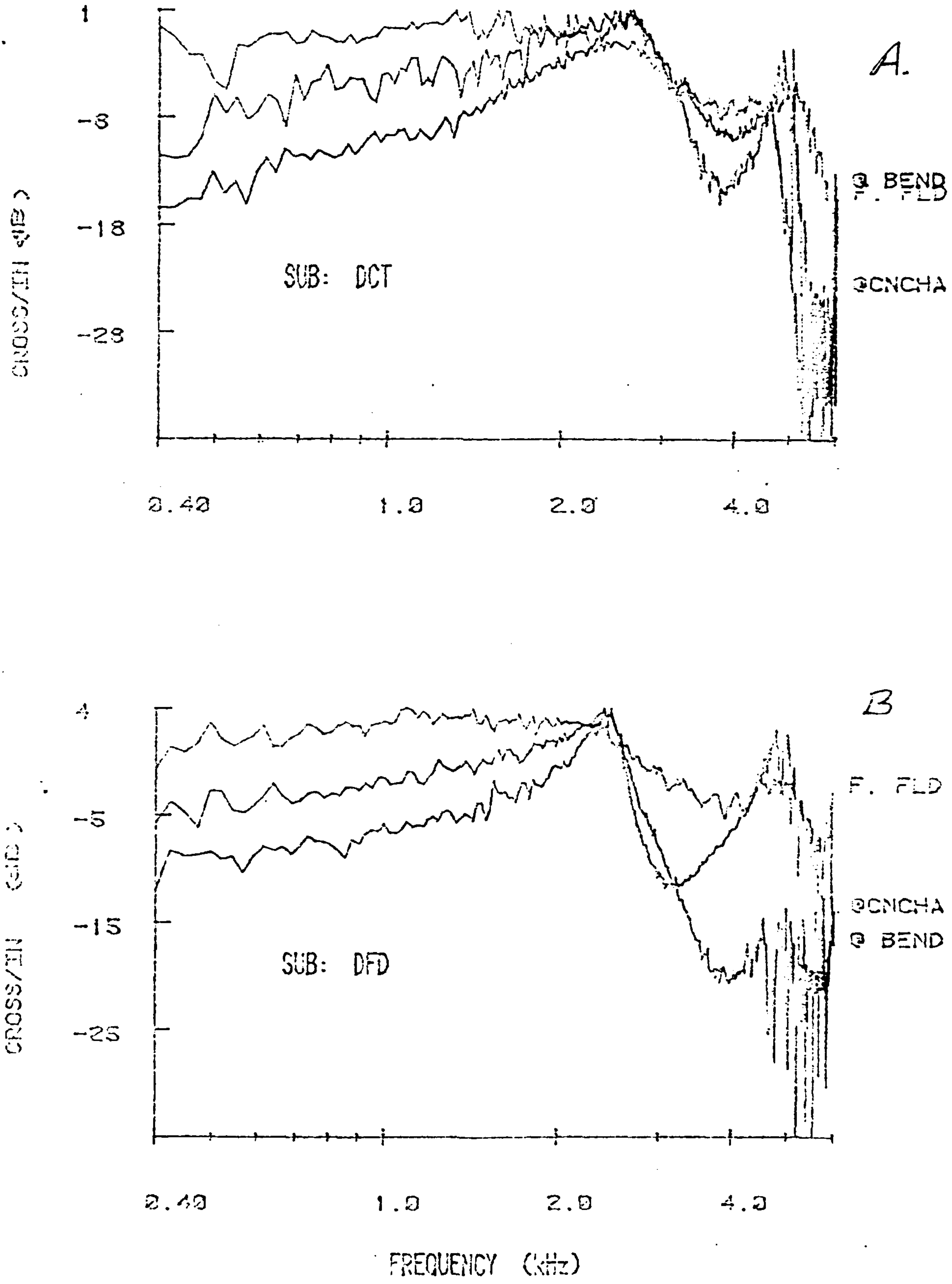


FIG 4

In the human ear the resonance-antiresonances are not so sharply peaked. XFRs between the probe tube and external microphones for three different subjects are shown for comparable probe tip locations. JPW's auditory canal was the least curved and the largest; DFD's canal was the most curved. The subject rested his chin on a firm pillow with head tilted so that the probe could be located within the microscope field of view.

For each subject the XFR was also measured without the head present (F. FLD.). The F.FLD. XFR shows the effect of the pillow, microscope, etc., that were left in position. The XFRs for JPW show little effect of probe position, and follow the F.FLD. curve. The XFRs for DFD show strong effects due to probe-tip position.

HUMAN *FIG 4*


A.
1
-8
-18
-28
CROSS/EN (dB)
SUB: DCT
@ BEND
F. FLD
@CNCHA
0.40
1.0
2.0
4.0
B
4
-5
-15
-25
CROSS/EN (dB)
SUB: DFD
F. FLD
@CNCHA
@ BEND
0.40
1.0
2.0
4.0
FREQUENCY (kHz)

C.

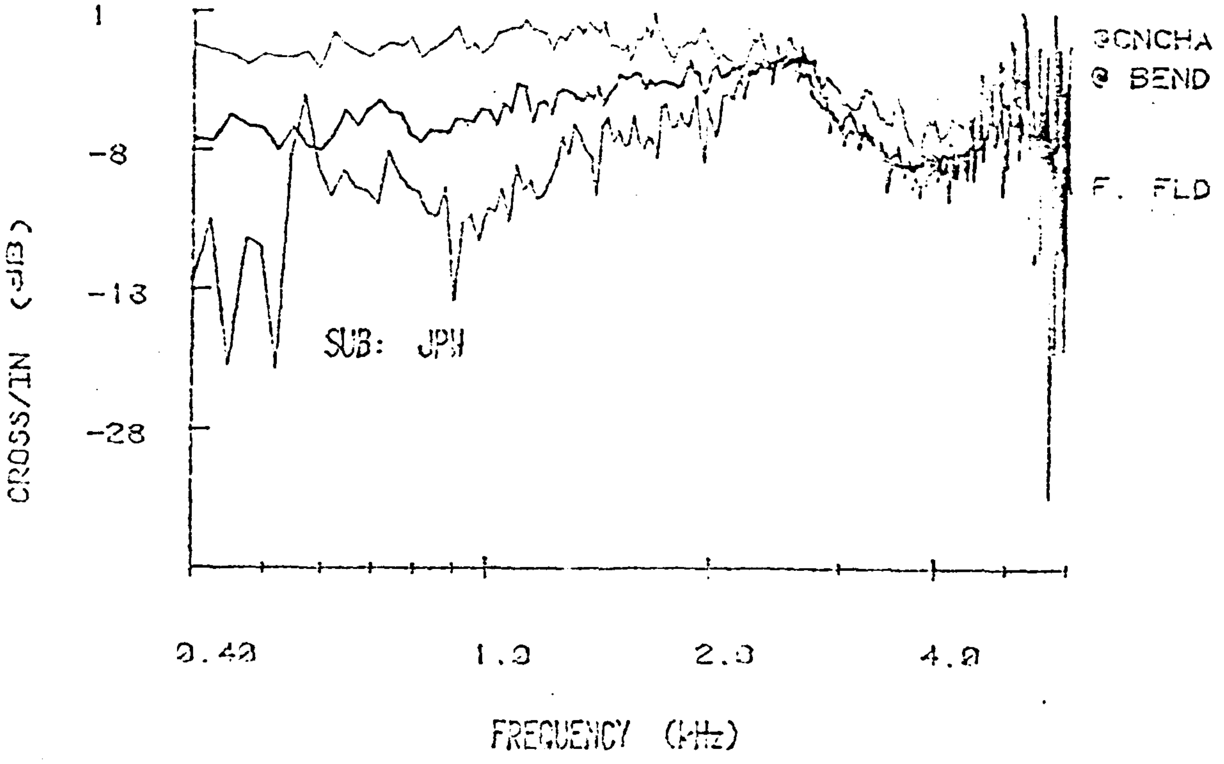

1
-8
-13
-28
CROSS/IN (dB)
SUB: JPH
CONCHA
@ BEND
F. FLD
0.40
1.0
2.0
4.0
FREQUENCY (kHz)

Fig 5

XFRs between the external microphone and the probe placed at four positions were determined for one subject. At tragus two slight resonances are seen. The lower peak occurs at about 2.5 kHz, the second between 3.5 and 4 kHz. The lower peak remains constant as the probe position changes, and the higher peak becomes anti-resonant as a still higher peak develops above 4 kHz with increasing depth of the probe into the canal.

