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Nonlinear Force Factor Measurement of an Electrodynamic Loudspeaker

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Summary
An electrodynamic loudspeaker is usually characterized using a linear lumped parameter model, whose physical parameters are assumed to be constant. Such a linear approximation is sufficient for small excitation levels, but becomes insufficient for larger ones. The model is therefore usually extended allowing a variation of the parameters with the displacement of the diaphragm, the current intensity in the coil, the frequency and many other physical quantities. One of the important nonlinear parameters is the force factor Bl that characterizes the magneto-electrical performance of the loudspeaker and that can be highly dependent on the voice-coil displacement. In this paper, we propose a simple and precise method to estimate the force factor Bl of the loudspeaker as a function of the displacement of the voice-coil. The voice-coil is displaced from its rest position electrically using a direct current and a low level swept-sine signal is fed to the loudspeaker. The signals of the electric tension, the current and the velocity of the diaphragm are recorded and used to estimate the force factor Bl. This process is repeated with different values of direct current to obtain the force factor as a static function of the voice-coil displacement. The experimental results obtained measuring an arbitrary 3.3-inch fullrange loudspeaker are shown.

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1. Introduction

Physical parameters of an electrodynamic loudspeaker (force factor Bl, voice-coil resistance R_e, voice-coil inductance L_e, mass M_{ms}, mechanical resistance R_{ms} and the stiffness K_{ms}) are widely used to characterize a loudspeaker. They are usually measured at small signal levels resulting in a linear model that is said to be valid for a low signal amplitudes [1, 2]. The model is usually no more valid for large signals and thus a nonlinear model incorporating nonlinear dependencies of the physical parameters is taken into account [3].

A traditional approach of nonlinear parameters estimation [4] is based on a given nonlinear model of a loudspeaker and on an algorithm based on an optimization routine which minimizes a cost function (e.g. least mean squared error signal). Thus, all the parameters are estimated at the same time. This model takes, among other nonlinearities, nonlinear stiffness $K_{ms}(x)$ as a function of displacement. Nevertheless, it has been shown in [5] and recently confirmed in [6] that the loudspeaker suspension exhibits much more complicated nonlinearity and that the model should take into account the stiffness $K_{ms}(x, x_{peak})$ as a function of the instantaneous and peak displacement. An important dependence of the mechanical resistance $R_{ms}(v)$ with instantaneous velocity has also been shown in [6].

If the model on which the traditional method is based is incomplete, all the parameters may be in error. E.g, if the nonlinear parameter K_{ms} is estimated wrongly due to more complex reality of suspension parts, not only the K_{ms} parameter but also the others may be in error since the minimization algorithm is applied. The estimated parameters of such a model are relevant only if they refer to a well defined model.

Since it is rather difficult to incorporate all the known physical phenomena into a model of an electrodynamic loudspeaker and to apply the minimization

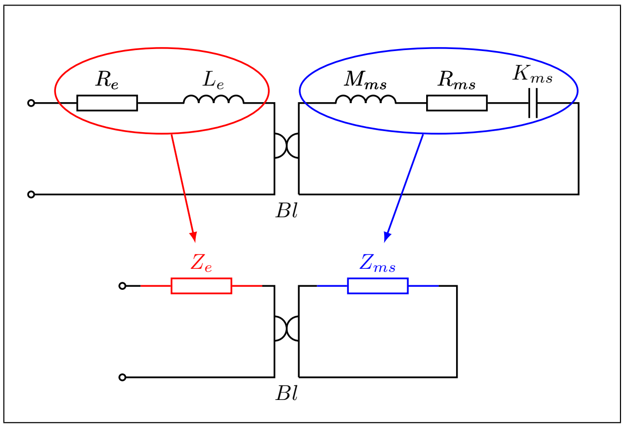

Figure 1. Equivalent circuit diagram for a loudspeaker with electrical part on the left side and the mechanical and acoustical part on the right side. A traditional circuit is depicted above; a more general circuit with two complex impedances Z_e and Z_{ms} is depicted below. The mechanical part incorporates also the acoustical load.

algorithm to find all the physical parameters of these phenomena, we propose a different approach based on a separate estimation of the force factor $Bl(x)$ as a function of displacement.

2. Description of the method

The method described in this paper is based on the following idea. Instead of estimating all the physical parameters of a loudspeaker at once using a model-fit algorithm based on cost function minimization, the method proposed in this paper estimates first the force factor independently of other parameters and separates the electrical impedance Z_e and the mechanical impedance Z_{ms}.

Thus, the only model on which the method is based is a generalized model of electrical and mechanical parts represented by their impedances, coupled with the force factor Bl as depicted in Figure 1.

