Precision Measurement of Loudspeaker Parameters

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ABSTRACT

A body of techniques for the accurate and repeatable measurement of loudspeaker drive-unit electro-mechanical parameters is presented. Pneumatic pressure is used to move the diaphragm in order for position dependent parameters to be measured over the full excursion range.

0 INTRODUCTION

Computer models of loudspeaker systems are widely used to predict performance in order to reduce expensive cut and try iterations. These models require a set of parameters describing the drive-unit, the enclosure and the passive electrical components. Parameters of moving-coil drive-units are conventionally derived from impedance measurements using small amplitude test signals with and without an added mass or test volume. [1-5] It has been found that the different techniques used to measure parameters can give unacceptably high variance in parameter values. In other words, two measurement methods may end up predicting two substantially different enclosure designs as being the optimum for the same drive-unit.

Performance prediction accuracy also suffers from measuring only at rest-position. This amounts to an assumption that the drive-unit is a linear device. Measurements show that normal operation of a loudspeaker commonly results in cone excursion to positions where parameters change by 2 to 1 or more. Several more recent investigations have dealt with this problem. [6-11]

This paper describes a practical measurement system which deals with the amplitude and position dependencies of real drive-units. This system differs from previous approaches by combining the following techniques: 1, The diaphragm is moved through its practical range of excursion by pneumatic pressure. 2, Position-dependent characteristics such as force factor and suspension stiffness are isolated and measured over the excursion range. 3, Basic electro-mechanical parameters of the drive-unit as a driven mass-spring-damper system are measured as directly as possible. 4, Suspension characteristics are measured under conditions which simulate normal operation, thereby capturing the influence of creep, aerodynamic drag and other second-order characteristics which are not measured separately at present.

The data obtained from the measurement system is a set of electro-mechanical (E-M) parameters, two of which are presently shown as a function of excursion (x). At any given diaphragm position, the data may be mapped to conventional Thiele-Small parameters for analysis and system synthesis using the T-S model. Full use of the position dependent data, however, requires a non-linear model based on E-M parameters. This model promises prediction of distortion and frequency response change as the excursion limit is approached.

1 USE AND MEASUREMENT CONDITIONS

Drive-units are most commonly approximated by a linear model such as the Thiele-Small model. [2-5] Parameters are usually derived from measurements made at the lowest practical amplitude which is consistent with using a linear model. A problem can arise from straightforward application of this principle, however. Suspension material properties such as "stiction" may require motion approximating that which is found in service in order to exhibit their "effective" value. This is akin to the requirement of dither in a digitization process. In practice, accuracy may be improved by adding an "exercise" signal to the low-amplitude probe signal or, in some cases, by increasing the probe signal to provide its own exercise.

Consider the 165 mm moving-coil woofer with free-air resonance frequency plotted as a function of sine-wave measurement amplitude in Fig. 1. Resonance is shown to vary from 42 Hz to 73 Hz when measured over a range of test amplitudes. If the resonance shift is due solely to a change in compliance (a reasonable assumption given that the only other potential variable is the moving mass) the resulting effect on the Theile-Small parameters is shown in the table accompanying Fig. 1. The low-resonance parameters (high test amplitude) suggest using this driver in a 20 liter vented-box while the high-resonance parameters (low test amplitude) suggest a large sealed box!

It is tempting to dismiss further investigation by stating that such a non-linear drive-unit is unworthy of our consideration. Unfortunately, all drive-units measured to date, by the author, show some degree of this variation. Also, when the role of compliance non-linearity is more fully understood, it is found that it often plays a minor role in system performance. In other words, compliance variation may hopelessly distort the model without distorting the sound.

Measurements of another drive-unit show the error in assuming that the drive-unit is linear with regard to displacement. Figure 2 shows a time record of the excursion of a sealed-box woofer playing music program material. Power input was within the manufacturer's recommendation and excessive distortion was not heard. Peaks of $\pm$ 5 mm are seen, which can be considered to be quite ordinary. Figures 3 and 4 plot the measured motor force factor (Bl) and the suspension spring constant (Kms) as a function of excursion for the unenclosed driver. A 2 to 1 variation in force factor and a 4 to 1 variation in suspension compliance are observed over the $\pm$ 5 mm excursion range. The meaning of this is that under operational conditions, a high-quality drive-unit may undergo dramatic variations in key parameters on a continuous basis. Clearly, parameters evaluated at only rest-position values do not adequately describe the drive-unit in normal operation.

Variation of force factor over the excursion range is considered here to be the non-linearity of primary importance. It is well known that a moving-coil direct radiator loudspeaker may have a wide range of flat response. That is, for a constant voltage input the acoustic output is proportional and independent of frequency. Assuming that the radiating surface is small with respect to the wavelength, constant acceleration of the radiator over the range frequencies is required. Assuming that air load variations and suspension stiffness are insignificant compared to the moving mass load, the driving force must be constant with frequency by Newton's claim that acceleration is equal to force divided by mass. The force produced by a moving-coil motor is equal to Bl*i. That is, force is the product of magnetic field strength (B), length of wire in the field (l), and the current flowing in the wire (i). In the range of flat response, voice-coil impedance is nearly constant or resistive. Current, then, is nearly proportional to voltage. This satisfies the condition for flat response; a mass accelerated by a frequency-independent force. Within this important range of flat response, the only factor which is clearly position dependent is Bl, the interaction of the coil and the magnetic field.

At and below a direct radiator's primary resonance frequency, suspension stiffness becomes equal to and surpasses the mass reaction to the driving force. While this is below the "flat" frequency range, it is important to downward response extension and the transition from flat to roll-off. Thus, suspension stiffness variations with position become important below the "flat" range. Diaphragm excursion is highest in this range making the importance of suspension linearity second only to force factor linearity.

However, in the Thiele-Small model suspension linearity becomes critically important because four of the five T-S parameters contain suspension stiffness as a factor in their definition. If the suspension non-linearity results in a poor estimate of its average or effective value, the entire model will be in error. The electro-mechanical model, on the other hand, isolates suspension compliance maintaining accuracy of the other parameters. The E-M model may also be extended to handle non-linearity data.

Other physical and electrical characteristics of a drive-unit which are position dependent are mechanical damping, inductance and semi-inductance. [12] For many practical designs, these are less influential than force factor and suspension stiffness variations. Still others include creep and thixotropy. [13] Aerodynamic and fluid damping losses may be velocity dependent as well as position dependent. These factors are certain to be increasingly incorporated into future models as their measurement becomes practical.

2 PARAMETER CONVERSION

While Thiele and Small used many measured properties of drive-units in their analysis and synthesis of systems, only a small number of combined properties constitute the T-S parameters in general use. These are:

f_S Free air resonance frequency of the drive-unit (Hz)
V_{AS} Equivalent acoustic volume of the suspension (m^3)
Q_{ES} Electrical Q of the drive-unit (no units)
Q_{MS} Mechanical Q of the drive-unit (no units)
R_E Resistance of the voice-coil (ohms)

If we add one additional simple measurement, that of diaphragm area (S_D), these T-S parameters may be mapped to a set of electro-mechanical parameters and vice-versa. It is necessary for the two Q values to remain separated and not combined into a total Q (Qt).

