On the origin and measurement of noise emission in pneumatics

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Abstract

Noise is a circumstance of ordinary life and mainly originated by continually growing dynamic and the rapid development of society. In the industrial environment there are noise-intensive parts that influence the condition of present operators negatively. Thus, measures of noise abatement have been investigated intensely by industrial companies as well as federal agencies. As a subdomain of fluid power pneumatics is especially known for characteristic noise emission by the use of air as power transmission. The transient decompression of air from pressure levels up to 8 bar and partly high flow rates nearby sonic speed cause the emergence of direct airborne noise at vent ports of pneumatic components.

The following paper outlines the mechanisms that induce the emission of high sound pressure levels. In order to achieve reproducible results a test bench for varying pneumatic standard components is introduced. Based on a selection of those components results are compared to standardized measurement procedures whether fulfilling the standardizations' requirements. In conclusion, two benefits are achieved. Firstly, standardization is derived enabling neutral comparison of standard pneumatic components' noise emission. Secondly, the measures can be evaluated to determine the most promising way to redesign pneumatic components of lower noise emissions.

KEYWORDS: pneumatics, noise emission, noise reduction, sound pressure level, standardization

1. Introduction

The analysis of industrial noise emission is a growing topic in current research efforts due to the detrimental influence on the human organism. Not only the impact on health should be considered but also the economic consequences caused by presbycusis or deafness.

Especially in heavy machinery as a main application of fluid power the transmission of strong forces might lead to severe sound pressure levels (SPL). Pneumatics, however, with working pressures up to 8 bar are traded way below such nominal forces. Since the working fluid which is used for power transfer is usually cyclically compressed air there is an immediate coherence to noise generation at exhaust air ports. Additionally, the transfer of mechanical oscillations in compressors, actuators, valves etc. to surrounding air volumes (structure-borne noise) amplifies the total SPL. Although there are efforts of noise measurement standardization that define specific values to characterize the emitted noise of industrial components, pneumatic standard components have not been considered yet.

This paper is divided into two major topics. Firstly, the generation of sound induced by the utilization of pneumatic standard components (i.e. valves and actuators) is described with focus on exhaust air noise emission as well as structure-born noise due to mechanical oscillations. Secondly, the knowledge about the noise character is used to evaluate the applicability of current noise measurement standards. Therefore, the standards' requirements have to be critically reviewed in terms of test environment, volume of test objects, noise character, quality of measurement equipment and the relevant measurement quantities. Based on the choice of a suitable measurement procedure the development of a test bench is described to compare different standard components.

As a conclusion, the applicability of the measurement standard for pneumatics is proven. Furthermore, selected quantitative measurements are shown that provide information of which noise emission level has to be expected on the one hand as well as the prospective opportunities of noise reduction methods on the other hand.

2. Noise generation in pneumatics

Pneumatic is known as a low-cost, clean and simple drive technology. Due to the usage of air as power transfer fluid there is an implicit connection to the generation of noise emissions. Additionally, oscillations inside of the mechanical structure lead to transfer energy to the surrounding air volume which is called structure-borne noise. Both phenomena are described subsequently.

2.1. Exhaust air noise

As a basic mechanism of pneumatics exhaust air noise can be characterized as direct fluidic noise or airborne noise respectively since the surrounding air at outlet ports is directly excited by the emanating working fluid. Due to the pressure difference between surrounding and working air the compensation induces rapid and turbulent motion of air molecules which induce pressure fluctuations. These changes can also be interpreted as the temporal change of atmospheric pressure at a specific location in space. This *acoustic wave* is described by its amplitude Δp and cycle duration T (cf. **Figure 1**).

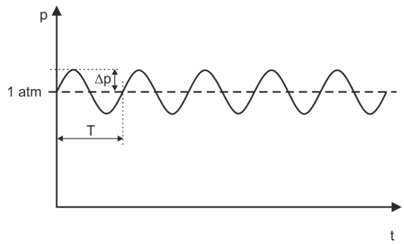

Figure 1: Acoustic wave as local pressure oscillation

Usually the description of acoustic waves is done by the usage of the reciprocal cycle time - the frequency f. It has to be mentioned that the wave's amplitude in Figure 1 is exaggeratedly visualized since the audible oscillations occur within the range from 10^{-5} Pa to 10^{3} Pa which is comparatively low with respect to the standard atmospheric pressure of 10^{5} Pa (approx. 1 atm). Due to the large scaling the sound pressure level SPL is introduced in (1) as the logarithmic ratio of the pressure oscillation amplitude and the reference pressure p_0.

