A TECHNIQUE FOR THE MEASUREMENT OF FORCE FACTOR (Bl) IN MOVING-COIL TRANSDUCERS

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1.INTRODUCTION

The performance of moving-coil loudspeakers compares unfavourably with other parts of a sound reproducing system: a fact emphasised by dramatic improvements which have taken place in programme sources, with the advent of digital audio. The performance deficiencies are very apparent at low frequencies, the reproduction of which demands large cone excursions and high power levels. During the last two decades, developments in moving-coil loudspeaker driver technology seem to have concentrated more on cone/diaphragm performance. We have seen the widespread introduction of plastic cones, domes, and flat-plane direct radiators. The majority of loudspeaker units adhere to the original Rice-Kellogg structure, and the motor part, consisting of the magnet system and coil seems to have undergone relatively little development beyond the widespread adoption of ceramic magnets forced on the Industry by material-supply dificulties We are beginning to see use being made of Neodymium magnets, but the pole-piece design tends to remain much as it has always been, and to incur the same engineering compromises, which result in a less than ideal performance. The mischievous aspects of the traditional structure arise from three main causes:-

1) Eddy currents in the centre pole.
2) A magnetically-developed force, for a given coil current, which varies with the position of the coil.
3) Variations in the gap flux due to the current in the coil,which give rise to a non-linear force/current relationship, even with the coil at one specific position. (this effect is sometimes known as flux multiplication.)

Of these, the first has predominant influence at higher frequencies above a few hundred Hz. The phenomena has recently been extensively analysed by Vanderkooy in [1] and is not further considered in this paper.

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In elementary treatments, the behaviour of moving-coil systems is often represented by equations (1) and (2) below:

$$F = BlI \quad . \quad . \quad . \quad (1)$$

$$E = Blv \quad . \quad . \quad . \quad (2)$$

where F = force, v = velocity, I = current, E = EMF

The quantity - flux density B, times length of wire l in the coil - is sometimes called "Force Factor", and has the dimensions of a transduction coefficient. As can be seen from the above equations, it applies equally to electrical-to-mechanical transduction, or mechanical-to electrical transduction. The term $(Bl)^2$ appears in equations relating electrical and mechanical impedances in equivalent circuits. This concept of a fixed transductance coefficient Bl is only strictly true when the whole of the coil sits at all times in a perfectly uniform field. This condition could be met in the case of a short coil situated within a long gap, but for low frequency loudspeakers which need large cone/coil excursions, this is not usually considered a viable option, because of magnet cost. The alternative solution of a long coil overhanging a shorter gap is usually adopted. In this case, part of the coil sits in a fairly uniform strong field between the front plate and the centre pole, but the remaining parts of the coil are situated in fringe fields, as illustrated in Fig 4. Clearly "Bl" is a less simple concept in this case where B is non-uniform throughout the length of the coil winding. Baxandall has derived [ref.2] expressions for a transduction coefficient $\bar{B}l$ which are appropriate in this situation, where $\bar{B}$ is the mean flux density averaged over the whole length l of the winding. Baxandall's derivation is given in appendix 1, and it yields the following equations:

$$F = \bar{B}lI \quad . \quad . \quad . \quad (3)$$

and

$$E = \bar{B}lv \quad . \quad . \quad . \quad (4)$$

from which it follows that:

$$\frac{F}{I} = \frac{E}{v} = \bar{B}l$$

provided that E/v is measured at the same current I.

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Although these equations have been arrived at somewhat formally, intuition suggests that the mean flux density throughout the length of the coil winding must be the significant quantity.

The purpose of the measurement technique described in this paper is to determine how the factor $\bar{B}l$ varies with coil displacement and current. Such variations cause harmonic and intermodulation distortion. The measurement technique yields data describing the $\bar{B}l$ profile (or profiles with current as a parameter) in digital form, for easy interface to a computer; so enabling the distortion to be readily computed. The distortion figures may then be compared with perception thresholds given in reference [4].

