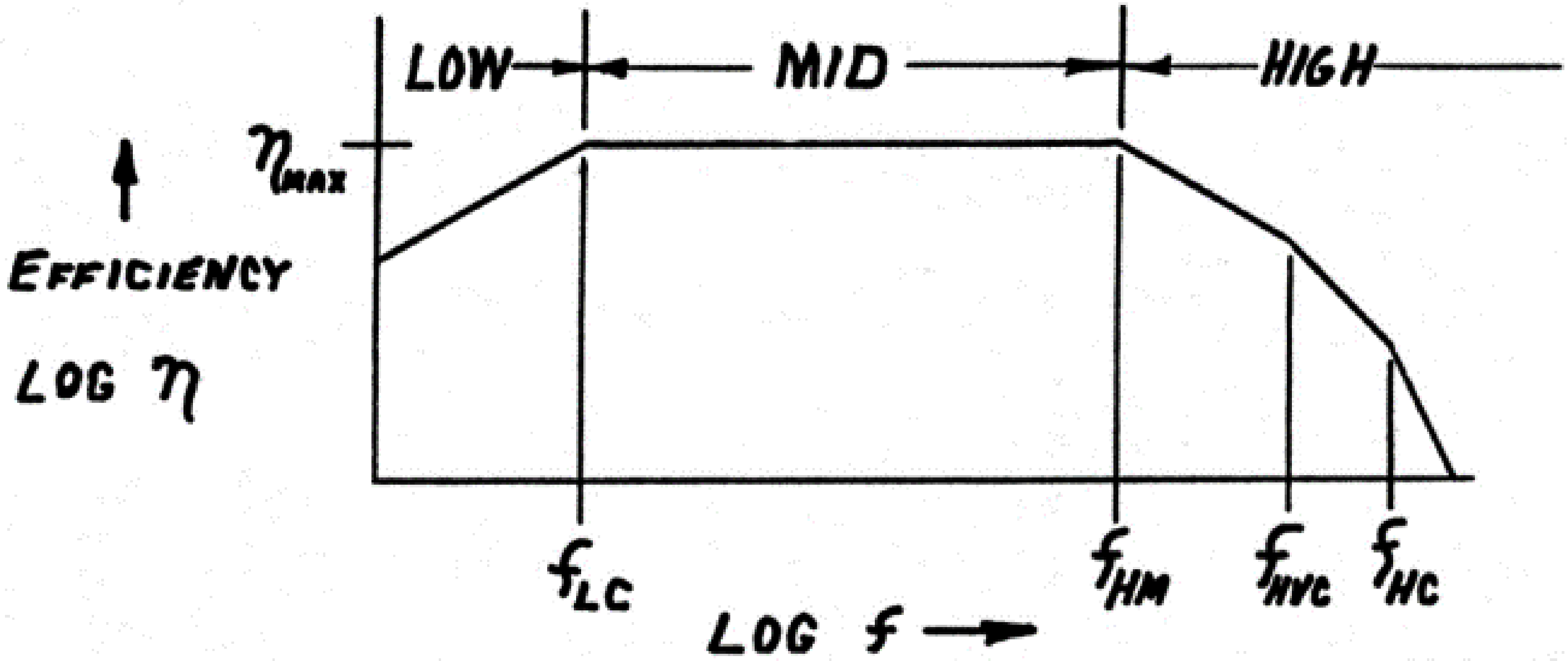


Fig. 3. Idealized frequency response of horn-driver system. Horn cutoff frequency $f_c$ is assumed to be very much lower than $f_{LC}$ ($C_{MET}$ very large). The midrange band is defined primarily by driver and back cavity compliance rolloff on the low end ($f<f_{LC}$) and driver effective moving mass rolloff on the high end ($f>f_{HM}$). Secondary high-end rolloffs due to driver voice-coil inductance ($f>f_{HV}$) and front cavity compliance ($f>f_{HC}$) are exhibited.

