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Annoyance due to modulation noise and drop-outs in magnetic sound recording

D. J. H. Admiraal, B. L. Cardozo, G. Domburg and J. J. M. Neelen

It is possible to carry out many kinds of physical measurement with great accuracy on a product intended for human use and still not obtain a conclusive answer to the question of the product's usability. This is because human perception also enters into the picture. If the investigation is extended to include a representative number of human subjects it will be discovered, however, that human perception obeys certain laws. These can often be quantified, as has been done for example in the theory of the chromaticity diagram and in the international definitions of loudness. More particularly in the context of noise abatement, a further step has been taken and efforts have been made to express the concept of annoyance in numerical terms, leading to reproducible results. Something of the same sort is attempted in the article below, which deals with the annoyance caused to the listener by two imperfections of magnetic sound recording that are hard to avoid: modulation noise and the spontaneous occurrence of short interruptions or 'drop-outs'. The subject belongs naturally to the range of studies performed by the Institute for Perception Research (IPO), where the authors carried out the work.

Noise and 'drop-outs' in magnetic sound recording

The recording of sound on magnetic tape has reached a high degree of perfection. An inherent imperfection of the process, however, is the noise added to the original audio signal. When the conditions are good the noise may be barely perceptible, but under less favourable conditions it is distinctly audible and can sometimes be annoying. In this article we shall be concerned with the audibility of one particular type of noise and with the annoyance it causes.

There are in fact two kinds of noise. In the first place there is the background noise, which is always present during playback and is particularly obtrusive in the absence of a signal or when the signal is weak. Efforts are made to reduce this noise by improving the quality of the tapes and also by magnetizing the tape as fully as possible. One method includes a process of signal compression and expansion (the Dolby system). Another approach is to attenuate the highest frequencies during the reproduction of weak signals, since these are the components of the noise that are most disturbing to the listener ('Dynamic Noise Limiter').

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Apart from this noise, which is an independent addition to the signal and may therefore be called additive noise, there is also what is termed multiplicative noise. This only occurs when a signal is recorded on the tape (i.e. during the 'modulation' of the tape); its strength is proportional to that of the signal. It takes the form of amplitude modulation of the signal. It is this kind of noise, called 'modulation noise', that will be dealt with here. Under certain conditions modulation noise can be annoying, as appears from listening tests that we have carried out and which will be described below. Its reduction deserves just as much attention as that of additive noise.

Another annoying effect that has been the subject of considerable attention is the effect known as 'drop-out', i.e. short interruptions (really attenuations) of the signal that occur during the playback of magnetic tapes. They may be caused by inhomogeneities in the magnetic layer, or they may be due to dirt, fingerprints, creases in the tape, etc. This effect is most troublesome with cassette tapes. For a fraction of a second the signal almost or completely vanishes. The effect might be regarded as a very low-frequency component of modulation noise, but in an oscillogram of the playback signal (fig. 1) it can be clearly distinguished from the

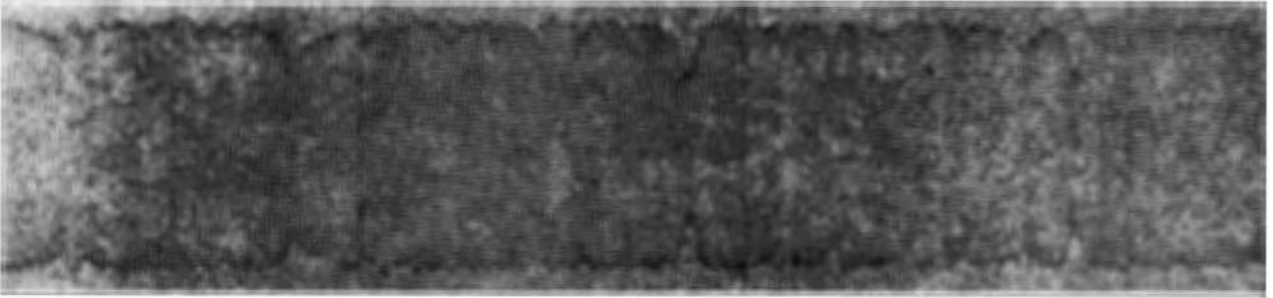


Fig. 1. Oscillogram of a sinusoidal tone at 5000 Hz, obtained from a magnetic tape. It shows, in addition to the low-frequency amplitude modulation in which the modulation noise appears, a number of short attenuations in the signal amplitude ('drop-outs'). The distance between two vertical lines corresponds to 0.1 second.

other amplitude variations, and it makes a quite different impression on the listener.

Our listening tests have shown that the annoyance caused by drop-outs depends on their duration, the degree of signal attenuation and their distribution in time. A measuring instrument has been developed in which these aspects are evaluated in the same way as they were in the listening tests; the instrument gives a reading of the results in terms of a numerical 'annoyance rating'. Some forty of these instruments are now being used in the laboratories of magnetic-tape manufacturers and users all over the world [1].

Causes of modulation noise

Although in this article we are only concerned with the perception and subjective evaluation of the interfering effects mentioned above, it will nevertheless be useful to touch briefly on the causes of modulation noise.

An important cause is the inhomogeneous distribution of the magnetic particles in the tape. The particles each form a single magnetic domain and are thus fully magnetized; consequently they tend to form clusters during the manufacture of the tape [2]. In magnetizing the tape the maximum magnetization will consequently vary from place to place. Another contributory factor is that the thickness of the magnetic layer is not completely uniform.

