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JOINT INSTITUTE FOR AERONAUTICS AND ACOUSTICS
STANFORD UNIVERSITY

FINAL REPORT

ON

NASA NAG 1-17

THE ANNOYANCE OF IMPULSIVE HELICOPTER NOISE

FOR THE PERIOD
JANUARY 1981 TO DECEMBER 1981

SUBMITTED TO

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
LANGLEY STATION, HAMPTON, VIRGINIA 23665

BY THE

JOINT INSTITUTE FOR AERONAUTICS AND ACOUSTICS
DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
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ABSTRACT.

96 impulsive and non-impulsive sounds were rated for annoyance by 10 subjects. The signals had the same amplitude spectrum with a maximum frequency of 4.75 KHz. By changing the phase of the spectral components different levels of impulsivity were obtained. The two impulsive signals and the one non-impulsive signal were created by placing the spectral components in cosine, sine, and random phase respectively. The signals had coefficients of impulsivity of 10.8, 7.9, and -0.2 respectively. Further, signals had intensity levels 89 and 95 dBA, pulse repetition rates 10 and 20 Hz, and half the signals had pink noise added at a level 12 dBA lower than the level of the sound. Each signal lasted 3 seconds and was repeated 4 times. The significant results were: The four females and six male subjects rated the impulsive sounds respectively 3.7 dB less annoying and 2.6 dB more annoying than the non-impulsive sounds. Overall, impulsivity had no effect. The high pulse repetition rate increased annoyance by 2.2 dB. Addition of pink noise increased annoyance of the non-impulsive sounds 1.2 dB, but decreased the annoyance of the impulsive sounds 0.5 dB.

THE ANNOYANCE OF IMPULSIVE HELICOPTER NOISE

P. Henckel, A. Ahumada
Joint Institute for Aeronautics and Acoustics
Department of Aeronautics and Astronautics
Stanford University, Stanford, California 94305

INTRODUCTION

The necessity and usefulness of a correction for impulsivity in predicting the annoyance of helicopter sounds is a matter of controversy. Helicopters tend to produce pulse trains in which most of the energy is concentrated in a small proportion of the pulse period. Some have felt that this impulsive quality of the sound leads to a greater annoyance than would have been predicted on the basis of the amplitude spectrum of the sound. To test this hypothesis, field tests and laboratory studies have been done with results usually ranging from no apparent effect of impulsivity (ref. 1-4) to apparent impulsivity effects corresponding to intensity effects up to 7 dB (ref. 5-11). Some studies have even found impulsive noise to be slightly less annoying (ref. 12-14).

Procedures have been proposed for correcting spectrum-amplitude based measures of annoyance, such as EPNdB, for the effects of impulsivity. The most popular proposals are the crestfactor (CF) and the coefficient of impulsivity (CI). Both are designed to be added to the PNdB level for a 0.5 s period. The formulas are

$$CF = L(peak) - L(rms) - 12$$

where L(peak) is the peak A-weighted sound pressure level and L(rms) is the root-mean-square A-weighted sound pressure level for the period, and

$$CI = (16 \log (S/P^2)) - 2.4$$

where P is the rms A-weighted sound pressure and S is the rms value of the difference between the square of the sound pressure and the square of P. The proposed corrections are limited to a maximum of 6 dB.

In the studies referenced above, when impulsivity as measured by the above formulas was varied, other features of the sounds varied at the same time. The lack of agreement in the studies about the effects of impulsivity could have been mainly a result of the inability of the EPNdB or other similar measures to correctly account for the effect on annoyance of these other factors.

In 1980 (ref. 14) we conducted three studies in an attempt to compare the annoyance of sounds that differed in impulsivity but were otherwise as similar as possible. The pulse trains were constructed with identical Fourier amplitude spectra so that all features which depend only on the amplitude spectrum and its slow time history were the same for these pulse trains. Impulsivity as defined by the above formulas was varied among the pulse trains by varying the relative phases of the Fourier series components. The computer used for these experiments only allowed spectral components with frequencies up to 600 Hz.

Three nearly identical experiments were run. The second was run as a replication of the first because we were so surprised at the results. Only one aspect of the procedure was changed, the duration of the sounds was increased from 3 s to 12.5 s because most of the earlier studies had actual or simulated flyovers with durations longer than 3 s. The third experiment was another replication designed to make the experiment more similar to the other studies done in this area. Other studies typically used volunteer subjects having a wider an older age range than that of our college students, so we replicated the experiment on volunteer secretaries from the department.

The main results of these three experiments are summarized in table I. The experiments are described in details in ref. 14. We found that subjects rated the impulsive sounds significantly less annoying under all three experimental conditions. These results contradicts most other results reported in the litterature.

The present study was designed to analyse these differences more closely. The sound from real helicopters and aircrafts have frequency components of much higher frequencies than used in the described experiments (where the max. frequency was 800 Hz). Our new computer allowed us to use signals with much higher frequencies (up to 15 KHz).

Further, the impulsive signals used in the first three studies consisted basicly of a sound impulse repeating itself, but with no noise between the impulses. Noise from real helicopters consists of a mixture of many sound sources, f.ex. the noise impulses created by the main rotor superimposed on the more constant engine- and wind noise. We therefore used impulsive signals that sometimes had a random noise signal superimposed.