The minimum set of electro-mechanical parameters is:

M_{MD} Moving mass of the diaphragm (kg)
C_{MS} Suspension mechanical compliance (m/N)
R_{MS} Mechanical resistance (Ns/m)
Bl Motor force factor (N/A)
R_E Resistance of the voice-coil (ohms)
S_D Diaphragm area (m^2)

The mapping procedure is straightforward as long as mass is expressed in kilo-grams (kg), force is expressed in Newtons (N) and dimensions in meters (m), square meters (m^2) etc. First, note that R_E and S_D are exactly the same for each set. Next, the air mass load (M_{M1}) for both sides of an unbaffled drive-unit (free-air) is calculated [1 p. 230]. This is added to M_{MD} in T-S parameter calculations. Also, it is useful to calculate the angular free-air resonance frequency (ω_S). The constants for velocity of sound (c) and density of air (ρ_0) are also needed.

To map to T-S from E-M

Define constants:

$$c = 345 \text{ m/s}$$

$$\rho_0 = 1.18 \text{ kg/m}^3$$

Preliminary calculations:

$$M_{M1} = (2.67)\, \rho_0\, (S_D/\pi)^{3/2}$$

$$\omega_S = 1 / [(M_{MD} + M_{M1})\, (C_{MS})]^{1/2}$$

Then:

$$f_S = \omega_S / 2\pi$$

$$V_{AS} = \rho_0 c^2 S_D^2 C_{MS}$$

$$Q_{ES} = (\omega_S M_{MD} R_E) / (Bl)^2$$

$$Q_{MS} = 1 / (\omega_S C_{MS} R_{MS})$$

$$R_E = R_E$$

$$S_D = S_D$$

To map to E-M from T-S

Define constants:

$$c = 345 \text{ m/s}$$

$$\rho_0 = 1.18 \text{ kg/m}^3$$

Preliminary calculations:

$$M_{MI} = (2.67)\, \rho_0 (S_D / \pi)^{3/2}$$

$$\omega_S = 1 / [(M_{MD} + M_{MI})(C_{MS})]^{1/2}$$

Then:

$$M_{MD} = (S_D^{\ 2} \rho_0 c^2) / (\omega_S^{\ 2} Vas) - M_{MI}$$

$$C_{MS} = V_{AS} / (S_D^2 \rho_0 c^2)$$

$$R_{MS} = (S_D^2 \rho_0 c^2) / (Q_{MS} V_{AS} \omega_S)$$

$$Bl = [(S_D^2 \rho_0 c^2) / (V_{AS} Q_{ES} \omega_S)]^{1/2}$$

$$R_E = R_E$$

$$S_D = S_D$$

Since we can map from E-M to T-S, we are free to measure E-M parameters for use in a T-S model. One reason for doing this is because we may have greater confidence in the accuracy of the measurement of the E-M parameters. For instance, Bl may be simply and accurately calculated from the force on the diaphragm produced by a steady current. It may be preferable to use the T-S model for prediction because it is familiar or because of its general availability.

However, many will prefer to use the E-M parameters directly in an electro-mechanical model. One advantage is that the non-linearity of a parameter such as suspension compliance can be easily included enabling distortion prediction. Another advantage is that improvements to a drive-unit are more easily communicated in the electro-mechanical domain. For instance, a requirement for higher sensitivity immediately suggests a higher force factor (Bl) and a lower diaphragm mass (M_{MD}). In the Thiele-Small domain, a low Q_{ES} may be the dominant factor. However, Q_{ES} can be lowered by lowering F_S with a more compliant suspension which will have no effect on passband sensitivity.

3 MEASUREMENT SYSTEM COMPONENTS

The parameter measurement system described here consists of the following components:

Test chamber of 0.21 m^3 which rotates 180^0
Laser position transducer with voltage output
Chamber pressure transducer with voltage output
Microphone inside test chamber and preamp
Known non-magnetic mass
Pressure source, voltage controlled
Current-source amplifier with remote sense
Application specific electronic functions
Microsoft Windows computer
Data acquisition and control card
Measurement software
Analysis software
Prediction software

The components, except for the computer, are housed in a workstation as shown in Fig. 5. The system is intentionally partitioned into a general purpose "drive-unit laboratory" suitable for manual experimentation and the software control for performing repeated standard measurements. Interface is an input/output box with BNC connectors for external instruments and a parallel connection to the computer's data acquisition board. After a new procedure is developed manually, the software can be updated for a new standard measurement.

The test chamber is a shallow cylinder which provides a large volume of air with a short distance to the nearest reflecting surface. This allows a simple air load assumption to be made to a reasonably high frequency. A sub-chamber of one-half the linear dimension allows the assumption to extend an octave higher for high-resonance speakers. An assortment of baffle sizes allows drive-units of up to 457 mm (18 inch) nominal diameter to be mounted.

The test chamber rotates 180^0 to allow gravity to act on the moving mass forcing it towards or away from the magnet and allowing moving mass and force factor to be determined. It was initially found that the deflection of the structure of the test chamber and mounting board produced error in this measurement. This was corrected by employing a rigid measuring frame encircling the drive-unit, but mechanically isolated from the test chamber. It provides mounting for a rear position transducer to monitor the magnet position of the unit under test as well as locating the diaphragm position measurement transducer in front, Fig. 6. As the chamber flexes, the two position readings are subtracted, canceling the error due to test chamber flex. Measurement resolution to 10 micro-meter is achieved in practice.

The application specific electronics and power amplifier are housed in the workstation. All transducer inputs are signal conditioned, calibrated and amplified to a nominal ± 10 volt range suitable for the data acquisition card. Amplifier current and voltage at the drive-unit are sensed and signal conditioned in a similar manner. Analog input signals are required to be within the ± 10 volt range. Digital control signals are 0 to 5 volt. Front panel LED's offer approximate metering for setup and indicate various out of range conditions. It is expected that precise measurements will always be made with external instruments or the data acquisition card.

Special functions, such as those required for the self-oscillation method of resonance frequency measurement, are contained within the electronics package. Thus, no basic measurement function depends on the computer.

The data acquisition and control software is written in a Microsoft Windows virtual instrument environment. The user selects a measurement and dialogues with the software to set parameters and collect data. The display contains virtual controls, analogue meters, waveform displays and alpha-numeric readouts. Repetitive aspects of a measurement may be automatically sequenced by the software and automatically downloaded into the analysis program.

The analysis program is written in a Microsoft Windows spreadsheet and accepts data either manually or by dynamic data exchange which is a Microsoft Windows function. This program converts the data into E-M and T-S parameters and plots force factor and suspension stiffness as functions of position. It also performs a polynomial curve fit to the non-linear data to obtain the non-linearity coefficients for distortion prediction. A drive-unit report is produced which may be printed out or filed as a data base record.

The prediction program is SPEAK for Windows, written by Earl R. Geddes. The graphical user interface is Visual Basic for Windows. Number crunching is performed in compiled Fortran 90 which is transparently accessed as a dynamic link library. This program is written to use the E-M parameters as effectively as possible for performance prediction. It also contains a distortion prediction capability which uses the non-linearity coefficients as input.

