FLUCTUATION STRENGTH OF FM-TONES

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INTRODUCTION

Sinusoidally frequency-modulated pure tones (FM-tones) elicit one of two different kinds of auditory sensation, depending on the speed of modulation. In the case of modulation frequencies above about 20 Hz *roughness* is perceived (Kemp, 1982). Lower modulation frequencies lead to an auditory sensation called *fluctuation strength*. While fluctuation strength of amplitude-modulated tones has been described in several papers (e.g. Terhardt, 1968, Schöne, 1979, Fastl, 1982a), fluctuation strength of FM-tones as yet is largely unexplored. This paper describes the dependence of fluctuation strength of FM-tones on modulation frequency, frequency deviation, center frequency, and sound pressure level.

METHOD

Seven subjects with normal hearing, 26-37 years of age, took part in the experiments, which took place in a sound-isolated booth. The FM-tones were presented monaurally through an electrodynamic earphone (Beyer DT 48) with a free-field equalizer (Zwicker and Feldtkeller, 1967, p. 40). A method of magnitude estimation was applied, involving comparisons between pairs of FM-tones. The tones were switched on and off at minima of the frequency modulation, i.e. at the lowest actual frequency within a cycle. To avoid audible clicks, the amplitude of the FM-tones was switched on and off using a Gaussian-shaped gating signal with 10 ms rise/fall time. The FM-tones had a duration of 4 s and were separated by an interstimulus interval of 800 ms. The pauses between pairs lasted 3 s. The first FM-tone of a pair was assigned a number (e.g. 100) representing the magnitude of its fluctuation strength. Relative to this standard, the subjects had to scale the fluctuation strength of the second FM-tone within each pair. The subjects were asked to base their judgements only on fluctuation strength and to ignore differences in timbre, pitch, loudness, and in particular roughness. For each stimulus parameter, two sets of experiments were performed: one with a standard of large fluctuation strength (assigned 100) and another with a standard of small fluctuation strength (assigned 10). During a session, each combination of standard and comparison was presented four times in random order. The corresponding four numbers, assigned to identical stimuli by each subject, generally differed by less than ± 10, indicating only small intra-individual differences.

For each comparison the responses of the seven subjects were compiled, leading to a total of 28 datapoints, for which medians and interquartile ranges were calculated. For each standard, the correlated medians and interquartiles were normalized relative to the maximal median value, which was set to 100% relative fluctuation strength. In the figures, the standards are indicated by filled symbols.

RESULTS AND DISCUSSION

Fig. 1 shows the dependence of fluctuation strength of FM-tones on modulation frequency. The fluctuation strength F relative to its maximal value F_{max} is plotted as a function of modulation frequency f_{mod}. The center frequency of the FM-tones was f_m = 1500 Hz, the frequency deviation Δf = 700 Hz and the sound pressure level L = 70 dB.

