

the worse the distortion. Unfortunately, the ear is adept at sensing very low levels of distortion, especially intermodulation distortion.

The concept of transforming electrical energy into acoustic energy introduces ideas of impedance matching and transducers. Without going into the intricacies of acoustics theory, the following simplified treatment of the method of "electrical analogy" may be helpful. The complete sound reproduction system from amplifier to air can be represented by an electrical equivalent circuit—see Fig. 1a. The constant-voltage generator has an internal resistance,  $R_s$ , which is typically  $0.2\Omega$  for modern amplifiers. The voice coil of the driver unit contributes inductance,  $L$ , and pure resistance,  $R$ . The essential function of the driver unit is that of energy transducer, which can be represented as a transformer with a turns ratio of  $Bl:1$ . The primary current,  $I_p$ , gives rise to a force  $f_p$  which, as it were, flows in the secondary circuit. The voltage induced back across the primary,  $V_p$ , reflects the velocity,  $u_c$ , of the voice coil. Thus,  $I_p = f_p / Bl$  and  $V_p = Bl u_c$ .

The primary impedance,  $Z_1$ , is related to the secondary impedance,  $Z_2$ , as follows

$$Z_1 = V_p / I_p$$

and

$$Z_2 = u_c / f_c$$

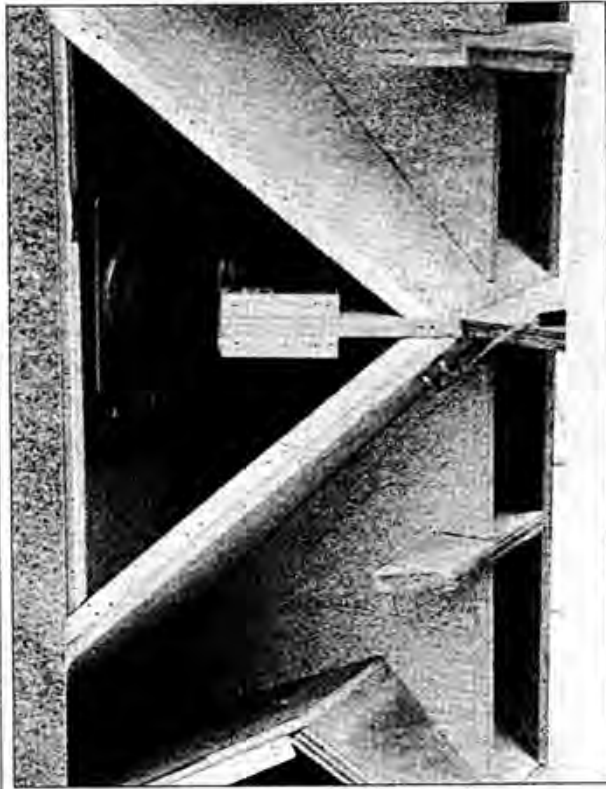
so that

$$Z_1 = (Bl)^2 Z_2 \quad [9]$$

The term  $Bl$  is the magnetomotive force factor, which is measured in tesla per metre ( $T m^{-1}$ ).

Note that in the secondary circuit impedance is the inverse of the better known mechanical analogue where voltage corresponds to force and current to velocity. In the present system, known as the mobility system (Ref. 2), inertia becomes a shunt capacitance and spring resistance becomes a shunt inductance. Hence, the moving mass of the speaker is represented by capacitance  $MMD$ , while the stiffness of the suspension and any enclosed volume (e.g. in infinite baffle designs) of air are represented jointly by inductance  $CMS$ . The acoustic load is represented by  $A$ , the acoustic mobility, which is the reciprocal of acoustic impedance.

For maximum energy transfer, the blocking effects of the mechanical inertia and stiffness have to be minimized. In the



mobility system, this amounts to reducing the magnitude of  $B-A$  (particularly the real part) below the shunt admittances of  $MMD$  and  $CMS$ . Then,  $B-A$  will predominate in the secondary load.

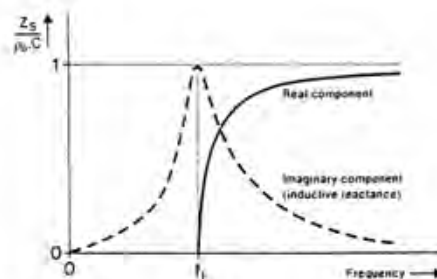
The accompanying step is to reduce the size of the primary series impedances as reflected in the secondary—see Fig. 1b. At low frequencies,  $L$  may be disregarded. Considering the difficulty of achieving large enough values of acoustic impedance (i.e., low enough values of acoustic mobility,  $B-A$ ), every effort has to be made to reduce the moving mass and stiffness of the suspension. Furthermore,  $Bl$  needs to be maximized to minimize the dissipative effect of  $R$ . The closed cabinet or infinite baffle

design reduces stiffness by the use of a large enclosed volume, increases  $ZA$  by the use of a large cone, and then fails to reduce the moving mass (which includes a cylinder of air in front of the cone that is about a third of the cone radius deep). Such designs seldom achieve energy efficiencies much above 4%, in spite of decades of research.

### The horn as an acoustical transformer

For a sound wave propagating along an exponential horn, the particle velocity and pressure vary in proportion to the diameter of the horn. The specific acoustic impedance

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