Psychoacoustic analysis of pneumatic switching valve noise

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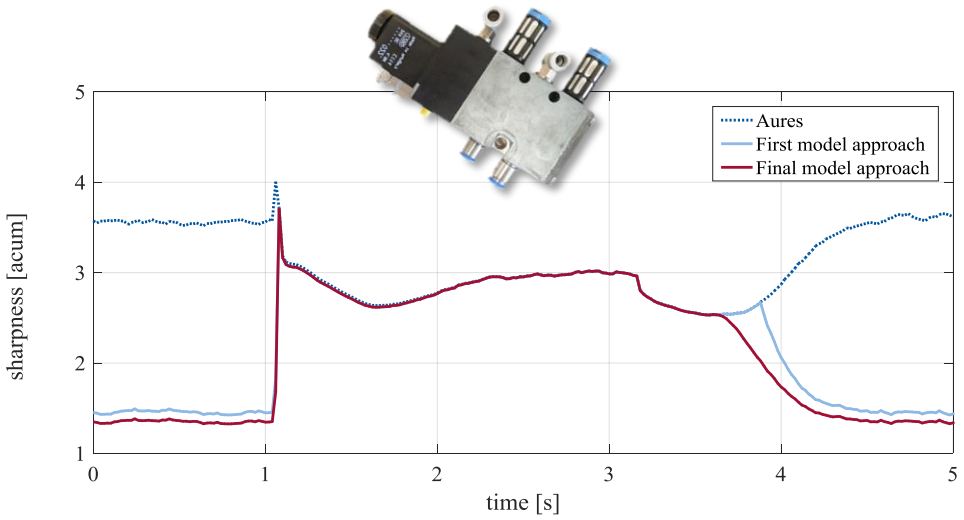


Motivation

Results of **Regular** noise analysis of **pneumatic standard components**

- A-weighted sound pressure levels (**SPL**) **within regulatory limits**
- **Noise** still described as **unpleasant**
- **Psychoacoustic** measures **reinforce** the **subjective perception**

Analysis focused on **psychoacoustic noise** emission of pneumatic **valves** and **exhaust ports**

Outline

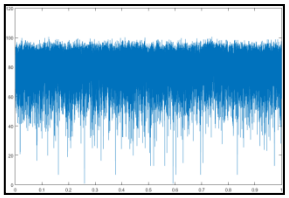
Acoustics (A) vs. Psychoacoustics (PA)

Acoustic Analysis

Psychoacoustic Analysis

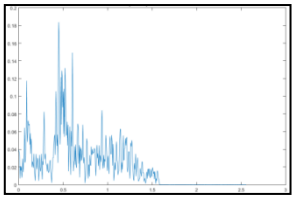
Measurement

Transient sound pressure



FFT

Frequency transformation

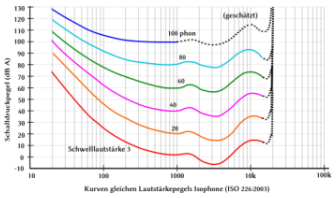


SPL

Sound pressure level

Weighting

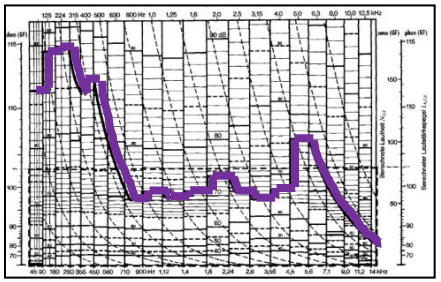
Frequency dependent hearing



Detailed frequency weighting

Definition of

- Loudness
- Sharpness
- ...



