THIRD EUROPEAN ROTORCRAFT AND POWERED LIFT AIRCRAFT FORUM

Paper No 55

PSYCHOACOUSTIC STUDIES OF IMPULSIVE NOISE

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September 7-9, 1977

AIX-EN-PROVENCE, FRANCE

ASSOCIATION AERONAUTIQUE ET ASTRONAUTIQUE DE FRANCE

SUMMARY :

A subjective evaluation of helicopter impulsive noise is described. The study investigates various types,degrees, levels and frequency of impulsive noise. A subjective correction, as a function of these parameters changes, is established relative to a non-impulsive noise, using the method of comparison by pairs. In some cases, a correction of up to 7 PNdB is found.

An impulsivity coefficient is also defined,which gives good correlation with these subjective corrections. This coefficient is used to calculate the corrected EPN dB for evolutive noise (flyover). Differences between calculated and subjectively assessed evolutive levels,give a standard deviation of 1.3 EPN dB.

1. INTRODUCTION

In many walks of life, people are exposed to various degrees of impulsive noise. Some examples are the noises from repetitive hammer blows, pneumatic drills, motorcycles, and in some cases, helicopter rotors. This latter device can generate a sharp impulsive sound in some low speed flight conditions, and sometimes a lower pitched frequency impulsive noise,in high speed forward flight.

At the present time, there appears to be some debate, as to whether the present subjective noise units dBA, dBD, PNdB, TPNdB, EPNdB, etc ... adequately describe the annoyance of impulsive noise. In the case of helicopter impulsive noise, some investigators suggest a correction to these present units is necessary, while others argue that at least one of the established units is representative of the noise.

In view of the forthcoming certification of helicopter noise, a psychoacoustic study was made by the Helicopter Division in cooperation with the Aircraft Division of Aérospatiale to try and subjectively quantity the annoyance of helicopter impulsive noise. The study was supported by the "Ministère de la Culture et de l'Environnement" and the "Service Technique Aéronautique - Section Moteurs".

2. SUBJECTIVE EVALUATION

The method used to subjectively evaluate impulsive noise, is the method of comparison by pairs. Here five levels of non-impulsive noise (see section 4) are each played twice. The ten levels are compared at random with the impulsive noise to be evaluated making one noise judgement (10 pairs). Sometimes, the non-impulsive noise is played first and in other cases it is played second. For each comparison, the Jury (see section 3) is asked simply "- which noise is the most annoying ? -". The percentage of jury who find the non-impulsive noise more annoying is then plotted against the difference in level between the non impulsive (NI) and the impulsive noise (I) measured in some subjective dB unit (ΔdBA, ΔPNdB, ΔTPNdB). The mean curve between the I before NI and NI before I curves is chosen to be the characteristic response curve, as illustrated in figure 1. The annoyance correction ΔdB is then considered to be that when 50 % of the jury find the I and NI level equally annoying.

3. JURYS

The subjective evaluation was made using two sets of jury. Because of the size of the anechoic chamber, the number of people tested at any one time, was limited to six.

The first set judged 90 pairs of stationary noises (non evolutive) making 9 noise judgements. There were 68 persons making the judgement comprising :

- 50 military personnel between 20 and 30 years of age,
- 6 persons between 30 and 40 years old,
- 12 persons between the ages of 50 and 70 years.

After audiometer tests, 62 person's judgements were retained for evaluation of the noises.

The second set evaluated 180 pairs (18 noise judgements) of both stationary and evolutive noises. After audiometer tests, 54 people's judgements were used, comprising :

- 47 military personnel between 20 and 30 years old
- 7 persons between the age of 30 and 60 years.

The accuracy of the subjective evaluation can be calculated from the gradient of the characteristic response curve (Figure 1). The above specified jury gave a 90 % confidence level, for the 50 % agreement point, of ± 1.3 dB.

4. NOISE SIGNALS TESTED

Two types of noise were investigated. The first was a non-evolutive (stationary) noise similar to that made by a non-moving source. The second was an evolutive noise (time varying) equivalent to a moving source such as in fly-over.

In the stationary case, the non-impulsive noise was actual helicopter noise, which was basically broad-band in nature. This noise was electrically mixed, as illustrated in Figure 2, with real helicopter impulse signals. The amplitude and repetition frequency of the impulse could be varied, but the period to pulse width of the signal was held constant.

For the evolutive case, real evolutive helicopter noise from fly-over measurements were used for the non-impulsive signals. These signals were mixed with real helicopter impulse signals, whose amplitude was varied manually to simulate the approach effect. The resultant signal was considered realistic, except for the absence of Doppler effect on the impulsive signal.

In addition to the helicopter noise, two types of stationary motor cycle signatures were also evaluated.

5. PARAMETERS INVESTIGATED

For the stationary tests, the following parameters of impulsivity were investigated.

(a) Two types* of helicopter impulse signals : light and heavy as illustrated in Figure 3.

(b) Three degrees+ of impulsivity : weak, medium, and strong, as shown in Figure 4.

(c) Four impulse repetition frequencies : 10, 17.5, 25 and 35 Hz, with the repetition period to pulse width constant.

(d) Two levels[x] of impulsive noise : 90 and 100 PN dB.

(e) Three motorcycle signatures : 2 types of motorcycle and 2 engine speeds (one level only) as illustrated in Figure 5.

In the case of the evolutive tests, the following four parameters were investigated :

(a) Two types of helicopter : light and heavy

(b) Two repetition frequencies : 10 and 17.5 Hz

(c) Three levels : 90, 95 and 100 EPN dB.

(d) Two flight speeds : 70 and 148 kt.

* Type implies pulse shape.

+ Degree implies magnitude of impulse signal in comparison with broad-band base noise.

x Level implies total magnitude of both impulse and base noise.

6. RESULTS OF THE NON-EVOLUTIVE TESTS

The results of the stationary tests, are summarized in Table 1. The parameter changes investigated are given in the first 4 columns, and the subjective corrections are given, in the last three columns.

The following observations are made :

(a) A subjective correction of the order of 0 and 7 dB appears to be necessary between, non-impulsive and highly impulsive noise, irrespective of whether dBA, PNdB or TPNdB units are used.

(b) The most significant parameter is the degree of impulsiveness (column 3). However, above a certain degree, the subjective corrections tend to approach a value in the region of 6 dB.

(c) Considering the statistical variations in this study, there does not appear to be any consistant effect of level or repetition frequency (constant period to pulse width) on the subjective correction.

(d) Other impulsive sounds (motorcycle) can give a subjective correction scatter in the same region as helicopter impulsive noise.

7. IMPULSIVITY INDICATOR

Because it is found that the subjective correction varies as some function of impulsivity, it is preferable to try and find a suitable coefficient of impulsivity which accounts for this effect. The coefficient which appears to give the best collapse of date is defined as :

$$\text{C.I. "A" or "D"} = \frac{\overline{p^4}}{(\overline{p^2})^2} \quad * \qquad (1)$$

p is the sound pressure time history, where the bar represents the time average. "A" or "D" indicates that the time history has been "A" or "D" weighted to give a subjective impulsivity coefficient.