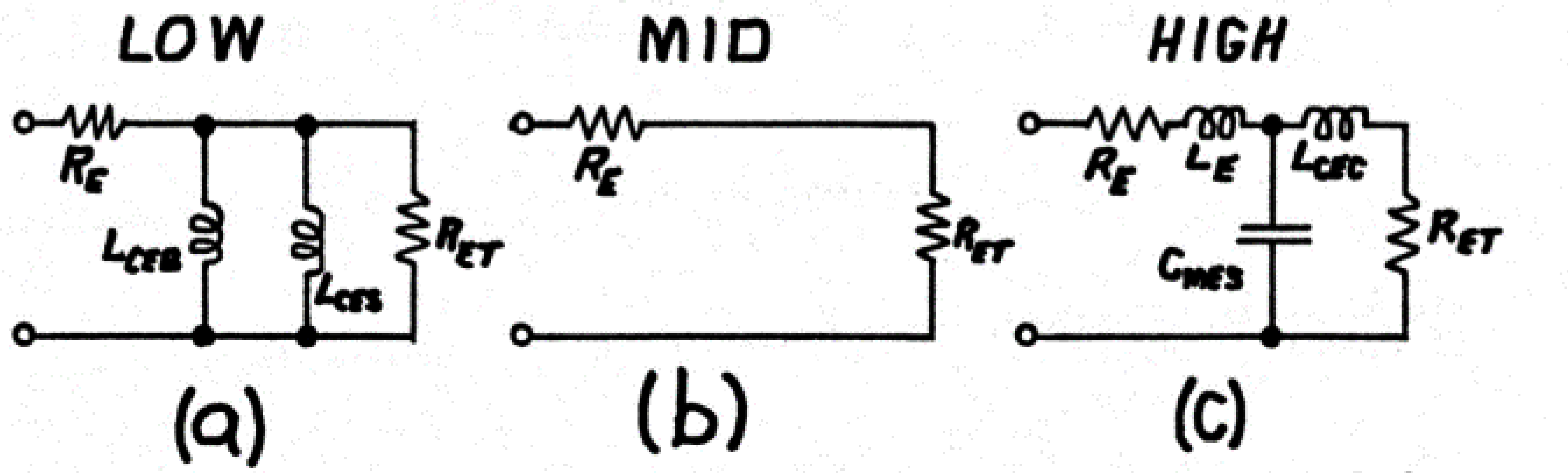


Fig. 4. Reductions of the horn-driver system simplified electrical equivalent circuit of Fig. 2 in each frequency band indicated in Fig. 3. It is assumed that $f_C \ll f_{LC}$ as in Fig. 3.

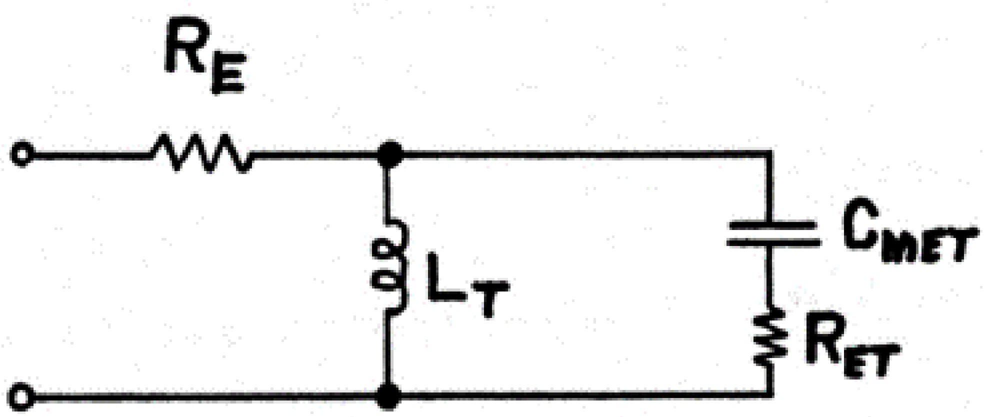


Fig. 5. Reduction of the simplified horn-driver system electrical equivalent circuit of Fig. 2 in the low frequency band but considering the effects of horn cutoff. Note that in this region both $C_{MET}$ and $R_{ET}$ are non-constant functions of frequency. For the case of an infinite exponential horn however, $C_{MET}$ is constant and positive above cutoff ($f \geqslant f_C$). Note that $L_T = L_{CEB} L_{CES}/(L_{CEB}+L_{CES})$.

dependent on driver moving mass, driver voice coil inductance, and front air-chamber compliance.