The basic product development cycle may start with a "what if" design in the prediction program. The drive-unit specifications including linearity requirements are generated and submitted for sample building. The samples are measured and the parameters are entered into the prediction program to determine the effect of any changes. Practical optimization of the drive-unit can begin through iteration of drive-unit parameters, crossover components and cabinet design. When the optimum drive-unit has been obtained, a physical system is built and measured. Experience has shown good confirmation of prediction by measured performance.

4 MEASUREMENT SYSTEM FUNCTIONS

Symbols and abbreviations:

g acceleration due to gravity. 9.8 m / s^2
p test chamber pressure re. atmospheric. N / m^2
x diaphragm displacement from rest position. Away from magnet is positive.

Measurement functions:

current-source Power amplifier with current output independent of load.

p-servo to x Displacement of diaphragm to a specified axial position, x by regulation of pressure in the test chamber.

p-servo to p Regulation of chamber pressure to a specified value.

mag-servo to x Displacement of diaphragm to a specified axial position, x by regulation of current in the voice-coil.

rotate Rotation of test chamber to allow gravity to act on diaphragm.

f_S oscillation Resonance frequency. The f_S oscillation mode differentiates the output of the position transducer obtaining diaphragm velocity. This signal is fed via a voltage-controlled amplifier to a current-source power amplifier connected to the drive-unit voice-coil such as to produce positive feedback and oscillation at the drive-unit's resonance frequency. The oscillation amplitude is stabilized by the voltage-controlled amplifier to a setable constant excursion amplitude. Resonance frequency is measured with a frequency counter.

probe tone A sine wave applied to the voice-coil at moderate amplitude by a current-source amplifier. Acoustic output is picked up by a microphone inside the test chamber.

chamber speaker A small, high-resonance sealed-box speaker system located inside the test chamber. It is used to produce a flat pressure response inside the chamber to be picked up by the drive-unit under test or by an external microphone.

5 METHODS

1.0 **Break-in**. A break-in process is recommended. Drive-unit storage may cause the diaphragm suspension to drift away from its normal or in-use position. Break-in, with the drive-unit axis in the in-use orientation (usually horizontal), restores the normal diaphragm position. The recommended procedure pneumatically stretches the suspension to one excursion extreme then the other and continues to alternate decreasing the excursion each time until x is at zero. This process can be completed in less than one minute.

1.1 **Pneumatic.**

1 Select p-servo to x mode.
2 Set x = 0 mm (p will = 0)
3 Set x = 1mm, note P(+1 mm)
4 Increment x until the 1 mm p change is 4 times $p_{(+1mm)}$
5 Repeat for - direction
6 Alternate between + and -, decrementing by 1 mm until x = 0
7 Recalibrate x = 0 at new rest position

2.0 **$Bl_{(0)}$, Force Factor at rest position**. With the drive-unit axis vertical up, a known mass (M) is carefully added to the diaphragm while increasing current such that the diaphragm is not deflected. The steady current required to support the mass is recorded, allowing Bl to be calculated from $Bl = F / I$. $F = g*M$. $g = 9.8\ m/s^2$

2.1 **Force balance.**

1 Rotate test chamber axis to vertical up
2 Select mag-servo to x mode
3 Set x = 0 mm, note amplifier current, $I_{(0)}$
4 Slowly add mass allowing servo to maintain x = 0, note $I_{(mass)}$
5 Calculate $Bl = F / (I_{(mass)} - I_{(0)})$

3.0 **$Bl_{(x)}$, Force Factor over Excursion**. The preferred method applies a moderate-amplitude probe tone in the mass-controlled frequency range to the voice-coil from a current source and observes relative acoustic output over the excursion range. [7] Acoustic output is closely proportional to Bl under these conditions. A current source is used to avoid the influence of changing voice-coil inductance. The relative Bl thus obtained is calibrated at the x = 0 position by the results of the previous procedure.

This method is relatively free from influence of suspension creep, stiction, thixotrophy and non-linear stiffness. One must use care at extreme conditions of the suspension, however. If the resonance is shifted upward in frequency such that it approaches the probe tone frequency (commonly 350 Hz), an increase in acoustic output no longer indicates higher Bl. Also, under extreme stress conditions, the diaphragm may be deformed and alter the acoustic output independently of Bl. The alternate force balance method suggested may extend the excursion range of Bl measurement in these cases although with some loss of accuracy. $Bl = F / I$. $F = g^*M$. $g = 9.8\ m/s^2$.

If possible, the diaphragm should be taken to the extremes of excursion allowed by the suspension for Bl measurement. For completeness, this should result in a Bl reduction of at least 50% of the rest-position value.

3.1 **Probe Tone.**

1 Select p-servo to x mode.
2 Set x = 0 mm
3 Set probe tone from current source to produce 100% set level
3 Increment x over excursion range. Note amplitude %
4 For each x, multiply $Bl_{(0)}$ by % for Bl(x)

3.2 **Force Balance.**

1 Rotate test chamber axis to vertical up
2 Select p-servo to p mode.
3 Select mag-servo to x mode
4 Set p = 0
5 Set x = 0 mm, note amplifier current, $I_{(0)}$
6 Slowly add mass allowing servo to maintain x = 0, note $I_{(mass)}$
7 Calculate $Bl = F / (I_{(mass)} - I_{(0)})$, $F = g^*M$
8 Increment x to next value chosen
9 Increase p to produce I close to 0 mA. Let system stabilize
10 Repeat steps 5,6 & 7 for this x
11 Repeat steps 8,9 & 10 for entire range of x

4.0 **M_{MD}, Moving Mass of Diaphragm.** Diaphragm mass is assumed to be constant over x in this analysis. The most accurate way to determine diaphragm mass is to cut it out of the drive-unit and weigh it. Half of the spider, half of the surround and half of the lead out wires should be included. Of course, this method destroys the drive-unit.

The preferred non-destructive method for determining M_{MD} is to use the drive-unit's magnetic force to balance the force of gravity acting on M_{MD} . The key to accuracy in this measurement is to avoid displacing the suspension while changing its orientation in the gravitational field. The diaphragm tends to fail to return to its original position when displaced and released. Accuracy also requires that the measurement of relative position of diaphragm to drive-unit basket be of high resolution. With the existing equipment the method is accurate for drive-units with resonance below about 70 Hz.

A second method is to measure resonance frequency before and after the addition of a mass, M^1. The shift downward in frequency allows M_{MD} to be calculated without knowing the suspension stiffness, only assuming that it remains constant. With the conventional "added mass" method for determining Thiele-Small parameters, the act of adding the mass, even to a horizontal-axis drive-unit, displaces the non-linear suspension to a new stiffness value. The new stiffness value results in error in the M_{MD} calculation. With the present equipment, the mass may be added without displacing the suspension.

