Perception of Fluctuating Sounds

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Introduction

Fluctuating sounds easily attract the listener's attention and can therefore have a profound impact on sound quality. To better understand the human perception of fluctuating sounds and to model it for automatic quantification, it is necessary to evaluate this sensation through jury tests. The stationary perception of fluctuating sounds was examined in detail for synthetic sounds depending on various modulation parameters: modulation rate, modulation type (AM / FM: amplitude / frequency modulation), degree of modulation, frequency deviation. Several jury test results can be found in the literature for these types of signals [1-3]. However, these existing studies are insufficient to provide an accurate model that can be applied to technical sounds and takes temporal effects into account. This paper therefore describes jury tests that were carried out to obtain information on the fluctuation perception of less-investigated phenomena: the fluctuation perception for technical sounds and temporal effects.

Literature data

The main dependencies of the fluctuation strength F of modulated sounds are the modulation rate f_m, the level L and the modulation depth d / frequency deviation Δf. These dependencies are shown in the following with listening test results from [1-3] and an additional interpolation equation for each dependency. By considering each factor as independent / orthogonal, the fluctuation strength of a modulated sinusoidal signal can be approximately estimated by interpolating the functions for each individual influence. An additional requirement is that the signal has a fixed modulation type, level, and frequency deviation. This enables the indirect calculation of the absolute value of fluctuation strength of any real and technical sound, which is judged against a synthetic sound.

First, the influence of the modulation rate on the fluctuation strength of AM signals, as shown in Figure 1,

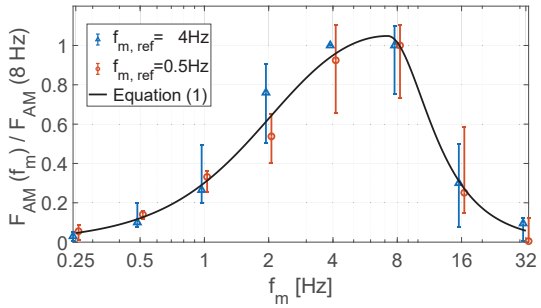

Figure 1: Influence of modulation rate on the fluctuation strength of amplitude-modulated 1-kHz pure tones of 70 dB SPL and 40-dB modulation depth: experimental data from magnitude estimation tests with two references from [1] and a fitting function according to Equation (1).

is modeled as a bandpass function:

$$\frac{F_\mathrm{AM}(f_\mathrm{m})}{F_\mathrm{AM}(8\ \mathrm{Hz})} = \frac{1.05}{\left|1 + a_\mathrm{AM}(f_\mathrm{m}) \cdot \left|\frac{f_\mathrm{m}}{f_\mathrm{AM}} - \frac{f_\mathrm{AM}}{f_\mathrm{m}}\right|^2\right|^{b_\mathrm{AM}(f_\mathrm{m})}} \quad (1)$$

with $f_\mathrm{AM} = 7.22$ Hz and

$$a_\mathrm{AM}(f_\mathrm{m}) = \begin{cases} 0.31; & f_\mathrm{m} < f_\mathrm{AM} \\ 0.82; & f_\mathrm{m} \geq f_\mathrm{AM} \end{cases}; \quad b_\mathrm{AM}(f_\mathrm{m}) = \begin{cases} 0.71; & f_\mathrm{m} < f_\mathrm{AM} \\ 1.13; & f_\mathrm{m} \geq f_\mathrm{AM} \end{cases}$$

The influence of the modulation rate on the fluctuation strength of FM signals, as shown in Figure 2,

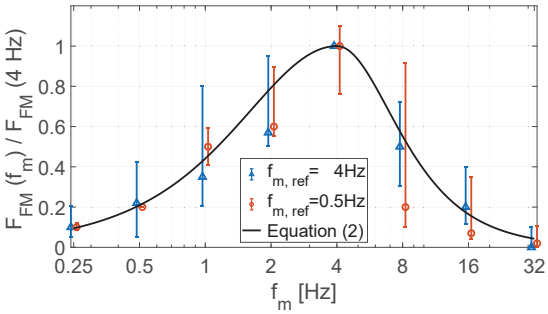

Figure 2: Influence of modulation rate on the fluctuation strength of frequency-modulated pure tones of 70 dB SPL with a carrier frequency of 1.5 kHz and a frequency deviation of 700 Hz: experimental data from magnitude estimation tests with two references from [1] and a fitting function according to Equation (2).