Yet another important cause of modulation noise is the variation in the gap between tape and magnetic head. This may be due to surface roughness of the tape, but also to soiling of the head or of the tape. As a result there are fluctuations in the field that records the signal on the tape. The resulting modulation noise (called 'asperity noise' [3]) is often the most serious in practice.

In this last form of modulation noise the lowest frequencies are strongest. The spectral power density (noise power per Hz bandwidth) can be approximately represented by a curve that is flat below 35 Hz and decreases by 6 dB per octave above it; see *fig. 2*.

Hearing threshold and masking

The characteristics of the ear obviously play an important part in the perception of modulation noise. In the first place its perception depends on whether or not the modulation noise exceeds the threshold of audibility. The lower curve in *fig. 3* gives the threshold for single (sinusoidal) tones; a logarithmic plot is given of the intensity required for a tone of a particular frequency to be just perceptible to the average ear. The sensitivity of the human ear is highly frequency-dependent and is greatest between 3000 Hz and 4000 Hz.

Whether or not a sound is heard depends not only on its intensity but also on whether or not other sounds are present. A stronger sound may mask a weaker one, i.e. make it inaudible. In this way the modulation noise is often masked by the sound signal itself. The masking is also frequency-dependent, and is particularly pronounced at closely adjacent frequencies. This can be seen from the other curves in *fig. 3*, which relate to the masking of single tones by noise in a narrow frequency band around 1000 Hz; the nearer the tone is to 1000 Hz, the stronger it must be to be heard. As can be seen, the masking effect of the noise band extends much farther towards the higher frequencies than towards the lower frequencies.

Audibility and annoyance

A sound, or more generally an acoustic effect, can be made so weak that it becomes inaudible to the human ear. When the sound is then made stronger again, the threshold of audibility will eventually be exceeded. In this process it is essential that the listener should know the sound and thus be able to recognize it. Only then does a threshold value have any significance. In our experiments we always ensured that the subjects taking part were thoroughly familiar with and capable of recognizing the modulation-noise effect and the drop-outs. This is vital to the manner in which the degree of annoyance is determined. Our initial assumption is that the annoyance increases monotonically with the mod-

ulation depth, or, in the case of the drop-outs, with the modulation depth and also with the duration of the interruption.

To indicate the annoyance due to unwanted sound in terms of a number on a scale, we can take the threshold of audibility as the zero of the scale. We also found that after some practice the subjects could in fact give quantitative estimates of annoyance that increased monotonically with the intensity of the unwanted sound. We therefore asked the subjects to give their judgement of the annoyance h due to the modulation noise in certain passages of music, on the following scale:

- $h = 0$ no modulation noise audible,
 1 modulation noise audible but not annoying,
 2 modulation noise annoying,
 3 modulation noise very annoying.

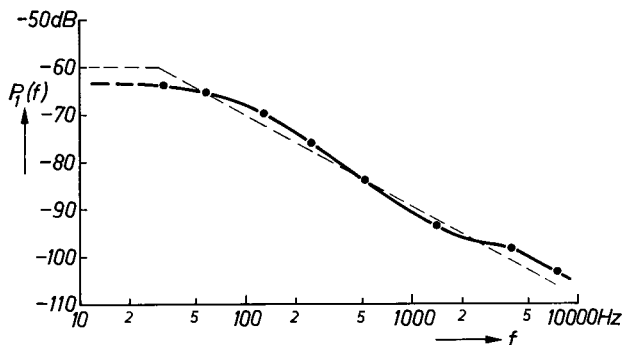


Fig. 2. Frequency spectrum of modulation noise measured on a tape containing a recording of a sinusoidal tone at 1000 Hz (solid curve), and curve approximating to it (dashed). $P_T(f)$ is the power density of the noise, i.e. the power in a frequency band 1 Hz wide, given in dB relative to the power of the sinusoidal tone. f frequency.

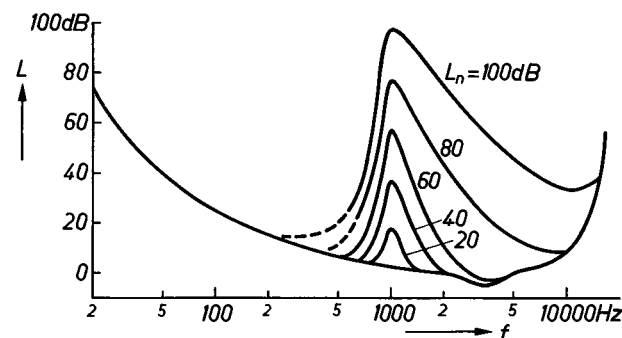


Fig. 3. Threshold curves for the human ear. The lower curve gives the hearing threshold for sinusoidal tones, and is a plot of the level L which a sinusoidal tone of frequency f must have to be only just audible to the average human ear (0 dB corresponds to a sound-pressure amplitude of 2×10^{-5} N/m²). The other curves show how this threshold curve changes when noise at a level L_n is present in a narrow band around 1000 Hz. The narrow noise band has a masking effect here, which is particularly marked at the higher frequencies. (From E. Zwicker and R. Feldtkeller, *Das Ohr als Nachrichtenempfänger*, 2nd edition, S. Hirzel Verlag, Stuttgart 1967.)