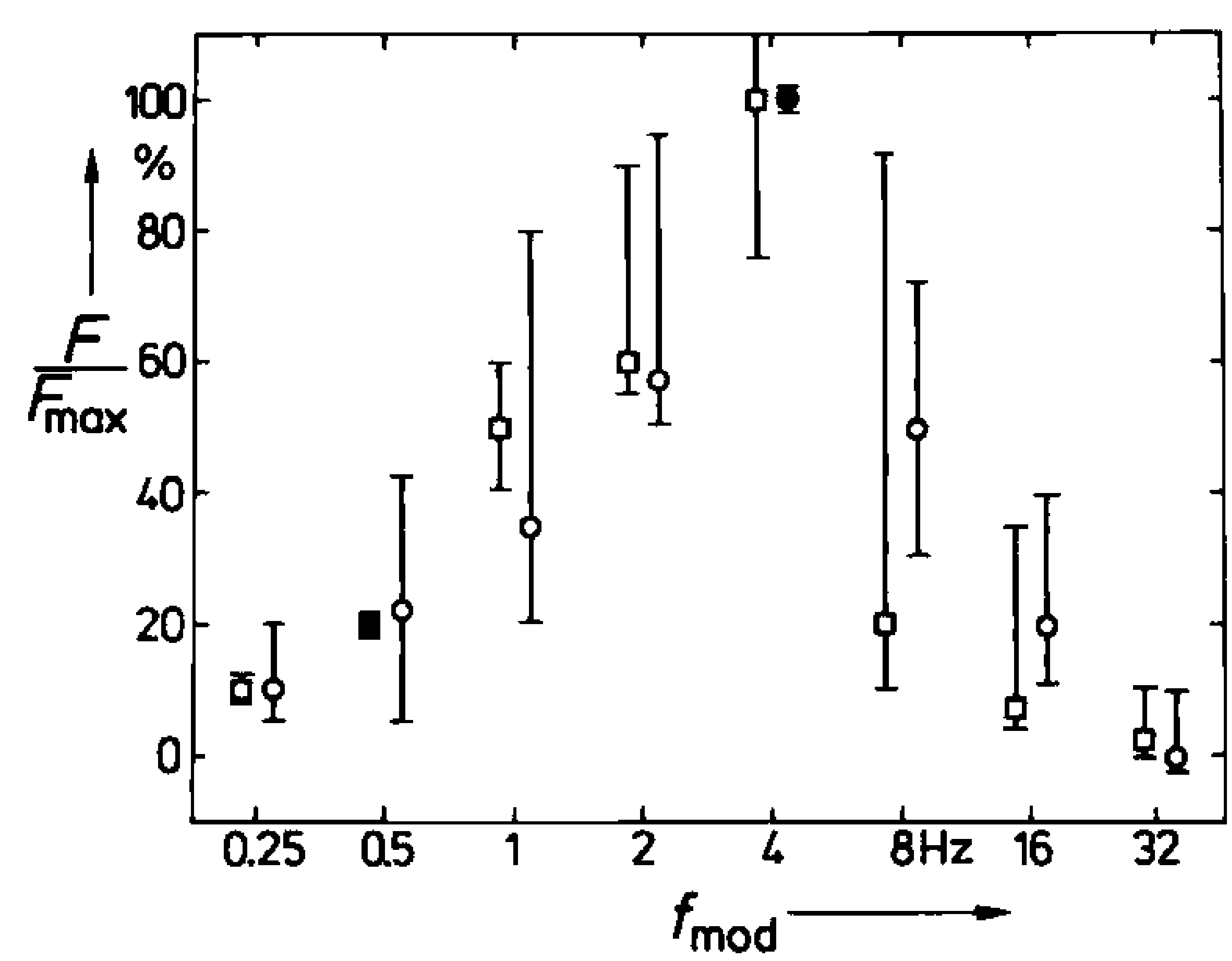

Fig. 1. Fluctuation strength of sinusoidally frequency modulated pure tones as a function of modulation frequency. f_m = 1500 Hz, Δf = 700 Hz, L = 70 dB. Circles: standard with f_{mod} = 4 Hz; squares: standard with f_{mod} = 0.5 Hz.

The results depicted in Fig. 1 indicate that fluctuation strength of FM-tones shows a bandpass characteristic with a maximum at f_{mod} = 4 Hz. The two standards yielded almost the same results, except at f_{mod} = 8 Hz where large interquartiles show up due to inter-individual differences. Fluctuation strength of *amplitude*-modulated tones and broadband noise also exhibits a bandpass characteristic as a function of modulation frequency, with a maximum around 4 Hz (see Fastl, 1983). Even roughness of FM-tones shows a bandpass characteristic, however, with a maximum near 70 Hz modulation frequency (Kemp, 1982). It diminishes for lower modulation frequencies and becomes almost negligible around 16 Hz, where fluctuation strength begins to take over as the dominant sensation.

Fig. 2 shows the dependence of fluctuation strength of FM-tones on frequency deviation. For FM-tones with f_m = 1500 Hz, f_{mod} = 4 Hz and L = 70 dB, fluctuation strength starts to be perceived at about Δf = 20 Hz and increases approximately linearly with the logarithm of frequency deviation. Again, both standards lead to almost the same results. Significant values of fluctuation strength ($F/F_{max} \geq 10\%$) are reached if the frequency deviation exceeds about 10 JNDs (for details see Fastl, 1983). For *roughness* of FM-tones, Kemp (1982) found an increase slightly faster than linear with the logarithm of frequency deviation.

