New Method of Characterizing Driver Linearity*

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A simple novel method of determining nonlinear parameters for electrodynamic loudspeaker drivers is presented and verified. The method requires substantially the same equipment as is required for linear (Thiele–Small) measurements, making it readily accessible to existing laboratories. Example linearity parameters are found and used to fit a model that is a logical extension of an existing model. The accuracy of extracted parameters is verified by comparing measured and simulated distortion in both acoustic and drive current measurements. Excellent agreement is found in the dominant second- and third-harmonic distortion, especially about the driver resonant frequency. The nonlinear parameters may be used to perform comparisons between drivers or to accurately model the linearity performance of separate parts of a driver and their impact on the performance of a system.

0 INTRODUCTION

Considerable interest has been shown in the literature recently toward the problems of loudspeaker linearity [1]–[5], [7], [8]. Some models address only nonlinearity in the *Bl* product [5]. In [1] Kaizer presents an overall Volterra model fitted to harmonic and intermodulation measurements (in addition to straightforward linear measurements). This model produces "reasonable agreement" between calculated and measured distortion in the output signal of an accelerometer added to the driver cone. In [3] Klippel extends Kaizer's model and identifies parameter measurement as the principal obstacle. Again acoustic harmonic and intermodulation measurements are used to determine parameters.

In these instances parameters are extracted by a numerical error-minimization process designed to select the parameter vector that best permits the model to predict the observed (nonlinear) behavior. Beyond any concerns associated with pitfalls in achieving optimization with many dimensions, the authors are presented with a difficulty—checking the validity of a model whose parameters are selected using the very behavior the model is attempting to predict. Almost any model, no matter how uncorrelated with the physical reality of the system it models, can achieve the feat of predicting that behavior upon which it is optimized. This is not a problem unique to loudspeaker drivers.[1]

The addition of the accelerometer by Kaizer provides a different observable phenomenon by which to check the model's prediction with measurements not used in its fitting. While truly dynamic position sensing may be applied to the cone of a driver, complex equipment is required. The simple accelerometer may disturb the driver and in any case provides a signal removed from position by a second derivative. This signal is not far removed from the spectra to which the model is fitted.

Most recently Olsen has approached the measurement of nonlinearity in the mechanical components by making mechanical meaurements [8]. This approach avoids pitfalls of previous methods. Apparently carried out simultaneously with this work, it resembles the work reported

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[1] An example is the wide variety of models of III-V semiconductor devices, whose physical workings are not well enough understood to permit a single, meaningful, physically realistic model to be developed [9].

here in several ways. However, it requires special equipment that must be carefully mounted to the driver under test using glue. Furthermore no verification of the extracted functions has been reported so far, and it is thus unclear how effective the method is.

Results obtained to date have, often by the cited authors' own admissions, not been spectacular. Shortcomings are typically excused because the "model breaks down at higher frequencies due to the nature of hysteresis effects, eddy currents, and cone breakup effects."

In this manuscript we present:

1) A physically based behavioral driver model incorporating *Bl*, inductance, and compliance nonlinearity effects, and which could readily be expanded to incorporate heating effects in R_e [7]

2) A procedure to fit the model to a driver employing solely linear parameters[2] and simple, mechanical measurements, involving neither nonlinear acoustic nor nonlinear impedance measurements

3) Verification of the equivalent nonlinear circuit model and curve-fitting procedure by demonstrating good agreement between prediction and measurement of the acoustic and current distortion of the driver.

Because the model requires only linear parameters and simple mechanical measurements, it may be obtained for a driver using methods already at the disposal of most laboratories. Since it is physically based, it provides direct insight into the causes of distortion within the driver. It can predict nonlinear distortion both in the acoustic output and in the current drawn by the driver.

1 METHOD

The basic idea is to determine the linear equivalent circuit of a driver at each position in a range of cone displacements, and to deduce the nonlinear behavior from the variation in linear behavior. The varying cone displacements are achieved by passing a direct current through the voice coil. The linear parameters at each position may be determined from measurements of small-signal impedance. Once the variation of the linear circuit elements with instantaneous cone position is known, the driver's dynamic nonlinear performance may be simulated. The effectiveness of the characterization can be checked by comparing predicted distortion (in either the acoustic output or the current into the driver terminals, or both) with measurements made using dynamic distortion measurement equipment such as a spectrum analyzer. Because there are no measurements common to the processes of fitting and verifying the model, the check becomes a very powerful measure of the effectiveness of the method.