The subjects were allowed not only to interpolate on this scale but also to extrapolate. Extrapolation is important since the annoyance scale does not have any natural upper limit as it has a natural lower limit. Fixing an upper limit would face the subject with a problem: he would be inclined to evaluate the most annoying stimulus at the highest scale value permitted. Since he does not know beforehand whether there is an even more annoying stimulus to come, he will tend to avoid the upper limit.

Modulation noise

A problem in listening tests with modulation noise is that it is difficult to present the subjects with music without modulation noise for comparison. This would require music that had not in any way been recorded.

Logically, we should therefore have had the same music played live during the listening tests. But this seemed too drastic a solution in the circumstances. In any case, we found that it was not absolutely necessary, since tape recordings of high quality are available (the 'master tapes' used in making records) on which the modulation noise is negligible; indeed, artificial modulation noise has to be added for the audibility determination.

In determining the audibility of modulation noise we also used sinusoidal signals generated directly by electrical methods. In addition, tape recordings of these signals were made with very low modulation noise, and these recordings again confirmed that, provided sufficient precautions are taken in these experiments, there is no need to avoid the use of recorded music.

Audibility

In the design of listening tests in which the subjects are asked to assess the annoyance they experience from modulation noise, it is important to know where the limits of audibility lie. We therefore carried out preliminary audibility tests, first using well defined signals of simple form, including a single sinusoidal tone modulated by white noise, i.e. noise with a uniform spectral power density P_1 . This noise was limited in frequency by a lowpass filter with a variable cut-off frequency f_n . The modulated signal then consists of a carrier at the frequency f_c of the sinusoidal tone with two sidebands extending to $f_c - f_n$ on one side and to $f_c + f_n$ on the other.

The amplitude of these sidebands depends on the modulation depth. This indicates the ratio of the mod-

[1] The inclusion of a measurement of this type in an international standard on which to judge the quality of audio tapes is currently being studied in the IEC (International Electrotechnical Commission).

[2] G. Frens, H. F. Huisman, J. K. Vondeling and K. M. van der Waarde, Suspension technology, *Philips tech. Rev.* **36**, 264-270, 1976 (No. 9).

[3] E. G. Trendell, The measurement and subjective assessment of modulation noise in magnetic recording, *J. Audio Engng. Soc.* **17**, 644-653, 1969.

ulating-signal amplitude to the amplitude of the carrier. In the case of our noise band, however, we cannot simply speak of an amplitude. We therefore put the modulation depth at $m = 1$ when, as in the modulation by a sinusoidal tone, the total mean power P_n of the sidebands is half that of the carrier P_c ; as an equation:

$$m = \sqrt{2P_n/P_c}. \quad (1)$$

In practice we prefer to use the signal-to-noise ratio S/N , i.e. the difference in dB between the level of the wanted signal and that of the modulation noise:

$$S/N = -10 \log_{10}(P_n/P_c) \text{ dB} = -20 \log_{10} m + 3 \text{ dB}. \quad (2)$$

The larger the value of S/N , the less is the likelihood that the noise will be audible.

We are interested in the signal-to-noise ratio $(S/N)'$ at which the modulation noise is only just audible. This depends on the frequency and amplitude of the sinusoidal tone and on the highest frequency f_n of the noise. We can determine this audibility limit experimentally with the arrangement shown by the block diagram in *fig. 4*, where a subject hears the signal through the headphones and can adjust the level of the noise to his audibility threshold. The mean result obtained in this experiment by a number of subjects with a sinusoidal signal at 1000 Hz is indicated by the measured points in *fig. 5*. We see that as the bandwidth of the noise increases, the noise level has to decrease very rapidly if the modulation noise is to remain inaudible.

An explanation for this, and for the clearly defined plateau at 1000 Hz, can be found from the threshold curves in *fig. 3*. We consider the threshold curve for a signal level of 80 dB and show it in *fig. 6* on a linear frequency scale, since this simplifies the representation of the sinusoidal tone with the two sidebands of equal width.

Depending on the bandwidth f_n of the modulating noise, there are four different cases.

A. The noise sidebands remain within the 'critical bandwidth' B_c . The human ear can integrate the incident acoustic energy within such a critical frequency band into a single total impression. In our case the noise will not then be distinguishable from the sinusoidal tone, but will be heard, if the noise level is high enough, as a distinct fluctuation in the amplitude of the sinusoidal tone. The critical band for our experimental tone of frequency $f_c = 1000$ Hz is about $\frac{1}{6} f_c$ wide; the noise bandwidth in this case is thus given by $f_n < \frac{1}{12} f_c \approx 80$ Hz. It appears from the measurements (*fig. 5*) that the audibility threshold here lies at a signal-to-noise ratio $(S/N)' \approx 20$ dB. It follows from equation (2) that this corresponds to a modulation index of $m = 0.14$. The definition we have taken for

the modulation index for noise signals implies that at $m = 1$ the standard deviation σ of the noise is equal to $1/\sqrt{2}$ times the amplitude a of the carrier. If $m = 0.14$, then $\sigma = 0.14a/\sqrt{2} = 0.1a$. This means that the amplitude fluctuates between $0.9a$ and $1.1a$ for 68% of the time, a variation of ± 0.8 dB. It is known that these are in fact fluctuations in level that are only just audible.

