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16. Abstract

The displacement of a threshold from its measured-in-the-quiet value to the value it takes in the presence of another sound is masking. Measurement of that displacement is masking audiometry. And the measurement of displacements at a large number of frequencies produces masking patterns. This paper concerns itself with a procedure that produces masking patterns with good precision, sensitivity, and rapidity without the problems of tonal interference and beats that normally interfere with the determination of masking patterns. Several applications of the techniques are suggested, including one for determining the auditory effects produced by aircraft noises, and one for testing hearing protectors.

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NOISE AUDIOMETRY

I. Introduction.

The basic components of a common, general-purpose audiometer are a tone generator, an attenuator, perhaps a switch, and something to transduce the generated signal into an acoustic signal. The resulting test *tone* is almost invariably the stimulus chosen for clinical measurement, and frequently is picked for laboratory tests. This paper describes an audiometric device whose test signal is not a tone, but a narrow band of noise.

The concept of a test signal that is, in reality, a band of noise is certainly not new. Palva, Goodman, and Hirsh[5] reviewed much of the history of this sort of testing. However, previous applications were to specific research tasks, were cumbersome to use, and were slow in providing data—far too slow for the clinic, and often less than ideal for the laboratory.

A noise audiometer differs from narrow-band audiometric masking devices in that the *noise band* serves as the *stimulus* to the ear being tested rather than as something to interfere with responses at the opposite ear. Too, the bandwidth is narrower (but variable according to the needs of the user), and the intensity of the sound is continuously variable so that audiometric thresholds can be measured. In the CAMI prototype, the center frequency of the noise band is also continuously variable. In its diagnostic configuration, the device is a Békésy audiometer that uses a noise-band rather than a tonal signal. Thus, it overcomes problems of complexity of design and of use, it eases the interpretation of results, and it provides rapid testing and repeatable results.

Such an instrument is advantageous because it is resistant to the problems of testing patients with tinnitus, because it is capable of permitting rapid testing of hearing protectors in sound fields where standing-wave patterns would destroy the validity of the results, because it is essentially impervious to monaural-diplacusis effects, and because it can allow the rapid determination of masking patterns in normal or pathological ears without confounding the data with acoustic-beat artifacts.

II. Background.

The displacement of a threshold from its measured-in-the-quiet value to the value it takes in the presence of another sound is called masking. Measurement of that displacement can be called *masking audiometry*, and the measurement of a series of such displacements across the acoustic spectrum produces graphs that are representative of *masking patterns*—pictures of the auditory system's responses to various interfering signals. These patterns indicate something about the function of the basilar membrane and of the auditory nervous system, and they are critical to an understanding of how we perceive pitch, so masking patterns have been a matter of interest to auditory theorists for a long while.

In 1924, Wegel and Lane[7] made their first systematic explorations of the masking effects of one tone on another. Their procedure, although tedious, was thorough, and permitted them to describe almost everything in the universe of sensations produced by tonal interactions. However, every one of their measurements included conditions in which these very interactions interfered with adequate measurement of the masking. The greatest problems arose when their two tones were close enough in frequency to beat, although further difficulties occurred at harmonic partials when combination tones and subjective harmonics interfered similarly.

Later investigations tried in several ways to overcome these confounding and obscuring sensations, and the best of these techniques came from the 1950 work of Egan and Hake.[1] They replicated parts of the Wegel and Lane study, but they did it using a narrow band of noise in place of the tone whose masking effect was being investigated. Necessarily, the interaction between tone and noise was less severe than that between tone and tone, so the masking-pattern curves lacked the irregularities and discontinuities that had been necessary to include in the earlier study.

Wegel and Lane used a tone selected from one of several frequencies available to them, and presented it at one of several constant sensation levels. Then, in the presence of this fixed, tonal masker, another tone was introduced—the *probe tone* or *test tone*—and its threshold was determined. In the Egan and Hake procedure, the tonal masker was replaced by a narrow-band-noise masker, and in its presence, a probe-tone threshold was measured. In each case, the amount by which the test tone's threshold was elevated from a measurement made in the quiet was taken as the masking effect of the original tone or noise band on a tone of the test frequency.

For tonal maskers, letting the probe approach the masking frequency leads to beats, and because the beats are far easier to hear than the tone itself, thresholds are improperly lowered in the very range in which accuracy is more-than-usually important. Because subjects cannot separate the tone from the beat, measurement loses precision throughout the frequency ranges where beats occur.

The problem is both simplified and exaggerated when the two tones are made identical in frequency and phase. The beats vanish, to be sure, but the listener can no longer differentiate between the test tone and the masker in any way. At the time that this difficulty was most troublesome, George Miller[4] had not yet noted that a differential threshold is equivalent to a measurement of the masking of a signal by itself.