[2] The linear parameters are related to, but are not, Thiele–Small (T–S) parameters. We refer to them as T–S parameters to honor their inspiration.

2 NONLINEAR MODEL

This paper extends the familiar series–parallel resonant circuit topology into a nonlinear model while retaining the 25 years of intuition it has cultivated in this field. Fig. 1 shows the equivalent circuit used. It strongly resembles the traditional model—a parallel resonant part, a series resistance R_e, and a series inductance—but includes a minor extension suggested by Wright [10]. This is the shunted/unshunted series pair for voice-coil self-inductance. However, in our case all but R_e become functions of the cone displacement x.

Kaizer [1] has correctly stated that if analysis is restricted to adequately low frequencies, then the dominant sources of nonlinearity are functions of the cone displacement—namely, force factor *Bl*, coil self-inductance L_e, compliance C_{ms}, and suspension losses R_{ms}.

Small [11] gives the definitions of the linear mechanical parameters. Making them nonlinear functions of x,

$$R_{et}(x) = \frac{1}{R_{ms}(x)Bl(x)^2} \tag{1}$$

where $R_{ms}(x)$ is a nonlinear function representing the suspension's mechanical resistance,

$$L_{cet}(x) = Bl(x)^2 C_{mt}(x) \tag{2}$$

where $C_{mt}(x)$ represents the mechanical compliance of the driver suspension and box, and

$$C_{mes}(x) = \frac{M_{ms}}{Bl(x)^2} \tag{3}$$

where M_{ms} is the constant mechanical mass of the driver

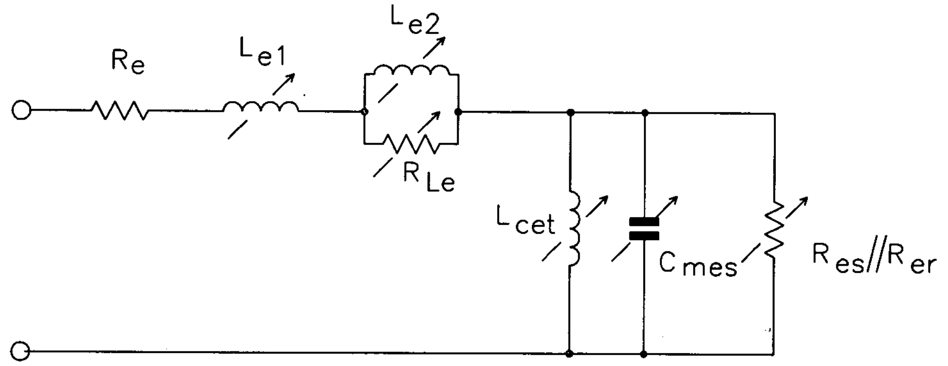

Fig. 1. Equivalent nonlinear circuit of driver.

diaphragm assembly, including air load. With the components represented as nonlinear functions of x the model embodies nonlinear compliance and suspension losses, with the nonlinear Bl factor underlying all of these components.

The problem is now to obtain the six nonlinear functions. Values of them, for any single displacement, can be obtained experimentally by measuring the driver impedance versus frequency and solving numerically for component values by the least-squares method. The displacement x is varied by applying a dc current, and the nonlinear trend of each component with dc current is obtained. By the additional measurement of cone position versus applied dc current, the nonlinearities may be expressed as functions of x. Also, by measuring the force factor at the cone equilibrium position $Bl(0)$, $Bl(x)$ can be derived from $C_{mes}(x)$ and the driver parameters separated and expressed in mechanical or electrical terms.

We represent the six functions with polynomials. These may be fitted to the tables of values for various displacements by straightforward mathematical methods [12].

The validity of this method rests on the assumption that the electrical properties do not vary significantly with the drive current (that is, the Bl product is not significantly affected by the dc displacement-control current nor by any signal current). We also rely on the assumption that the mechanical properties, including suspension-related ones, are not significantly frequency dependent. With some drivers this assumption appears not to hold.

3 DRIVER CHARACTERIZATION

The characterization of a driver involves two stages—measurement of the physical properties of the driver and extraction of the parameters from the data. The measurements are detailed in Sections 3.1–3.3, the extraction in Section 3.4.

