6th Congress of Alps-Adria Acoustics Assosiation
16.-17. October 2014
Graz, Austria

Austrian Acoustics Association
Österreichische Gesellschaft für Akustik

ISBN: 978-3-200-03921-6

The correction of low frequency non-linearities due to non-optimal Qtc in loudspeakers by the use of negative feedback

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Abstract:
Q_{tc} is the total quality factor of the low frequency driver in a sealed box and it is determined by the total quality factor of the driver itself (Q_{ts}) and the volume of the enclosure that houses the driver. The most commonly used value of Q_{tc} is 0.707, because it provides the flattest frequency response and the most acceptable rolloff of 12dB per octave, and it is achieved by adjusting the volume of the enclosure to the know Q of the chosen low-frequency driver. However, there are certain situations (due to space constraints, for instance) when the enclosure for the driver must be considerably reduced from its optimum size, leading to a significant increase of the loudspeaker's resonance frequency, bumps in its frequency curve and a steeper rolloff. It is common practice that these unwelcome nonlinearities in the frequency response are partially compensated with the help of suitable equalizers.

However, this article explores the possibility of using negative feedback to correct these nonlinearities in the frequency response of loudspeakers in sealed boxes of suboptimal volume and provides experimental results of the proposed method applied to a low-frequency driver in sealed boxes of different sizes.

Key words: loudspeaker, sealed box, Q_{tc}, negative feedback, low-frequency nonlinearities.

1. INTRODUCTION

Once a low-frequency driver (i.e. woofer) is fitted inside a sealed box, its operating parameters change. The cone of the driver becomes loaded with the air trapped inside the box (i.e. its compliance and viscous losses) and, as a result, the overall compliance of the cone decreases. The block diagram of a sealed-box woofer is shown in Figure 1.

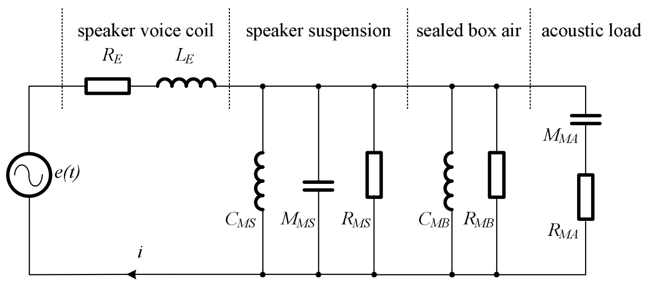

Fig. 1. Block-diagram of sealed-box woofer

In such a system, apart from the mechanical system of the woofer itself, as defined by C_{ms}, M_{ms} and R_{ms}, it is necessary to take into account the compliance of the air inside the box C_{mb} and its viscous losses R_{mb}, as well. The acoustic load is determined by the mass of air M_{ma} and the radiation resistance R_{ma} of the woofer.
The low-frequency driver itself can be described with three parameters: the total quality factor of the driver Q_{ts}, equivalent air volume V_{as} and the driver's resonance frequency f_s.
When installing the low-frequency driver into a sealed box of volume V_b, the total quality factor of the system Q_{tc} and its resonance frequency can be calculated as:

$$\frac{V_{as}}{V_b} = \left\{\frac{Q_{tc}}{Q_{ts}}\right\}^2 - 1 \quad (1)$$

$$f_c = f_s \frac{Q_{tc}}{Q_{ts}} \quad (2)$$

where:

V_b volume of the sealed box,
Q_{tc} total quality factor of the system and
f_c resonance frequency of the system.

The optimal value of Q_{tc} is commonly considered to be 0.707 as it provides the best transfer function and impulse response of the driver. Using Equation 1 above and known values of Q_{ts} and V_{as}, we can also calculate the optimal volume of the sealed box for a specific low-frequency driver.
Figure 2 shows a set of transfer functions for the test driver with the following parameters: V_{as}=16l, f_s=40Hz and Q_{ts}=0.42. The driver was simulated for sealed boxes of different sizes and its transfer functions were calculated using loudspeaker simulation software.