The values of the unweighted coefficient are, respectively; 1.5, 3 and ∞ for a sine wave, white noise and a Delta function. For a pure periodic pulse train of pulse width "a" and period "T" the unweighted coefficient gives a simple mathematical description of the "spikeyness" of the signal, thus :

$$\text{C.I.} = k \frac{T}{a} \qquad (2)$$

* The calculation procedure for C.I. used in this paper is defined in the Appendix.

k depends on the pulse shape ; for example, a rectangular pulse k = 1 and a triangular pulse k = 1.8. If "T" increases or "a" decreases, the impulsivity increases. If T/a is constant, then the impulsivity is constant, irrespective of the impulse size or repetition frequency.

8. SUBJECTIVE CORRECTION VERSUS IMPULSIVITY INDICATOR

Subtracting the difference of $10 \log_{10}$ of equation (1) for an impulsive and a non-impulsive noise, and equating to the subjective correction, one obtains :

$$\Delta dB = K\ (10 \log C.I.A._{I} \ - \ 10 \log C.I.A._{NI}) \qquad (3)$$

Here K is some constant or function which gives the subjective correction in terms of the difference in computed impulsivity.

Figures 6 and 7 show the subjective corrections from table (1) plotted as a function of CI "A" and CI "D" respectively. There appears to be a trend in the data as indicated by the drawn lines.
The correction starts at about CI = 3, 10 log CI = 5 dB, which is the approximate value for the base noise with which the impulse signal is mixed. The slope of the drawn lines, K in equation 3, is approximately 1.5, with a levelling off at high impulsivity. Bearing in mind, the subjective accuracy of this study $\pm$ 1.3 dB and the number of data points, the subjective correction for a CI value greater than about 6 (8 dB), is interpreted as having a constant value. These lines are used later to calculate the subjective corrections in the evolutive noise case, considered in section 12.

9. INFERENCE OF NON-EVOLUTIVE TESTS

Subjectively evaluating the annoyance of impulses implanted in a non-impulsive noise, as this study has done, involves a combination of two concepts, (a) the subjective comparison of changes of impulsivity - (b) the subjective comparison of impulsive and non-impulsive noise. This in turn raises two questions :

Q.1. For a purely impulsive or an impulsively dominated noise (discrete spectrum and ordered phase), do the present subjective units dBA, PNdB, etc ...adequately describe the changes of impulsivity, including a consistant under or over estimation ?

Q.2. Is there a subjective difference between an impulsive noise (discrete spectrum and ordered phase) and a non-impulsive noise (broadband spectrum and random phase) assuming that they both have the same energy and spectrum envelope ?

Regarding the first question, there is a well defined mathematical relationship between impulsivity and the acoustic spectrum. If the present subjective units represent the frequency response of the ear, with regards to annoyance, then there should be no subjective correction change with spectrum change, i.e. impulsivity change. According to figures 6 and 7, there does not appear to be such a change at high impulsivity, although there is a consistant correction of about 6 dB. Therefore, assuming that the hearing mechanism does not suffer any non linear effects, the answer to question one appears to be "YES".

Refering to question two, if the answer to this question is also yes, then the subjective correction should vary as the impulsivity varies from weak to strong (change of phase from random to ordered). Any spectrum change should give no effect, as this is the consequence of the answer to Q1. According to figures 6 and 7, there is in fact such a change, indicating that the answer to question 2 is "YES".

Thus the "knee" effect in figures 6 and 7 could be explained mainly in terms of phase. For non-impulsive noise, with purely random phase, CI = 3 (5 dB), the present subjective units adequately describe the annoyance. At high impulsivities, purely ordered phase, CI > 6 (8 dB), the present subjective units consistantly under estimate the annoyance by about 6 dB. For weak impulsivity, 10 log CI between 5 and 8 dB (quasi random phase region) there is progressive subjective correction given by $K \approx 1.5$ in equation 3.

10. OTHER IMPULSIVITY INDICATORS

In addition to the impulsivity indicator defined in section 7, there are four other definition of impulsivity currently under investigation. Three of the definitions are effectively based on the degree parameter (crest factor as it is sometimes refered to), and the fourth, the last one discussed below, includes additional information of pulse shape and pulse period to duration ratio, similar to the definition in section 7.

(a) The impulsivity coefficient proposed by Westland Helicopters (1), is basically the logarithmic ratio in dB. of the peak signal value measured with a 200 μs rise time and 50 μs descent time of an octave band signal centered at 250 Hz, divided by the "A" weighed rms value of the signal.

(b) The coefficient of impulsivity proposed by South Africa (2), is the difference between the "impulse" and the "slow" values of the signal measured with a B and K type 2606 sound level meter.

(c) The coefficient proposed by the USA (3), is simply the difference between the peak and rms, "A" weighted sound pressure measured over 0.5 sec. The peak value is measured using a B and K sound meter type 2209 in the "peak hold" "A" setting.(In practice, it is found better to "eye" estimate the MEAN peak value, using an oscilloscope).

(d) The United Kingdom (4), impulsivity indicator is defined as :

$$I = \left\{ \frac{\overline{p^2_{VF}} - \overline{p^2_S}}{\overline{p^2_S}} \right\}^2 \; *$$

$\overline{p^2_{VF}}$ and $\overline{p^2_S}$ are the time averaged squared values of the signal for very short and very long measurement times respectively. It can be shown that for very short measurement times of p_{VF}, the above equation approaches :

$$I = C.I. - 1 \;, \quad C.I. = \frac{\overline{p^4}}{(\overline{p^2})^2}$$

That is, the UK coefficient in the limit, is the French coefficient minus one.

11. COMPARISON OF IMPULSIVITY INDICATORS

Figure 8 shows the various impulsivity indicators plotted versus the subjective corrections evaluated in this paper.

Figures (9) and (10) show the Westland and South Africa data, the correlation between the impulsive coefficients and subjective correction is not good. The USA coefficient is plotted in figure 8 (C). The scatter in data here is much less than in figures 8 (a) (b), but the weakly impulsive region (shaded region) appears to be badly defined. i.e. the coefficient does not appear to give continuous or gradual change over from weak to strong impulsivity.
The NPL coefficient is plotted in figure 8 (d) using τ = 10 ms (see appendix). This coefficient gives good definition, similar to the French coefficient, particularly in the region of weak impulsivity. If τ = 0.1 ms, had been used, the data collapse would have been almost identical to that of the French data in figure 6, as explained at the end of section 10. Note that using a log scale for the impulsivity indicator, the NPL data tends to lie along a curve in the weakly impulsive region, whereas the French data tends to be linear in scale.

* The calculation procedure of C.I. used in this report, is defined in the Appendix.

12. CORRECTED EVOLUTIVE DATA

Having found a description of impulsivity which gives reasonable correlation with the subjective correction, the evolutive noise signals discussed in sections 4 and 5, were measured each half second and a subjective correction made according to equation (1) and the correction lines drawn on figures 6 and 7. An example of the corrected evolutive noise is shown in figure 9.

Table 2 summarises the evolutive data examined. The first three columns give the evolutive parameter changes, the fourth column gives the EPN dB subjective correction, assessed by the jury, and the last two columns give the EPN dB calculated correction using the A and D weighted time history corrections given by figures 6 and 7.

