Psychoacoustic evaluation of noises produced by propellers with asymmetrical blade spacing

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Instrumental evaluations (e.g. Dobrzynski, InterNoise 90) showed that propeller noise can be reduced by asymmetrical blade spacing. Compared to conventional propellers with 6 blades and symmetrical spacing of 60°, propellers with asymmetric spacing of 15° produce about 3 dB(A) less level, in particular for high helical blade tip Mach numbers HBTMN. Since the aerodynamic propeller performance is not affected by asymmetrical blade spacing, this technique might be regarded as an effective means for noise reduction of propelled aircraft. However, before drawing such a conclusion based solely on instrumental evaluations, subjective evaluations of sounds from asymmetrically spaced propellers are advisable. Therefore, loudness, sharpness, pitch strength, and annoyance of the propeller sounds were studied in psychoacoustic experiments. The results showed that propellers with symmetric vs. asymmetric blade spacing elicit almost the same loudness and annoyance when measured in lab studies. However, in particular at high HBTMN, propellers with asymmetric blade spacing produce less sharpness and pitch strength.

1 INTRODUCTION

Despite the fact that nowadays larger aircraft usually are equipped with jet engines, the interest in propelled aircraft is still viable. Since the sound characteristics of jet vs. propelled aircraft are rather different, specific studies aiming to reduce the noise of propelled aircraft are necessary. Along these lines, Dobrzynski[1] showed that propeller noise can be reduced by asymmetrical blade spacing. Compared to conventional propellers with 6 blades and symmetrical spacing of 60°, propellers with asymmetric spacing of 15° produce about 3 dB(A) less level, in particular for high helical blade tip Mach numbers. Since the aerodynamic propeller performance is not affected by asymmetrical blade spacing, this technique might be regarded as an effective means for noise reduction of propelled aircraft.

However, before drawing such a conclusion based solely on instrumental evaluations, subjective evaluations of sounds from asymmetrically spaced propellers are advisable.

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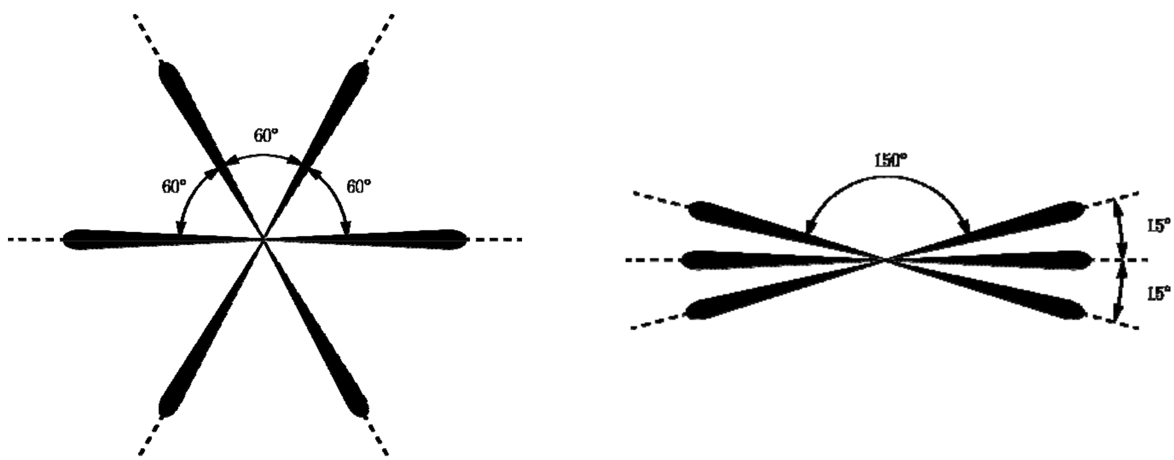
Therefore, loudness, sharpness, pitch strength, and annoyance of the propeller sounds were studied in psychoacoustic experiments. The results are discussed in view of the question, whether asymmetric spacing of propeller blades has also advantages concerning subjective evaluation. In addition, expectations of the influences of loudness, sharpness or pitch strength on annoyance as measured in lab studies are challenged.

2 STIMULI

Recordings in a wind tunnel of propellers with 1.7 m diameter and symmetric vs. asymmetric blade spacing were made available by Dr. W. Dobrzynski[1] of the Deutsches Luft- und Raumfahrtzentrum (DLR). Propellers with six blades and helical blade tip Mach numbers (HBTMN) of 0.65, 0.70, 0.75 and 0.78 are considered. The sketches in figure 1 illustrate that one propeller had symmetric blade spacing with 60°, and the other propeller asymmetric blade spacing with 15°.



a) *b)*

Fig. 1 - Schematic illustration of the layout for the propeller with symmetric blade spacing (a) vs. the propeller with asymmetric blade spacing (b).

