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A RECIPROCITY BASED TECHNIQUE FOR INVESTIGATING CONTRALATERALLY STIMULATED OTO-ACOUSTIC EMISSIONS

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ABSTRACT

The existence of the olivo-cochlear efferent neural system has led to theories of feedback mechanisms in the auditory system, possibly involving the contralateral ear, and exerting physiological control over cochlear micromechanics. Oto-acoustic emission phenomena can be used as a sensitive method of monitoring cochlear micromechanical properties in the search for such a feedback mechanism. One such phenomenon is stimulus frequency emission, well documented ipsilaterally but as yet undocumented contralaterally. A novel technique relying on the principle of acoustic reciprocity was designed for detecting the existence of any active physiological source at the frequency of a contralateral acoustic stimulus. The results of preliminary experiments carried out on normally hearing subjects with and without spontaneous oto-acoustic emissions (SOAE) do not indicate obvious correlation between the deviation from passive linearity and SOAE activity. The results do not support the hypothesis of contralateral emissions with levels significantly greater than the body conducted component of the stimuli levels used here. The experimental results, however, are limited by the sensitivity of the reversible transducers used.

INTRODUCTION

There is increasing evidence that efferent fibres entering the cochlea (i.e., nerves conducting signals towards the cochlea from the brainstem) form tonotopic connections between the cochleae (Fex, 1962; Robertson, 1985; Warr & Guinan, 1979). The afferent neural responses to stimulation of these fibres is also well documented (Klinke, 1969; Murata, 1978; Bonfils, 1986; Gifford, 1987). The crossed olivo-cochlear bundle, where the cochlear nerves meet, has provided a basis for theories of a contralateral feedback mechanism actively controlling cochlear micromechanics (Fex, 1965; Mountain, 1980; Siegel, 1982; Brown, 1983; Bonfils, 1986; Kim, 1986).

Because of their cochlear origin and susceptibility to changes in the micromechanical behaviour of the basilar membrane in the cochlea, oto-acoustic emissions can be used to monitor any efferent induced changes in the cochlea. For example, Mountain (1980) used distortion product emissions in guinea pigs

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to show a change in cochlear nonlinearity caused by electrical stimulation of the crossed olivo-cochlear bundle. He introduced two tones (f_1 and f_2), and measured the distortion product $2f_1 - f_2$.

Stimulus Frequency Emissions (SFE)

There is considerable evidence supporting the existence of sounds generated within a cochlea at the same frequency as a tone of long duration stimulating that cochlea (Kemp, 1979; Kemp & Chum, 1980; Wilson, 1980, Whitehead, 1986). The ipsilateral cochlea acts as an active source of sound at the same frequency as the stimulus, adding vectorially to the sound field present in the ear canal. Because the emitted sound amplitude is generally less than the stimulating tone amplitude while the frequencies of the signals are identical, special methods must be used to separate SFE from the stimulus, based on phase variation and nonlinear amplitude saturation of the emission. This detection problem, separating stimulus from emission, is similar to the problem of detecting a contralateral effect.