As can be seen from comparing the jury assessed and calculated corrections, the agreement is very good except for the two types of heavy helicopter, V = 148 and 170 kt. There is no explanation offered for these two results, nor was there any possibility of rechecking the data.

Never the less the overall standard deviation between the jury assessed and the calculated corrections using figures 6 and 7 is only 1.7 and 1.3 dB respectively, i.e. the D weighting appears to give a marginally better result than the A weighting.

13. CONCLUSIONS

A subjective evaluation of impulsive noise has been carried out using the method of comparison by pairs. The accuracy of this method using a jury sample of 60 people with ages between 20 and 70 years, gave a 90 % confidence level of ± 1.3 dB.

The impulsivity parameters investigated included (i) type (pulse shape) (ii) degree (magnitude of impulses compared with the non-impulsive noise) (iii) level (total magnitude of both impulses and non-impulsive noise) (iv) pulse repetition frequency (v) pulse duration and (vi) evolution time (flight speed).

Owing to the high cost of establishing each noise judgment, it was not possible to investigate each of the above parameters in detail. Only 27 noise judgements (270 noise pairs) were completed to cover all the above parameter changes. Never the less, the study has shown some interesting trends.

I. It was found that the annoyance of impulsive noise, in comparison with non-impulsive noise, was underestimated by up to 6 dB, irrespective of the current subjective units used (dBA, dBD, PNdB, TPNdB). It should be pointed out that TPNdB was not very different from PNdB, because most of the energy of the pulses lay below 500 Hz.

II. The parameter that had the greatest influence on the subjective correction was the degree of impulsivity. However, above a certain value , this parameter appeared to give no further general change. The interpretation is that the degree parameter describes the domination effect of the impulse noise over the non-impulsive noise, where the prevailing signal characteristic changes from random to ordered phase. After this transformation is complete, the current subjective units give a reasonable description of annoyance, but with a constant error in the region of 6 dB.

III. The coefficient of impulsivity that appears to give the best description of this transformation process, is defined as :

$$\frac{\overline{p^4}}{(\overline{p^2})^2}$$

where p is the "instantaneous sound pressure and the bar indicates that the signal has been time averaged. This coefficient includes the degree effect described above and also the additional properties of pulse shape (k) and pulse period to duration ratio (T/a). For a purely impulsive signal, C.I. = k T/a, the coefficient is independent of pulse amplitude and frequency.

IV. For a non impulsive noise, where no subjective correction is required, the above coefficient, with an "A"or "D" weighted time history, gives a C.I. = 3 (5 dB). For highly impulsive noise, where the subjective correction becomes approximately 6 dB, the coefficient of impulsivity is C.I. > 6 (8 dB). In the transformation region where 3 < C.I. < 6, the approximate subjective correction can be calculated using equation (3) in the main text.

V. It is interesting to note, that another definition of impulsivity proposed by the United Kingdom (NPL), approaches the definition of that given above, as the "short" integration time in the NPL calculation approaches zero. Other definitions of impulsivity based mainly on the degree of impulsivity; Westland, South Africa and USA proposed coefficients, appear to give poor subjective correction definition in the region of weak impulsivity. However the USA coefficient does give a much better collapse of data than the Westland and the South Africa coefficient.

VI. Finally, evolutive (flyover) data was corrected according to the C.I. value defined in item III and the "A" and "D" weighted correction curves. The standard deviation between the jury assessed and that found by the above method was 1.7 and 1.3 EPNdB respectively. That is the "D" weighting appeared to give a marginally better result.

The main indication of this study is that purely impulsive noise (discrete spectrum noise) is approximately 6 dB more annoying than non-impulsive noise (continuous spectrum noise) - all other things being equal. Comparing like with like should give no relative error.

REFERENCES

1. Westland Helicopters Limited, Yeovil, Somerset - England

2. National Mechanical Engineering Research Institute, Pretoria - South Africa.

3. Minutes of meeting, Annex A, Noise from aircraft ISO/TC 43/SC I/WG2 London, March 1977.

4. National Physical Laboratory, Teddington, Middlesex - England.

APPENDIX

The French impulsivity coefficient, after A or D weighting, was computed as :

$$CI = \frac{\frac{1}{N} \sum_{i=1}^{N} p_i^4}{\left(\frac{1}{N} \sum_{i=1}^{N} p_i^2 \right)^2}$$

N is the total number of samples in a given signal interval (t = 0.5 sec.)

Sampling frequency used = 5 K/sec.

Therefore N = 5 K x 0.5 = 2.5 K

The NPL impulsivity coefficient, after "A" weighting, was computer as :

$$\overline{I} = \frac{1}{n} \sum_{j=1}^{n} \left\{ \frac{f_j - s}{s} \right\}^2$$

$$f_j = \frac{1}{m} \sum_{i=1}^{m} p_i^2 \;, \quad s = \frac{1}{n} \sum_{j=1}^{n} f_j \;, \quad N = m.n$$

n is the number of periods, ($i = 1 \longrightarrow n$) in the signal time t = 0.5 sec.
m is the number of periods in each n period ($i = 1 \longrightarrow m$) of duration τ.
The total number of periods is therefore N = m.n
Sampling frequency used = 5 K/sec., N = 2,500.
Short period time used τ = 10 m/s, thus $m = \frac{10}{1000}$ 5K = 50 and

$$n = \frac{2.5K}{50} = 50$$

TABLE N° 1

Impulsivity parameters investigated and their subjective corrections judged by the jury (stationary noise).

Type	Frequency of impulse	Degree of impulse	Level PNdB	Corrections Δ dBA	Δ PNdB	Δ TPNdB
Helicopter						
Heavy	10 Hz	Medium	90	6,2	5,7	6,0
"	"	Strong	"	6,8	5,9	6,4
"	"	Medium	100	6,9	5,8	5,2
"	"	Strong	"	4,9	5,6	4,9
Light	"	Weak	90	1,3	0,9	0,9
"	"	Medium	"	4,7	5,8	5,4
"	"	Strong	"	6,4	7,3	6,6
"	"	Weak	100	1,2	0,9	0,8
"	"	Medium	"	3,5	4,2	3,7
"	"	Strong	"	4,4	5,4	4,5
"	"	Weak	90	2,2	2,8	-
"	"	Weak	"	0,3	0,1	-
"	17,5 Hz	Strong	"	5,2	4,4	-
"	25 Hz	Strong	"	7,4	6,4	-
"	35 Hz	Strong	"	5,6	5,8	-
Motorcycle						
(1)	27 Hz	-	99,5	1,8	4,1	-
(1)	58 Hz	-	97,7	4,3	7,0	-
(2)	24 Hz	-	100	1,2	3,2	-

TABLE N° 2

Comparison between subjective and calculated corrections for evolutive noise (advancing helicopter).

Hel. type and forward speed	Frequency of impulse Hz	Level EPNdB	Δ EPNdB (Jurys)	Δ EPNdB calculated "A"	Δ EPNdB calculated "D"
Light V = 70 kt	10	95	4,2	3,6	3,5
Heavy (1) V = 70 kt	17,5	95	2,1	1,4	1,6
Heavy V = 148 kt	17,5	95	1	3,6	2,9
Heavy (2) V = 70 kt	17,5	95	4	0,3	1,3
Heavy V = 70 kt	17,5	90	2,3	2,8	2,6
Heavy (1) V = 70 kt	17,5	95	2,5	3	2,5
Heavy (1) V = 70 kt	17,5	100	2,1	2,5	2,3

(1) - (2) Two types of heavy helicopter.

