Psychoacoustic analysis of pneumatic switching valve noise

REVIEWED

Maximilian Waerder, M.Sc., M.Sc.*, Univ.-Prof. Dr.-Ing. Hubertus Murrenhoff* and Olaf Uszynski, B.Sc.*

RWTH Aachen University, Institute for Fluid Power Drives and Systems (IFAS), Campus Boulevard 30, D-52074 Aachen, Germany*
E-Mail: maximilian.waerder@ifas.rwth-aachen.de

Pneumatic components and systems are usually considered to be rather unpleasant according to their acoustic appearance especially in the area of industrial large-scale production plants. Within these applications the major part of the noise emission coincides with the outlet ports of valves where the working medium is depressurized. However, former research and development have yield constructive measures and components as mufflers reducing the absolute magnitude of the measurable sound level to a tolerable range. Regulations and legal requirements might thus be satisfied, yet the subjective perception of the sound still tends to be labeled as uncomfortable or even unbearable. These aspects are not considered within the typical metrics of the sound pressure or power level. In order to achieve objective comparisons and an absolute classification of the sound perception psychoacoustic analysis might be adduced. In this study, the correlation between fluidic and psychoacoustic parameters is investigated. The differences according to the sharpness and loudness during operation of a valve are analysed and a methodology on a possible interpretation and evaluation of the psychoacoustics is given. In detail, the dependency of pressure drop, magnitude of the volume flow through a switching valve with standard exhaust muffler on the noise characteristics is presented. Due to presented results, an enhancement of the models was required and will be discussed in this paper correlating the sharpness to the level of perceptible noise. As a conclusion, the investigation posts a proposal for a psychoacoustic benchmark of pneumatic valves leading to an advanced objective and more suitable way of evaluating noise emissions. Hence, nuanced optimization measures in early phases of development are possible.
Keywords: Pneumatics, Noise, Acoustics, Psychoacoustics, Valve design
Target audience: Pneumatics, Design Process, Systems

1 Introduction

During the last decades the relevance of psychoacoustics within acoustic investigations has been rising. This special research area does not only deal with acoustics from the physical point of view but from the human perception perspective. The motivation for extending conventional acoustic analysis lies in the inaccuracy of disregarding the disparity between physical stimulus and human perception. This can lead to insufficient legal noise limits referring to sound pressure levels which can be complied, although the sound remains loud or unpleasant.

Although psychoacoustics is already an integral part of many domains (e.g., automotive, communication engineering, etc.) there are no detailed studies in the field of pneumatics yet. Thus, pneumatic standard components are analysed to emphasize the relation between fluidic and psychoacoustic parameters, enabling more accurate measures and utilising these for optimisation in the early conception phase. The long-term goal is to achieve a highly diversified relation-matrix of pneumatic standard components and their psychoacoustic characteristics depending on fluidic parameters. On the other hand, the psychoacoustic character of an overall system that can be derived from the knowledge of the installed components. Therefore, it is necessary to investigate existing psychoacoustic models (e.g. loudness and sharpness), identify the advantages and disadvantages and to proof the applicability of the models for pneumatic purposes.

2 Theoretical basis

2.1 Necessity of psychoacoustics

Acoustic is the well-known science of sound and its propagation in air. Psychoacoustic though is an incipient part of acoustics that deals with the effect of the humanly perceived sound. Acoustical measures (i.e., sound pressure and particle velocity) are explicit physical quantities whereas psychoacoustic values describe the subjective sensation of these values. Although these sensations vary among each individual, there are some similarities following certain regularities. Therefore, the main function of psychoacoustics is to objectify the subjective perception.

In common speech words such as *loud/quiet, high/low, roaring, jarring, pleasant/unpleasant, squealing, droning* and much more are used to describe an acoustic perception. The difficulty is to quantise these characteristics of a sound in order to achieve comparability. Psychoacoustic research has already been yielding approaches for this challenge /8/. Two of the fundamental psychoacoustic measures (i.e., loudness and sharpness) are thus introduced in the following. Particular attention is laid upon the opportunity of using these measures for describing pneumatic valves' exhaust noise.

2.2 Loudness

A high sound pressure is a rough criterion to compare noises. However, if the spectral composition of the noises is different, the sound pressure of one sound might be higher although the other sound is sensed louder. This is based on the filter effects of the human hearing. The first step to integrate this phenomenon in common acoustic analysis is the A-weighting which is a filter function applied to the spectral distribution of the sound pressure or power level. It is a simplified model of the filter effects and already an inherent part of standard acoustics /4/. Nevertheless, this simplified model leads to massive deviations for certain noises so that the parameter loudness is introduced.