If the relationship of eq. (1) holds, analysis reveals individual breakpoint frequencies of:

1. Driver moving mass corner,

$$f_{HM} = \frac{B^2 \ell^2}{\pi R_E M_{MD}} = 2f_{HS}; \tag{7}$$

2. Driver voice coil inductance corner,

$$f_{HVC} = \frac{R_E}{\pi L_E} \quad ; \quad \text{and} \tag{8}$$

3. Front cavity compliance corner,

$$f_{HC} = \frac{2\rho c^2 R_E S_D^2}{B^2 \ell^2 V_{FC}} \tag{9}$$

where $V_{FC}$ is the volume of the front cavity.

In a real world horn design, the composite high frequency rolloff is a complex combination of all three corner frequencies taken together. These three frequencies do give a designer a rough idea of the high frequency behavior of the system, however. In a practical situation these breakpoints are often ordered as $f_{HM} < f_{HVC} < f_{HC}$.

## Reactance Annulling

The low frequency efficiency of a horn loaded system at frequencies near horn cutoff may be increased somewhat by minimizing the effects of the horn's throat air mass reactance by a process known as reactance annulling. This method, which was first used by Klipsch [5] and later refined by Plach and Williams [6] [7], uses the compliance reactance of the combined effects of the driver's suspension and rear cavity compliance to offset the horn's throat mass reactance.

Analysis of the equivalent circuit at low frequencies, with the appropriate throat resistive and reactive values substituted for an infinite exponential horn [9, eq. 4.2] (shown in Fig. 5), reveals that reactance annulling is the same as equating the lower bound of the resistance controlled region of the driver mounted in its closed-box rear cavity to the horn's cutoff frequency:

$$f_{LS}\,(1+\alpha) = f_C = 2\, f_{LBC}\;. \tag{10}$$

With the information that $\alpha = C_{MS}/C_{AB}$ and

$$C_{AB} = \frac{V_B}{\rho_0\, c^2\, S_D^2} \tag{11}$$

where $V_B$ is the effective rear cavity volume, eq. (10) may be solved for $V_B$ yielding:

$$V_B = \frac{\dfrac{\rho_0\, c^2\, S_D^2\, C_{MS}}{2\pi f_C\, B^2 l^2\, C_{MS}}}{\dfrac{\phantom{x}}{R_E}} - 1 \tag{12}$$

If the total compliance is set primarily by the box ie $C_{AB} \ll C_{MS}$. eq (12) reduces to:

$$V_B = \frac{\rho_0\, c^2\, R_E\, S_D^2}{2\pi f_C\, B^2 l^2} \tag{13}$$

Eqs. (13) and (1) may be combined to yield:

$$V_B = \frac{S_T\, c}{2\pi f_C} = \frac{S_T \lambda_C}{2\pi} \tag{14}$$

where $\lambda_C$ = wavelength at cutoff, which is a simple practical form first derived by Klipsch in 1941 [5, eq. 3].

Low-Frequency Maximum Acoustic Output :

The maximum acoustic output of the horn system at low frequencies is primarily set by the maximum displacement capabilities of the driver, the maximum thermal capabilities of the driver, and non-linear air compression distortion in the back cavity.

Considering only the driver's displacement limitations, the power radiated into an infinite tube of area $S_T$ by a flat piston of area $S_D$ undergoing sinusoidal oscillations of peak amplitude $x_p$ is given by Olson [4, eq. 7.23]:

$$P = \frac{2\pi^2 \rho_o c \, S_D^2 \, x_p^2 \, f^2}{S_T} \qquad (15)$$

This expression can be rewritten in terms of the horn's cutoff frequency $f_C$ and the maximum low-frequency displacement limited output power $P_{AR}$, by noting that for a well designed finite exponential horn with optimum mouth size [8], the low-frequency efficiency is down no more than 0.3 dB from the maximum midband efficiency at 1.26 $f_C$.