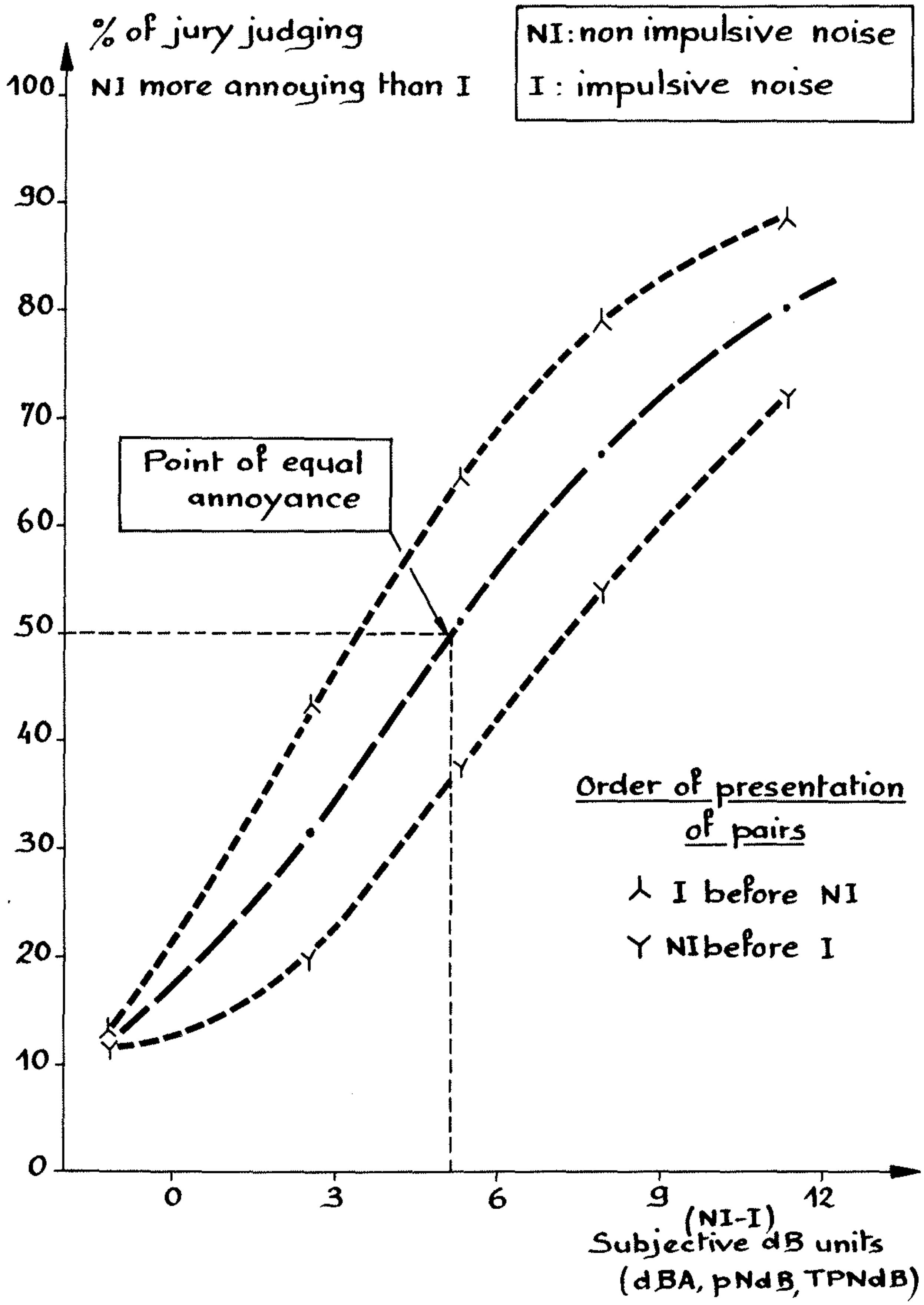

Figure (1) JURY RESPONSE CURVE

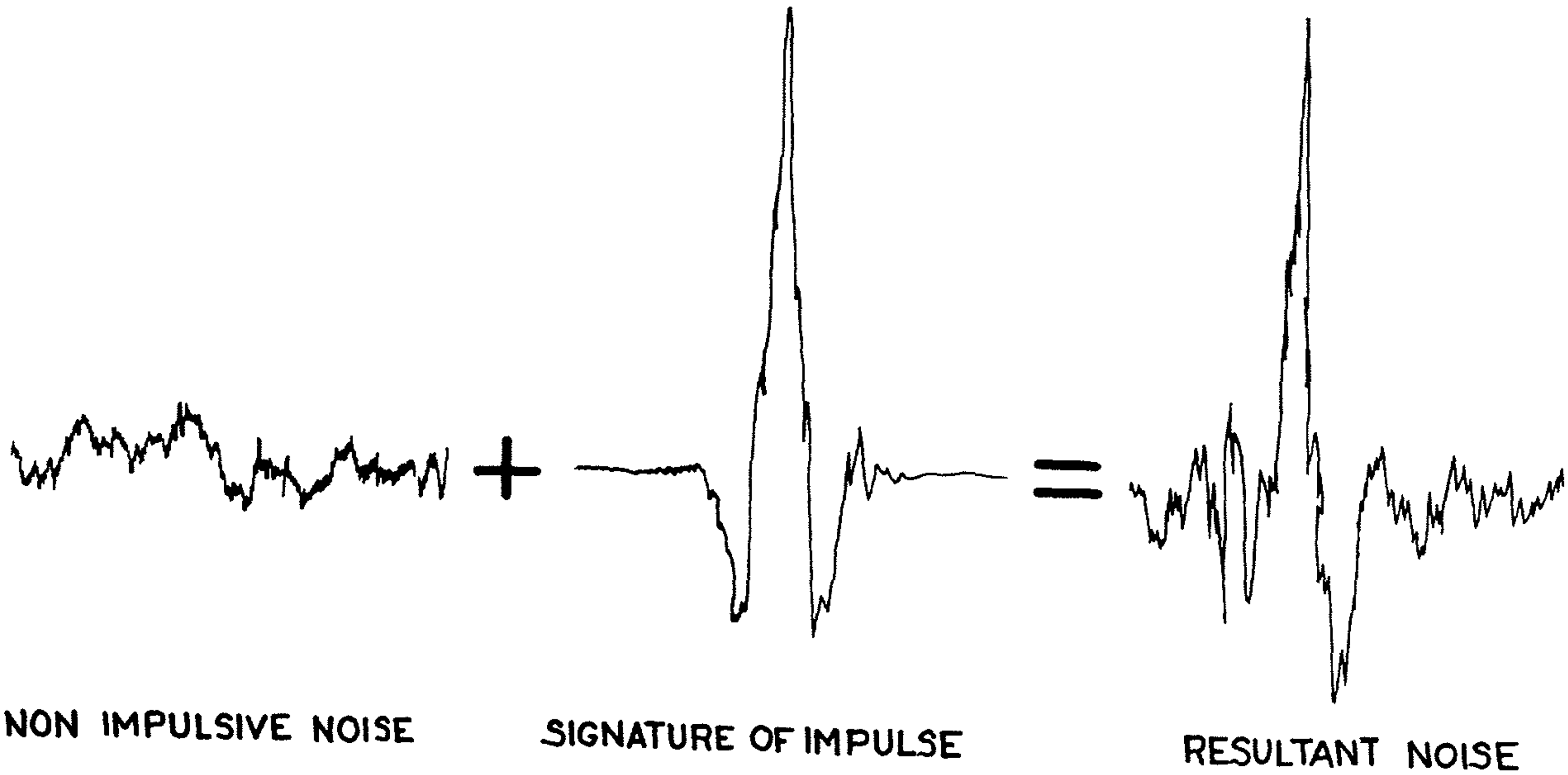

Figure 2. GENERATION OF HELICOPTER NOISE SIGNAL

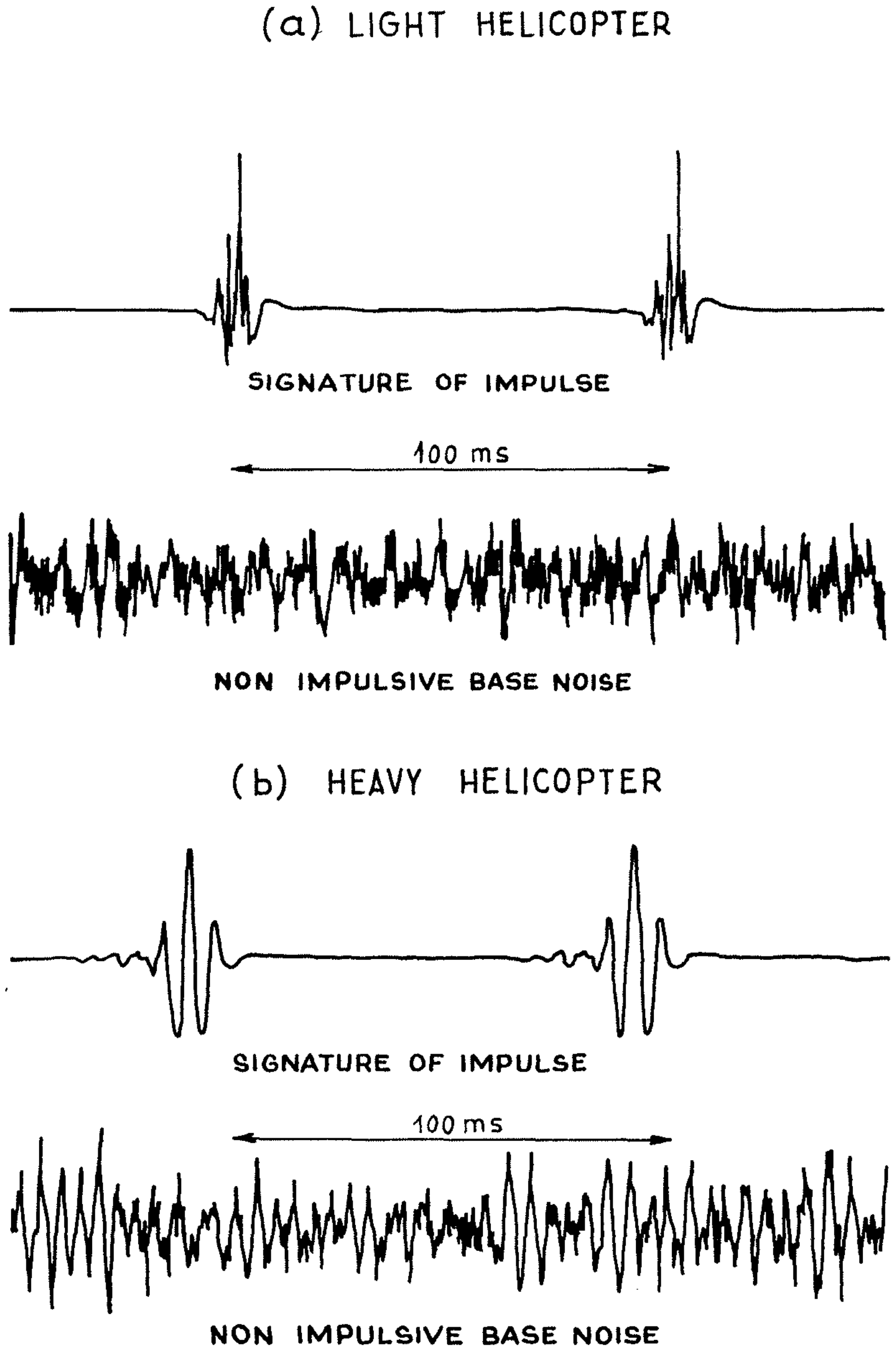