When Egan and Hake[1] substituted a narrow band of noise for the fixed masker, they overcame most of the difficulties inherent in the older procedure. Still, they were limited by their equipment to a single center frequency—410 Hz—for their noise, which was 90-Hz wide at the half-power points. They also thought that they had a problem because their noise band was less wide than a critical band, but that concern turns out to have been unnecessary and inappropriate.[2]

The data from Egan and Hake's work is smooth rather than discontinuous, but otherwise shows strong similarities to the Wegel and Lane work, and fills in some questionable segments with sensible and reasonable values. If there are flaws in the work, they are only that the available filters limited the number of testable frequencies, and that the measurement of discrete-frequency thresholds is time consuming. The idea of using noise bands for the measurement of tonal masking, though, is very good. If the Egan and Hake technique could be reversed, it would be even better. That is, if the test tone (rather than the fixed masker) were a narrow-band noise, then masking audiograms for *any* interfering signals could be made without concern for the confounding interactions of nearly matched tones. Ideally, such a procedure would also incorporate continuous frequency and sound-pressure variation (rather than discrete), both for complete coverage of the ranges under investigation, and for ease of testing. In other words, the method would be the sort of Békésy-audiometric device that this paper describes.

III. Design.

A masking pattern is a graph of the interfering effects of a signal on other signals, throughout the acoustic spectrum. If a noise-band audiometer is to be used for measuring masking patterns, it must meet a number of criteria (and, as it turns out, if it meets the criteria for masking audiometry, it also meets the criteria for a number of other diagnostic and research uses):

1. it should allow the threshold of the interfering signal to be measured,

2. it should allow probe-threshold determinations both in the presence and in the absence of the interfering signal,

3. it should permit continuous frequency variation,

4. it should not allow either the interfering signal or the probe (the test band of noise) to fatigue the listener,

5. it should not allow beats or difference tones between the probe and any component of the interfering signal, no matter what that signal might be, and

6. it must permit the subject to distinguish easily between the interfering signal and the probe.

In constructing a prototype, it was considered that the major functions were related to the functions of a standard Békésy audiometer, and so such an audiometer (Grason-Stadler model E–800) was used as the foundation of the system. Figure 1 shows the essential components that permit the modified use. The motor-driven oscillator and the recording attenuator are part of the Grason-Stadler audiometer; everything else is extra. Several amplifiers, attenuators, and switches are not shown—they were necessary to handle gain and impedance problems, in this particular case, but would not have been necessary had different components been available. At any rate, their inclusion would have cluttered rather than clarified the figure.

The motor-driven oscillator from the audiometer can be switched either directly to the recording attenuator—for standard audiometry—or into an amplitude-modulation system (such as Grason-Stadler model E3382B) where its output serves as the carrier for the probe in masking or noise-audiometry measurements. The modulation signal is a low-frequency noise source, reaching, at the lower end, as close to dc as possible; the prototype uses a noise band of 5–75 Hz. The output of the modulator, then, is a band of noise, 150-Hz wide, centered at the carrier-oscillator frequency. Because the carrier is continuously variable, the noise band can be shifted continuously through the frequency range that is to be tested. The test signal from the modulator is then returned to the recording attenuator, and automatic noise-band audiometry becomes possible.

(The construction is less complicated with the Grason-Stadler 1701 audiometer, which has provision for modifying the tone before it enters the recording attenuator without rebuilding or modification. However, the system can be put together from individual components almost as easily as it can be constructed even with the 1701 audiometer's special features, so one need not be deterred