can also be modeled with a bandpass function:

$$\frac{F_\mathrm{FM}(f_\mathrm{m})}{F_\mathrm{FM}(4\ \mathrm{Hz})} = \frac{1}{\left|1 + a_\mathrm{FM}(f_\mathrm{m}) \cdot \left|\frac{f_\mathrm{m}}{f_\mathrm{FM}} - \frac{f_\mathrm{FM}}{f_\mathrm{m}}\right|^2\right|^{b_\mathrm{FM}(f_\mathrm{m})}} \quad (2)$$

with $f_\mathrm{FM} = 4$ Hz and

$$a_\mathrm{FM}(f_\mathrm{m}) = \begin{cases} 0.46; & f_\mathrm{m} < f_\mathrm{FM} \\ 0.60; & f_\mathrm{m} \geq f_\mathrm{FM} \end{cases}; \quad b_\mathrm{FM}(f_\mathrm{m}) = \begin{cases} 0.59; & f_\mathrm{m} < f_\mathrm{FM} \\ 1.00; & f_\mathrm{m} \geq f_\mathrm{FM} \end{cases}$$

Knowing from [1] that the fluctuation strength for the AM signal in Figure 1 with the modulation rate of 4 Hz is 1.3 vacil and that the fluctuation strength for the FM signal in Figure 2 with the modulation rate of 4 Hz is 2.0 vacil, an absolute value of fluctuation strength can then be obtained for every other synthetic signal with a different modulation rate.

The influence of the sound pressure level L in dB on the fluctuation strength of AM and FM signals, shown in Figure 3, can be modeled as an exponential function using different parameters a and b for each signal type (AM / FM):

$$\frac{F_\mathrm{AM/FM}(L)}{F_\mathrm{AM/FM}(70\mathrm{dB})} = a \cdot b^{\frac{L}{40\ \mathrm{dB}}} \quad (3)$$

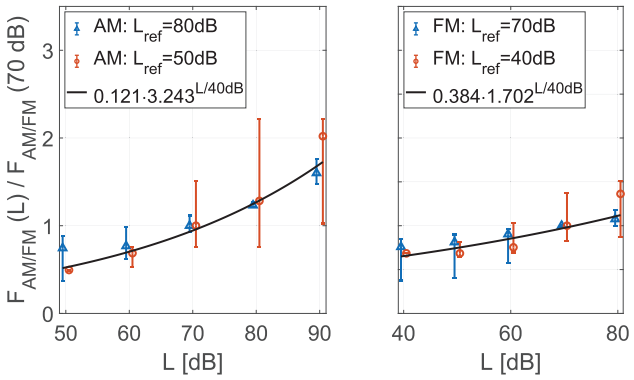

Figure 3: Influence of the level L on the fluctuation strength of AM and FM sinusoids with the same stimulus parameters as in Figures 1 and 2, but a modulation rate of 4 Hz: experimental data from magnitude estimation tests with two references from [2] along with fitting functions according to Equation (3) with parameters a and b as indicated in the legends.

With FM signals, the frequency deviation and the carrier frequency have a very strong influence on the perceived fluctuation strength as shown in Figure 4.

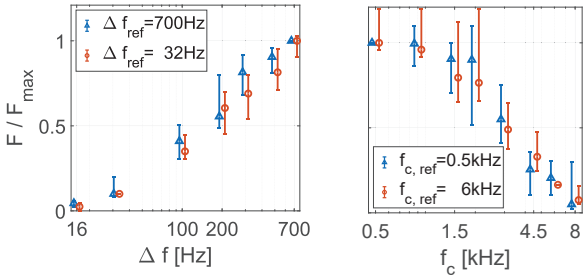

Figure 4: Dependencies of the fluctuation strength of FM signals on the frequency deviation for a fixed carrier frequency $f_c = 1.5$ kHz (left) and on the carrier frequency for a fixed frequency deviation $\Delta f = 200$ Hz (right) from magnitude estimation tests with two references [3].

However, it is possible to approximate both influences in one equation by considering the frequency deviation relative to the excited critical bands around the carrier frequency f_c by the difference $\Delta z(\Delta f) = B(f_c + \Delta f) - B(f_c - \Delta f)$, $B(\cdot)$ being the transformation from Hz to Bark_{HMS}[1] as defined in [4]. The influence can be modeled with a high pass as shown in Equation (4) and the results can be seen in Figure 5 and 6:

$$\frac{F_{\text{BW}}(\Delta z)}{F_{\text{BW}}\big(\Delta z(200\ \text{Hz})\big)} = \frac{0.65 \cdot \Delta z/\text{Bark}_{\text{HMS}}}{\sqrt{1 + (0.35 \cdot \Delta z/\text{Bark}_{\text{HMS}})^2}} \qquad (4)$$

