ОБМІН ПРАКТИЧНИМ ДОСВІДОМ ТА ТЕХНОЛОГІЯМИ

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NEW METHOD OF MOTIONAL FEEDBACK IN LOUDSPEAKERS

Main features and differences of new method of motional feedback (MFB) were shown via linear simulation of closed-box loudspeakers. In this method the signal of MFB is summary electrical equivalent of acceleration, velocity and displacement of the loudspeaker's diaphragm. It is shown that the loudspeakers with such MFB are stable and have better characteristics of transient processes.
Keywords: electromechanical feedback, combined method, efficiency.

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НОВЫЙ МЕТОД ЭЛЕКТРОМЕХАНИЧЕСКОЙ ОБРАТНОЙ СВЯЗИ В ГРОМКОГОВОРИТЕЛЯХ

С помощью моделирования на основе линейной модели громкоговорителя закрытого типа показаны основные особенности и отличия метода организации электромеханической обратной связи (ЭМОС) в громкоговорителях, сигнал обратной связи для которой является суммарным электрическим эквивалентом ускорения, скорости и смещения диафрагмы громкоговорителя. Показано, что громкоговорители, охваченные такой обратной связью, являются устойчивыми и обладают лучшими характеристиками переходных процессов.
Ключевые слова: электромеханическая обратная связь, комбинированный метод, эффективность.

Introduction

Control theory provides a uniform method for changes of the control system (control object) with using feedback [1]. Under certain conditions the negative feedback (NFB) can qualitatively and quantitatively improve system performance through efficient redistribution of energy inside [2]. Except of stability questions for heterogeneous systems, such as loudspeakers, there are specific problems of feedback signal forming. The feedback signal for loudspeakers should be an electrical equivalent of sound pressure, but mechanical-to-electric conversion by microphone cannot be used in practice [3]. That is why the signal from electromechanical transducers (accelerometer, rate meter, and displacement meter) and its combinations are used like feedback signal. Systems with such motional feedback (MFB) have nonuniform correction capability in the target frequency range [4].

The new method for reduce of drawbacks of MFB in loudspeakers is proposed in this work. Viability of proposed solutions is tested by linear modeling.

New method of combined MFB in loudspeakers

In [3, 4] shows several possible MFB methods with different way for forming a feedback signal. With help of simulations based on a linear model of closed-box loudspeaker [5], the main features of each class of MFB is displayed, given their short analysis from in terms of automatic control theory. Specifically stated previously that the combined MFB, wherein the feedback signal represents the summer total equivalent of the acceleration, velocity and displacement of the loudspeaker cone, provides most uniform depth of feedback , and hence the better correction capability. More detailed research of this method of MFB is interested, because method, supposably, have high potential efficiency. Generalized block diagrams of systems for organization of combined MFB are shown in Fig. 1. The main differences between them are the ways of forming a feedback signal:

1. In case of fig. 1a feedback signal produces by one transducer and three-way electronic scheme of processing. Accelerometer produces signal, which proportional to the acceleration of loudspeaker's cone, one- and two-stage integration blocks produce electrical equivalents of velocity and displacement from primary signal.

2. Variant in fig. 1b generates the desired feedback signal with three separate sensors.

Despite the seeming simplicity of the circuit in fig. 1b, the use of the circuit of fig. 1a is more preferably to use for several reasons. In particular, some types of sensors involve mechanical contact with a movable loudspeaker's cone, which leads to a change in its fundamental parameters and sensitivity decrease. This decrease the more than greater the number of used sensors [3]. In addition, schemes of forming a feedback signal based on the velocity or displacement sensors require the operation of ideal differentiation, which fundamentally impossible to implement in real systems, also real differentiating chains provide additional noise [6]. At the same time the introduction of the integrator in feedback loop increases the stability of the system [7], and the accelerometer has a better signal-to-noise ratio [6]. The normalization of the signals output from the three individual sensors, which required for equivalence in signal feedback, may cause some difficulties in practical design.

