INPUT CURRENT REQUIREMENTS OF HIGH-QUALITY LOUDSPEAKER SYSTEMS

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Abstract: Based on an analysis of the equivalent circuit of a multiway loudspeaker, the possibility of large drive currents is predicted for a class of non-sinusoidal band- and amplitude-limited signals. The current builds up as coherent sum of two parts; charging of the driver reactances, and simultaneous current drain by several drivers.

The input current of three commercial loudspeaker systems was measured using a signal derived from on the analysis. The results show that a loudspeaker may draw currents three to six times larger than those calculable from the rated speaker impedance. This indicates that certain generally accepted power amplifier design criteria should be reconsidered.

1. INTRODUCTION

Audio power amplifiers are normally designed to deliver full power into a "rated" load. In international standards (1,2), this load is invariably specified as a pure resistor, normally 8 ohms in value. In more modern draft standards (3), a parallel capacitor is sometimes specified for checking the amplifier stability under various signal conditions.

Loudspeakers have a "rated" impedance, normally 8 ohms. This impedance is measured using swept sinusoidal tones, and international standards (4) prescribe that the actual impedance may not be less than a given minimum, usually 80 % of the rated value, in any part of the rated frequency range of the loudspeaker.

For an amplifier designer familiar with international standards (1-5), it would then be obvious that the peak output current required to drive a loadspeaker is simply the peak output voltage of the amplifier, divided by the rated impedance of the loudspeaker. In the case of a 100 watt amplifier this would lead to a peak output current of, say, 5 amperes to an 8 ohm loudspeaker.

The purpose of this paper is to show that the required output current capability is considerably larger, typically by a factor of 3 to 6. Thus, the required peak output current for the above 100 W amplifier may be in excess of 30 A in the case of normal musical signals and typical commercial loudspeakers. In the case of a 250 W amplifier with a 4 ohm rating, the worst-case peak current capability required could be close to 100 A.

The paper is based on previous work on distortion in the amplifier-loudspeaker interface (6-9), and on measurements of loudspeaker behaviour under non-sinusoidal excitation (10).

2. LOUDSPEAKER EQUIVALENT CIRCUIT

The dynamic loudspeaker provides a complex load to the amplifier. The total compliance of the cone suspension and the loudspeaker cabinet, and the cone mass, form a damped mechanical resonance, typically in the frequency range of 30-80 Hz for the woofer and at correspondingly higher frequencies for the midrange and the tweeter. Other mechanical resonances are created by the different moving parts of the cone, excited by the voice coil, but not necessarily rigidly coupled to it. All these mechanical resonances behave like tuned circuits connected to the voice coil resistance and inductance. The cross-over filters also exhibit complex reactive behavior, especially around the cross-over frequencies.

Energy is stored in all these reactances, especially at the resonances. Since a reactance cannot dissipate energy, and the internal dissipation in the loudspeaker is relatively low at these resonances, the stored energy will create oscillatory behaviour in the circuit. Fig. 1 shows a strongly simplified equivalent circuit of a loudspeaker, taking into account only major effects discussed.

3. LOUDSPEAKER CURRENT

Let us analyze an amplifier working into two different loads. A pure resistance R_r is used when measuring the rated characteristics of the amplifier. A loudspeaker, here represented by the grossly simplified equivalent circuit of Fig. 1, is the true load. To facilitate the analysis, the loudspeaker is assumed to have a linear resistance R and no generator effects. It is stressed that this circuit is far from perfect, but the purpose of the analysis is to illustrate the basic mechanism only, not to calculate it to a high degree of accuracy. It will become evident that all these approximations do not affect the general outcome of the analysis.

Following the analysis presented in detail in Ref. (6), the input voltage to the loudspeaker equivalent circuit is taken to be a step function from -1 to +1. The impedance of the loudspeaker circuit is

$$Z_L = R(s^2LC + sL/R + 1) / (s^2LC + 1) \quad , \qquad (1)$$

which in time domain yields the current flowing into the circuit

$$i(t) = [1 - \frac{2}{Q} \exp(-\frac{\omega t}{2Q}) \sin \omega t]\ v_1/R \quad , \qquad (2)$$

where

$\omega = (1/LC - 1/4R^2C^2)^{\frac{1}{2}}$ is the resonant frequency of the loudspeaker cone, terminals short-circuited,

$Q = \omega RC$ is the quality factor at the resonance, and

v_1 = step function amplitude.

