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THE SELECTION OF MODULATION WAVEFORM FOR FREQUENCY MODULATED SOUND FIELD STIMULI

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ABSTRACT

Frequency modulated (F.M.) tones are used in sound field audiometry in order to avoid problems caused by standing waves. To provide uniform sound fields and be sufficiently frequency specific, the F.M. stimulus should possess a uniform distribution of energy within the frequency limits set by its bandwidth, and a very rapid fall off of energy outside these limits. This paper compares several practical modulation waveforms with regard to how well they meet these constraints. The modulation waveform affects the spectral characteristics both within the signal band and outside it. Sinusoidal modulation provides very steep skirts at the band edges but somewhat non-uniform energy distribution within the band. Triangular and ramp modulation improves uniformity within the band at the expense of shallower skirt slopes. Square wave modulation provides neither uniform energy distribution within the band nor steep skirt slopes. The skirt slope is required to be steeper than the maximum audiogram slope likely to be encountered. Both sinusoidal and triangular modulation meet this requirement but triangular modulation is preferred because of its more uniform energy distribution within the band. Square wave and ramp modulation are not suitable for use in audiometric warble tone generators.

INTRODUCTION

Sound field testing is finding an increasing use in audiology, both for the measurement of aided hearing and for measurement of the hearing of those too young to tolerate headphones. Frequency modulated tones, which are the stimuli most commonly used in sound field testing, can be specified by the parameters of centre frequency, frequency deviation, modulation rate, and modulation waveform. Optimum values for frequency deviation (closely related to the stimulus bandwidth) and modulation rate have been discussed by us elsewhere (Dillon and Walker, 1982b; Walker and Dillon, 1982). This paper addresses the problem of selecting the most appropriate modulation waveform. The modulation waveform, of course, describes the manner in which the instantaneous frequency of the signal sweeps back and forth about the centre frequency. Although several different waveforms have been used, there has been no study of the relative advantages of each.

Stimuli used in sound field testing should satisfy two constraints. Firstly, the distribution of stimulus power within the stimulus bandwidth should be as uniform as possible. This ensures that the resulting reverberent sound field will also be as uniform as is possible for the particular bandwidth and centre frequency under consideration (Dillon and Walker, 1982a). Secondly, the stimulus power outside the desired bandwidth should fall off as quickly as possible. If the fall-off slope (or skirt-slope by analogy with filter responses) is insufficiently steep, then hearing impaired people with steeply sloping hearing losses will be able to hear the stimulus by perceiving the portion of the stimulus power which is contained in a frequency region far removed from the centre frequency, where their hearing losses are less severe. Thus, insufficiently steep skirt slopes will cause the hearing loss to be underestimated. This paper will compare how well different modulation waveforms meet these two criteria.

METHOD

The spectra of stimuli generated with sinusoidal, triangular, ramp, and square wave modulation waveforms were measured using a Spectral Dynamics SD360 spectrum analyser linked to a Hewlett Packard HP-85 desk top computer. In-band characteristics were examined qualitatively using both short and long term spectral measurements. Stimulus skirt slopes for the triangular modulation waveform were measured quantitatively using long term spectra, and compared to audiogram slopes obtained from a survey of NAL cases and from a survey reported in the literature.

RESULTS AND DISCUSSION

Stimulus Slopes

The relative advantages of different modulation waveforms can be qualitatively understood by examining the short term frequency spectra of frequency modulated tones. These spectra, such as the ones shown in figure 1, show how the "instantaneous" spectrum changes during each modulation cycle. (Each short term spectrum is not really an instantaneous spectrum, but is rather the spectrum of a portion of the waveform, the duration of which is short compared to the modulation period. Each "slice" shows the spectrum of a portion of the waveform at successively later intervals of time). Figure 1. (a) shows the spectrum for a signal of 1 kHz centre frequency when modulated by a sinusoidal tone. It is clear from this figure that the stimulus power is well contained within the range of frequencies swept by the signal. It can also be seen, although less clearly, that more signal power will be found near the band edges than in the band centre, because the instantaneous frequency "dwells" longer near the edges. By comparison, the spectrum for a triangularly modulated tone shown in figure 1(b) snows that for this stimulus, the power will be more uniformly distributed within the band.