Potential

$L_p \downarrow$  Less noisy/ More convenient

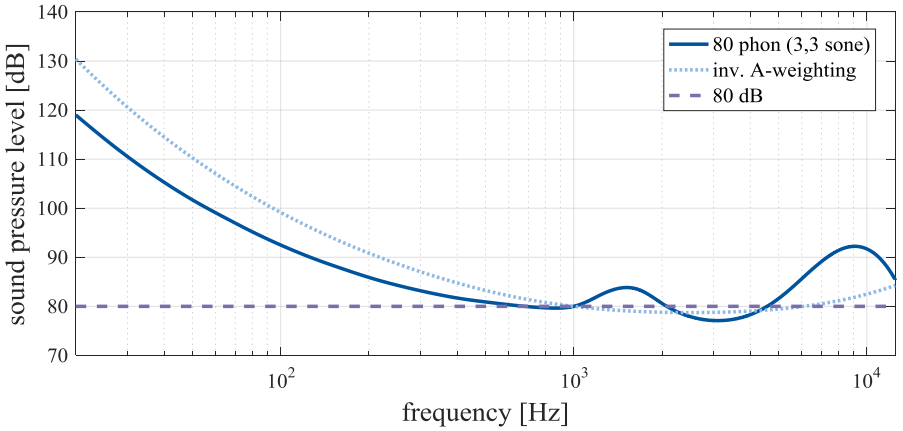
Objectification of subjective measures

Sources: DIN 45631, 1991; DIN 226, 2006; Zwicker, 2013

PA Parameters – Loudness & Sharpness

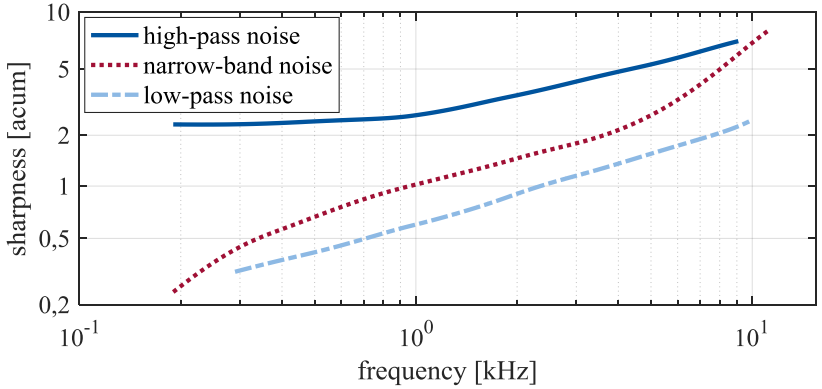
Loudness

- **A-Weighting** only **rough estimation** of human hearing perception
- **Loudness** is a **more advanced model** based on hearing experiments



Sharpness

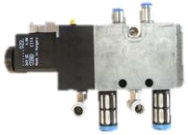
- **Sharpness objectifies** sounds described as ***squealing*** or ***jarring***,
  e.g. vacuum cleaner
- Mainly **influenced by spectral envelope and center frequency** of spectrum