B. The noise exceeds the critical bandwidth, but has not yet reached the frequency f_1 , where there is a minimum in the masked hearing threshold. We see in *fig. 6* that the 'left shoulder' of the noise spectrum, i.e. the frequencies around $f_c - f_n$, will now be audible first. Because of the steep left-hand side of the masking curve, the audibility threshold falls rapidly with rising f_n (the steeply falling part of the curve in *fig. 5*).

C. The noise extends beyond f_1 . The modulation noise is audible at f_1 , irrespective of where the lower limit of the noise lies between 0 Hz and f_1 Hz. This explains the plateau in *fig. 5*.

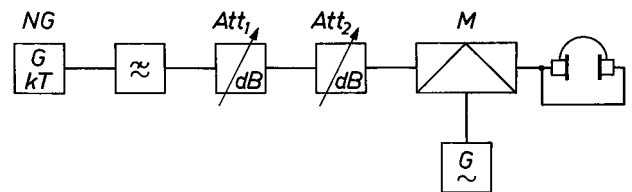


Fig. 4. Experimental arrangement for determining the audibility threshold of modulation noise, when the signal consists of a single sinusoidal tone. The noise, from a noise generator *NG*, is limited in bandwidth by a lowpass filter to a frequency f_n before being passed through two variable attenuators *Att₁* and *Att₂*. In the modulator *M* a sinusoidal tone from a sine-wave generator is modulated by this noise; the subject hears the output signal through headphones. The subject adjusts the attenuator *Att₂* to a level at which he can only just hear the modulation noise. There is a risk that in doing so he will be unconsciously influenced by the setting for a previous experiment; the experimenter therefore always sets the attenuator *Att₁* to a different position between the individual experiments.

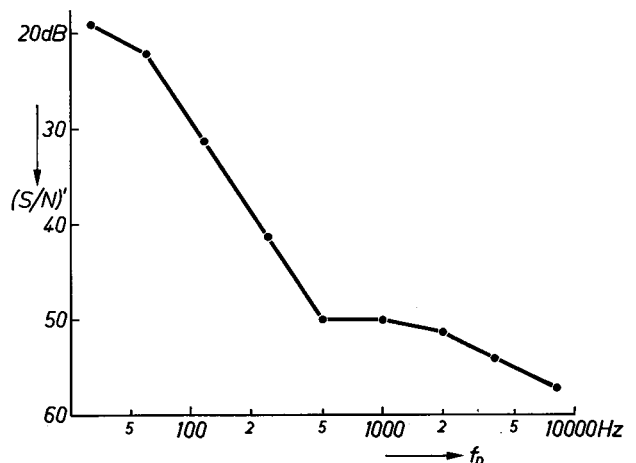


Fig. 5. Audibility threshold of modulation noise for a sinusoidal tone at 1000 Hz. The signal-to-noise ratio $(S/N)'$ at which the noise is only just audible is plotted as a function of the bandwidth f_n of the noise modulating the sinusoidal tone. The tone has a sound-pressure level of 80 dB.

D. If the bandwidth of the noise is greater than 1000 Hz, then 'the lower sideband is reflected against 0 Hz'. This implies that the energy content of the lower part (up to $f_n - 1000$ Hz) is doubled, so that the level rises by 3 dB. In fig. 6 this is shown for $f_n = 1500$ Hz, and the doubled sideband thus extends beyond f_1 . Because of this the threshold has still fallen by 3 dB; the modulation noise is audible at f_1 as it was before.

On the right-hand side of the masking curve the hearing threshold has a second minimum, whose frequency we call f_2 . For the masking curve relating to a signal level of 80 dB, both minima are at about the same level (fig. 3). For the 60-dB curve, however, the second minimum is about 10 dB lower. If the noise band at a signal level of 60 dB is made so wide that the upper sideband reaches this minimum, then modulation noise at a level about 10 dB lower becomes audible, and we would then have to distinguish a fifth and subsequent cases.

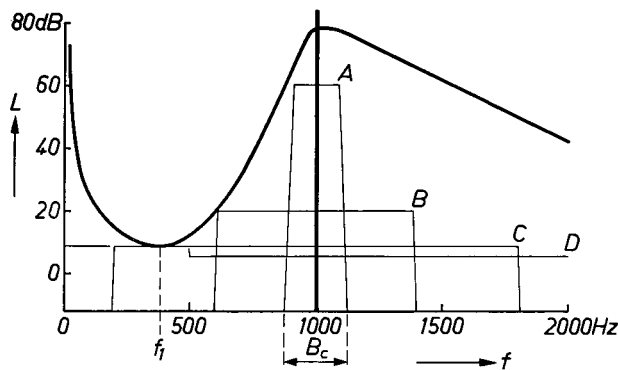


Fig. 6. The threshold curve for $L_n = 80$ dB from fig. 3, displayed on a linear frequency scale. The figure includes the frequency spectrum of a sinusoidal tone at 1000 Hz modulated in amplitude by noise in the band 0 to f_n Hz, for different values of f_n (cases A, B, C, D). In each case the level is shown at which the modulation noise is only just audible. B_c critical bandwidth at 1000 Hz. f_1 frequency of the left-hand minimum of the threshold curve.