Finally, we wanted to test whether the slope of the impulsive waveform would be a better predictor for the annoyance than the impulsivity. We therefore used impulsive signals with different soundpressure slopes. We should emphasize here, that all sounds, impulsive and non-impulsive, with the same pulse repetition rate, had identical amplitude spectra. The experiment itself was done under controlled laboratory conditions with a design appropriate to minimize the effects of experimental noise on the data.

EXPERIMENT

Method

Subjects

Nine Stanford University undergraduate students and one middleaged laboratory technician served as subjects. They were run individually and each received $ 4 for participating. All claimed normal hearing and were naive toward the experimental purpose and procedure.

Apparatus

An Apple II microcomputer supported by two disk drives was used both for generating the stimuli and for controlling the experiments.

The synthesized signals were stored in the memory of the computer. They were output at a sampling rate of 30 KHz through a Tecmar model "Apple D/A DA101" 12 bit digital-to-analog converter. The signals were mixed with white and/or pink noise at different levels in a self designed switch box and signal mixer which was controlled by the computer. A two stage Krohn-Hite 3323R active filter was set to low pass the analog output below 4.7 KHz to minimize digital ringing. A Sony TA-F30 Integrated stereo amplifier feeding a set of KOSS Pro/4AAA dynamic headphones binaurally completed the signal path.

The sound levels were initially calibrated with a Bruel & Kjaer 2203 sound level meter, and a Bruel & Kjaer 4103 artificial ear. When running the experiments levels were calibrated with a Ballantine true rms voltmeter model 320A connected parallel over the headphones.

Stimuli

The original waveform used was synthesized using the model shown on fig. 1. This is an idealized helicopter noise impulse model of Boxwell and Schmitz (ref. 15). The parameters used for the waveform in this series of experiments were tau=5 msec., eta=0, beta=0, which means the original impulse is a triangular wave lasting 5 msec. This impulse was repeated each 100 msec creating a pulse repetition rate of 10 Hz. This waveform was Fourier analyzed. The obtained Fourier spectrum was modified and used for the synthesis of three stimuli. Components above 4 KHz were gradually attenuated proportionally to their frequency in a way so all frequencies above 4.75 KHz were totally attenuated. The resulting spectrum is shown on fig. 2 labelled 'no pink noise'. It is obvious that the signal has most of its energy at low frequencies. Parts of the spectrum between 0 and 1 KHz are plotted magnified on fig. 3. The spacing between the spectral lines is 10 Hz, which is the same as the pulse repetition rate. The three waveforms used in the experiment were all synthesized from the same spectrum and are shown on fig. 4.

Figure 4 shows the time history of the three signals. Waveforms labelled A are measured at the output of the 4.7 KHz lowpass filter. The waveforms labelled B are measured as the microphone output from the artificial ear and should represent the waveform of the signals at the subjects' eardrums. These waveforms are shown enlarged on fig. 5.

The waveform named 'cosine' wave was synthesized using the spectrum on fig. 2 with each spectral component at its original phase. This signal is also a maximum impulsivity signal as it have all its components in cosine phase, which creates impulses of maximum height.

The waveform named 'sine' wave was synthesized by using the same spectrum by putting all spectral components in sine phase, which means that all components will have a positive slope at time 0. Consequently, we obtain a signal with maximum steep slope.

The third waveform named 'random' was generated by putting each spectral component at a phase randomly between zero and two pi. The coefficients of impulsivity for the signals 'cos' and 'sin' are 10.8 and 7.9 respectively, well above the maximum proposed correction of 6 dB. The random waveform has a coefficient of impulsivity of -0.2.

On output the pulse trains were subject to three manipulations. First, the signals were manipulated so the pulse repetition rate was either 10 or 20 Hz. Second, the intensity was varied between 89 and 95 dBA by the swithcbox/mixer. Third, pink noise was superimposed on half of the signals through the switchbox/mixer at a level 12 dBA lower than the level of the sound from the computer. The resulting combined spectrum is shown on fig. 2 labelled 'with pink noise'. The pink noise is perceived as fairly loud when the sound is impulsive (signals 'cos' and 'sin'), but hardly audible when the signal is non-impulsive ('rnd'). The level of the pink noise is so low that the overall level of the signals as well as the coefficients of impulsivity do not change. All signals had a white noise masker signal added in order to mask a low level, high frequency ringing sound specially heard with the 'sin' waveform (probably caused by imprecission in the signal synthesis calculation). The level of this white noise masker was 54 dBA, and the noise was hardly noticeable.

It should finally be mentioned that all signals with the same pulse repetition rate have the same spectrum. The signals with 20 Hz pulse repetition rate were generated by dumping every second value of the waveform. This means, that the spectrums of the signals with 10 and 20 Hz pulse repetition rates are not the same.

Procedure

Subjects were tested individually. They were instructed that they would hear a series of sounds lasting 3 seconds each. They were to rate the sounds for annoyance on a scale from one to nine with one being "least annoying", 9 being "most annoying". It was strongly emphasized that the subject should use the full answer range if possible. To this end, the subjects first heard all 24 sounds in the "presentation trials". Then the subjects did between three and eight "practice blocks" each consisting of 8 trials. The rating was done verbally after each signal finished and was entered into the computer by the experimenter. The subjects continued with practice blocks until they used the full answer range reasonably well.

