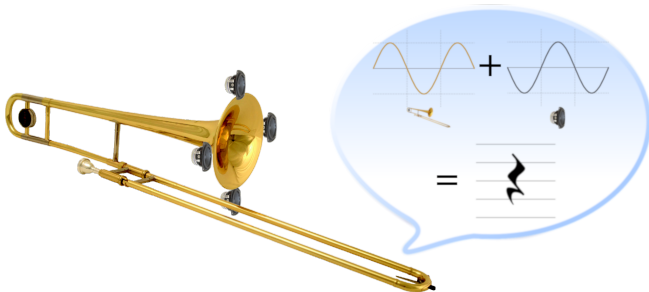


# Loudspeaker Optimisation for Active Control of Trombone Radiation

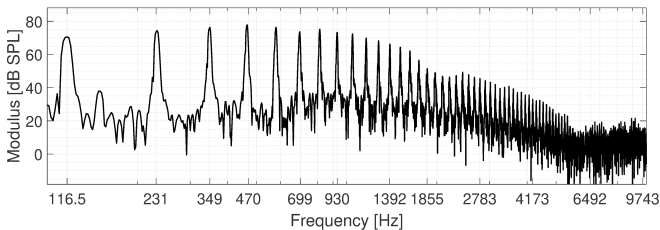


Colas Cavallès, Christophe Ayrault, Manuel Melon, Joël Gilbert and Bruno Gazengel  
email: [colas.cavailles@univ-lemans.fr](mailto:colas.cavailles@univ-lemans.fr)

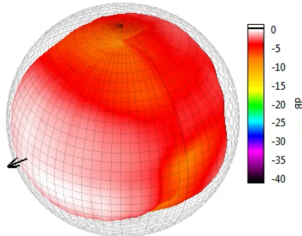
Laboratoire d'Acoustique de l'Université du Mans, LAUM - UMR 6613 CNRS, Le Mans  
Université, Avenue Olivier Messiaen, 72085 LE MANS CEDEX 9, France

# Trombone spectrum & directivity (Eyring, Leishman, & Strong, 2014)

$$L_p(1m) = 110 \text{ dB SPL}$$

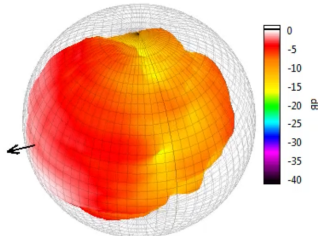


Harmonic = 466 Hz



Frequency Response

Harmonic = 932 Hz



Frequency Response



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# Sound level reduction: passive mute

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(Klawikowski, 2019)

# Sound level reduction: passive mute

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(Klawikowski, 2019)

## Advantage:

Trombone sound level reduced  
- between 10 and 20 dB  
(Ancell, 1960)

# Sound level reduction: passive mute

## Context

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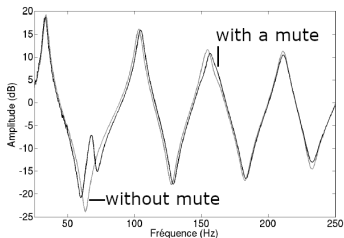
Conclusions



(Klawikowski, 2019)

**Advantage:**

Trombone sound level reduced  
- between 10 and 20 dB  
(Ansell, 1960)



(Meurisse, 2014)

# Sound level reduction: passive mute

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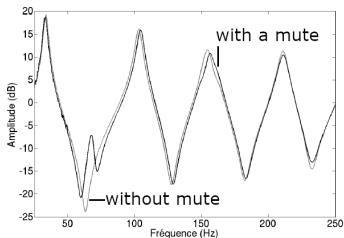
Conclusions



(Klawikowski, 2019)

## Advantage:

Trombone sound level reduced  
- between 10 and 20 dB  
(Ansell, 1960)



(Meurisse, 2014)

## Drawback:

Input impedance so timbre and  
way of playing changed

# Sound level reduction: active mute

Control actuator suspended at trumpet bell opening (Pickett, 1998)



## Drawbacks:

- too heavy,
- sound muffled,
- high sound level to provide (up to 130 dBSPL).