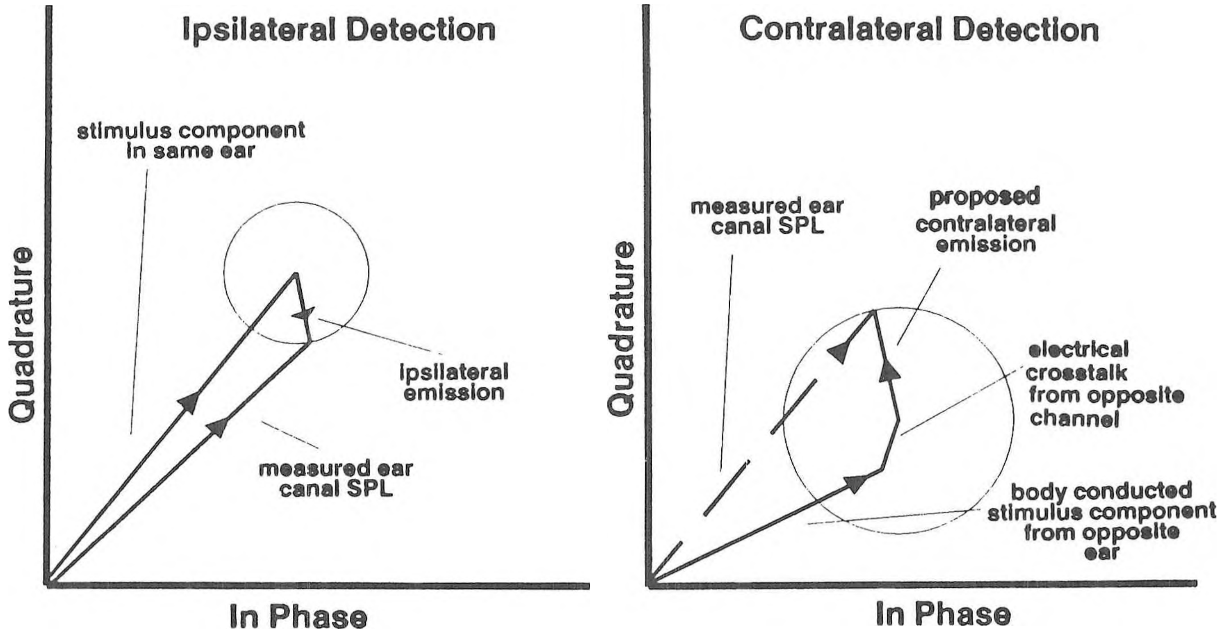


Figure 1. The problem in detecting Stimulus Frequency Emission (SFE) phenomena is separation of the stimulus component from the physiologically generated component in the measured signal.

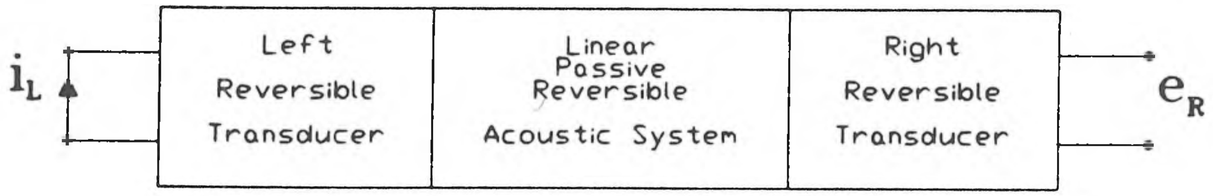
Direct measurement of any contralateral active emission is probably impossible because an unknown portion of the stimulus will be transmitted between the ears through body conduction (See Figure 1). In the frequency range of interest here (250 to 4,000 Hz) the attenuation of the body conducted signal is between 40 and 70 dB. At a given frequency the stimulus and the body conducted signals will, however, have a fixed phase and amplitude relationship. The activation threshold of efferent neurons to acoustic stimuli in animals has been shown to vary, with most units having thresholds above 40 dB SPL, and many with thresholds between 60-70 dB SPL (Fex, 1965). Thus, the most effective stimuli levels will generally be detected to some degree in the opposite ear. As an example, Buno (1978) indicated that contralateral acoustic stimuli levels above 30 dB SPL may have been more effective in influencing cat auditory nerve activity, but the resulting body conduction masked primary neuron responses in the opposite ear. A method is thus required for separating the acoustically transmitted contralateral sound from any possible emission activity generated by the contralateral ear at the stimulus frequency.

Acoustic Reciprocity

The reciprocity theorem states simply that at two terminals of any passive, linear, reversible system (as represented in Figure 2):

$$i_L/e_R = i_R/e_L \qquad (1)$$

where i_L is a current source on the left side, and e_R the open-circuit voltage on the right side. The right side of Equation (1) represents similar parameters when the current source and open circuit have been transposed.



$$\frac{i_L}{e_R} = \frac{i_R}{e_L}$$

Figure 2. Reciprocity principle demonstrated in a linear, passive, reversible system.