HUMAN

FIG 5

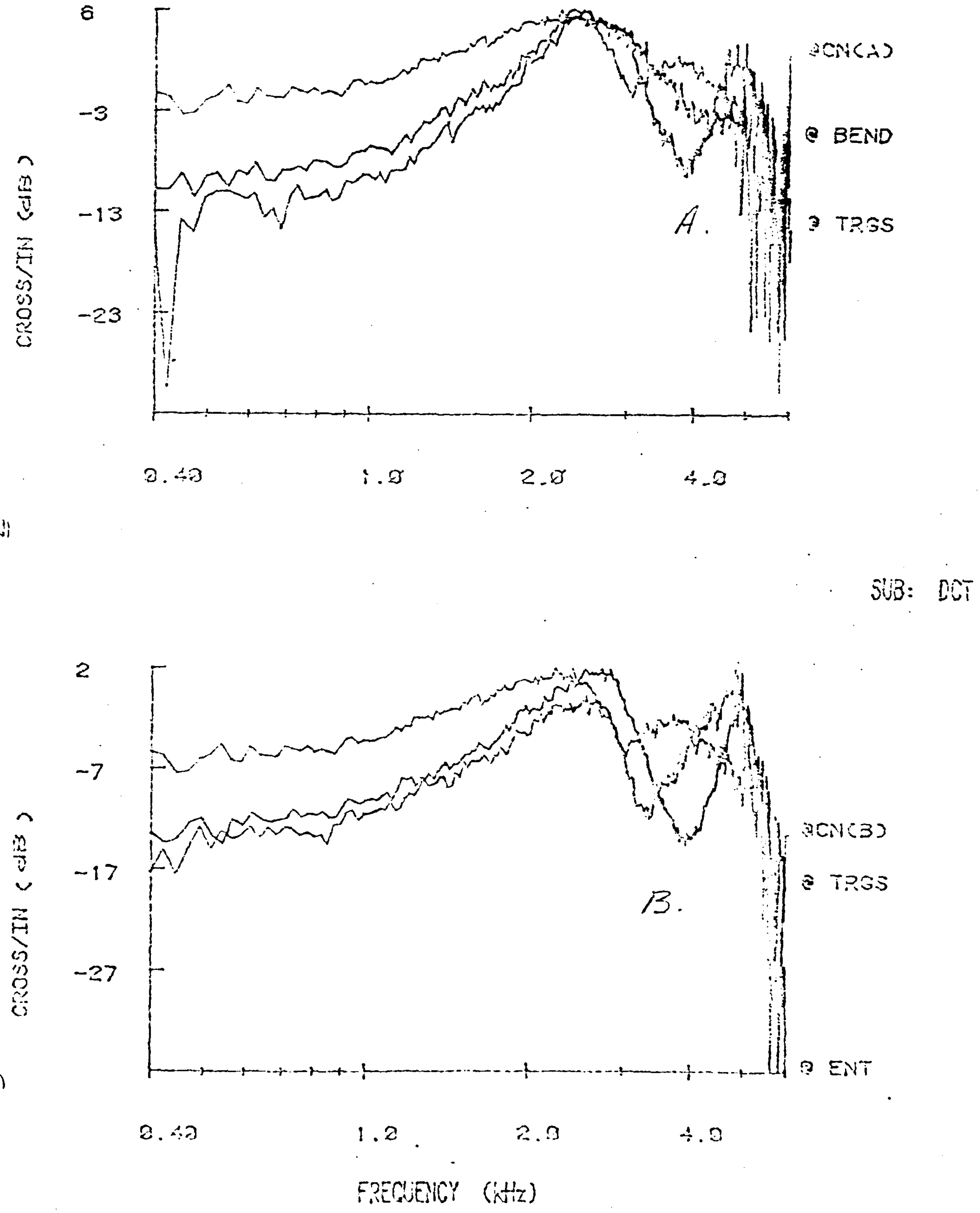
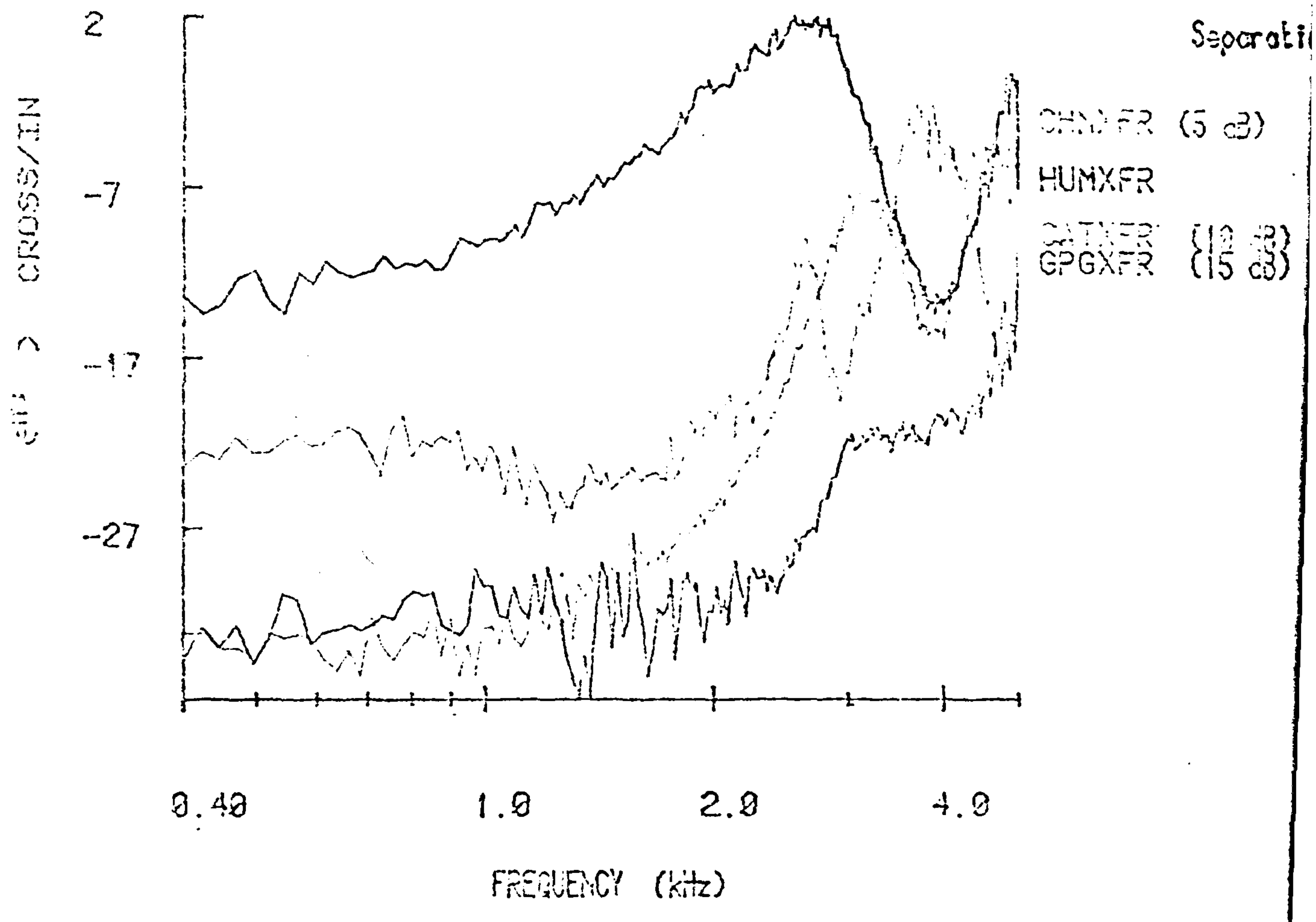

6
-3
-13
-23
CROSS/IN (dB)
@CN(A)
@ BEND
@ TRGS
A.
0.40
1.0
2.0
4.0
SUB: DCT
2
-7
-17
-27
CROSS/IN (dB)
@CN(B)
@ TRGS
@ ENT
B.
0.40
1.0
2.0
4.0
FREQUENCY (kHz)

FIG 6

XFRs between the external microphone and probe were measured for the human, chinchilla, cat and guinea pig. The probe location was as near to the tympanum as possible for each specie. In the cat and guinea pig the probe was inserted through a small incision in order to place it near the tympanum. The XFRs shown below are offset for clarity. Our measurements show relatively large peak-to-peak variations across frequencies which can be attributed to the presence of the pinnae.

Fig 6


Separati
2
-7
-17
-27
dB > CROSS/IN
CHMXFR (5 dB)
HUMXFR
CATXFR (10 dB)
GPGXFR (15 dB)
0.40
1.0
2.0
4.0
FREQUENCY (kHz)

MM2

CM SPECTRUM IN THE CHINCHILLA

D. C. TEAS, R.E. HILL, D.F. DOLAN, J. P. WALTON
UNIVERSITY OF FLORIDA GAINESVILLE, FLORIDA
AND
J. H. PATTERSON, C. H. BURDICK
U. S. ARMY AEROMEDICAL RESEARCH LABORATORY, FT. RUCKER, AL.

We have used the method described in the previous paper to study the spectrum of the cochlear microphonic (CM) in response to stimulation by high intensity, low-frequency noise. Our observations are limited to low-pass bands of noise with cut-off's at 100 and 200 or 250 Hz. since still lower frequencies could not be delivered at sufficiently strong intensities. The stimuli were delivered with two Altec 15 in. speakers housed in a single cabinet. As expected the output spectra show CM voltage in frequency regions outside the input passband.