Now the experimental sequence took place. When finished, the subjects were asked about their opinions and feelings about the sounds, the experimental procedure, and the rating scale.

Finally, they were debriefed concerning the content and the aims of the experiment. A complete session lasted approximately 45 minutes.

Design

A within subject completely factorial randomized design was used. The subjects were each presented a different random order of 96 experimental trials. This resulted from the crossing of the three waveforms (cos,sin,rnd) with two levels each of pulse repetition rate (10, 20 Hz), sound intensity (89 dBA, 95 dBA), noise (pink noise at a level either equal to 0 dBA or 12 dBA under the sound intensity) and four replications for each combination of these factors.

RESULTS

Results will be reported as statistically significant if the level of significance exceeds $p<.01$ unless otherwise specified.

Table II shows the means of the annoyance ratings for each subject averaged over the four replications of each signal.

An analysis of variance (ANOVA) was conducted on the ratings from each subject separately using the pooled interactions with replications as the errorterm. This analysis showed the following:

- Nine of the ten subjects rated the sounds significantly different. T-tests performed for each individual showed that no subject rated the two impulsive sounds (cos,sin) as significantly diffferent at even the .05 level of significance. All except subject 10 rated each of the impulsive sounds as significantly different from the non-impulsive sound. But, the subjects did indeed not agree about whether the impulsive sounds were more or less annoying than the non-impulsive sounds.
- All subjects rated the 95 dBA sounds significantly more annoying than the 89 dBA sounds.
- Eight of the ten subjects rated the sounds with 20 Hz pulse repetition rate as significantly more annoying than the sound with 10 Hz pulse repetition rate. Subject 4 rated the high pulse repetition rate sound as significantly less annoying than the sound with low pulse repetition rate. Subject 1 showed no significant ($p<.05$) effect of pulse repetition rate.
- No clear tendencies were apparent for the sound with or without pink noise superimposed. Subject 1, 2, and 10 rated the sounds with pink noise as significantly ($p<.05$) less annoying than sounds without pink noise. Subjects 3,5, and 9 rated the sounds with pink noise as significantly ($p<.05$) more annoying than sounds without pink noise.
- A few different interaction terms showed significance. These will be described later.

It appears from table II that sex is an important factor in the rating of the effect of impulsivity. This variable was not part of the original design, so the significance of its effects are probably overestimated. All subjects are pooled in "group ALL". For the sake of further analysis, the subjects will be split up in two subgroups based on sex, with the 8 male in one group and the 4 females in the other. An ANOVA was performed with sex as a group variable and all others as repeated measures. The sound factor was not a significant main effect, but it interacted significantly with the sex factor.

Separate repeated measures ANOVAs were done for the two groups to clarify the nature of the interactions with sex.

The mean ratings for the 2 subgroups and for all subjects pooled are shown in table III, where also significance levels are shown. The average standard deviation for replications of the same sound was 1.38 for males, 1.33 for females, and 1.36 overall.

The males rated the impulsive sounds an average of 1.1 points more annoying than the non-impulsive sounds, whereas the females rated the impulsive sounds 1.6 points less annoying. The impulsivity effect was significant at the .05 level of significance for the females. When all subjects were pooled, the subjects on average rated impulsive and non-impulsive sounds nearly equally annoying.

The 95 dBA sounds were rated 2.6 points more annoying than the 89 dBA sounds for all three groups, and this effect was significant.

Signals with 20 Hz pulse repetition rate were for the three groups rated 0.8, 1.2, and 0.9 points more annoying than the signals with 10 Hz pulse repetition rate. The effect was significant only for the last two groups.

The addition of pink noise to the signals did not have a significant maineffect on the annoyance ratings.

The replication effect was significant and reflected an increase in annoyance ratings over trials. The mean rating for all subjects were for the four replications: 5.82, 5.83, 6.24, and 6.31 points respectively. The replication effect interacted significantly with intensity: The ratings grew less with time at the high intensity.

Few interactions were significant. Sound type interacted significantly with the noise factor: The mean rating for the impulsive sound decreased 0.23 points when pink noise was superimposed, whereas the mean rating for the non-impulsive sound increased 0.53 points when the noise was present. The three way interaction between the factors pulse repetition rate, noise, and sex showed significance. Both males and females rated the 20 Hz pulse repetition rate sounds as on average 0.5 points less annoying when pink noise was superimposed than when no noise was added. The same effect was present for the males for signals with 10 Hz pulse repetition rate. But the females rated these signals as 1.0 point more annoying when pink noise was present than when no noise was added.

DISCUSSION

One of the factors in the experiment was intensity. The 6 dB difference between the two levels of this factor and the corresponding average rating of these two levels make it possible to translate rating differences into a dB difference for all factors using linear interpolation. By applying this method to table III we get table IV.

