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THE INTERMODULATION TESTING OF SOUND BROADCAST TRANSMITTERS

THE PROBLEM

IN ANY SYSTEM OF SOUND COMMUNICATION the listener is the final judge of system quality. It is the listener who must judge whether the sound heard is a close enough reproduction of the 'live' original. Unfortunately for engineers the amount of distortion that a listener will tolerate depends on many factors, among them, the type of sound he is listening to, where he is listening to it, whether he is a critical listener or not, and even the mood he is in. This makes it necessary for the equipment designer to be able to make measurements to establish the quality of his equipment. It is also important to establish a single universal method of measurement so that valid comparisons between equipments may be made.

In spite of the fact that no sane person would ever choose to spend time listening to a single pure tone, most equipment tests are carried out with such an input. Distortion of this single tone within a piece of equipment produces 'harmonics', that is, multiple frequencies of the single test tone. The relative amount of these harmonics is measured and used to assess the quality of the equipment.

One may ask, however, to what extent the presence of these harmonics upsets the listener. The very name 'harmonic' indicates that the sound is pleasant rather than discordant, and the sound of all musical instruments contains a large number of harmonics. As is known, the characteristic sound of an instrument depends on the relative amplitudes of its harmonics. In the classic example of the oboe, the fundamental is entirely absent and from the audio engineer's point of view the sound may be said to be 100% distortion. Clearly then, the presence of harmonic distortion may affect the musical quality of the sound, but it does not in itself produce any unpleasant effect.

TWO-TONE TESTS

It is, however, clear from listening tests that non-linearities can produce some very unpleasant effects and so one must look to another mechanism to explain this. In order to understand what happens notice that, in general, the waveform to be transmitted through the system is of a complex nature consisting of many rather than one frequency. In music these frequencies are normally harmonically related, but for speech this is not necessarily so. Since it is difficult both mathematically and practically to deal with a large number of discrete tones, as a first step consider what happens to two tones, and further to simplify the analysis consider initially two tones of equal amplitude.

Results of a mathematical analysis are shown in Table 1. The transfer characteristic of the equipment is assumed to contain three terms only at this stage, one proportional to $(V \text{ in})$, one to $(V \text{ in})^2$ and one to $(V \text{ in})^3$. Later two further terms will be considered,

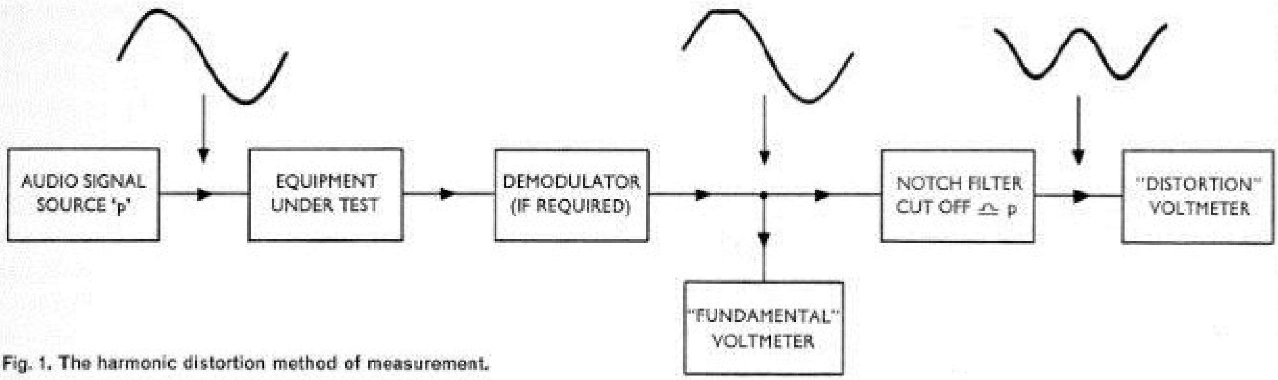

Fig. 1. The harmonic distortion method of measurement.

but these are the predominant terms and enable an initial pattern to be obtained. The input is of two audio tones of angular frequency p and q, and in the radio-frequency amplifier these are assumed to modulate a carrier of angular frequency w. In the case of the r.f amplifier only those outputs lying within the passband of the amplifier tuned circuits are shown in the table. It will be seen that in addition to the harmonic distortion terms (at frequencies $2p$, $2q$, $3p$ and $3q$) there are also outputs at frequencies obtained by mixing together p with its harmonics and q with its harmonics. These additional products are the 'intermodulation products'. Clearly although p and q may be harmonically related, these intermodulation products (I.P's) will not, in general, be harmonically related to p or q or each other. Moreover, they are of comparable amplitude with the harmonic distortion products. The terms at frequencies $p+q$ and $p-q$ are equal or nearly equal in amplitude to those at $2p$ and $2q$. These products all arise from the V^2 term and are hence known as second-order products. The products in $2q-p$, $2p-q$, $2q+p$, $2p+q$ are about three times as large as the terms in $3p$ and $3q$. These arise from the V^3 term and are third-order products. It is these discordant intermodulation products which cause offence to the listener and which are the reason for ensuring the linearity of the transmission system. It may be argued, therefore, that what should really be measured are the I.P's.