3.1 Impedance Sweeps

Fig. 2 shows the equipment used to extract the impedance curves. It consists of an HP4192A low-frequency impedance analyzer, controlled via IEEE488 bus by a personal computer. The HP4192A utilizes a four-terminal method to measure vector impedance and can be made to interface with an external dc current source easily. We constructed a current source capable of sourcing or sinking up to 1.5 A. These signals were used to drive the test driver in a nonported enclosure.[3]

Care may have to be taken with some drivers in making these measurements in order to prevent suspension hysteresis effects from interfering with results. The cone must be settled into its displaced equilibrium position prior to impedance measurement.

3.2 Current–Displacement Curve

The cone's displacement due to dc current was measured using an NC milling machine with digital position readout, as shown in Fig. 3. After setting the dc current to the required value, the bed of the milling machine

[3] This was done to simplify driver mounting and to facilitate acoustic distortion measurements.

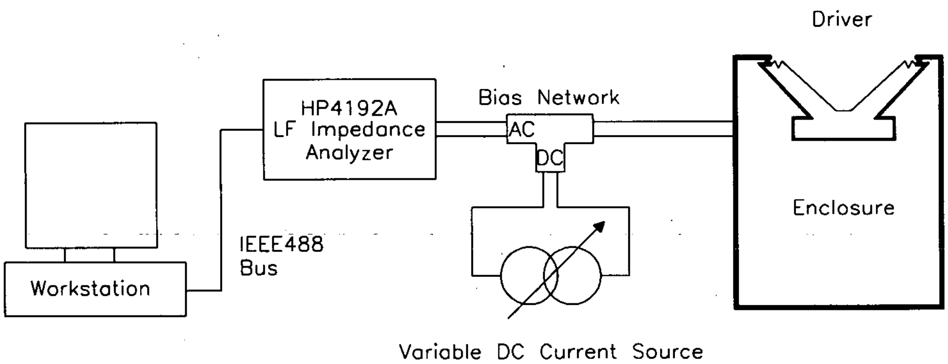

Fig. 2. Block diagram of equipment setup for measuring driver impedance for various dc coil currents.

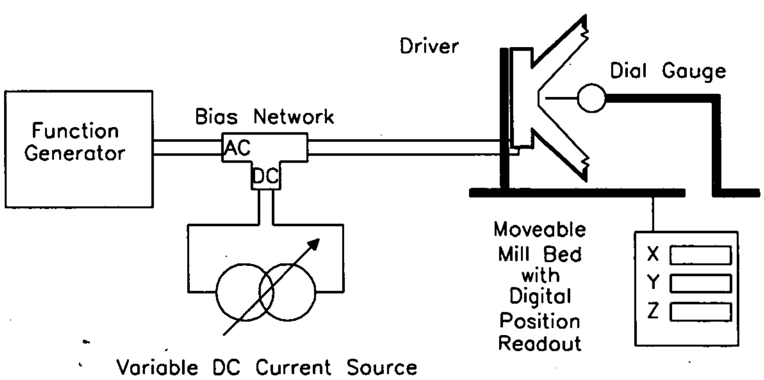

Fig. 3. Block diagram of equipment setup for measuring cone displacement against dc coil current.

was extended until contact was made with the cone. By superimposing a small ac signal onto the dc current injected into the driver, the cone gives an audible buzz on contact with a whisker or the feeler of a dial gauge attached to the chassis, facilitating the measurement of the displacement. Again hysteresis effects may require that care be taken with the measurements, especially with larger drivers.

3.3 Zero-Displacement *Bl*

The measurement of the driver's force factor at zero cone displacement was achieved by a simple "balance of forces" method. First with the driver axis horizontal to prevent the cone from sagging under gravity, a whisker attached to the driver chassis is positioned so as to just touch the cone. Then the driver is positioned vertically and the cone weighted with a series of known masses. The dc current required to return the cone to its equilibrium position is noted. By plotting the added mass versus applied dc current, $Bl(0)$ can easily be found from the gradient.

3.4 Computation

The first step in the calculation is the extraction of box-modified T–S parameters for each impedance sweep. We accomplished this by straightforward numerical optimization (minimization of the mean square error). Values of M_{ms} and R_e are determined. (R_e is treated as constant; dc measurements suggested that its variation was negligibly small in the case of the drivers we have examined). Weighting of the data was achieved not by varying the weight of any individual data point but by varying the point density in different regions, chiefly increasing the number of measurements near the parallel resonance. After this extraction one constructs data files containing the value of various circuit components tabulated against dc displacement current.