The loudness is based on the loudness level in *phon*, which results from auditory experiments and indicates how loud a noise is sensed compared to a reference signal at 1 kHz. Figure 1 illustrates the essential differences between A-weighting and loudness.

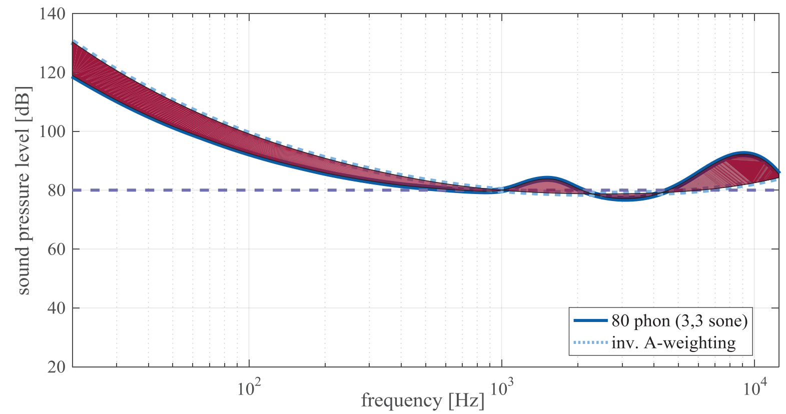

Figure 1: Loudness, loudness level and A-weighting concerning 80 dB

By definition, the reference signal at 1 kHz and a sound pressure level of 80 dB is set to 80 phon. Here, one can identify the sound pressure level of a test signal at a certain frequency to be sensed equally loud as the reference signal, i.e., a signal at 100 Hz and 92 dB having the same loudness level. The red section illustrates the deviation between the loudness level and the A-weighting. The difference rises up to 10 dB at towards low frequencies which corresponds to a factor > 8 for incoherent noises. The frequency range between 1000 and 4000 Hz is, furthermore, strongly varying due to the human hearing. Thus, for detailed comparison of narrow band noise perception the application of loudness is mandatory.

The most common method of loudness calculation is the graphical method by Zwicker /1/. Typically, the specific loudness *N* is given over the pitch *z* denoted by *bark*. Bark is an alternative frequency scaling which is normalised in a certain manner so that a doubling in bark is equivalent to a noise that is sensed twice as high. Figure 2 visualizes the complete process of calculating the total loudness of a measured sound pressure signal with respect to Zwicker.

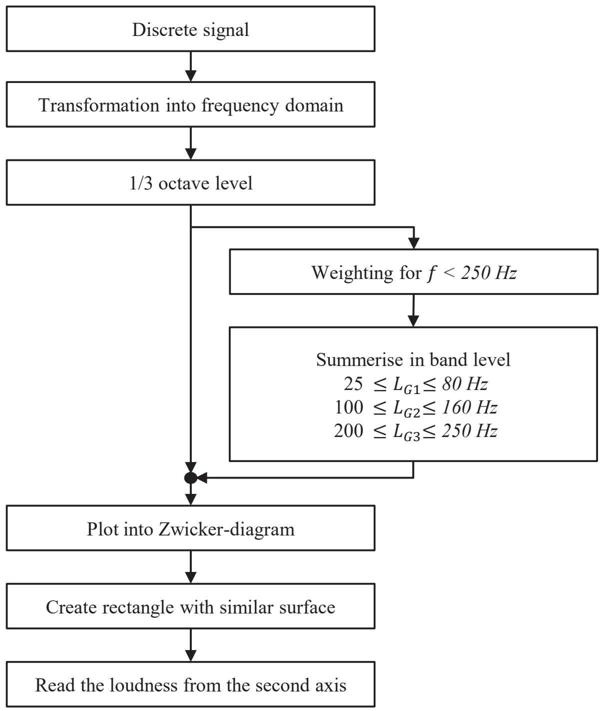

Figure 2: Flowchart for the loudness calculation by Zwicker

First of all, the time-varying signal is transformed into the frequency domain commonly using the Fourier-Transformation to determine the sound pressure level for each third octave. Depending on the center frequencies, the sound pressure level is either plotted straight in the Zwicker-template or first summarized in critical bands. The summary is necessary since the third octaves above 300 Hz are only an admissible approximation for the critical bands. The total loudness is obtained creating an equally-sized rectangle. For more detailed information on this method see /1/.