The loudspeaker is excited using a small-signal level, small enough to ensure that the force factor Bl is constant within the given excursion range, but high enough to avoid a signal-to-noise ratio issue. The type of excitation signal can be of any kind allowing a frequency response measurement, i.e. sine-wave step by step, swept-sine, MLS, white noise, or any other. In this paper a swept-sine signal is used.

Next, the signals of electrical tension, electrical current (using a current probe) and velocity (using a vibrometer) are acquired and used to calculate two transfer functions:
1) the transfer function between the current and the voltage $U(f)/I(f)$ (can be seen as the input impedance $Z_{in}(f)$) and
2) the transfer function between the velocity and the current $V(f)/I(f)$.

2.1. Force factor estimation

The equation (1) describes the coupling between the electrical and the mechanical part. The electrical domain is represented by impedance of the voice-coil $Z_e(f)$. When the moving mass moves with a velocity $V(f)$, the electrical domain is coupled to the mechanical one via the force factor Bl. The electrical tension $U(f)$ at the terminals of the loudspeaker is thus seen as a sum of two contributions: one from the electrical impedance of the voice-coil as $Z_e(f)I(f)$ and second as $BlV(f)$ called electromotive force.

$$U(f) = Z_e(f)I(f) + BlV(f). \tag{1}$$

Dividing the equation (1) by the current $I(f)$ and expressing the electrical impedance $Z_e(f)$ separately, we get

$$Z_e(f) = \frac{U(f)}{I(f)} - Bl\frac{V(f)}{I(f)}, \tag{2}$$

where $U(f)/I(f)$ is the total impedance $Z_{in}(f)$ seen on the input terminals of the loudspeaker. In Figure 2 both impedances (the electrical $Z_e(f)$, plotted as red and the total $Z_{in}(f)$, plotted as green) are depicted. It is obvious that the difference between both impedances is caused by the term $BlV(f)/I(f)$ coming from the mechanical coupling and causing a resonant effect.

It is also obvious that the electrical impedance of the voice-coil $Z_e(f)$ is almost flat (a straight line). Its real part is a constant in an ideal case or a slightly increasing curve due to the presence of eddy currents, the imaginary part divided by the angular frequency should behave very similarly.

The estimation of the force factor Bl is based on the idea that the electrical impedance $Z_e(f)$ should not exhibit any resonance effect near the resonant frequency of the loudspeaker. Let consider the true force factor Bl to be unknown for the moment. The only known variables are two transfer functions $U(f)/I(f)$ and $V(f)/I(f)$ obtained from the measurement. For the sake of clarity, let consider an obviously wrong estimation $\hat{Bl} = 0$. What would happen, if the estimated $\hat{Bl}$ was set to zero? According to the equation (2) the input impedance $Z_{in}(f)$ exhibiting a resonance would be equal to the electrical impedance $Z_e(f)$ which is not possible since there is no physical reason for such a resonance-kind variation of $Z_e(f)$. The estimated value of $\hat{Bl} = 0$ must be obviously rejected.

Increasing the estimation of the force factor $\hat{Bl}$ from zero to more realistic values leads to a decrease of the resonance effect in $Z_e(f)$ as depicted in Figure 3, where the real and the imaginary part of the resulting $Z_e(f)$ for several values of estimated $\hat{Bl}$ are depicted. With increasing value of $\hat{Bl}$ the real part decreases its resonance-kind curve up to a certain moment where the real part of $Z_e(f)$ becomes flat (red line in Figure 3). If we increase the estimated value of $\hat{B}l$ the real part of $Z_e(f)$ starts to exhibit an anti-resonant-kind curve. A similar tendency can be found in the imaginary part of $Z_e(f)$.

The estimated force factor $\hat{B}l$ for which both the real and the imaginary part of $Z_e(f)$ do not exhibit any resonance is taken as the true value of the force factor Bl.

This kind of approach is based on a very simple idea and the estimation of the force factor Bl is clearly not dependent on a correct estimation of other parameters of the loudspeaker. Moreover, it leads to a separation of the electrical impedance $Z_e(f)$ and the mechanical impedance $Z_{ms}(f)$ that can be studied independently.

In the following section we will study the precision of the method on an arbitrary chosen loudspeaker and on a real measured data.

3. Precision of the proposed method

The illustration in the previous section has shown that increasing the estimated value of the force factor $\hat{B}l$ leads to a certain value of $\hat{B}l$ where the real and the imaginary part of the $Z_e(f)$ do not exhibit any resonance-kind behavior; this value is considered to be a true Bl. To study the precision of such an estimation, we choose an arbitrary 3.3-inch fullrange loudspeaker and we use a swept-sine signal with start and stop frequency $f_1 = 10\ Hz$ and $f_2 = 500\ Hz$ respectively. The amplitude of the swept-sine signal is set to $U_0 = 0.1\ V$. This amplitude leads to a peak displacement $x_{peak} = 60\ \mu m$ which we consider to be an amplitude small enough in comparison with the maximum allowed displacement $x_{max} = 3\ mm$ given by the manufacturer and also small enough to make an assumption of an almost constant Bl within this small region of excursion.