Table 1
RELATIVE AMPLITUDES OF DISTORTION PRODUCTS

Assumed transfer characteristics:
A.F stages: $V\,\text{out} = a_1(V\,\text{in}) + a_2(V\,\text{in})^2 + a_3(V\,\text{in})^3$
R.F. stages: $V\,\text{out} = b_1(V\,\text{in}) + b_2(V\,\text{in})^2 + b_3(V\,\text{in})^3$
$V\,\text{in} = \cos pt + \cos qt$ for a.f stages
$V\,\text{in} = \cos wt[1 + m(\cos pt + \cos qt)]$ for r.f stages

Frequency	*A. F distortion product*	*R. F distortion product*
$p-q$	$\frac{1}{2}a_2$	$\frac{15}{16}b_3\,m^2$
$2q-p$	$\frac{3}{4}a_3$	$\frac{5}{32}b_3\,m^3$
q } Input	a_1	b_1
p } frequencies	a_1	b_1
$2p-q$	$\frac{3}{4}a_3$	$\frac{5}{32}b_3\,m^3$
$2q$	$\frac{1}{2}a_2$	$\frac{1}{2}b_3\,m^2$
$p+q$	$\frac{1}{2}a_2$	$\frac{15}{16}b_3\,m^2$
$2p$	$\frac{1}{2}a_2$	$\frac{1}{2}b_3\,m^2$
$3q$	$\frac{1}{4}a_3$	$\frac{1}{16}b_3\,m^3$
$2q+p$	$\frac{3}{4}a_3$	$\frac{5}{32}b_3\,m^3$
$2p+q$	$\frac{3}{4}a_3$	$\frac{5}{32}b_3\,m^3$
$3p$	$\frac{1}{4}a_3$	$\frac{1}{16}b_3\,m^3$

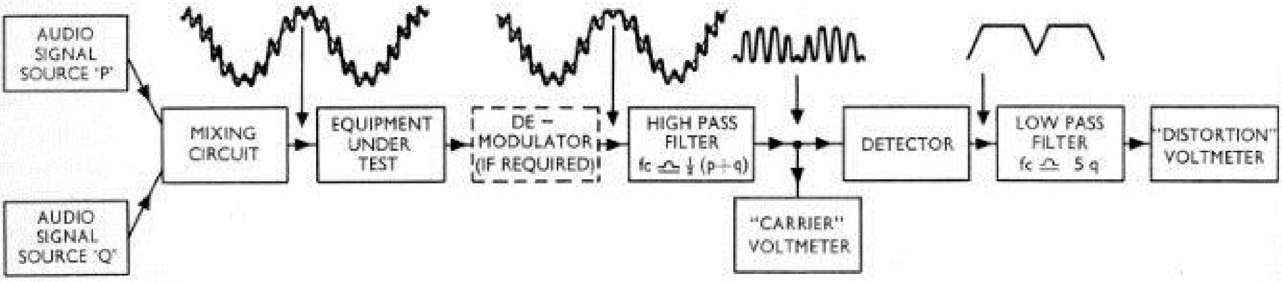

Fig. 2. S.M.P.T.E/B.S method of measurement: $V_p \bumpeq \frac{1}{4}V_q$, $p \bumpeq 50q$.

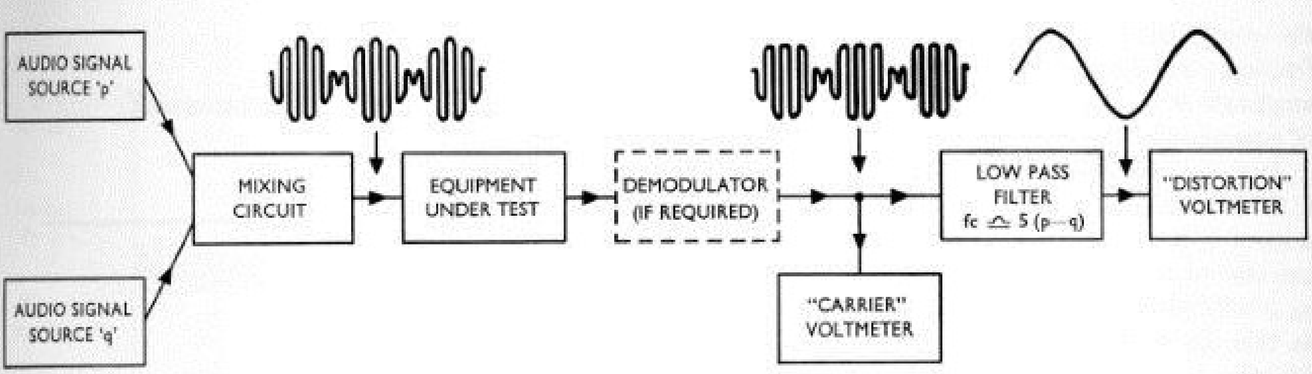

Fig. 3. C.C.I.F method of measurement $Vp = Vq$, $p \doteq q$.

