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Annoyance penalty of amplitude-modulated sound

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ABSTRACT

Amplitude-modulation (AM) appears in various kinds of noise sources. The nature of periodic AM sound can be described by e.g. AM frequency, AM depth, and equivalent spectrum of sound pressure level (SPL). There is little research concerning the effect of these factors on annoyance. Our purpose was to determine the penalty of periodically AM sounds for a range of AM frequency, AM depth, and spectrum of equivalent SPL. Forty participants rated the annoyance of 70 AM sounds and 22 reference sounds. The three independent variables of AM sounds were AM frequency (7 levels, from 0.25 to 16 Hz), AM depth (5 levels, from 1 to 14 dB), and SPL spectrum (2 alternatives). All AM sounds were played at 35 dB L_{Aeq}. Reference sounds were played at levels from 29 dB to 49 dB L_{Aeq}. They enabled the determination of penalty of AM sounds. All sounds were created from pseudorandom noise. The results showed a significant effect of all three independent variables on annoyance. The effect of both AM frequency and AM depth was very large. The penalty values varied from -1 to +12 dB. The results can be used in the development of penalty schemes of AM sounds.

Keywords: Psychoacoustics, annoyance, amplitude modulation

1. INTRODUCTION

Many regulations involve a penalty, k [dB], to be added to the measured or predicted equivalent A-weighted SPL, L_{Aeq} [dB], in order to counteract the negative effect of the specific feature on annoyance. The specific features mentioned in many regulations so far are impulsivity and tonality.

Besides sound level, impulsivity, and tonality, a fourth special property of sound, which can be auditorily sensed, is amplitude modulation (AM). Two reviews (1,2) suggest that a penalty should be applied to AM sound of wind turbines because of the additional annoyance caused by AM. AM means that the amplitude of a carrier sound varies with time. If the variation is periodic, the frequency of AM sound, f_m [Hz], can be defined. The frequency can be constant or randomly changing. AM exists in the sound of, e.g. sea waves reaching the coast, pulsating road traffic noise, wind turbine noise, helicopter, ventilation, and low-speed engine. The strength of AM can be described by D_m [dB], which is the difference between the maximum and minimum value of the A-weighted SPL.

Several psychoacoustic experiments have studied the annoyance of AM sounds (3, 4, 5, 6, 7). They suggest that AM increases the annoyance of sound if a certain level of D_m is exceeded. Most of the abovementioned references have focused on the AM sounds of wind turbines. Because AM can be found also in other present or future sources of environmental noise, it would be important to study the annoyance of AM sound with a generic study without having strong connection to any realistic sound source.

Our purpose was to determine the annoyance penalty of AM sound as a function of the modulation frequency and modulation depth. The study was conducted for two different spectra.

2. MATERIALS AND METHODS

We conducted a psychoacoustic laboratory experiment with forty voluntary participants (mean 27 years, 28 female, 12 male). The independent variable was the *experimental sound* (later: *sound*) and the dependent variables were *loudness* and *annoyance*. However, we focus on *annoyance* in this study.

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Each participant rated the annoyance of 92 sounds using an eleven-point response scale of ISO/TS 15666 from 0 (Not at all) to 10 (Extremely much).

The experimental sounds consisted of AM sounds and reference sounds. Reference sounds were used to determine the penalty. The AM sounds were created as combinations of three independent variables: modulation depth (5 levels), modulation frequency (7 levels), and spectrum (2 levels). Altogether, we had 5x7x2 AM sounds, i.e. 70 sounds. All AM sounds were presented at an overall level of 35 dB L_{Aeq}. The reference sounds were presented at levels from 29 to 49 dB L_{Aeq} in 2 dB steps. Reference sound had the same equivalent SPL spectrum as the AM sound but AM was absent. Because we had AM sounds with two different spectra, we had also two sets of reference sounds.

The experimental sounds were produced synthetically (MATLAB). First, broad-band pseudo-random noise was weighted to achieve the two spectra S1 and S2 (Figure 1a). Spectrum S1 represents a typical non-tonal wind turbine noise and spectrum S2 represents urban road traffic noise. However, the sounds were generic since they were created from pseudorandom noise.

These two spectra acted as the carrier waves for the AM sounds. The amplitude of the carrier wave was varied sinusoidally with modulation index m:

$$m = \frac{10^{D_m/20} - 1}{10^{D_m/20} + 1}$$

where D_{m} [dB] is the modulation depth. The carrier wave was multiplied with quantity Q

$$Q = 1 + m \cdot \sin(2\pi f_m t)$$

to induce the modulation in the steady noise. Here, f_m [Hz] is the modulation frequency, and t [s] is time. Time was discretized by

$$t = (0, 1, 2, \dots,\ n_s - 1)\frac{1}{f_s},$$

where n_s is the number of the samples, and f_s [Hz] is the sampling frequency (44.1 kHz). The carrier wave was modulated with only one modulation depth at one modulation frequency. Twenty-second-long sound samples were created, and they were looped until the participant gave the response. The sounds were presented within frequency range from 25 to 5000 Hz.