The incentive for such measurements which quantify $\bar{B}l$ effects is two-fold:first to promote a better understanding of the functioning of new designs of motor using new materials; secondly, to enable a digital processor system to be designed which will compensate for the variations in $\bar{B}l$ due to coil displacement and current, and thereby produce a loudspeaker system with greatly reduced distortion.

2. PRINCIPLE OF MEASUREMENT

Establish a known incremental displacement.

Establish a constant amplitude of coil vibration.

Measure the open-circuit coil EMF.

2.1 Establishing known incremental displacement.

This is not as easy as it sounds! It might well be thought that all that is needed is a variable dc source connected to the voice coil, and a dial gauge to measure the cone/coil position. Unfortunately, the mechanical hysteresis and creep in the loudspeaker's suspension, combined with variable (current-dependent) coil resistance make it impossible to position the coil manually,with any accuracy. A simple position servo overcomes these problems. Fig.1 is a block diagram. The elements are a displacement transducer which provides a voltage-analogue of the coil displacement, relative to the centre pole as a spatial reference point. This displacement voltage is compared with a reference voltage at the input of an integrating error amplifier.

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The output current of the error amplifier feeds an actuator (which may be for convenience, another loudspeaker). The actuator is mechanically coupled to the loudspeaker under test by a light, rigid tie rod. The negative feedback loop operates to reduce the position error to zero. There is negligible residual error if the amplifier has high gain: e.g. 100dB. Because the error amplifier is integrating, vibration of the coil is permitted, and the servo controls mean position.

The displacement of the voice coil can be varied by varying the reference voltage. If the reference voltage is provided by an 8-bit digitally generated staircase waveform, the coil will travel a desired excursion in 255 increments. If we want to explore $\bar{B}l$ over an excursion of +/- 8mm, this will give a resolution of 0.06mm.

A suitable displacement transducer [3] is illustrated in Fig.2. An air-cored solenoid attached to the centre-pole is excited at about 2Mhz. This solenoid is surrounded by a conductive (e.g. copper) cylinder,fixed to the voice coil/cone. When the cylinder is symmetrically disposed about the centre of the coil, the rf voltages at its two ends are equal. The dc outputs of the two rectifiers are equal, but opposite.Hence the net output is zero. As the cylinder is moved axially, the eddy current losses in the two halves of the solenoid become unequal, and a proportional dc output is produced. Accuracy is better than 2% over our assumed 16mm excursion, and the transducer is very easily calibrated against a dial gauge.

When it is desired to map $\bar{B}l$ profiles with current as a parameter, a high impedance (variable) dc source is connected to the voice coil of the loudspeaker under test. Its coil will try and move as a result of this current, but the position servo will always win! The servo cancels the force generated by the dc current in the voice coil of the loudspeaker under test by establishing an equal and opposite force from the actuator coil. It is also possible to measure $\bar{B}l$ at a fixed voice coil position with voice coil current as a variable. To do this the reference voltage can be stopped at a particular "stair" (position). Since, in this stationary situation, l is constant, the measurement of the product $\bar{B}l$ reflects the value of the gap flux $\bar{B}$ as a function of coil current. Curves of $\bar{B}$ versus I can be obtained by use of a ramp current waveform.

2.2 Establishing a constant amplitude of coil oscillation. The voice coil is caused to oscillate at a fixed frequency,say 200Hz. To control the oscillation at a constant amplitude, either peak-to-peak displacement,or the velocity, or the acceleration of the coil may be monitored; which ever is most convenient. Acceleration can be readily monitored; moreover completely independently of anything else that is going on by use of a bimorph piezo-electric element (e.g.from a pick-up cartridge) which is weighted at one end, and attached to the voice coil at the other end.