The problems associated with out-of-band energy are most clearly illustrated in parts (c) and (d) of figure 1. For both ramp and square-wave modulated signals, there is a point in the modulation cycle at which the instantaneous frequency of the signal jumps rapidly from one frequency to another. Such discontinuities are always associated with a spread of energy, or "splatter" to frequencies far removed from the ongoing signal frequency. This splatter can be clearly observed in figure 1 (c) and (d). (Although the amount of splatter appears to vary randomly from one modulation period to the next, this is partly an experimental artefact related to the relative timing of the spectrum analyser and the modulation frequency. In fact, the amount of splatter will vary somewhat from

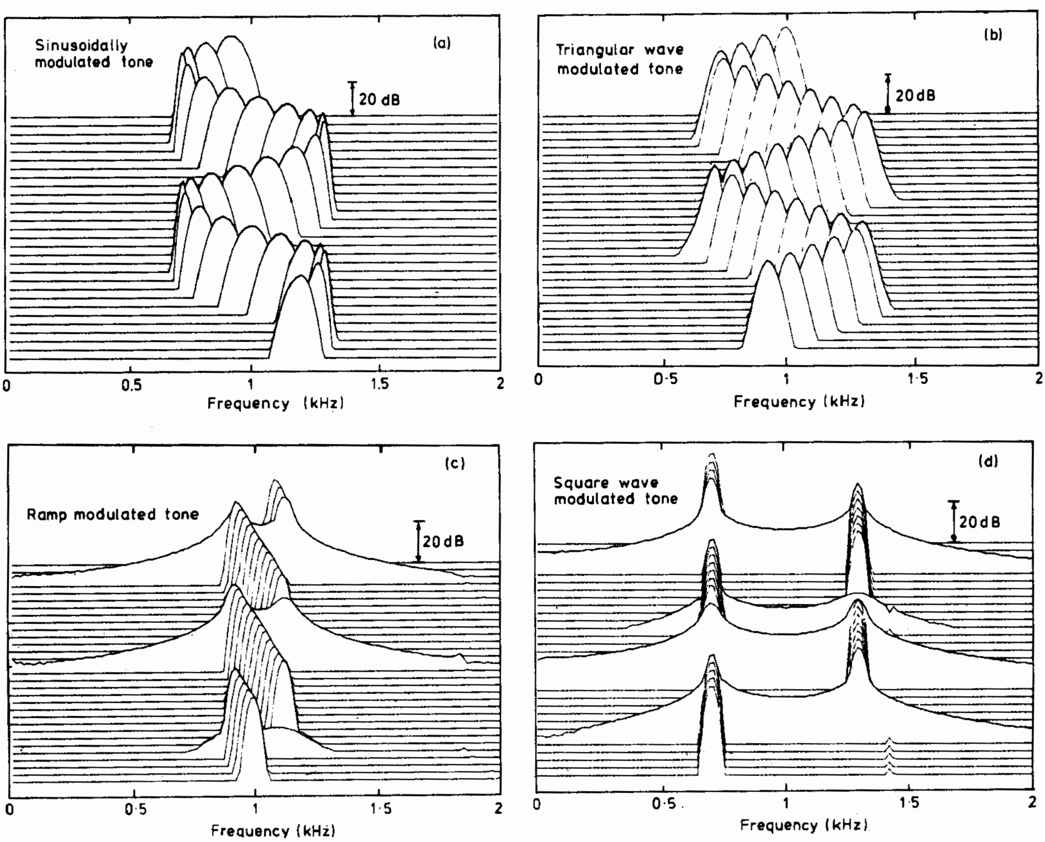

FIG. 1: Short term spectra for a 1 kHz centre frequency modulated at 0.75 Hz by sinusoidal, triangular, ramp, and square waveforms. Note that the frequency deviation is ±100 Hz for the ramp waveform and ±300 Hz for the others. The interval between adjacent spectra is 50 ms.

cycle to cycle depending on the phase of the signal at the time of the frequency jump).

On the basis of these short term spectra, some types of modulation waveforms can be readily rejected. Square wave modulation is clearly unsuitable since it has the greatest amount of energy splatter (and consequently excessively shallow skirt slopes), and the worst in-band power distribution. There is a concentration of power at the band edges because the instantaneous frequency remains stationary at each band edge for 50% of the modulation cycle. Despite its obviously unsuitable characteristics, Staab and Rintelmann (1972) found that 50% of audiometer manufacturers surveyed utilised rectangular modulation. Similarly, a ramp modulation waveform can be rejected because it has more out-of-band energy splatter than triangular modulation, without having any offsetting advantages in its in-band characteristics. This leaves us with a choice between triangular and sinusoidal modulation, the former having better in-band characteristics and the latter better out-of-band characteristics.