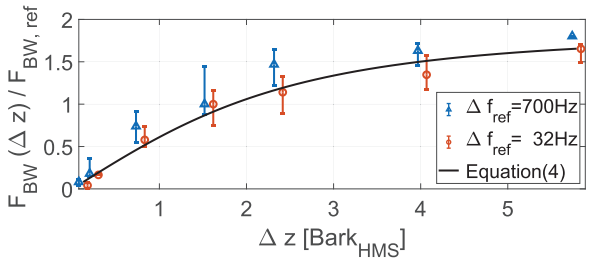

Figure 5: Influence of the frequency deviation on the fluctuation strength of FM signals: experimental data from [3] (see Figure (4), left) along with a fitting function according to Equation (4). $F_{\text{BW, ref}} = F_{\text{BW}}\big(\Delta z(200\ \text{Hz})\big)$.

[1] The index HMS refers to the **H**earing **M**odel of **S**ottek (see [4]).

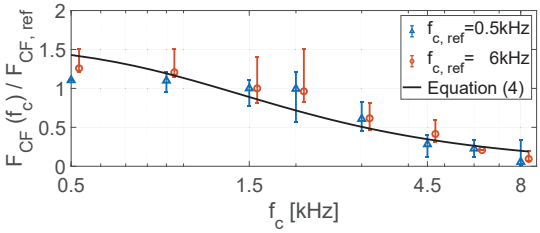

Figure 6: Influence of the carrier frequency on the fluctuation strength of FM signals: experimental data as in Figure (4), right, along with a fitting function also using Equation (4) as in Figure 5. $F_{\text{CF, ref}} = F_{\text{CF}}(f_c = 1.5\ \text{kHz})$.

Listening experiments

Three listening tests were performed with 22 participants (between 25 and 59 years, 6 female and 16 male, all with self-reported normal hearing) in order to estimate the temporal effects of fluctuation perception and to determine the fluctuation strength of technical signals. In order to ensure a calibrated playback, the sounds were presented diotically via a digital equalizer (HEAD acoustics LabP2 frontend), ArtemiS SUITE software and Sennheiser HD 650 headphones in a sound-attenuated listening studio.

Test for temporal effects

In the literature there is no information on how long a signal must be heard to achieve full fluctuation. This prevents the modeling of transient effects in fluctuation signals as well as reasonable estimates for nonstationary sounds. The listening tests presented here were performed to fill this information gap.

A magnitude estimation test was performed to estimate the time it would take for a fluctuating sound to achieve its full fluctuation strength. In this test, two sounds with the same fluctuation parameters but different durations were played one after the other with a pause of 1 s. The duration of the second sound did not exceed the duration of the first sound, which was considered as a reference for fully perceived fluctuation. The participants then assessed how strong the fluctuation of the second sound was compared to the first sound, in a magnitude scale from 0 (“no fluctuation”) to 100 (“same fluctuation”) with steps of 5.

This test was performed for both AM and FM signals with the following stimuli:

Table 1: Stimuli used to analyze the temporal effects of fluctuation

Modulation rate [Hz]	Durations [s]	Reference duration [s]
0.25	2; 4; 6; 8	8
0.50	1; 2; 3; 4	4
1.00	0.5; 1; 1.5; 4	4
2.00	0.25; 0.5; 0.75; 1; 2	2
4.00	0.25; 0.375; 0.5; 2	2
8.00	0.125; 0.25; 0.375; 0.5; 0.625; 2	2
16.00	0.125; 0.25; 0.5; 1; 2	2

Test for technical sounds

Objectively assessing the fluctuation of technical sounds is a very difficult task, as the signals are often considerably different. At the same time, the modeling benefits most from well-defined (synthetic) signals, so that the dependencies can be better understood.

In order to facilitate the evaluation of technical sounds and to obtain the advantages of the synthetic signals, a magnitude estimation test between technical signals and their "synthetic counterparts" was carried out. We define synthetic counterparts as signals that have a similar modulation rate and modulation depth as the analyzed technical signals. The technical signals, and their properties used to model their synthetic counterparts, are presented in Table 2.