Dividing Eq.(2) by the current flowing into an equivalent "rated load resistor" R_r , we obtain the ratio

$$I(t) = \frac{i(t)\ \text{speaker}}{i(t)\ \text{rated load}}$$

$$= \frac{R_r}{R} [1 - \frac{2}{Q} \exp(-\frac{\omega t}{2Q}) \sin\omega t] \quad . \qquad (3)$$

Eq. (3) represents damped oscillation at the cone resonant frequency. There are negative minima and positive maxima at

$$T = \frac{1}{\omega}(\arctan 2Q + n\pi) \quad , \qquad (4)$$

where n is an integer.

The maxima and minima assume the values

$$I(T) = \frac{R_r}{R} [1 - \frac{4}{(1 + 4Q^2)^{\frac{1}{2}}} \exp(-\frac{\arctan 2Q + n\pi}{2Q})]. \qquad (5)$$

Some typical waveforms of Eq. 3 are plotted in Fig. 2 under the assumption that $R_r/R = 1$. The values of the first minima and maxima from Eq. (5) are plotted in Fig. 3 as functions of Q. The amplitude of the oscillation increases with decreasing Q, the reason for this apparently strange behaviour being that a low-Q resonant circuit absorbs more energy from the broad signal spectrum.

Three important things can be seen from this analysis

* In response to a positive-going step voltage, the loudspeaker current swings after a while to a negative value, the amplitude of which depends on the Q of the resonance.
* If a negative-going step voltage is introduced during the negative undershoot of the loudspeaker current, the peak negative current will reach a large value as shown in Fig. 5.
* In this simple model, the magnitude of the current is inversely proportional to the voice coil resistance.

4. MULTIWAY SYSTEMS

In a multiway loudspeaker system, the drivers are connected parallel via cross-over networks. Fig. 6 shows the initial current response of the Yamaha NS 1000 M speaker to a step function. The first negative-going notch is the midrange driver response, whereas the second comes from the woofer. Also the tweeter exhibits similar behaviour, but it cannot be seen in Fig. 6 because of its short duration.

It is then evident that a class of signals exists, which will excite several of the drivers simultaneously so that the respective currents superimpose. A typical example of such a signal is a sequence of alternate step functions with varying timing. This type of signal resembles the composition of normal musical signals, for example percussion instruments. It is to be noted that no requirements are being made with regard to the risetime of the step functions, as it suffices that the spectral components are contained within the normal audio band. The only requirement is the timing of the steps and impulses.

This situation is illustrated in Figs. 6 through 8. They depict measured low-level current responses for three commercial loudspeakers:

- Linn Sara, an English two-way high fidelity speaker,
- Yamaha NS 1000 M, a Japanese semiprofessional three-way monitor speaker, and
- Genelec 1051 A, a Finnish high fidelity three-way speaker.

The measurements were done using the Hewlett-Packard HP 3582A FFT Spectrum Analyzer and a custom-made signal generator. The input waveform was a binary sequence of -1/+1 transitions, so arranged that first a relatively long 3 to 6 ms positive pulse excites the woofer into its negative-going current peak, at which moment a rapid sequence of pulses excites the midrange into its corresponding current peak. By virtue of the parallel structure of the multiway loudspeaker concept, these currents add up, causing high momentary current peaks.

These currents should be compared to the "rated current" flowing into an 8 ohm resistor for the same input voltage, as shown in Figs. 6 - 8 with dashed lines. Table 1 shows the actual relative peak currents for the loudspeakers tested.

TABLE 1

8 ohm resistor	Linn Sara	Yamaha NS 1000 M	Genelec 1051 A
1	5,3	3,6	3,7

It should be noted that only the woofer and the midrange responses were fully excited in these experiments. It is conceivable that higher peak currents could result, if the signal would have been designed so as to fully excite the tweeter aswell. Further increase in current could be realized if the level of the measurement signal would be sufficiently large as to excite driver nonlinearities or cause cross-over inductor saturation.

