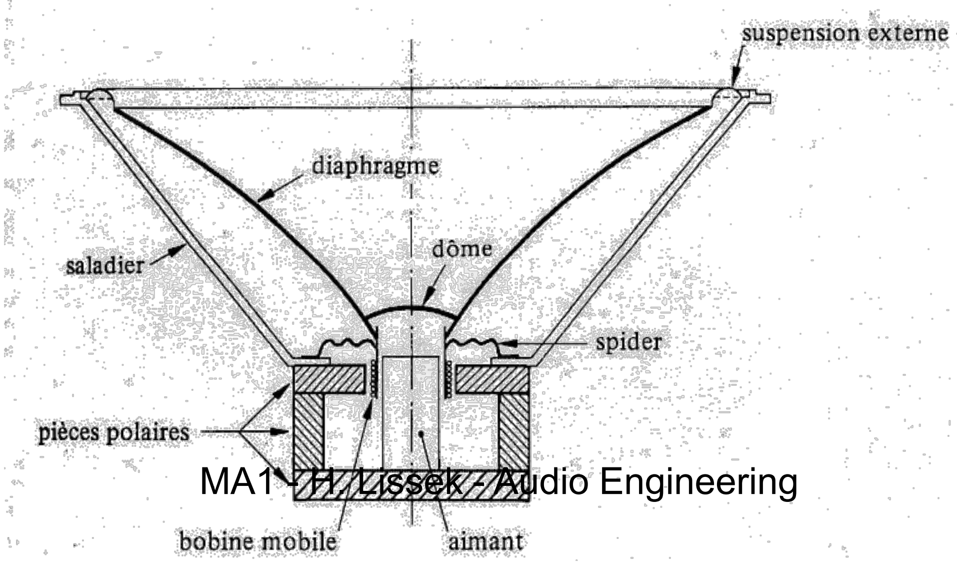
5.2 Electrodynamic loudspeaker

Definitions

Electrodynamic loudspeaker, with moving coil + radiating cone:

- elastically suspended *diaphragm* with *spider* and *external* suspension
- *moving coil*, attached to the diaphragm
- *magnetic circuit* of the driver
- *basket*= open frame (made of metal)



Radiation

If radiation through a horn: *indirect radiation*

Else: *direct radiation*

In a general sense, loudspeaker on infinite baffle (piston behavior):

- after f and dimensions (w. resp. $/\lambda$),

  loudspeaker= small pulsating source in 2π sr

- identical velocity at each point of diaphragm: $\underline{q}_d = S_d \underline{v}_d$

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Bandwidth

zone of f where the sound pressure generated by the loudspeaker is constant

LF limit:

- omnidirectional radiation ➔ constant P_a

  since $P_a = R_{ar} q_d^2$ ➔ q_d shall vary in $1/f$
- mobile system=resonator, force independant of f