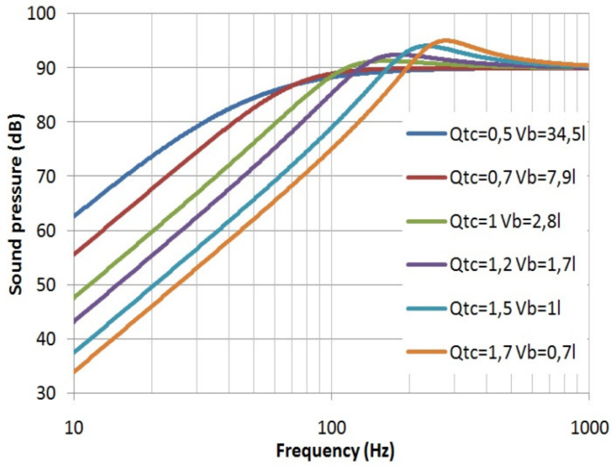

Fig. 2. Driver's transfer functions for different Q_{tc} and V_b values

As can be seen from Figure 2, a reduction in box volume increases the loudspeaker's rolloff and causes bumps in its frequency response around the resonance frequency. The most favorable box volumes for the tested driver thus come out to be 3 and 8 litres, with Q_{tc} between 0.707 and 1.
However, there are certain situations when circumstances will not allow for the driver to be installed in an optimal-size box required to achieve the most favorable Q_{tc} of 0.707, but a much smaller-sized enclosure. In such situations, the resulting nonlinearities in the driver's frequency response and its increased rolloff are partially compensated with the help of active equalizers, of which the most popular and widely used is the Linkwitz Transform.
The Linkwitz Transform circuit allows users to simulate and define ("transform") desired values of Q_{te} and f_e based on the known Q_{tc} and f_c values of the (non-equalized) driver, using a simple mathematical spreadsheet which calculates the values of equalizer elements and the equalization needed to achieve the desired box response. Figure 3 shows the frequency responses of the non-equalized test driver, the equalizer and the equalized test driver enclosed in a box whose volume V_b is 1 liter, Q_{tc} is 1.5 and f_c is 166Hz. The target values chosen for this example are Q_{te} of 0.7 and f_e of 60Hz.

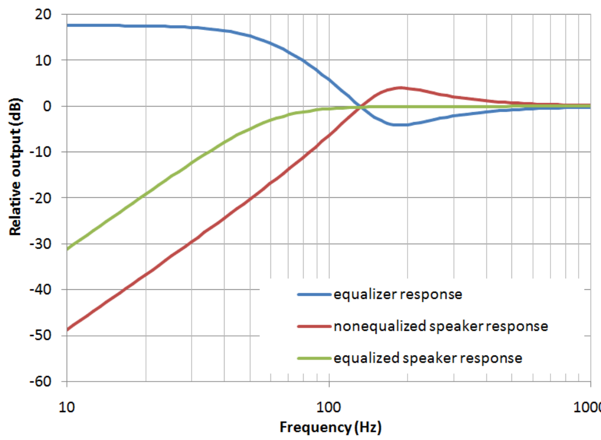

Fig. 3. Frequency responses of non-equalized driver, equalizer and equalized driver

As the above figure clearly shows, it is indeed possible to equalize the frequency response of low-frequency drivers installed in boxes of suboptimal value. However, in order for these drivers to operate properly, it is critical that the maximum linear excursion of the cone x_{max} is large enough.
Figure 3 also shows that, in this example, in order to equalize the frequency response of the test driver, the equalizer increases the input signal by 18dB in the lowest frequency range. This increase, in turn, results in a large cone excursion and considerably higher distortion in the lowest frequency range. For that reason, a rumble filter (i.e. a higher-order high-pass filter with a cutoff frequency of about 20Hz) is occasionally added to the system to protect the loudspeaker from cone over-excursion.

2. THE DESIGN OF THE NEGATIVE FEEDBACK CIRCUIT FOR THE LINEARIZATION OF THE FREQUENCY RESPONSE OF SEALED-BOX LOUDSPEAKERS

As stated in the introduction, it is possible to use an equalizer to equalize the frequency response of the loudspeaker. To apply this in practice, one would need to have a speaker cone with large linear excursion and low non-linear distortion, which would dramatically increase the cost of its production and still have questionable results in the end.
However, there is a safe way to increase the linearity of the loudspeaker's frequency response while keeping nonlinear distortion at low levels, and it relies on the use of negative feedback. The block diagram of this negative feedback circuit is given in Figure 4.