Figure 2 illustrates the spectra for the propeller with symmetric blade spacing (left) and asymmetric blade spacing (right) at different helical blade tip Mach numbers HBTMN.

Since the recorded propeller sounds reached sound pressure levels up to 115 dB, for the psychoacoustic experiments all SPLs were reduced by 30 dB in order not to jeopardize the subjects' hearing system. Stimuli were arranged in pairs with 5 s duration, 50 ms Gaussian-shaped gating signal, and a 2 s silent interval. The pause between pairs was chosen to 4 s.

Sounds were presented diotically in a sound attenuating booth via electrodynamic headphones (Beyer DT 48) with free-field equalizer according to Fastl and Zwicker[2].

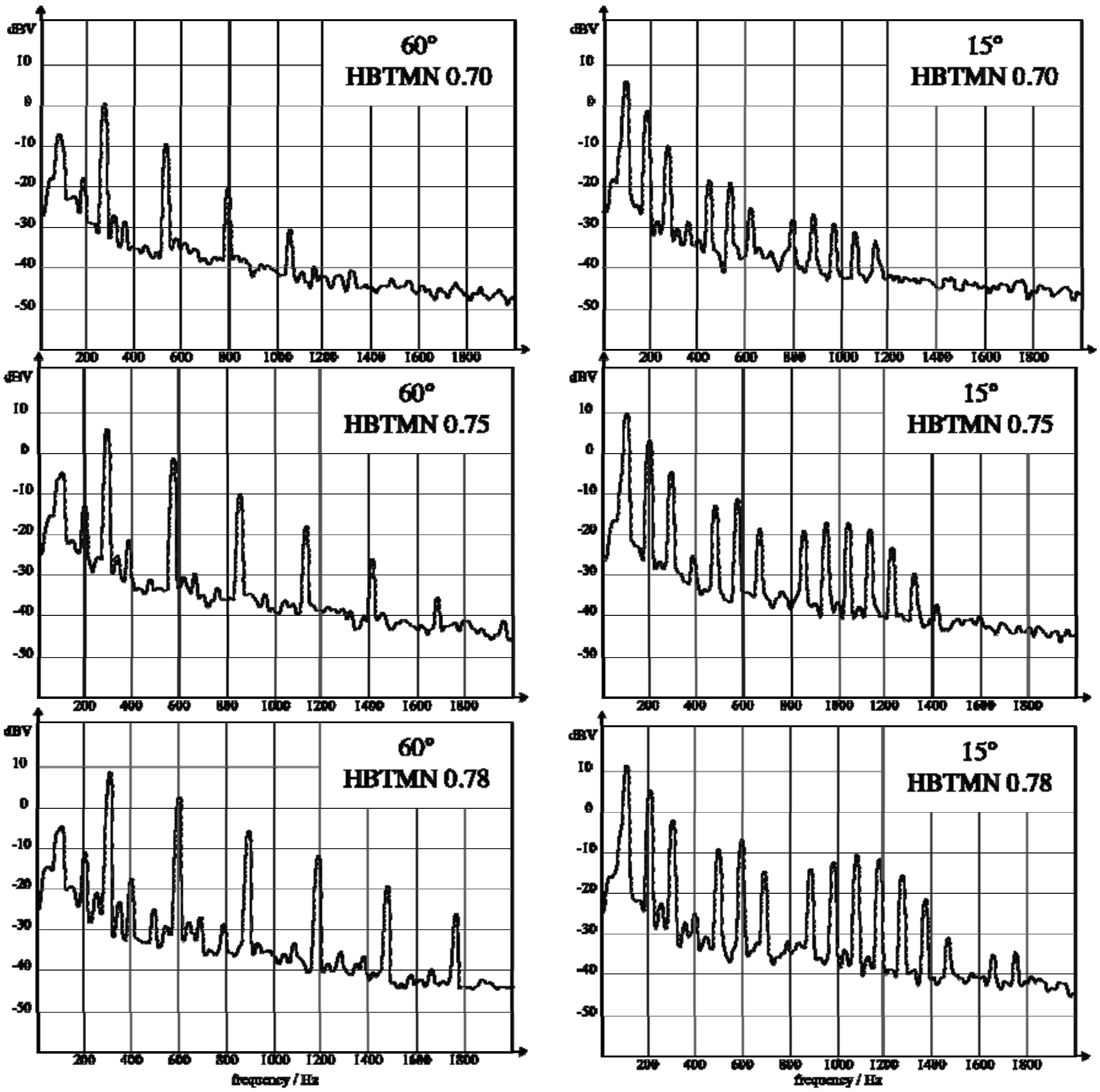


Fig. 2 - Spectra for the propeller with symmetric blade spacing (left) vs. the propeller with asymmetric blade spacing (right) at helical blade tip Mach numbers HBTMN of 0.70, 0.75, and 0.78.