250 Hz LOW-PASS NOISE

FIG 1

As the intensity of the noise delivered to the speakers increases the spectrum of the output (CM) increases relatively more just above the roll-off of the input power spectrum and also about 1 octave above the cut-off frequency of the low-pass noise. The input spectrum is about 40-50 dB down from the peak within the passband. Since the input spectrum is in the baseline noise above the cut-off frequency, the uncorrelated noise term for spectral regions outside the passband is relatively large and the XFRs are noisy in these regions. At 118 dB (measured at the external microphone) the input spectrum also shows a peak above the roll-off of the passband.

FIG 1A

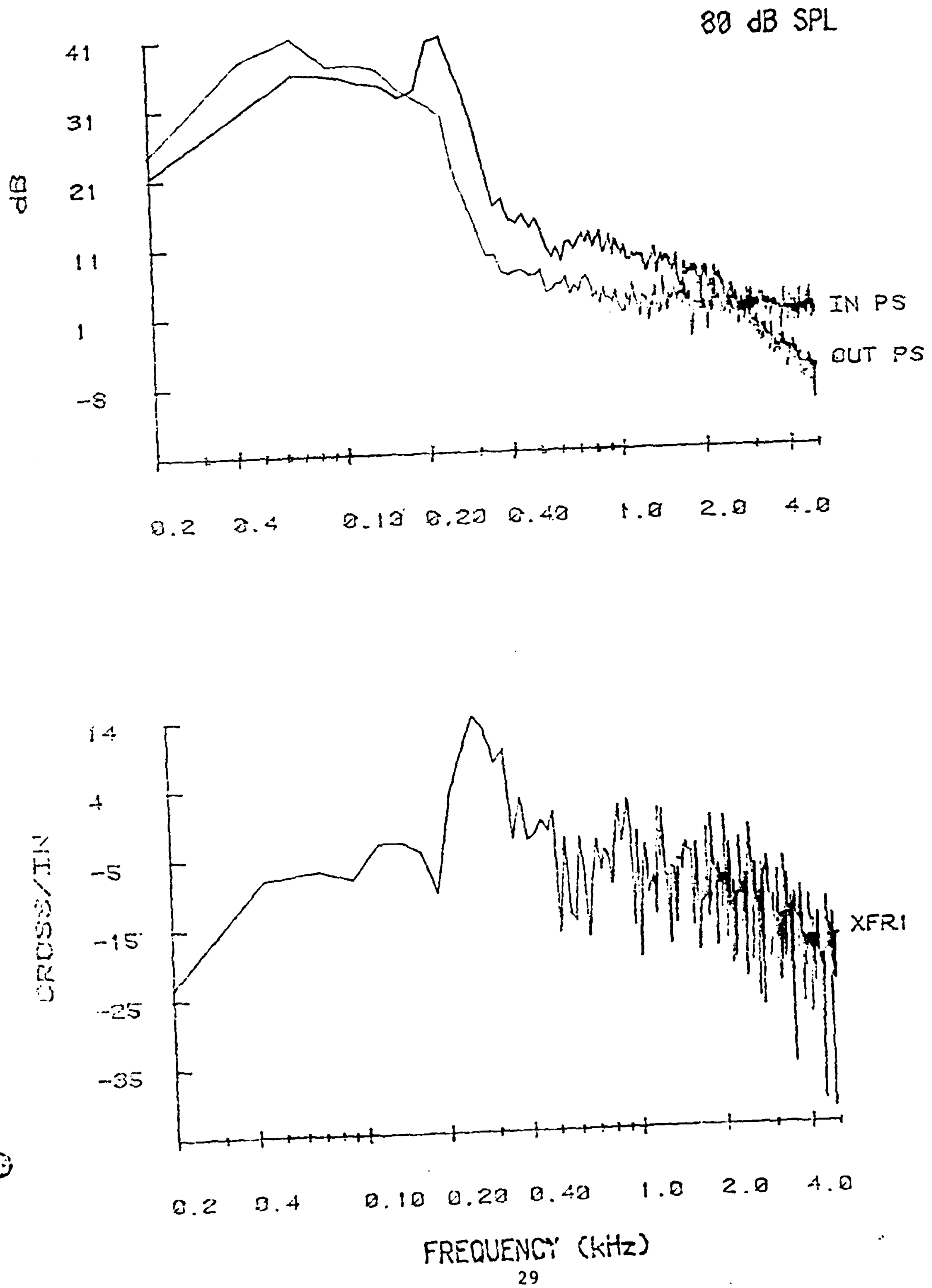

80 dB SPL
dB
41
31
21
11
1
-9
IN PS
OUT PS
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
CROSS/IN
14
4
-5
-15
-25
-35
XFR1
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
FREQUENCY (kHz)

FIG 1B

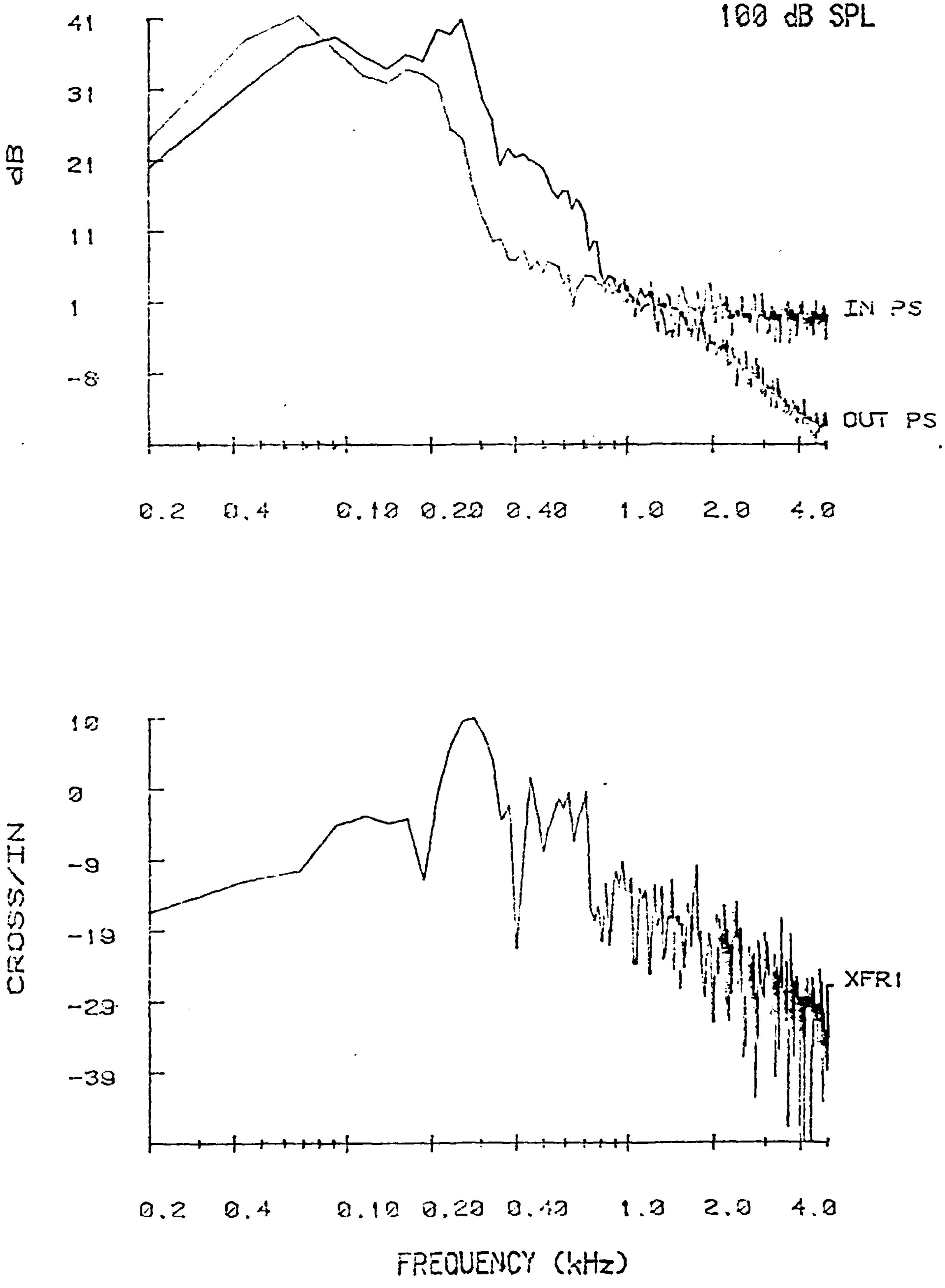

100 dB SPL
dB
41
31
21
11
1
-8
IN PS
OUT PS
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
CROSS/IN
10
0
-9
-19
-29
-39
XFR1
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
FREQUENCY (kHz)