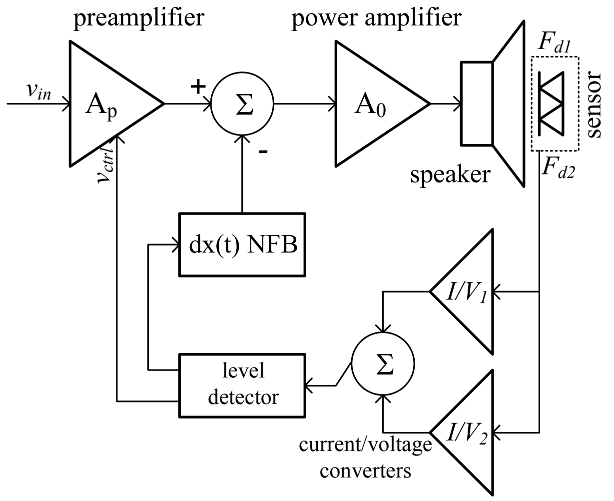

Fig. 4. Block-diagram of negative feedback implementation in active loudspeakers

The negative feedback circuit shown above consists of a cone position sensor, an NFB signal converter, a control circuit, a voltage-controlled preamplifier and an output power amplifier which drives the loudspeaker.

The most critical part of the circuit is the sensor for the conversion of cone displacement into electrical signal, which is then used as the negative feedback signal. The linearity of the sensor determines how successfully linear and non-linear distortion will be suppressed.

The NFB signal converter and the control circuit are used for the conversion of the current signal from the optical cone position sensor into the voltage signal, its equalization and addition to the input signal. The control circuit also generates the control signal for the voltage-controlled preamplifier in order to limit the signal seen by the output amplifier and thus prevent cone over-excursion in the lowest frequency range at high power levels. The transfer function of the preamplifier A_p is given in Figure 5.

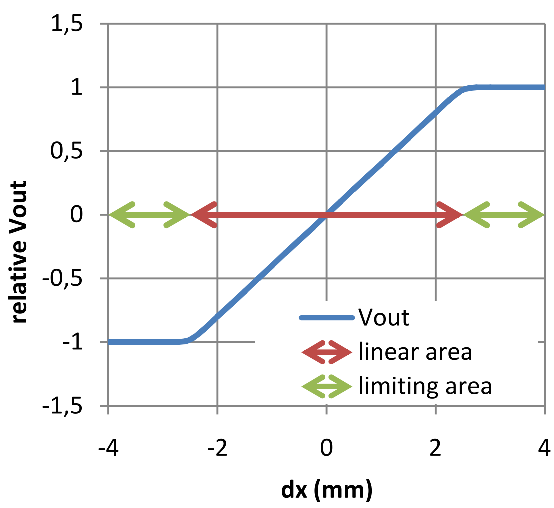

Fig. 5. Transfer function of preamplifier A_p

The transfer function of the entire system can be easily expressed as:

$$p_{out} = k_{dx} v_{in} A_p A_0 \frac{1}{k_{gx}} \; for\ dx \le dx_{max} \qquad (3)$$

$$p_{out} = p_{max} \;\; for\ dx > dx_{max} \qquad (4)$$

where:

p_{out} sound pressure,
k_{dx} conversion coefficient of the system, and
k_{gx} negative feedback coefficient.

3. CIRCUIT IMPLEMENTATION AND MEASUREMENT

Figure 6 shows the design of the cone position sensor. The optical cone position sensor used here consists of two optocouplers and a light-obstructing barrier placed inside the driver's voice coil assembly. As the barrier moves, the amount of light seen by the receiving diode of the optocouplers changes linearly and so does the current running through the optocouplers. The change in the current that flows through the receiving diode is linear with respect to the change in cone position (i.e. cone movement) whereas the amount of linear and non-linear distortion suppression will depend on the linearity of the sensor.

Fig. 6. Optical cone position sensor implementation

The linearity of the position sensor was measured with a precision laser distance meter and the results are laid out in Figure 7.

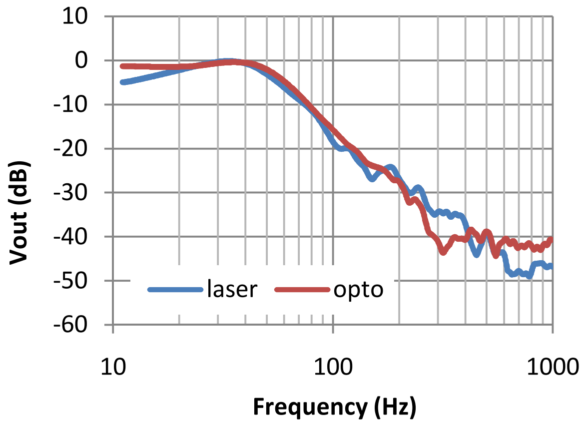

Fig. 7. Transfer functions of laser distance meter and optical position sensor

The measuring setup is shown in Figure 8. It consists of a computer-aided signal processing unit, a control device containing the circuits implemented as per Figure 4 above, a measurement microphone, the test driver used in the experiment and the sealed box that houses the driver.