3 EXPERIMENTS

3.1 Subjects

Eleven subjects aged 21 to 45 years (median 25 years) with normal hearing ability (maximum deviation of ISO standard curve 15 dB) took part in the experiments.

3.2 Procedures

For the ratings of loudness, sharpness, pitch strength, and annoyance a procedure of **magnitude estimation** was applied. Subjects were presented pairs of propeller sounds. The respective first sound in a pair was kept constant and assigned the number 100. Relative to this value, the respective second sound in a pair should be scaled with respect to the magnitude studied. If for example loudness is assessed, and the second sound produces only one fifth the loudness of the first sound, the subject should assign the number 20. Each subject rated each sound four times in different sequence. From the resulting 44 data points, medians and inter-quartiles were calculated and are given in the figures.

For the annoyance ratings, the subjects should imagine a situation as follows: They would be sitting in their living room, reading a book, and under these circumstances the propeller sounds would be heard.

For the pitch matching experiments, an **adjustment** procedure was chosen. Propeller sounds were looped and the subjects had command of a switch: in one switch setting they heard a propeller sound, in the other switch setting a pure tone which they could vary in pitch using a potentiometer. Subjects could listen alternately to each of the sounds as long as they wished. When they had accomplished the pitch match, the frequency of the pure tone was taken as a measure of the pitch elicited by the respective propeller. The pitch of each propeller sound was judged by each subject four times in different sequence.

4 RESULTS AND DISCUSSION

4.1 Loudness and annoyance

Figure 3 shows the results for loudness and annoyance ratings as a function of the helical blade tip Mach number, HBTMN. Data for loudness vs. annoyance were collected at least three days apart.

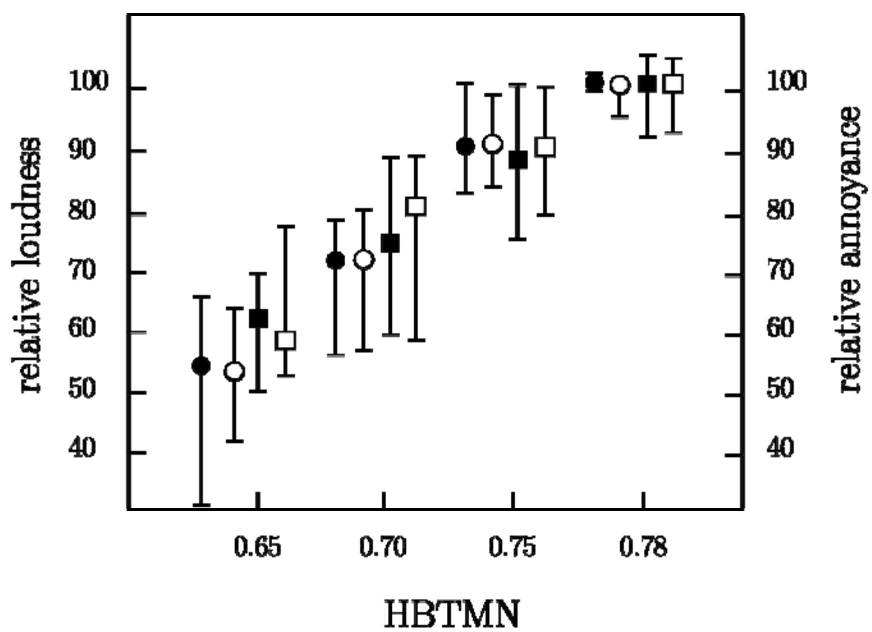


Fig .3 - Rating of loudness (unfilled symbols) and annoyance (filled symbols) for sounds from propellers with symmetric blade spacing (circles) vs. asymmetric blade spacing (squares) as a function of helical blade tip Mach number HBTMN.

The data displayed in figure 3 suggest that there is not much difference between loudness (unfilled symbols) and annoyance rating (filled symbols) of the propeller sounds, at least concerning the "laboratory annoyance" studied here. As expected, both loudness and annoyance increase with increasing helical blade tip Mach number.