STANDARD METHODS

Two standard inputs and three methods of measurement are in use in various fields for this purpose.

A block diagram of the normal test arrangement for harmonic distortion measurement is shown in Fig. 1. The demodulator is required where the equipment under test is a modulated r.f device such as a sound broadcast transmitter. Normally one meter is used and is switched between the 'fundamental' and 'distortion' positions. The notch filter may be replaced by a high-pass filter.

Fig. 2 shows the test arrangement for one system of I.P measurement which has been known for some years as the S.M.P.T.E method and more recently adopted in British Standard 3860: 1965 for audio equipments. In this system of measurement a low-frequency tone of relatively large amplitude is used in conjunction with a high-frequency low-amplitude tone (normally one-quarter amplitude, fifty times frequency). In effect the low-frequency tone sweeps the high-frequency tone across the amplitude range of the equipment. The system is similar to that used for measuring the differential gain in television equipment. At the output of the equipment the low-frequency tone is removed by a high-pass filter and the high-frequency tone modulated by the low-frequency tone by an amount depending on the non-linearity of the equipment remains. This tone is then detected in the same way as an amplitude-modulated carrier and the modulation depth used as a measure of the intermodulation. Both these systems produce a single measurement of intermodulation.

A second system of measurement known as the C.C.I.F (strictly C.C.I.T.T) method is diagrammatically shown in Fig. 3. This uses two equal-amplitude tones with a small frequency difference. The non-linearities of the equipment cause the two tones to beat together to produce a difference-frequency output. The test tones are removed from

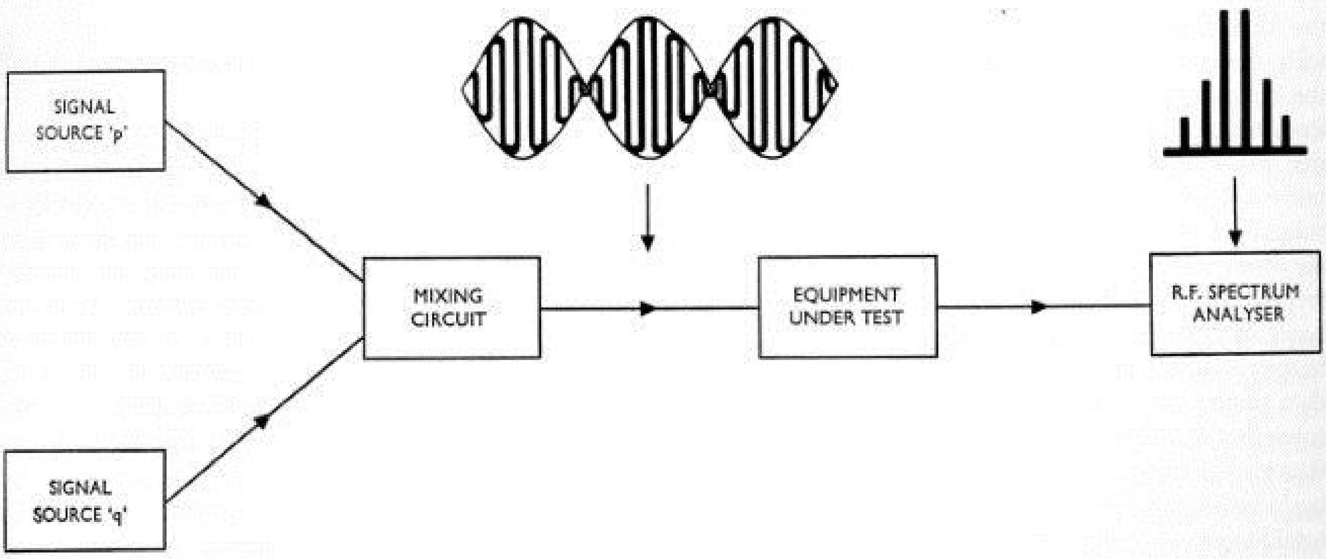

Fig. 4. C.C.I.F/C.C.I.R method of measurement.

the output by a low-pass filter and this difference-frequency amplitude, measured relative to the peak amplitude of the input signal, is taken as the measure of intermodulation.

The C.C.I.F method is adapted according to C.C.I.R rules for use with r.f amplifiers in i.s.b transmitters (Fig. 4). In this case one obviously cannot use one tone of the input at a low audio frequency as it will not pass through the input-tuned circuits, so that the S.M.P.T.E/B.S method cannot be used. Equally it will not be possible to measure the difference frequency by the C.C.I.F method. However, by using two tones at r.f frequencies at small frequency separation and of equal amplitude and observing that there are intermodulation products of the form $2p-q$, $3p-2q$, etc, close to the test frequencies, a measure of non-linearity can be obtained. In order to do this it is necessary to use a narrow-band r.f spectrum analyser which displays on an oscilloscope the r.f spectrum around the test tones. A vertical scale on the face of the cathode-ray tube is calibrated directly in dB and the relative magnitudes of the individual distortion products can be read off directly.