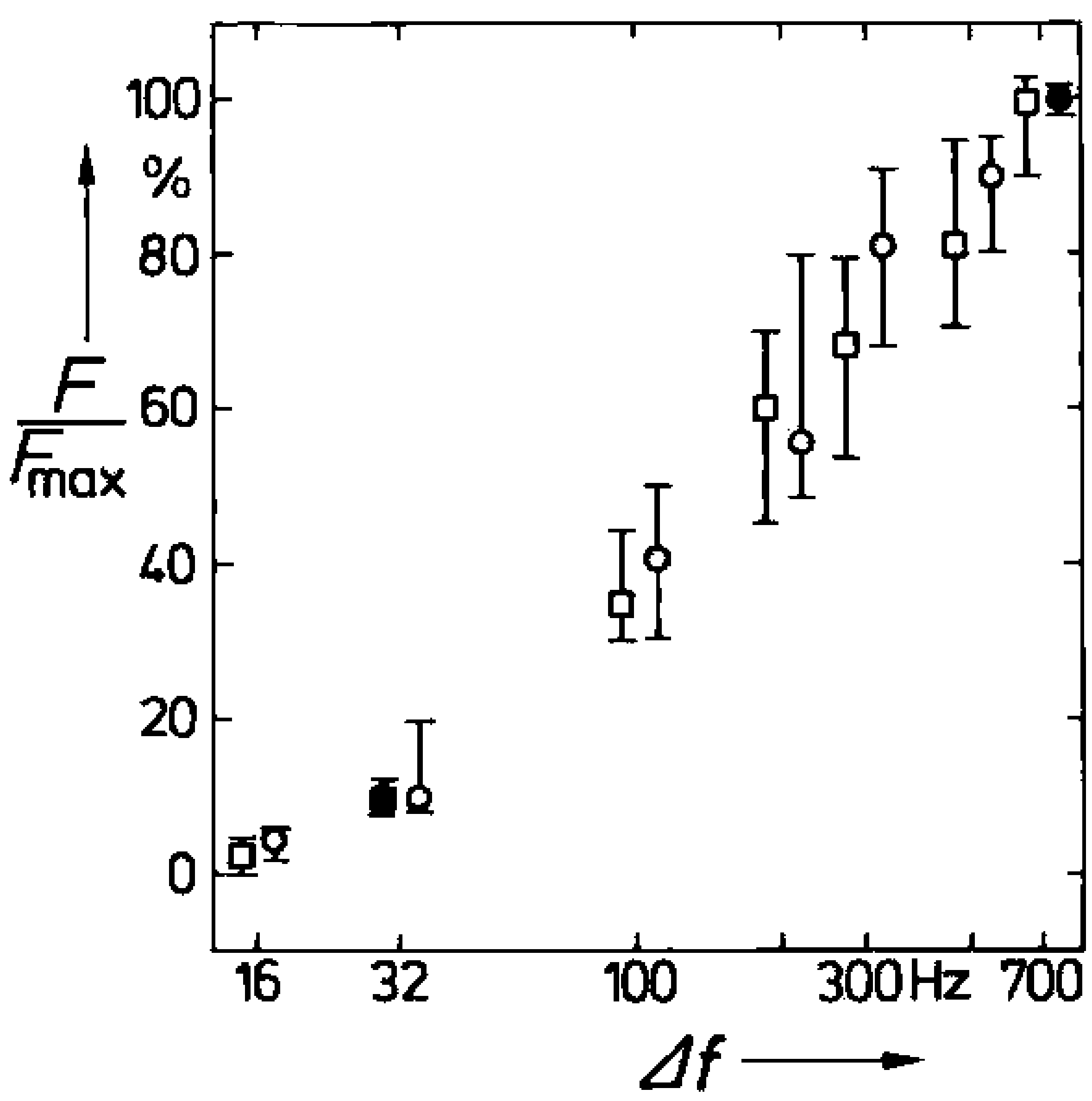

Fig. 2. Fluctuation strength of sinusoidally frequency modulated pure tones as a function of frequency deviation.
f_m = 1500 Hz, f_{mod} = 4 Hz, L = 70 dB.
Circles: standard with Δf = 700 Hz;
squares: standard with Δf = 32 Hz.