FIG 1C

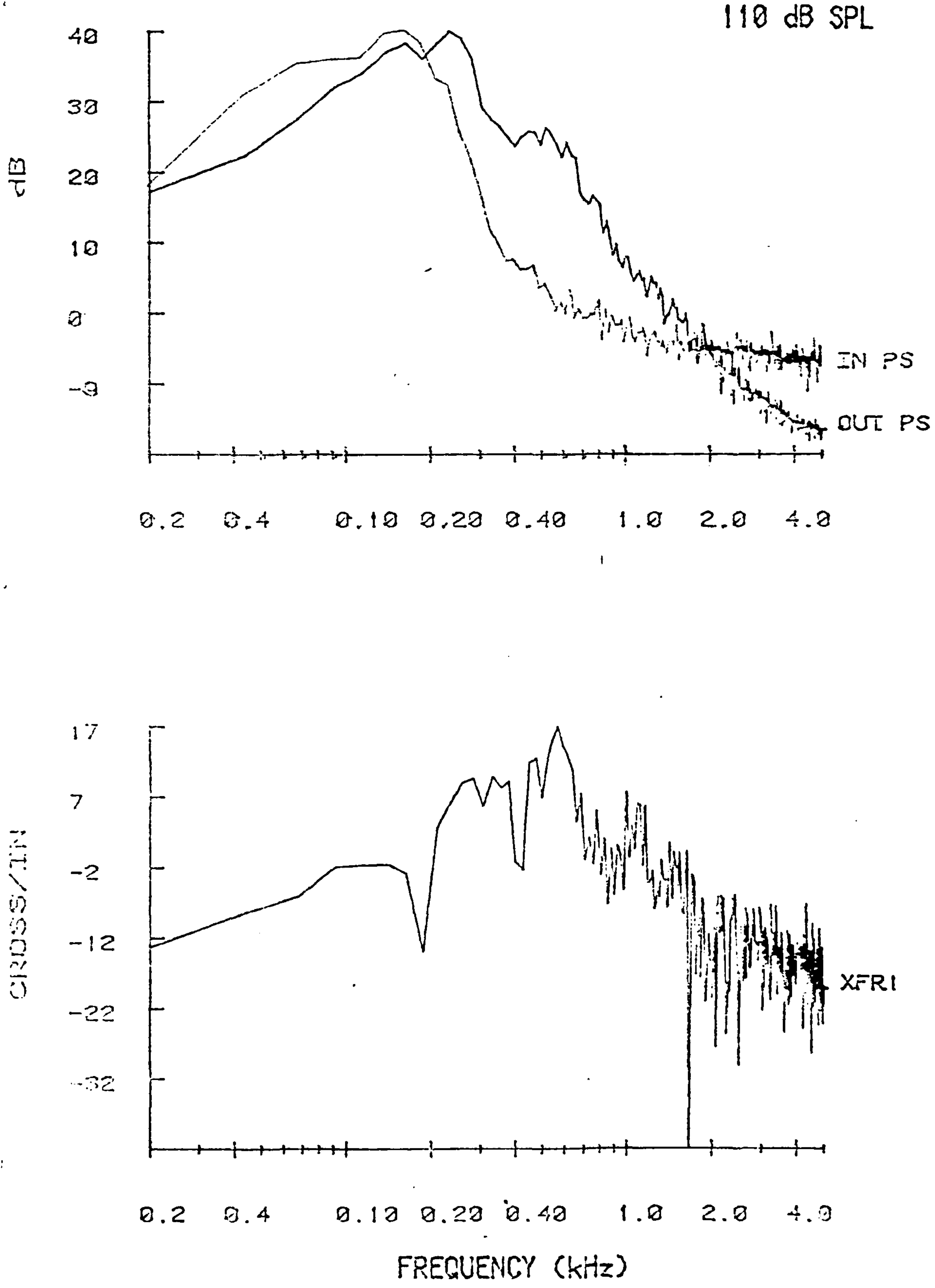

110 dB SPL
dB
40
30
20
10
0
-9
IN PS
OUT PS
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
CROSS/IN
17
7
-2
-12
-22
-32
XFR1
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
FREQUENCY (kHz)

FIG 1D

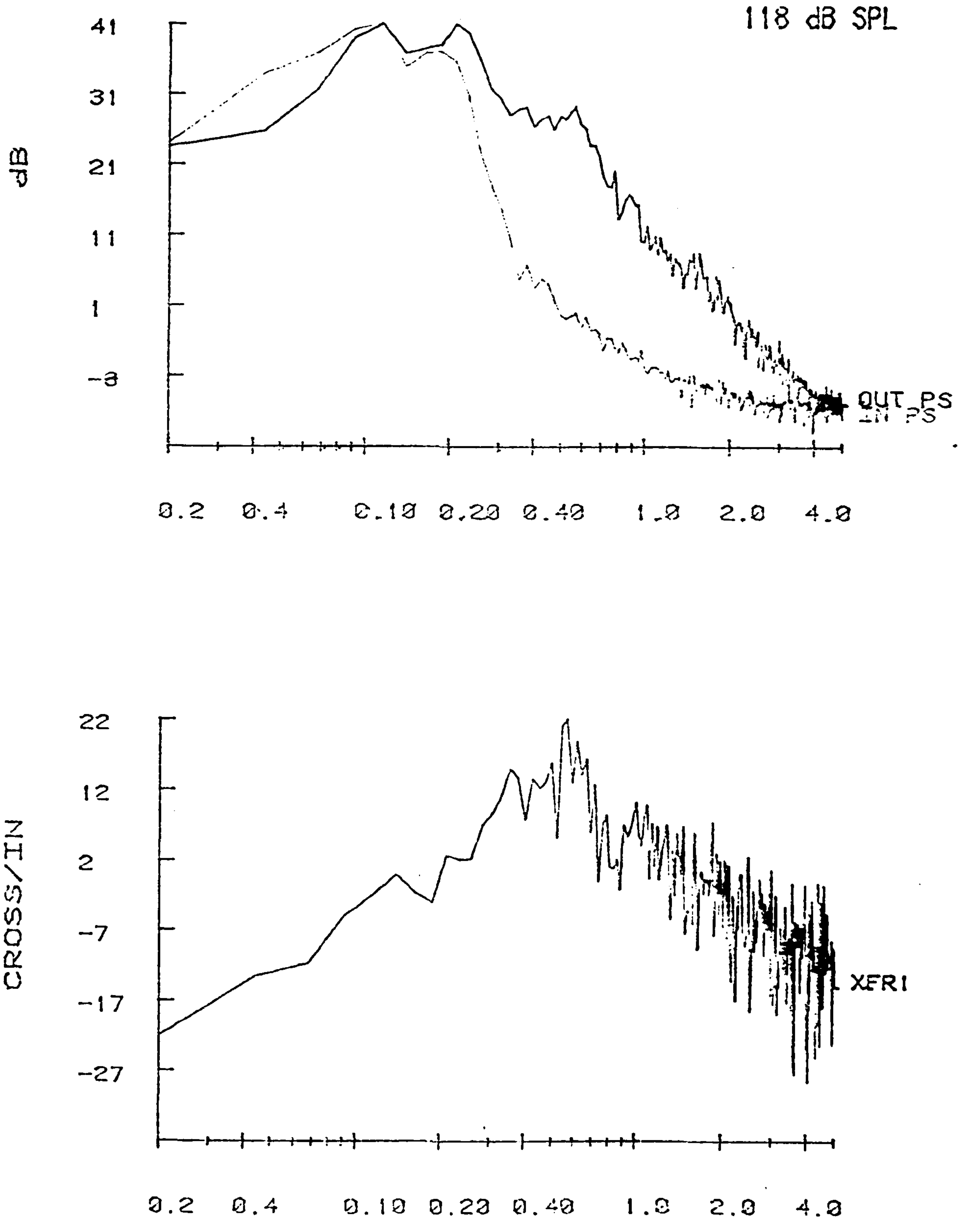

118 dB SPL
dB
41
31
21
11
1
-8
OUT PS
IN PS
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
CROSS/IN
22
12
2
-7
-17
-27
XFR1
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
FREQUENCY (kHz)

Fig 2

100 Hz LOW-PASS NOISE

Although the difference between the Input-Output spectra can be seen, the XFRs are less clear than for the 250 Hz low-pass noise. At 110 dB the peak of the XFR lies above the passband of the input, at about 200 Hz.