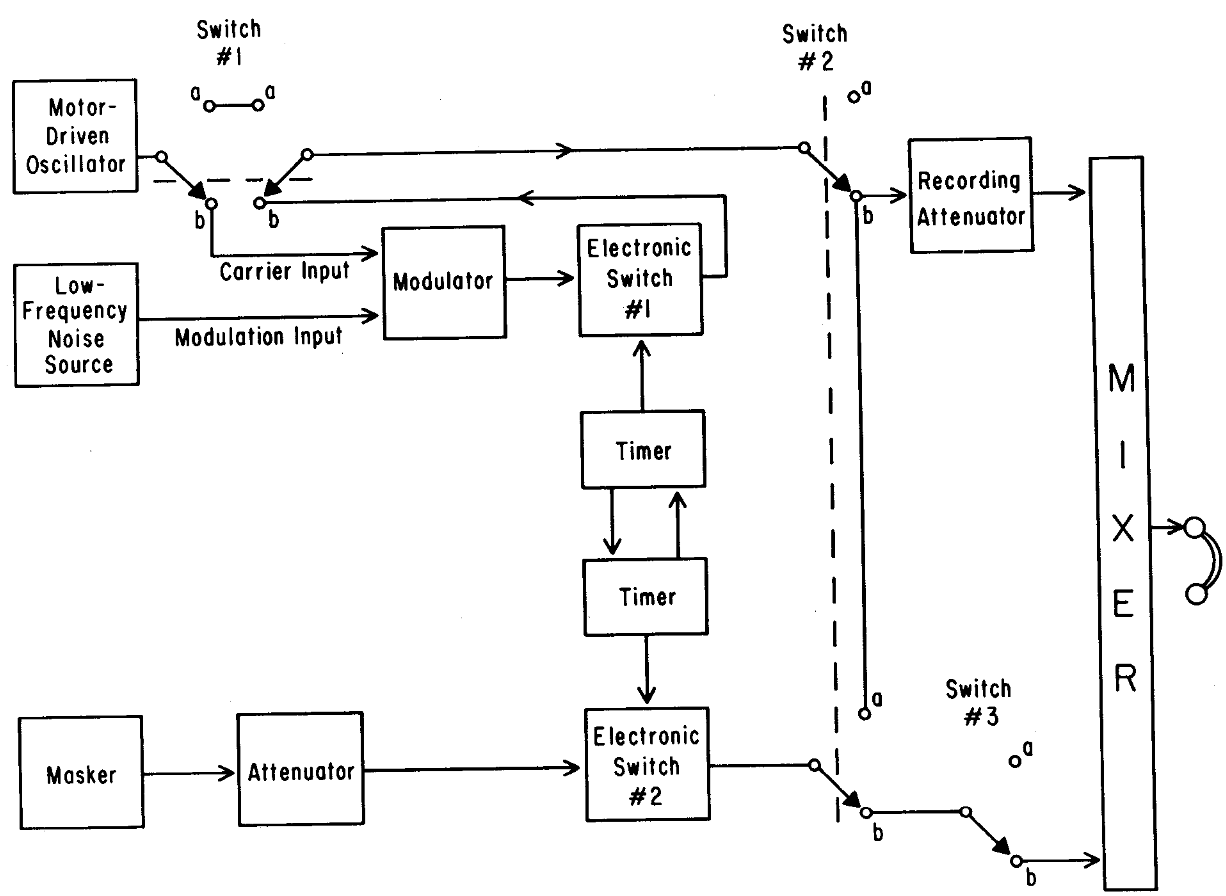

FIGURE 1. Block diagram of noise audiometer.

from trying the device on grounds of equipment complexity.)

One problem that becomes obvious in the study of masking patterns is that listeners can sometimes show fatigue effects from continuous exposure to the masker. To overcome that difficulty, two gates or electronic switches must be added. One, in the masking channel, interrupts that signal for 200 msec out of every 800 (Fig. 2). The other turns the probe on for 400 msec, centered in the on-cycle of the masker. The program thus starts with the masker coming on for 100 msec. Then, while it is still on, the probe tone comes on for 400 msec, and goes off while the masker continues for another 100 msec. Finally, after 200 msec of silence, the cycle is repeated. Subjects always find this to be an easy way to distinguish the masker from the test tone, and additionally, the masker serves as a kind of pedestal upon which the test tone appears. The pedestal becomes a reference signal, and the subject's task is simply to discriminate whether a change occurred. If it did, he responds; if it did not, he waits for the change to happen.

IV. Results.

The six criteria for a masking audiometer are met, as listed in Table 1: (1) with Switch #2 in position *a*, a masking-signal threshold can be plotted; (2) with Switches #1, 2, and 3 in positions *b*, *b*, and *a*, respectively, a noise-band audiogram is plotted, and with all the Switches at *b*, a masking audiogram with a noise-band probe is produced; (3) continuous frequency variation results from the use of a motor-driven beat-frequency oscillator; (4) fatigue is kept minimal by the gating arrangement; (5) beats and difference tones are no problem because the probe is a noise band; and (6) the introduction of the pedestal permits the listener to distinguish between the masker and the probe with little difficulty.

TABLE 1.—Functions of the system shown in Fig. 1.