COMPARISON OF SYSTEMS

In deciding which, if any, of these test systems to use with broadcast transmitters consideration must be given as to whether each of these methods checks all the possible distortion products. Since the transmitter will contain both audio and r.f stages, both these cases must be taken into account.

Fig. 5 illustrates the simple spectrum of frequencies produced by a single-tone input to an amplifier. The transfer characteristic of the amplifier is here, and in the following discussion, assumed to extend up to the fifth term, i.e one in V^5, and so harmonics up to the fifth are present. The length of the lines indicates from which of the terms in the transfer characteristic the particular product is derived, and does not necessarily indicate their relative amplitudes. If the stage is an audio amplifier and frequency p is towards the lower end of the passband, then all these distortion terms (harmonics) are likely to fall within the passband of the equipment. A measurement of total harmonic distortion will give a proper indication of the quality of the equipment. If however p lies towards the upper frequency limit of the equipment, then the harmonics will be attenuated by the drooping high-frequency response of the equipment and the total harmonic distortion measurement will be unduly optimistic. With an r.f stage the harmonics will all lie outside the passband of the tuned circuits and will be severely attenuated.

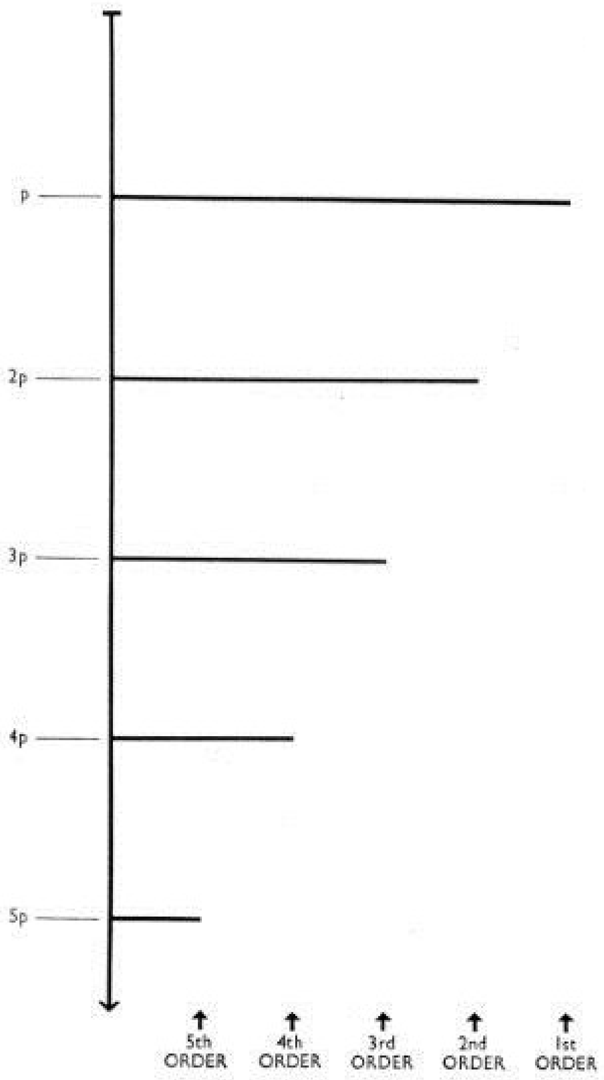

Fig. 5. Amplifier output spectrum for single-tone input (harmonic distortion).

The corresponding spectrum from a two-tone input of the C.C.I.F type is shown in Fig. 6. With this system the low-frequency intermodulation products are measured and the diagram shows that these arise from even-order terms only, so that the method leaves the odd-order terms unmeasured. It is not unknown for the third-order term to be the most prominent, a drawback in this method of testing. In the C.C.I.R method of testing r.f amplifiers, where the same type of input is used, the frequencies near to the test tones are measured and these can be seen to be odd-order products only. This might be considered a similar shortcoming of method, but in fact it is impossible for even-order distortion terms to produce