The next step involves fitting polynomials of appropriate order to various data sets. First a fit is made to the current–displacement data. This is used to replace the value of the dc current associated with each sweep with its correct cone displacement. Subsequently an approximation polynomial is fitted to each component value and to $Bl(x)$. Thereafter each is associated with a set of coefficients relating its value to the displacement. (These are our model parameters.) The order of the polynomial used in each regression was selected by fitting a range of orders and finally selecting the highest order above which the coefficients became negligible, or above which ripples became visible in the range of interest. Our experience suggests that seventh order is generally quite adequate, and hence measurements should be carried out for about 20 values of displacement in order to provide an adequate number of samples for the regression.

The computations may be carried out with a variety of software packages. We used Excel for the parameter extraction. For the polynomial fitting and plotting we used Graftool. Measurement control software was written in C. Once the parameters have been determined, a suitable behavioral modeling tool (such as PSPICE [6]) can be used to determine predictions of nonlinear cone displacement and driver terminal current for any arbitrary drive signal. Acoustic distortion is also readily obtained. We hope to transfer to an integrated framework (such as Hewlett-Packard's IC-CAP) that will orchestrate all measurements, perform extraction and simulation, and plot results.

4 EXAMPLE

An example characterization was carried out on a Peerless 831921 200-mm driver. This driver has a modest power rating and is made with a polypropylene cone with foam surround.

4.1 Measurements

Fig. 4 contains three plots associated with the measurements described in Sections 3.1–3.3. It provides a visual summary of the data used in fitting the model to the driver.

4.2 Computed Functions

Fig. 5 contains plots of the nonlinear functions computed from the data presented in Fig. 4. This figure provides a visual summary of the driver component nonlinearities. If the object of the modeling is to determine the nonlinearity of one or more driver parts, this figure represents the desired output, that is, this figure displays the functions representing the nonlinear contribution of the various components of the model.

5 VERIFICATION OF NONLINEAR PARAMETERS

Following the method in [7], the driver-current and the acoustic distortion can be predicted using the nonlinear model implemented as a behavioral model in SPICE. Fig. 6 gives the equivalent circuit as implemented in SPICE. The effective formulas for current in two of the inductors are shown as an example. Note that values for Bl and cone position are computed by the subsidiary loops at the bottom of the circuit using nonlinear voltage-controlled voltage sources. Position is computed from velocity and the Bl product, and the Bl product from position.

Predictions made with this model may be compared with measurements. It is this comparison that provides our independent verification of the validity of the process and the success of the measurements.

5.1 Distortion Measurements

Fig. 7 depicts the equipment setup used to measure distortion in both the driver current and the driver acoustic near field [13]. Figs. 8 and 9 display typical comparisons of predicted and measured current spectra. Table 1 tabulates values of predicted and measured SPL total harmonic distortion and Table 2 gives values of driver-current total harmonic distortion. We attribute the larger discrepancies at the higher frequency of 238 Hz to the relatively small cone excursion involved.

6 CONCLUSION

Remarkable agreement has been obtained between measured acoustic and impedance distortion and values predicted using a behavioral model fitted to linear and mechanical measurements. Nonlinear contributions from various sources within a driver have been isolated. This new approach provides a powerful tool in the design of more linear loudspeaker drivers in the form of straightforward assessment of driver components.