2.3 Sharpness

The psychoacoustic value *sharpness* is introduced to investigate the auditory phenomenon described by the words *high/low, squealing* and *jarring* and is defined by DIN 45692 /2/. This value also enables a quantitative comparison of two acoustic events and is denoted in *acum*. The decisive influence on the sharpness is the spectral envelope and the centre frequency which was determined by means of empiric acoustic experiments (cf. Figure 3). Furthermore, the loudness has a slight influence on the sharpness. Therefore, the specific loudness is used for sharpness-calculation.

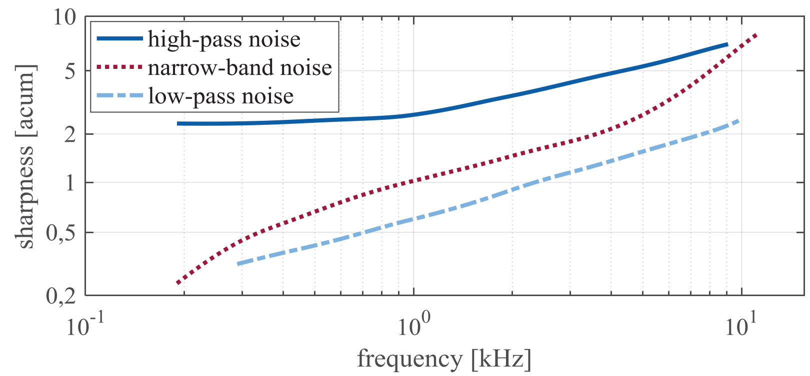

Figure 3: Results of hearing tests for determining the relation between sharpness and frequency

These results illustrate the proportional relation between the centre frequency and the sharpness. To match the results of the hearing tests, the specific loudness needs to be weighted. The weighting-function is used to determine the spectral centroid subsequently. Equation (1) shows the analytic relation between the sharpness *S* and the specific loudness *N'* /2/.

$$S = c \cdot \frac{\int N'(z)\, g(z)\, z\, dz}{\int N'(z)\, dz} \qquad (1)$$

The factor *c* is set to 0,11 in order to meet the requirement of defining a reference signal of 1 kHz to 1 acum. The function *g* is the weighting-function and the only distinguishing feature of the different calculation methods. According to /2/ common methods are given by Aures (Equation (2)) and DIN 45692 (Equation (3)) /2/. On the other hand, the formulation by Zwicker /8/ is given by (Equation (4)). Equation (2) reflects the fact that the total loudness *N* is given by the integral over the specific Loudness $N'(z)$ from 0 to 24 bark which is the entire defined frequency scale.

$$g_A(z) = 0{,}078\, \frac{e^{0{,}171\, z}}{z}\, \frac{\int_{z=0}^{z=24} N'(z)\, dz}{\ln\left(0{,}05 \cdot \int_{z=0}^{z=24} N'(z)\, dz + 1\right)} \qquad (2)$$

$$g_D(z) = \begin{cases} 1, & z \leq 15{,}8 \text{ Bark} \\ 0{,}15\, e^{0{,}42\,(z-15{,}8)} + 0{,}85, & z > 15{,}8 \text{ Bark} \end{cases} \qquad (3)$$

$$g_Z(z) = \begin{cases} 1, & z \leq 16 \text{ Bark} \\ 0.066\, e^{0{,}171\,(z)}, & z > 16 \text{ Bark} \end{cases} \qquad (4)$$

The weighting-functions by DIN 45692 and by Zwicker are very similar, yet Aures increases the dependence of the loudness. It is not possible to make a general statement which model should be preferred, however, for high loudness fluctuation the model by Aures is mostly used /7/.

These two parameters are most commonly used in the field of psychoacoustics and will be investigated in the following by means of influencing these parameters by pneumatic process measures.

3 Test bench setup and measurement procedure

Following paragraphs show the test bench design and the conducted measurement procedures with respect to the mentioned psychoacoustic parameters. The psychoacoustic analysis is based on measurements that are executed in a full anechoic chamber with absorbent material on all surfaces. The dimensions of the measurement room are 4,5 m x 4,5 m x 2,2 m. The test setup is shown in Figure 4 where the measurement object is installed on an existing test bench.