Table IV presents the mean ratings of each factor averaged over all other factors and replications. From this table it is clear that the effect of impulsivity is more complex than the results from our earlier (1981) experiments which are summarized in table I. In those experiments the maximum frequency of the spectrum was 600 Hz. We found then that the subjects on average rated the impulsive sounds respectively 2.7, 3.5 and 4.5 dB less annoying than the non-impulsive sounds in the three experiments. This effect was significant at a .01 level in each experiment. This is clearly not the case in the present experiment.

The results (see table II and IV) revealed that impulsivity (signals 'cos' and 'sin') on average had no effect on annoyance. But if we look at the individual scores it becomes apparent that the sex of the subjects seemingly has an important effect. All females rated impulsive sounds significantly less (3.7dB) annoying than non-impulsive sounds. Most of the 6 male subjects behaved exactly opposite, and on average they rated the impulsive sounds 2.6 dB more annoying than the non-impulsive sounds. The effect for the male subjects was not significant, though. A closer look at the male subjects revealed, that the one subject, that rated opposite the rest of the male subjects was the older subject (age approximately 50). This therefore suggests that also age might have an important influence on annoyance of impulsive sound.

This ageeffect is in opposition to the results from our 1981 experiments were we exactly tested for the age effect, and found no significant effect. The difference between the 2 series of experiments is the increased high frequency content of the present signals. But any conclusion concerning age effect must await further testing.

If we exclude the 'old' male subject, the rest of the male subjects rate the impulsive sounds as significantly (4.1 dB) more annoying than the non-impulsive sounds.

Whether this sexual (and maybe age) difference in annoyance of these impulsive sounds is a general characteristic or a pure coincidence in this experiment would require further testing. At the moment we can only hypothesize about the reasons for these difference.

Several of the male subjects mentioned that they had a distinct physical feeling of discomfort when they listened to the impulsive sounds. They felt that something pounded on their head and eardrums and typically said: "The beats are getting at me". None of the female subjects expressed these sensations.

As mentioned earlier, t-tests revealed that subjects didn't rate the cosine and sine phase impulses significantly different. Therefore, the increase in slope did not influence the perceived annoyance of the impulsive signals.

The effect of pulse repetition rate was in the 1981 series of experiments reported in table I very small, though the tendency was towards increased annoyance for increased pulse repetition rate. This phenomenon is more pronounced in the present experiment, where a pulse repetition rate of 20 Hz on average significantly increased the annoyance 2.2 dB over noise with pulse repetition rate of 10 Hz. It appears that increased frequency spectrum makes the effect of pulse repetition rate much more pronounced.

The analysis also showed that the annoyance increases significantly over trials (up to 1.1 dB after 4 trials). This is not surprising. Annoyance is generally considered as correlated to duration, so the longer duration increases annoyance. This is confirmed here.

Finally, the noise factor. Half of the signals had pink noise (also cutoff at 4.7 KHz) superimposed at a level 12 dBA under the level of the signal. This doesn't increase the overall sound pressure level nor the coefficient of impulsivity of the signals. The noise had no effect on the annoyance by itself, although the pink noise was perceived as fairly loud when the signal was impulsive. On the other hand, the pink noise had a significant effect (level .05) in interaction with the sound factor.

Addition of the pink noise increased the annoyance of the non-impulsive sounds 1.2 dB, but it decreased the annoyance of the impulsive sounds with 0.5 dB. As some subjects expressed it: "The background noise had a soothing (or muffling) effect". This is an interesting example of a situation where annoyance can be decreased by adding more noise.

The noise level was 12 dBA under the signal level. We don't expect that we just by increasing the level of the pink noise can decrease the annoyance of the impulsive sound much more. But further research is needed to clarify this question.

Finally, a few remarks concerning the use of a limited rating scale. The annoyance scale used was limited to ratings 1 through 9. A problem with this kind of scale can be a certain floor and/or ceiling effect. Whether this was the case here is hard to say. We found that intensity interacted significantly with replication. Low intensity signals increased in annoyance over replications, whereas ratings of high intensity signals stayed the same. This could indicate a ceiling effect in the way that subjects started out with high ratings of the high intensity sounds. Even if these signals became increasingly annoying over trials there was not much room left on the scale for higher ratings. Whether this is caused by a ceiling effect or other reasons can probably only be tested with an experiment using an open-ended rating scale. On the other hand, the subjects were asked about their feelings about the scale used. No one felt that they were limited by the scale; most actually felt the scale was too wide.

Concluding we can say that the increase in frequency content of the impulsive signals compared to our 1981 experiments had certain, distinct effects. It confused the annoyance characteristics of impulsive sound, created distinct sex differences in annoyance ratings, and increased the effect of high pulse repetition rate. The results do still not support most of the research done elsewhere which stated that increased impulsivity leads to increased annoyance.

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Table I. Effects of impulsivity and pulse repetition rate on annoyance in three experiments expressed in dB relative to one level of each factor. Level of significance is indicated. Exp. I: Mean age of subjects = 19 years, signal duration 3 sec. Exp II: Mean age of subjects = 19 years, signal duration 12.5 sec. Exp. III: Mean age of subjects = 36 years, signal duration 3 sec.
(From Ahumada, Fish, Henckel (1981) - ref. 14).