7 ACKNOWLEDGMENT

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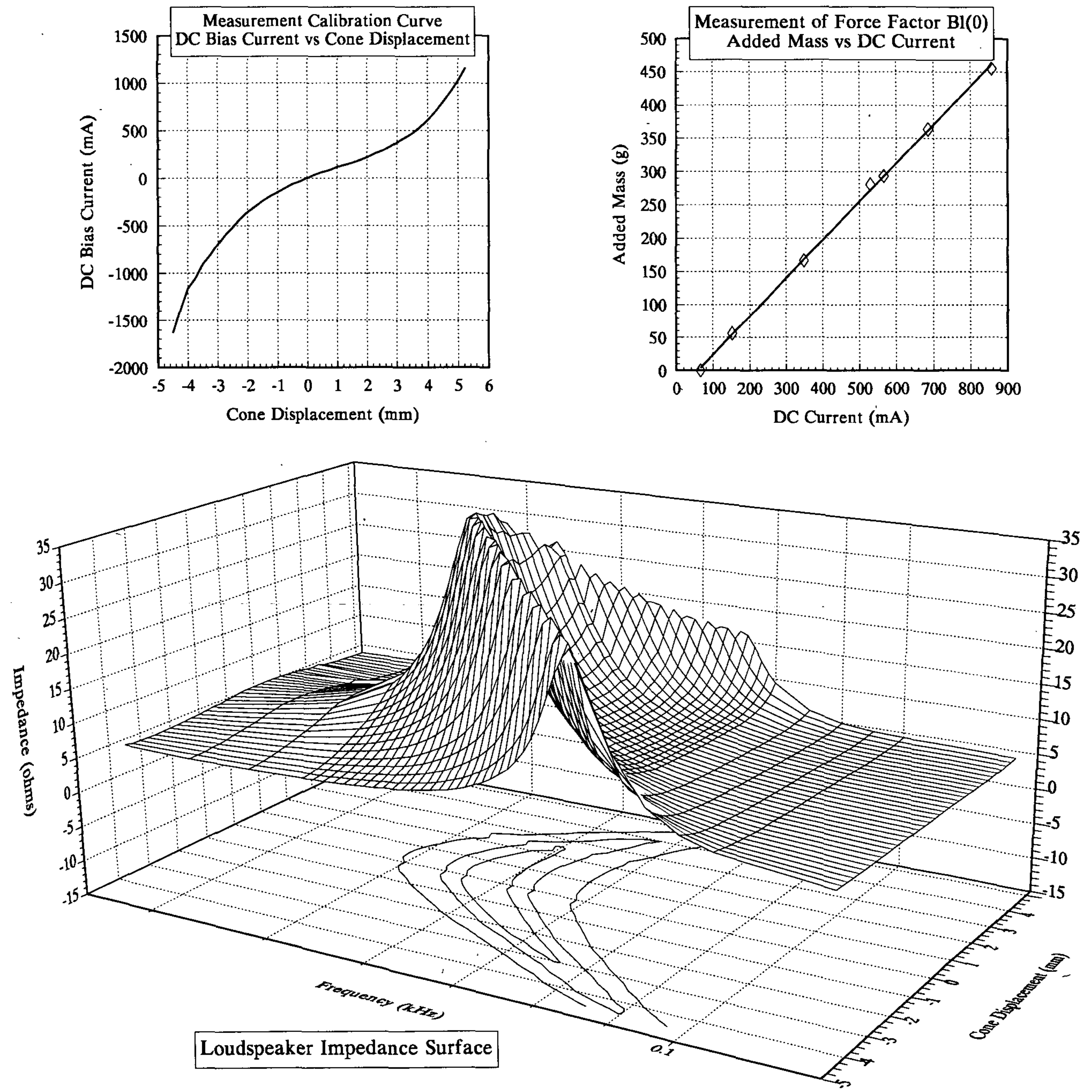

Fig. 4. Plot of data used for parameter extraction of Peerless 831921 driver. Impedance data were decimated for clarity.