4.1 **Gravitational Force Balance.**

1 Rotate test chamber axis to vertical upward
2 Select mag-servo to x mode
3 Set $x = 0$. Note amplifier current
4 Rotate test chamber axis to vertical downward. Note amplifier current.
5 Calculate force of gravity on diaphragm. $F = 0.5\ Bl\ (I_{up} - I_{down})$
6 Calculate $M_{MD} = F / g$. $g = 9.8\ m/s^2$

4.2 **Added Mass**

1 Rotate test chamber axis to vertical upward
2 Select mag-servo to x mode
3 Set $x = 0$
4 Select f_S oscillation mode. Note frequency
5 Slowly add M^1 allowing servo to maintain $x = 0$. Note frequency
6 Calculate $M_{MD} = M^1 / [1 - (f_S / f_S^1)^2]$

5.0 **C_{MS}, Suspension Mechanical Compliance.** Suspension compliance is the least well-behaved of the E-M parameters. That is, it seldom behaves like a simple spring. The approach of the preferred measurement method is to simulate in-use conditions by exercising the suspension dynamically while it is being measured to include non-linear and time-dependent factors. A better way would be to use a more complete model, but it is not at all certain that a more complex model would result in significantly more accurate performance prediction.

The "exercising" of the suspension comes from the excursion of the f_S oscillation. This is regulated to 0.1 of x_{max} by the voltage-controlled amplifier. The value of x_{max} is taken here to be the smaller of: 1, half of the peak to peak excursion over which the Bl retains 70.7% of its rest-position value, or 2, half of the peak to peak excursion over which the C_{MS} retains 25% of its rest-position value. That is, x_{max} may be determined by either force factor non-linearity or suspension non-linearity.

C_{MS} is calculated from test chamber resonance frequency and M_{MD}. The basic formula is: $C_M = 1 / [(2\pi f)^2 M_M]$. To be accurate, this requires that the chamber air compliance, the front air load and the chamber mass load be accounted for. This is covered in Beranek [1] p. 217 to 219 and p. 230. Current-source drive is used to eliminate the effect of voice-coil inductance on measurement of resonance frequency.

Five other methods are suitable for drive-units which have noisy or unstable f_S oscillations. This can be caused by high mechanical damping, low force factor or a resonance above 200 Hz or so using the current equipment. Fortunately, most woofer and full-range drive-units can be made to self-oscillate near their rest position where the suspension is most compliant. This is the excursion range in which it is most important to "exercise" the suspension for accurate measurements.

At greater displacements, the suspension typically stiffens and the importance of the "not well behaved" factors becomes insignificant. Any of the other methods may be substituted for measurement of this outer range. Note that the number 5.6 method, acoustic transmission, requires no connection to the voice-coil. Thus, C_{MS} may be measured for a drive-unit with the coil entirely out of the gap and consequently having no Bl at this position. Technicians in the speaker repair business know that, voice-coils do indeed find their way into such locations. Knowledge of parameters in this area may allow improving reliability at the design stage. It is desirable to measure C_{MS} to + and - positions of reduction to 20% of the rest-position value.

Figure 7 shows C_{MS} measurements on one drive-unit made with all six techniques. The particular drive-unit has a suspension travel much longer than the coil overhang. The f_S oscillation technique, shown by the heavier line, only worked for the -6 mm to +8 mm range because of Bl falloff beyond this. Any of the alternate methods extends this to $\pm$10 mm with acceptable accuracy.

5.1 **f_S Oscillation**

1 Select p-servo to x mode
2 Select f_S oscillation mode
3 Set x = 0
4 Set peak of oscillation displacement = 0.1 x_{max}. Note frequency.
5 Increment x over excursion range. Note each frequency.
6 Calculate C_{MS} at each x

5.2 **Impedance Curve**

1 Select p-servo to x mode
2 Set x = 0
3 Plot impedance curve. Note resonance frequency
4 Increment x over excursion range. Plot impedance, note resonance
5 Calculate C_{MS} at each x

5.3 **Acoustic Maximum**

1 Select p-servo to x mode
2 Set x = 0
3 Apply current source response test signal to drive-unit
4 Measure amplitude response with near field microphone
5 Integrate amplitude response curve
6 Note frequency of response peak at resonance
7 Increment x over excursion range repeating 4,5 & 6
8 Calculate C_{MS} at each x

5.4 **Mechanical Maximum**

1 Select p-servo to x mode
2 Set x = 0
3 Apply current source response test signal to drive-unit
4 Measure displacement response
5 Differentiate displacement response
6 Note frequency of response peak at resonance
7 Increment x over excursion range repeating 4,5 & 6
8 Calculate C_{MS} at each x

5.5 **Voice-coil Maximum**

1 Select p-servo to x mode
2 Set x = 0
3 Apply random signal to chamber speaker
4 Measure transfer function using voice-coil as generator
5 Note frequency of maximum transmission at resonance
6 Increment x over excursion range repeating 4 & 5
7 Calculate C_{MS} at each x

5.6 **Acoustic Transmission**

1 Select p-servo to x mode
2 Set x = 0
3 Apply random signal to speaker inside test chamber
4 Measure transfer function to near-field microphone
5 Note frequency of maximum transmission at resonance
6 Increment x over excursion range repeating 4 & 5
7 Calculate C_{MS} at each x

6.0 **R_{MS}, Mechanical Resistance.** Mechanical resistance is assumed to be a velocity-dependent resistance at the present level of the E-M model. The observed failure of a diaphragm to return to it's original position after being displaced and released, however, indicates the presence of some degree of friction or plastic deformation. As with the C_{MS} measurement, a dynamic "exercising" of the suspension is used to lump all resistances in a manner relating to in-use conditions. For the most common speakers, those with little mechanical damping compared to electrical damping, the assumptions are justified by the fact that large variations in R_{MS} have little effect on loudspeaker performance.

Aerodynamic drag within the drive-unit will also show up as mechanical resistance. This resistance is known to be a non-linear function of velocity. For certain drive-units which are intentionally damped by restricting air flow, it may be advisable to measure RMS as both a function of diaphragm position and velocity.

The preferred method for measuring R_{MS} is based on measuring the magnitude of the voice-coil impedance at resonance. [14] All of the conditions for accomplishing this are present when C_{MS} is measured by the preferred f_S oscillation or by impedance curve methods. In addition, damping may be estimated from the bandwidth of any of the curves generated by the various methods of determining C_{MS}.

6.1 **f_S Oscillation**

1 Select p-servo to x mode
2 Select f_S oscillation mode
3 Set $x = 0$
4 Set peak of oscillation displacement = $0.1\ x_{max}$. Note Z_{max}
5 Increment x over excursion range. Note Z_{max}
6 Calculate R_{MS} at each x. $R_{MS} = (Bl)^2 / (Z_{max}-R_E)$

6.2 **Impedance Peak**

1 Select p-servo to x mode
2 Set $x = 0$
3 Plot impedance curve. Note Z_{max}
4 Increment x over excursion range. Note Z_{max}
5 Calculate R_{MS} at each x. $R_{MS} = (Bl)^2 / (Z_{max}-R_E)$

7.0 **R_E, Voice-coil Resistance.** Accurate measurement of voice-coil resistance is important to prediction accuracy. A simple digital multimeter may be used if it has resolution to 0.01 ohm and if the operator insures a good connection to the drive-unit. It is also necessary to "zero out" the resistance in the test leads. The preferred method is more complicated, but accuracy is assured.