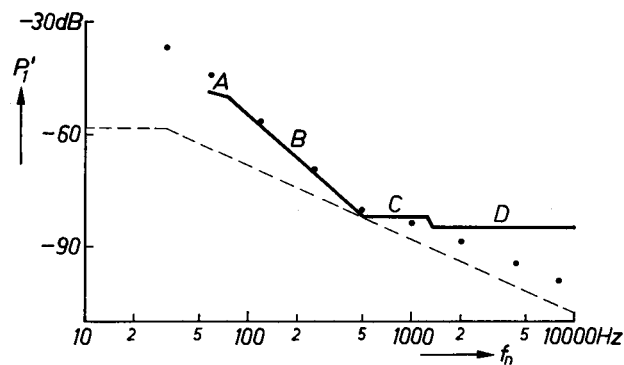


Fig. 7. Power density $P_1'(f)$ at which the noise sidebands of a sinusoidal tone at 1000 Hz are only just audible; the sinusoidal tone is amplitude-modulated by white noise in a frequency band $0 - f_n$. The curve was derived from the masked hearing threshold for a sinusoidal tone at a level of 80 dB (fig. 3). The measurement points are from fig. 5. The dashed curve gives the frequency spectrum of modulation noise of a level that can only just be heard.

We shall confine ourselves here, however, to the one case of a sinusoidal tone of 80 dB. From the foregoing we can deduce the power density P_1' (the power per Hz of bandwidth) that the noise sidebands should have as a function of the cut-off frequency f_n for the noise to be raised to the audibility threshold. This is shown in fig. 7. In this figure we have repeated the measurement points from fig. 5, but now the power density of the noise is plotted instead of the signal-to-noise ratio. In both cases the power of the 1000-Hz sinusoidal tone is the reference (0 dB), but since the power in 1 Hz of the noise band is very small, the ratios to this reference, and hence the difference in decibels, are much greater. It can be seen that the calculated threshold levels are in reasonable agreement with the measurements.

From fig. 7 we can also read off the maximum permissible level of the modulation noise occurring in practice around a sinusoidal tone of 1000 Hz if the noise is to remain inaudible. For this purpose we can draw in fig. 7 the approximating spectrum from fig. 2. As soon as the modulation-noise spectrum goes above the dashed curve, the modulation noise becomes audible, first of all at frequencies around f_1 .

Annoyance

Annoyance may be said to be experienced when the modulation noise occurs with a signal having a meaningful content, and that is usually not a sinusoidal tone but music. Here, however, the *audibility* of the noise is different from that in the experiments described above; the noise is now less easily perceived. This is because its occurrence is unpredictable, owing to the continual changes of volume and frequency in music. What is more, music never consists of a single sinusoidal tone but always contains more than one frequency and often very many frequencies, so that the noise may be masked over a large part of the hearing spectrum.

It follows from this that recordings of a solo instrument will be more vulnerable than those of an orchestra. Looking for the most vulnerable situation in which to carry out the annoyance determinations, we compared twelve solo instruments with each other: violin, cello and double-bass; piccolo, flute, oboe, clarinet and bassoon; trumpet, horn, trombone and tuba. A passage played by each instrument, lasting 25 seconds, was recorded a number of times, modulated by noise at different levels. The subjects were asked to make an assessment in terms of the *h*-scale described above. The most vulnerable instrument proved to be the flute, followed by the piccolo, oboe and horn. The double-bass, cello, tuba and bassoon were relatively unaffected. This confirms that modulation noise is heard most easily in music with a single (high) fundamental tone and with a small number of higher harmonics.

The somewhat breathy character of the flute did not apparently lessen the audibility of the modulation noise, particularly in its third octave.

We also tried to find the most sensitive listening conditions. These were to listen through headphones to a stereophonic signal. The annoyance determinations were carried out under these conditions, incoherent noise being presented in the left-hand and right-hand channels as it would be in actual listening to stereophonic recordings.

After these preparations we were ready to begin with the annoyance determination proper. This was done in a listening experiment on a somewhat larger scale. Eighteen subjects took part, including eight audio technicians who were professionally responsible for the quality control of sound recordings.

These subjects were presented with 12 identical fragments of music each lasting 20 seconds and recorded in random order with six different signal-to-noise ratios; each signal-to-noise ratio was thus presented twice. The modulation noise approximated the actual frequency spectrum, as described earlier (fig. 2): flat up to 35 Hz, and decreasing by 6 dB per octave above this frequency. The subjects assigned an h -value to each fragment.

The series of 12 fragments belonged to different categories: orchestral (Handel, *Water Music*), piano (Schumann, *First Sonata*) and a passage from a flute solo (Debussy, *Le Syrinx*). In addition to these fragments the subjects were also occasionally presented with a sinusoidal tone of 1000 Hz (also lasting 20 seconds), again recorded on magnetic tape. This was done to enable us to deduce the influence of the

use of magnetic recordings from a comparison with the experiments using a directly generated sinusoidal tone. All the fragments were presented at a volume such that the loudest passages were 70 dB above the threshold of audibility.

The means of the assessments made by the eighteen subjects are presented in fig. 8. The results confirm that flute music is the most sensitive of all to modulation noise. For flute music the modulation noise is perceptible as soon as the signal-to-noise ratio goes below about 40 dB. We know (see fig. 6) that the modulation noise then becomes audible in a frequency band near 500 Hz, and is thus clearly distinguishable from the music.

With orchestral music, on the other hand, the modulation noise does not become audible until the signal-to-noise ratio is less than about 20 dB. Here only the very low-frequency components of the noise are not masked by the signal and these are heard as an audible amplitude modulation of the music. With increasing modulation depth this is soon experienced as very annoying: curve *O* in fig. 8 rises steeply.