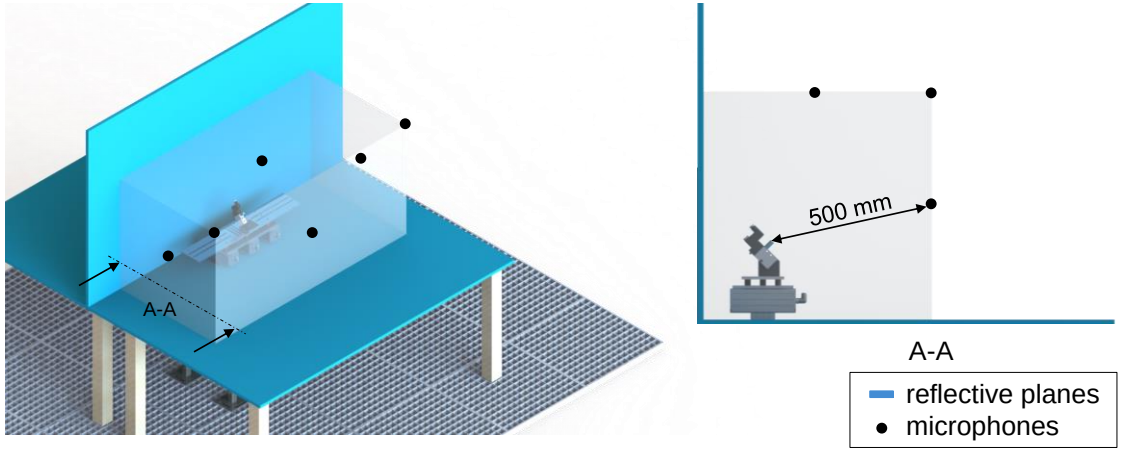


Sources: DIN 45631, 1991

Outline

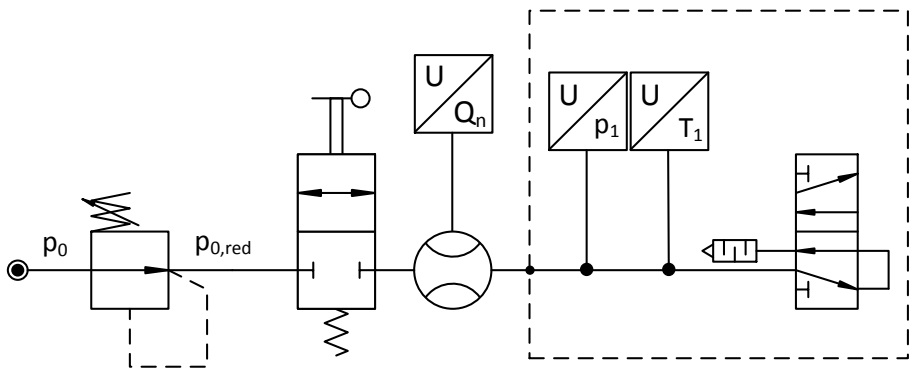
Test Bench Setup





- Setup **based on DIN ISO 3744** with 6 microphones
- Measurements
  - Stationary exhaust
  - Transient actuator exhaust

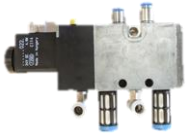
Circuit Diagram

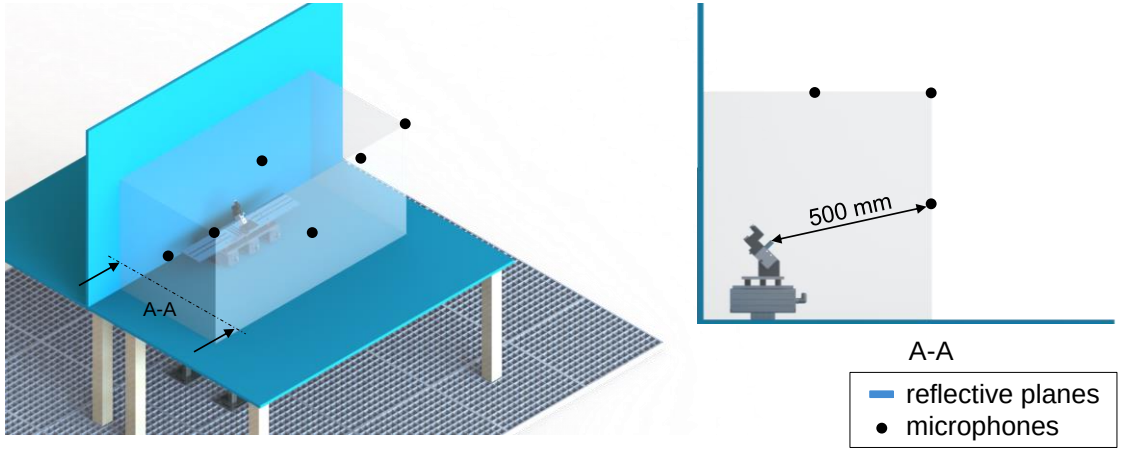


Parameter	Scope	
	min	max
$p_{inlet,rel}\ [bar]$	0	4
$Q_n\ [Nl/min]$	0	800

Sources: DIN ISO 3744, 2006

Test Bench Setup





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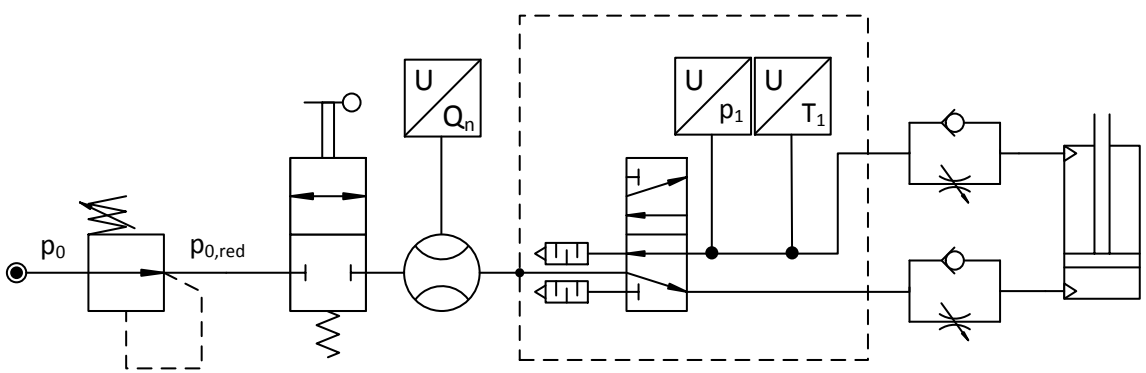
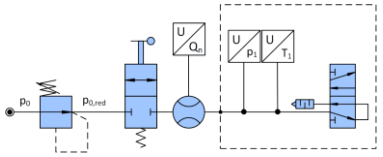