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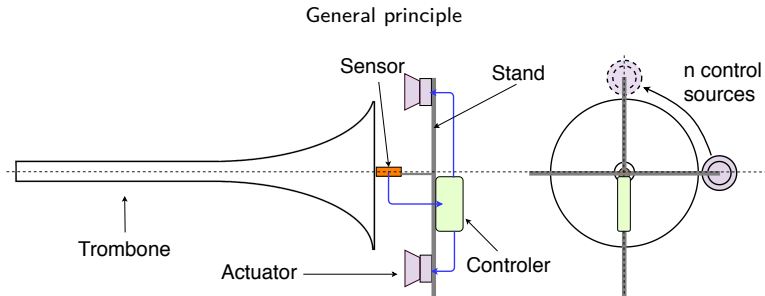
Aim of this work

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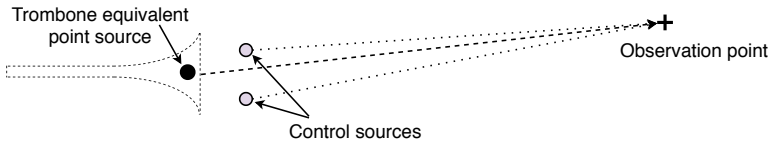
Conclusions



- Aim of the work : control the radiated power of the trombone
- Constraints : low modification of impedance, light



# Aim of this work



- Work objectives:
  - trombone equivalent point source:
    - ▶ Position? Volume velocity?

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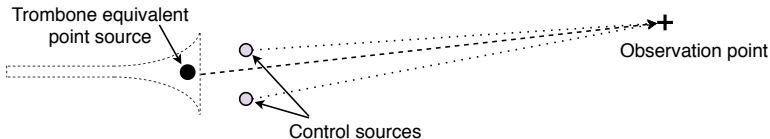
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# Aim of this work



- Work objectives:
  - trombone equivalent point source:
    - ▶ Position? Volume velocity?
  - loudspeaker:
    - ▶ Required diaphragm excursion, electrical power, number of speakers?

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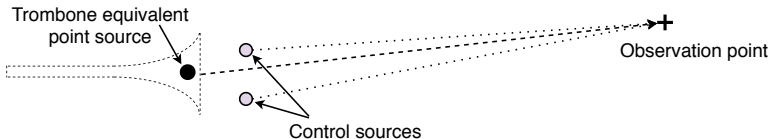
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# Aim of this work



- Work objectives:
  - trombone equivalent point source:
    - ▶ Position? Volume velocity?
  - loudspeaker:
    - ▶ Required diaphragm excursion, electrical power, number of speakers?
  - optimal control:
    - ▶ Impact of number and position of the control sources on radiation?

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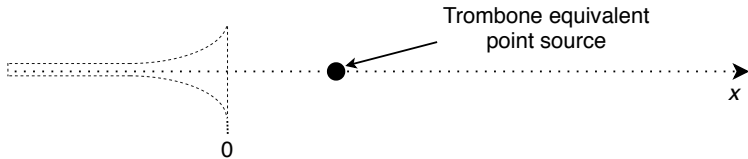
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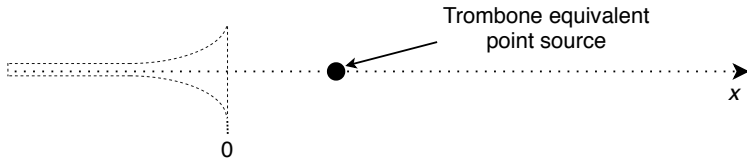
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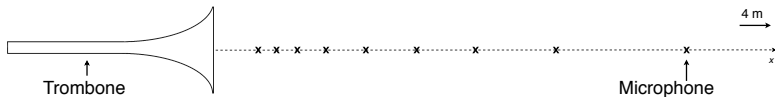
Conclusions



Position and volume velocity according to:

- the frequency (fundamental and harmonics),
- the dynamic marking (piano, mezzo-forte, forte).