$$L_P = 10 \lg \frac{p^2}{p_0^2} \text{ dB} \quad (1)$$

The illustrated acoustic wave symbolizes a pure sinusoidal tone which is suitable for describing the wave's properties yet comparatively rare in technical noise emission. Referring to the acoustic literature /1/, **Figure 2** shows two different propagations of volume flow out of a standard exhaust port. Depending on the Reynolds number *Re* which is defined by

$$Re = \frac{v \cdot d}{\nu} \tag{2}$$

the flow characteristics change essentially. The threshold Re_{krit} deviding the areas of laminar (right) and turbulent (left) flow is not strictly defined. Even though the geometry of the exhaust port is constant, the flow characteristics lead to totally different noise emissions. On the one hand, laminar flow noise is mainly defined by the frequency of the eddy detachment which is usually rather narrow-band. On the other hand, rapid eddy decay, especially in between the triangle shaped mixing zone, cause licentious change in velocity and pressure respectively. Emerging noise is broadband which is basically a superposition of several acoustic waves with different amplitudes at all frequencies of the audible area.

Figure 2: Turbulent (left) and laminar (right) flow at exhaust port /1/

To characterize the noise emission by its energy the sound power level (SWL) L_w is introduced as the output acoustic energy of a source per time. For Mach numbers (ratio of flow velocity to sonic speed) of above 0.7 a rough determination of the SWL next to air exhaust ports is given by (3)

$$L_W \approx 5 \cdot 10^{-5} \cdot \rho \cdot \frac{\pi d^2}{4} \cdot \frac{v^8}{c} \tag{3}$$

with air density *ρ.* Even though the dependence on the flow velocity at smaller Mach numbers decreases to the fourth power it is obvious that it is the main determinant.

The standard solution to this issue in the pneumatic industry is achieved by absorption mufflers as shown in **Figure 3**. Three different types of mufflers are presented which only differ in the way of mounting the porous material and the material itself respectively. The functionality of noise reduction is given by this material where the air has to pass through. The acoustic power is converted to heat energy what leads to a decrease of fluid velocity. Thus, the noise emission can be reduced significantly.

Figure 3: Common types of exhaust air silencers /2/

2.2. Structure-borne noise

The other mechanism leading to noise emission is the structure-born noise. In comparison to airborne noise the excitation occurs by mechanical oscillations of elastic materials. The oscillations conduct through the material by longitudinal, shear, torsional or bending waves. The reason for these oscillations in a pneumatic context might be given by external forces that are either due to collisions (e.g. cylinder rod hits its end position) or induced by internal flow forces. However, the excitation of air takes places at the outer shell of the component through the momentum transfer between the mechanical structure and air molecules.

Since air density (accordingly the momentum) is comparatively low the flow force induced noise can rather be neglected. Thus, it appears that the exciting forces in pneumatics are given by the collisions of mechanical parts in assemblies. Speaking of actuators, there has already been development to reduce firstly the noise emission and secondly, even more important, the danger of permanent attrition that might lead to premature failure of the component. The state of the art solution is the end cushioning. Most of the manufacturers offer three different types of realizations. Flexible cushioning pads are a low-cost solution with rather worse damping functionality. The more advanced implementation is the pneumatic cushioning which can be either adjustable or even self-adjusting with respect to the damping coefficient. Both variants have the common functionality – reducing the cylinder's velocity (i.e. the kinetic energy) at the end stop by closing the standard exhaust duct and leading the air flow through a smaller orifice. Thus, the back pressure increases and the cylinder movement is slowed down.

3. Noise measurement

In order to analyze and improve the noise emission subsequently it is of particular importance to develop a standard measurement procedure achieving reliable, repeatable and comparable results of pneumatic standard components. The international standardization committee has already defined a detailed catalogue of procedures for noise measurement of a huge scope of industrial components. Those are summarized in several parts of DIN EN ISO 45635 /3/. Unfortunately, pneumatic standard components are not included which is why this paper outlines the transfer of general noise measurement standards to possibly complement the scope of DIN EN ISO 45635. The following chapters describe the available standard methods and the measurable acoustic parameters.