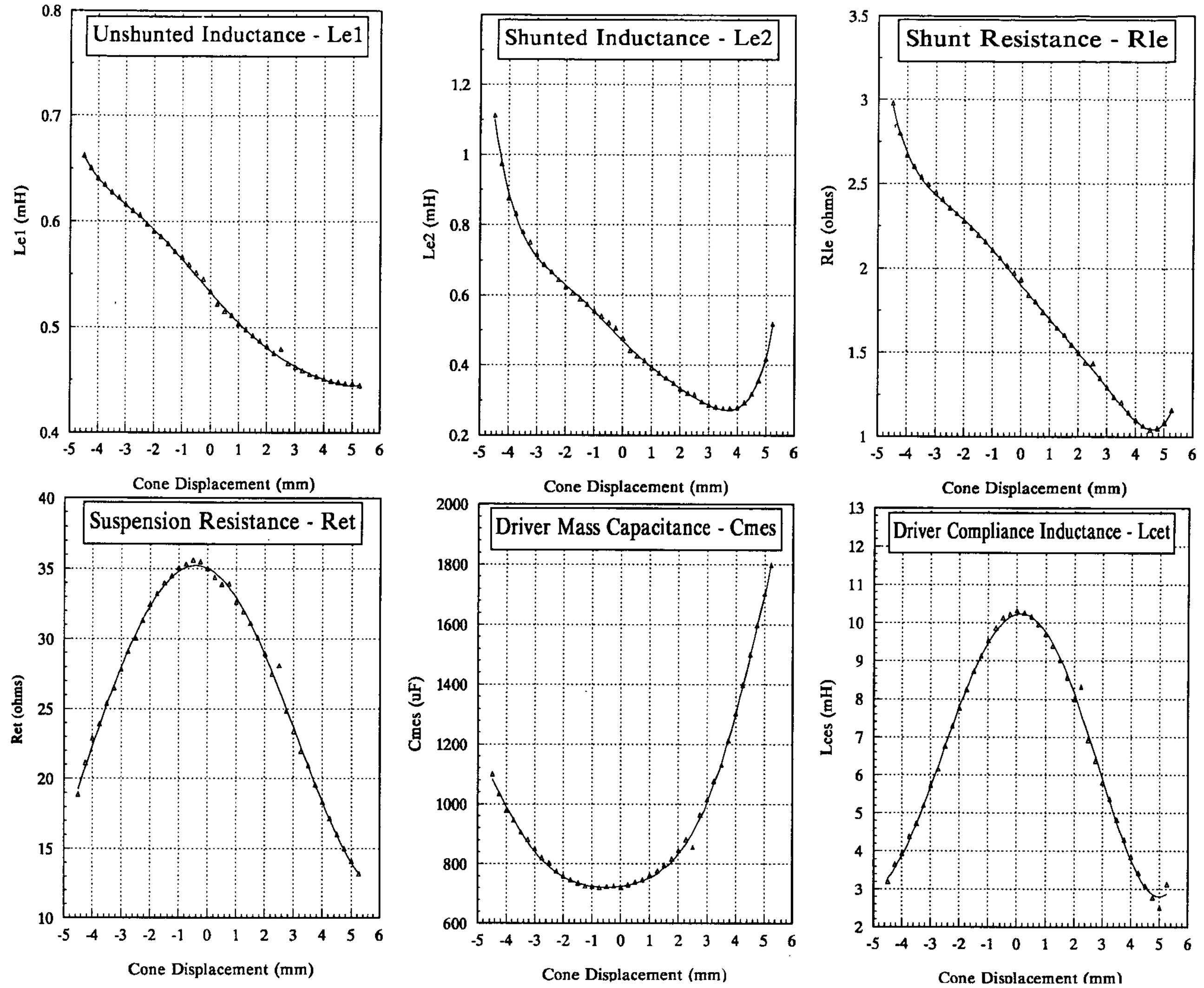

Fig. 5. Plots of nonlinear parameters extracted for 831921 driver. L_{e1}, L_{e2}, R_{Le}, R_{et}, C_{mes}, and L_{cet} versus cone displacement. Note that R_{et} and L_{cet} are box-modified equivalent parameters.