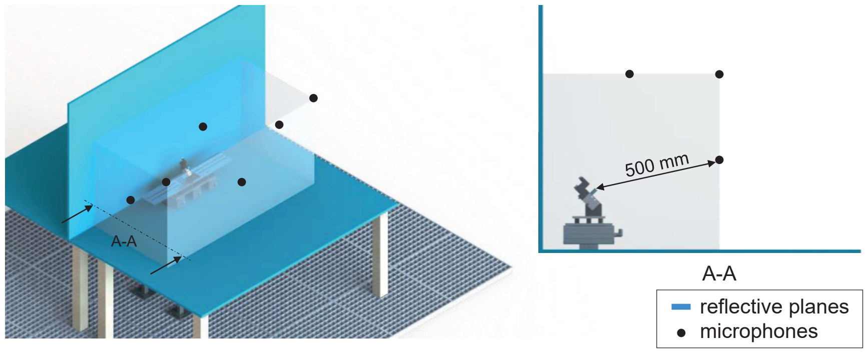

Figure 4: Test bench for acoustic measurements of valve exhaust noise

The test bench is originally designed for recording of the sound power level featuring two orthogonal reflecting planes according to DIN EN ISO 3744 /3/. The sound power measurement of pneumatic components on this test bench is already introduced in /6/. In general, six microphones are located at the centres of each plane (shadowed grey areas) and the two corners. For psychoacoustic measurements, only the microphone in the frontal mid plane is considered as reference with a measurement distance of 500 mm.

All microphones are type 40AE by G.R.A.S. Sound and Vibration and being calibrated at the beginning of each measurement series at 1 kHz and 104 dB. The acoustic values are recorded by a LMS SCADAS Mobile Frontend. The signal processing is mainly conducted with LMS Test.Lab, only graphical rearrangement is done with Matlab/Simulink. The fluidic sensors (i.e. pressure, temperature and standard volume flow) are evaluated by a Beckhoff Automation measurement system.

The pneumatic schematic in Figure 5 shows the overall system for the stationary measurement of a switching valve with installed exhaust muffler. The outlets of the 5/2 directional control valve are connected to achieve a stationary flow through the muffler. The stationary measurements serve the determination of the relation between the fluidic and acoustic parameters. Therefore, the system pressure is controlled by a mechanical pressure reducing valve. The volume flow is derived by the according flow resistances of the system. In order to start the measurements, a manual 2/2 valve is used. The fluidic parameters are captured by the inline pressure, temperature and mass flow sensors before the inlet of the valve.

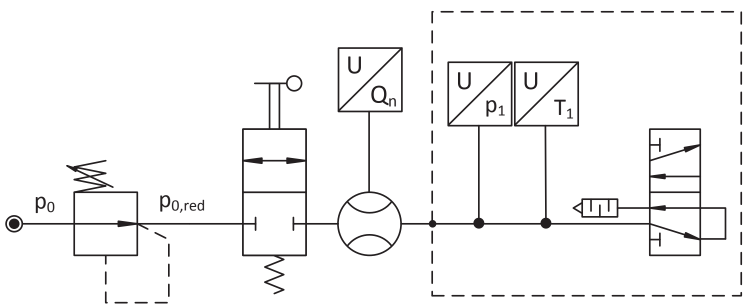

Figure 5: Schematic for stationary measurements of a control valve with exhaust muffler

During transient measurements the 5/2 directional control valve is used to move a standard differential cylinder with 16 mm rod diameter and 800 mm stroke. The actuator is located outside the acoustically relevant area since the noise of movement and braking are not supposed to be considered. The procedure is similar to the stationary measurements but, additionally, the cylinder-velocity is set to a certain value by exhaust air throttling.

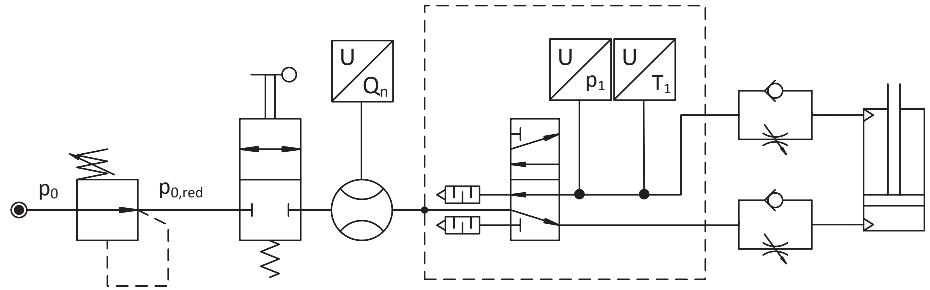

Figure 6: Schematic for instationary measurement of a control valve with exhaust muffler

For both setups the exhaust air is the main sound source of interest. The inner flow noise through the valve can be neglected since the amplitude of the emitted sound pressure level is significantly lower. Table 1 summarizes the operating ranges of pressure, volume flow and the cylinder velocity that are considered during the measurements.