➔ flow velocity varies in $1/f$ if controlled by mass

➔ low limit of *B* = resonance frequency of the mobile system

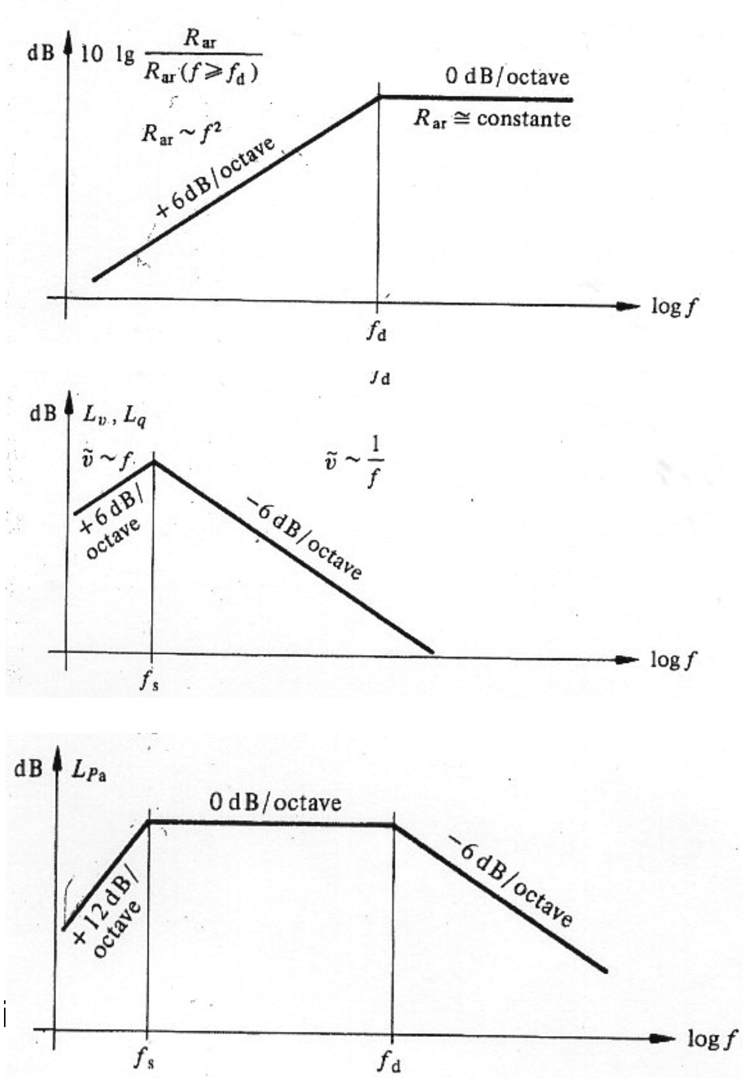
Bandwidth

HF limit:

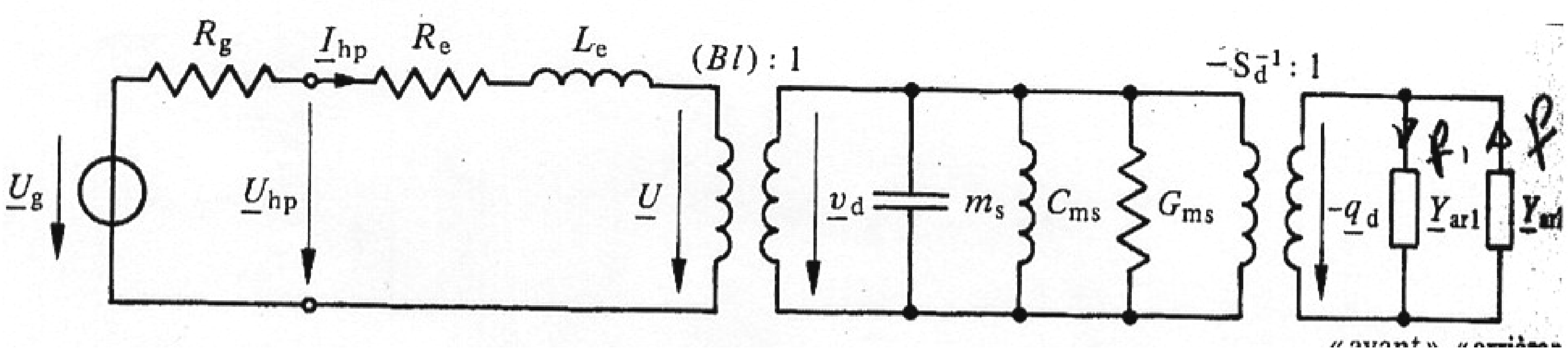
- *ka* high enough: constant radiation resistance
- since q_d varies in $1/f$

➔HF limit: $ka=\sqrt{2}$

$$f_d = \frac{c}{\sqrt{2}\pi a}$$



Scheme of a loudspeaker in infinite baffle



Equivalent acoustic scheme

suppression of 2-ports by denoting:

$$\underline{p}_g = \frac{Bl}{S_d\left[R_g + R_e + j\omega L_e\right]}\underline{U}_g$$

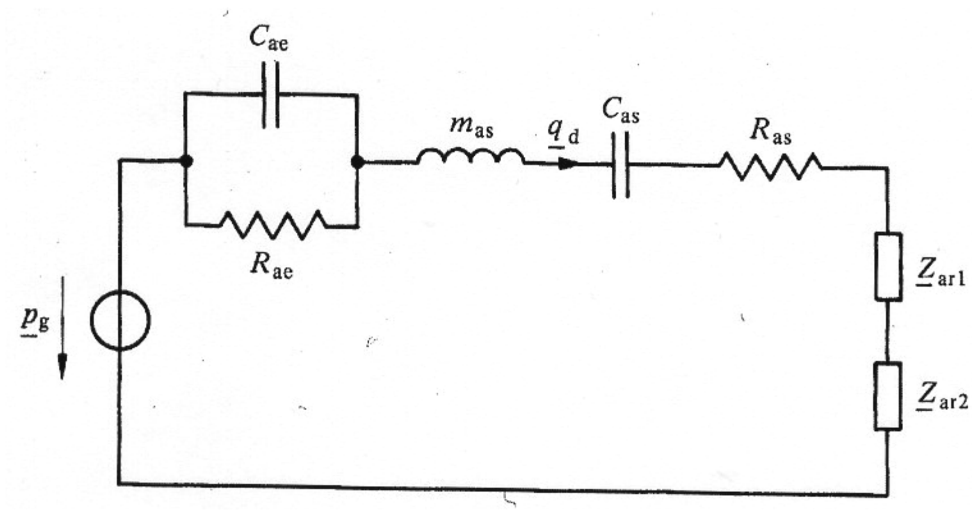
$$R_{ae} = \frac{(Bl)^2}{S_d^2(R_g + R_e)}$$