In the emission detection method presented here, **i** represents the driving current entering the terminals of a linear reversible transducer used as a sound source, and **e** is the open circuit voltage appearing at the transducer terminals when the same transducer is used as a microphone. Any acoustic system which contains non-reversible, active or nonlinear elements may not comply with (1). Because SFE are the result of active sources within the cochlea, they can be indicated by deviations from the identity (1). It is important to realize, however, that violation of (1) due to nonlinear or active elements, when $\mathbf{i}_L$ and $\mathbf{i}_R$ are the same, requires asymmetry with respect to the two system terminals. Reciprocity thus detects bilateral asymmetry in the active and nonlinear properties of the hearing system. This can be a benefit of the method as symmetrical sources of nonlinearity (such as similar middle ear reflexes) do not affect the results.

Application of the Reciprocity Method

We can use the reciprocity method to measure the acoustic transfer function from one electroacoustic transducer in one ear to a similar transducer in the other. By comparing measurements made both ways, we can show any difference from a passive, linear, reversible system.

The reciprocity based method presented here detects deviation from the passive, linear case, when one ear is stimulated as compared to the case when the other ear is stimulated. Thus, the result from two ears is a single curve showing deviation from passive linearity as a function of frequency. If there was no asymmetrical nonlinearity (a unilateral acoustic stapedius reflex is an example of this type), the curve would indicate the difference in the source activity between the ears. A curve that was not significantly different than zero would be evidence that no contralateral SFE can be detected at those stimuli levels. The curve is ideal for correlating with differences in other frequency varying aural properties, for example, spontaneous oto-acoustic emissions (SOAE). These SOAE are sinusoidal vibrations produced within the cochlea, and transmitted outward towards the ear drum. They generate measurable tones in the ear canal, with frequencies of 1 - 3 kHz and levels of -20 to +20 dB SPL.

Subjects with SOAE in one ear were used to validate asymmetries detected with the reciprocity technique. The relationship between SOAE and ipsilateral SFE was studied by Zwicker & Schloth (1984), who indicated that the two types of emissions are similar in nature and may be closely related. An SFE maximum was found at the SOAE frequency, and spacing in the SFE maxima closely resembles the spacing of SOAE in subjects with multiple emissions. Thus, it was assumed here that contralateral emission activity, if present, may have a local maximum at frequencies close to the SOAE in that ear.

If SFE are evoked in the contralateral ear as a result of the reciprocity test stimulus, they could be due to either body conducted sound, efferent neural activity, or a combination of both. This method will not differentiate between these factors; other methods must be used to investigate which factor is most important.

METHODS

1. Two identical insert probes were constructed, each containing a linear reversible acoustic transducer (Knowles subminiature magnetic speaker) and fitted with flexible rubber ear tip for sealing within the outer ear canal. A computer driven switching circuit allowed either the open circuit voltage (Microphone operation) or driving current (loudspeaker operation) from each probe to be monitored on a separate channel of the Bruel & Kjaer 2032 dual channel signal analyzer (Figure 3).