FIG 2A

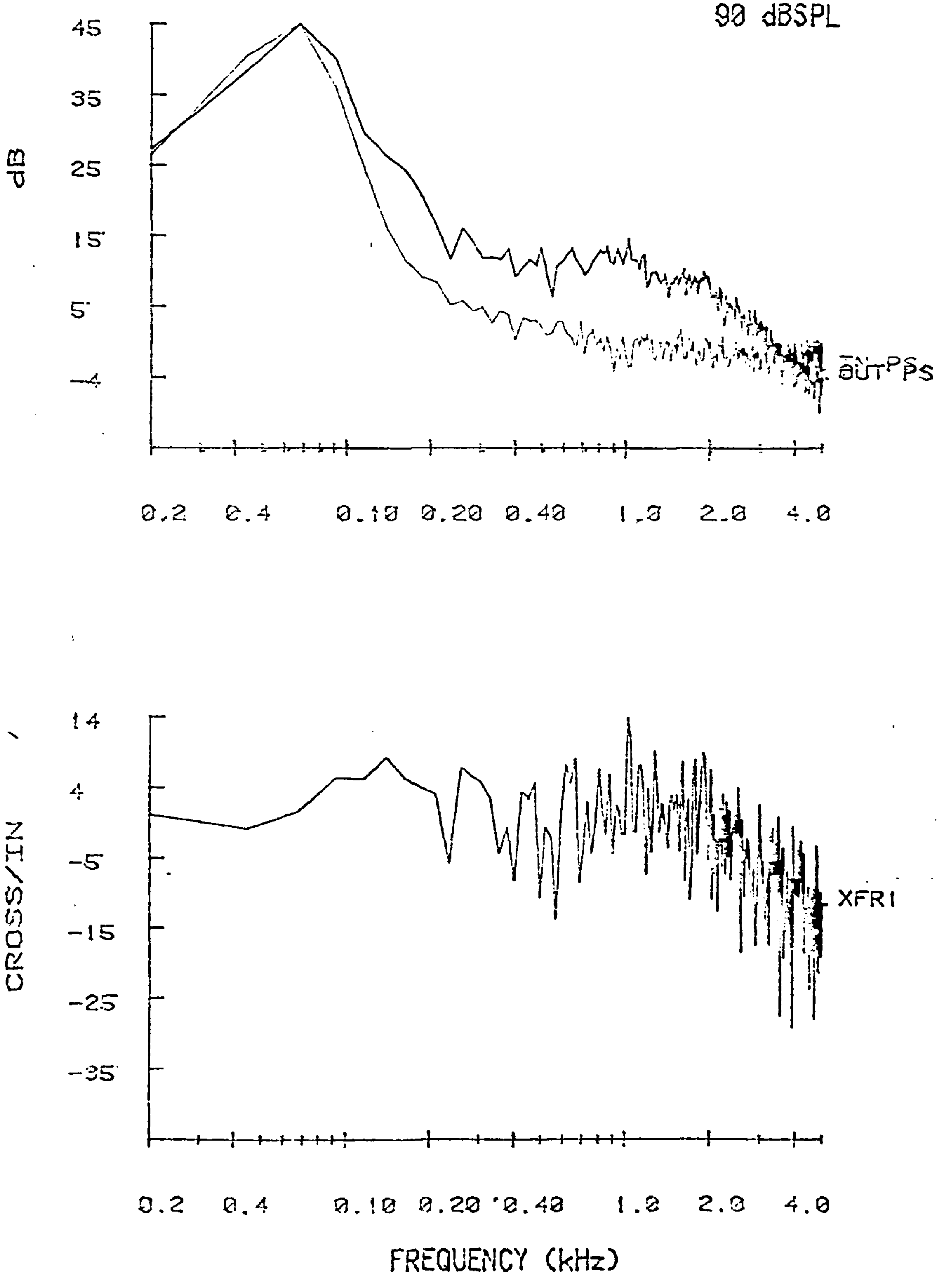

90 dBSPL
dB
45
35
25
15
5
-4
OUT PS
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
CROSS/IN
14
4
-5
-15
-25
-35
XFR1
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
FREQUENCY (kHz)

FIG 2B

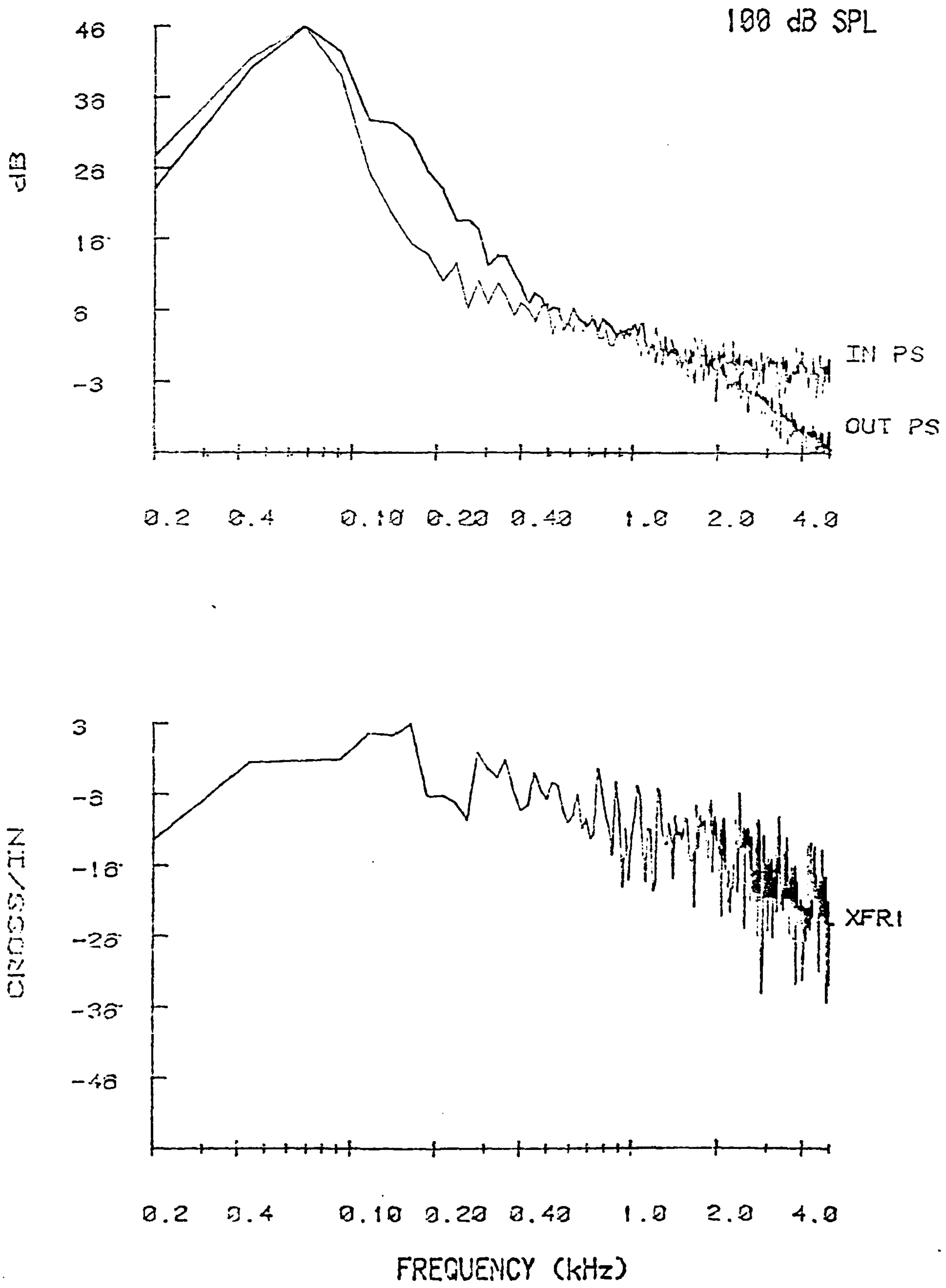

100 dB SPL
46
36
dB
26
16
6
-3
IN PS
OUT PS
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
3
-6
CROSS/IN
-16
-26
-36
-46
XFR1
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
FREQUENCY (kHz)