With the sinusoidal tone the modulation noise becomes audible when the signal-to-modulation-noise ratio is less than about 45 dB. The experiments described above can be compared with experiments using a 1000-Hz sinusoidal tone that had not been recorded on tape by referring to the dashed curve in fig. 7; this gives the spectral power density of modulation noise with the spectrum used here, which is only just audible with a 1000-Hz sinusoidal tone at 80 dB. In this case, a recalculation gives a signal-to-noise ratio of 42.5 dB. The figure of about 45 dB found with a sinusoidal tone on tape agrees sufficiently well with this to make it reasonable to assume that the modulation noise inherent in this tape recording did not play any significant role.

Drop-outs

As we saw earlier, the short interruptions (drop-outs) that may occur during the playback of a magnetic tape can be attributed not only to inhomogeneities in the tape but also to dirt, creases in the tape, etc. Nevertheless, there are considerable differences on this point between various types of tape, and a low number of drop-outs is regarded as an indication of tape quality [4].

The drop-outs vary in duration from a few milliseconds to more than 100 milliseconds; the short drop-outs, however, are much more numerous than the long ones. The attenuation D is generally lower in the short drop-outs, since the level seldom changes at a rate faster than 1 dB/ms.

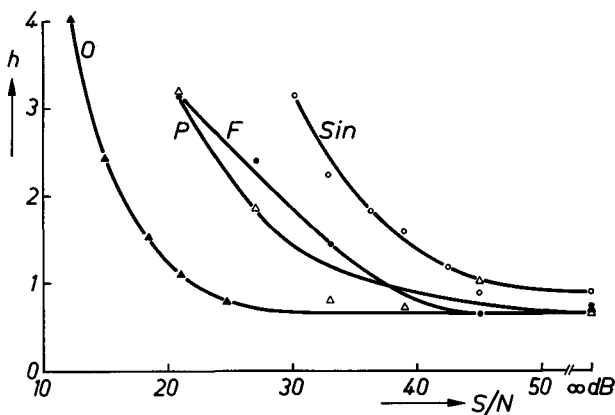


Fig. 8. The annoyance value h of modulation noise at different signal-to-noise ratios S/N for different categories of music and for a sinusoidal tone at 1000 Hz. *O* orchestra. *P* piano. *F* flute. *Sin* sinusoidal tone. The results are mean values for eighteen subjects. The fact that the mean values are not at $h = 0$ (modulation noise inaudible) even in the absence of deliberately applied modulation noise, must be attributable to the tendency of subjects to avoid extreme values of the h -scale.

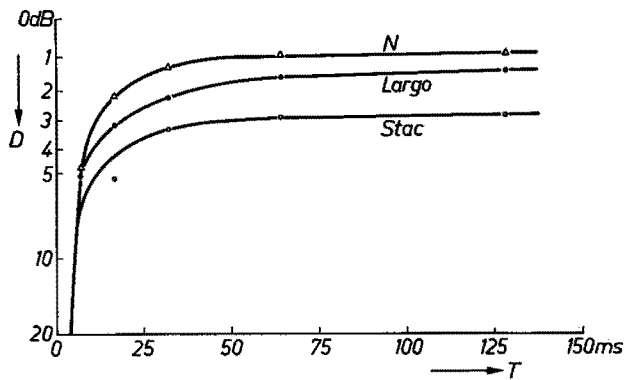


Fig. 9. The depth D which drop-outs of duration T must have to be only just audible. Curve N relates to 'white' noise, curve $Largo$ to slow, sustained music and curve $Stac$ to staccato music. Mean values for two subjects for regular repetition of the effect at a frequency of 2 Hz.

Drop-outs of this kind are difficult to avoid entirely. In sound recording it is sufficient if they cause no significant perceptual disturbance. It is therefore important to examine the conditions under which they are audible — depending also on the programme on the tape — and, going a step further, to consider how much annoyance they cause when they are audible. This annoyance can then be a measure of the quality of the tape in this respect. The answer to these questions can again only be obtained from listening experiments in which the questions are put to the subjects.

To determine audibility and annoyance, it is desirable to have drop-outs whose parameters can be varied. A special instrument was therefore built for the listening experiments; this instrument permits attenuations of variable duration and depth to be inserted in a signal. The fall and rise times of the signal can also be varied.

Audibility

The effect we are considering may be regarded as amplitude modulation of short duration. This means that sidebands will appear for a short time in the frequency spectrum. These sidebands are most likely to be heard when the acoustic signal itself is a narrow-band signal. When a sinusoidal tone drops out and recovers sufficiently quickly clicks can in fact be heard which are louder the steeper the transition.

In reality we rarely encounter pure sinusoidal tones, so that clicks are not heard. For an initial exploratory audibility experiment we therefore chose a signal consisting of 'white' noise; even when the transitions are steep, no clicks are heard.

This initial experiment was carried out with two subjects, who heard the noise signal through head-

phones. At a rate of twice per second the signals were then interrupted for periods of 4, 8, 16, 32 and 64 milliseconds; the subjects were asked to adjust the depth of the attenuations to a level at which they were only just audible. The settings chosen by the two subjects showed good agreement; the mean results are given as curve N in fig. 9. Attenuations lasting 4 ms are found to be inaudible in white noise, however deep; longer attenuations, on the other hand are found to be audible when their depth is only 1 dB.