# Experiment



## Context

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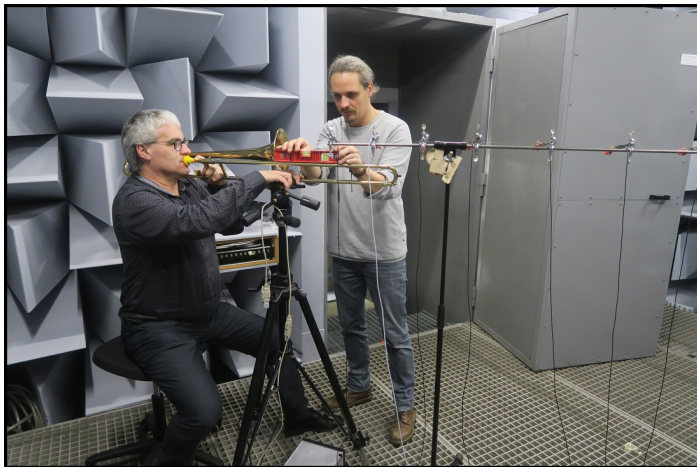
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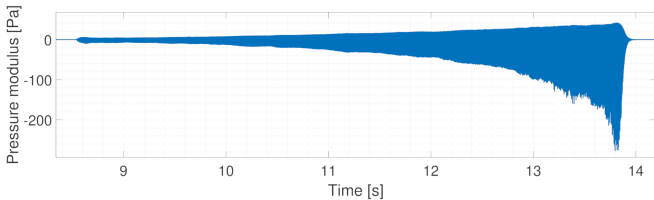
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# Experiment

## Sound at 23 cm from horn

B flat 4 ( $f = 466$  Hz) during 5 seconds.



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# Experiment

## Sound at 23 cm from horn

### Context

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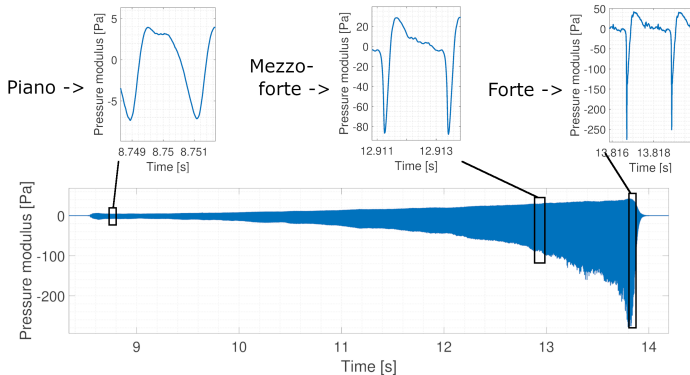
### Primary source characterization

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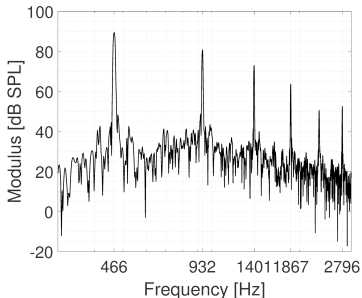
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B flat 4 ( $f = 466$  Hz) during 5 seconds.



# Volume velocity & position calculation

Example for one dynamic marking, for one note and one microphone position:



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# Volume velocity & position calculation

Example for one dynamic marking, for one note and one microphone position:

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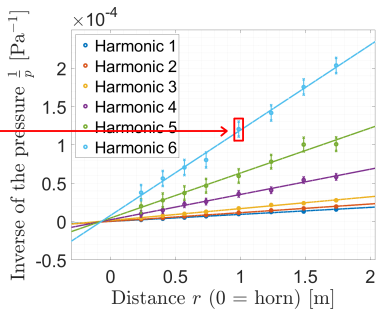
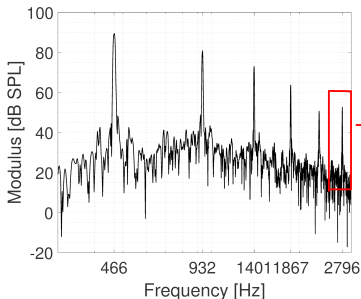
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# Volume velocity & position calculation