3.1. Standardizations

The methods applied in DIN EN ISO 45635 are basically summarized in DIN EN ISO 3740 /4/. It lists nine further standards that offer the opportunity to determine the SWL. The main differentiation lays in the determination of either the sound pressure or intensity. Measurement of intensity has the benefit of extraneous noise independence, yet there is the need of advanced measurement equipment. Thus and furthermore the circumstance that there is the availability of an anechoic measurement chamber at the Institute for Fluid Power Drive and Controls RWTH Aachen University the sound pressure methods are favored. Based on environmental parameters the most suitable standard has been chosen as DIN EN ISO 3744 /5/. **Table 1** outlines the important parameters for the application of the standard. The only critical characteristic values are the extraneous noise level (stated as K_1) and the environment criteria (stated as K_2). These limitations will be further discussed in Chapter 4.3.

Parameter	DIN EN ISO 3744
Environment	Free field over reflecting planes
Environment criteria	$K_2 \leq 2$ dB
Test volume	No limitations
Noise character	No limitations
Extraneous noise	$K_1 \leq 1{,}3$ dB and $\Delta L \geq 6$ dB
Meas. equipment	Class 1

Table 1: Selection criteria with respect to DIN EN ISO 3740 /4/

3.2. Determination of acoustic parameters

The SPL of a sound source is the target quantity that has to be determined but there are certain steps that have to be taken into account before it can be achieved. Firstly, the pressure oscillations are converted to electronic signals usually by capacitor microphones to accomplish the further data processing. After collecting the pressure gradient it is be converted to the SPL referring to (1). Secondly, a Fourier transformation is done to extract the signal's spectrum. For detailed signal processing information specialist literature is recommended. Once the spectrum is known the most significant adjustment is performed – the A-weighting. **Figure 4** shows both the reason why it is appropriate to weight the frequency spectrum and the actual damping for weighting functions A to D. The left graph shows the contours of equal-loudness sentiency of human beings. For example, a tone of frequency 1000 Hz and SPL of 0 dB is sensed as equally loud as a tone of 100 Hz and 20 dB. This frequency dependency has been taken up by weighting filters (right side). The A-weighting is the one that fits human sensitivity the most which is why it has become standard in acoustic measurements. Filters B, C and D are only used for special applications.

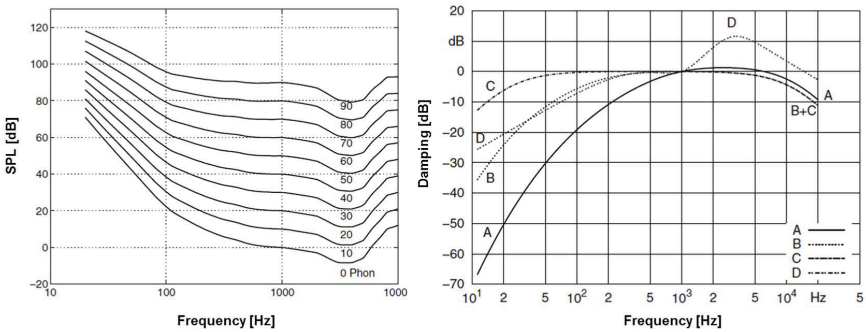

Figure 4: Equal-loudness contour (left) and weighting filter (right) /6/

Once the signal is A-weighted it is averaged over the frequency band and the number of microphones with respect to each individual measurement area. Using the corrective factors K_i which is described in Chapter 4.3, the averaged, corrected, A-weighted SPL $\overline{L_{pA}}$ is determined by (4)

$$\overline{L_{pA}} = \overline{L_{pA}'} - K_1 - K_2 \text{ dB} \quad (4)$$

4. Application of pneumatic noise measurement standard

Utilizing the introduced noise measurement techniques the following sections outline the development of a suitable test bench for different pneumatic components (especially actuators and valves) in an anechoic room. Furthermore, the chosen system parameters and the validation of the standard's requirements are presented.

4.1. Test bench development

DIN EN ISO 3744 requires the allocation of the measurement object on a sufficiently wide reflex baffle to ensure a free acoustic field in absence of any obstacles.

Depending on the objects' outer dimensions and the directivity of the object, it can also be positioned in between two or three orthogonally arranged baffles. The size and numbers of available microphones determine the definition of a specific measurement surface where the microphones are attached to. **Figure 5** illustrates the chosen setup.

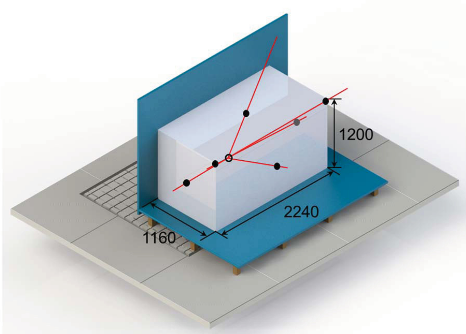

Figure 5: Test setup with microphone position

Two reflex baffles are arranged orthogonally where the intersection centre point is approximately aligned with the geometric centre of the component. The measurement surfaces consist of a cuboid shaped design whose outer dimensions are dependent from the ones of the measurement object (exemplarily shown for a 500 mm stroke actuator) to keep the microphone's positions equidistant. Six microphones are arranged on each face's mid as well as on two of the vertexes as shown in Figure 5. Furthermore, the microphones are faced towards the geometric centre what is supposed to be equal to the acoustic centre.