Parameter	Scope	
	min	max
$p_{inlet,rel}\ [bar]$	0	4
$Q_n\ [Nl/min]$	0	800
$v_{cyl}\ [m/s]$	0,01	0,5

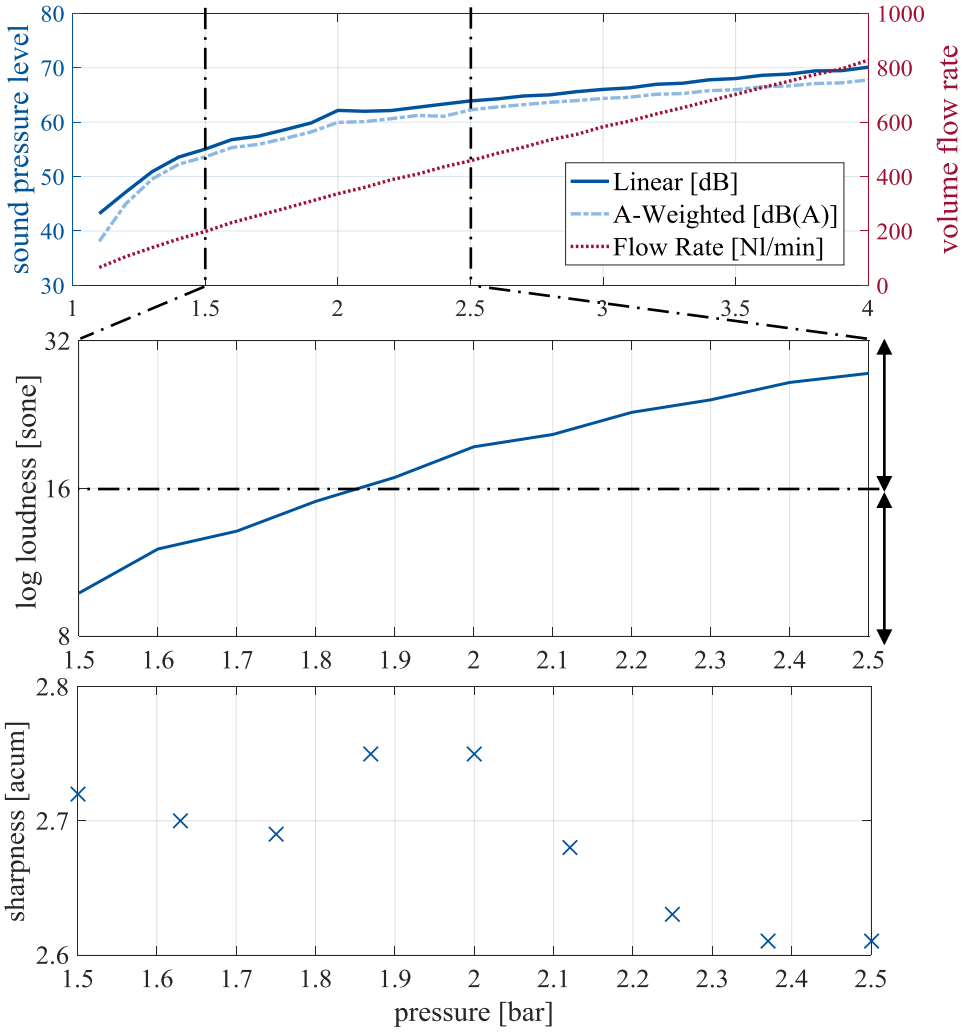
Sources: DIN ISO 3744, 2006

Measurement Results - Stationary

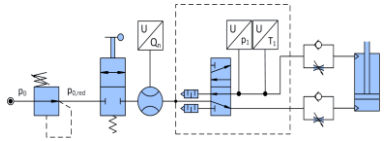


- **SPL increases with inlet pressures** due to higher velocities (40 to 65 dB)
- Loudness
  - **Logarithmic scale offers intuitive interpretation** of human perception
  - Distance of appx. 2 corresponds to a doubling
- Sharpness
  - **No significant trend**, yet it shows a maximum at transition to super critical flow
  - **Minimum at highest volume flow**