Table 2: Synthetic stimuli used to estimate the fluctuation strength of technical sounds

Technical signal	L [dB]	f_c [Hz]	f_m [Hz]	FM: Δf [Hz] / AM: d [dB]
Actuator A (FM)	74	1000	1.25	100
Actuator B (FM)	75	560	7.00	250
Actuator C (FM)	75	390	0.70	40
Scissors (FM)	75	1000	3.00	350
Steps on snow (FM)	77	300	1.40	150
Washing machine (AM)	77	300	1.00	40
Water drops (FM)	77	400	2.00	200
Wiper (FM)	77	250	1.50	60

The test design was similar to the magnitude estimation used in the test for the temporal effects but with the additional step that the participant had to select which of the sounds exhibited the lower fluctuation strength. Then the absolute magnitude of the fluctuation strength of the stimulus with less fluctuation was assessed between 0 and 100 with steps of 5 compared to a value of 100 for the other sound. Each pair of sounds was played four times, twice with the synthetic reference at the beginning and twice with the technical sound first.

Removal of outliers

An outlier analysis was performed from the test with the technical sounds in order to remove participants with less consistent and reliable ratings. To achieve this, the results of the repetitions in the test with the technical sounds were used. In this case, participants are expected to have almost the same score on all replications, so the average standard deviation of their four comparisons should be small for all pairs. All participants with a standard deviation greater than 40 % (3 participants) were considered outliers and their results were removed from all tests. The results for the repetitions with all participants (including the outliers) are shown together in Figure 7, with the outliers marked with red dots.

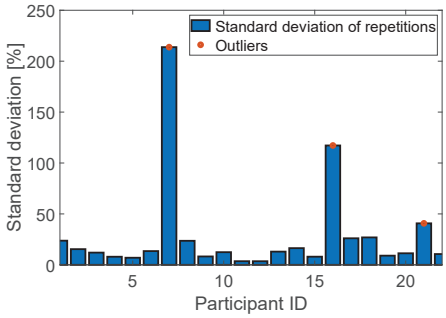

Figure 7: Variation of results for repeated comparisons in the magnitude estimation of the technical sounds. The 3 outliers with a standard deviation greater than 40 % are marked with red dots.

Temporal effects of fluctuation perception

The results for the listening tests to evaluate the duration dependence of the fluctuation perception can be seen in Figures 8 and 9 for AM and in Figures 10 and 11 for FM signals respectively with mean values and 95 % confidence interval. For low modulation rates of 2 Hz and below, the results seem to depend on the number of periods of the presented sounds. For these modulation rates an almost full perception of fluctuation can be seen after presenting 2 periods.

For modulation rates of 4 Hz and higher, the experimental data can be fitted using an exponential function $F/F_{\max} = A \cdot \left(1 - \exp(-t/T)\right)$ with a similar time constant $T = 0.22$ s for each case (time to reach 95 %: 0.66 s).

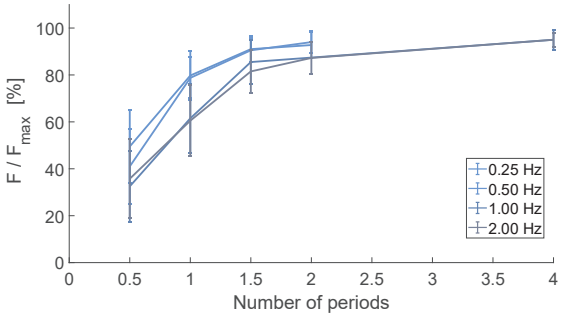

Figure 8: Dependence of fluctuation strength on signal duration (number of periods) for amplitude-modulated signals with modulation rates of 2 Hz or lower.

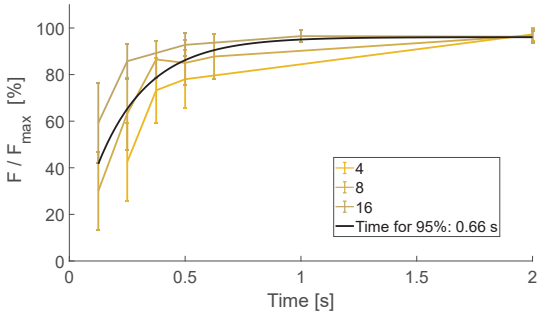

Figure 9: Dependence of fluctuation strength on signal duration for amplitude-modulated signals with modulation rates of 4 Hz or higher along with a fitting function.

The results for the frequency-modulated signals show the same tendency. The time constant of the exponential fitting function is slightly higher, about 0.25 s.