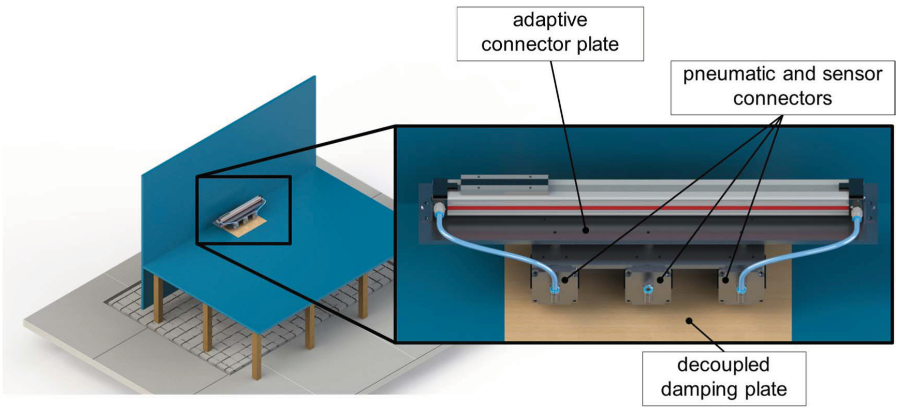

Figure 6: Test bench for individual pneumatic standard components

The actual test bench design is shown in **Figure 6**. The components are mounted on an adaptive connector plate which is mounted on a low-vibrational and rigid substructure in turn. The structure is yet decoupled from the reflective surfaces where the microphones are positioned on to avoid interferences between mechanical vibrations and the actual noise measurement. All pneumatic and sensor connection lines are led through the construction to the downside of the horizontal reflex baffle. Underneath, the peripheral equipment (i.e. measurement amplifiers, trigger valve and mass flow sensor) is capsuled to exclude extraneous noise effects.

4.2. System parameters

Noise emissions not only depend on the components themselves but also on the system parameters setup. Thus, a parameter set is defined achieving comparable results and giving the opportunity to classify the influence of each parameter to the noise emission. The examined parameters are summarized in **Table 2**. The direction of the movement has to be considered with differential actuators because of the difference of effective areas. Additionally, two constant system pressures and load masses are used for analyzing the influences of different kinetic energies that have to be transformed. The last parameter is the setting of end cushioning that might reveal the effectiveness of noise reduction by appropriate usage.

Parameter	Range
Direction	In / Out
System pressure	4 bar / 7 bar
Mass	0 kg / 2 kg
End cushioning	Open / Adjusted

Table 2: Operating parameters

4.3. Validation of standard's requirements

As shown before, there are two corrective factors K_i that have to be calculated with respect to measurement environment and the influence of extraneous noise. The first part is quickly treated since it is a simple calculation of the anechoic room geometric and absorbent properties. For the current setup K_2 is evaluated to 0.8 dB which is below the restrictive threshold of 1.3 dB. The evaluation of K_1 is, however, more elaborate. Depending on the differential SPL which is the difference between measured SPL during observed operation and stagnation, K_1 is either 0, calculated with respect to DIN ISO 3744 or the measurement is invalid if the differential SPL is below 6 dB as shown in **Figure 7.** Using the corrective factors, the corrected, averaged, A-weighted SPL can be calculated for each component.

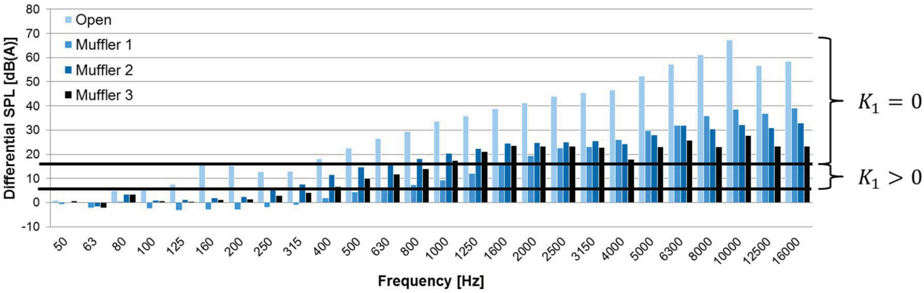

Figure 7: Differential SPL for three different mufflers determining correct K_1

5. Selected results

In the following, a few selected results of the first measurements of a rodless actuator are extracted and presented. **Figure 8** shows the difference in the SPL of a single actuator and a combination of an actuator and a corresponding valve. It is obvious that the SPL increases by approximately 10 dB(A) which is yet not trivial because firstly it depends on each particular SPL and secondly they could also interfere destructively which might even reduce the noise emission. Thus, every system setup should be treated very carefully.