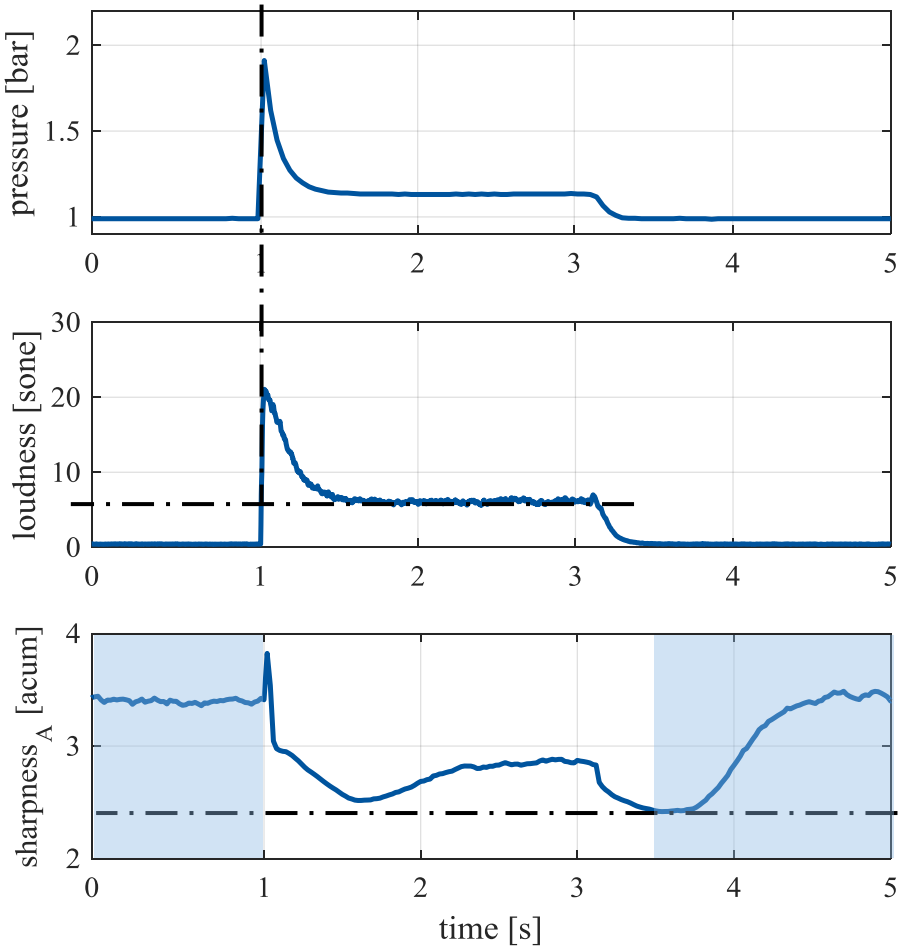
Remarks



Measurement Results - Transient



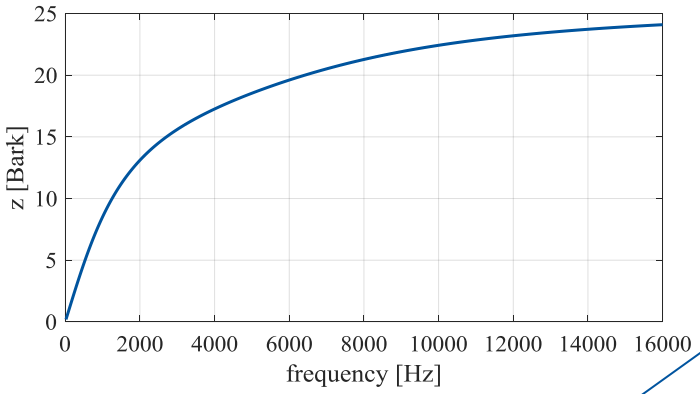
- Transient measurements show a **peak of loudness when** the **movement** of the actuator **starts**
- After acceleration, **loudness converges** to a constant level until movement stops
- Sharpness leads to **two impressing conclusions**
  1. Changes during stationary movement
  2. Level during rest represents its maximum



More detailed analysis of the sharpness model necessary

Model Sensitivity Analysis

- **Sharpness** is a **function based on** frequency scale **Bark** (parameter *z*)



$$S(z) = c \cdot \frac{\int N'(z)\, g_i(z)\, z\, dz}{\int N'(z)\, dz}$$

- Calculation by **weighted loudness function**
- Different existing weighting functions
  - Zwicker, DIN 45692
  - **Standard given by Aures**