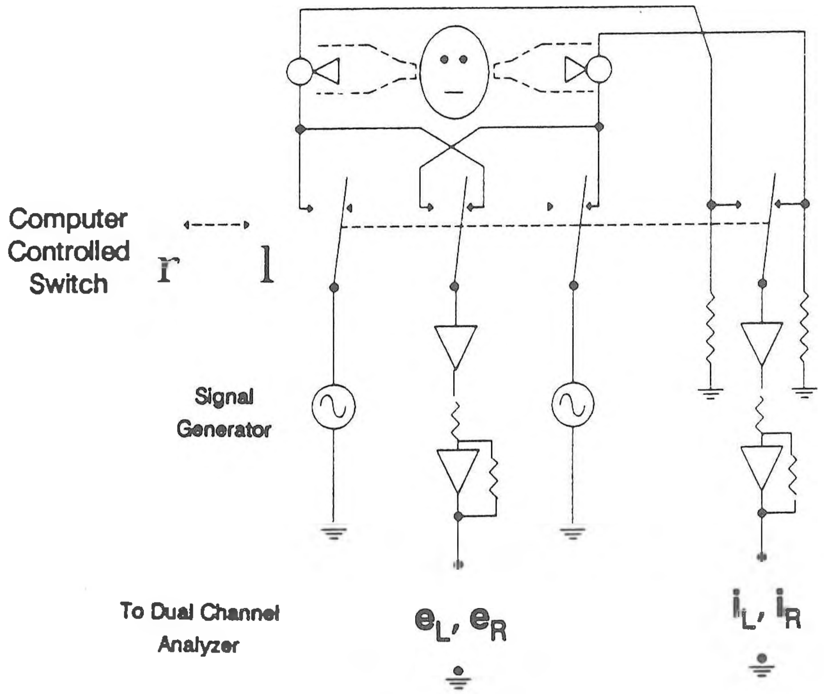


Figure 3. Schematic of reciprocity measurement apparatus.

2. The spontaneous emission activity in each ear was recorded by simultaneously performing spectral analysis on the signal from each probe when used as a microphone. The spectra were found using a Fast Fourier Transform technique. Spontaneous emissions are noted as narrow band frequency spikes >5 dB above the ear canal noise spectrum. A second probe with miniature electret microphones was also used, providing increased sensitivity to -20dB SPL (re 20 μPa)

3. The sound source probe had its driving voltage adjusted until the current input matched that determined in a previous calibration run. This probe's current (i_L) and the opposite probe's open circuit voltage (e_R) were then simultaneously recorded by computer with the ratio (i_L/e_R) calculated for several averages.

4. A rest period (10 seconds of silence) allowed the stimulated ear to recover from the effects of the tonal stimulus. This was intended to reduce any masking, adaptation, or suppression effects.
5. The circuit is then automatically reversed with a tone generated in the former microphone probe and picked up in the probe which was previously the source. The new ratio (i_R/e_L) is similarly calculated; in a passive linear system $(i_L/e_R)-(i_R/e_L) = 0$.
6. Steps 3,4 and 5 were repeated for all the desired stimulus frequencies.

Stimulus Amplitude and Frequency

The stimulus frequency range was chosen as 1000-2000 Hz, as SOAE occur most often within this range. The upper frequency limit was set at 2000 Hz as a large increase was noted in interaural attenuation beyond this range. The stimulus current driving the loudspeaker at each frequency was selected so as to give relatively uniform levels of body conducted sound in the contralateral ear, across the stimulus frequency range. The current i is thus a function of probe acoustic load impedance and inter-aural attenuation and varies with frequency. For this reason, the SPL in the stimulated ear was not held constant. At a specific frequency, however, the SPL in the stimulated ears will be nearly the same. Any difference in stimulated ear SPL is a result of asymmetry in aural acoustic load between the right and left ears, resulting from different ear canal geometry, for example. To account more accurately for amplitude nonlinearity the stimuli could be adjusted to give the same SPL in each ear. The first experiments were simplified by assuming such differences would be small.

The reciprocal nature of the system was verified with the probes coupled by an air filled tube. This test was repeated with the cavity filled with sufficient attenuation to simulate conditions between the ears. Deviation from passive linearity in this case is shown in Figure 4. Ideally, these data should be zero for all frequencies.

Electrical Noise and Artifacts

The background noise for each microphone measurement was measured at the time of spontaneous emission detection. This allows a measurement to be discarded if it falls "beneath the noise floor". This noise includes a component resulting from slight electrical cross-talk between the channels, present even after scrupulous electrical grounding and shielding. This component was recorded by monitoring the amplitude and phase of the signal present in the microphone probe during stimulation while that probe was removed from the ear canal. This small component was later subtracted vectorially from the total signal measured with the microphone probe in the ear.

The unavoidable random (thermal) noise generated within the probe microphones, and also within the head and auditory system, will affect the measurement. This effect on the results is again limited to the degree of asymmetry in those factors.