While the short term spectra shown above are adequate for eliminating some waveforms, the information they provide is not sufficiently quantitative to enable us to decide whether the skirt slope associated with the triangular waveform is acceptably steep. However, the skirt slope can be measured from the long term spectrum of a stimulus. By "long term spectrum", we mean that the analysing time of the spectral analyser is long compared with the modulation period of the stimulus. The long term spectra for sinusoidal and triangular modulated tones are shown in figure 2.

These long term spectra appear quite different from the short term spectra shown previously. Because the portion analysed is long enough to encompass several modulation periods, the periodicity of the modulation waveform ensures that the signal spectrum can only contain power at multiples of the modulation frequency. Thus, a line spectrum results, but only those components that are near the stimulus band are found to contain a significant amount of power. The exact shape of the resulting spectrum depends on the centre-frequency, modulation frequency, frequency deviation, and in particular, the ratio of frequency deviation to modulation frequency (Dillon and Walker, 1982a). Despite these variations, some generalizations about the relative shapes for sinusoidal and triangular modulation waveforms can be made.

1. Sinusoidally modulated tones always contain a greater power density at the band edges than elsewhere within the band, although the effect is not nearly as marked as for square wave modulation.

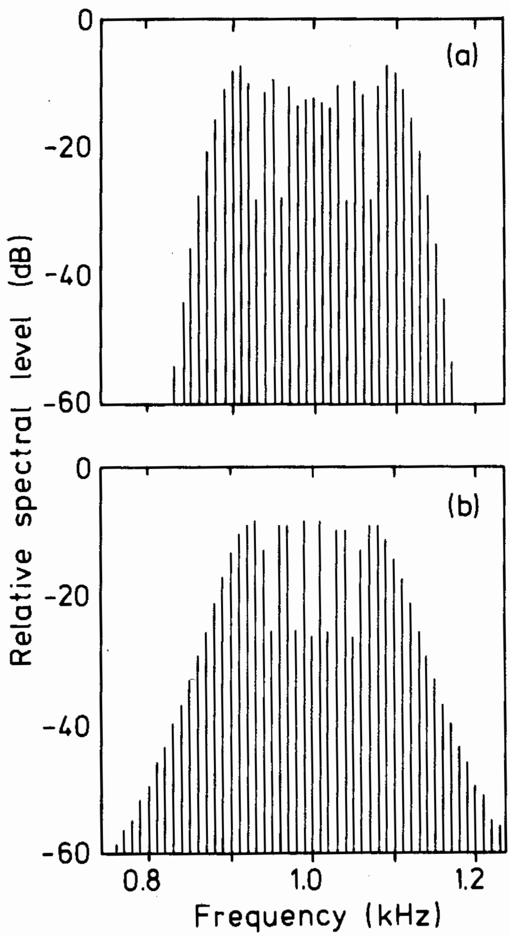

FIG. 2: Long term spectra for (a) sinusoidal and (b) triangular wave modulated tones. Both have a centre frequency of 1 kHz, a frequency deviation of ± 100 Hz, and a modulation rate of 10 Hz.

2. Triangularly modulated tones always have shallower skirt slopes than do sinusoidally modulated tones (for the same values of modulation rate, frequency deviation, and centre frequency). This increased splatter for the triangular waveform occurs because the change in instantaneous frequency at the band edges is not as smooth as for the sinusoidal waveform.

The skirt slopes have been measured for a range of centre frequencies, deviations, and modulation rates, for both sinusoidal and triangular modulation. The resulting values for triangular modulation are shown in figure 3.

Examination of these data reveals that the skirt slope is proportional to centre frequency, f_o, and is inversely proportional to the square root of both frequency modulation, f_m, and frequency deviation f_d. (The first of these is predic-

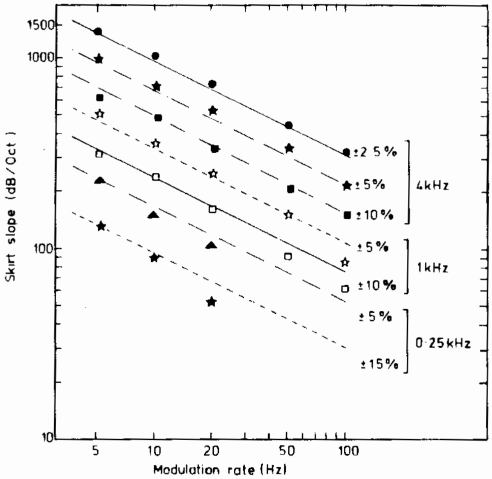

FIG. 3: Measured skirt slopes of triangularly modulated tones of various centre frequencies, deviations, and modulated rates. The lines passing through the points show the slopes predicted by the equation given in the text.