The preferred method uses a pair of wires to conduct current through the voice-coil and a second pair to monitor the voltage drop across the coil. The present technique is to use a second pair of wires to the voice-coil for remote voltage sense for accuracy in all tests. This feature allows monitoring the voltage and current of any DC applied to the voice-coil.

7.1 **Resistance:** $R_E = V_{VC} / I_{VC}$.

8.0 **S_D, Projected Area of Diaphragm.** The preferred method is to measure diaphragm diameter including 1/3 of the surround or outer suspension on each side. From this S_D is calculated. This can be applied to oval speakers by placing the drive-unit face down on a copier and copying onto square grid paper. The number of the squares more than 50% inside the 1/3 surround line times the area of a square equals S_D. A second method, force/pressure, may be useful for diaphragms of unusual shape or of questionable rigidity. A third method is Professor J.R. Ashley's rule of thumb: The effective piston radius in centimeters is equal to the advertised diameter in inches. Use it when all else fails.

8.1 **Effective Diameter:** $S_D = \pi\ (0.5\ D)^2$

8.2 **Force/Pressure**

1 Select p-servo to x mode
2 Set $x = 0$
3 Connect manual input current-source to drive-unit. Set $I = 0$
4 Note pressure, p_0
5 Set $I = I_{test}$. (0.1 to 1.0 amp). Note pressure, p_{test}
6 Calculate $S_D = Bl_{(0)} I_{test} / (p_0 - p_{test})$

6 X PARAMETERS

The preceding measurements provide data points of a Bl versus x function and a C_{MS} versus x function. It is desirable to have a simple interpretation of this information such as a single number for X_{max} , the peak maximum diaphragm displacement. It would be further desirable to express the data in an analytic form for non-linearity prediction of a loudspeaker system.

In the author's experience, a fall off of Bl from the rest position value to below 70.7% (-3 dB) can produce audible amplitude modulation of a higher frequency tone by the low frequency one producing the excursion. Also, a reduction of compliance to below 25% can produce audible bass distortion. It is recognized that the degree of non-linearity in the drive-unit which is permissible depends greatly on the enclosure and other aspects of the system design. This is particularly true for acoustic suspension designs where the linear air spring dominates the compliance. These criteria are only offered as simple, yet improved, criteria for an X_{max} specification.

The positive and negative excursions should be considered separately. The smaller of the Bl or the CMS limit should be used in each direction. Xmax is calculated as 1/2 the sum of the two, even if excursion in one direction is greater than the other.

Additional information could be provided by identifying suspension (CMS) and magnetic (Bl) limits separately:

Xsus = Suspension limited excursion
Xmag = Magnetic limited excursion

For performance prediction, the entire data set of Bl and CMS over the x range may be used as a lookup table. In the current SPEAK for Windows software, second-order polynomial coefficients of a best-fit curve to the data are required. The polynomial is of the form:

$$Bl_{(x)} = Bl_{(0)} (1 + ax + bx^2)$$

Where a and b are the non-linearity coefficients, x is excursion and $Bl_{(0)}$ is rest position Bl.

C_{MS} commonly approaches very small values at the excursion extremes. This results in a curve shape which is not naturally approximated by a second order polynomial (a parabola). For this reason, SPEAK for Windows uses the reciprocal quantity of suspension stiffness (K_{MS}) which receives a better fit from a second-order polynomial. This is of the form:

$K_{MS(x)} = K_{MS(0)} (1 + ax + bx^2)$

Definitions are similar to those of the above example.

Figures 8 and 9 show Bl and KMS as well as a quadratic approximation over the range of ± 5 mm for the 6 X 9 - inch drive-unit discussed previously.

7 DRIVE-UNIT REPORT

At present, a drive-unit report contains the following information:

Date, place, name of measurement technician

Drive-unit manufacturer, model, sample number, description
- Total mass
- Outside diameter, depth
- Magnet height and diameter
- Top plate thickness
- Piston diameter, surround width, cone depth
- Voice-coil diameter

Electro-mechanical rest-position parameters

Thiele-Small rest-position parameters

X parameters
- Xmag, Xsus
- Bl non-linearity coefficients, a and b
- K_{MS} non-linearity coefficients, a and b

Inductance and semi-inductance

On-axis and 30^0 anechoic frequency response

Plot of Bl versus position with quadratic approximation

Plot of CMS and KMS versus position with quadratic approximation

All measured data, measurement methods and test condition data

8 ADDITIONAL TESTS

The measurements described so far may be considered as basic for the purpose of modeling a loudspeaker system. Many other measurements to extend the model or to deal with specific problems are possible with the present equipment. These include:

Inductance versus position
Semi-inductance versus position
Diaphragm acoustic leakage resistance versus position (requires a flow meter)
Flux modulation by voice-coil current versus position
Thermal capacity versus position
Suspension creep, stiction and thixotrophy
Cone flex from pressure
Surround or dome collapse checked over position and pressure
Magnetic fluid stability checked over position and pressure

Although this measurement system was developed primarily to study woofer and full-range moving-coil drive-units, many tests can also be used to characterize mid-ranges, tweeters and passive radiators.

9 USAGE EXAMPLES

The developmental version of the present system has been in use since early 1991 with hundreds of drive-units measured so far. Originally, the testing took several hours per drive-unit. With the present improvements in mechanization and the addition of software data acquisition and control, test time to finished report is about 15 minutes.

An early problem solved with the measurement system was a high percentage of manufactured speakerphone speakers failing to meet a 400 Hz distortion specification. The speaker manufacturer had found a loose correlation between distortion and high resonance frequency but softer suspensions failed to correct the problem. Excursion testing revealed that the position of highest compliance for the high-distortion samples was not at the rest position.

The speaker used a lightly corrugated spider which was initially soft but stiffened quite sharply just off center. The outer suspension was quite linear. After assembly, the two suspensions pulled against each other slightly. This forced the spider into its non-linear region at diaphragm rest position. Forward cone motion further stiffened the spider and rearward motion loosened it. The result was high even-order distortion products. It was found that a sample batch of 25 defective speakers could all be made to meet the specification by offsetting the rest position to the rear by 0.3 mm using pneumatic pressure. The manufacturing solution was to change the gluing fixture to eliminate the rest-position stress.

A second problem was design of an optimized sub-woofer drive-unit for an automobile manufacturer. The speaker was to be a standard 6-inch by 9-inch unit mounted in the rear package shelf with the trunk as an enclosure. It was desired to obtain as much low-frequency output as possible within the constraints of cost, total mass and input power available. With magnet size essentially specified by the low mass and cost constraints, SPEAK for Windows was used to estimate optimum voice-coil overhang and other parameters to maximize excursion. The suspension and mechanical clearances were designed to accommodate this. Samples from the speaker vendors were measured for excursion parameters and the specification refined. After several sample iterations, a design which could produce twice the excursion of the best previous production design from the same maximum input was achieved.

10 CONCLUSION

The drive-unit parameter measuring system described in this paper was developed to meet the needs of the loudspeaker system design engineer. Its precision of measurement does not come from a greater number of significant figures describing unstable parameters. The approach is rather to identify and measure the cause of the non-linearity as well as the parameters. An electro-mechanical model of drive-units is suggested to enable modeling the effects of the non-linearities.