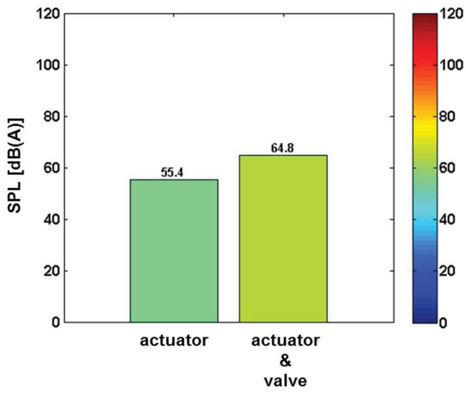

Figure 8: Noise emission by increasing the number of sound sources

Another result is given by **Figure 9**. With a maximum actuator velocity of approximately 0.95 m/s the change of system pressure shows no influence on the SPL (left) which is obvious since the kinetic energy is kept equal. On the right side, load mass is increased from 0 to 2 kg. Since the mass influences the kinetic energy by the power of two there is a distinct raise of the SPL almost until the human pain threshold of 80 dB(A).

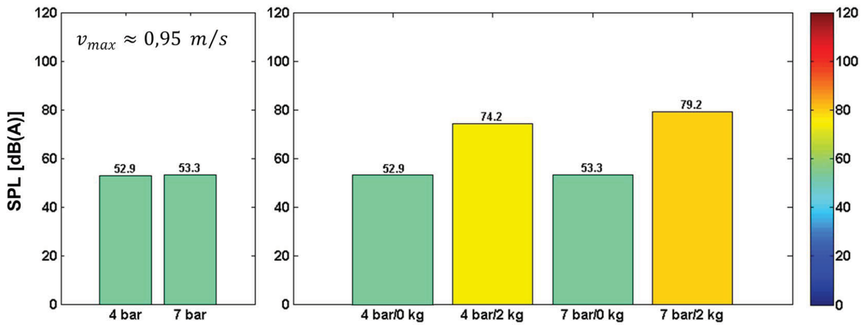

Figure 9: Influence of load mass and system pressure

6. Conclusion and outlook

This introduced paper outlines the approach of developing a standard procedure for noise measurements of pneumatic standard components. The superior aim of the research project is the reduction of the noise emission to act in accordance with the current industrial safety regulations and to improve the attractiveness of pneumatic systems in low-noise environment.

The general mechanisms that lead to high noise emission of pneumatic components are firstly presented and explained. Subsequently, the current standardizations in noise measurements were introduced and reviewed with respect to the applicability on pneumatics. The second part shows the development and parameter setup of the current test bench design to measure and qualify noise emissions. The system parameters are analyzed and the important system quantities are measured achieving better knowledge about the influence on noise emission and validation data for subsequent acoustic simulation approaches.

Looking forward, standard components and different system setups have to be measured and evaluated. Based on these experiences simulation techniques will be used to evaluate the opportunities of reducing the effective noise emission by either changing design properties or adjusting system preferences.

7. References

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/5/ DIN EN ISO 3744:2009-2011. Bestimmung der Schallleistungs- und Schallenergiepegel von Geräuschquellen aus Schalldruckmessungen, 2011

/6/ Möser, M. Technische Akustik, 8th Edition, Springer Verlag, Berlin, 2009

8. Nomenclature

c	Speed of sound	m/s
d	Exhaust port diameter	m
K_i	Corrective factors	dB
L_p	Sound pressure level (SPL)	dB
$\overline{L_{pA}}$	Corrected, Averaged, A-weighted SPL	dB(A)
$\overline{L_{pA}}'$	Averaged, A-weighted SPL	dB(A)
L_W	Sound power level	dB
ν	Kinematic viscosity	m²/s
p	Pressure	N/m²
p_0	Reference pressure	N/m²
Re	Reynolds number	-
ρ	Air density	kg/m³
v	Fluid velocity	m/s