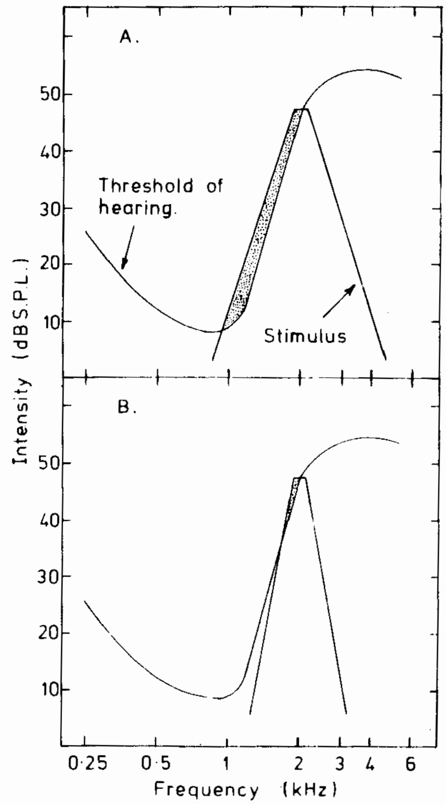

FIG. 4: Illustration of the (a) increased error caused when the stimulus slope is less than the audiogram slope, and (b) the negligible extra error when the stimulus slope is greater than the audiogram slope.

table on simple grounds). The constant of proportionality has been determined by eye, and the data is well fitted by the equation

$$\text{Slope} = 7.5f_o/(f_m f_d).$$

The value for f_d is measured from the band centre to the band edge and is thus equal to half the total frequency deviation or stimulus bandwidth.

Audiogram Slopes

The data (or equation) presented above allow us to determine what skirt slope any particular triangularly modulated stimulus will have. We now need to determine a criterion for establishing whether any particular slope is acceptable. Figure 4 shows a sloping hearing loss (expressed in threshold SPL) and superimposed are the simplified spectra of two different stimuli, differing only in their skirt slopes. In figure 4(a) the stimulus skirt slope is less than that of the audiogram slope.

A large error in threshold determination will result because of the stimulus power lying above the threshold curve. By contrast, the stimulus spectrum shown in figure 4(b) will lead to only small errors in measured threshold (which occur even for infinite skirt slopes whenever a non-zero bandwidth is used). It is clear from figure 4 that large errors can occur whenever the stimulus skirt slope is less than that of the audiogram slope. We thus take as our minimum requirement that the skirt slope exceed the highest audiogram slope likely to be encountered. Data about audiogram slopes has been obtained from two sources. Rosler and Anderson (1978) examined file records for a large number (unspecified) of patients and selected for further study 41 patients with steeply sloping audiograms. These patients were then subjected to further study by obtaining thresholds at closely spaced discrete frequencies in the frequency region containing the steepest loss. The second source of data was a small survey of 120 NAL cases. This survey noted the hearing loss at octave frequencies recorded on the clinical record card. In a seperate series of measurements performed on 21 NAL clients for other purposes (Dillon and Walker, 1982b) we noted that the maximum audiogram slope when measured with closely spaced discrete frequencies was, as an approximation, twice that which it appeared to be if only the hearing loss at octave frequencies was observed. Thus, the data from the survey were doubled to provide a better estimate of the greatest slope likely to be found in each frequency region. The resulting maximum slopes, along with the average maximum slopes for the group tested by Rosler and Anderson, are shown in Table 1.

TABLE I. Maximum audiogram slopes obtained from Dillon and Walker (1982b) and Rosler and Anderson (1978).

	Audiogram Slope (dB/Octave)	
Frequency Region (Hz)	Dillon & Walker	Rosler & Anderson
250-500	40	80
500-1000	80	160
1000-2000	90	190
2000-4000	120	250
4000-8000	110	500

The slopes from Rosler and Anderson are much steeper than ours, but it should be noted that their cases were selected from a much larger sample. (They conclude that slopes of this magnitude will only be found in some few per thousand cases). Our data, on the other hand, indicate audiogram slopes that could be encounted some 1% of the time.