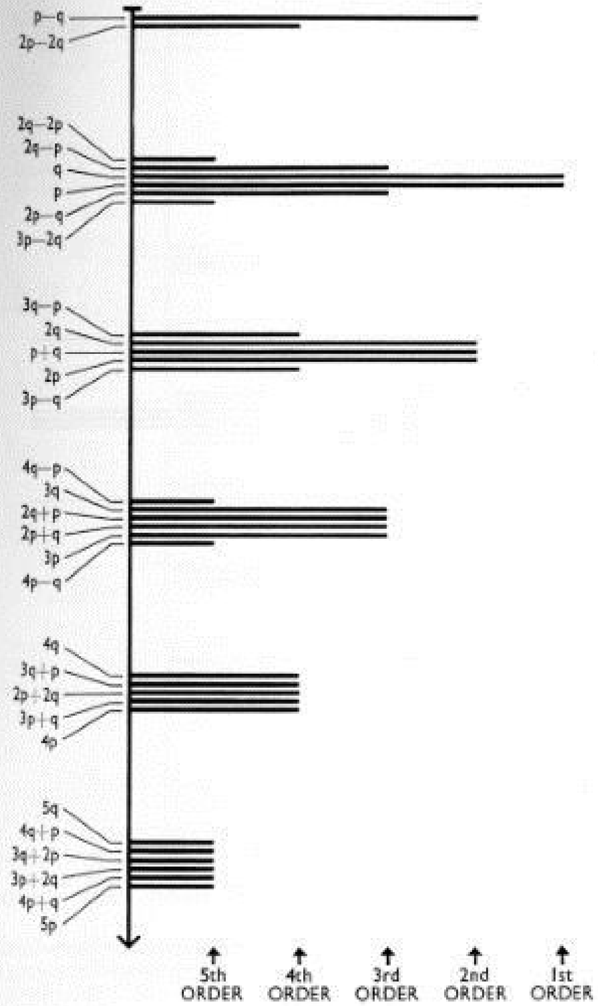

Fig. 6. Amplifier output spectrum for two-tone input ($p \simeq q$) (C.C.I.F method). Drawn for $\frac{1}{2}(p+q) = 20(p-q)$, e.g $p = 1025$Hz, $q = 975$Hz.

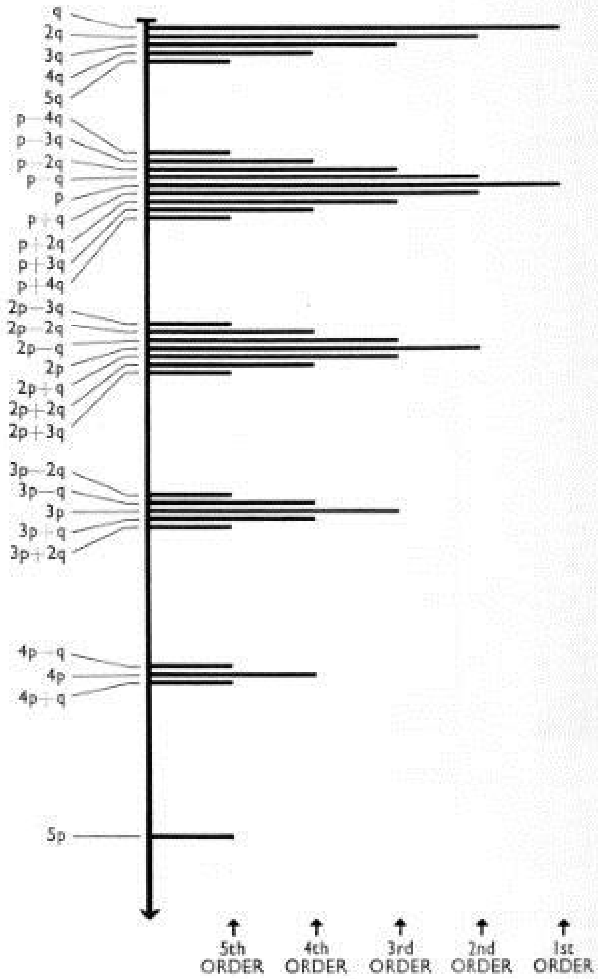

Fig. 7. Amplifier output spectrum for two-tone input (S.M.P.T.E/B.S method). Drawn for $p = 20q$, e.g $p = 1000$ Hz, $q = 50$ Hz.

distortion products lying within the passband of an r.f amplifier. This phenomenon will appear again in other diagrams. It is also interesting to notice that at the r.f harmonic frequencies the number of distortion sidebands, arising from a given distortion term, increases as the harmonic frequency increases. This increase in distortion can be clearly heard when listening to the harmonics of an amplitude-modulated transmitter.

Fig. 7 shows the spectrum obtained with the S.M.P.T.E/B.S method. In this case, the terms measured are those lying around frequency p and amplitude-modulating it. It will be seen that all distortion terms produce intermodulation in this region so that no term is neglected in the measurement. Furthermore, unless $p+4q$ lies outside the passband, which means that p lies very close to the end of the passband itself, the result is not affected by the high-frequency limit of the response curve. For audio work it is therefore clearly superior, hence its choice as the British Standard.

AMPLITUDE-MODULATED WAVES

What happens when an amplitude-modulated wave with single-tone modulation is applied to an amplifier can be appreciated by reference to Fig. 8. Note that around the carrier frequency, distortion products corresponding to audio harmonics, are generated but that they all arise from odd-order terms. In such circumstances if the test tone is well within the passband of the amplifier, then total harmonic distortion