Switch Positions			Function
Switch #1	Switch #2	Switch #3	
any	a	any	Masking-signal threshold
a	b	a	Tonal audiogram
b	b	a	Noise-band audiogram
a	b	b	Masking audiogram with tonal probe
b	b	b	Masking audiogram with noise-band probe

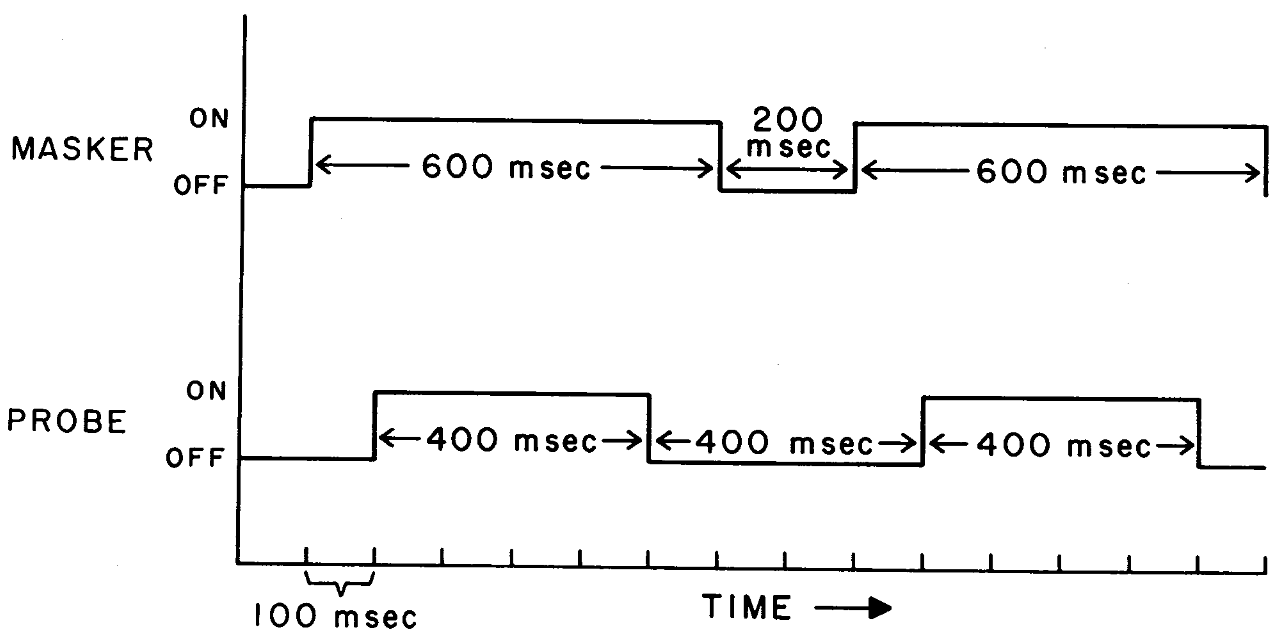

FIGURE 2. Switching program for noise audiometer.

Thresholds can still be measured in the usual ways (Table 1), so standard audiometry is possible without tearing down the equipment. But most important of all, the system allows any kind of signal to be investigated for its masking properties, no matter how complex, and no matter how filled with tonal components, without particular influence from beats. The same device can be used to study the masking effects of tones, noise bands, recordings of vowels, of aircraft-engine sounds, and indeed of whatever signals one wishes.

Further, the system allows the option of using a tonal probe, as Wegel and Lane did. It also allows the use of discrete frequency variation by simply disconnecting the oscillator motor, or of limited-frequency-range testing by operating the motor slowly.

V. Application.

As a diagnostic device, the noise audiometer is at least as accurate as pure-tone audiometers, although its major value in this function may only be that it produces a signal that is unlikely to confuse naive listeners about what is expected of them. Further, it solves the problems of audiometry in patients with tinnitus and with monaural diplacusis. It is usable both for discrete-frequency and continuous-frequency tests. It can discriminate between patients with Jerger's[3] Type II audiometric patterns and all others.[6] When it is used to operate a bone-conduction receiver, it offers for the first time a Rainville-Jerger (SAL) technique producing data throughout the audible frequency range.

The noise audiometer also permits rapid testing of ear-protective devices (for this function, it is used to drive a loudspeaker), and it allows the tests to be made without concern about standing-wave patterns that would destroy the validity of the results. It allows rapid determination of the immediate effects of any environmental (or other) noise on hearing, and it does so without confounding the data with acoustic-beat artifacts. The most obvious application of these techniques is to the measurement of the ways in which aircraft noise can interfere with normal auditory processes.

The method is quite precise despite the inherent variability of Békésy audiometry. And what loss in precision one does have to accept is made up for in the ease of test administration.

The cost of incorporating a noise audiometer into an audiological armamentarium can vary over a wide range. For most physicians, the price would probably be excessive, but for a facility with advanced equipment already in use, the device can be added at fairly low cost and minimal time.

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