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

Table 1: Operating ranges for stationary and transient measurement

4 Results

4.1 Stationary measurements

In order to compare the acoustic with the introduced psychoacoustics analysis, different stationary measurements are performed and analysed. The first measurement, which is depicted in Figure 7, shows the RMS averaged sound pressure and volume flow with respect to the inlet pressure.

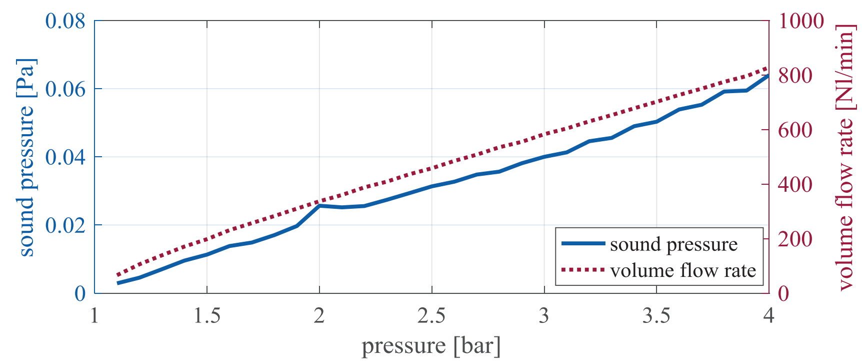

Figure 7: Sound pressure and volume flow over inlet pressure

The linear proportional relation between the quantities is obvious. Yet, there is no remarkable change in sound pressure when the flow regime changes to supercritical state at approximately 2 bars. Comparing the results to the averaged sound pressure level and its weighted function (cf. Figure 8) the shape of the curve changes to a root-form, which can be explained by the logarithmic definition of the sound pressure level.

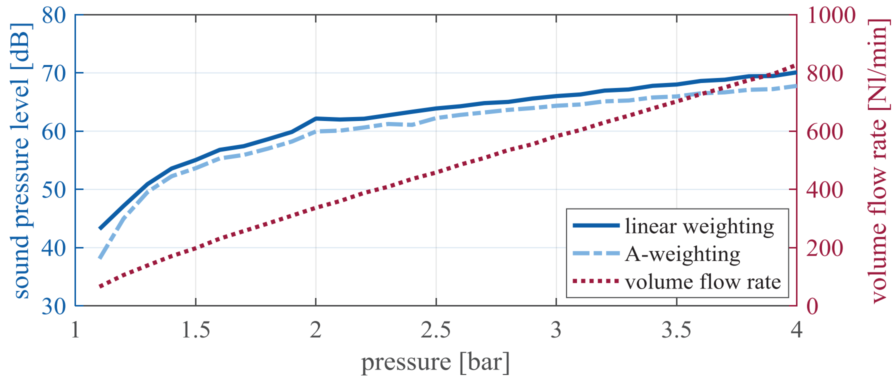

Figure 8: Sound pressure and volume flow over the inlet pressure

When comparing the two similar courses of the sound pressure level and the course of the loudness in Figure 9 no obvious difference is seen. Yet, this fact is valid only for the current system setup. For a different spectral distribution, the effect of the loudness calculation would have an increased impact. Firstly, aeroacoustic noises from unsteady shear stress (as they occur in turbulent flow regimes) scale with the third power of fluid velocity (according to aeroacoustic theory /5/). Secondly, the fluid velocity is lowered due to the decrease in system pressure. Thus, the turbulence occurrence decreases as well, leading to a shift of dominant frequencies towards lower values. The damping effect of the human hearing, which is implied in the weighting filter, leads to a significant decrease of the sound pressure level.

Furthermore, the loudness not only enables a qualitative comparison of noise sources but also implies information about the actual perceived amplitude of the sound. The logarithmic scale to the basis of two (see red dashed lined in Figure 9) visualizes the circumstance in a way that doubled perceived loudness is geometrically equidistant. For more detailed analysis the scope between 1.5 and 2.5 bar is pictured.

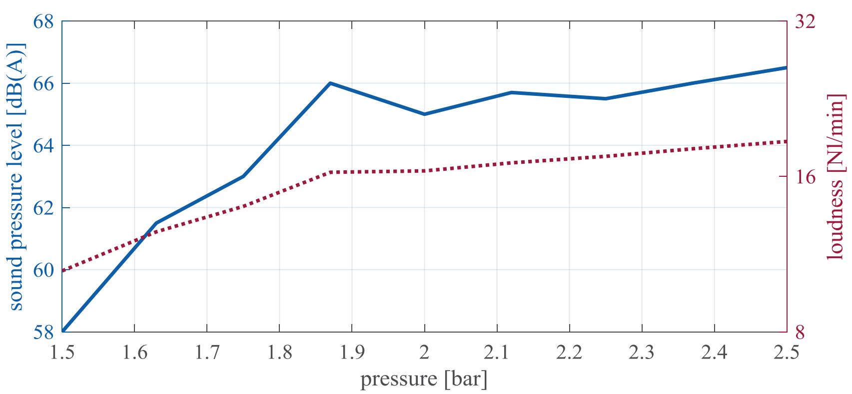

Figure 9: Loudness linear (left axis) and logarithmic (right axis) over the system pressure