The starting point (plant) for the MFB is low-frequency amplifier and loudspeaker series connection. The transfer function of plant can be represented as (1):

$$W_0(s) = K_0(s) \cdot \frac{s^2 \cdot \omega_0^{-2}}{s^2 \cdot \omega_0^{-2} + s \cdot \omega_0^{-1} \cdot Q^{-1} + 1} \qquad (1)$$

where $K_0(s)$ – transfer function of sound amplifier; ω_0 – resonance angular frequency of movable loudspeaker system; Q – total quality factor of loudspeaker; $s = j \cdot \omega$ – complex operator.

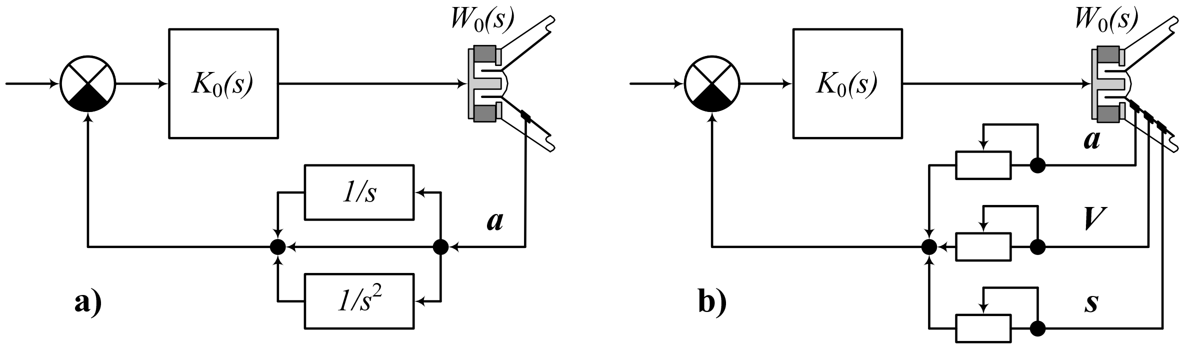


Fig. 1. Block diagram of the organization of the proposed method of MFB:
a) an indirect method based on the accelerometer and processing system b) a direct method using a separate acceleration, velocity and displacement sensors

In this case transfer function $W_{A+V+S}(s)$ of closed-box loudspeaker with combined MFB can be represented as (2):

$$W_{A+V+S}(s) = \frac{K_0(s) \cdot s^2 \cdot \omega_0^{-2}}{s^2 \cdot \omega_0^{-2} \cdot \left(K_0(s)+1\right) + s \cdot \omega_0^{-1} \cdot \left(K_0(s)+Q^{-1}\right) + \left(K_0(s)+1\right)} \qquad (2)$$

Efficiency of combined MFB action can be estimated by the size and changing of the feedback depth $F_{A+V+S}(s)$, which for this case has the form (3):

$$F_{A+V+S}(s) = \frac{s^2 \cdot \omega_0^{-2} \cdot \left(K_0(s)+1\right) + s \cdot \omega_0^{-1} \cdot \left(K_0(s)+Q^{-1}\right) + \left(K_0(s)+1\right)}{s^2 \cdot \omega_0^{-2} + s \cdot \omega_0^{-1} \cdot Q^{-1} + 1} \qquad (3)$$

The depth of feedback is used to determine correction degree for plant and feedback behavior, which may vary depending on overall gain of the MFB circuit, and depending on the frequency. In this regard, its frequency dependence should be positive, uniform, and maximum.

Undesirable changes in loudspeaker, such as different types of distortion, may change loudspeaker output. The degree of changes in MFB can be rate with sensitivity function $S_{A+V+S}(s)$ (4):

$$S_{A+V+S}(s) = \frac{1}{F_{A+V+S}} = \frac{s^2 \cdot \omega_0^{-2} + s \cdot \omega_0^{-1} \cdot Q^{-1} + 1}{s^2 \cdot \omega_0^{-2} \cdot \left(K_0(s)+1\right) + s \cdot \omega_0^{-1} \cdot \left(K_0(s)+Q^{-1}\right) + \left(K_0(s)+1\right)} \qquad (4)$$

It is obvious that the sensitivity function (4), which is the inverse MFB depth (3) claim its minimal value, which means that the maximum error-correcting capability of the system, and from a physical standpoint - minimizing all kinds of distortion in the loudspeaker.