EXPERIMENT		I	II	III
SOUND	IMP. - NON-IMP.	-2.7 **	-3.5 **	-4.5 **
PULSE REP. RATE	20Hz - 10Hz	+1.5 *	+0.3	+1.1

** p<0.01
 * p<0.05

Table II. Mean annoyance ratings over 4 replications for each subject.

SOUND -PHASE		IMPULSIVE -COS				IMPULSIVE -SIN				NON-IMPULSIVE -RANDOM			
PULSE REP. RATE, Hz		10		20		10		20		10		20	
PINK NOISE		-	+	-	+	-	+	-	+	-	+	-	+
SUBJ. -SEX	INT. dBA												
1-M	89	5.0	3.0	3.3	3.8	5.5	4.3	5.0	4.3	3.0	3.8	3.8	4.5
	95	7.5	5.8	7.3	5.3	7.8	7.0	8.8	5.8	5.3	4.0	5.3	4.8
2-M	89	6.5	3.8	6.8	5.5	5.3	5.5	7.0	5.0	2.3	2.3	2.5	4.3
	95	7.5	6.8	9.0	8.5	6.5	6.8	8.3	8.0	5.0	5.3	7.0	7.5
3-F	89	4.3	4.3	5.5	3.8	3.5	4.5	5.0	4.3	3.8	5.3	6.5	7.3
	95	5.0	7.5	6.8	8.0	6.8	7.8	7.5	8.5	8.3	9.0	8.8	9.0
4-M	89	6.8	7.3	4.5	5.0	7.5	7.0	4.0	6.3	3.8	4.5	4.5	5.3
	95	8.5	8.5	8.3	7.8	9.0	9.0	8.3	8.5	7.3	6.8	6.8	7.5
5-M	89	5.3	5.5	6.5	4.8	3.8	3.8	7.0	4.0	2.0	2.3	2.0	2.8
	95	6.8	7.8	8.8	8.5	5.8	7.5	9.0	8.8	3.8	5.5	6.3	7.8
6-M	89	2.3	3.8	5.0	5.5	4.8	2.3	5.8	5.3	7.3	7.5	6.8	7.5
	95	5.3	5.3	7.5	7.8	7.0	6.0	8.5	7.8	9.0	9.0	8.8	9.0
7-M	89	3.3	2.8	4.8	5.0	3.5	3.8	4.3	3.5	1.8	2.0	3.0	3.5
	95	7.8	5.0	8.5	8.8	7.0	5.8	8.5	8.3	3.5	5.0	5.8	6.0
8-F	89	2.8	3.3	7.0	4.0	2.3	4.3	6.0	4.5	4.5	6.5	6.8	7.3
	95	6.3	7.0	9.0	7.8	5.3	7.3	7.5	7.5	7.3	8.3	8.8	9.0
9-F	89	2.3	5.5	4.3	4.5	2.5	4.0	4.8	5.0	6.5	7.3	8.0	8.8
	95	5.3	7.3	7.3	6.8	4.0	7.5	6.8	7.0	8.5	9.0	9.0	9.0
10-F	89	5.0	1.8	6.5	4.8	5.0	5.3	7.3	5.3	5.5	5.5	6.8	5.3
	95	7.3	7.8	9.0	8.3	8.0	7.8	8.8	8.8	6.8	8.5	9.0	9.0

Table III. Mean ratings for different groups of the 10 subjects averaged over repetitions, subjects and all other factors. The sounds 'cos', and 'sin' are impulsive, 'rnd' is non-impulsive. The pink noise had a level 12 dBA lower than the level of the noise it was superimposed to. Levels of significance are shown.

	SUBJECTS	MALES	FEMALES	ALL
SOUND	ORIG	6.1	5.8 *	6.0
	SIN	6.3	5.9 *	6.1
	RND	5.1	7.4	6.0
INTENSITY	89 dBA	4.5	5.1	4.8
	95 dBA	7.1 **	7.7 **	7.4 **
PULSE REP.RATE	10 Hz	5.4	5.8	5.6
	20 Hz	6.2	7.0 **	6.5 **
PINK NOISE	NO	5.9	6.2	6.0
	YES	5.7	6.6	6.1

** $p<0.01$
* $p<0.05$

Table IV. Mean ratings in dBA relative to one level of each factor for different groups of the 10 subjects averaged over subjects and all other factors. The sounds 'cos' and 'sin' are impulsive. The sound 'rnd' is non-impulsive. The level of the pink noise was 12 dBA lower than the level of the noise it was superimposed to.