Use is then made of a further (second) servo system, as illustrated in Fig.3,to keep the amplitude constant, despite variations in suspension stiffness and $\bar{B}l$ of the actuator. This time, the reference voltage is fixed.because we want a fixed amplitude of vibration. The ac output of the acceleration transducer is first filtered to reject harmonics generated by the suspension, or $\bar{B}l$ non-linearities. The sinusoidal output of the filter is precision rectified, and compared with the reference voltage at the input to the error amplifier. The error amplifier output drives a voltage-controlled amplifier inserted between the oscillator and the power amplifier coupled to the actuator. As before the servo system operates to reduce the error between the acceleration amplitude and the reference voltage to zero. As a point of detail,the voltage-controlled amplifier is readily implemented with a transconductance amplifier chip such as the CA3080; and the 200Hz oscillator and tracking bandpass filter is readily implemented with an MF10 switched capacitor chip. A typical amplitude of vibration is 0.01mm peak-to-peak.

A common power amplifier is used for the two servos: note the "displacement" and "staircase" inputs in Fig.3. The complete system is the combination of Figs 1 and 3.

2.3 Measurement of the open-circuit EMF of the voice coil. There is hardly anything to say about this. The open-circuit EMF is equal to $\bar{B}lv$. Having established constant velocity by keeping acceleration and frequency constant (as described in the previous section) the measured voice coil EMF is proportional to $\bar{B}l$. The ac voltage is filtered by a further tracking filter to reduce the noise bandwidth,and to remove the effects of non-linearities in the loudspeaker being measured; and precision rectified. The resulting dc can be fed to a chart recorder to plot the $\bar{B}l$ profile versus cone/coil displacement; or to plot $\bar{B}l$ as a function of current.

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An (8 bit) analogue-to-digital converter may be connected in parallel with, or in place of the chart recorder, to provide a digital output to a computer. Since the sweep rate is low (say 1 stair/s) there is no need for an anti-alias filter or sample-and-hold circuit. In real application with dynamic audio programme signals; the instantaneous coil current is not related to instantaneous coil position, because of the system inertia, and the complexity of the transduced mechanical impedance network.

3. MEASUREMENTS

Some measurements have been made on a well respected 300mm loudspeaker, and these provide an illustration of the use of the measurement system. Fig. 4 is an illustration of the magnetic field distribution for a magnet system where the front of the centre pole is flush with front plate. There is a shallow fringe field at the front of the front plate, and a much more extended fringe field inside, at the rear of the front plate.

Fig. 5 is a plot of $\bar{B}l$ versus coil displacement. $\bar{B}l$ is in arbitrary units, relative to zero, which is displaced below the bottom of the reproduced portion of the chart. Displacement units are approximately 2mm per division, and are labeled with the corresponding hexadecimal number from the staircase counter. 00 on the left, corresponds to the cone being in an outward position; and FF on the right, corresponds to cone being in an inwards position. The position of the front plate is drawn on the lower part of the diagram, and the coil is shown in its mid-span position, where it overhangs the front plate by about 7mm at the front, and about 8mm at the rear. When the coil is driven forward from this position by 8mm, corresponding to displacement 00, the inner end of the coil is aligned with the inner surface of the front plate. Further forward movement leaves part of the strong field in the gap unused, and so $\bar{B}l$ falls off very steeply beyond this point. When the coil is driven inward from mid-span by 7mm, corresponding to displacement EF, the front of the coil is aligned with the front of the front plate, and Bl falls off more steeply beyond this point.

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The manufacturer's quoted linear excursion is +/- 6mm, and this is identified in Fig.5 as the span between OF and CF, where $\bar{B}l$ falls to 7.7 (85% of its maximum value). The parabola-like $\bar{B}l$ profile results in odd-order distortion products. At larger excursions it may be observed that the profile is asymmetrical. The asymmetry gives rise to even-order distortion, with the associated "dc component", which in this case is manifest as a shift in mean position of the coil as the signal level is changed.

Fig. 6 shows the flux-multiplication effect. The top curve relates to a 0.5 amp current (dc) flowing in one direction, and the lower curve relates to the same current flowing in the opposite direction. Only the direction of current flow has been changed. It can be observed that as the coil is driven forward from the mid-span position (7F) there is a minor change in $\bar{B}l$ profile which is greatest at displacement 3F. It is suggested that this is because the current in the coil modifies the shape of the front fringe field. As the coil is driven further forward, the two curves converge from about OF onwards. This seems reasonable, since a coil which is hanging off the front of the centre pole cannot influence the gap flux. There is no convergence in the inward direction, and again this seems reasonable, because the coil then surrounds the centre pole.