To make the experiments more realistic, we repeated them using music. Since the nature of the music was likely to have some influence, two contrasting pieces were chosen: one was a slow and solemn piece (Handel's 'Largo' arranged for string orchestra) and the other was a dynamic and staccato piece (Schubert's *Marche Militaire* No. 1 played by a symphony orchestra). The results are also given in fig. 9. As might be expected, the interruptions in staccato music are not so readily audible as in sustained music.

It may in any case be concluded from these audibility experiments that interruptions shorter than 10 ms are in practice inaudible. When interpreting the results it should also be borne in mind that the perceptibility of the drop-outs is virtually at a maximum, because of the periodic repetition used and because the subject can adjust the threshold himself. In practice the drop-outs occur at unpredictable moments and the attenuations must therefore be deeper for them to be audible. We shall return to this point presently. The limits of audibility thus found provide indications as to how long and how deep the drop-outs have to be in listening experiments designed to determine their annoyance value.

Annoyance

The subject's assessment of the annoyance caused by drop-outs will naturally depend to a great extent on how interested he is, on the nature of the music and on the listening conditions. We have already mentioned that the effect is more annoying in slow and sustained music than in fast, staccato music; the interruptions are also more noticeable in recordings with a great deal of reverberation than in those with little reverberation, and more noticeable with solo instruments than in orchestral playing. More annoyance is experienced with single-track recordings than with stereophonic two-track recordings, where the two tracks are not usually affected simultaneously. The drop-outs are more clearly perceptible when listening through headphones than when listening to loudspeakers; sound

[4] W. van Keuren, An examination of drop-outs occurring in the magnetic recording and reproduction process, *J. Audio Engng. Soc.* 18, 2-19, 1970.

reflections in the room then appear to have some smoothing effect.

To avoid having to differentiate the results to allow for all these conditions, we concentrated the experiments on the worst case: sustained music with much reverberation, heard through headphones. Very suitable pieces were an organ solo (M. E. Bossi, *Thème et variations*, Op. 115) and a violin solo (J. S. Bach, Sonata No. 1 in G, BWV 1001).

To allow more weight to be attached to the annoyance evaluations a larger number of subjects was selected: fourteen, including six audio technicians. In assessing a number of fragments of music they were asked to express their opinion in a numerical value on the h -scale referred to above.

The annoyance of the short drop-outs depends partly on whether they occur in isolation or in groups. In the listening experiments the two cases were kept distinct. First of all, fragments of music 20 seconds long were played in which one drop-out occurred with a length of 10, 30, 128 or 474 ms and a depth of 4, 8 or 16 dB (the combination of 10 ms and 4 dB was omitted). The annoyance values were averaged over all the subjects and over all the pieces of music and the result is shown in *fig. 10*. The scatter in the values that were averaged was such that 95% fell within a region of 0.2 to 0.5 units. In this figure, curves for $h = 0, 1, 2, 3$ have been interpolated between the measured values.

The h -scale is seen to have been fully used by the subjects, and there was even some extrapolation beyond $h = 3$. The annoyance experienced from a drop-out longer than 100 ms is apparently not very dependent on the duration, and this dependence is greatest when the attenuation is very high.

Fig. 10 also shows the audibility threshold for slow and sustained music, as represented by the *Largo* curve in *fig. 9*. As can be seen, this does not coincide with the curve $h = 0$ but lies about 1.5 dB above it. The difference can be explained from the fact that the signal did not drop out at fixed times during the annoyance experiments, but unexpectedly, and furthermore the subjects could not adjust the magnitude of the attenuation to the audibility threshold. The curve $h = 0$ is therefore more realistic than the *Largo* curve.

The effect of repetition on the annoyance experienced was investigated by introducing the drop-outs in the same piece of music not once but twice, four times or eight times; in this case the drop-out duration was always 31 ms and the attenuation 8 dB. The annoyance then appears to increase almost linearly with the number of drop-outs per fragment (*fig. 11*), at least as long as the drop-outs do not follow one another too rapidly. If the interval between them becomes less than 1 s, this causes additional annoyance (*fig. 12*).

The DAMA annoyance meter

For comparing different tape samples the manufacturer cannot of course keep on recruiting subjects to take part in listening experiments. The DAMA annoyance meter was therefore designed ('Drop-out Annoyance Measuring Apparatus'). A photograph is shown in *fig. 13*. This instrument detects short interruptions during the playback of the tape, and on the basis of

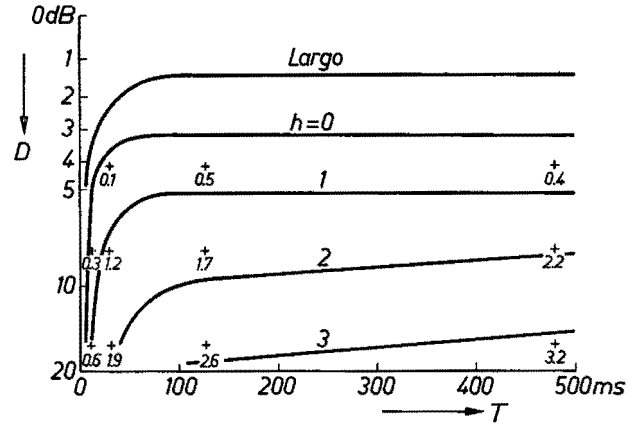


Fig. 10. Lines of equal annoyance rating h , drawn in a field of annoyance evaluations of drop-outs of duration T and depth D . The experiments were made with fragments of music lasting 20 s, each containing one drop-out. The h -values at the measured points are the mean assessments for 14 subjects. The *Largo* curve from *fig. 9* is repeated here.