	SUBJECTS:	MALES	FEMALES	ALL
SOUND	COS - RND	+2.4	-3.8 *	-0.1
	SIN - RND	+2.8	-3.5 *	+0.2
INT.	95dBA - 89dBA	+6.0 **	+6.0 **	+6.0 **
PULSE REP. RATE	20 Hz - 10 Hz	+1.8	+2.7 **	+2.2 **
PINK NOISE	'yes' - 'no'	-0.4	+0.8	+0.1

** $p<0.01$
* $p<0.05$

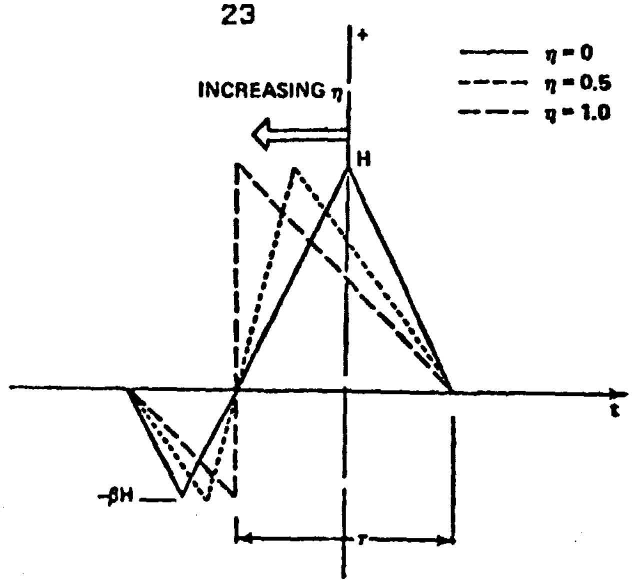

Fig. 1 Idealized analytic helicopter impulse. In this experiment tau=5 msec, beta=0, and eta=0 (from ref. 15).

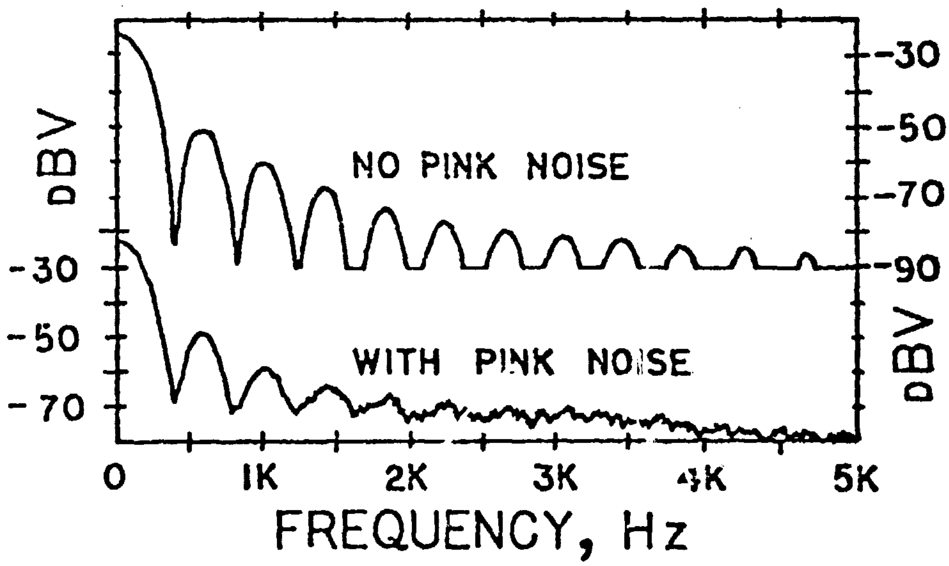

Fig. 2 Powerspectrum of all signals with 10 Hz pulse repetition rate. Upper curve is spectrum for signals without pink noise. The 'floor' at -90 dB is created by the spectrum analyzer and not by the amplitude of the spectral components. Lower curve is spectrum for signals with pink noise superimposed at a level 12 dBA under the level of the signal.