As can be seen from Figs. 6-8 and Table 1, the worst-case momentary current drain of a nominally 8 ohm loudspeaker may be up to six times larger than anticipated. The signals that excite this kind of behaviour can be considered as fully possible, legitimate musical passages. They may not be frequent, but if an amplifier is not allowed to enter the region of voltage clipping, it should not be allowed to current-clip, either.

5. CONCLUSIONS

It has been shown that

* Under conditions where the loudspeaker is excited with certain amplitude- and band-limited signals, the output current demanded from an amplifier may grossly exceed the rated output current.

It follows that

* A new way of characterizing amplifier output is needed. Instead of power specification to a fictitious resistive load, a more appropriate way could be to specify peak output voltage and peak output current.
* Amplifier distortion should also be specified at the elevated current levels, since this may be a legitimate operating region.
* Methodology should be developed to observe loudspeaker linearity at high momentary current levels.

It can be speculated that

* Many of the present commercial amplifier designs may exhibit current-related nonlinearities and/or current limiting in the case of normal music and ordinary commercial loudspeakers. This may be one of the reasons for the reported tonal differences between various power amplifiers of otherwise comparable specifications, as this effect will not be revealed in conventional amplifier testing.
* Some loudspeakers may exhibit various forms of response aberrations if an amplifier is capable of supplying the larger current levels in question.
* Many of the presently used power amplifier protection circuits operate upon sensing the output current, and may have been designed under false premises of operating just a little above the rated output current.

6. ACKNOWLEDGEMENT

This paper is based on theoretical work of one of the authors (MO) and on measurements and experimental verification by the others (IM and AV). The authors wish to express their gratitude to J. Lammasniemi of the Technical Research Centre of Finland for his early work on this subject.

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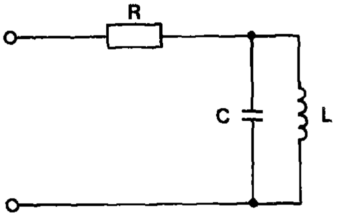

Fig. 1. A strongly simplified loudspeaker equivalent circuit. L and C are the cone dynamic mass and the suspension compliance, respectively, and R is the voice coil resistance.

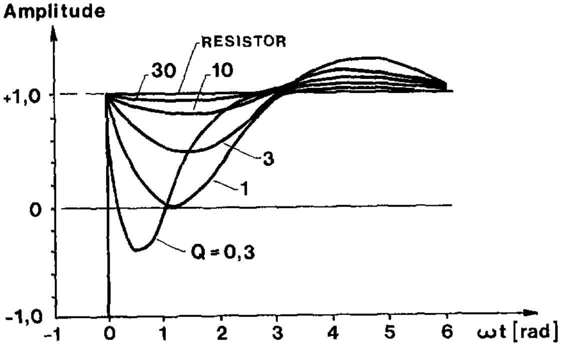

Fig. 2. Typical current waveforms from Eq.(3) as functions of normalized time, with the resonance quality factor Q as parameter. The loudspeaker-generated oscillation is large, especially for low values of Q. The corresponding waveform for resistive load is shown with a solid line.

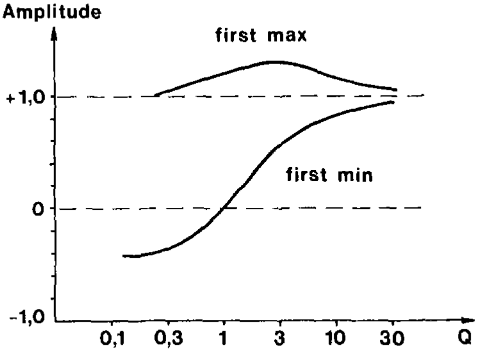

Fig. 3. The values of the first minimum and the first maximum of the loudspeaker current from Eq.(3), as function of the resonance quality factor Q.

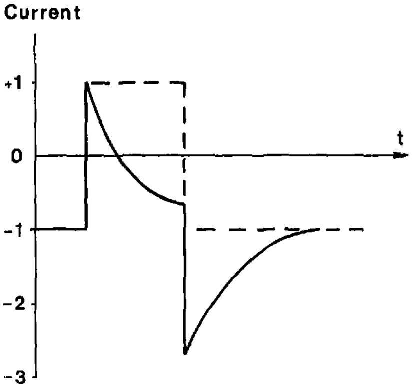

Fig. 4. Current waveform in the equivalent circuit of Fig. 1, when a positive-going step and a negative-going step have a worst-case timing. The solid line indicates the loudspeaker current, while the dotted line shows the current in an equivalent resistor R.