Aures

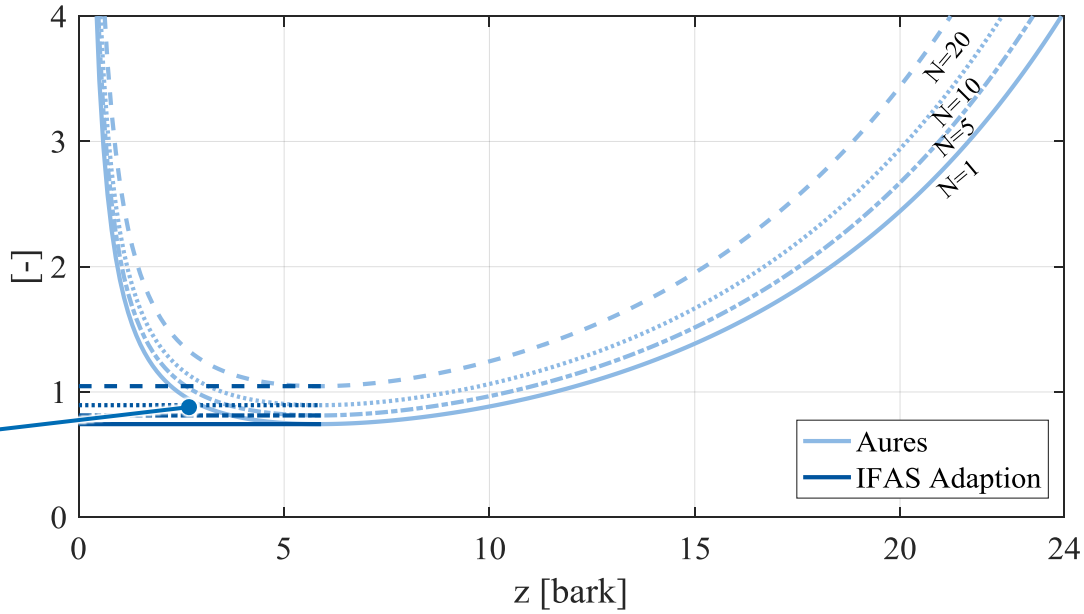
$$g_A(z) = 0{,}078 \underbrace{\frac{e^{0{,}171 \cdot z}}{z}}_{\text{frequency scaling}} \underbrace{\frac{\int_{z=0}^{z=24} N'(z)\, dz}{\ln\left(0{,}05 \cdot \int_{z=0}^{z=24} N'(z)\, dz + 1\right)}}_{\text{loudness scaling}}$$

Outline

Model Adaption – Frequency Scaling

- Analysis of frequency scaling for constant loudness levels
  - Discontinuity at 0 Bark
  - **Overestimation of low frequency noise** (e.g. structure oscillations, base frequencies)

$$g_A(z) = 0.078\,\frac{e^{0.171\cdot z}}{z}\,\frac{\int_{z=0}^{z=24} N'(z)\,dz}{\ln\left(0.05\cdot\int_{z=0}^{z=24} N'(z)\,dz + 1\right)}$$



- Functional adaption
  - Localization of function's minimum
  - Constant extrapolation by the minimum's value