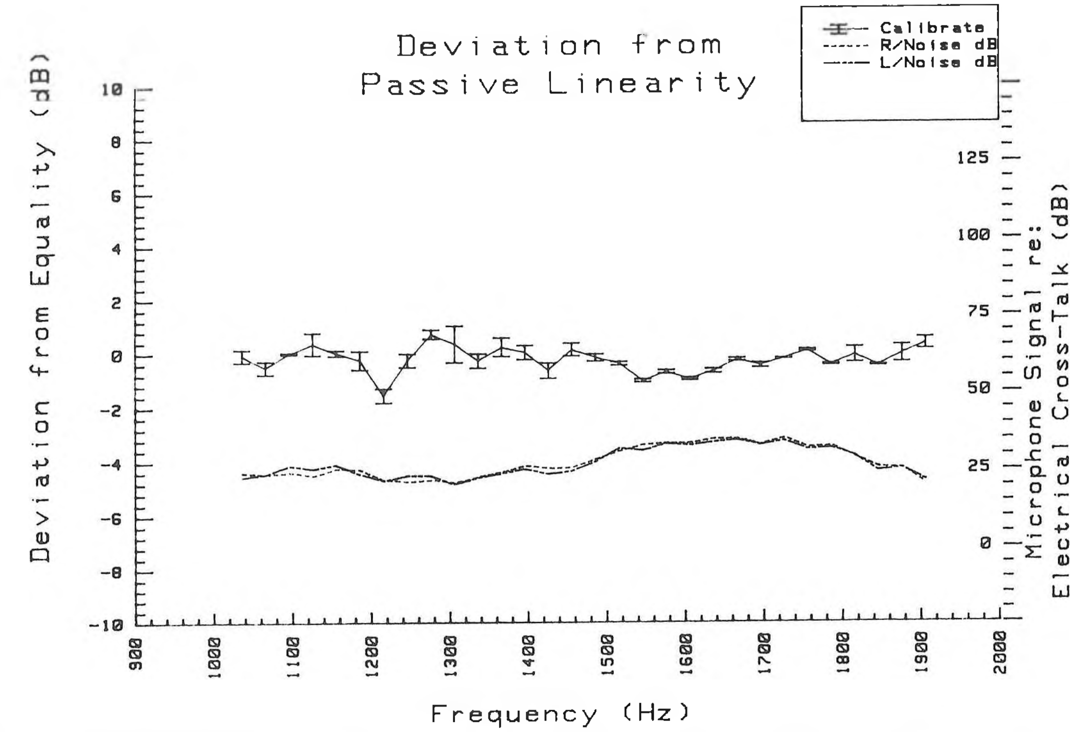


Figure 4. Deviation from ideal reciprocity in a passive linear acoustic system. Calibration measurement in a tube coupler containing attenuating foam. Upper curve indicates deviation and refers to left axis, lower curves indicate microphone probe signal relative to electrical noise and refer to the right axis.
Note: Calibration with sound source signals 25 dB lower than those used in human measurements.