FIG 3 - TYPE OF HELICOPTER IMPULSIVE NOISE

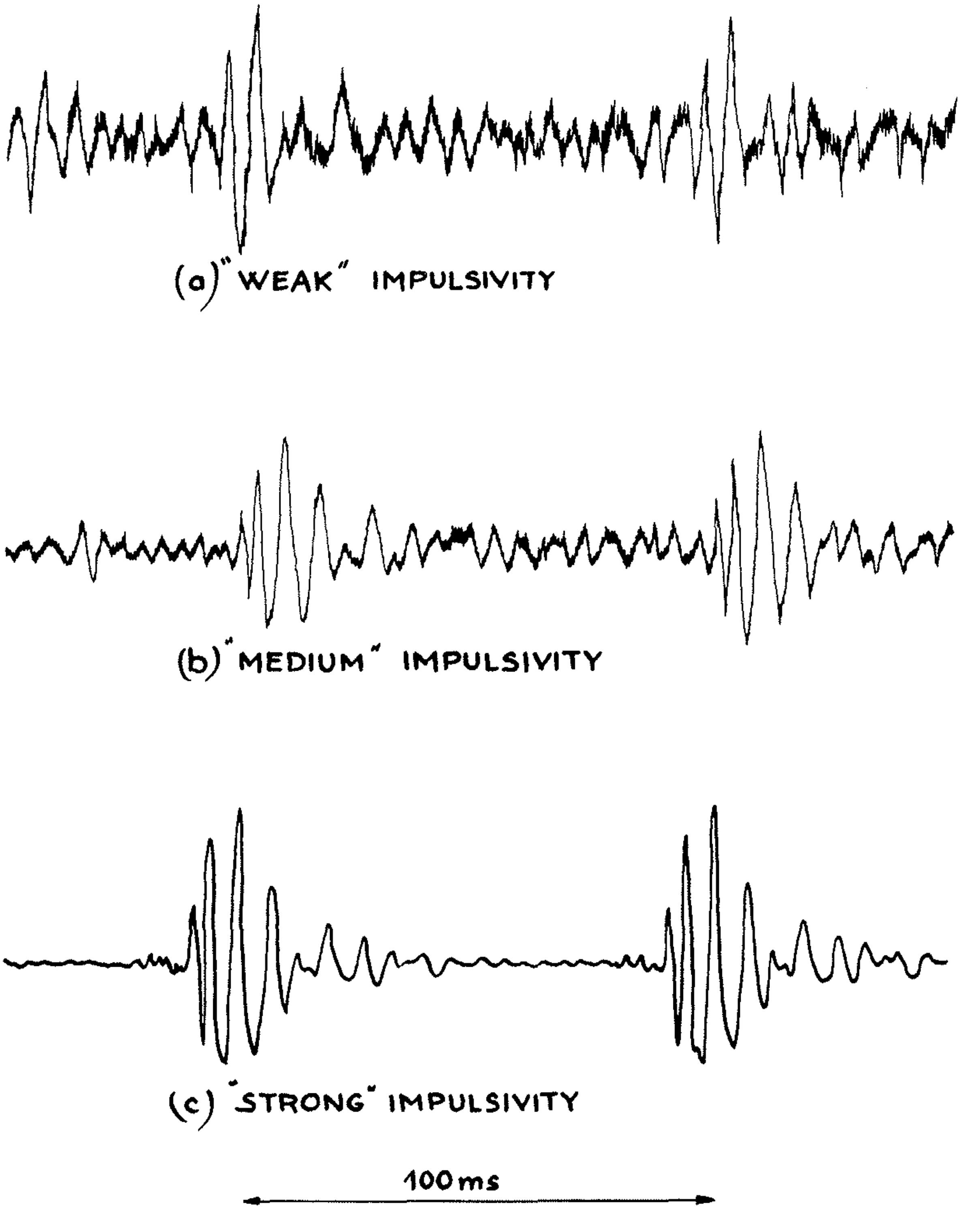

Figure 4. DEGREE OF HELICOPTER IMPULSIVE NOISE

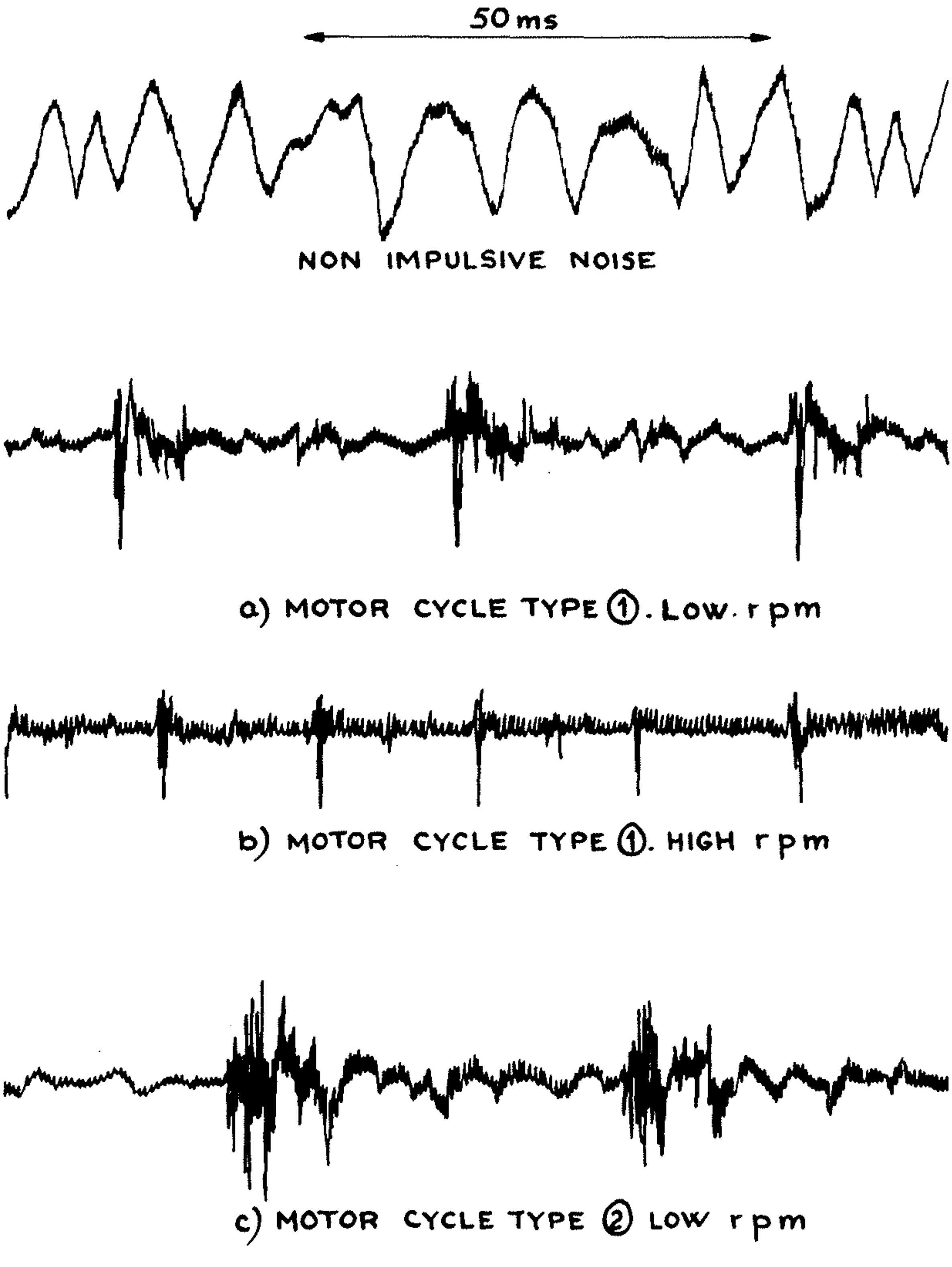