Moreover, when comparing results illustrated by circles vs. squares, and taking into account the magnitude of the inter-quartile ranges, the type of blade spacing seems to have relatively little influence on both loudness and annoyance rating.

A clear advantage of -3 dB(A) for the asymmetric spacing of the propeller blades as demonstrated by Dobrzynski[1] for physical measurements of A-weighted sound pressure is not reflected in the subjective evaluations displayed in figure 3.

When taking the often used rule of thumb that 10 dB reduction in level should correspond to a halving of perceived loudness, i.e. a drop from 100 to 50, a reduction by 3 dB should produce a drop from 100 to about 81.

However, when comparing data represented in figure 3 by unfilled circles and unfilled squares, usually the squares are found at the same height as the circles or even somewhat higher. Despite some spread of the inter-quartile ranges of the data displayed in figure 3, at HBTMN = 0.78, the prediction by the rule of thumb definitely fails: The unfilled square would be situated near 81, but the median shows up at 100 with the lower inter-quartile near 93.

This means that the advantage of the asymmetric spacing ascertained by Dobrzynski[1] for physical measurements of A-weighted sound pressure level is *not* reflected in subjective evaluations of loudness.

4.2 Sharpness

Figure 4 shows the results for the rating of sharpness as a function of helical blade tip Mach number, HBTMN. Circles represent data for the sharpness of sounds from propellers with symmetric blade spacing, squares for sounds from propellers with asymmetric blade spacing.

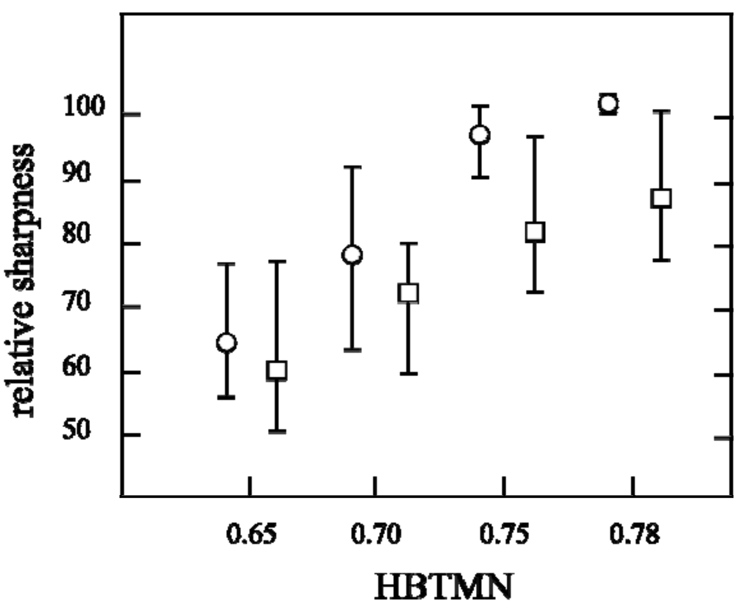


Fig .4 - Rating of sharpness for sounds from propellers with symmetric blade spacing (circles) vs. asymmetric blade spacing (squares) as a function of helical blade tip Mach number HBTMN.

The data displayed in figure 4 suggest that – in particular at high values of the helical blade tip Mach number – the propeller with asymmetric blade spacing (squares) produces less sharpness than the propeller with symmetric blade spacing (circles).

One reason for this behavior may be that for the asymmetric blade spacing spectral components of the rotational noise show up at lower frequencies than for the symmetric blade spacing (compare right and left spectra in figure 2).

4.3 Pitch strength

Figure 5 shows the results for the rating of pitch strength as a function of helical blade tip Mach number, HBTMN. Circles represent data for the pitch strength of sounds from propellers with symmetric blade spacing, squares for sounds from propellers with asymmetric blade spacing.