Graphics dependencies of the transfer function (2), representing the amplitude-frequency characteristics of the system at different values of gain $|K_0(s)|$ and in comparison with the same characteristics of loudspeaker without MFB shown in fig. 2. Common feature for loudspeakers with combined MFB, except reduction of signal level, which inherent to any system with negative feedback, is the reduction of amplitude-frequency characteristic's gibbosity due resonance damping.

Graphics dependencies of the feedback depth (3) shown in fig. 3. It can be seen positiveness of feedback depth from these charts, and, previously, lack of self-oscillation in loudspeakers with combined MFB. Form of curves differentiates proposed combined MFB from another ways of motional feedback introduction.

For case, when total quality factor of loudspeaker Q=1, module of feedback depth is frequency-independent and constant. This means that the correction's properties of feedback are high and stable all over frequency range with all distortion reduction.

This short analysis of basic expressions describing loudspeaker with MFB has general character. That is why for determine features and properties of combined MFB and loudspeaker with this type of feedback should separately perform more deep research of the temporal and frequency characteristics, stability of the system etc. To assess the ability of the speaker with MFB to exact transformation of the input signal, or for analyze of fidelity of sound reproduction, it is also advisable to carry out simulation and evaluate the waveform at the loudspeaker's output in comparison with reliably knowing the waveform at its input.

Note that the expressions (2-4) were obtained by using a set of mathematical operations on rational fractions, such as bring to a common denominator, and have the minimal realization forms. These forms involve reduction of order of the polynomial with help of pole-zero pair exclusions form transfer function. Minimal realization is relevant from the point of view of mathematics and used in many works dedicated to motional feedback in loudspeakers. But for some cases of feedback equations for transfer functions in minimal realization forms can create certain disagreements. Transfer function of system with feedback represents system behavior in frequency space, and allows us to estimate new features and properties, that have arisen due to feedback.

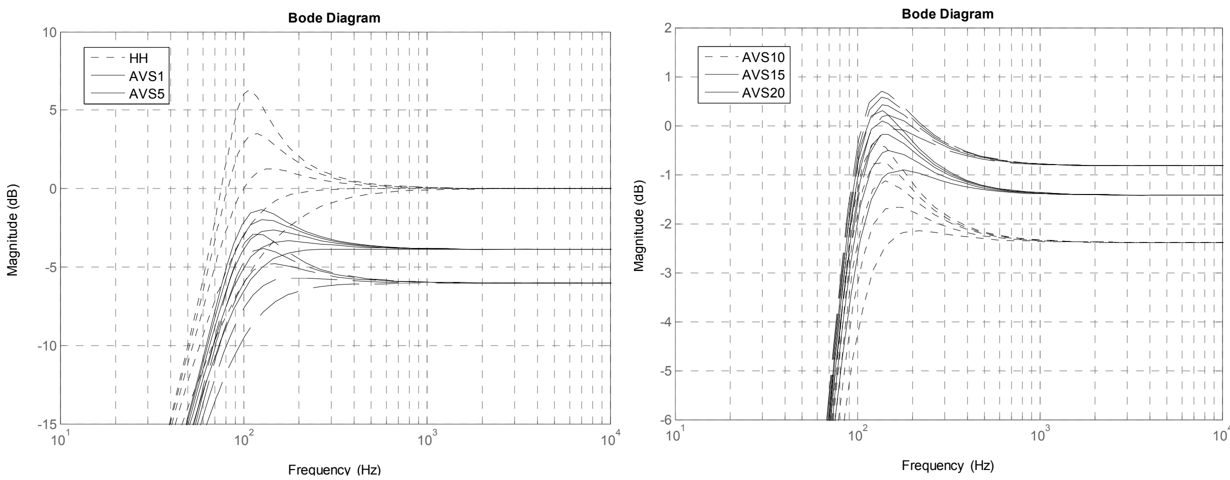


Fig. 2. Bode plots for loudspeaker with MFB:

HH – closed-box loudspeaker model on low-frequency range, with single transducer and resonant frequency $\omega_0 = 2 \cdot \pi \cdot 100$ with different values of quality factor Q = [0.5, 0.707, 1, 1.4, 2]; AVS1 - the same system, but with combined MFB for the case of unit feedback; AVS5 - the same systems with combined MFB and 5dB gain; AVS10 - the same systems with combined MFB and 10dB gain; AVS15 - the same systems with combined MFB and 15dB gain; AVS20 - the same systems with combined MFB and 20dB gain.