A sinewave of 0.5 amp peak current represents an rms power of 1 watt in 8 ohms (the nominal impedance of the loudspeaker). The flux shift shown in the curves is quite modest at this level, and results in under 1% second harmonic distortion. However, at 100 watts power level (well within the loudspeaker's rating) the current will be 5 amps peak. If the centre pole is magnetically operating in a linear region of its B-H curve then the separation of the two curves will be 10 times greater than shown. Even-order distortion can be cancelled by push-pull operation of two loudspeakers, but the shift in cone position due to the even-order terms will remain, and may shift the operating point of the voice coil into a very non-linear region. The behaviour of the loudspeaker in this condition depends on whether it is voltage or current driven. With conventional voltage drive, it is possible for the coil to be driven right out of the gap, where it is prone to burn out, due to reduced cooling.

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ACKNOWLEDGEMENTS

The author is deeply grateful for the very helpful contributions in discussion of Peter Baxandall and Stanley Kelly, during the preparation of this paper; and to Linda Payne, for doing the drawings.

REFERENCES

[1] J.Vanderkooy. "A Model of Loudspeaker Driver Impedance Incorporating Eddy Currents in th Pole Structure" J.Audio Eng. Soc. Vol 37 number 3,pp 119-128.(1989 March)

[2] P J Baxandall ; private communication

[3] D.R.Birt "Displacement Transducer for use with Electrodynamic loudspeakers" UK Patent application GB 2,207,323 published 25 January 1989.

[4] L D Fielder and E M Benjamin. "Subwoofer Performance for Accurate Reproduction of Music". J. Audio Eng. Soc. Vol 36 number 6, pp 443-455. (1988 June).

APPENDIX 1

When B is non-uniform throughout the length of the coil winding, equations (1) and (2) may then be replaced by

$$F = I \int_0^l B\,dx \quad \cdot \quad \cdot \quad \cdot \quad (a)$$

$$E = v \int_0^l B dx \quad \cdot \quad \cdot \quad \cdot \quad (b)$$

where x is the distance along the wire, of total length l, at which each value of B applies.

Equation (a) may be written as

$$F = Il \times \frac{1}{l} \int_0^l B dx \quad \cdot \quad \cdot \quad (c)$$

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and equation (b) as

$$E = vl \times \frac{1}{l}\int_0^l B\,dx \quad \cdot \quad \cdot \quad (d)$$

In these latter equations, $\frac{1}{l}\int_0^l B\,dx$ is simply the mean flux density averaged throughout the length l of the coil winding; and denoting this by $\bar{B}$ gives

$$F = \bar{B}lI \quad \cdot \quad \cdot \quad \cdot \quad (3)$$

$$E = \bar{B}lv \quad \cdot \quad \cdot \quad \cdot \quad (4)$$

When, at any one specific position of the coil, $\bar{B}$ is dependent on coil current, then assuming that the magnetic circuit is operating in a linear regime, one can write

$$\bar{B} = \bar{B}_o + kI \quad \cdot \quad \cdot \quad \cdot \quad (e)$$

where k is a constant, and $\bar{B}_o$ is the mean flux at I = 0
Hence, by substituting (e) in (3), we may write

$$F = (\bar{B}_o + kI)\,Il$$

$$= \bar{B}_o Il + kI^2 l \quad \cdot \quad \cdot \quad (f)$$

from which $dF/dI = \bar{B}_o l + 2Ikl \quad \cdot \quad (g)$

But F/I, from (3) and (e), is given by

$$F/I = \bar{B}_o l + Ikl \quad \cdot \quad \cdot \quad (h)$$

The motional EMF is

$$E = \bar{B}lv \quad \cdot \quad \cdot \quad \cdot \quad (4)$$

which from (e) becomes

$$E = (\bar{B}_o + kI)lv$$

or

$$E/v = \bar{B}_o l + Ikl \quad \cdot \quad \cdot \quad (j)$$

Comparing (g),(h) and (j)