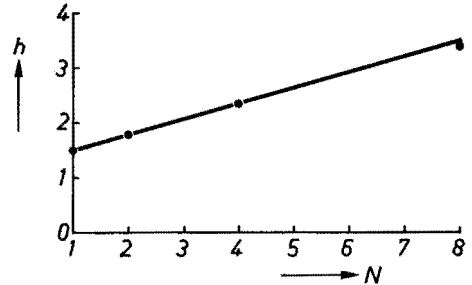


Fig. 11. The annoyance rating h (mean for 14 subjects) plotted against the number of drop-outs N contained in one fragment of music lasting 20 s. Each additional drop-out increases the annoyance rating h by about $\frac{1}{4}$.

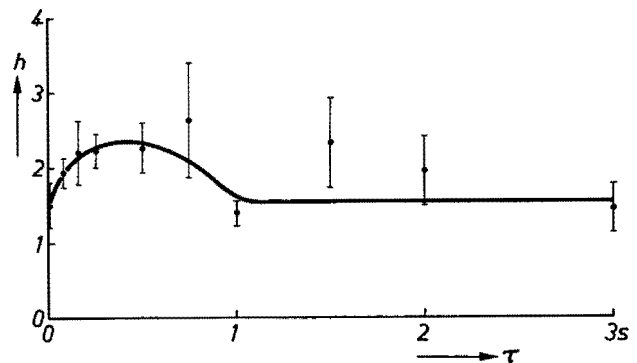


Fig. 12. When the time τ between two drop-outs is shorter than about one second, the annoyance caused is greater than that corresponding to the curve in *fig. 11*. If the h -values there are reduced to $N = 1$, i.e. if they are reduced by $\frac{1}{4}$ ($N - 1$), the result is $h \approx 1\frac{1}{2}$. If the interval τ is taken into consideration, however, this h -value only applies when $\tau > 1$ second.



Fig. 13. The DAMA annoyance meter ('Drop-out Annoyance Measuring Apparatus'), which automatically determines the annoyance ratings of drop-outs in the signal on an audio tape.

their duration, depth and frequency it calculates an annoyance value that links up as closely as possible with the findings of the listening experiments described [5]. The instrument gives a digital reading of the annoyance value, which can also be recorded on paper. The measurements are carried out on tapes on which a continuous sinusoidal tone, typically at 3000 Hz, is recorded.

The instantaneous value of the signal, measured by a peak detector, is compared in the annoyance meter with various thresholds, which are in a fixed ratio to the signal amplitude averaged over a long period. Differential amplifiers detect which thresholds are exceeded and thus determine the magnitude of the attenuation. In another part of the instrument, which contains delay lines for 10 ms, 20 ms and 50 ms, the duration is divided into different categories. A switching matrix then delivers an annoyance value, depending on the depth and duration of the drop-out, which corresponds to the h -numbers in fig. 10. The annoyance value is stored in a register.

The annoyance meter divides the signal into periods of 20 seconds. If the signal drops out repeatedly in one period, h -points are added as 'penalty points'. If the repetitions occur within one second, the annoyance values are further increased. The annoyance meter sums the annoyance values over 20 seconds. A typical recording is shown in fig. 14.

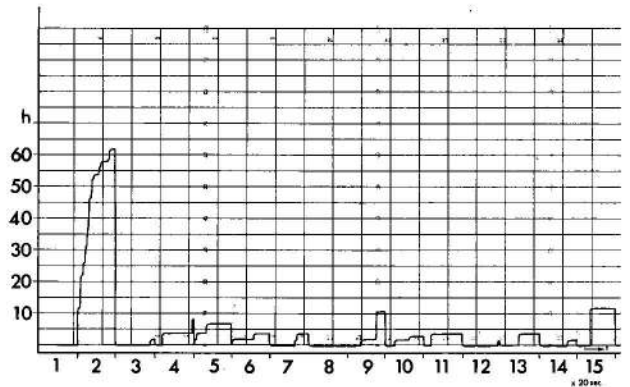


Fig. 14. Example of an automatic recording of the annoyance rating h during 15 successive periods of 20 s, i.e. during a time of five minutes. During each period the h -values are accumulated; at the end of each period the h -counter is reset to zero. In period 2 the annoyance value is by far the greatest. In period 3 some annoyance is registered only towards the end (up to $h = 2$), in period 8 no annoyance is registered at all. To avoid fractions, the figures on the h -scale here are four times greater than in the listening tests.

Summary. In addition to a constant background noise, sound recordings on magnetic tape may also suffer from modulation noise and 'drop-outs'. The level of the modulation noise is proportional to that of the signal. Modulation noise is more readily audible in recordings of solo instruments than in orchestral music; listening tests have shown that for the flute the audibility threshold lies at a signal-to-noise ratio as high as 40 dB. The frequency with which drop-outs occur is a matter of tape quality. Listening tests have been carried out to determine the annoyance caused by drop-outs as a function of their duration, the degree of attenuation and the frequency of occurrence. The results of these experiments have been applied in the DAMA annoyance meter, which can measure these quantities for an audio tape and assign a quality rating to it.

[5] D. J. H. Admiraal, A drop-out annoyance measuring apparatus 'DAMA' to check magnetic tapes, to be published shortly.