The sharpness as displayed in Figure 10 does not follow a regular pattern. However, the minimum at 1.1 bar leads to the assumption that a briefly existing noise yields a sharpness perception. Yet, the maximum is just reached by a small deviation of the inlet pressure to 1.25 bar. Furthermore, the sharpness does not have a straight proportional relationship with respect to the volume flow since there is a clear decrease from 2 to 2.5 bar.

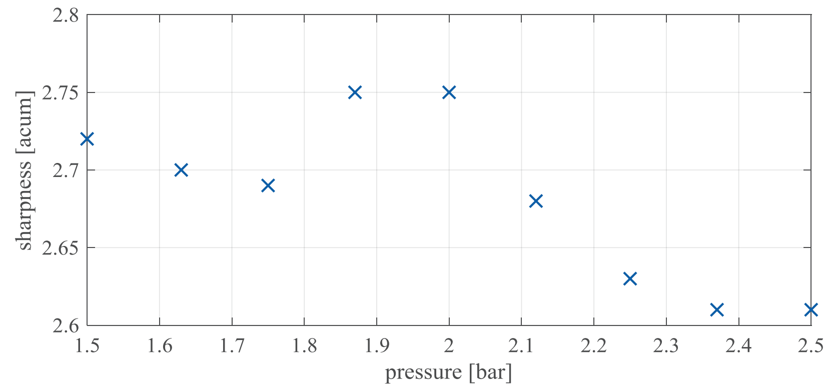

Figure 10: Sharpness over system pressure

4.2 Instationary measurements

On the basis of the stationary results, the behaviour of the psychoacoustic parameters for transient measurement is to be investigated. Figure 11 shows the system pressure, loudness and sharpness versus time for the transient movement of a cylinder. The beginning of the movement is accompanied by a large change in pressure and loudness. When the cylinder is already moving, a stationary phase is given until the piston approaches the end position.

The values for the different sharpness models are compared subsequently. While the methods by Zwicker and DIN 45692 show quite similar results, the model by Aures seems to include off-set by 1 acum. The reason for this is that the weighting-function by Aures is highly dependent on the loudness (cf. Equation (2)). The most interesting fact though is that the sharpness value at rest (for the beginning as well as for the end of the cycle) is higher than the averaged moving sharpness measurement. Since this fact lacks a logical explanation, the model and potential improvements will be discussed in the following paragraph more detailed.

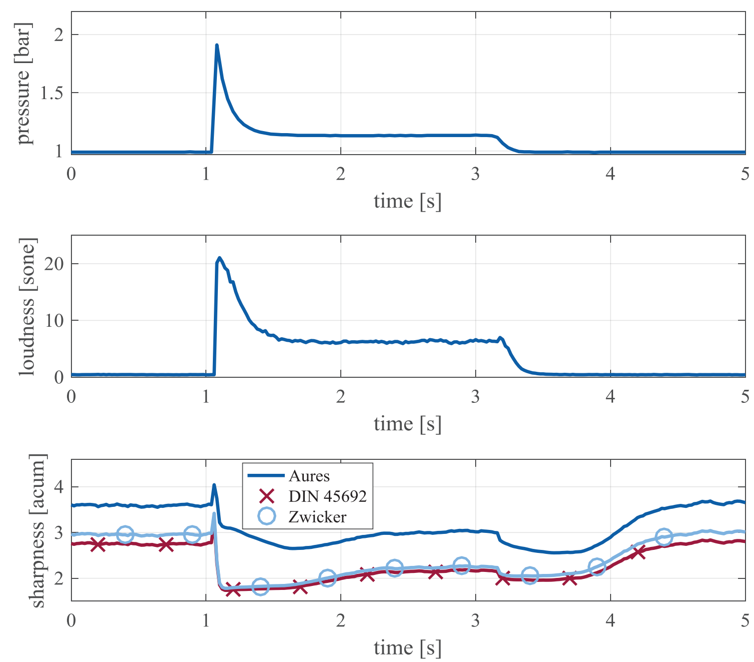

Figure 11: Pressure (top), loudness (middle) and sharpness (bottom) over time for transient actuator movement

5 Model adaptions

The given results lead to the conclusion that a non-audible background noise has a higher sharpness value than a present and much louder noise of a cylinder in motion. Therefore, it is necessary to review the existing sharpness models. Since the model by Aures is preferred for noises with high fluctuations in loudness, it is reasonable to focus on this one /7/.