$$F/I = E/v$$

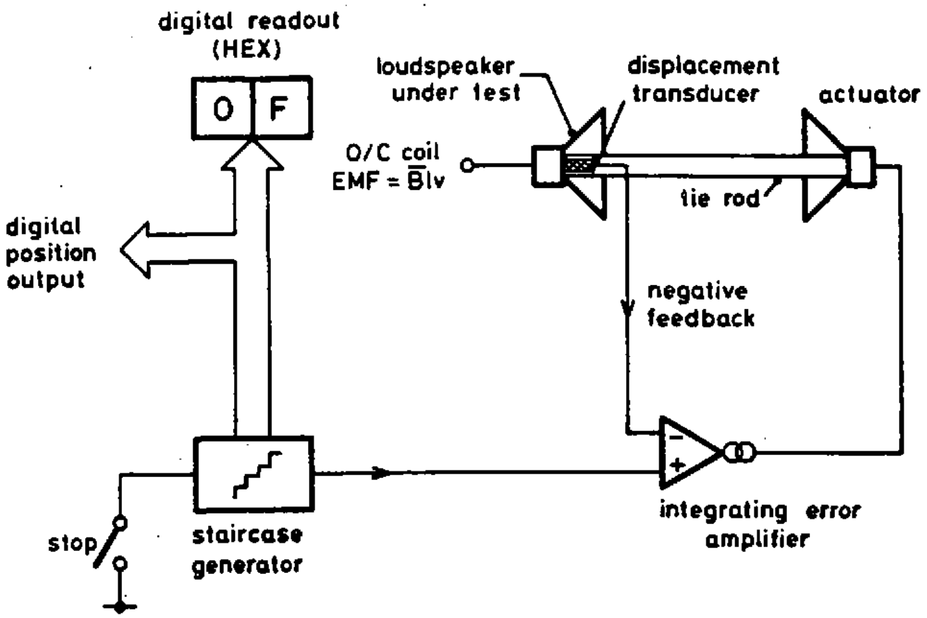


FIG 1. DISPLACEMENT SERVO

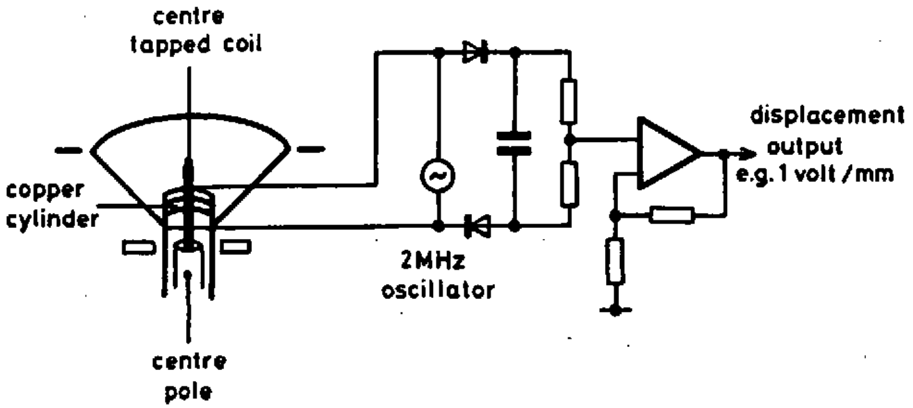


FIG 2. DISPLACEMENT TRANSDUCER

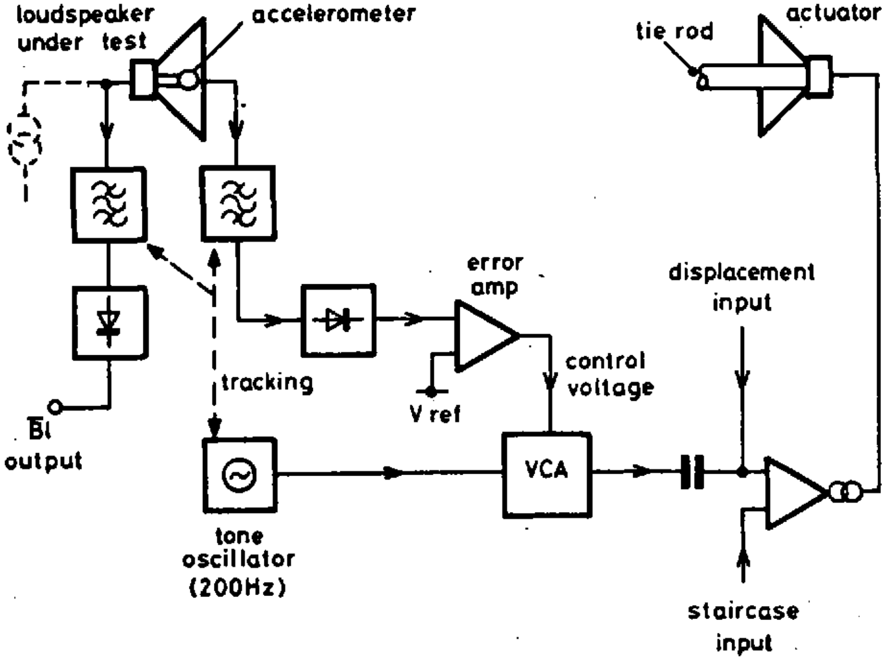


FIG 3. VIBRATION AMPLITUDE SERVO