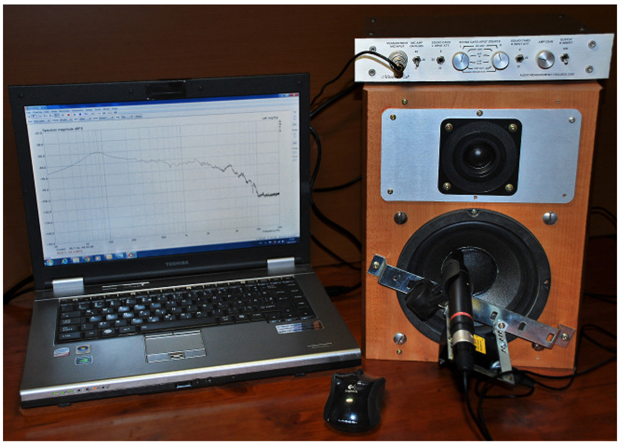

Fig. 8. Measuring setup

4. MEASUREMENT RESULTS

Figure 9 shows the measured frequency response of the test loudspeaker for 4 different scenarios: first when the driver is unenclosed and then when it is enclosed in three different boxes of 8, 4 and 2 liters, respectively.

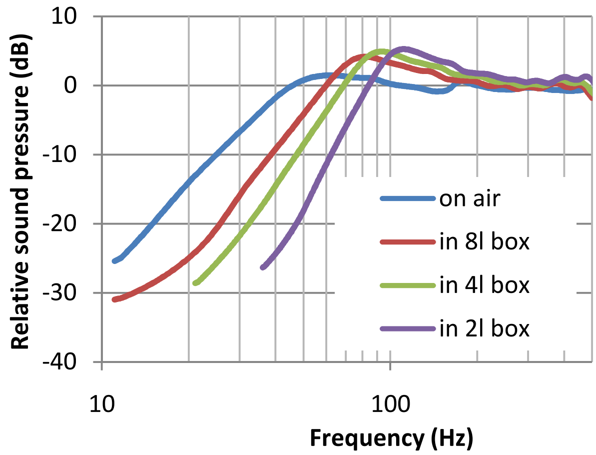

Fig. 9. Relationship between loudspeaker frequency response and box volume

The above figure clearly shows the earlier discussed increase in the resonance frequency f_c of the loudspeaker when installed in a sealed box and the occurrence of bumps in its frequency response.

In the next step, negative feedback was applied to the test system and the results can be seen in Figure 10.

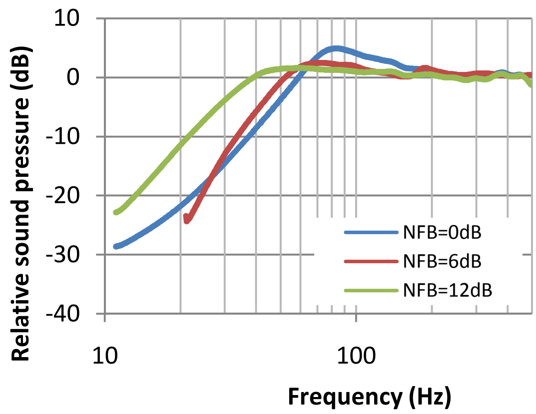

Fig. 10. Relationship between loudspeaker frequency response and applied negative feedback

The application of negative feedback can flatten the frequency response of the loudspeaker and reduce its rolloff frequency from 70Hz down to 30Hz. However, it should be kept in mind that doing so requires a considerably larger excursion x of the loudspeaker's cone at the lowest frequencies, as shown in Figure 11.