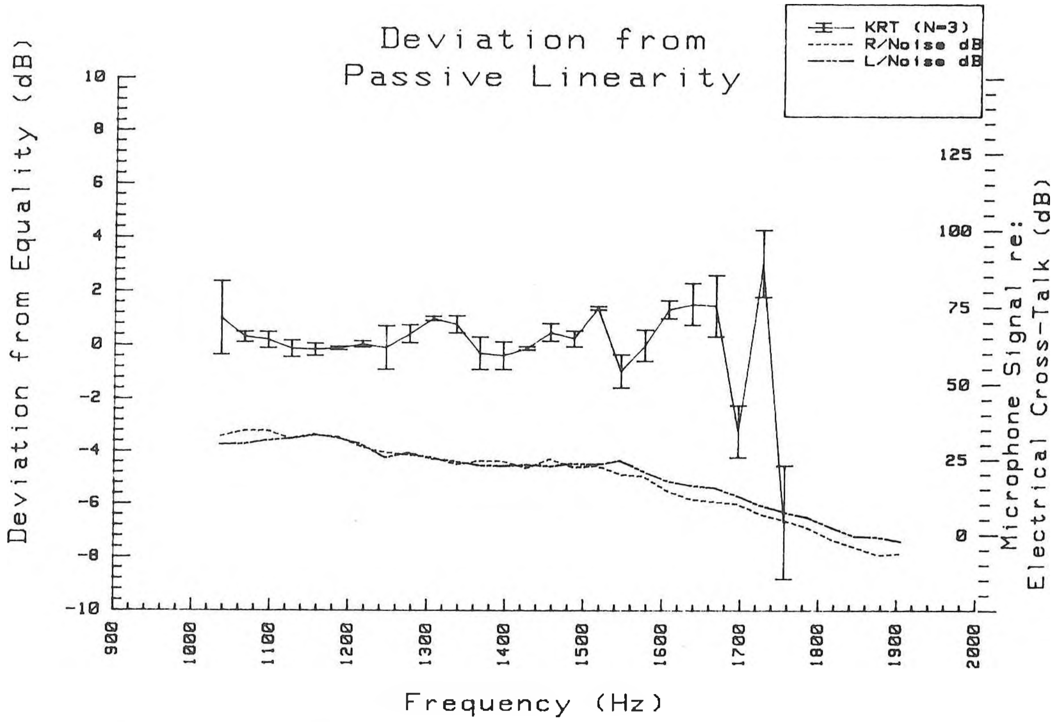


Figure 5. Deviation from passive linearity in one non-SOAE subject with three measurements performed at each frequency. Lower curves indicate microphone probe signal relative to electrical cross-talk noise and refer to right axis. Frequencies at which points on the lower curves are below 5 dB are excluded from the upper deviation curve.

RESULTS

The experiment was performed on 10 normally hearing subjects. Of these subjects, four had no history of SOAE, four had SOAE activity at the time of measurement, and two had a history of SOAE but no activity at the time of measurement. Results of a measurement on one non-SOAE subject are shown in Figure 5. Each data point is the average of three reciprocity measurements at that frequency. Compared with the calibration run (Figure 4), there is little significant deviation from passive linearity below 1600 Hz. The measurements above 1600 Hz do show deviation. However, even though the source amplitude was increased over this range, the levels of body conducted sound at these frequencies was significantly less than that at lower frequencies. The ratio of microphone signal amplitude to electrical cross-talk is indicated on a separate axes; it is possible that deviations at higher frequencies are due to poorer response of the measurement system at lower signal levels.

The results from subjects with SOAE are not obviously or systematically different from those of non-SOAE subjects. In most cases, passive linearity is best attained at those frequencies (<1500 Hz) where interaural acoustic transmission is greatest. In this range, the stimulus SPL in the contralateral ear was approximately 40 dB. Ipsilateral SFE with a stimulus of this level can be expected at levels 30 dB below the stimuli (Kemp & Chum, 1980). This would contribute very little to deviation from the passive linear case; any deviation found would likely be due to nonlinearity.

The results do not obviously indicate contralateral stimulus frequency emissions at levels significantly greater than a body conducted component of 40 dB SPL. Apparent asymmetry at lower stimulus levels and different frequency ranges suggest further study with more sensitive reversible transducers is necessary before a separate contralateral mechanism can be rejected. Indeed, it a greater deviation at lower stimulus levels should be investigated. Such deviations are compatible with a saturating emission mechanism. Further improvements in signal-to-noise ratios may be necessary through better ageraging techniques before this can be achieved, however.

While the experiments presented here do not reflect significant finds, the important result of this paper is the establishment of a theoretically valid and novel method for separating body conducted sound from active emissions, which can be extended in further experiments.

RECOMMENDATIONS

The method can be used to compare the difference in contralaterally stimulated ear canal sound levels to the difference in SFE activity measured using conventional methods. Thus, one can investigate whether the body conducted component of the contralateral stimulus creates SFE in the same way as stimuli sent into the canal of the emitting ear. Because of the different mechanisms through which body conducted stimuli enter the cochlea, it can be expected that the SFE generated by such sounds may have very different properties than those produced by "forward travelling" stimuli entering the oval window from the middle ear. The method may thus provide new ways for investigating latency characteristics of the conventional SFE mechanism.