$$C_{ae} = \frac{L_e S_d^2}{(Bl)^2}$$

$$R_{as} = \frac{R_{ms}}{S_d^2}$$

$$m_{as} = \frac{m_s}{S_d^2}$$

$$C_{as} = S_d^2 C_{ms}$$



Equivalent electric scheme

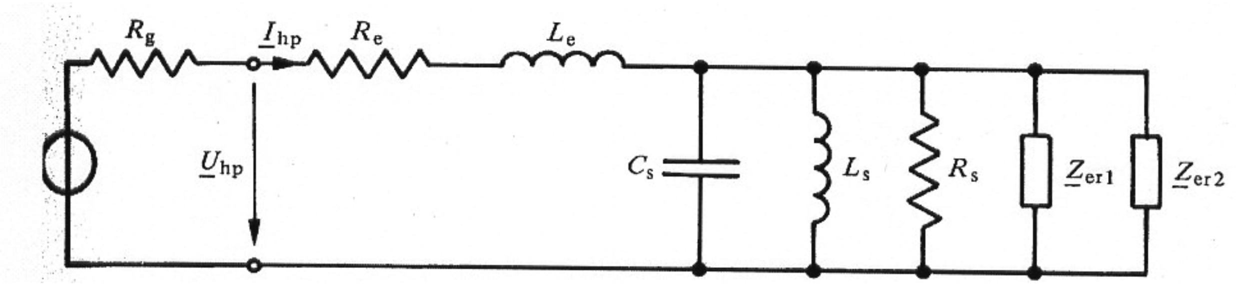
by denoting:

$$L_s = C_{ms}(Bl)^2 = \frac{C_{as}}{S_d^2}(Bl)^2$$

$$\underline{Z}_{er} = \frac{(Bl)^2}{S_d^2 \underline{Z}_{ar}}$$

$$C_s = \frac{m_s}{(Bl)^2} = \frac{m_{as}}{(Bl)^2} S_d^2$$

$$R_s = \frac{(Bl)^2}{R_{ms}} = \frac{(Bl)^2}{S_d^2 R_{as}}$$

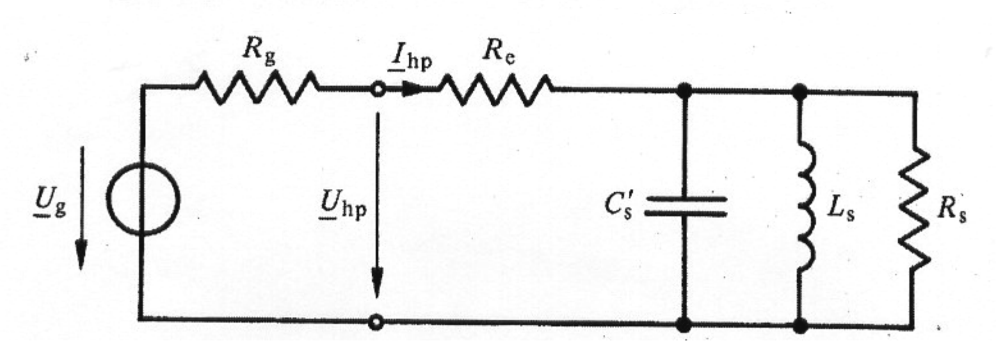


Low frequency approximation

below resonance frequency f_s:

- $(\omega L_e) << R_e$
- $2R_{ar} < R_{as}$
- X_{ar}=mass m_r, added to the acoustic masses:

$$m'_{as} = \frac{m_s + 2m_r}{S_d^2} = m_{as} + 2m_{ar}$$



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Small signals parameters

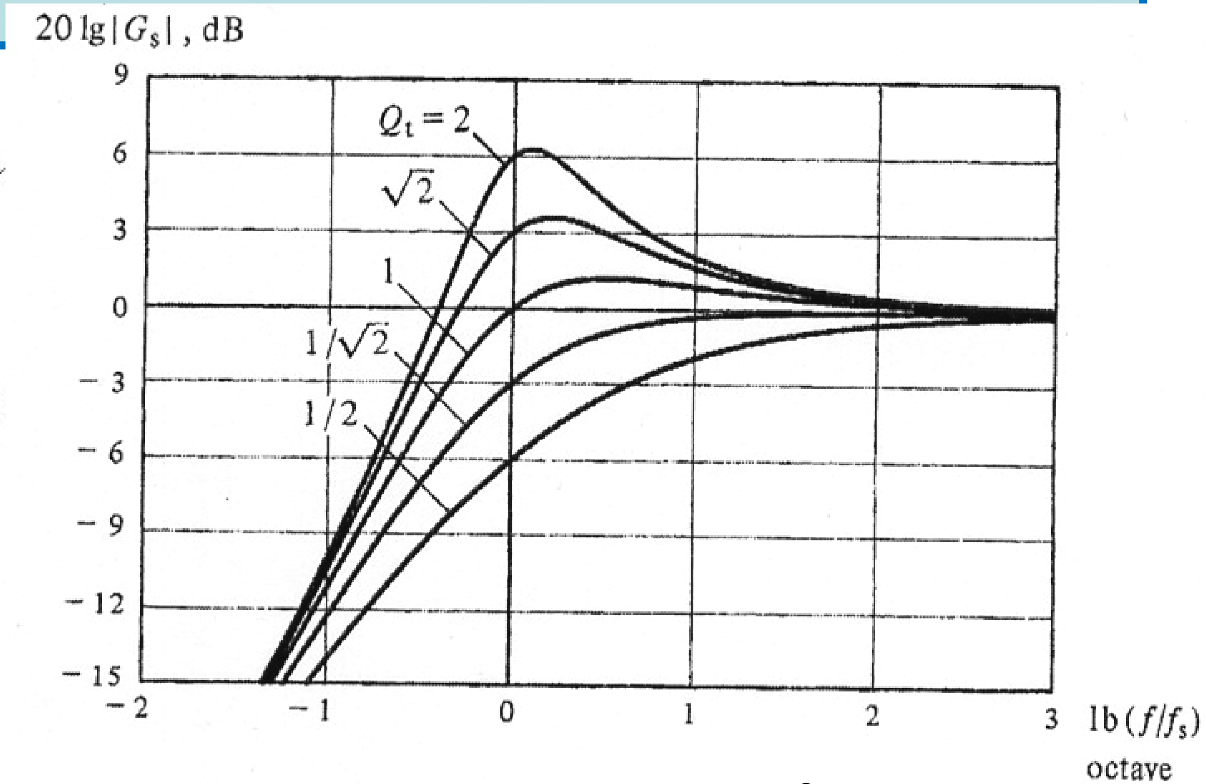
In the LF range,

small signals (or Thiele/Small) parameters :

- resonance frequency f_s $$f_s = \frac{1}{2\pi\sqrt{m'_s C_{ms}}} = \frac{1}{2\pi\sqrt{m'_{as} C_{as}}} = \frac{1}{2\pi\sqrt{C'_s L_s}}$$
- air volume equivalent to C_{as} $$V_{as} = \rho c^2 C_{as}$$
- electrical quality factor Q_{es} at f_s $$Q_{es} = \omega_s C'_s R_e = \frac{1}{\omega_s C_{as} \underbrace{R'_{ae}}_{R_{ae}|_{R_g=0}}}$$
- mechanical quality factor Q_{ms} at f_s $$Q_{ms} = \omega_s C'_s R_s = \frac{R_s}{\omega_s L_s} = \frac{1}{\omega_s C_{as} R_{as}}$$
- total quality factor Q_{ts} at f_s $$Q_{ts} = \frac{Q_{es}.Q_{ms}}{Q_{es} + Q_{ms}}$$
- S_d, R_e, L_e, Bl

Diaphragm volume flow

cf acoustic scheme



leads to:

$$\underline{q}_d = \Bigg[\underbrace{\frac{S_d}{Q_e Bl}\underline{U}_g}_{\underline{q}_s}\Bigg]\frac{1}{j\omega/\omega_s}\underbrace{\frac{(j\omega/\omega_s)^2}{(j\omega/\omega_s)^2 + Q_t^{-1}(j\omega/\omega_s)+1}}_{G_s(j\omega/\omega_s)}$$

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Acoustic power and pressure

Radiated power is $$P_a = R_{ar}\tilde{q}_d^2$$

then

$$P_a = \underbrace{\frac{2\pi\rho}{c}.f_s^2.\tilde{q}_s^2}_{P_{as}}.\left|G_s(j\omega/\omega_s)\right|^2$$

Sound pressure (omnidirectional radiation in 2π sr)

$$\tilde{p}(r) = \sqrt{Z_c \underbrace{\frac{P_a}{2\pi r^2}}_{I(r)}} = \tilde{p}_s\left|G_s(j\omega/\omega_s)\right|$$