In five years of use and development of the present apparatus, measurement time has been reduced from hours to minutes. The system has been successfully applied to solving many speaker manufacturing and application problems. The most important application has been optimization of real devices to include cost, maximum output, size, distortion and frequency response.

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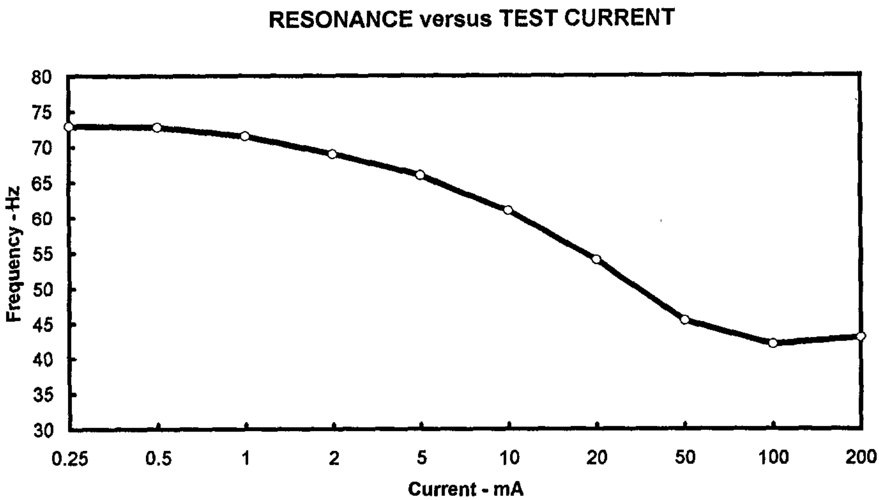

THIELE-SMALL PARAMETERS

LOW CURRENT		HIGH CURRENT	
f_S	73.0 Hz	f_S	42.0 Hz
V_{AS}	0.0085 m^3	V_{AS}	0.026 m^3
Q_{ES}	0.90	Q_{ES}	0.52
Q_{MS}	2.16	Q_{MS}	1.24
R_E	4.87 Ohm	R_E	4.87 Ohm
S_D	0.0133 m^2	S_D	0.0133 m^2

Figure 1. An extreme case of resonance frequency dependence on test signal amplitude is plotted for a 160 mm woofer. The effect on the Thiele-Small parameters for the extremes of resonance is shown in the table assuming that only C_{MS} has changed. The two test current choices are reasonable, but would lead to entirely different system designs. This problem is prevented by exercising the suspension while making the measurement.

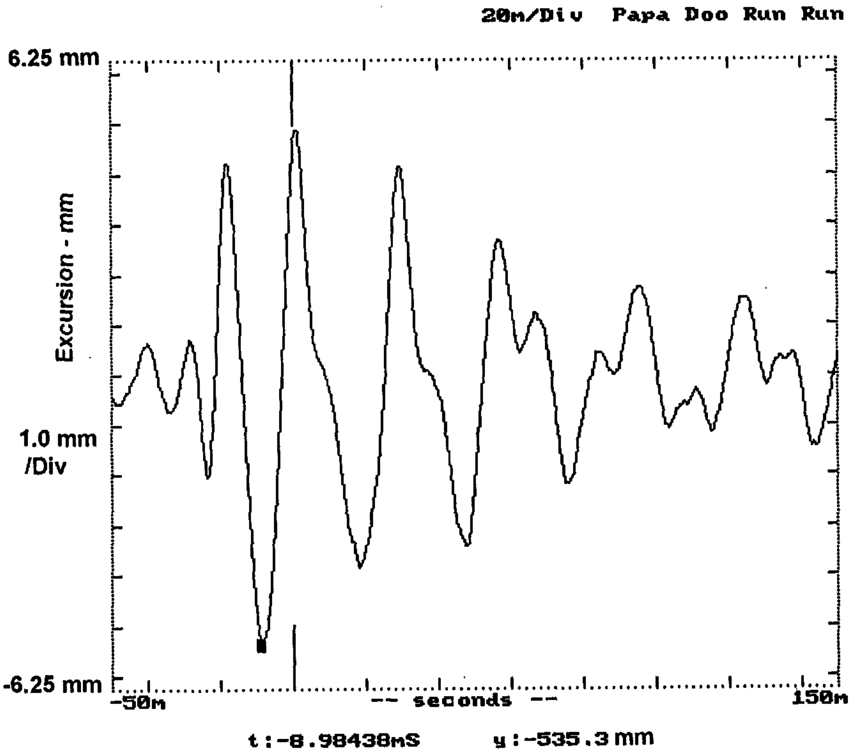

Figure 2. Time record over 200 ms of the excursion of a 160 X 231 mm (6 X 9 inch) automotive woofer in an infinite baffle driven by a music sound source just below clip point of the intended (15 watt) amplifier. Excursion to ± 5 mm was repeatedly observed with moderate audible distortion.

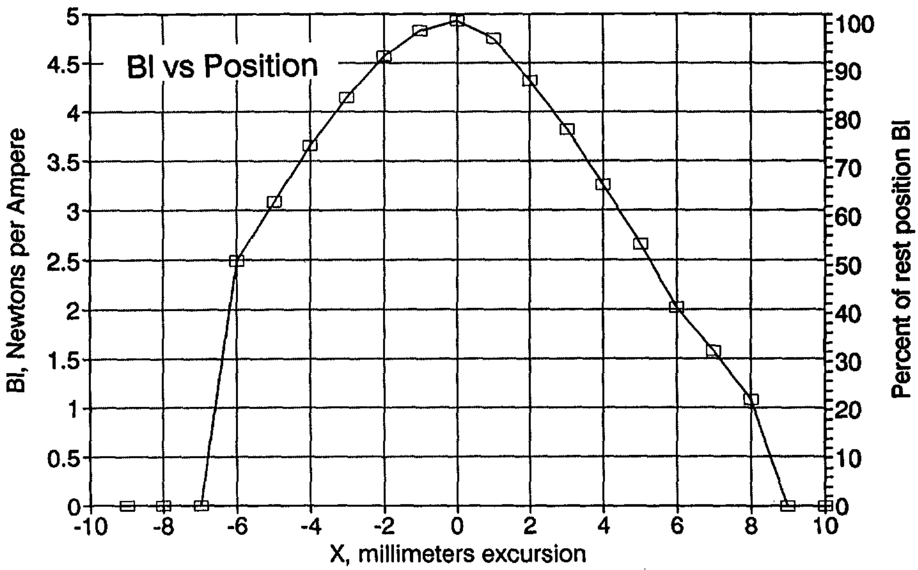

Figure 3. Bl factor versus excursion for the 6 X 9 inch automotive woofer. Bl drops to 50% of the rest position value by +5 mm of excursion.