Example for one dynamic marking, for one note and one microphone position:

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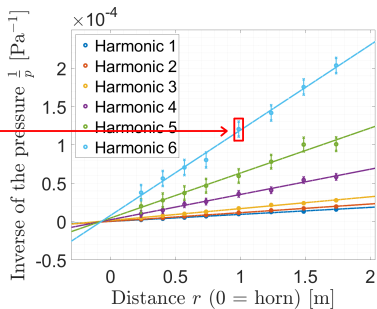
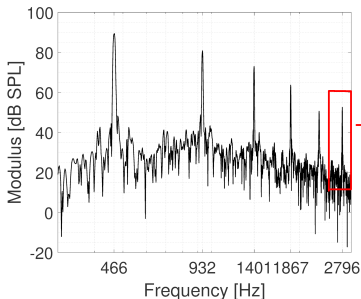
Aim of this work

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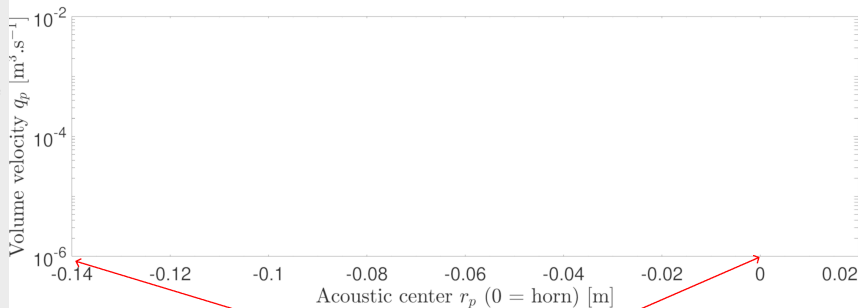
Linear regression  
on  $1/p = f(r)$



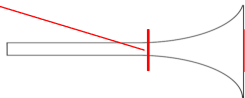
$$\begin{bmatrix} q_p \\ r_p \end{bmatrix}$$

# Result: Volume velocity versus position

$q_p$  according to  $r_p$  for B flat 4 ( $f = 466$  Hz)



Horn position  
on the x axis



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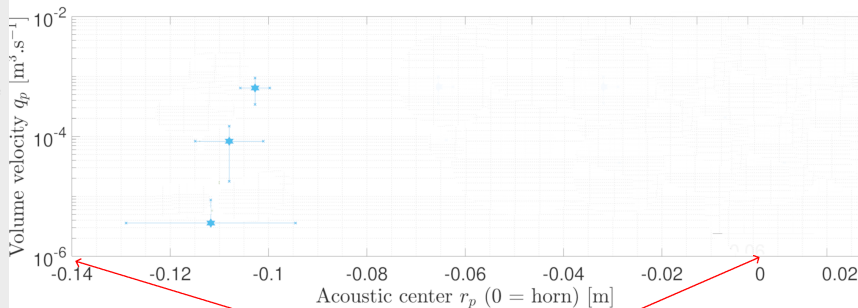
Control source  
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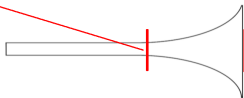
Conclusions

# Result: Volume velocity versus position

$q_p$  according to  $r_p$  for B flat 4 ( $f = 466$  Hz)