Figure 5. MOTOR CYCLE ACOUSTIC SIGNATURES

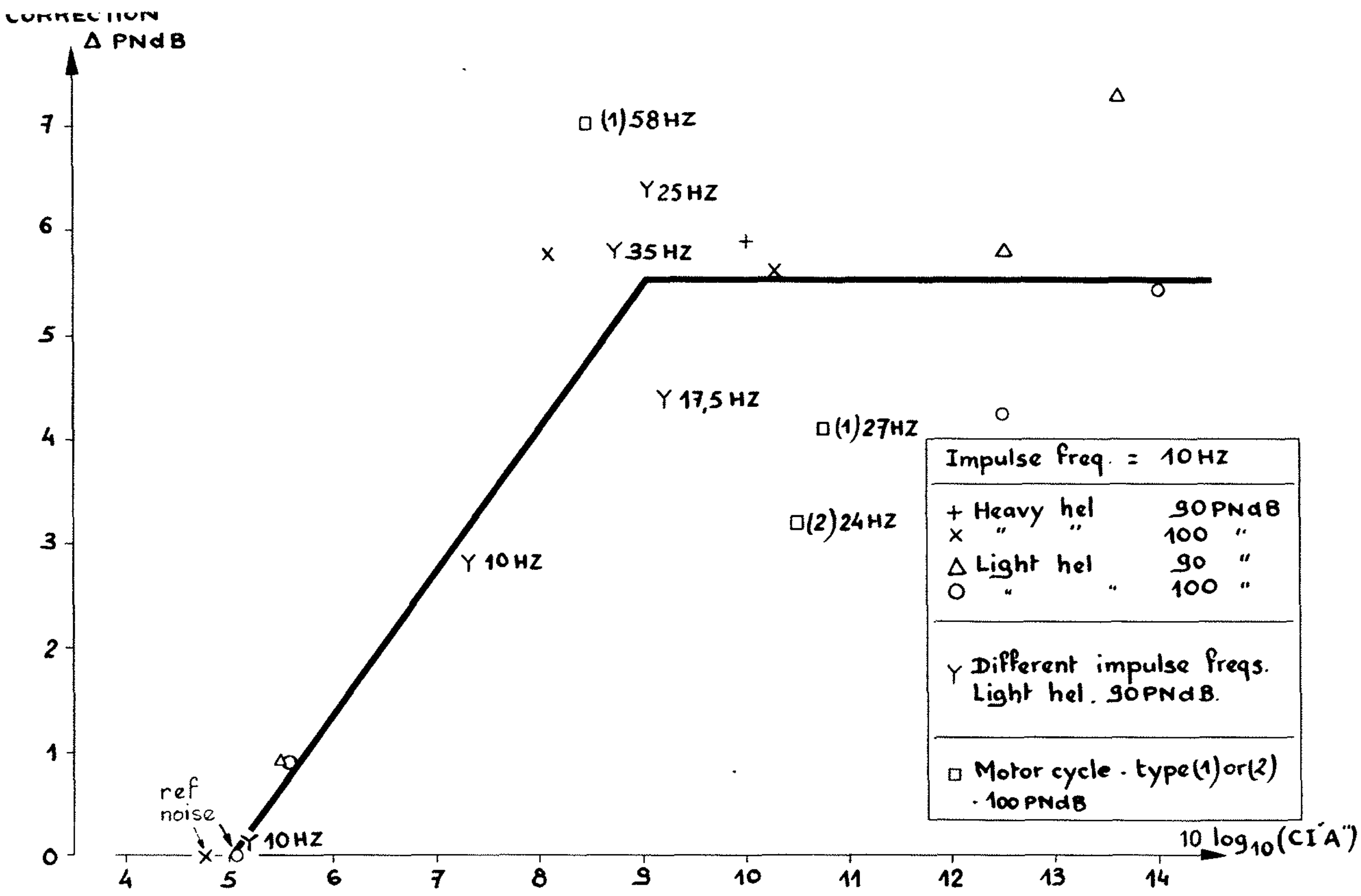

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Figure 6 – SUBJECTIVE CORRECTION VERSUS IMPULSIVITY COEFFICIENT ("A" WEIGHTED)