FIG 2C

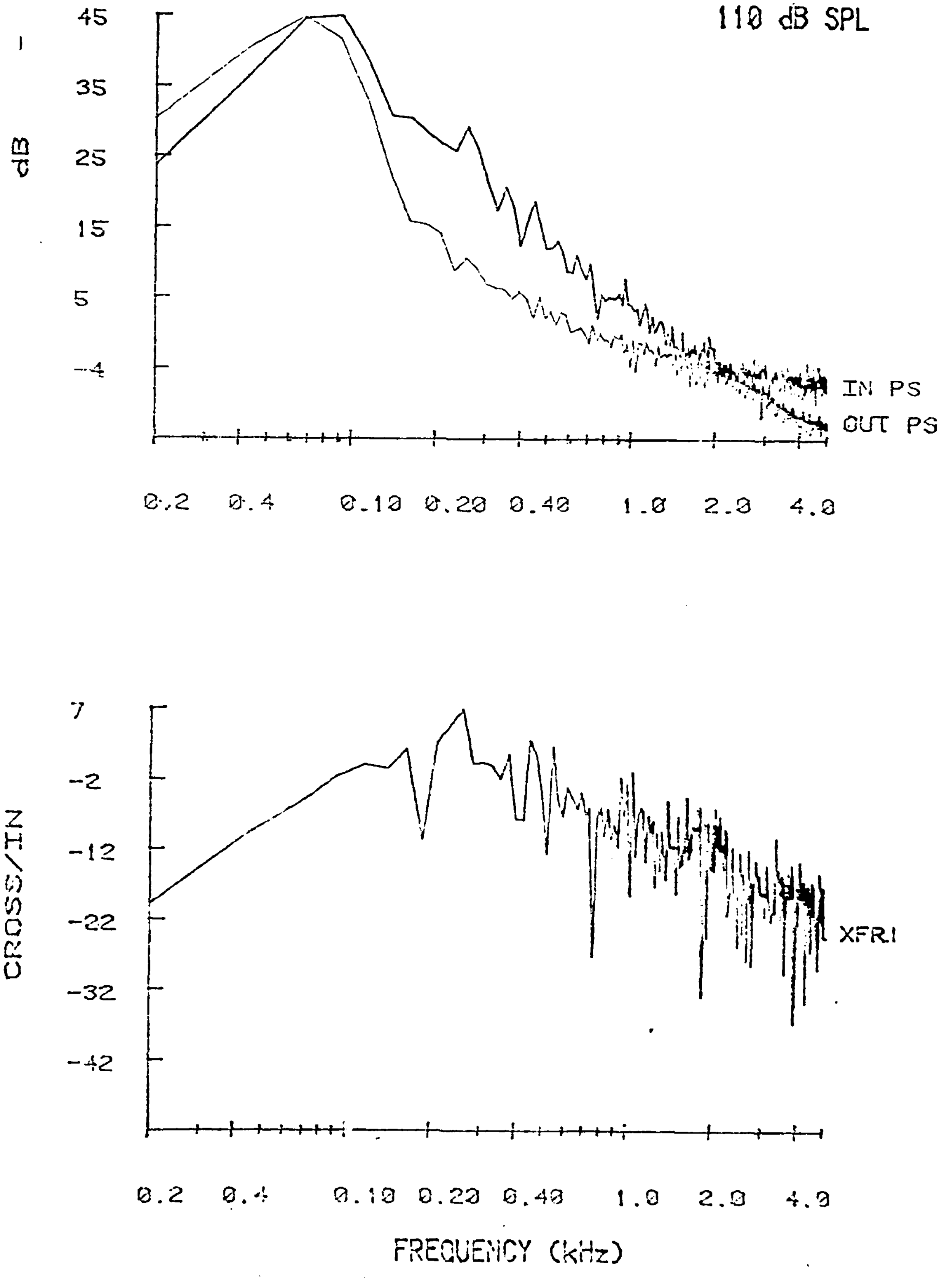

110 dB SPL
dB
45
35
25
15
5
-4
IN PS
OUT PS
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
CROSS/IN
7
-2
-12
-22
-32
-42
XFR1
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
FREQUENCY (kHz)

FIG 3

Output spectra for the 250 Hz low-pass noise presented at 3 intensities. The output in the frequency range above the input passband increases with intensity.

F/G 3

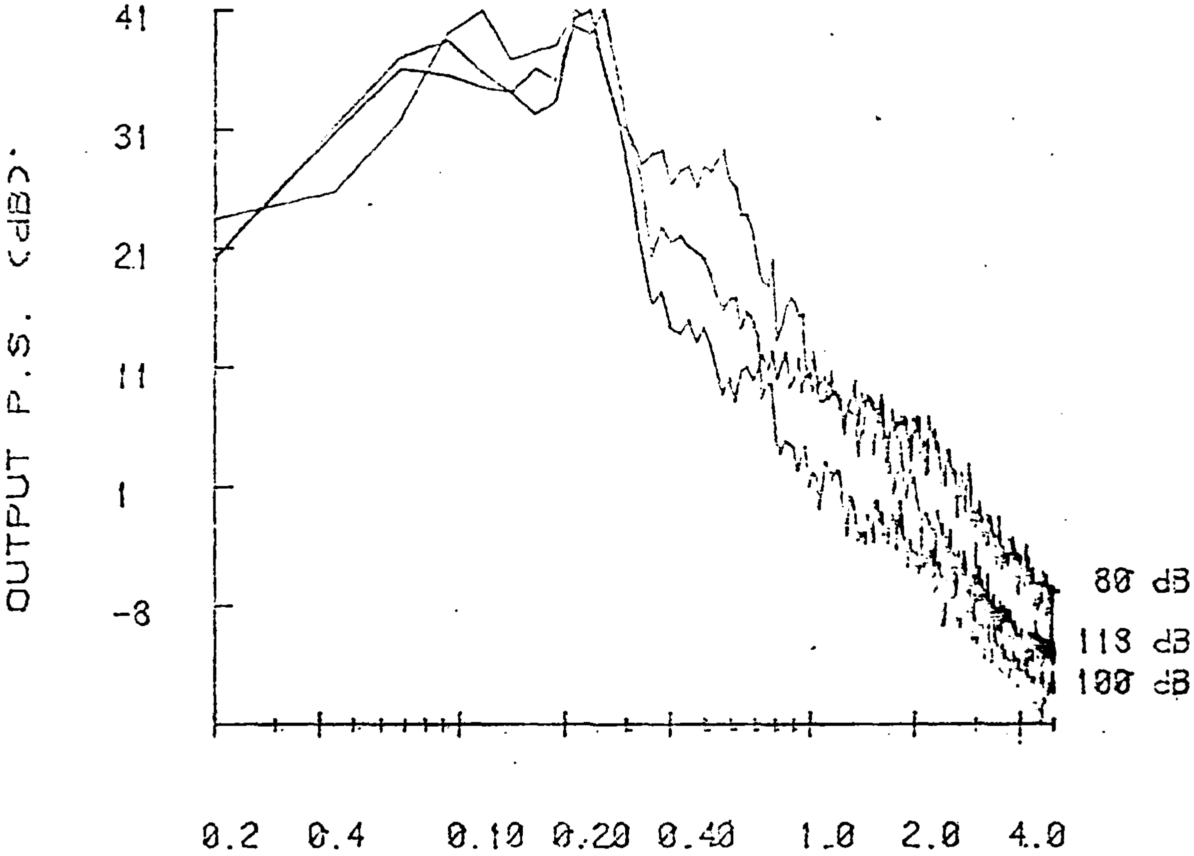

41
31
21
11
1
-8
OUTPUT P.S. (dB)
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
FREQUENCY (kHz)
80 dB
113 dB
100 dB

FIG. 4

The prominance of distortion peaks above the passband of the input varies among preparations. The output spectrum shown below has the most prominant peaks yet obtained. For the open bulla 3 clear peaks occur in the output spectrum (CM) above the cut-off frequency of the input passband. After sealing the bulla with dental cement the output spectrum was relatively smooth.

The output spectra and XFRs for the Open and Closed bulla conditions are contrasted in the last figure. The two XFRs show maxima at similar locations but the peaks are lost when the bulla is sealed.