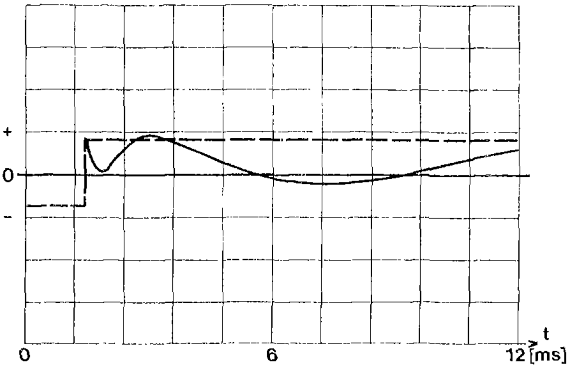

Fig. 5. Current waveform of the Yamaha NS 1000 M loudspeaker for a step function excitation. Dotted line shows the current in an equivalent resistor R. The first current notch is generated by the midrange, while the second originates from the woofer.

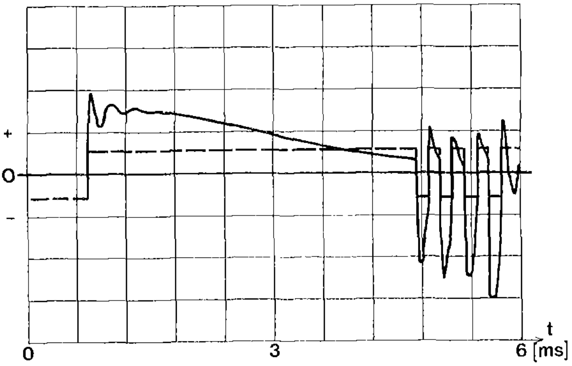

Fig. 6. Current waveforms into an 8 ohm resistor (dotted line) and into a Linn Sara loudspeaker (solid line). Signal waveform is selected to excite both the woofer and the tweeter simultaneously. Peak current is 5,3 times larger than the current into the 8 ohm resistor.

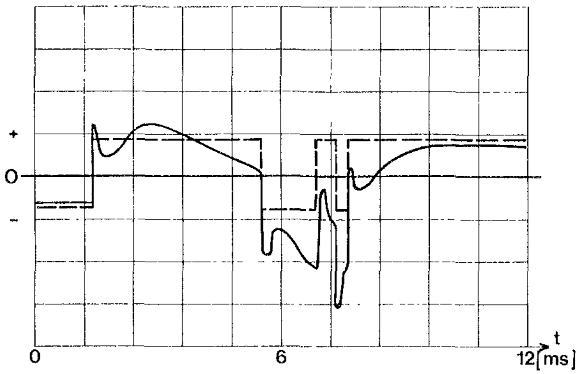

Fig. 7. Current waveforms into an 8 ohm resistor (dotted line) and into a Yamaha NS 1000 M loudspeaker (solid line). Signal waveform is selected to excite both the woofer and the midrange simultanously. Peak current is 3,6 times larger than the current into the 8 ohm resistor.

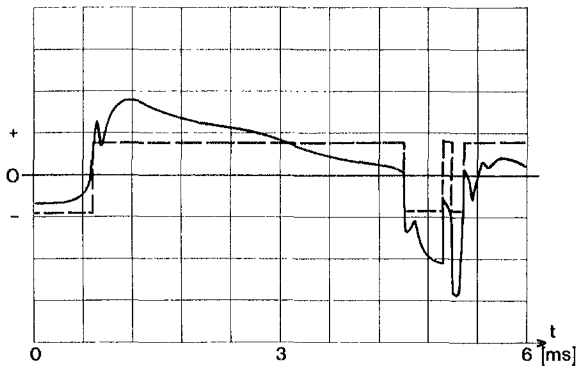

Fig. 8. Current waveforms into an 8 ohm resistor (dotted line) and into a Genelec 1051 A loudspeaker (solid line). Signal waveform is selected to excite both the woofer and the midrange simultaneously. Peak current is 3,7 times larger than the current into the 8 ohm resistor.