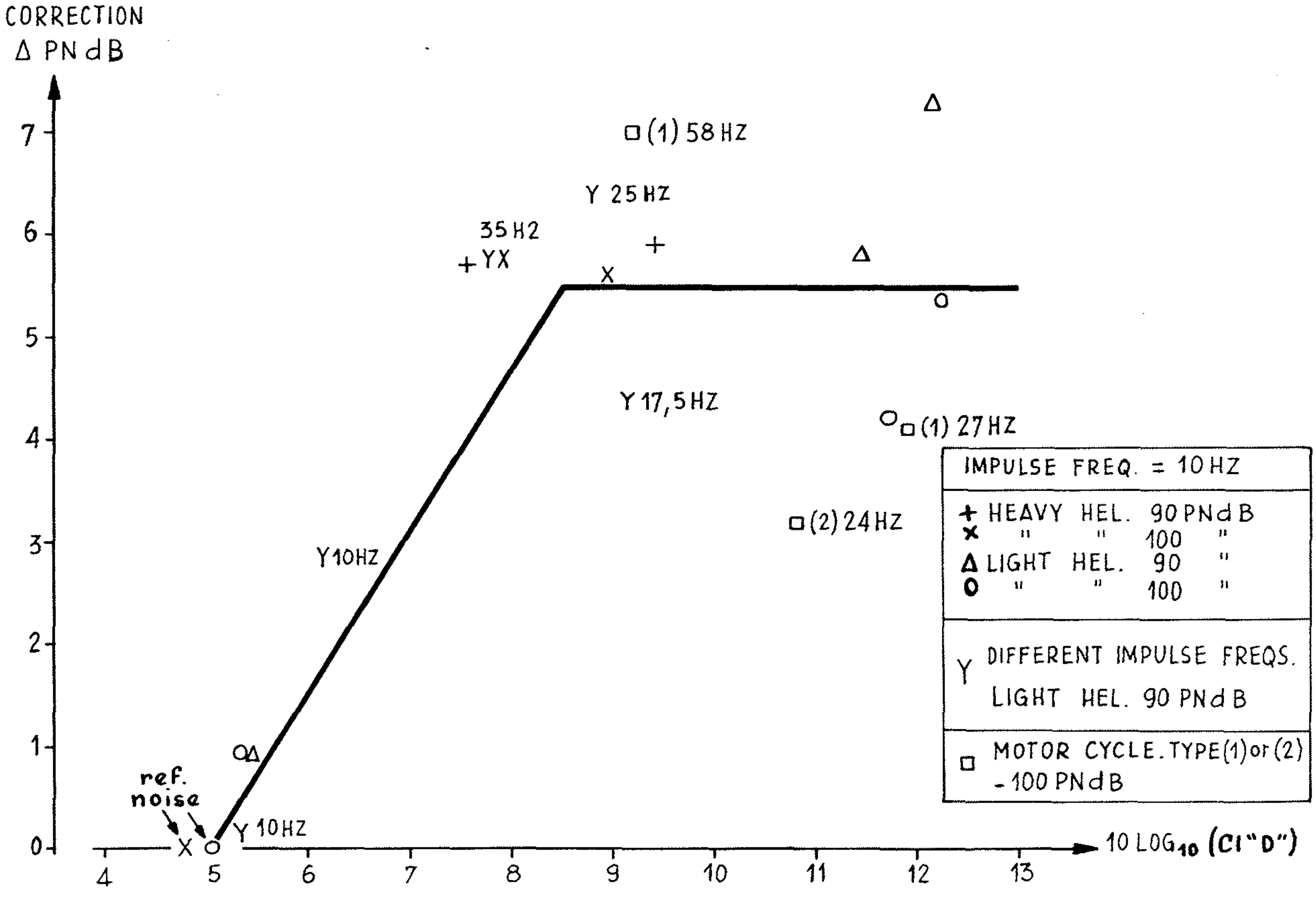

FIGURE 7. SUBJECTIVE CORRECTION VERSUS IMPULSIVITY COEFFICIENT

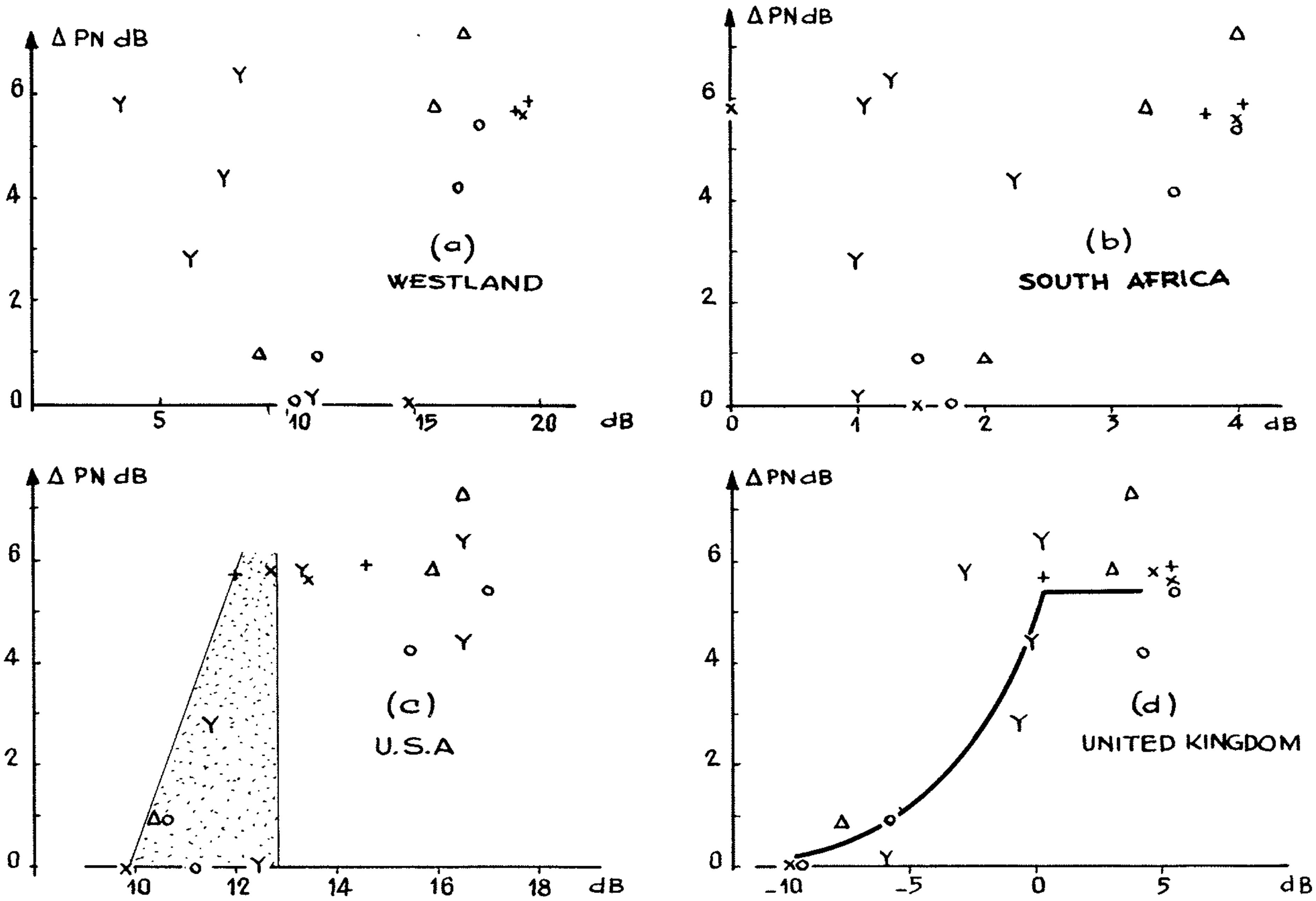