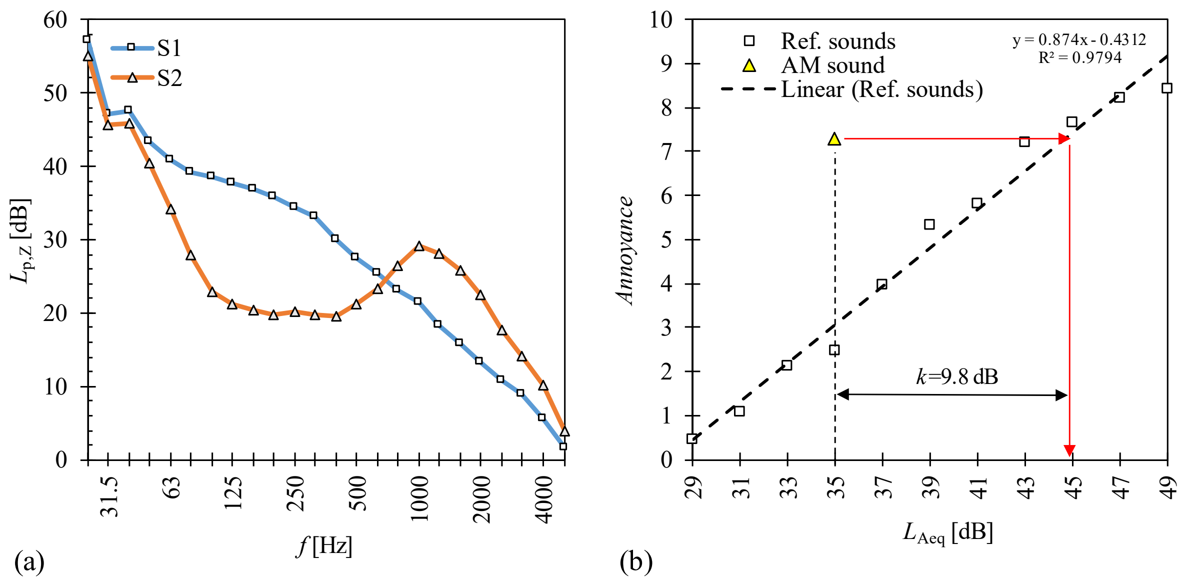

Figure 1. (a) Unweighted SPL, $L_{\mathrm{p,Z}}$, of spectra S1 and S2 versus frequency, f. (b) The principle of determining the penalty. The AM sound in this example has spectrum S1, D_{m}=8 dB, and f_{m}=8 Hz.

Before the experiment, the properties of the *sounds* were measured so that they met the desired properties with respect to overall level, overall spectrum, D_{m}, and f_{m}. The measurements were made with head-and-torso simulator since the sounds were presented to the participants with headphones.

The experiment was conducted in the psychoacoustic laboratory of Turku University of Applied Sciences in Turku during spring 2017. The background noise level was 21 dB L_{Aeq}. The experiment consisted of 12 phases. Phase 1 was the information consent form. The experiment was supported by the ethical board of Finnish Institute of Occupational Health. Phase 2 was an initial questionnaire which is not fully reported here. Phase 3 was the hearing threshold test. All participants had normal hearing. Phase 4 was the familiarization to the sounds. The participants could listen to some sound examples but they did not rate them yet. Phase 5 was the rehearsal of loudness rating for some sound examples. The results were not analyzed. Phases 6 and 7 were loudness rating blocks for two alternative spectra, respectively. It should be noted that both spectra were presented in different blocks but the order of the spectra were counterbalanced between participants. Phase 8 was a short break. Phase 9 was the rehearsal of annoyance rating for some sound examples. The results were not analyzed. Phases 10 and 11 were annoyance rating blocks for two alternative spectra, respectively. Both spectra were presented again in different blocks and the order of the spectra were counterbalanced between participants. Phase 12 was feedback and reception of 20 euros gift token.

The penalty was determined according to Figure 1b. The method was developed in Refs. (8) and (9). The annoyance penalty *k* of an AM sound is determined by estimating the L_{Aeq} of a reference sound which produces the same annoyance as the AM sound under investigation. The effect of variables on annoyance was determined using repeated measures ANOVA. The analyses were conducted for only 35 participants since five participants were removed to fulfill the normality criteria of ANOVA.

3. RESULTS AND DISCUSSION

We found a statistically significant effect of spectrum ($p<0.003$), modulation frequency ($p<0.001$), and modulation depth ($p<0.001$) on *annoyance*. The annoyance penalty values are shown in Figure 2. The effect of spectrum was small and complex compared to the effects of f_m and D_m.