FIG 4A

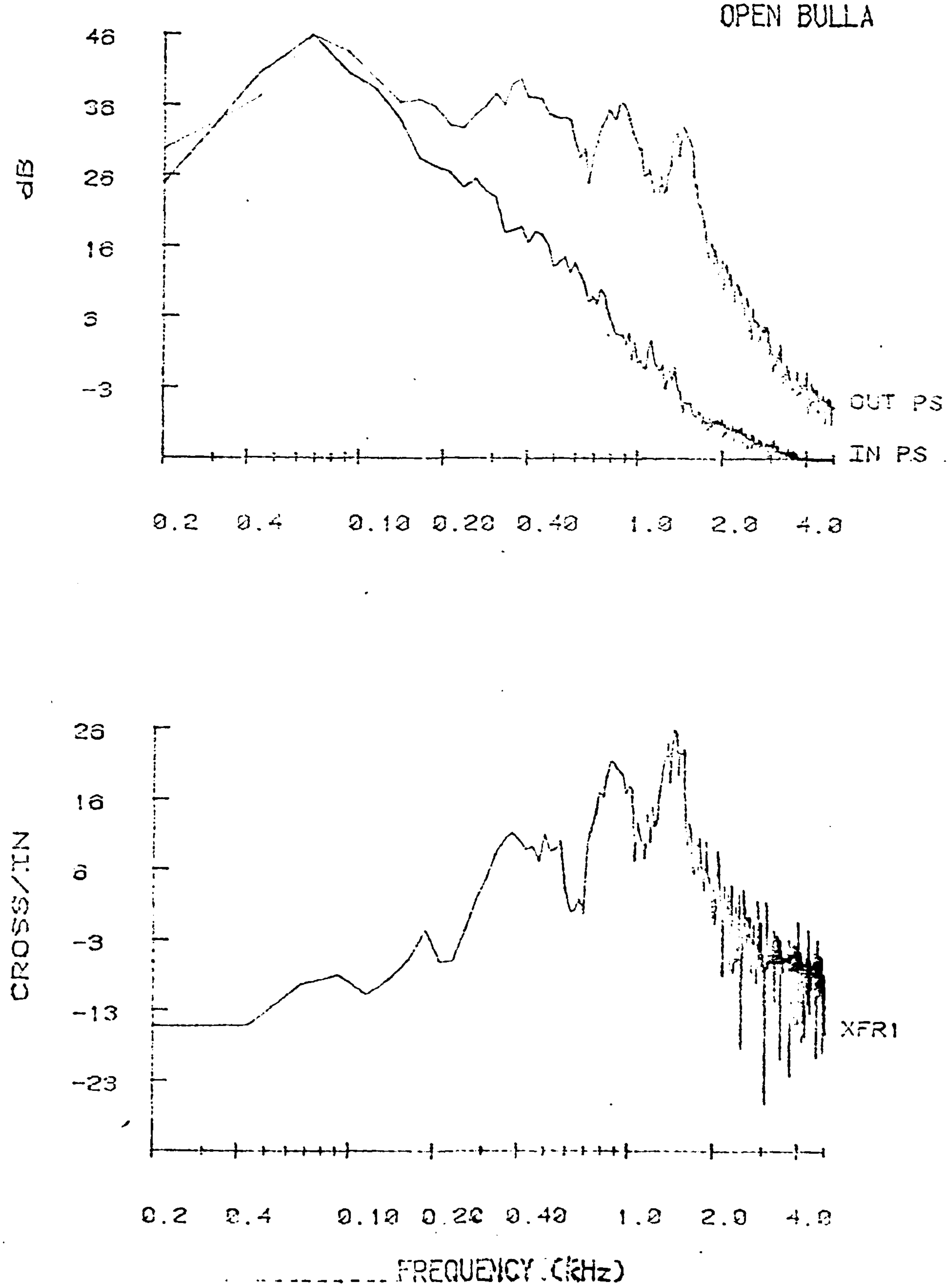

OPEN BULLA
46
36
26
16
6
-3
dB
OUT PS
IN PS
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
26
16
6
-3
-13
-23
CROSS/IN
XFR1
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
FREQUENCY (kHz)

Fig 4B

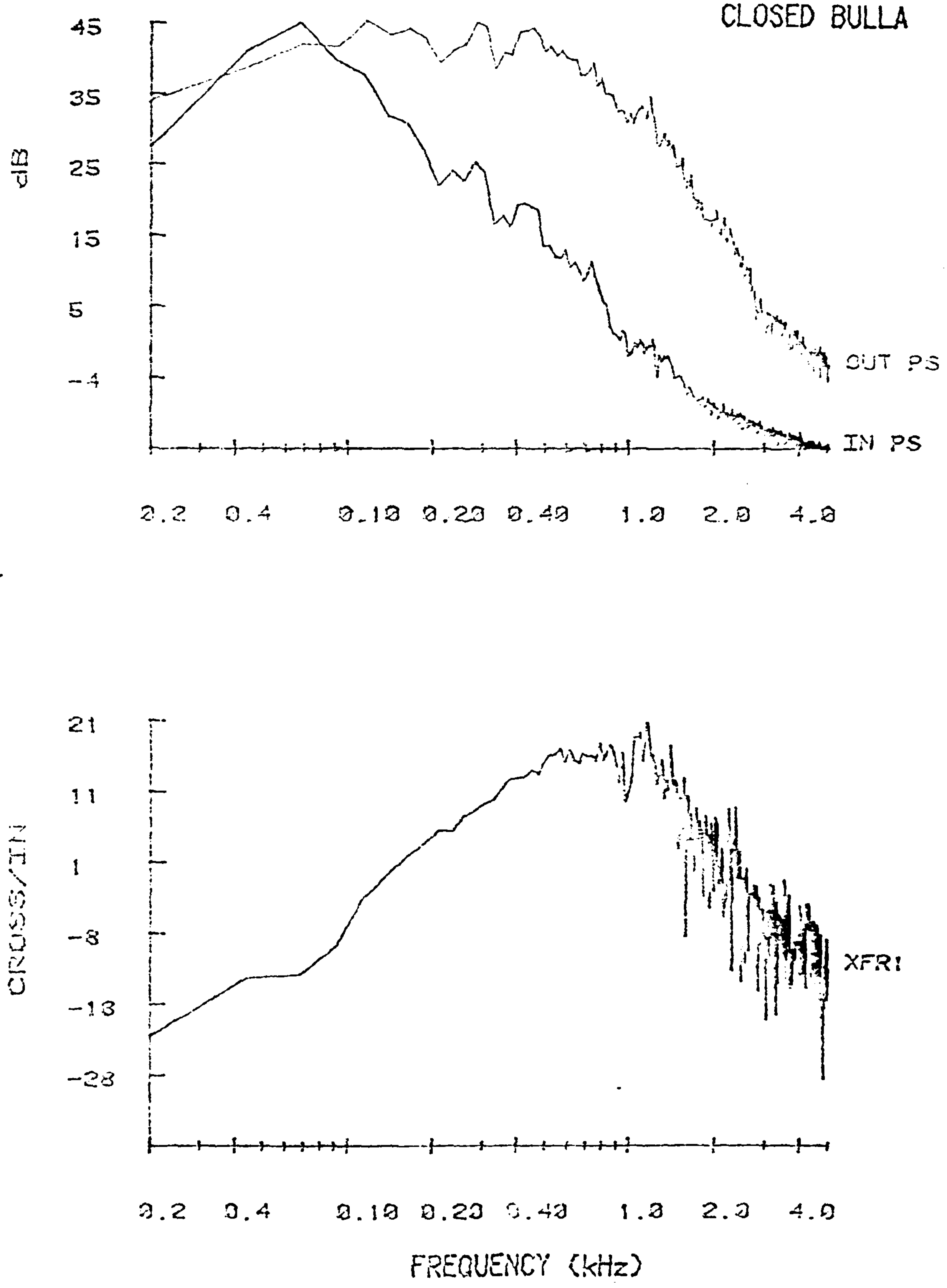
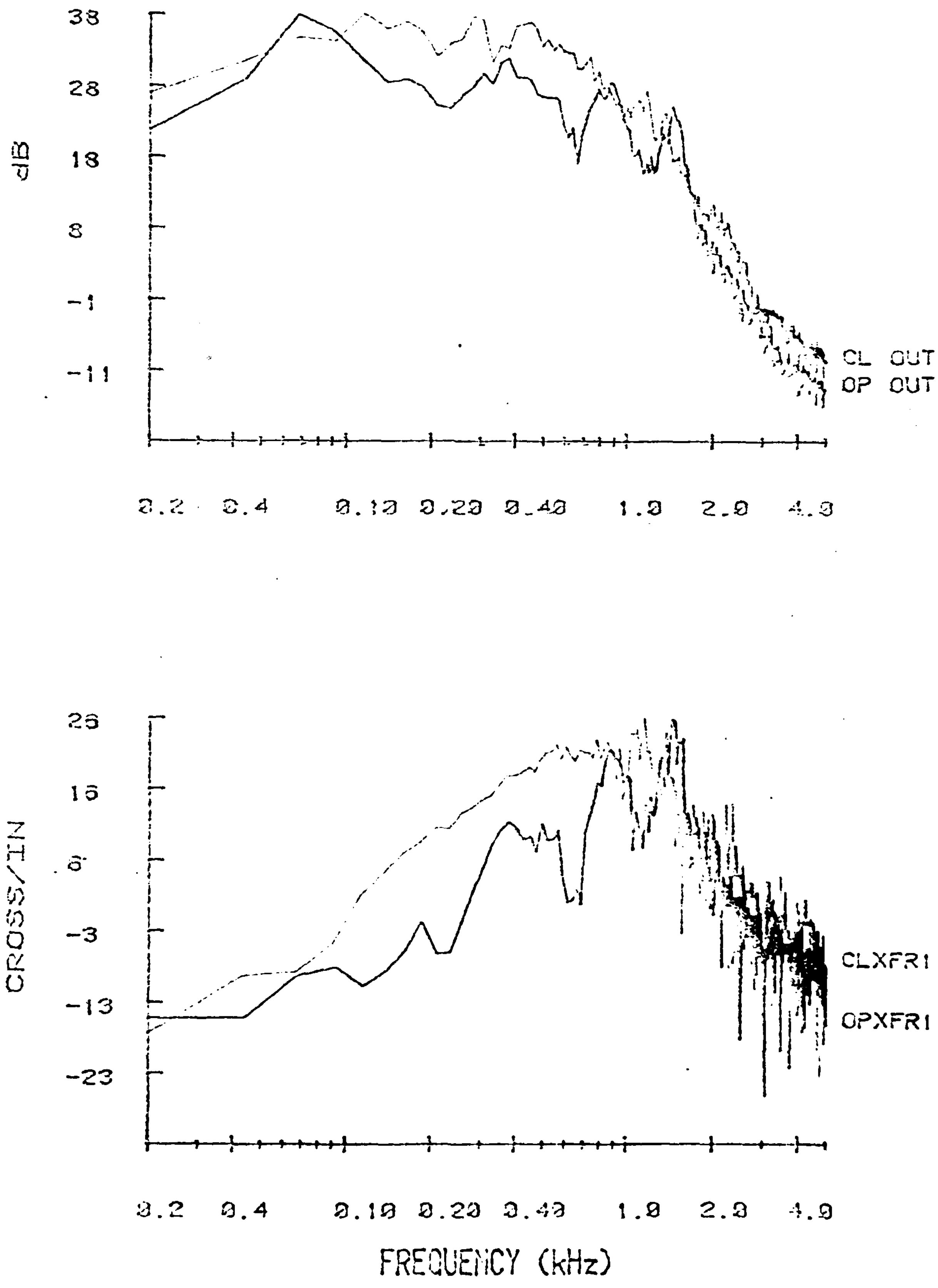