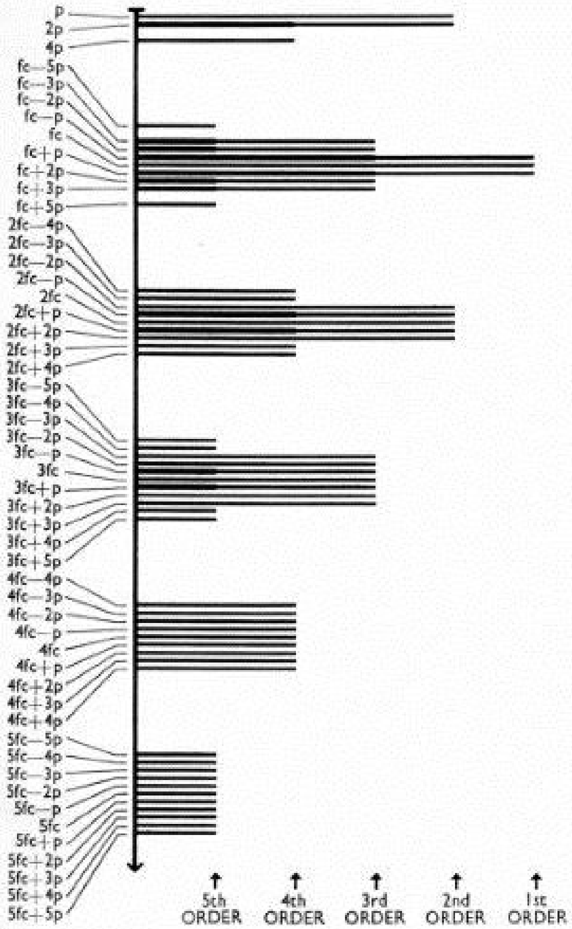

Fig. 8. Amplifier output spectrum for single-tone modulated carrier input.

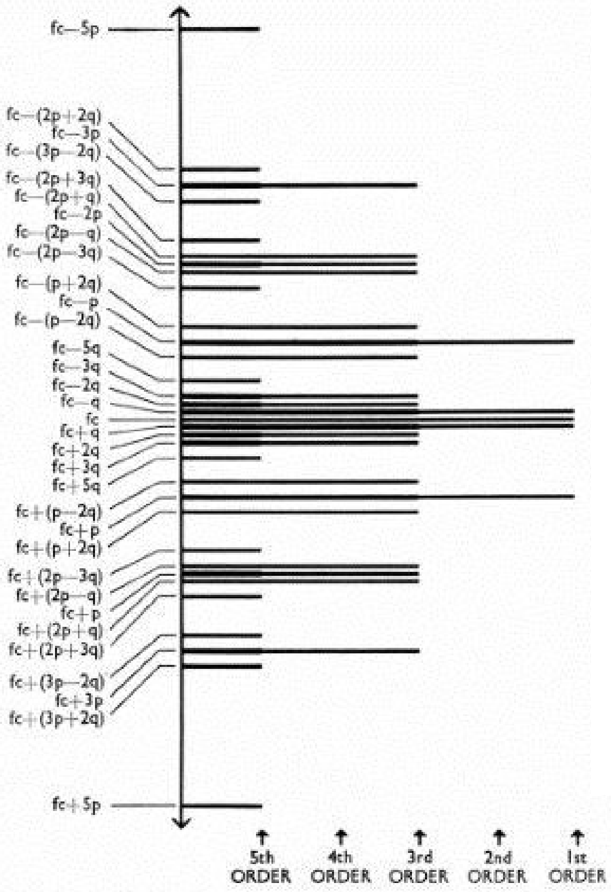

Fig. 9. Amplifier output spectrum near carrier frequency for two-tone modulated carrier input (S.M.P.T.E/B.S method). Drawn for $p=10q$, e.g $p=1000$Hz, $q=100$Hz.

testing will give a proper answer, but if p is towards the top of the passband then the answer will be too optimistic.

Fig. 9 shows the spectrum produced by a carrier modulated by two tones of the S.M.P.T.E/B.S type, which is considered to be the best for audio equipment. Only products within the r.f passband are included for clarity. If the distortion products lying near to the higher modulating frequency p are examined, only a single product arising from the third order can be seen, so that any fifth-order distortion will not be measured. Notice again the total absence of even-order distortion products.

The spectrum is produced by two tones of the C.C.I.F type, where the low-frequency, even-order products normally measured in this test method are totally absent (Fig. 10). However, both third-order and fifth-order terms are present around the test-tone frequencies so that a method which measures these to give the non-linearity of the stage could be used.

CONCLUSION

For a transmitter which will, in general, contain both audio and radio-frequency stages an input of two C.C.I.F-type tones will produce even-order distortion products at low frequencies in the audio stages and odd-order products near to the test-tone frequencies in both the audio and r.f stages. The effects of frequency-response limits can be eliminated by choosing the difference frequency to lie above the lower limit of the passband and measuring the products lying below the test-tone frequencies. This ensures that if the test tones are within the passband so are the measured distortion products. There is no way of measuring all these distortion products in such a way as to give a simple single measure of distortion. Each