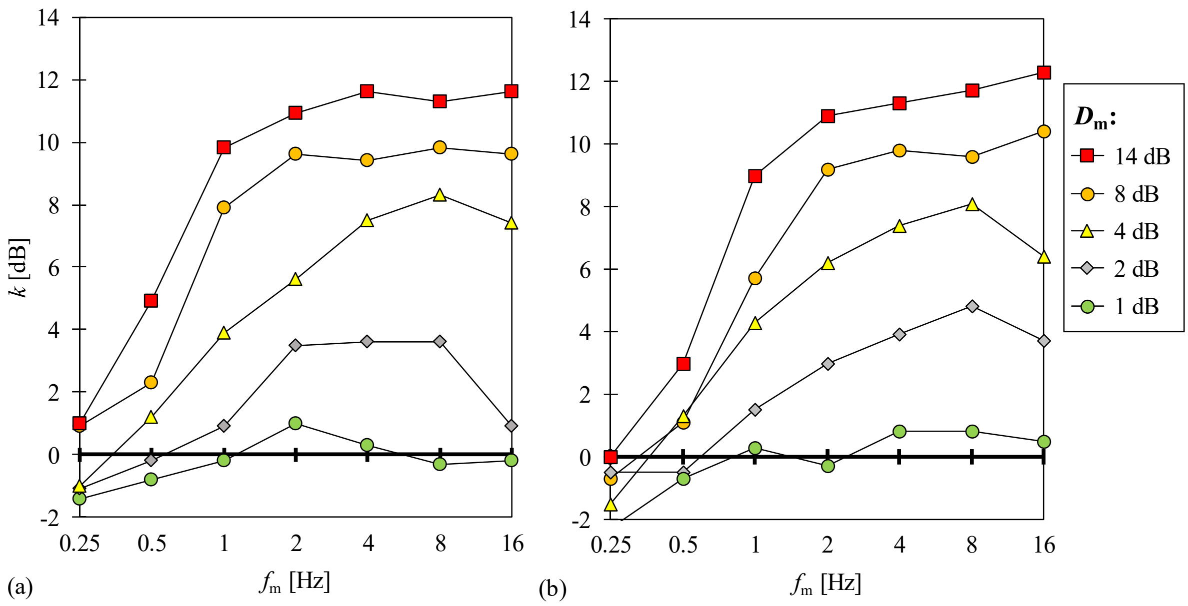

Figure 2. The annoyance penalty *k* as a function of modulation frequency, f_m, and modulation depth, D_m. (a) Spectrum S1. (b) Spectrum S2.

The largest penalty was around 12 dB for both spectra S1 and S2. The largest penalty values were obtained with the largest value of D_m and with f_m from 4 to 16 Hz. The statistical significance of the penalty values are not reported here but typically values $k < 1.5$ dB were not statistically significant. That means that the *annoyance* for an AM sound with $k < 1.5$ dB was not statistically significantly different from the *annoyance* of the reference sound presented at 35 dB.

Penalty increased systematically when f_m increased from 0.25 to 2 Hz. Within 2–16 Hz, the dependence of penalty on f_m was not clear. It seems that the annoyance does not change much within this range.

We found also negative penalty values when f_m was small. Some of negative penalties were also statistically significant. Sounds with negative penalty values sounded like sea waves on the coast. Sounds with natural cues are often rated less annoying than steady-state pseudorandom sounds (reference sounds) but this is only speculation.

Several previous studies have investigated the annoyance of AM sounds (3-7). Our study is among the most generic studies since our study is not dealing with any specific sound type and the range of f_m and D_m was exceptionally large. Hafke-Dys et al. (4) conducted a study which was very close to our study (overall level was 45 dB L_{Aeq}, f_m ranged from 0 to 4 Hz, D_m ranged from 0 to 9 dB, five different spectra were included). Our findings on the behavior of annoyance agreed well with their results. However, Hafke-Dys et al. did not present annoyance penalty values. Our study is among the first studies which presents the annoyance penalty as a function of a broad range of f_m and D_m.

Scientific penalty schemes for determining the penalty of AM sound have been requested by Refs. (1) and (2). Our data can be helpful in assessing the penalty that could be given due to the AM of industrial noise when f_m and D_m is known. However, it should be noted that our study was a laboratory study with synthetic sounds where the AM was periodic and constant. The results shall be applied to the assessment the annoyance penalty in field conditions cautiously because the nature of AM in real settings contains many properties which may affect annoyance, such as varying f_m and D_m. D_m can also depend on frequency of sound, i.e. some frequency bands involve stronger AM than the others. Furthermore, other specific factors of sound, such as tonality, impulsiveness, or specific spectra may affect the annoyance as well or even more than AM. Therefore, our study would benefit from a follow-up experiment involving real sounds recorded in the field.

4. CONCLUSIONS

We conducted a laboratory experiment where the annoyance penalty of synthetic amplitude modulated wide band noise was determined for a broad range of modulation depth (1 to 14 dB) and modulation frequency (0.25 to 16 Hz). The penalty values ranged from -2 to +12 dB. The penalty depended strongly both on the modulation depth and the modulation frequency. Our data can be useful in the development of penalty schemes.

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