Horn position  
on the x axis



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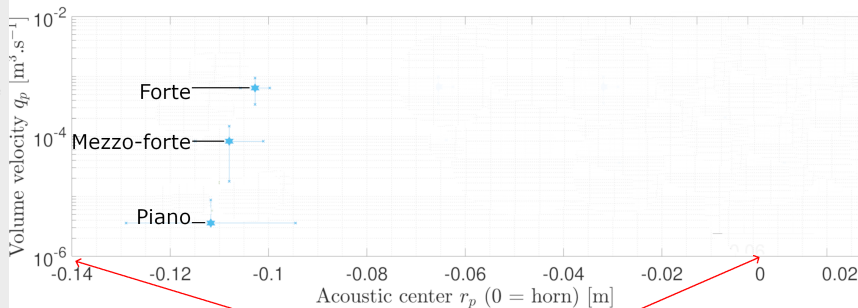
Control source  
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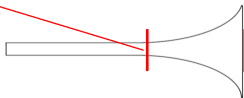
Conclusions

# Result: Volume velocity versus position

$q_p$  according to  $r_p$  for B flat 4 ( $f = 466$  Hz)



Horn position  
on the x axis



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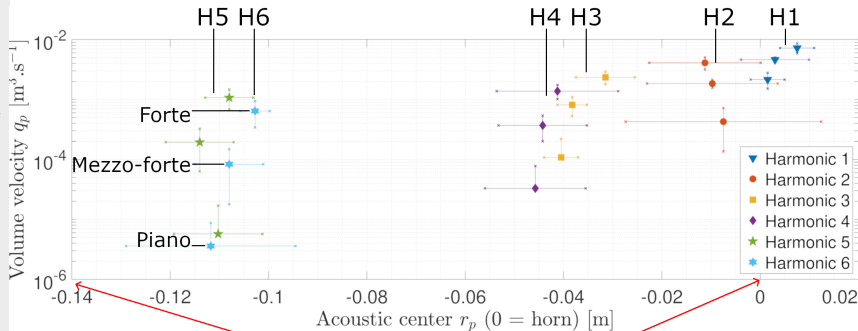
Control source  
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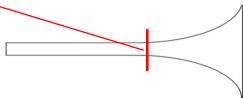
Conclusions

# Result: Volume velocity versus position

$q_p$  according to  $r_p$  for B flat 4 ( $f = 466$  Hz)



Horn position  
on the x axis





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# Loudspeaker volume velocity (Small, 1971)

## Context

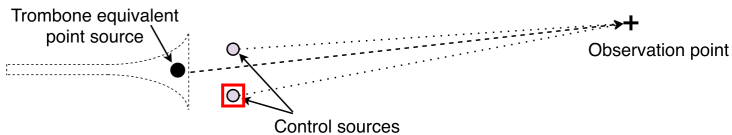
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# Loudspeaker volume velocity (Small, 1971)

Context

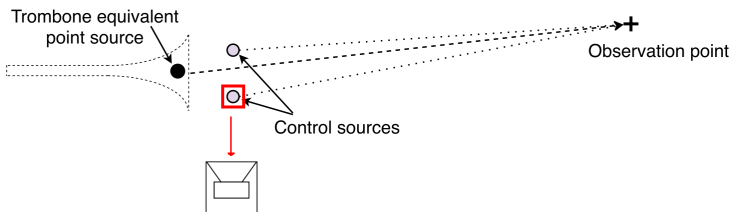
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# Loudspeaker volume velocity (Small, 1971)

## Context

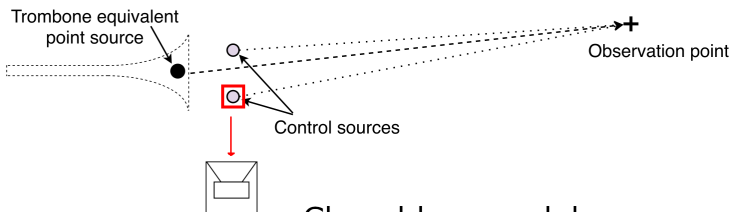
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## Primary source characterization