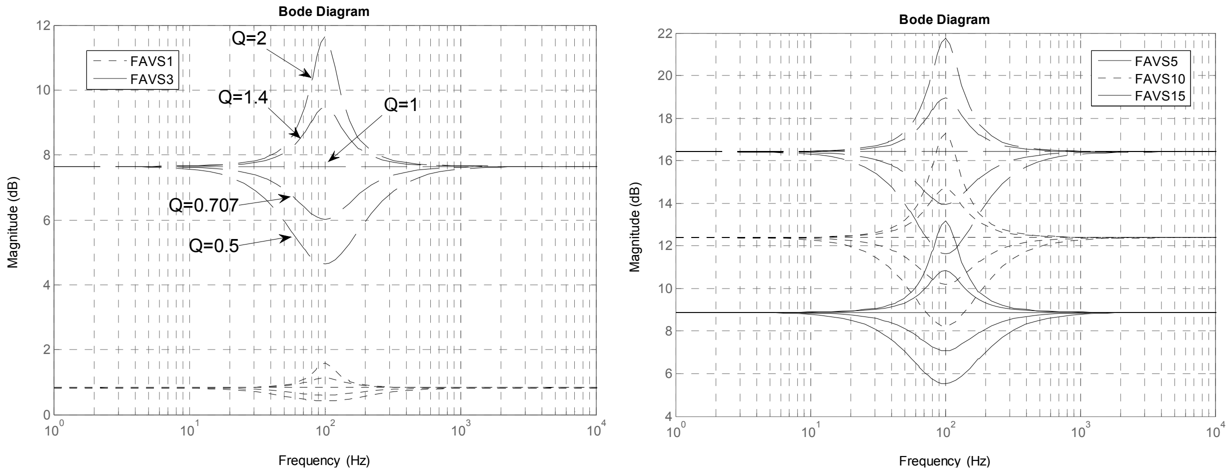


Fig. 3. Bode plots for MFB depth:

For closed-box loudspeaker model on low-frequency range, with single transducer and resonant frequency $\omega_0 = 2 \cdot \pi \cdot 100$ with different values of quality factor Q = [0.5, 0.707, 1, 1.4, 2]; FAVS1 - the same system, but with combined MFB for the case of unit feedback; AVS3 - the same systems with combined MFB and 3dB gain; AVS5 - the same systems with combined MFB and 5dB gain; AVS10 - the same systems with combined MFB and 10dB gain; AVS15 - the same systems with combined MFB and 15dB gain.

However, besides the known beneficial properties, namely the correction of existing distortions in the system, the feedback system can also have negative properties, namely, the tendency to self-oscillation. For cases of loudspeakers with different types of MFB, including the proposed combined type, the transfer functions in minimal realization have second order and with rules of control theory it should mean stability of the system at any gain [7]. At the same time, we know that for some classes of ЬАИ stability is not ensured, and it can be clearly seen on curves of feedback depth [3, 4]. Besides the introduction of feedback usually leads to higher order systems in comparison with the order of the plant [6]. Thus, the use of analytical expressions only in a minimal realization of transfer functions can lead to incorrect conclusions about the stability of systems, related, primarily, to the incorrect determination of the order of the system. Resolve existing contradictions, obviously, allows the recording of the transfer functions in the unreduced form.

For the proposed type of MFB the transfer function (1) in the unreduced form is fifth order expression, and can be represented in the form (5):

$$W_{A+V+S}(s) = \frac{K_0(s) \cdot s^5 \cdot \omega_0^{-5}}{s^5 \cdot \omega_0^{-5} \cdot \left(K_0(s)+1\right) + s \cdot \omega_0^{-4} \cdot \left(K_0(s)+Q^{-1}\right) + s^3 \cdot \omega_0^{-3}\left(K_0(s)+1\right)} \tag{5}$$

With the reduction of the common complex multiplier $s^3 \cdot \omega_0^{-3}$ in numerator and denominator of (5), it can be written in the original form (2), corresponding to a minimal realization.