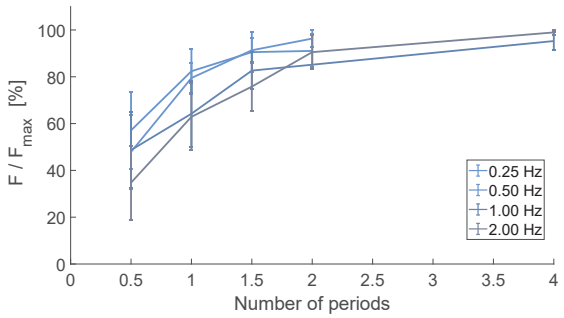

Figure 10: Dependence of fluctuation strength on signal duration (number of periods) for frequency-modulated signals with modulation rates of 2 Hz or less. The same tendency can be seen as with AM signals.

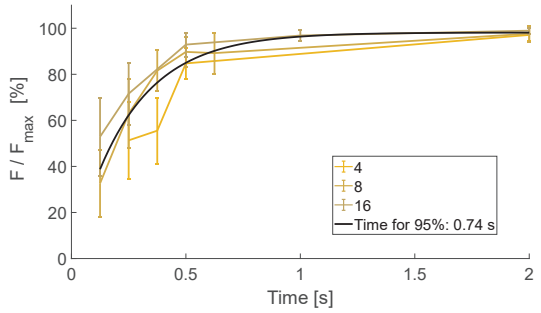

Figure 11: Dependence of fluctuation strength on signal duration for frequency-modulated signals with modulation rates of 4 Hz or higher along with an exponential fitting function as in Figure 9 (time to reach 95 %: 0.74 s).

Results for technical sounds

The results of the magnitude estimation experiment for the technical sounds can be seen in Figure 12.

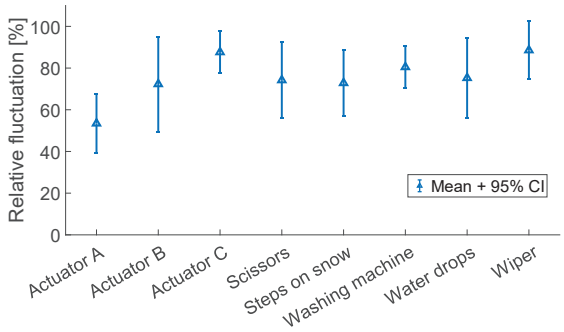

Figure 12: Magnitude estimation results for the technical signals compared to their synthetic counterparts.

It can be seen that the synthetic counterparts are always perceived as more fluctuating than the technical signals. It is important to note, however, that these results do not represent the absolute values of fluctuation strength, as they are only relative to the synthetic counterparts.

In order to estimate the absolute values of fluctuation strength, an interpolation of all dependencies presented at the beginning of this paper in Equations (1)-(4) is performed using the defined value of fluctuation strength for the reference signals. The results with the absolute fluctuation strength values, considering the average as the correct estimation, are presented in Table 3.

Table 3: Calculated fluctuation strength of technical sounds and its synthetic counterparts

Signal	**Relative fluctuation [%]**	**Synthetic reference *F* [vacil]**	**Technical sound *F* [vacil]**
Actuator A	53.4	0.464	**0.248**
Actuator B	72.3	1.307	**0.945**
Actuator C	87.6	0.189	**0.166**
Scissors	74.2	1.853	**1.375**
Steps on snow	72.8	1.096	**0.798**
Washing machine	80.5	0.507	**0.408**
Water drops	75.3	1.557	**1.172**
Wiper	88.6	0.656	**0.581**

Conclusions

Literature data on the main dependencies of the perceived fluctuation strength of AM and FM tones were reviewed and approximated by an equation for each dependency on the modulation parameters.

In addition, the dependence of the fluctuation strength of frequency-modulated pure tones on the frequency deviation and the carrier frequency could be expressed by just one equation depending on the excited number of critical bands.

To improve existing models of fluctuation perception, three listening tests were carried out to obtain information on the fluctuation perception of less-investigated phenomena, such as the time for a full perception of the fluctuation for AM and FM tones and the fluctuation perception of technical signals. It has been shown that two conditions must be fulfilled for a full perception of a fluctuating sound, namely the signal must have at least 2 periods and should be longer than about 0.7 s.

By interpolating the individual dependencies of the fluctuation on the modulation parameters, it was possible to estimate absolute values of the fluctuation strength for real sounds in a magnitude estimation test with their synthetic counterparts, which is a way to expand the literature data in such a way that they are also compatible with technical sounds.

Literature

[1] Fastl. H.; Zwicker. E., Psychoacoustics: Facts and Models, 3rd edition, Springer, 2006.

[2] Fastl. H., Fluctuation strength of modulated tones and broadband noise. In: Klinke, R. and Hartmann, R. (Eds.), Hearing – psychological bases and psychophysics, Springer, pp. 282-288, 1983.

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