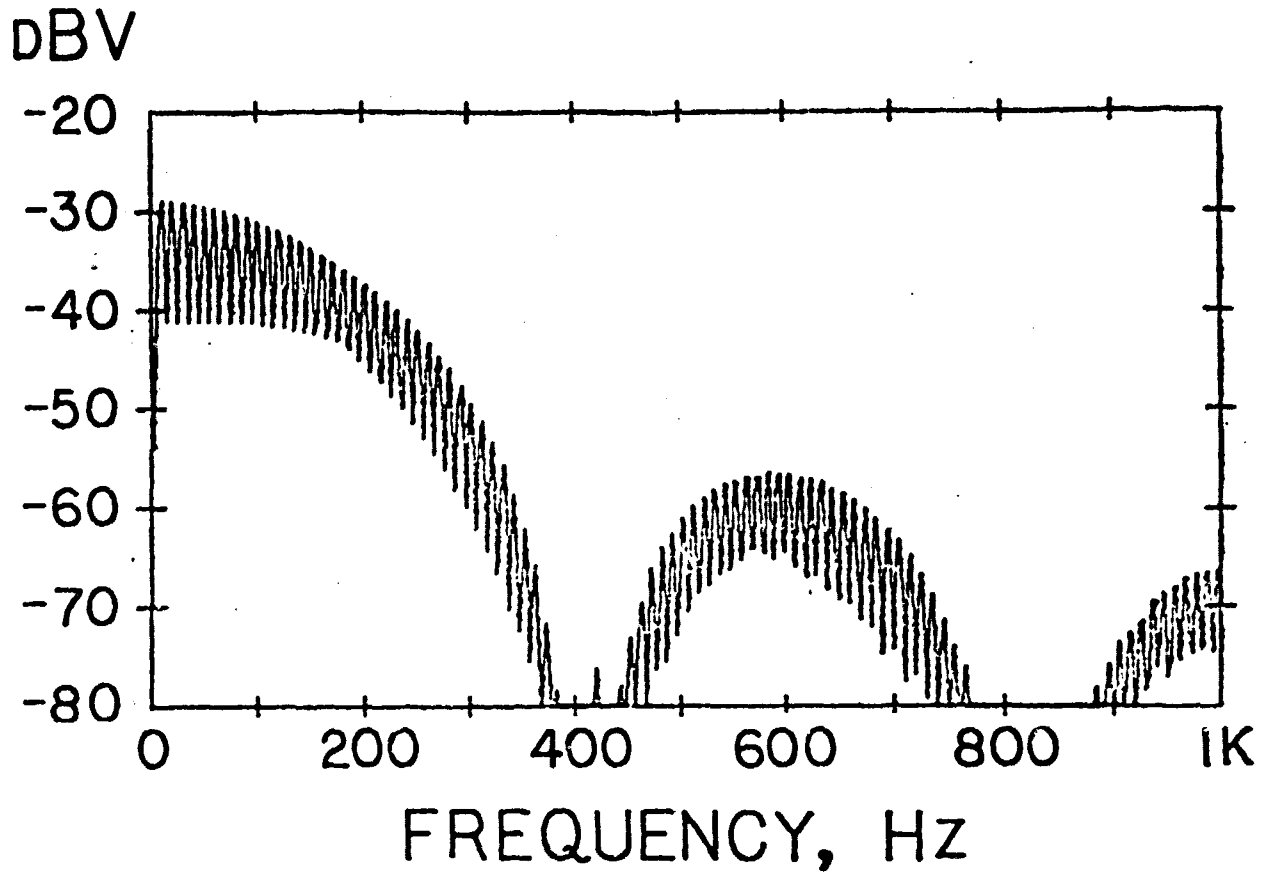

Fig. 3 Power spectrum for all signals with 10 Hz pulse repetition rate in the frequency range 0 to 1 kHz.