Comparison of Stimulus and Audiogram Slopes

Before the skirt slope of a triangularly modulated wave can be compared with an audiogram slope, it is necessary to specify which modulation rate and frequency deviation will be used, because the skirt slope is clearly affected by both of these. We have elsewhere recommended that a modulation rate of 20 Hz should be used (Walker and Dillon, 1982) and that the frequency deviation should vary with centre frequency, even when expressed as a percentage of centre-frequency (Dillon and Walker, 1982b). The recommended bandwidths are presented in table II. Table II also shows the "narrow" bandwidths that we recommend for use when testing people with very steeply sloping audiograms.

Figure 5 shows all the data which needs to be compared to assess the suitability of triangular modulation waveforms. The lower set of points show the highest slopes obtained from the survey of NAL cases outlined earlier. Immediately above this lies the hatched area which contains all the audiogram slopes obtained by Rosler and Anderson from their 41 selected clients. The dashed curve passing partly through and partly over the hatched area shows the stimulus slope that is obtained when the standard bandwidth stimuli are used. It is clear that the slope would be adequate for all the audiograms in the NAL survey, but would be insufficiently steep for some of Rosler and Anderson's cases. However, when the narrow bandwidth stimuli are selected, the skirt slope is found to be sufficiently high for all except one of Rosler and Anderson's cases, and has a generous safety margin for all the cases in the NAL survey. We thus conclude that triangular modulation, when used with stimuli of appropriate bandwidth or frequency deviation, pro-

TABLE II. Recommended bandwidths or frequency deviations which were used to calculate the stimulus skirt slopes.

Centre Frequency	Standard		Narrow	
(Hz)	(%)	(Hz)	(%)	(Hz)
250	±14.5	±36	±5.0	±12
500	±12.0	±60	±4.0	±20
1000	± 8.5	±85	±2.8	±28
1500	± 6.5	±97	±2.1	±32
2000	± 5.5	±110	±1.8	±37
3000	± 4.5	±130	±1.5	±45
4000	± 4.0	±160	±1.3	±54
6000	± 4.0	±240	±1.3	±81
8000	± 4.0	±320	±1.3	±108

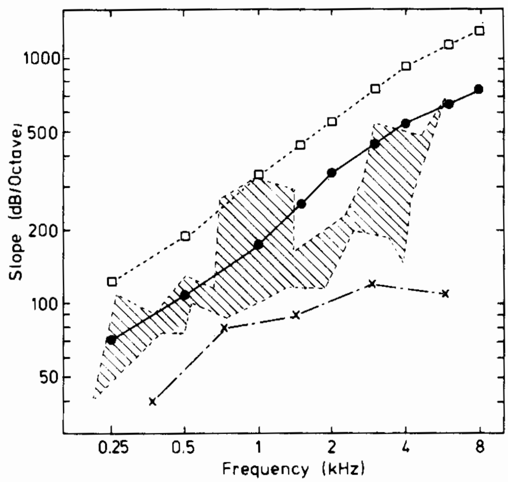

FIG. 5: Audiogram slopes and stimulus skirt slopes for triangular modulation versus centre frequency. Crosses show maximum slopes from Dillon and Walker 1982 (b). The hatched area encompasses all the measured slopes from Rosler and Anderson (1978). The circles and squares show the stimulus slopes obtained with "standard" and "narrow" bandwidth stimuli respectively when modulated by a 20 Hz triangular waveform.

vides skirt slopes steeper than virtually all audiogram slopes. (The one exception represents one in at least several thousands, and had a slope 2.5 times greater than the next steepest audiogram in that frequency region.)

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Sound field stimuli should ideally have a uniform distribution of power within the desired bandwidth, and have no power outside that bandwidth. Practical stimuli fall short of both these ideals. In particular, square-wave and ramp modulation waveforms lead to a very gradual fall-off of power outside the band limits and should thus not be used to generate sound field stimuli. The gradual slope is associated with the discontinuties in these modulation waveforms. Square wave modulation waveforms also have poor in-band characteristics. By contrast, triangular and sinusoidal modulation waveforms have much steeper skirt slopes. Although the skirt slopes for sinusoidal waveforms are steeper than those for triangular waveforms, the in-band characteristics are slightly inferior because of an accumulation of power at the band edges. A comparison of the triangular waveform skirt slopes with the steepest audiogram slopes likely to be encountered, revealed that the skirt slopes associated with triangular modulation are sufficiently steep not to cause appreciable error.

We thus conclude that triangular modulation waveforms are suitable for use in sound field generators, and may offer a slight advantage over sinusoidal modulation. We do not believe that the improvement in sound field uniformity will be large, however, so modifications to existing generators incorporating sinusoidal modulation do not seem justified. Existing generators using square or ramp modulation should be replaced or modified.

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