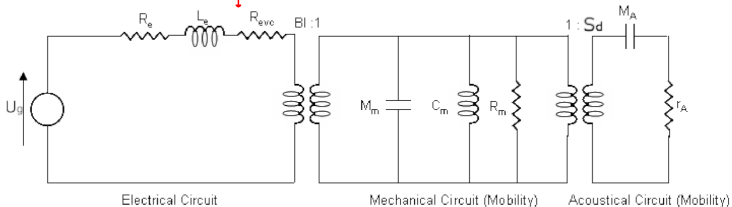
## Control source optimisation

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## Closed box model



# Loudspeaker volume velocity (Small, 1971)

Context

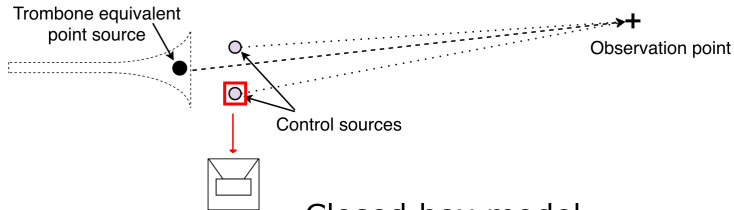
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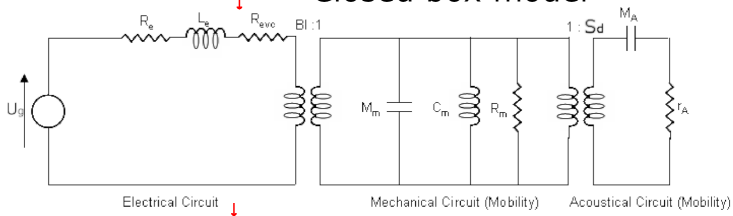
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## Closed box model



(Lund, 2019)

$$\frac{q_c}{U_g} = \frac{S_d}{Q_e \cdot BI} \cdot \frac{G_c(j\omega/\omega_c)}{j\omega/\omega_c} \quad (1)$$

$$G_c(j\omega/\omega_c) = f(R_e, C_m, R_m) \quad (2)$$

# Loudspeaker parameters

## Constraints

- $f_s = \pm 100$  Hz
- $x_{\max} = \pm 5$  mm
- High power capacity
- Weight: light
- Diameter:  $\leq 4$ "
- High sensitivity

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# Loudspeaker parameters

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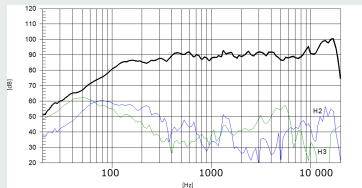
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## Constraints

- $f_s = \pm 100$  Hz
- $x_{\max} = \pm 5$  mm
- High power capacity
- Weight: light
- Diameter:  $\leq 4$ "
- High sensitivity

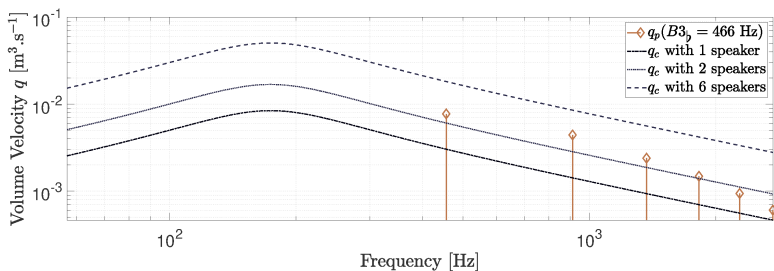
## Manufactured speaker: Beyma 3FR30Nd

- $f_s = 188$  Hz
- $x_{\max}$ :  $\pm 4.5$  mm
- Power capacity: 30 W
- Weight: 0.25 kg
- Diameter: 3"
- Sensitivity: 92 dB SPL  
1W/1m



# Required power

For one harmonic:



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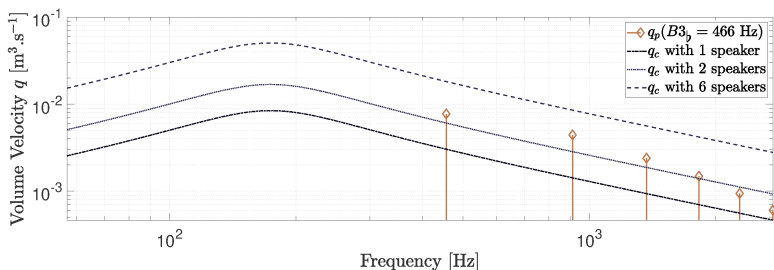
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# Required power