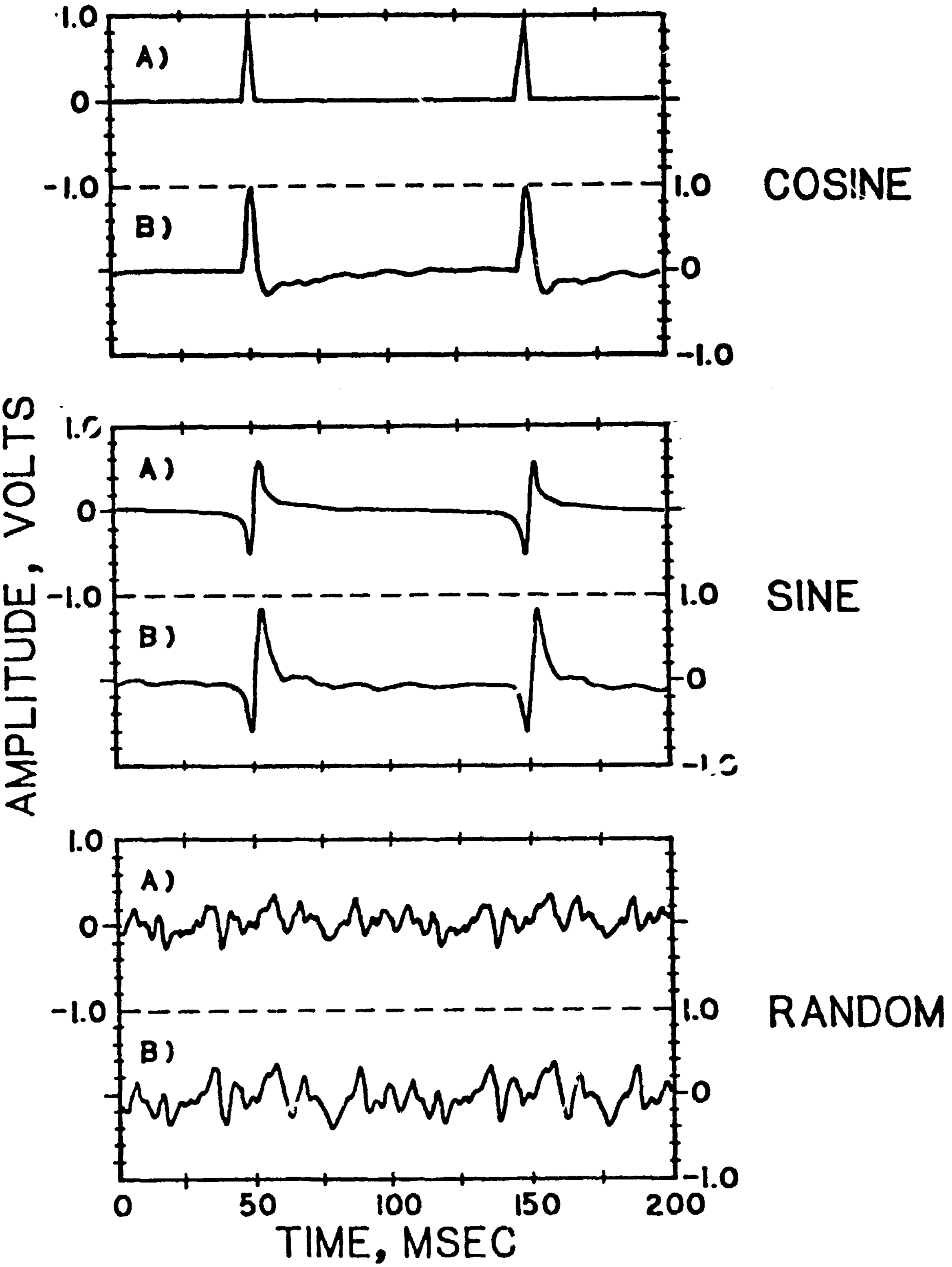

Fig. 4 Time history of the three waveforms used. All have pulse repetition rate 10 Hz, and all have the same amplitude spectrum (see fig. 2). The signals are named acccording to the phase of their frequency components. The waveform labelled A is the output of the 4.7 KHz low-pass filter. The waveform labelled B is the microphone output from the artificial ear.

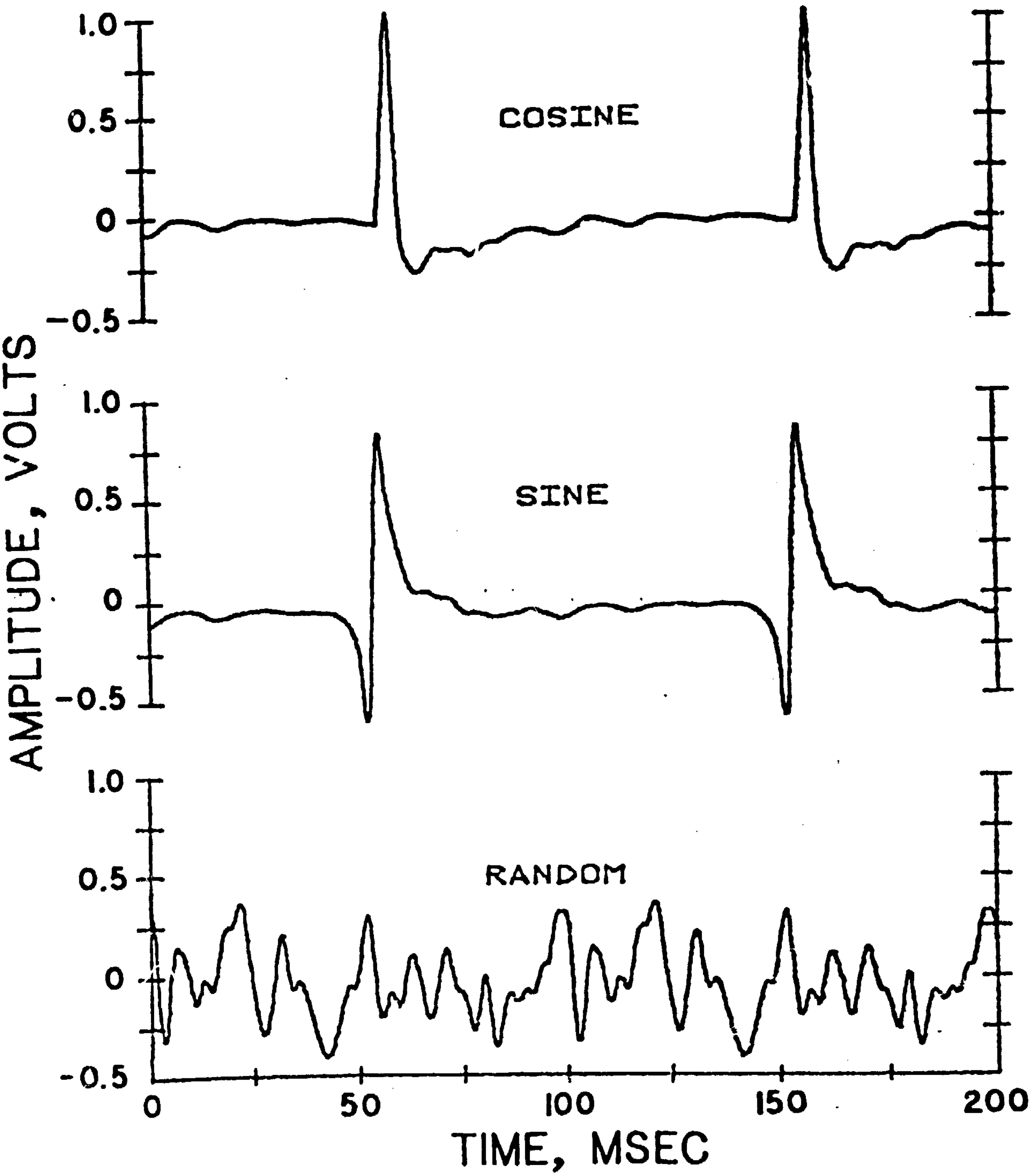

Fig. 5 Time history of the three waveforms used. All have pulse repetition rate 10 Hz and all have the same amplitude spectrum. The signals are named according to the phase of their frequency components. Signals are measured as the microphone output from the artificial ear (same as B waveforms on fig. 4) and should represent the waveform of the signals at the subjects' eardrums.