Model Adaption – Loudness Scaling

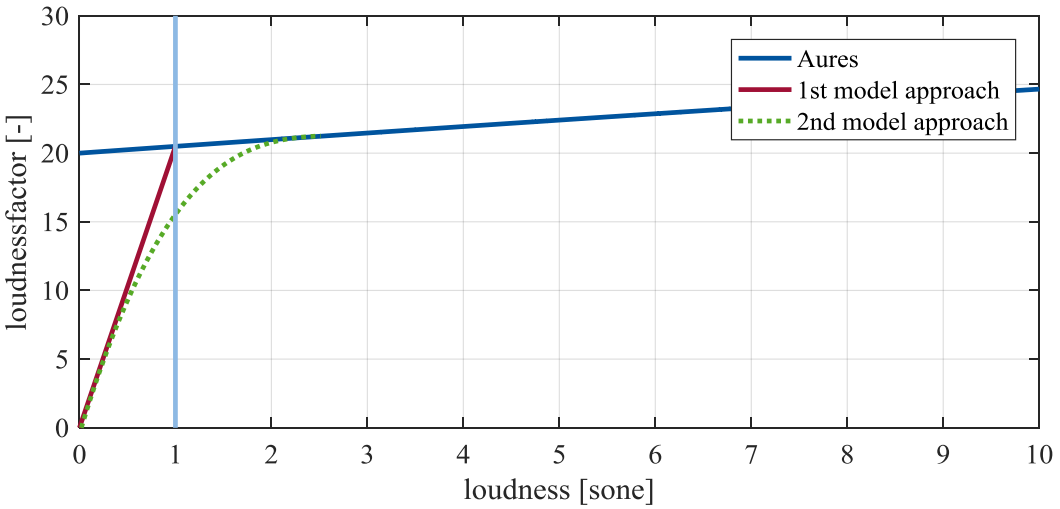
- Definition of loudness factor

$$a_A(N) = \frac{N}{\ln(0.05 \cdot N + 1)}$$

- Discontinuity at 0 sone evaluated referring to l'Hospital

$$\lim_{N \to 0} a_A(N) = \frac{\lim_{N \to 0} f'}{\lim_{N \to 0} g'} = 20$$

$$g_A(z) = 0.078 \, \frac{e^{0.171 \cdot z}}{z} \, \frac{\int_{z=0}^{z=24} N'(z)\, dz}{\ln(0.05 \cdot \int_{z=0}^{z=24} N'(z)\, dz + 1)}$$



- Functional adaption
  - **Artificial** linear **reduction of silent noise loudness factor**
  - **Polynomial** approximation **for continuous shape**