For one harmonic:



$$P = \left( \frac{Q_e B l}{S_d N_s} \right)^2 \frac{1}{2 \cdot Z_e} \sum_{i=1}^{N_h} \left| \frac{q_p(\omega_i) \cdot \frac{\omega_i}{\omega_c}}{G_C(\frac{\omega_i}{\omega_c})} \right|^2 \quad (3)$$

<b>Number of speakers</b>	1	2	3	4	5	6	7	8
<b>Needed power (W)</b>	476	119	53	30	19	13	10	7.5

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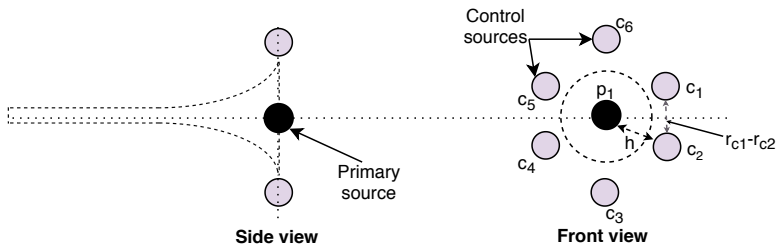
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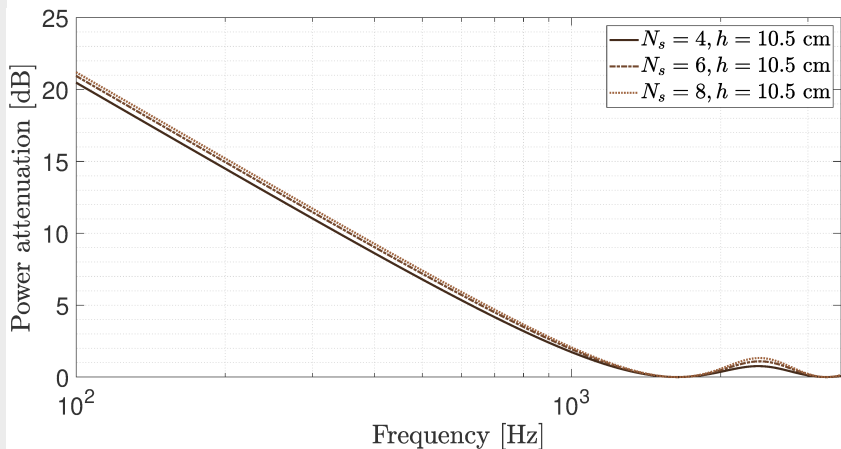
Conclusions

Disposition of primary and control sources for a control with a ring of monopoles



$$\frac{W_{tot}}{W_p} = 1 - \frac{N_s \text{sinc}^2(kh)}{\sum_{i=1}^{N_s} \text{sinc}(k|r_{c1} - r_{ci}|)} \quad (4)$$

## Power attenuation - Number of speakers impact (Bolton, 1995)



$$\frac{W_{tot}}{W_p} = 1 - \frac{N_s \cdot \text{sinc}^2(kh)}{\sum_{i=1}^{N_s} \text{sinc}(k|r_{c1} - r_{ci}|)} \quad (4)$$

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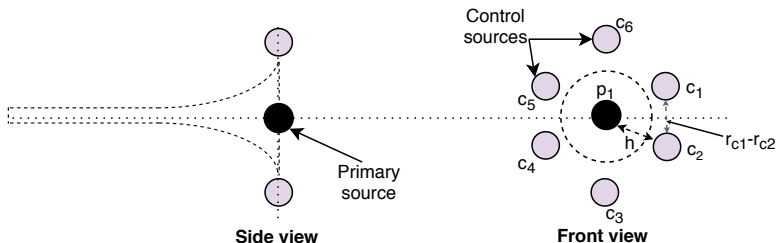
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Disposition of primary and control sources for a control with a ring of monopoles