As the weighting-function by Aures (cf. Equation (2)) has a high influence on the sharpness calculation, its actual influence with respect to the bark scaling is analysed. Figure 12 shows the weighting-function for different loudness values and the first approach of adaption. In the following, the annotation *UWM* indicates the model changes and adaptions.

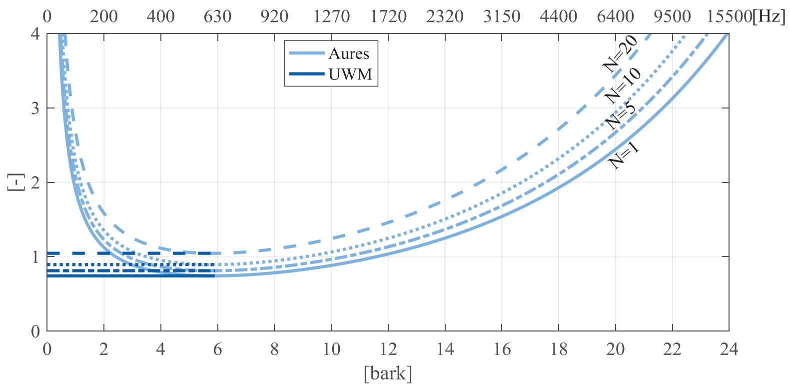

Figure 12: Weighting-function by Aures and the adaption for sharpness calculation

Comparing the weighting by Aures with the results of the sharpness hearing test (Figure 3) the sharpness should decrease or at least stay constant towards low frequencies. By the model adaption, the weighting function values below the minimum at 5,848 bark stays constant. This rising lower part of the weighting-function by Aures might lead to large deviations for certain applications.

Moreover, the part of the function that is depending on the loudness is shown in Equation (5) and additionally illustrated in Figure 13 by introducing the loudness factor *a*. The lower limit of the loudness-depending part converges at 20 leading to the discovered fact that a non-audible noise can still have a high (calculated) sharpness.

$$a_A(z) = \frac{N}{\ln(0{,}05 \cdot N + 1)} \qquad (5)$$

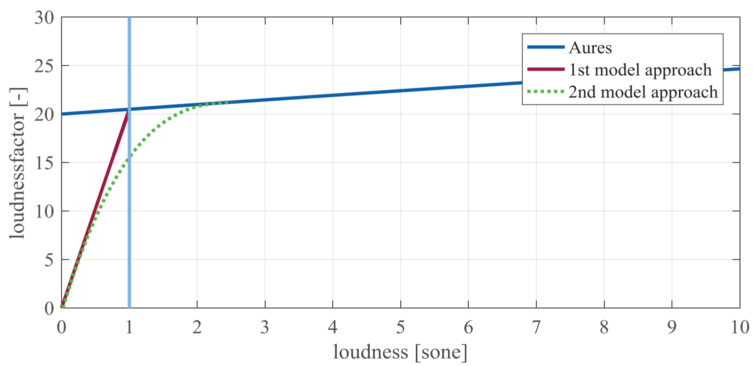

Figure 13: Loudness-depending part of the weighting by Aures and further model adaptions

By reducing the lower limit to zero it is ensured that a briefly existing noise also reaches a minimum with respect to the sharpness perception. The first model approach leads to a discontinuity in the calculated sharpness, which has mathematical reasons only. Thus, the loudness-depending factor is approached by a third-order polynomial as depicted in Figure 13 by the green dotted line.

The final analytic form of the extended weighting-function UWM with third-order polynomial approach is given by Equation (6) and (7).

$$g_{UWM}(z,N) = \begin{cases} 0{,}078\,\dfrac{e^{0{,}171\cdot z}}{z}\,a_{LF,UWM}(N)\,, & z \leq 5{,}848 \text{ Bark} \\ 0{,}0363\,a_{LF,UWM}(N)\,, & z > 5{,}848 \text{ Bark} \end{cases} \qquad (6)$$

with

$$a_{UWM}(N) = \begin{cases} 0.978\,(N - 2{,}79)^3 + 21.2399\,, & N \leq 2{,}323 \text{ sone} \\ \dfrac{N}{\ln(0{,}05 \cdot N + 1)}\,, & N > 2{,}323 \text{ sone} \end{cases} \qquad (7)$$