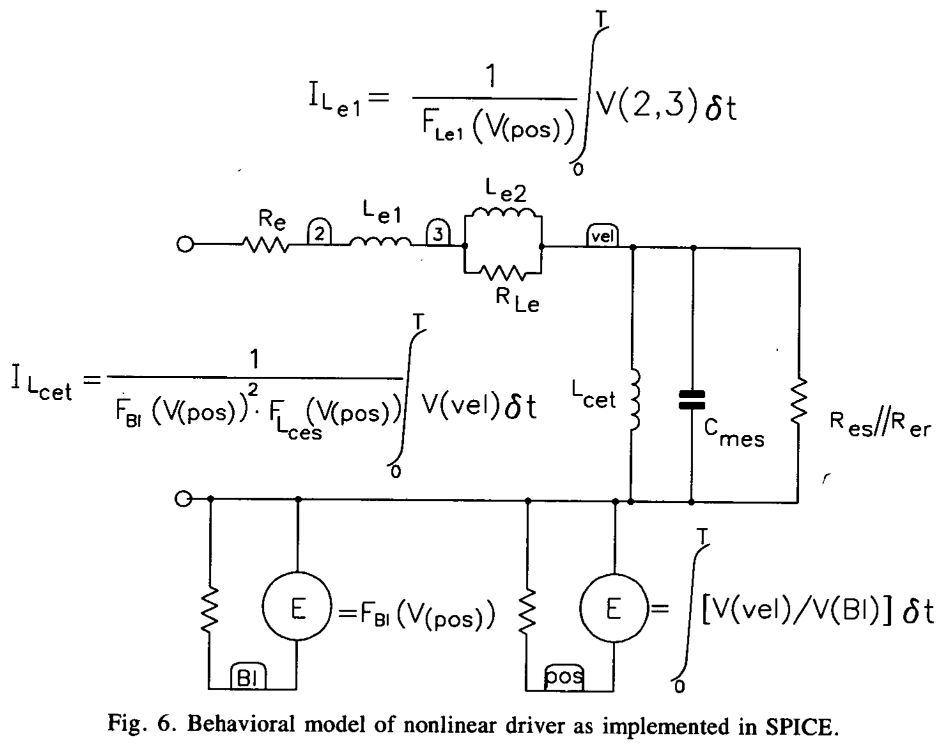

Fig. 6. Behavioral model of nonlinear driver as implemented in SPICE.

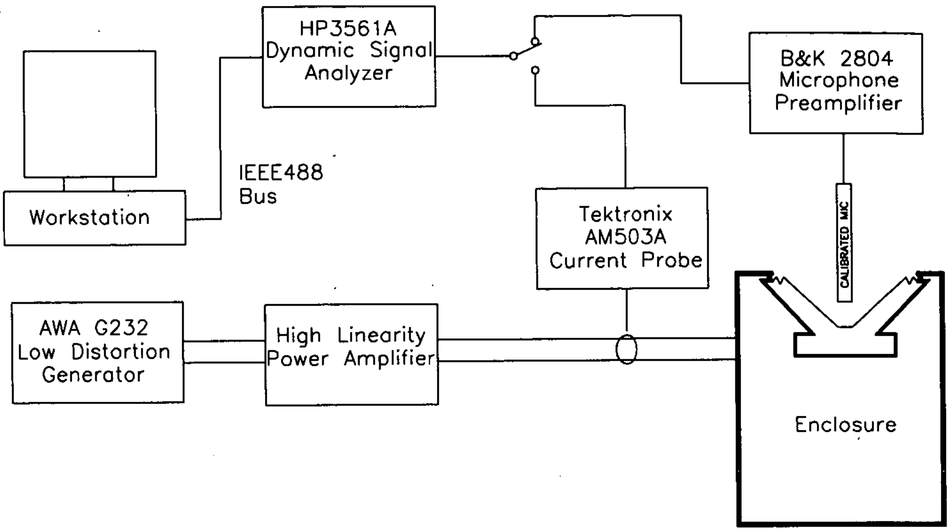

Fig. 7. Block diagram of equipment setup for measuring driver acoustic and current distortion.

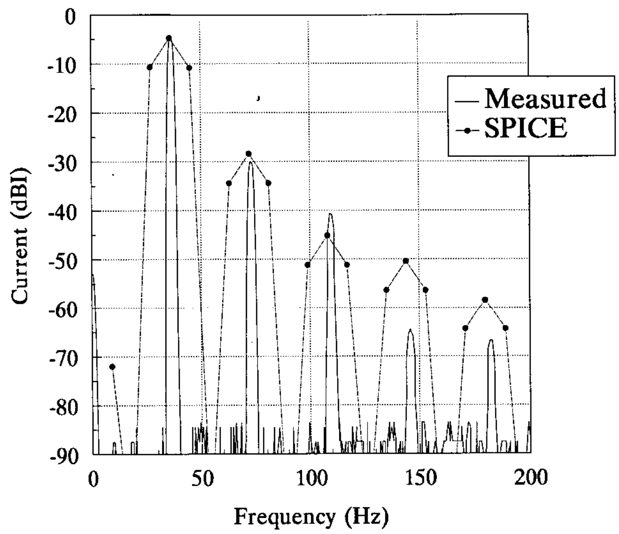

Fig. 8. Comparison of predicted and measured driver-current distortion at 36 Hz, +10 dBV input.