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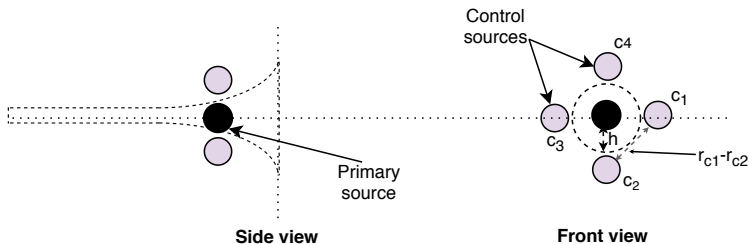
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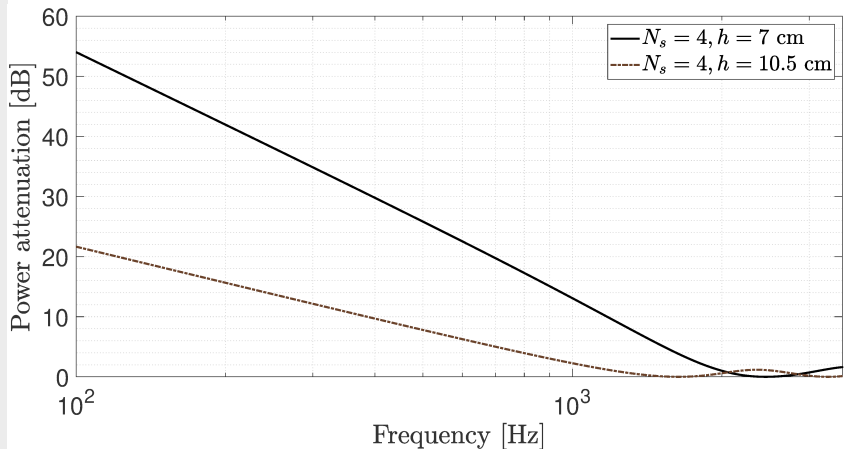
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Disposition of primary and control sources for a control with a ring of monopoles



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## Power attenuation - Position of speakers impact (Bolton, 1995)



$$\frac{W_{tot}}{W_p} = 1 - \frac{N_s \text{sinc}^2(kh)}{\sum_{i=1}^{N_s} \text{sinc}(k|r_{c1} - r_{ci}|)} \quad (4)$$

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## Conclusion:

- primary source:  $q_{p_{\max}} = 0,01 \text{ m}^3 \cdot \text{s}^{-1}$ ,  $-12 \text{ cm} \geq r_p \geq 0 \text{ cm}$ ,
- chosen loudspeaker:  $P_{\text{capacity}} = 30 \text{ W}$ , 4 speakers minimum to control the 6 first harmonics,
- optimal control: efficient attenuation until  $kh = n\pi$  ( $f = 1500 \text{ Hz}$ ).

## To be followed:

- optimal control model for shifting and moving primary source,
- comparison theory/experiment,
- impact of an external control on input impedance,
- directivity control.



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$$\frac{q_c}{U_g} = \frac{S_d}{Q_e \cdot Bl} \cdot \frac{G_c(j\omega/\omega_c)}{j\omega/\omega_c} \quad (5)$$

$$G_c(j\omega/\omega_c) = f(R_e, C_m, R_m) \quad (6)$$

$$G_c(j\omega/\omega_c) = \frac{(j\omega/\omega_c)^2}{(j\omega/\omega_c)^2 + Q_{tc}^{-1}(j\omega/\omega_c) + 1} \quad (7)$$

$$Q_{tc} = \frac{Q_{ec}Q_{mc}}{Q_{ec} + Q_{mc}} \quad (8)$$

$$Q_{ec} = \frac{Re}{\omega_c C_{as}} \left( \frac{S_d}{Bl} \right)^2 \quad (9)$$

$$Q_{mc} = \frac{1}{\omega_c C_m R_m} \quad (10)$$