The transfer functions $U(f)/I(f)$ and $V(f)/I(f)$ are then calculated from the measured data and the procedure of estimation of the force factor $\hat{B}l$ as described in previous section is run. In Figure 4, the real part of the electrical impedance is plotted for five different values of $\hat{B}l$: { 0, 1.0, 2.0, 2.5, 3.0 }. It is clear from the Figure 4 that the value of $\hat{B}l = 2.5$ Tm is a very good candidate for the true value of Bl since the real part of the impedance does not exhibit a lot of resonant-kind behavior. To show the precision of the force factor estimation, we choose three different values of $\hat{B}l$ that are much closer (1.2% deviation to both sides) to our good candidate from the previous result: $\hat{B}l$: { 2.47, 2.5, 2.53 }. The results, plotted in Figure 5, shows that choosing $\hat{B}l = 2.5$ Tm lead to more flat real part impedance $Z_e(f)$ that choosing the two other estimations $\hat{B}l = 2.47$ and $\hat{B}l = 2.53$. Note, that even if there is only 1.2 % difference between the $\hat{B}l$ estimations, the resulting real parts of

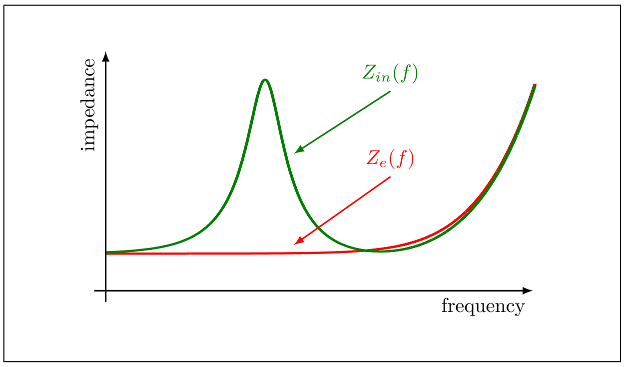

Figure 2. A typical loudspeaker impedance (absolute value) as a function of frequency; input impedance is plotted in green; electrical part impedance is plotted in red.

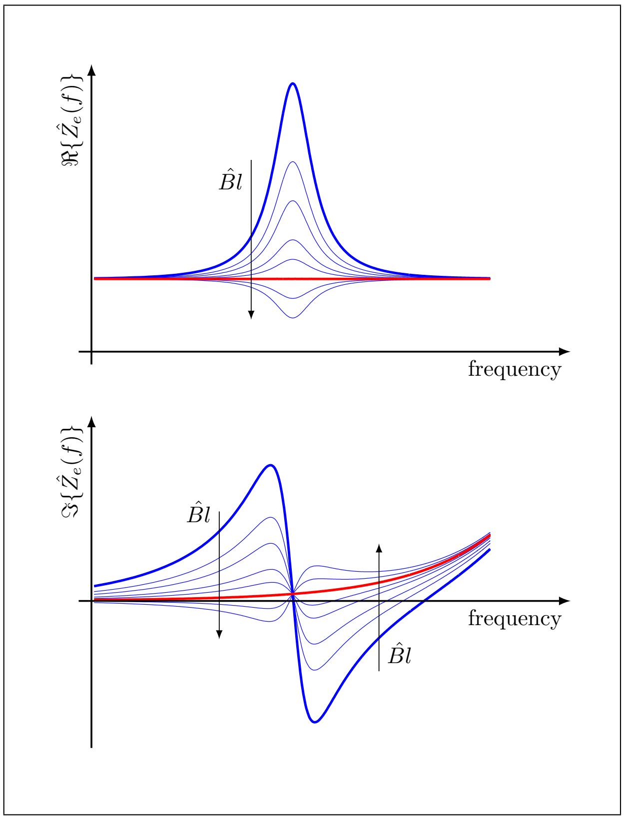

Figure 3. Simulation of influence of the $\hat{B}l$ estimation on the real and imaginary part of the estimated electrical impedance $\hat{Z}_e(f)$. Correct estimation of $\hat{B}l$ is plotted in red.

the electrical impedance $Z_e(f)$, depicted in Figure 5, reveal quite clearly which of these estimations is the best one.

We can conclude from this experimental result that the precision of the force factor estimation is approximately 1%. The precision can be increased by using a higher level of excitation signal leading to a better signal-to-noise ratio, but also to a higher peak displacement which can make the assumption of the constant Bl within a higher region of excursion weaker.