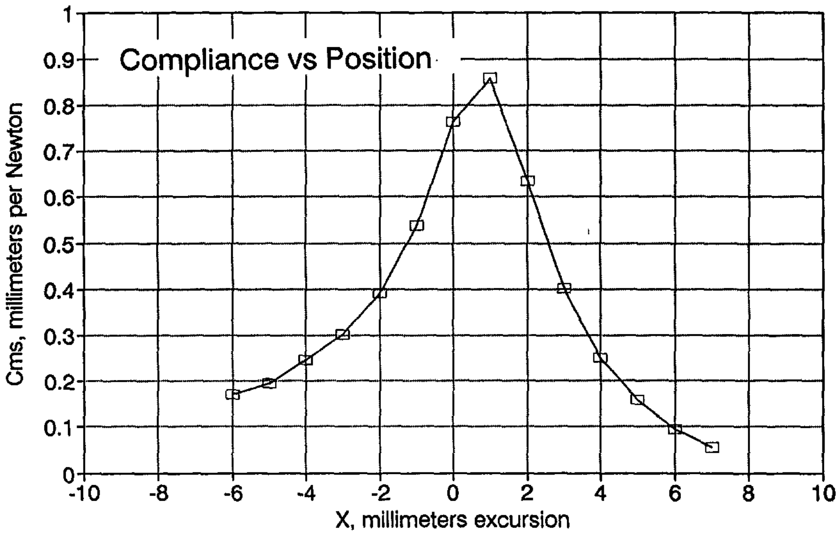

Figure 4. C_{MS} versus excursion for the 6 X 9 inch automotive woofer. C_{MS} drops to 20% by +5 mm of excursion.

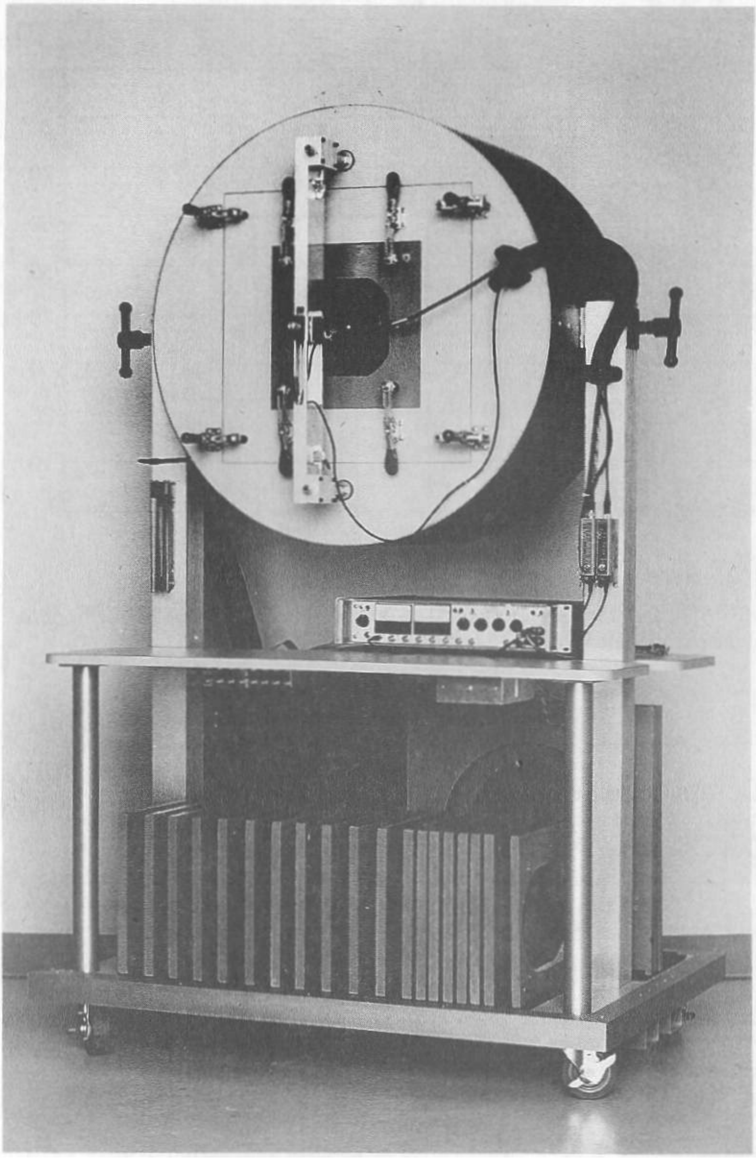

Figure 5. Overall view of the drive-unit measurements at excursion workstation. The cylindrical chamber rotates through 180^0.

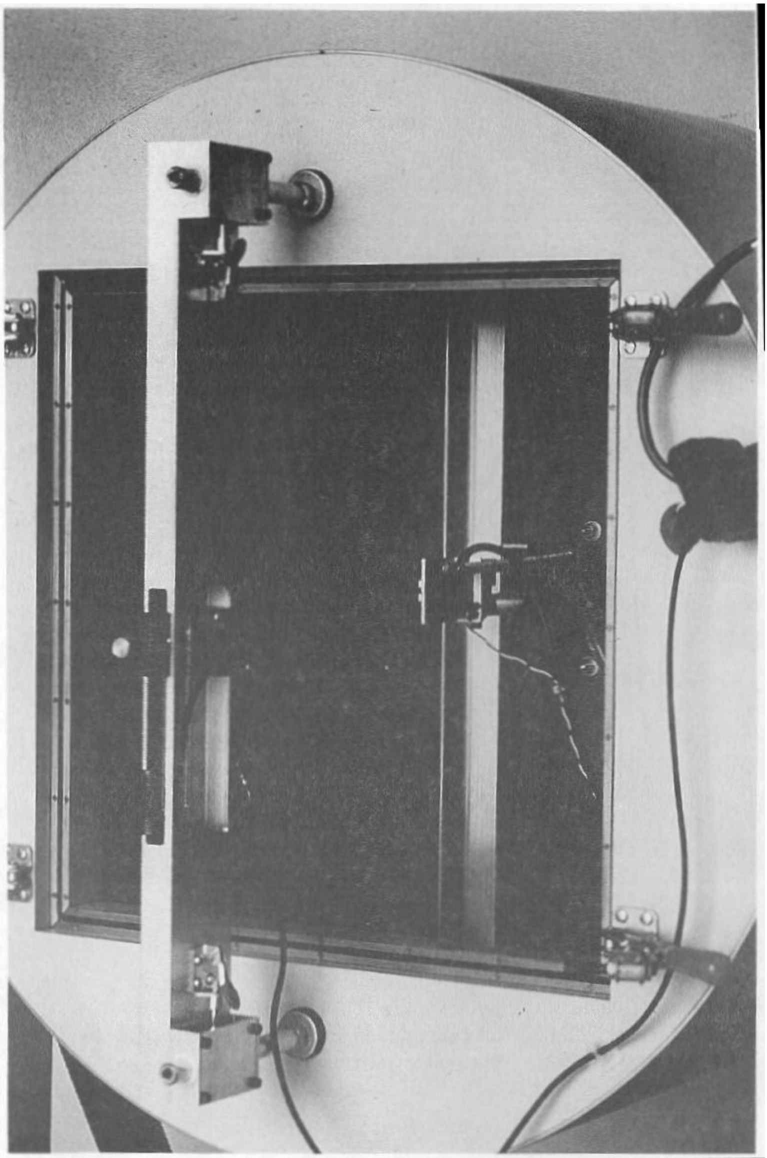

Figure 6. View of the laser position transducers and the interior of the test chamber.