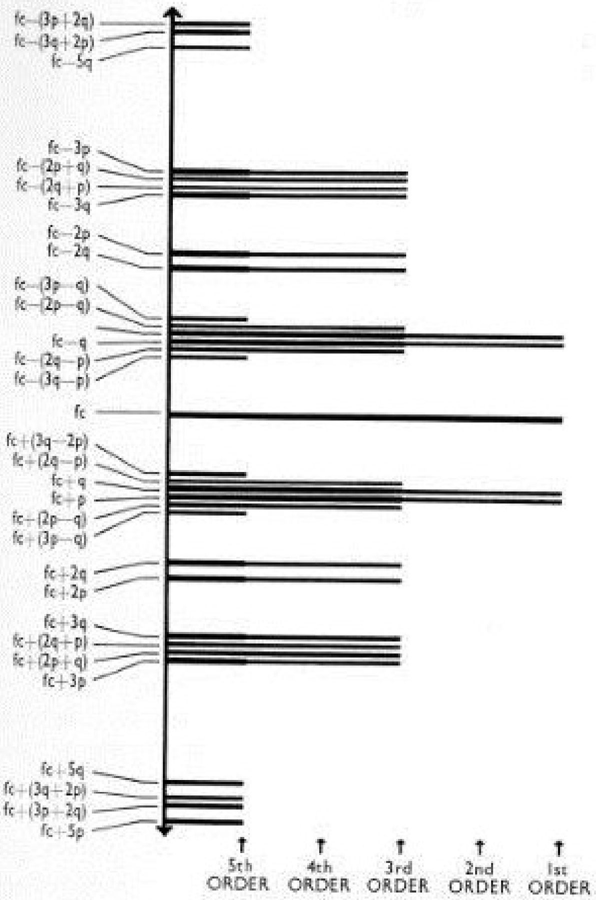

Fig. 10. Amplifier output spectrum near carrier frequency for two-tone ($p \simeq q$) modulated carrier input (C.C.I.F method). Drawn for $\frac{1}{2}(p+q) = 10(p-q)$, $p = 1050$Hz, $q = 950$Hz.

Table 2
MEASURED RESULTS

Equipment under test: Marconi 1kW M.F Transmitter Type B.6023

1. *Harmonic distortion*

Input frequency: 1,000Hz
Modulation depth: 75%
Total harmonic distortion by Hewlett Packard distortion meter: 2·2%
Individual harmonics as measured by wave analyser:
Second harmonic (2kHz): −39dB = 1·1%
Third harmonic (3kHz): −34dB = 2·0%
Fourth harmonic (4kHz): −39dB = 1·1%
Fifth harmonic (5kHz): −49dB = 0·35%
Higher-order harmonics—Negligible
Root sum square harmonics = 2·56%

2. *Intermodulation distortion*

Input frequencies: $p = 1{,}000$Hz, $q = 900$Hz
Peak modulation depth: 75%
Distortion products measured relative to either input frequency

Product order	*Type*	*Frequency*	*Level*		*R.F contribution*
Second	→ $p-q$	100Hz	−34dB	(2·0%)	No
	$p+q$	1,900Hz	−33dB	(2·2%)	No
Third	→ $2q-p$	800Hz	−34dB	(2·0%)	Yes
	$2p-q$	1,100Hz	−35dB	(1·8%)	Yes
	$2q+p$	2,800Hz	−34dB	(2·0%)	Yes
	$2p+q$	2,900Hz	−34dB	(2·0%)	Yes
Fourth	→ $2p-2q$	200Hz	−41dB*	(0·89%)	No
	$3q-p$	1,700Hz	−46dB	(0·63%)	No
	$3p-q$	2,100Hz	−46dB	(0·63%)	No
	$3q+p$	3,700Hz	−48dB	(0·40%)	No
	$2p+2q$	3,800Hz	−42dB*	(0·79%)	No
	$3p+q$	3,900Hz	−48dB	(0·40%)	No
Fifth	→ $3q-2p$	700Hz	−53dB	(0·22%)	No
	$3p-2q$	1,200Hz	−53dB	(0·22%)	Yes
	$4q-p$	2,600Hz	−45dB	(0·56%)	No
	$4p-q$	3,100Hz			No
	$4q+p$	4,600Hz	−59dB	(0·11%)	No
	$4p+q$	4,900Hz			No
	$3q+2p$	4,700Hz	−59dB	(0·11%)	Yes
	$3p+2q$	4,800Hz	−52dB	(0·25%)	Yes

→ Indicates typical product with frequency below test frequencies.

* Theory predicts these products should be twice (6dB higher) other distortion products of this order.

product must, therefore, be measured individually by means of a wave analyser.

A typical set of transmitter measurements compared with the results of harmonic testing are shown in Table 2. It will be seen that there is consistency of level among distortion products of the same order, particularly among the more significant ones, so that accepting one product as typical can be justified.

Notice also that among the fourth-order products the two involving $2p$ and $2q$ are 6dB higher than the others. This difference is predicted by theory and shows that by measuring at $2p-2q$, the worst product is taken. It is, of course, important when comparing results to ensure that the same voltage swings are being used in the equipment since the non-linearities normally increase with voltage swing. This is done in Table 2 by ensuring that comparison is made at the same peak modulation level.