Fig. 3 shows the dependence of fluctuation strength of FM-tones on center frequency. A frequency deviation of 200 Hz was used throughout. Up to a center frequency of about 1000 Hz, fluctuation strength is constant and decreases approximately linearly with the logarithm of f_m towards higher frequencies. This decrease can be understood in terms of the number of critical bands encompassed by FM-tones at different center frequencies but with a constant frequency deviation of Δf = 200 Hz. For example, the FM-tone at 500 Hz sweeps between 300 Hz and 700 Hz, i.e. between critical band rates of 3 Bark and 6.5 Bark, respectively. At 8000 Hz the modulation occurs between frequencies of 7800 Hz and 8200 Hz, corresponding to 21.1 Bark and 21.3 Bark. The critical band interval in the seond case has decreased from 3.5 Bark to 0.2 Bark, i.e. by a factor of 17.5. As shown in Fig. 3, the same factor is found for the difference in fluctuation strength at 500 Hz and 8000 Hz. However, it should be realized that only the maximum and the minimum of the actual frequency of the FM-tone are takten into account in this example. A more realistic description has to be based on the correlated masking patterns and is given in another paper.

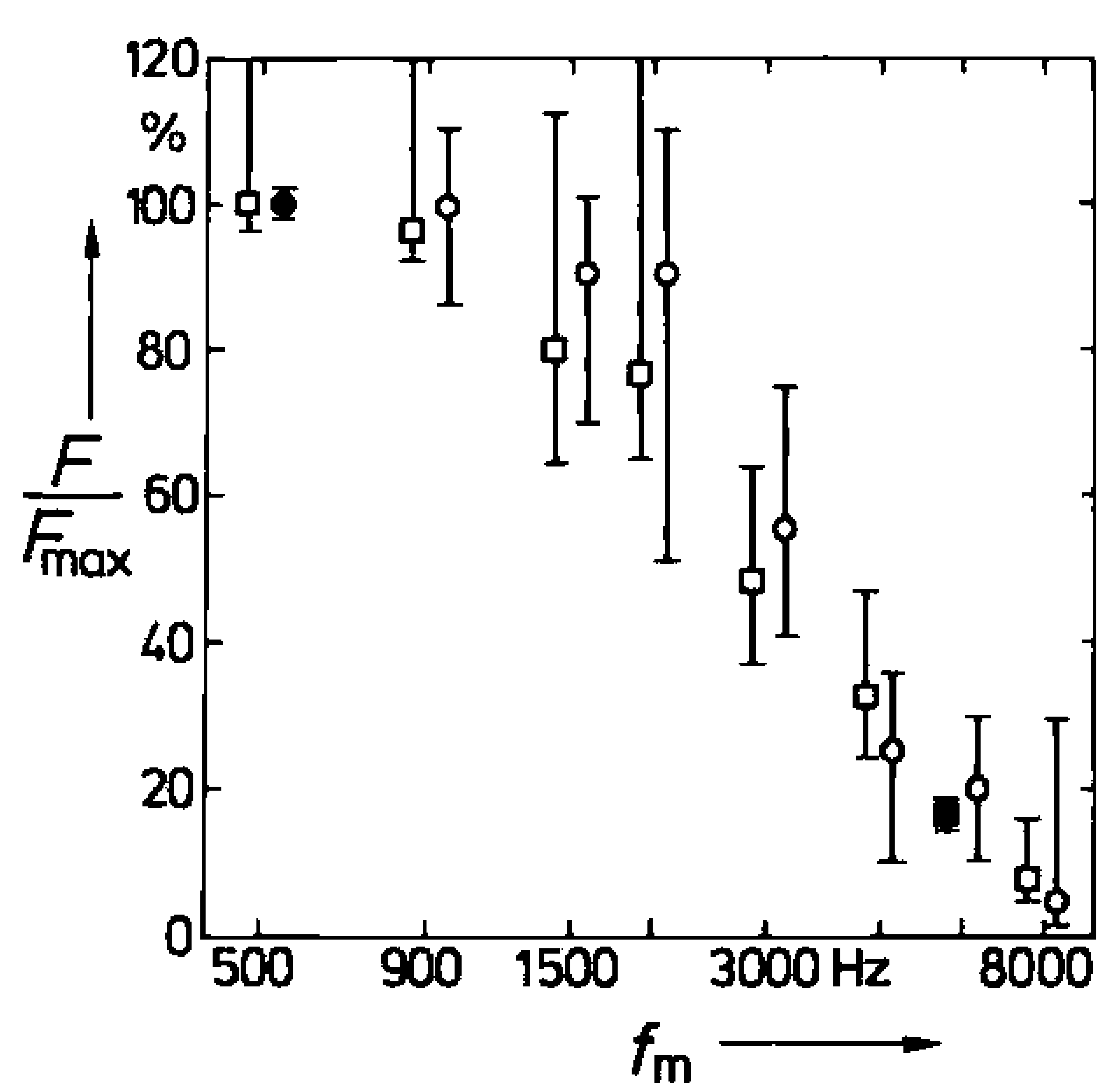

Fig. 3. Fluctuation strength of sinusoidally frequency modulated pure tones as a function of center frequency.
f_{mod} = 4 Hz, Δf = 200 Hz, L = 70 dB.
Circles: standard with f_m = 500 Hz;
squares: standard with f_m = 6000 Hz.