Amplitude- frequency characteristics for systems with transfer functions (2) and (5) are the same, but the eigenvalues of the polynomials (zeros and poles of the transfer function) will differ. Exception of some eigenvalues when the minimal realization form (2) is used instead of normal form (5) in case of proposed combined MFB does not cause characteristic changes in the properties of the system.

Unreduced forms of expressions for the feedback depth (3) and the sensitivity of the system (4) are, respectively, have the form (6) and (7):

$$F_{A+V+S}(s)=\frac{s^5\cdot\omega_0^{-5}\cdot\left(K_0(s)+1\right)+s^4\cdot\omega_0^{-4}\cdot\left(K_0(s)+Q^{-1}\right)+s^3\cdot\omega_0^{-3}\cdot\left(K_0(s)+1\right)}{s^5\cdot\omega_0^{-5}+s^4\cdot\omega_0^{-4}\cdot Q^{-1}+s^3\cdot\omega_0^{-3}} \quad (6)$$

$$S_{A+V+S}(s)=\frac{1}{F_{A+V+S}}=\frac{s^5\cdot\omega_0^{-5}+s^4\cdot\omega_0^{-4}\cdot Q^{-1}+s^3\cdot\omega_0^{-3}}{s^5\cdot\omega_0^{-5}\cdot\left(K_0(s)+1\right)+s^4\cdot\omega_0^{-4}\cdot\left(K_0(s)+Q^{-1}\right)+s^3\cdot\omega_0^{-3}\cdot\left(K_0(s)+1\right)} \quad (7)$$

Thus, in order to eliminate possible differences with known theoretical considerations, the need of writing expressions for the transfer functions without reducing the order. In the case of minimal realization, we must explicitly specify the actual order of the function and bring all the values of its eigenvalues.

Overall analysis of the properties of the proposed MFB type

To analyze loudspeaker with proposed type of MFB should use the known criteria of control theory, the definition of which is greatly simplified if plant is specified by the transfer function of the target model and the use of modern computer-aided design system, such as f Matlab ®.

Equality degrees of the numerator and denominator of the transfer function of the loudspeaker makes it proper transfer function, which means that there is a direct signal transfer from input to output, which is not taken into account in the algorithm of the temporal characteristics construction in Matlab ®. Curves of the temporal characteristics of the loudspeaker with proposed type of MFB are shown in Fig. 4. It can be seen the significant reduction of oscillation and better time of transients processes for loudspeakers with high quality factor.