where p_s is independant of f

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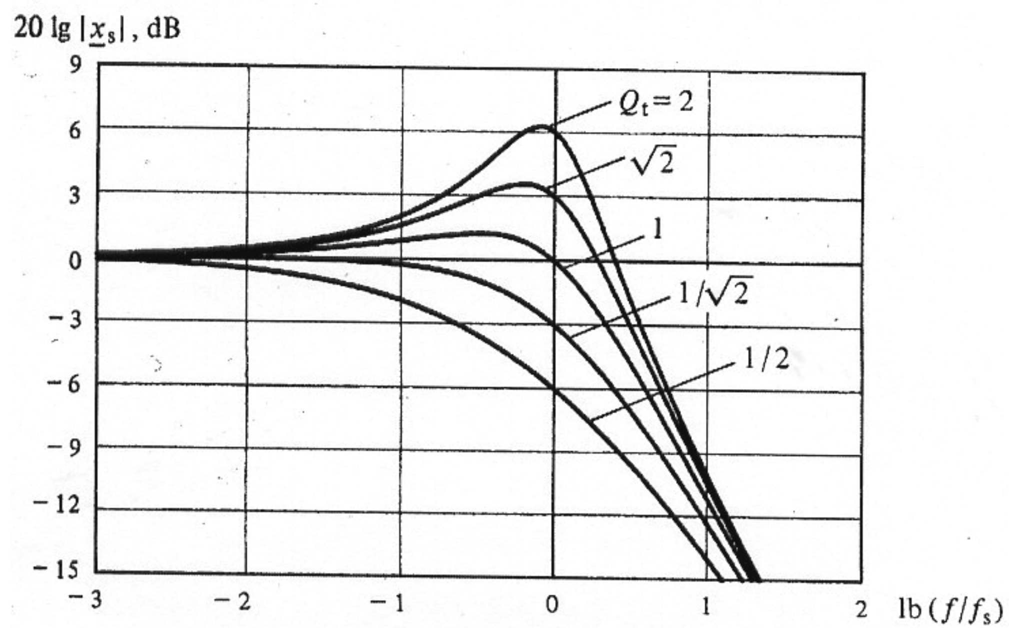
Diaphragm elongation

can be computed by integrating q_d

(multiply with $1/j\omega$ in harmonic state)

$$\underline{\xi}_d = \underbrace{\frac{\underline{U}_g}{\omega_s Q_e (Bl)}}_{\underline{\xi}_s} \cdot \underbrace{\frac{G_s(j\omega/\omega_s)}{(j\omega/\omega_s)^2}}_{\underline{x}_s}$$

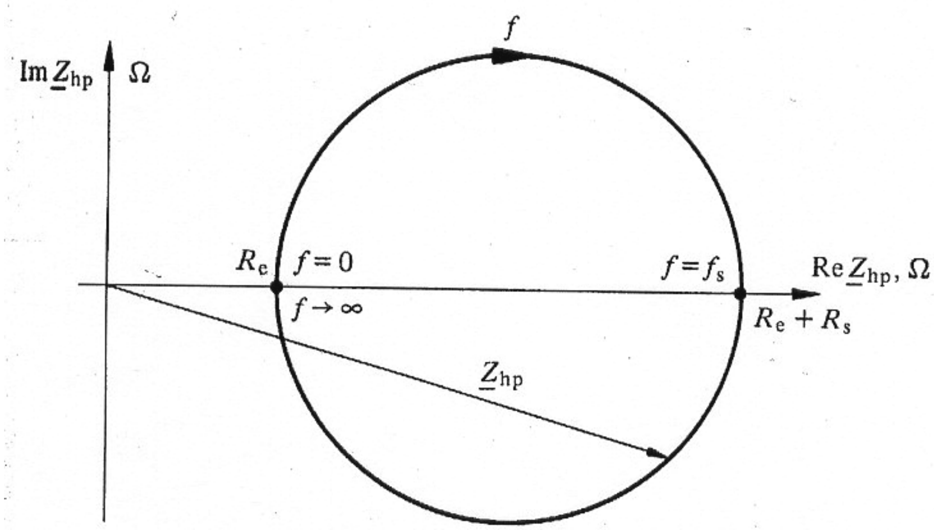


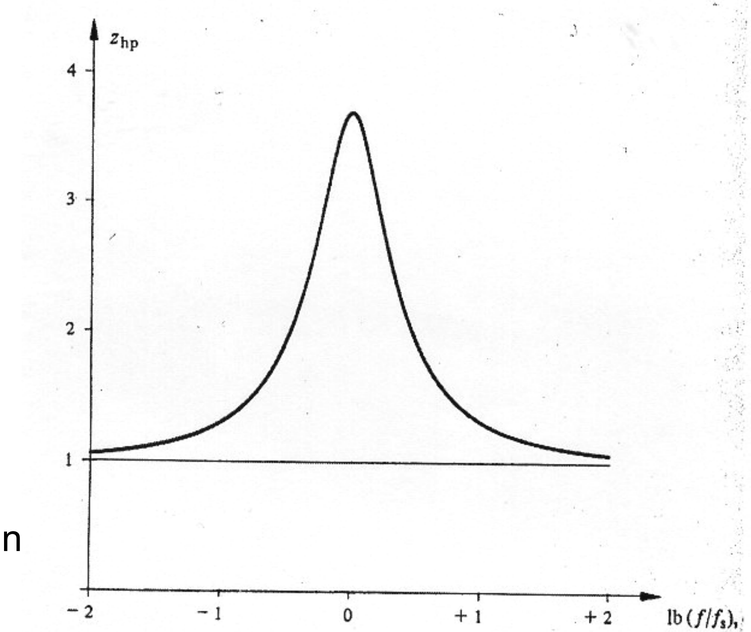
Input impedance

$$\underline{Z}_{HP} = \underline{U}_{HP} / \underline{I}_{HP}$$

At LF:

$$\underline{z}_{HP} = \frac{\underline{Z}_{HP}}{R_e} = 1 + \left[\underbrace{\left(\frac{Q_{ms}}{Q_{es}}\right) \frac{(j\omega/\omega_s)Q_{ms}^{-1}}{(j\omega/\omega_s)^2 + (j\omega/\omega_s)Q_{ms}^{-1} + 1}}_{Z\ \ /R} \right]$$



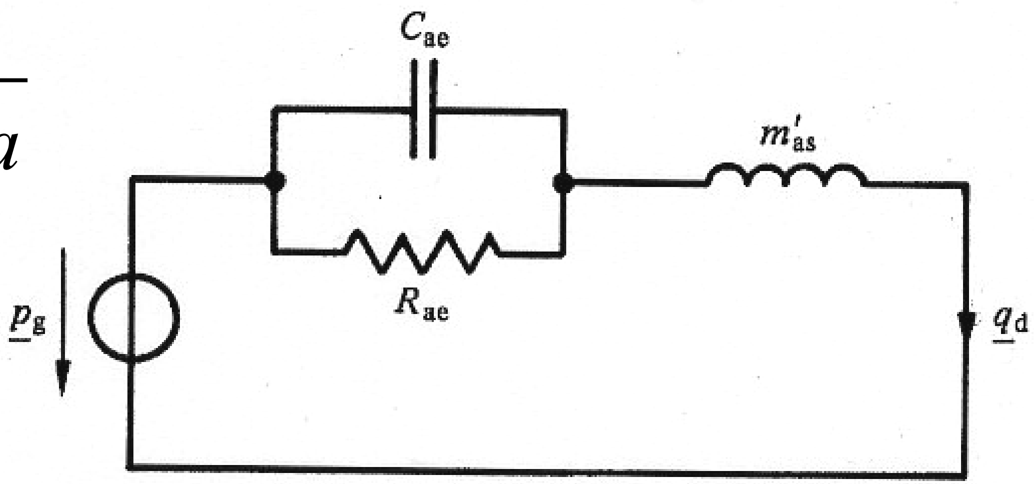


Behavior at high frequencies

HF=around $f_d = \frac{c}{\sqrt{2}\pi a}$

$(\omega L_e) >> R_e$

$\omega m'_{as} >> R_{as} + 2R_{ar}$



➔resonance for:

$$f_s' = \frac{1}{2\pi}\sqrt{\underbrace{\frac{(Bl)^2}{L_e m'_{as} S_d^2} - \frac{(R_g + R_e)^2}{L_e^2}}_{\text{if positive}}}$$

$$\underline{p}_g = \frac{Bl}{j\omega L_e S_d}\bar{U}_g$$

$$m'_{as} = m_{as} + 2\frac{X_{ar}}{\omega}$$

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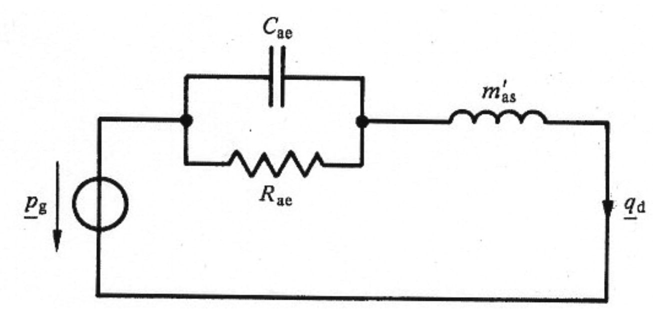
Behavior at high frequencies

below f'_s,

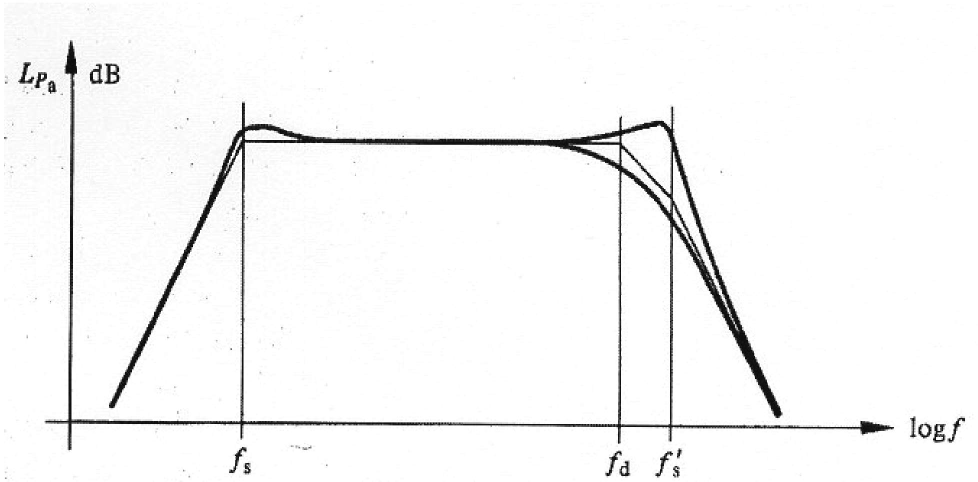
$$\underline{q}_d \cong \frac{\underline{p}_g}{j\omega m'_{as}} = \left(\frac{Bl}{j\omega L_e . j\omega m'_{as} . S_d} \right) . \underline{U}_g$$