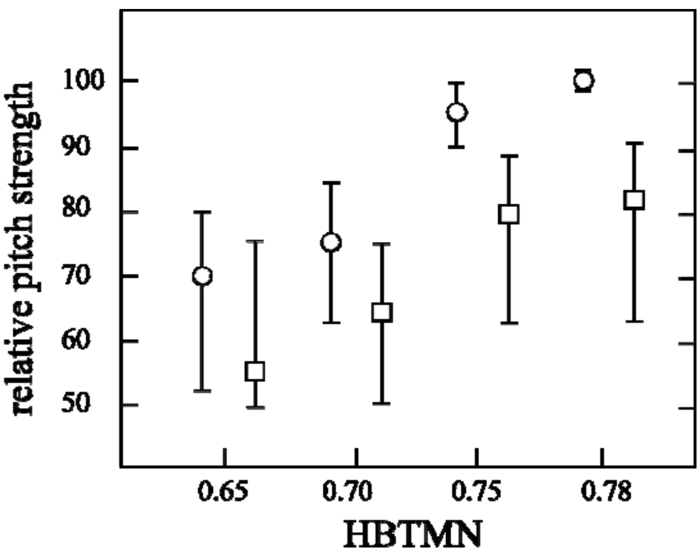


Fig .5-- Rating of pitch strength for sounds from propellers with symmetric blade spacing (circles) vs. asymmetric blade spacing (squares) as a function of helical blade tip Mach number HBTMN.

The data displayed in figure 5 suggest that pitch strength is lower for sounds from propellers with asymmetric blade spacing (squares) than for sounds from propellers with symmetric blade spacing (circles). This again may be understood on the basis of the spectra displayed in figure 2, since sounds with lower pitch elicit also less pitch strength (e.g. Fastl[3]). Noteworthy are the large inter-quartile ranges in figure 5, typical for larger inter-individual differences in this task.

4.4 Pitch matches

Regarding the different spectra of sounds from propellers with symmetric vs. asymmetric blade spacing, it can be expected that the different types of propeller elicit different pitch sensations at the same helical blade tip Mach number. Therefore, the pitches produced by the propeller sounds were matched to the pitch of pure tones.

Table 1 allows a comparison of the calculated frequencies for the rotational noises and the matched pitches.

Table 1 - Matched pitches of propeller sounds at different helical blade tip Mach numbers for propellers with 60° blade spacing vs. 15° blade spacing in comparison to calculated frequencies of rotational noises.

spacing	HBTMN	matched pitch	calculated frequency
60°	0.65	243 Hz	242.4 Hz
	0.70	257 Hz	261.1 Hz
	0.75	281 Hz	279.7 Hz
	0.78	296 Hz	290.9 Hz
15°	0.65	81 Hz / 138 Hz	80.0 Hz
	0.70	91 Hz / 172 Hz	87.0 Hz
	0.75	95 Hz / 187 Hz	93.2 Hz
	0.78	100 Hz / 192 Hz	97.0 Hz

The data displayed in Table 1 show that the matched pitches are pretty close to the calculated frequencies for the propeller with symmetric blade spacing of 60°. The same holds true for the pitch matches concerning the propeller with 15° asymmetric blade spacing, where, however, additional higher pitches are matched, corresponding roughly to a second harmonic of the basic frequency.

5 CONCLUSIONS

The advantages of propellers with asymmetric blade spacing as ascertained by Dobrzynski[1] in a reduction by 3 dB(A) for physical measurements of SPL could not be confirmed by psychoacoustic evaluations. In particular at high helical blade tip Mach numbers, loudness was rated by subjects rather similar for sounds from propellers with symmetric or asymmetric blade spacing.

Moreover, it could be shown that annoyance of the propeller sounds as measured in the laboratory is highly correlated to loudness. In addition, as illustrated by Table 2 this holds more or less also for sharpness and pitch strength. The Spearman rank correlations r_s between 0.854 and 0.983 are highly significant (α between 0.005 and 0.001).

Table 2 – Correlations between annoyance and loudness, sharpness, and pitch strength.

	r_S	α
annoyance - loudness	0,983	0,001
annoyance - sharpness	0,924	0,001
annoyance - pitch strength	0,854	0,005

A somewhat unexpected result of the present investigations should not be concealed: In sound quality engineering, frequently sharpness and pitch strength influence the annoyance of technical sounds (e.g. Fastl[4]), usually increasing it. However, as displayed in figure 3, in the present experiments on propeller sounds, loudness and annoyance ratings are rather similar despite differences in sharpness and pitch strength as displayed in figures 4 and 5.

When tentatively accepting the mentioned concepts of sound quality engineering, because of lower values of sharpness and pitch strength for asymmetric blade spacing, lower values of annoyance might also be expected for these products - in particular at higher helical blade tip Mach numbers. However, the results displayed in figure 3 clearly contradict such a prediction.

Therefore, more detailed psychoacoustic studies are necessary which ideally should be complemented by field studies in order to evaluate the advantages and disadvantages of propellers with asymmetric blade spacing from a practical point of view.

5 ACKNOWLEDGEMENTS

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