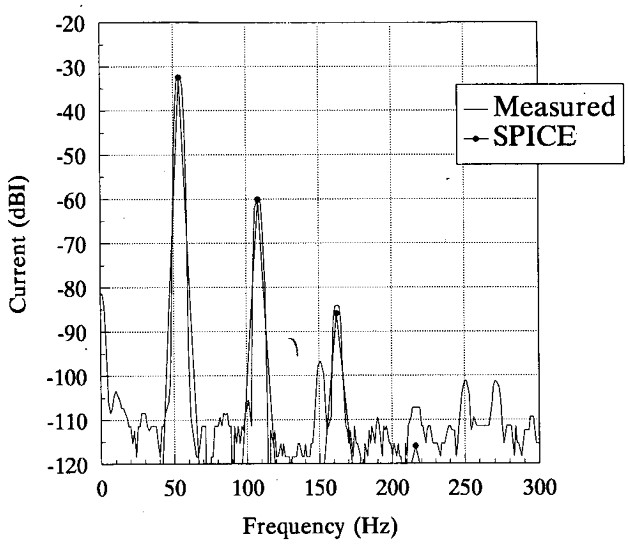

Fig. 9. Comparison of predicted and measured driver-current distortion at 54 Hz, −5 dBV input.

Table 1. Predicted and measured SPL total harmonic distortion.

Frequency	Level	Predicted	Measured
36 Hz	−5 dBV	−23 dB	−26 dB
54 Hz	+10 dBV	−29 dB	−31 dB

Table 2. Predicted and measured driver-current total harmonic distortion.

Frequency	Level	Predicted	Measured
36 Hz	+10 dBV	−24 dB	−25 dB
36 Hz	−5 dBV	−38 dB	−37 dB
36 Hz	−20 dBV	−53 dB	−52 dB
54 Hz	+10 dBV	−13 dB	−13 dB
54 Hz	−5 dBV	−28 dB	−28 dB
238 Hz	+10 dBV	−55 dB	−41 dB
238 Hz	−5 dBV	−63 dB	−44 dB

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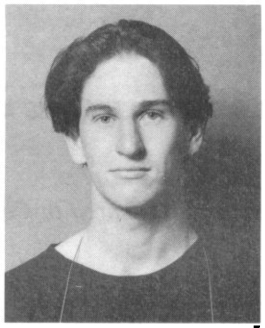
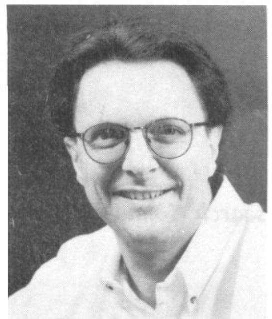


J. Kelly



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He has worked as a consultant in a variety of industries including radar and analog signal processing. Since 1988 he has been the manager of the Sydney Microwave Design Resource Centre, and is a senior lecturer and the electronics coordinator in the Department of Electrical Engineering at the University of Sydney. In 1993 he held a British Telecom Research Fellowship. He received the Electrical Engineering Foundation medal for Excellence in Teaching in 1994.

Since 1994 he has been working with Hewlett-Packard Systems Division in Santa Rosa and Macquarie University in Sydney on nonlinear measurement and modeling of GaAs FET devices. In 1995 he was a visitor at University College, London, and a guest lecturer at the University of Western Sydney. He is currently a visiting fellow at Macquarie University. He is a member of the Institute of Electrical and Electronics Engineers (IEEE), the Audio Engineering Society (AES), and the Institute of Radio and Electronics Engineers (IREE).

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Jonathan Kelly was born in Sydney in 1971 and went to school at James Ruse Agricultural College. He was awarded a Chancellor's Scholarship in Engineering at the University of Sydney. He graduated with First Class Honours in electrical engineering from the University of Sydney in 1995, and was awarded the Metal Manufacturer's Prize for outstanding thesis work. He works with the communications theory group at Sydney University on wideband channel modeling of microcellular systems. In his spare time he designs electronics for racing motorcycles.

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Glenn Leembruggen was born in Sydney in 1955, and received a B.E. from Sydney University in electrical engineering in 1977. After six years of designing audio test instrumentation for AWA, he cofounded Elecoustics Pty Ltd in 1983, and is its director and chief engineer. Elecoustics is a firm of consulting engineers, specializing in the design of loudspeakers, sound systems, and acoustics related to speech and music. In 1993 and 1995, the company received Achievement Awards from the AES for their sound system designs for the upper and lower Houses in the Australian Parliament and the High Court of Australia. On three recent occasions, Elecoustics-designed hi-fi loudspeakers won Loudspeaker of the Year awards from the Australian body CESA.

Mr. Leembruggen is a member of the AES and the Australian Acoustical Society and is currently lecturing at Sydney University on loudspeaker design. Among his interests are playing saxophone and clarinet and local issues of conservation and planning.