Therefore:

$$P_{AR} \approx \frac{3\pi^2 \rho_o c \, S_D^2 \, x_p^2 \, f_C^2}{S_T} \; . \qquad (16)$$

This equation may be combined with eq. (1) to yield:

$$P_{AR} \approx \frac{3\pi^2 \, B^2 l^2 \, x_p^2 \, f_C^2}{R_E} \; . \qquad (17)$$

CONVERSION

The relationships noted in Appendix I can be used to rewrite eqs. (1)-(5), (7)-(9), (12), and (16) in terms of the Thiele/Small driver parameters. In all cases $Q_{TS} \approx Q_{ES}$, due to the assumption that $Q_{MS} \gg Q_{ES}$.

## Efficiency

The expression giving the midband nominal efficiency eq. (6) remains the same, but the value of horn throat area to maximize this function eq.(1) may be written as:

$$S_T = \frac{2\pi f_S Q_{TS} V_{AS}}{c} , \tag{18}$$

which is the desired result.

## Frequency Response

The driver related corner frequencies which indicate the bounds of resistance controlled operation can be shows as:

$$f_{HS} = f_S/Q_{TS}, \text{ and} \tag{19}$$

$$f_{LS} = Q_{TS} f_S \tag{20}$$

These bounds roughly indicate the range over which a driver will be suitable for use as a horn driver considering small-signal operation only.

It is instructive to form the ratio of these two expressions ie $f_{HS}/f_{LS} = 1/Q_{TS}^2$, which indicates that a low value of $Q_{TS}$ (high motor strength, large magnets, etc.) is desirable for loudspeakers used as horn drivers if the widest operating bandwidth is desired.

## Low Frequencies

Eqs. (4) and (5) can be rewritten as:

$$f_{LC} = f_{LS}/2 = Q_{TS} f_S/2, \text{ and} \tag{21}$$

$$f_{LBC} = f_{LC} (1+\alpha) = \frac{Q_{TS} f_S}{2} (1+\alpha) \tag{22}$$

$$= \frac{Q_{TS} f_S}{2} \left(1+ \frac{V_{AS}}{V_B}\right) ,$$

where $\alpha = V_{AS}/V_B$ the ratio between the driver's compliance equivalent volume and the rear cavity box volume.

Mid Frequencies

The efficiency expression eq. (6) remains the same as noted before.

High Frequencies

The three HF breakpoint frequencies eqs. (7)-(9) can be shown in the form:

1. Driver moving mass corner,

$$f_{HM} = 2f_{HS} = 2f_S/Q_{TS}; \tag{23}$$

2. Driver voice coil inductance corner remains as before eq. (8); and

3. Front cavity compliance corner,

$$\begin{aligned} f_{HC} &= 2f_{LS}\beta = 2Q_{TS}\, f_S\, \beta \\ &= 2Q_{TS}\, f_S \frac{V_{AS}}{V_{FC}} \end{aligned} \tag{24}$$

where $\beta = V_{AS}/V_{FC}$ the ratio between the driver's compliance equivalent volume and the front cavity volume.

Reactance Annulling

The correct rear cavity volume for reactance annulling eq. (12) can be changed to:

$$V_B = \frac{V_{AS}}{\left(\frac{f_C}{f_{LS}} - 1\right)} = \frac{V_{AS}}{\left(\frac{f_C}{f_S\, Q_{TS}} - 1\right)} \quad . \tag{25}$$

which is a relatively direct compact form. It must be noted that normally $(f_C/f_{LS}) \angle 1$ or $f_{LS} < f_C$ which makes $V_B$ finite and positive. If $f_{LS} \approx f_C$ or $f_{LS} > f_C$, the driver is not well suited for operation in a horn at that specific cutoff frequency.

Low-Frequency Maximum Acoustic Output:

The expression for the displacement limited low-frequency output power eq. (16) can be combined with eq. (18) yielding:

$$P_{AR} = \left(\frac{3}{2}\pi\rho\, c^2\right)\left(\frac{1}{f_S\, Q_{TS}\, V_{AS}}\right) f_C^2\, V_D^2 \, . \tag{26}$$

For computation in SI metric units $3\pi\rho c^2/2 \approx 6.7 \times 10^5$.