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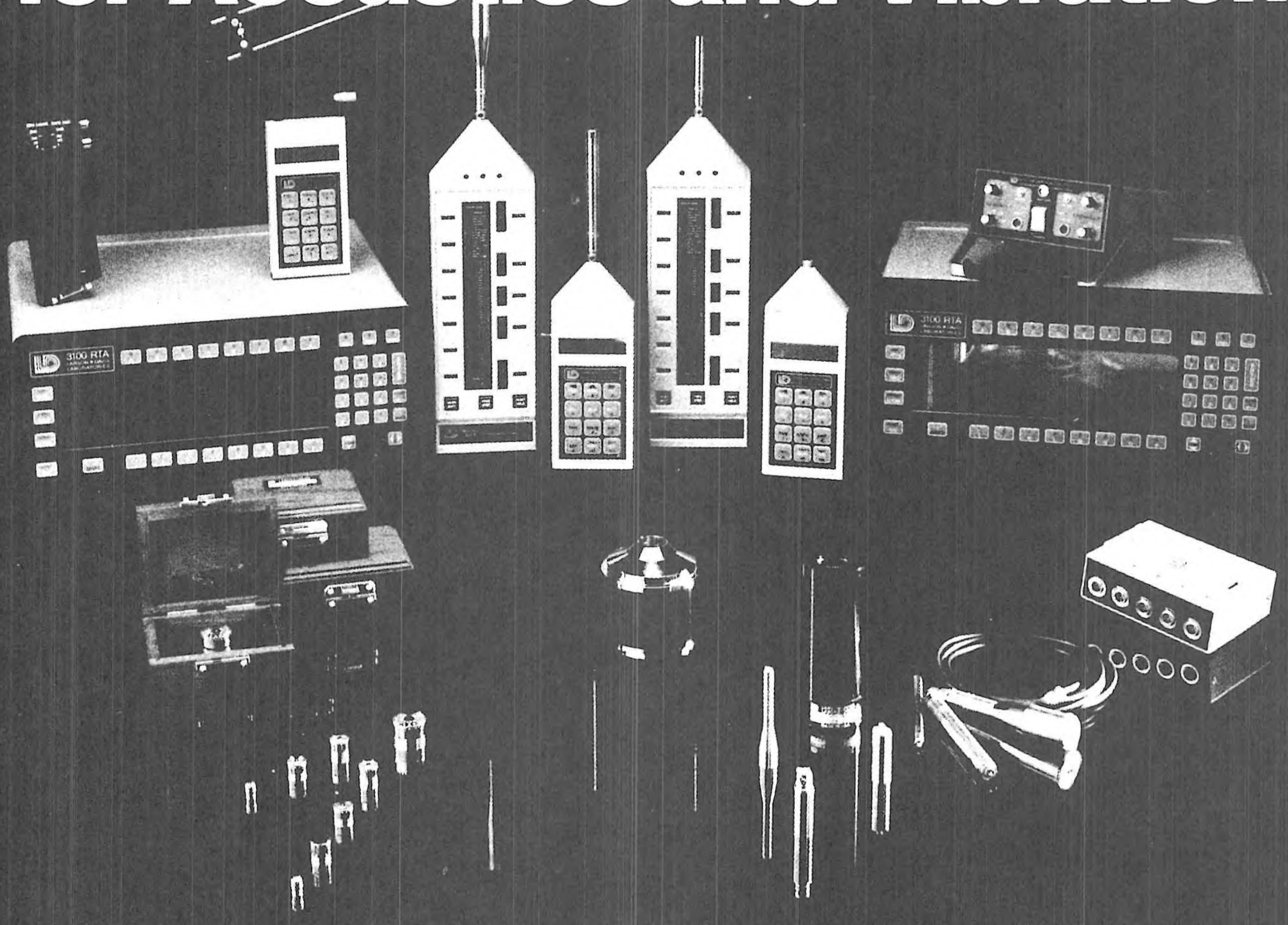

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