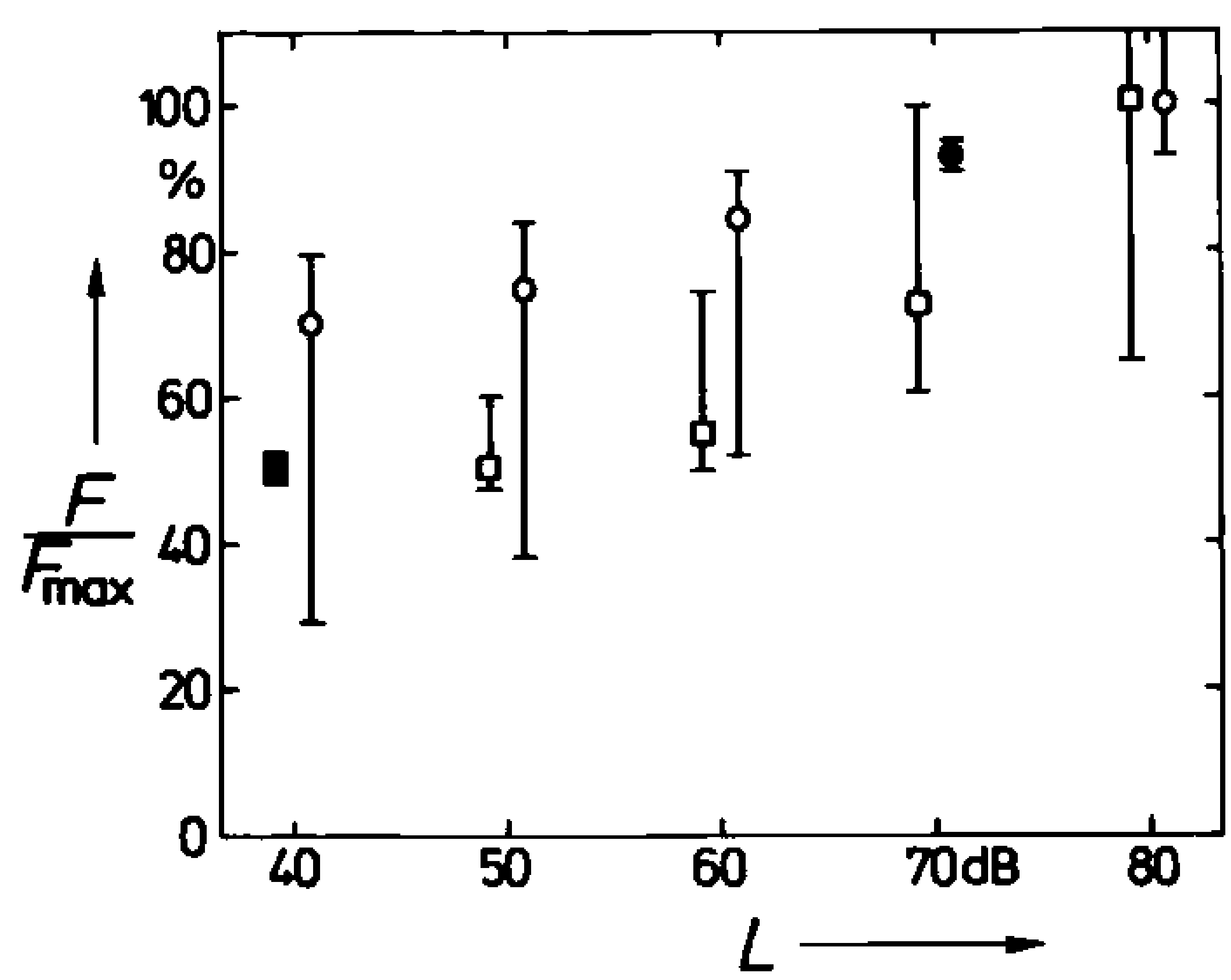

Fig. 4. Fluctuation strength of sinusoidally frequency modulated pure tones as a function of sound pressure level.
f_m = 1500 Hz, f_{mod} = 4 Hz, Δf = 700 Hz.
Circles: standard with L = 70 dB; squares: standard with L = 40 dB.

Fig. 4 shows the dependence of fluctuation strength of FM-tones on sound pressure level. For an increase in level of 40 dB, fluctuation strength increases on the average by a factor of about 1.7. The results clearly depend on the standard used. The large interquartile ranges for the 70 dB-standard (circles) are almost entirely due to large inter-individual differences. For *amplitude*-modulated tones and broadband noise, fluctuation strength increases by a factor of about 3 for an increase in level of 40 dB (Terhardt, 1968, Fastl, 1982b, 1983). This larger increase with level holds also for the *roughness* of FM-tones (Kemp, 1982).

SUMMARY

The fluctuation strength of sinusoidally frequency modulated pure tones, as a function of modulation frequency, shows a bandpass characteristic with a maximum at 4 Hz. For frequency deviations larger than about 20 Hz, fluctuation strength increases approximately linearly with the logarithm of frequency deviation. When the