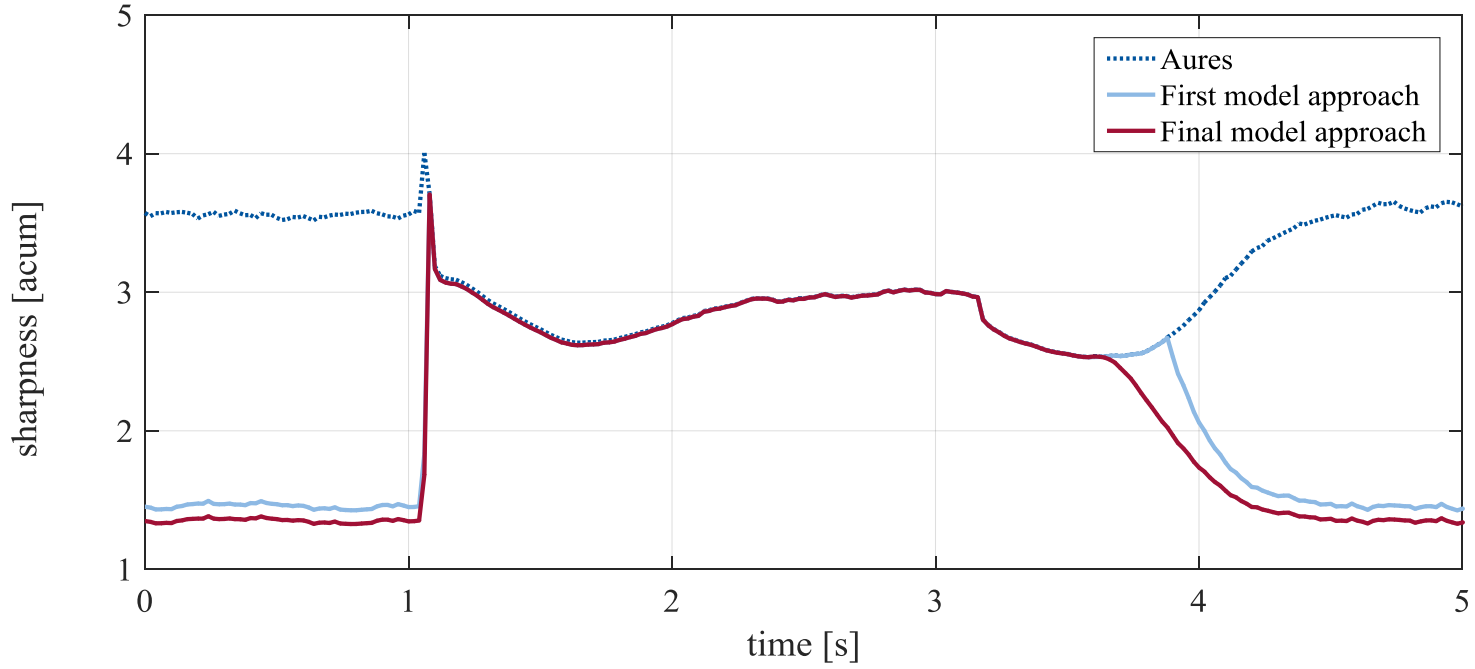
Validation of Adapted Model

$$S = 0.11 \cdot \frac{\int N'(z)\, g_{IFAS}(z)\, z\, dz}{\int N'(z)\, dz}$$

with

$$g_{IFAS}(z,N) = \begin{cases} 0.078\, \dfrac{e^{0.171 \cdot z}}{z}\, a_{LF,IFAS}(N), & z \le 5.848 \text{ Bark} \\ 0.0363 \cdot a_{LF,IFAS}(N), & z > 5.848 \text{ Bark} \end{cases}$$

$$a_{IFAS}(N) = \begin{cases} 0.978 \cdot (N - 2.79)^3 + 21.2399\,, & N \le 2.323 \text{ sone} \\ \dfrac{N}{\ln(0.05 \cdot N\ +\ 1)}\,, & N > 2.323 \text{ sone} \end{cases}$$

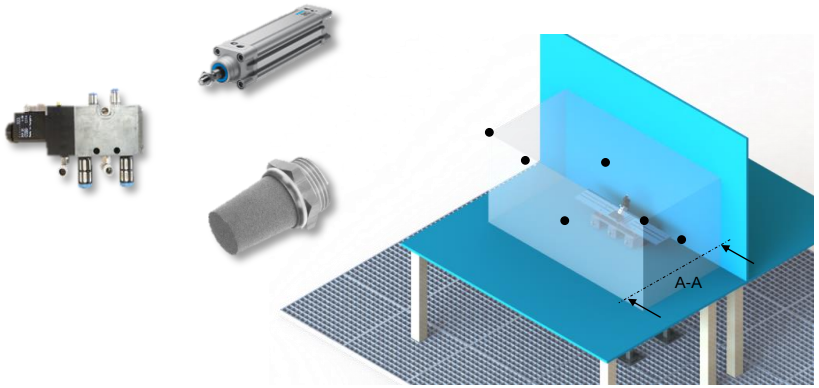


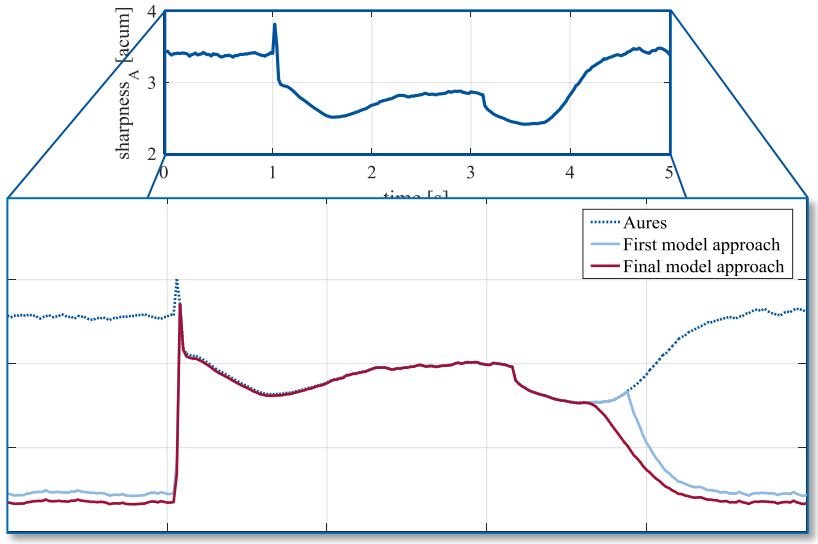
Outline

Conclusion & Outlook

- Summary
  - Motivation of **psychoacoustics** - Illustration of the **visualization benefits for human perception**
  - **Presentation** and **discussion** of **test bench** and **measurement** design
  - **Analysis of loudness** and **sharpness** results **focusing** on **physical reasonableness**
  - **Adaption of sharpness model** with validation of transient exhaust noise measurements

- Outlook
  - **Further psychoacoustic evaluation** of pneumatic noise
  - **Cooperation with medical/acoustic research** for the evaluation of sharpness model





Thank you for your attention!

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