decreases in $1/f^2$

R_{ar}~const. since $f > f_d$,

P_a in $1/f^4$ (-12 dB/octave)



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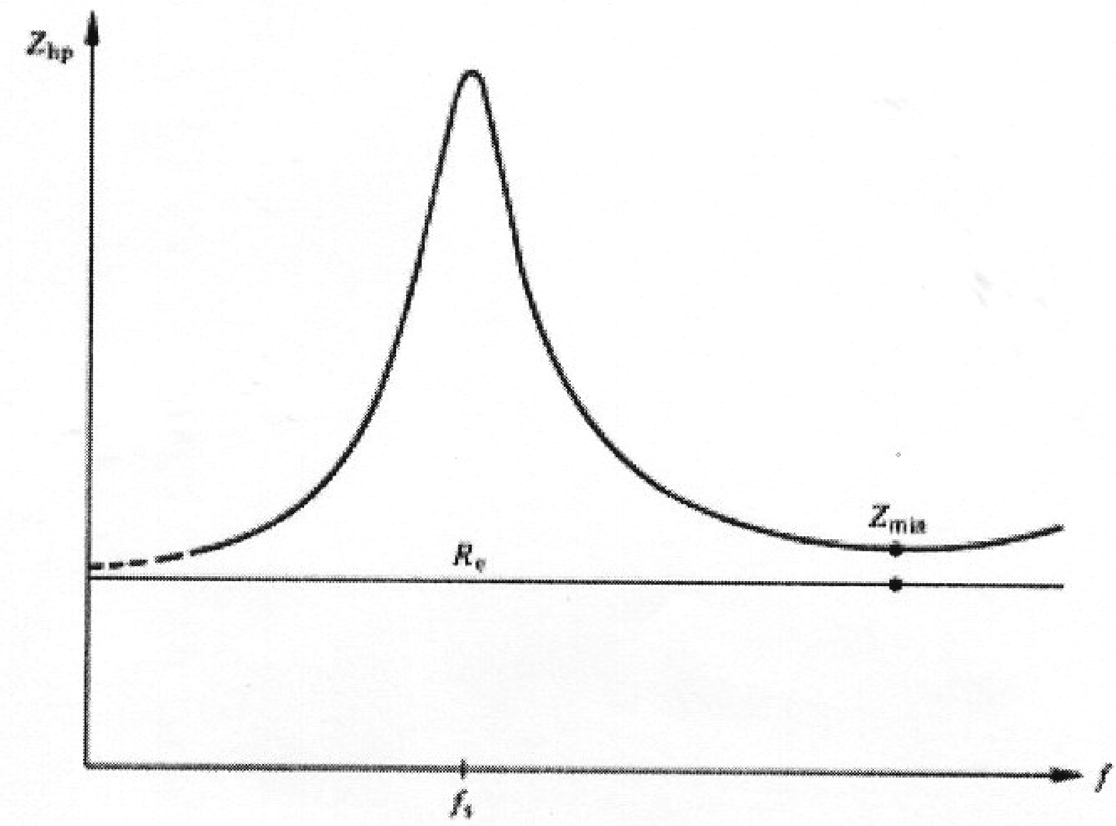
Input impedance in HF

L_e not negligible anymore

f>4.f_s, $\underline{Z}_{em}$ is negligible



Efficiency

$$\text{efficiency} = \frac{\text{radiated acoustic power}}{\text{provided electrical power}}$$

$$P_{er} = \left(\frac{U_g}{R_g + R_e} \right)^2 .R_e$$

$$\eta_s = \frac{P_{as}}{P_{er}} = \left\{ \frac{\rho}{2\pi c} \right\} \left\{ \frac{(Bl)^2}{S_d^2 R_e m'^2_{as}} \right\}$$

$$= 100. \left\{ \frac{4\pi^2}{c^3} \right\} \left\{ \frac{f_s^3 V_{as}}{Q_{es}} \right\}$$

Large signal parameters

Usage limitations:

- P_{th} nominal thermal power handling capacity of the driver : dissipation by heat in the driver
- $\hat{\xi}_{\max}$: maximum linear peak excursion of the cone.
- $\hat{\xi}_h$: maximum excursion of the driver before distorsion, defining a volume $\hat{V}_d = S_d \hat{\xi}_h$
- $U_g \leq \dfrac{\hat{V}_d Q_e \omega_s (Bl)}{\sqrt{2} S_d \underbrace{x_{\max}}_{\max(|x_s|)}}$ voltage limited by distorsion

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Specifications of a loudspeaker

- Physical characteristics
- Polarities of electrical terminals
- Small and large signals parameters
- Performances of the loudspeaker, nominal and limit conditions of use

Nominal quantities

- Nominal power P_n
- Nominal bandwidth B_n
- Nominal impedance Z_n

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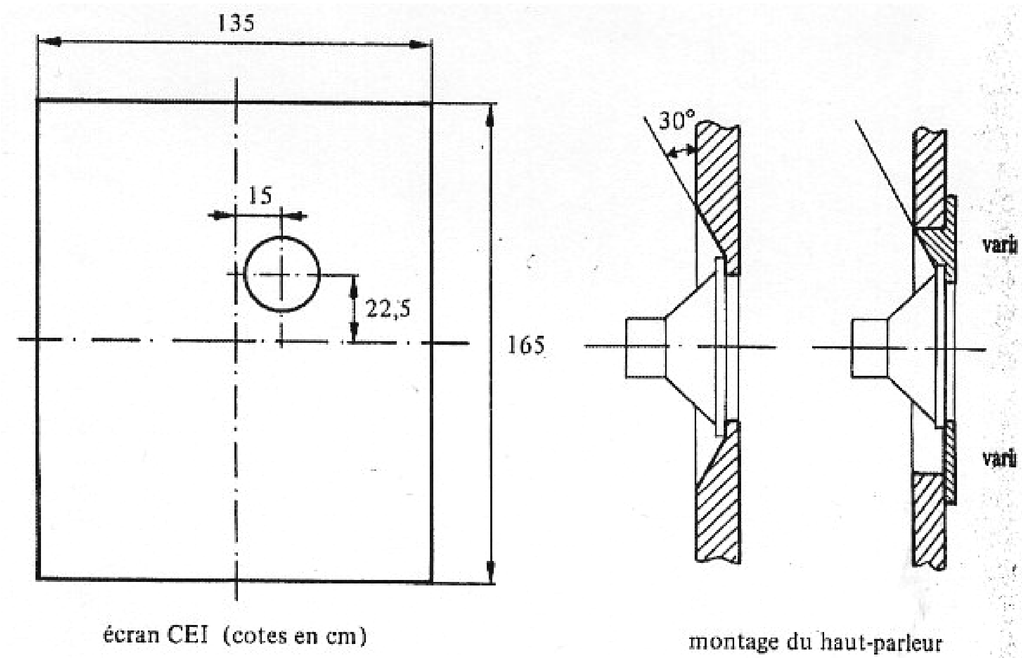
Response curve

- Free field
- Mounted on a normalized screen (IEC or AES)
- Distance of measurement
- Input power = 1/10 of nominal power



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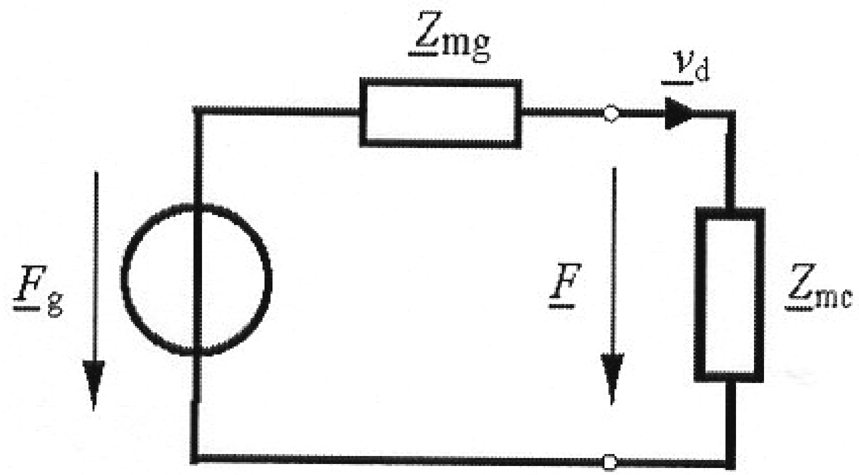
Equivalent Thévenin source

- Loudspeaker = equivalent Thévenin source
- Force source $\underline{F}_g = S_d \underline{p}_g$
- Source impedance $\underline{Z}_{mg}$ (mechanical + mechanical equivalent of R_e and L_e)
- Load impedance $\underline{Z}_{mc}$= front and rear radiation impedances



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