PROPOSED STANDARD METHOD

A diagram of the equipment necessary to measure I.P's by this suggested method is shown in Fig. 11. No standard method of measurement has previously been proposed for sound broadcast transmitters. This possible standard method may be summarized as follows:

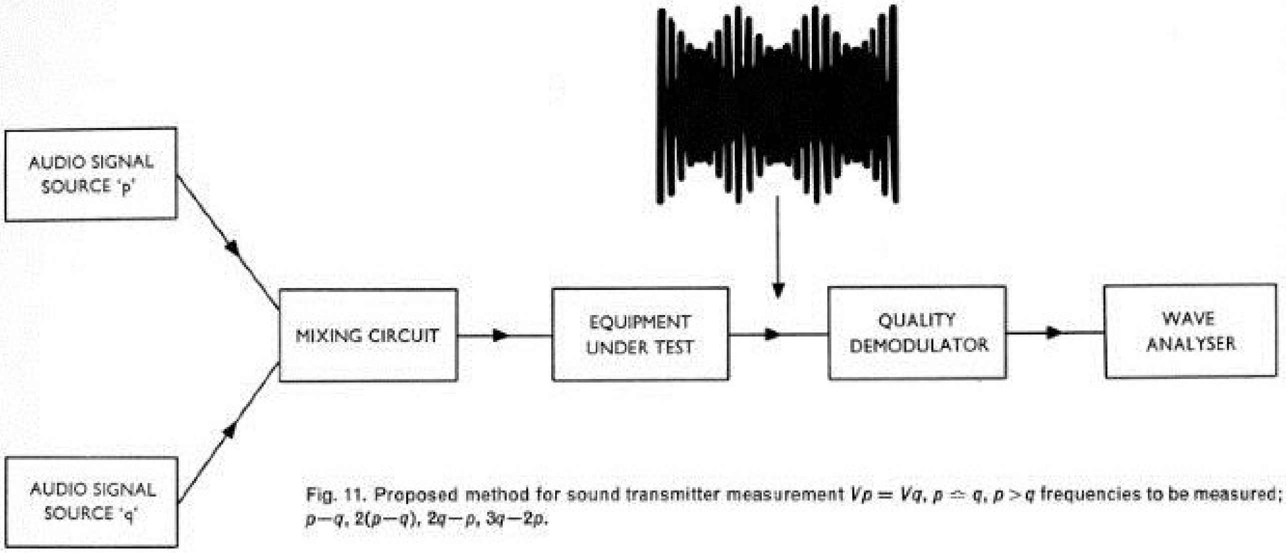

Fig. 11. Proposed method for sound transmitter measurement $Vp = Vq$, $p \simeq q$, $p > q$ frequencies to be measured; $p-q$, $2(p-q)$, $2q-p$, $3q-2p$.

Intermodulation distortion should be measured on sound broadcast transmitters (a.m) by applying two equal amplitude tones adjusted to modulate the transmitter to a stated peak modulation depth at frequencies p and q separated by 100–150Hz, neither tone lying below 800Hz. The transmitter output after demodulation is applied to a wave analyser and the products $p-q$, $2p-2q$, $2q-p$ and $3q-2p$ (p greater than q) measured relative to the demodulated amplitude of either test tone. The test is carried out with several combinations of test tones up to the frequency limit of the transmitter and at various modulation depths. The results to be expressed as: *Intermodulation distortion products less than x% up to y kHz at up to z% peak modulation depth.*

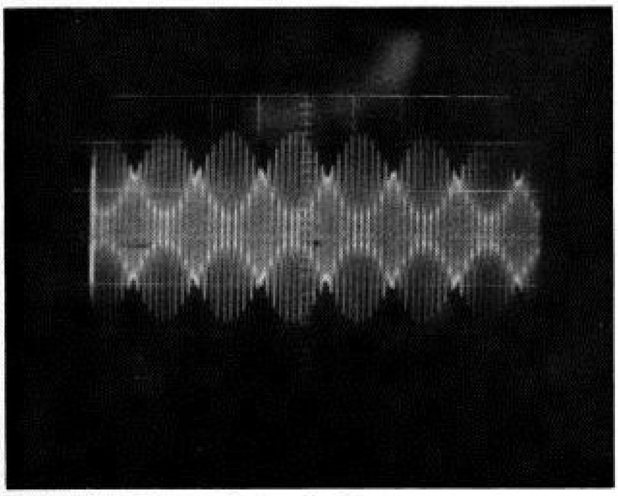

Fig. 12. An oscilloscope photograph of the test tones modulating a carrier at about 70%.

The choice of a frequency separation in the region of 100–150Hz assumes that the low-frequency response is still good at this frequency and the tones can be chosen so that when measuring there is no ambiguity with mains frequency harmonics. A lower frequency of 800Hz prevents ambiguity due to high-order, even-order terms being of higher frequency than high-order, odd-order terms.

The expression of the result in terms of the amplitude of either tone gives a result twice that obtained from the standard C.C.I.F method and this should be borne in mind when making comparisons.

Fig. 12 is an oscilloscope photograph of the test tones modulating a carrier at about 70%.

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