CLOSED BULLA
45
35
25
15
5
-4
dB
OUT PS
IN PS
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
21
11
1
-8
-13
-28
CROSS/IN
XFR1
0.2
0.4
0.10
0.20
0.40
1.0
2.0
4.0
FREQUENCY (kHz)

FIG 4C - Open & Closed Bottle Compared

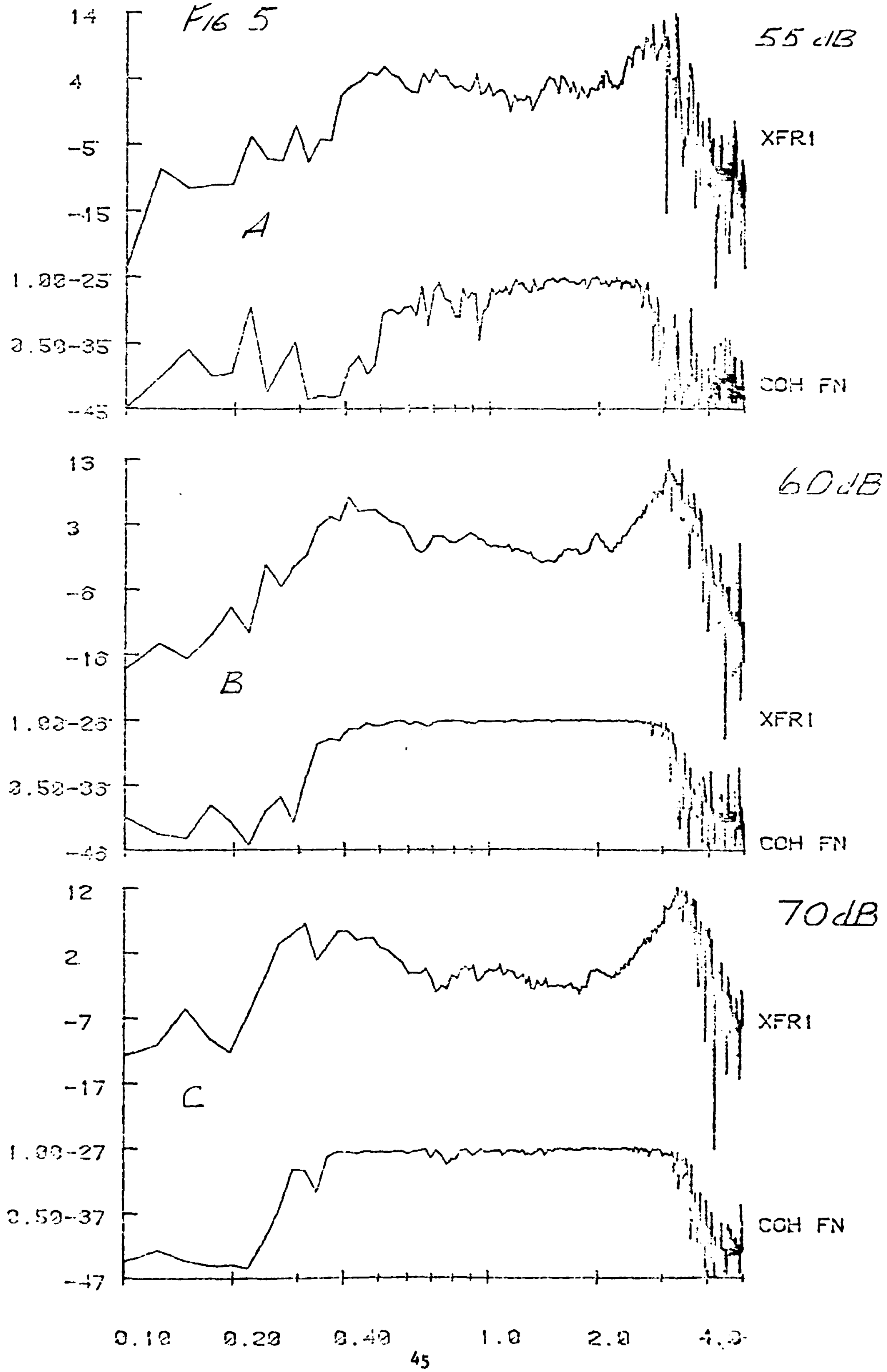


One of the difficulties in the use of this method to characterize the XFR for CM lies in the bandpass characteristic of a given recording location along the cochlear partition as stimulus intensity increases. For example, at Turn I the CM will be strong in the 3 to 5 kHz region for a low intensity broadband input. As the intensity of the broadband stimulus is increased, the bandpass for that location will increase to include lower frequencies. The CM voltage in the most sensitive frequency region (3 to 5 kHz) will first increase and then, at higher intensities, the Coherence function will decrease, indicating distortion. Our data show a fairly narrow range of intensities over which the COH remains at 1.0 in the most sensitive frequency region. Thus, with this method the XFR depends upon intensity and can give invalid results for a **broadband** stimulus if interpreted without recognizing the effect of cochlear location.

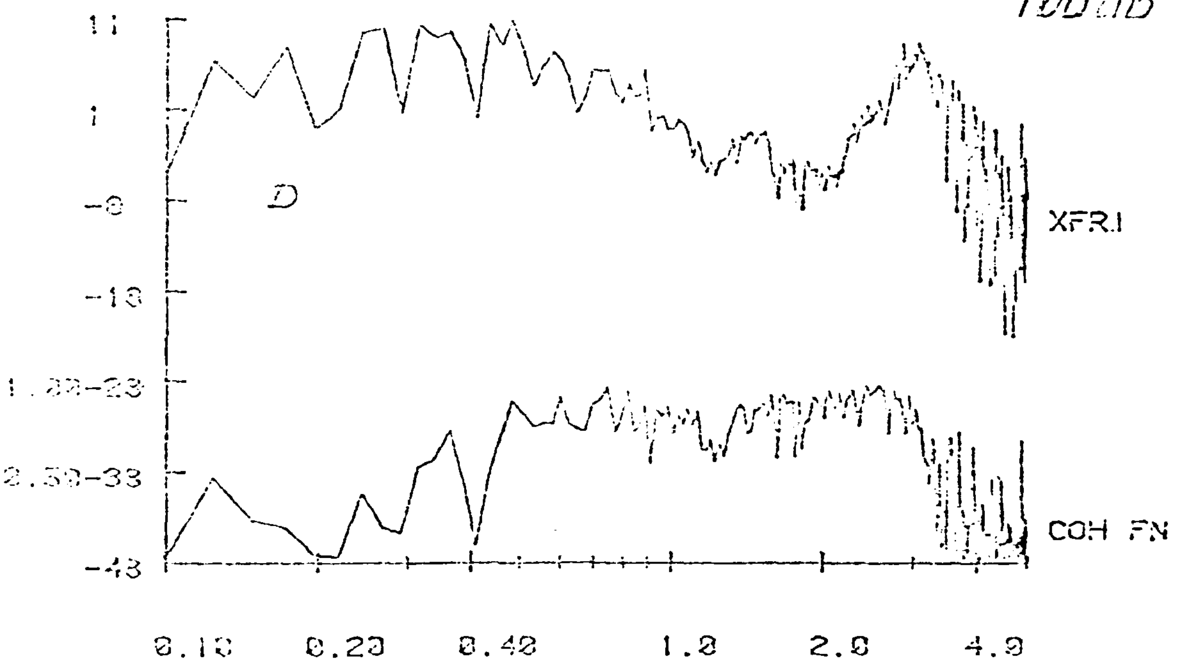
Fig. 5.

XFR and COH functions for Cochlear Microphonic (CM) response produced by 2 kHz low-pass noise band pre-emphasized with 0.7 kHz low-pass noise band. Free-field stimulation. External microphone measured SPL as indicated on each panel. The upper cut-off of the noise band was limited to 2 kHz in order to exclude the frequency band to which the Turn I electrodes were most sensitive. CM was recorded with differential electrodes in Turn I. At 55 dB (top panel) the COH is less than 1.0, indicating that XFR is suspect. At 60 dB, COH is very good. At 70 dB some distortion appears, but the COH is still good. At 100 dB the COH had deteriorated, due to distortion in the output waveform.

FIG 5


14
4
-5
-15
1.00-25
0.50-35
-45
55 dB
XFR1
COH FN
A
13
3
-6
-16
1.00-26
0.50-36
-46
60 dB
XFR1
COH FN
B
12
2
-7
-17
1.00-27
0.50-37
-47
70 dB
XFR1
COH FN
C
0.10
0.20
0.40
1.0
2.0
4.0

100dB



FILM