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Identifying the nonlinear mechanical behaviour of micro-speakers from their quasi-linear electrical response

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ABSTRACT

In this study model identification of the nonlinear dynamics of a micro-speaker is carried out by purely electrical measurements, avoiding any explicit vibration measurements. It is shown that a dynamic model of the micro-speaker, which takes into account the nonlinear damping characteristic of the device, can be identified by measuring the response between the voltage input and the current flowing into the coil. An analytical formulation of the quasi-linear model of the micro-speaker is first derived and an optimisation method is then used to identify a polynomial function which describes the mechanical damping behaviour of the micro-speaker. The analytical results of the quasi-linear model are compared with numerical results. This study potentially opens up the possibility of efficiently implementing nonlinear echo cancellers.

1. Introduction

Space restrictions in mobile devices, such as smart phones, lead to the use of small loudspeakers known as micro-speakers [1], which have limited, but still remarkable, sound outputs. In general, all loudspeakers behave nonlinearly to some extent. The dominant form of nonlinearity in larger speakers is often that in the suspension stiffness and the force factor [2] while in micro-speakers, the dominant nonlinearity has been shown to be a nonlinear mechanical damping characteristic. A large difference in the damping as a function of cone velocity has been observed when, measured either in air or in a vacuum [3], indicating that the nonlinearity is probably related to the airflow due to leakage through the case when the case volume is driven by the rear of the loudspeaker. The acoustic resistance of a small orifice is known to be nonlinear [4] being independent of the flow speed at low amplitudes, when the flow is laminar, but then rises in proportion to the flow speed at higher amplitudes, when the flow becomes turbulent.

When the micro-speaker is driven with a signal whose amplitude is characterised by sudden changes, such a speech signal for example, the effect of the nonlinear damping is to significantly reduce the peak response of the micro-speaker compared with a linear one. This means that the micro-speaker could be driven harder for a given limitation of the cone throw and thus produce higher sound pressure levels at frequencies above the speaker's resonance. The beneficial effect of the nonlinear damping is thus essentially one of dynamic range compression. A potential disadvantage of the nonlinear damping is the distortion that it generates, although it will be seen below that this can be surprisingly small. Another potential issue with such a nonlinear driver is that if a linear echo canceller [5] is used to attenuate the component of the response due to the signal driving the loudspeaker at the microphone, in a mobile phone for example, the cancellation cannot be perfect if the echo canceller assumes a linear model of the micro-speaker. Although nonlinear echo cancellers have been proposed, based on Volterra models [6–9], for example, these generally suffer from

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the curse of dimensionality, whereby the number of coefficients that needs to be identified rises as the power of the nonlinear order being modelled. If a linear echo canceller requires of the order of 1000 coefficients, for example, which is a typical number [5], then the number of coefficients required for a general Volterra model that captures second order nonlinearities is of the order of 1,000,000 and one which captures third order nonlinearities is of the order of 1 billion. Neural networks have also been used to model the nonlinear dynamics in an echo cancellers [10–12] in which case the complexity of these algorithms is not as high as in the case of volterra series, but their performance is also lower. A comparison of different linear echo cancellation arrangements can be found in Ref. [13] where an alternative way to improve the performance of the echo canceller has been investigated. In this study [13] the current driving the micro-speaker is proposed as a nonlinear reference signal for the echo canceller. This method can completely capture the nonlinearities introduced by the amplifier but only partially captures the nonlinearity introduced by the micro-speaker.

If the nonlinearity in the echo canceller is primarily due to the nonlinear mechanical damping, however, then only a few additional parameters needs to be identified over and above the number required to model the linear path.

This paper describes the identification of a dynamic model of the micro-speaker which takes into account the nonlinear damping characteristic by purely electrical measurements, avoiding any explicit vibration measurements, as was used in [3], and potentially opening up the possibility of efficiently implementing a nonlinear echo canceller. The paper is divided in five sections. In Section 2 the quasi-linear model of a micro-speaker characterised by nonlinear mechanical damping is derived. In Section 3 a model identification method based on the quasi-linear model is presented. Section 4 presents the results of the model identification carried out on a micro-speaker and conclusions are drawn in Section 5.

2. Quasi-linear model of the micro-speaker

In this section the mathematical model of a micro-speaker characterised by nonlinear damping is derived.

Fig. 1 shows the dynamics of a micro-speaker modelled as a single degree of freedom where M represents the cone mass, K the stiffness suspension and $g[\dot{x}(t)]$ is the nonlinear damping term. The equation of motion for this system can be written as:

$$M\ddot{x}(t)+g[\dot{x}(t)]+Kx(t)=Bli(t) \quad , \tag{1}$$

where $x(t)$ is the cone displacement, Bl is the electro-mechanical transduction coefficient and $i(t)$ is the current flowing though the coil. The coil of the micro-speaker is assumed to have negligible inductance but to have an electrical resistance R, so that the driving voltage, $v(t)$, is equal to:

$$v(t) = Ri(t)+Bl\dot{x}(t). \tag{2}$$

Solving Eq. (2) for $i(t)$ and substituting into Eq. (1) gives the equation of motion for the micro-speaker, when driven by a voltage signal as

$$M\ddot{x}(t)+h[\dot{x}(t)]+Kx(t)=\frac{Bl}{R}v(t) \quad , \tag{3}$$

where $h[\dot{x}(t)]$ is a nonlinear damping function including the linear damping term $\frac{Bl^2}{R}\dot{x}(t)$.

An interesting aspect of systems with nonlinear damping is that their behaviour can be reasonably well predicted using equivalent linear models, in which an equivalent linear damper varies as a function of the excitation level, which is termed quasi-linear. These quasi-linear models are particularly accurate for systems with nonlinear damping [14]. Ref. [14] shows that the analysis of systems characterised by nonlinear damping of the type used here to describe the dynamic behaviour of the micro-speaker, is simplified by the fact that there are no jump or bifurcation behaviour, as often found in systems characterised by nonlinear stiffness for example. Also the equivalent linear damping is chosen such that the power lost to damping is the same as in the system with nonlinear damping. Therefore, the dynamic of these systems can be well represented by an equivalent linear system, whose damping parameters depend on the form and amplitude of the excitation. As also shown in the next section even though the

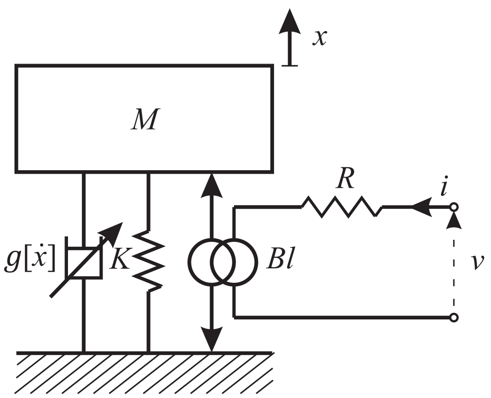

Fig. 1. Lumped parameter model of the micro-speaker.