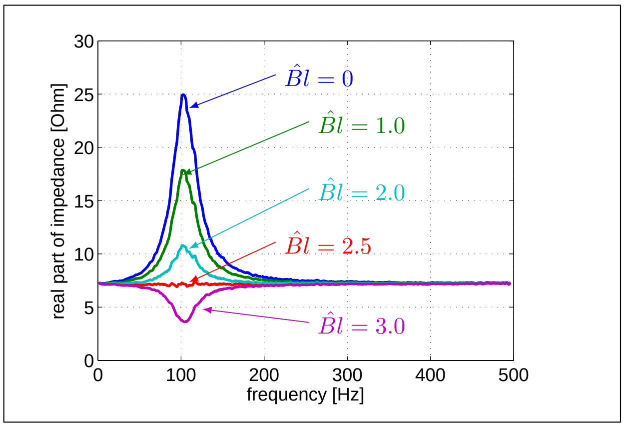

Figure 4. Influence of the $\hat{B}l$ estimation on real part on the electrical impedance $Z_e(f)$. Real measured data are used.

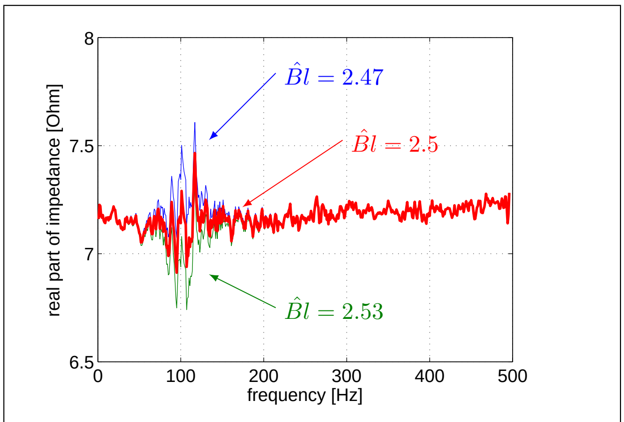

Figure 5. Influence of the $\hat{B}l$ estimation on real part on the electrical impedance $Z_e(f)$. Real measured data are used. Three different but very close estimations of $\hat{B}l$ are shown to emphasize the high precision of the proposed method.

4. Nonlinear force factor

The factor Bl is known to be dependent on the displacement, noted as $Bl(x)$. In order to estimated the force factor as a function of displacement, the previously described procedure can be used in a piecewise manner for several static displacement. The voice coil can be displaced statically either adding a DC component or using a pneumatic excitation. The first method, much more easier to be implemented, is used in this paper.

The estimation that was described in the previous section on our arbitrarily chosen loudspeaker was made with no DC component added; that is around the rest position $x = 0$. Next, we repeat the procedure for several different DC components added leading to a static displacement on both, positive and negative directions.

The results are depicted in Figure 6 and a comparison is made with a widely used commercial method using a Klippel analyzer. Both curves depicted in Figure 6 are very close to each other especially for a positive displacement values. The match is not so perfect for the negative values of displacement, where both methods give slightly different results with an approximately 5% difference. The difference between both estimations is one of the subjects of our present research.

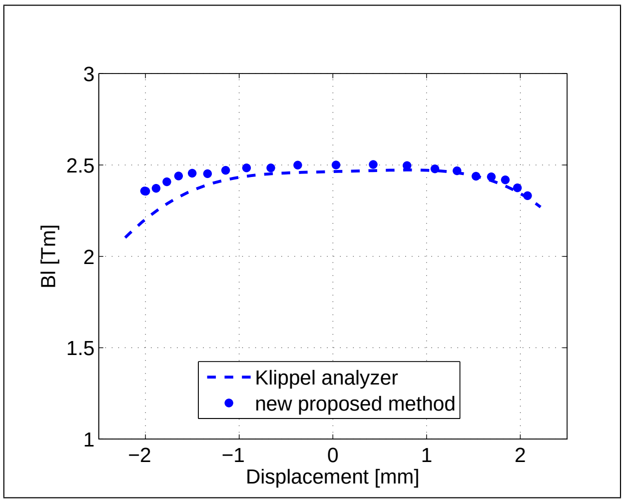

Figure 6. Force factor as a function of displacement estimated using the new proposed method and compared with the measurements realized using the Klippel analyzer.

5. CONCLUSIONS

In this paper, a method for measurement of the force factor of an electrodynamic loudspeaker has been introduced. The experimental results obtained measuring the force factor of an arbitrary loudspeaker have been shown. The measured force factor has been compared with the results from Klippel analyzer. The comparison has shown a slight difference between both methods.

The proposed method identifies the force factor independently on other parameters. Estimating the force factor, the mechanical and electrical parts are completely separated and their parameters can be then deduced. One must still take into account, that the measurement is made using a quasi-static approach, and thus the mechanical parameters may have a different physical meaning than those obtained using dynamic methods.

Despite the previous claim, the method presented in this paper estimates the force factor Bl with a very high precision independently on other loudspeaker parameters.

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