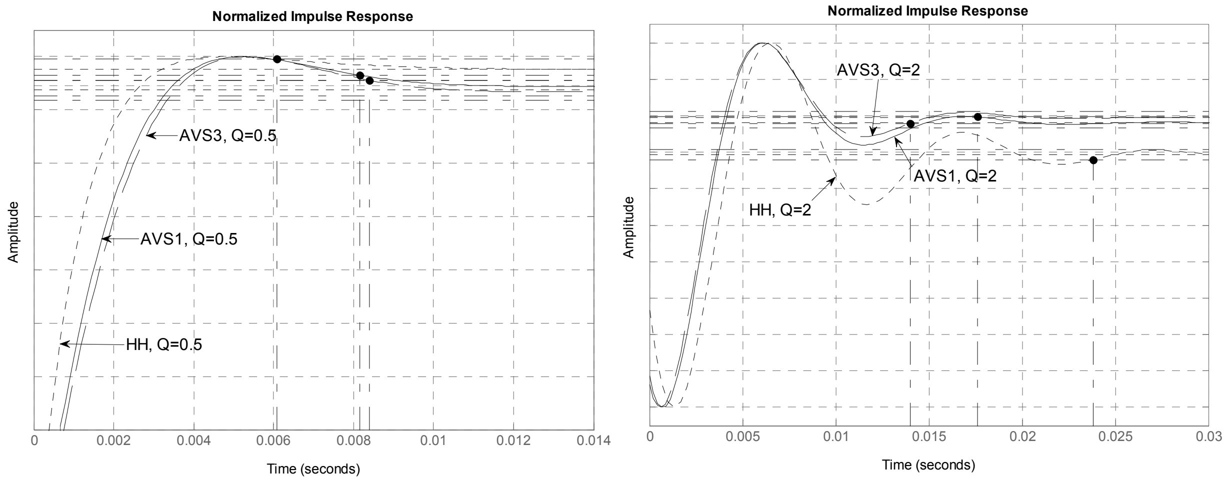
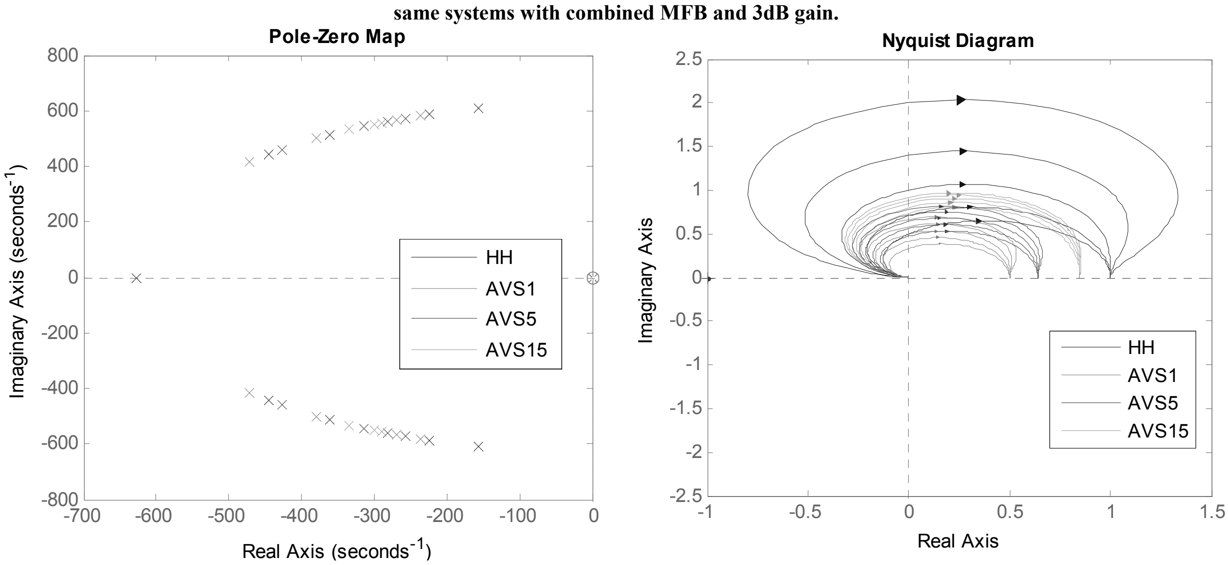


Fig. 4. Normalized impulse responses for loudspeaker with combined MFB:
HH – closed-box loudspeaker model on low-frequency range, with single transducer and resonant frequency $\omega_0 = 2\cdot\pi\cdot 100$ with different values of quality factor Q = [0.5, 2]; AVS1 - the same system, but with combined MFB for the case of unit feedback; AVS3 - the same systems with combined MFB and 3dB gain.



a) **b)**

Fig.5. Stability of the loudspeaker with proposed type of MFB:
a) Pole-zero map of transfer functions; b) Nyquist diagram; HH – closed-box loudspeaker model on low-frequency range, with single transducer and resonant frequency $\omega_0 = 2\cdot\pi\cdot 100$ with different values of quality factor Q = [0.5, 0.707, 1, 1.4, 2]; AVS1 - the same system, but with combined MFB for the case of unit feedback; AVS5 - the same systems with combined MFB and 5dB gain; AVS15 - the same systems with combined MFB and 15dB gain.

Stability of loudspeaker with proposed type of MFB supported by the fact that in the right side of the complex plane is no characteristic points of the transfer function (Fig. 5a). The presence of a pair of roots on the imaginary axis indicates neutrality of system. Symmetrical in vertical plane Nyquist diagrams (Fig. 5b) without coverage of critical point (-1, 0), indicates on the lack of self-oscillation, and this feature does not depends from loop gain.

Conclusions

Linear modeling shows that the combined MFB, wherein the feedback signal represents the total electrical equivalent of the acceleration, velocity and displacement of the loudspeaker diaphragm, has a high correction capability, characterized by a uniform feedback depth. This type of feedback provides damping of the resonance, while maintaining unchanged the frequency range, and also improves the quality of the transient processes, reducing the degree of oscillation impulse response.

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