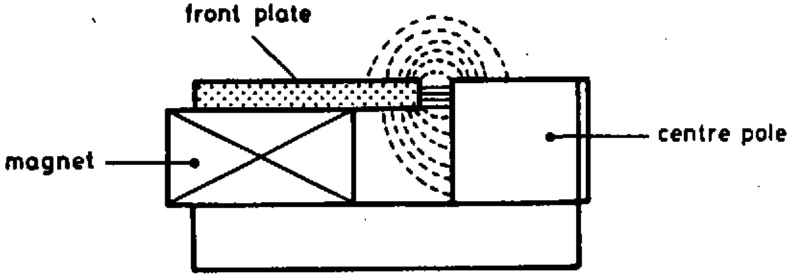


FIG 4. FLUX DISTRIBUTION

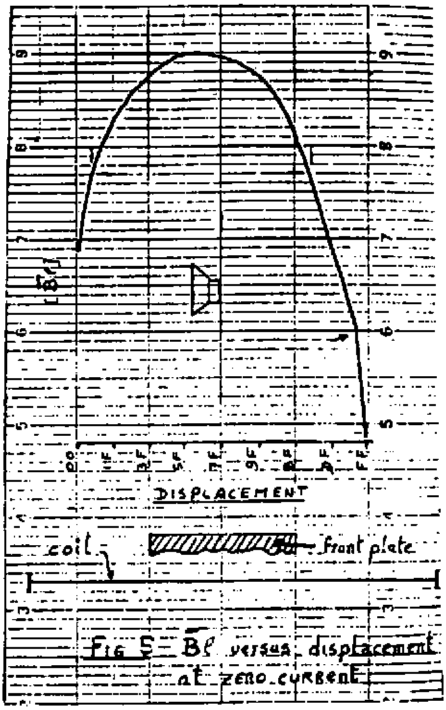
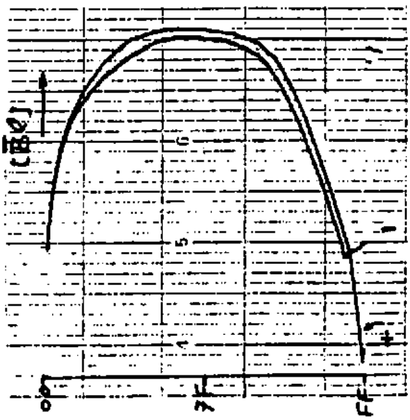


Fig 5 B̄ℓ versus displacement at zero current



B̄ℓ -vs- D
Fig 6 AT +/- 0.5 A