Fig : 8 _ COMPARISON OF IMPULSIVITY INDICATORS

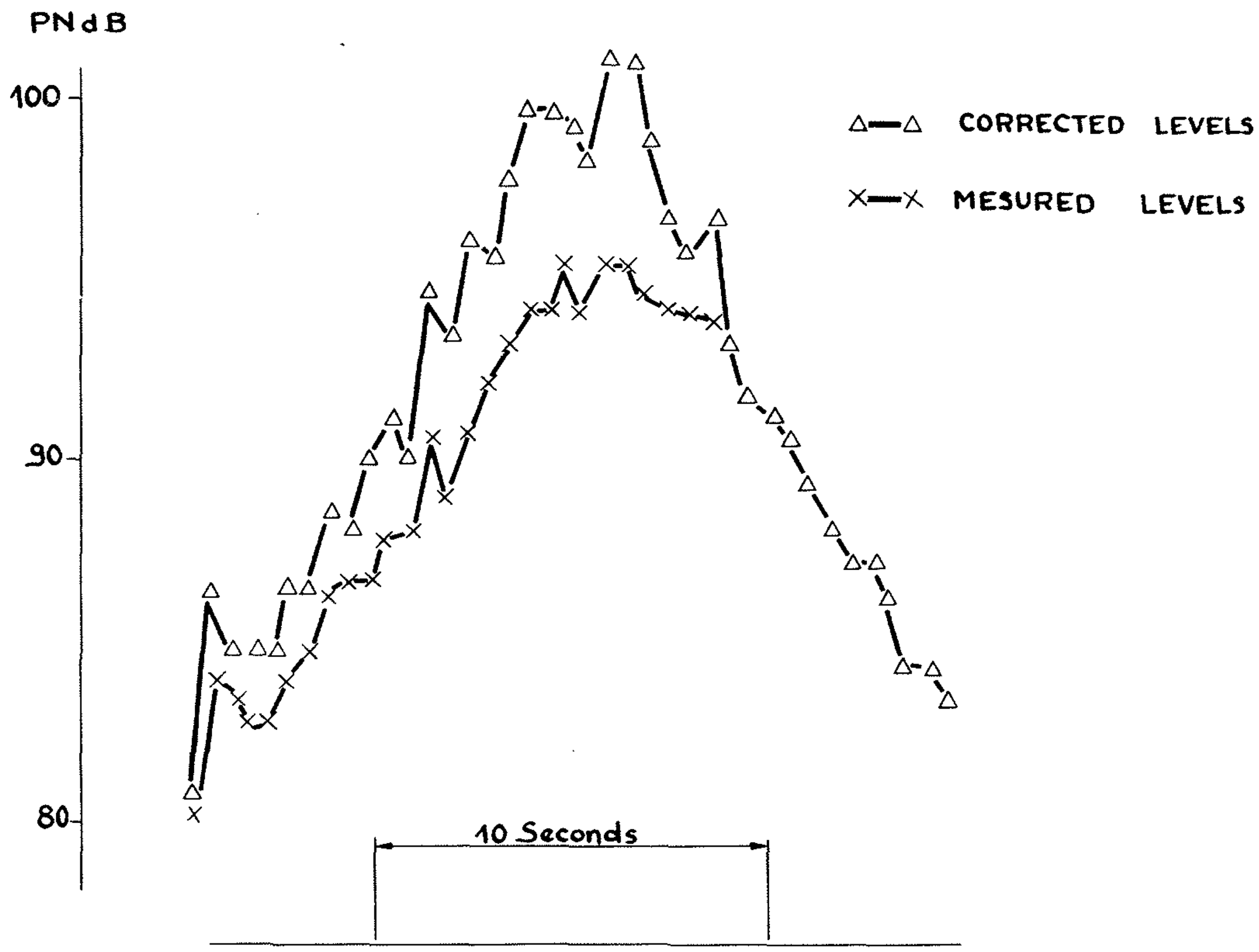

Figure 9. CORRECTED EVOLUTIVE IMPULSIVE NOISE