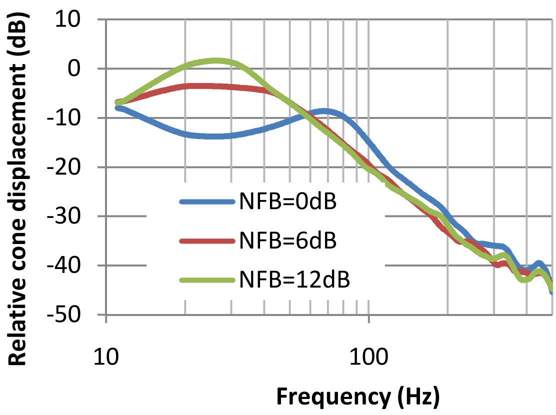

Fig. 11. Relationship between cone excursion and applied negative feedback

The application of negative feedback increases the required cone excursion by approximately 10dB, which becomes practically impossible to achieve at high sound pressure levels, where the cone would overload with excessive excursion.

The protection circuit that detects cone excursion serves to limit cone movement beyond x_{max}. The effect of this cone over-excursion protection circuit is shown in Figure 12.

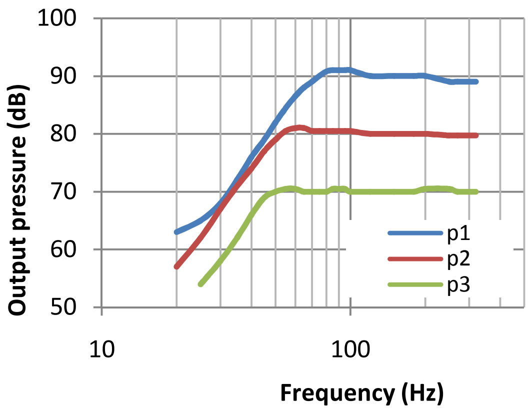

Fig. 12. Effect of cone over-excursion protection circuit

The above figure shows that, by limiting cone excursion, the protection circuit affects the rolloff of the loudspeaker in the amount depending on the sound pressure. At lower volume levels, the frequency response will thus increase by as much as one octave.

Harmonic distortion *THD* for the output pressure *p* of 90dB as measured in the near-field is presented in Figure 13.

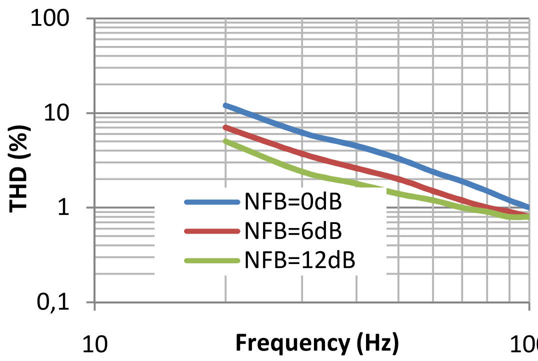

Fig. 13. Relationship between THD and applied negative feedback

Harmonic distortion decreases with the application of negative feedback by the amount slightly less than the amount of negative feedback applied.

5. CONCLUSION

The results of the experiment described in this paper show that it is possible to equalize the frequency response of the loudspeaker and extend its frequency range on par with other methods of active equalization (e.g. Linkwitz Transform) by applying negative feedback. The advantages of the proposed method include decreased harmonic distortion and the convenience of implementing a protection circuit that would prevent cone over-excursion at the lowest frequencies, which is a common issue with active equalization methods. The only major drawback of the method is the need to install the cone position sensor inside the voice coil assembly. However, it should be noted that for larger production runs, the cost of installation becomes quite negligible in terms of both time and money.

6. REFERENCES

[1] L. L. Beranek: **Acoustics**, NY: McGraw Hill, 1954
[2] M. Colloms: **High Performance Loudspeakers**, Fifth Edition, Chichester, England: John Wiley and Sons,1998
[3] Clark. J. Radcliffe, Sachin D. Gogate, **Velocity feedback compensation of electromechanical speakers for acoustic applications,** Michigan State University, 1997
[4] C-Y Chen, G T-C Chiu, C-C Cheng, H Peng: **Passive voice coil feedback control of closed-box subwoofer systems,** *IMechE2000*, 2000
[5] D. De Greef, J. Vandewege: **Acceleration feedback loudspeaker**, *Wireless World*, 1981, 32-36 [6] P.G. Mills, M.O. Hawksford: **Distortion reduction in moving-coil loudspeaker system using current-drive technology**, *J. Audio Engineering Soc.*, 1989, 37, 129-148
[7] J.F. Novak: **Performance of enclosures for low resonance high compliance loudspeaker**, *J. Audio Engineering Soc.*, 1959, 7, 29-37