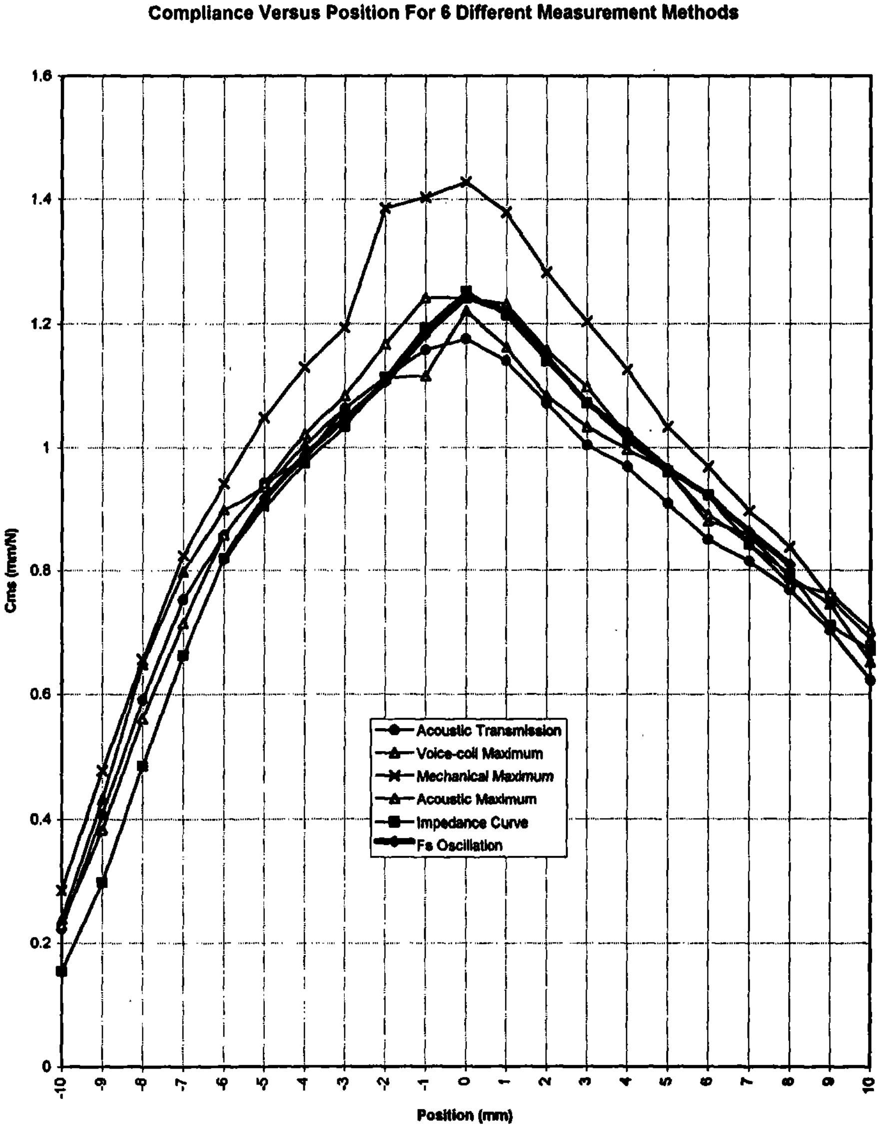

Figure 7. C_{MS} of a 178 mm woofer measured by six different techniques. The preferred technique, F_S oscillation, shown by the heavy line could only be applied between -6 mm and +8 mm for this long-travel suspension. The other techniques extend the measurement range and confirm each other reasonably.

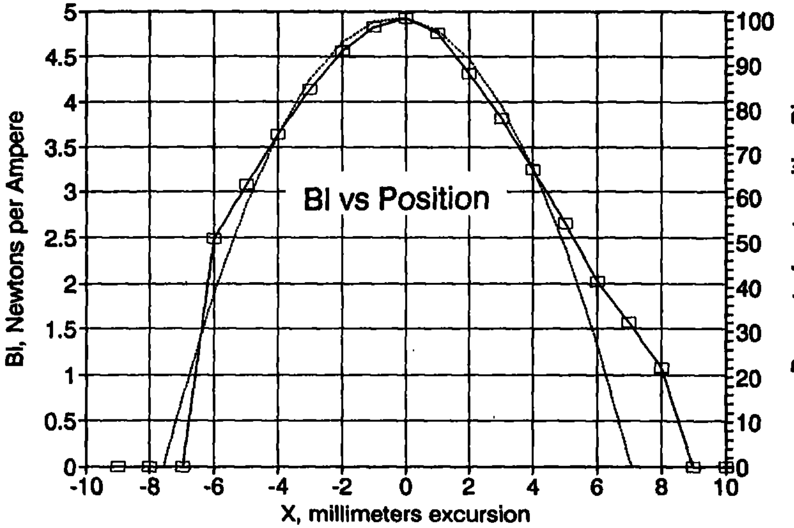

Figure 8. Bl versus position for the 6 X 9 inch automotive woofer also showing the quadratic approximation.

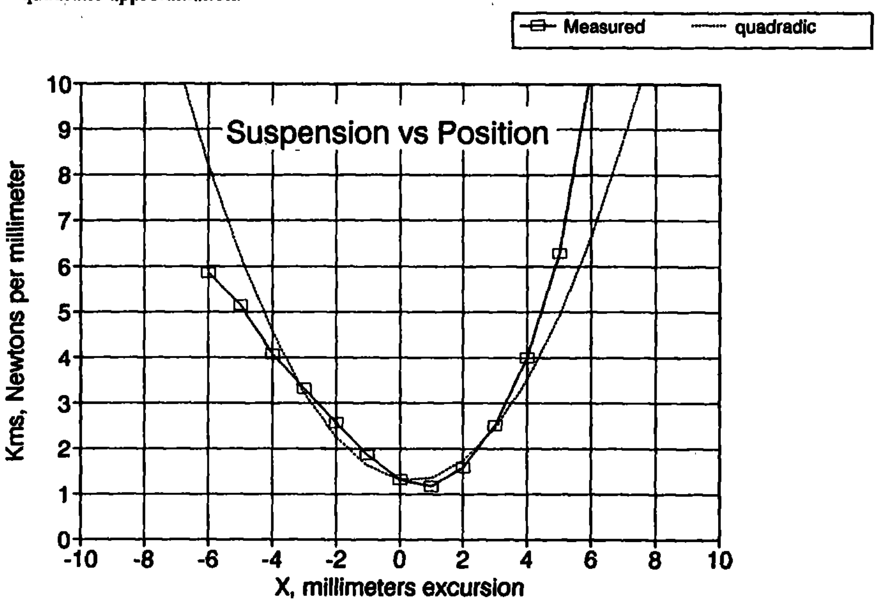

Figure 9. K_{MS} versus excursion for the 6 X 9 inch automotive woofer showing the quadratic approximation. The coefficients of the terms of the quadratic for K_{MS} and Bl are used to predict distortion.