frequency deviation is held constant, the fluctuation strength of FM-tones is found to be independent of center frequency for low tones, and to decrease with increasing center frequency. The latter effect can be related to the number of critical bands encompassed by the FM-tones. For an increase in level of 40 dB, fluctuation strength of FM-tones increases by a factor of about 1.7.

REFERENCES

Fastl, H. (1982a) *Beschreibung dynamischer Hörempfindungen anhand von Mithörschwellen-Mustern.* Hochschul Verlag, Freiburg.

Fastl, H. (1982b) Fluctuation strength and temporal masking patterns of amplitude modulated broadband noise. *Hearing Research* 8, 59-69.

Fastl, H. (1983) Fluctuation strength of modulated tones and broadband noise. In: *Hearing - Physiological Bases and Psychophysics* (R. Klinke and R. Hartmann, Eds.) Springer, Berlin.

Kemp, S. (1982) Roughness of frequency-modulated tones. *Acustica* 50, 126-133.

Schöne, P. (1979) Messungen zur Schwankungsstärke von amplitudenmodulierten Sinustönen. *Acustica* 41, 252-257.

Terhardt, E. (1968) Über akustische Rauhigkeit und Schwankungsstärke. *Acustica* 20, 215-224.

Zwicker, E. and Feldtkeller, R. (1967) *Das Ohr als Nachrichtenempfänger.* 2. erw. Auflage, Hirzel-Verlag, Stuttgart.