Figure 14 shows the recalculated results compared to the model by Aures for the first and second model approach. The range of actuator movement leads to the same sharpness calculation with all model approaches. This behaviour is requested due to the Aures model evaluation by means of hearing tests for high loudness values. However, the desired results are achieved as the sharpness values are significantly lower during the resting phase. The difference between the model approaches of the loudness factor can be observed at 3,6 s. While the discontinuous description (cf. red line of Figure 13) leads to a discontinuity in the sharpness as well, the polynomial model yields a smooth transition at the end of the movement. It has to be mentioned, that the model approach proposed here is based on acoustical relevance interpretation. Ensuring a physiological and acoustical correctness, further hearing tests and model validations for other noise sources are mandatory.

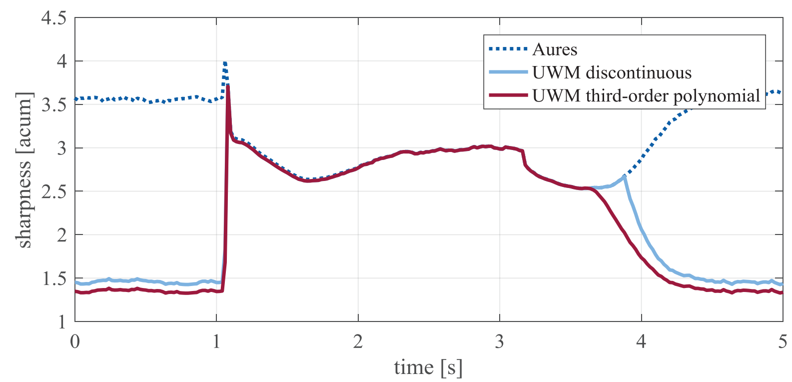

Figure 14: Sharpness of transient noise emission by Aures and new model approaches

6 Summary and Conclusion

The aim of this paper is the derivation of a model for psychoacoustic calculations and to determine relations between fluidic and psychoacoustic parameters. The results can be used for a deeper and more characterizing interpretation of noise emission in industrial context especially considering the reasonableness of legal sound pressure level limits for industrial safety. Furthermore, the analysis enables targeted optimization measures to lower undesired hearing phenomena and statements in early planning phases.

By the means of stationary measurements of a switching valve with a standard exhaust muffler, a proportional relation between the loudness and the system pressure is shown. Furthermore, using the loudness a quantitative comparison of two sounds according to their acoustics is possible, unlike using conventional acoustic parameters. Referring to this, a logarithmic plot to the basis two is appropriate as a doubling of the loudness is equidistant. The result of this paper is given by a new sharpness model which arises from the fact that the current models are unreasonable for the test case observed in this study. During the rest phases of a differential actuator no perceptible noise is emitted, however, the sharpness level is higher than during the cylinder movement phase. The reliance on the loudness is taken into account insufficiently. The new model, based on the Aures sharpness model solves this problem and lowers the sharpness value for almost negligible sounds. Comparing it to the original model, the results are the same for standard loudness ranges (e.g., for a moving cylinder). As a conclusion, an acoustic event below the hearing threshold is not supposed to induce the auditory presence of sharpness.

Further works are required to evaluate the new sharpness model based on hearing test regarding different noise characteristics (e.g. with low or varying loudness and different spectral distribution). Moreover, it is necessary to investigate other psychoacoustic parameters as roughness and fluctuation to make an even more differentiated statement about the acoustic character of a component or system respectively.

7 Acknowledgements

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Nomenclature

Variable	*Description*	*Unit*
a_{A}	Loudness-depending part of the weighting-function by Aures	[-]
a_{UWM}	Extended loudness-depending part of the weighting-function	[-]
c	Scaling factor for sharpness calculation	[-]
g_{A}	Weighting-function by Aures for sharpness calculation	[-]
g_D	Weighting-function by DIN 45692 for sharpness calculation	[-]
g_{UWM}	Extended Weighting-function for sharpness calculation	[-]
g_Z	Weighting-function by Zwicker for sharpness calculation	[-]
Q_n	Standard volume flow	[Nl/min]
N	Loudness	[sone]
N'	Specific loudness	[sone]
$p_{inlet,rel}$	Relative inlet pressure	[bar]
p_0	System pressure	[bar]
S	Sharpness	[acum]
T_1	Inlet temperature	[K]
v_{cyl}	Cylinder velocity	[m/s]
z	Frequency spacing / Pitch	[Bark]

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