Acoustic methods for leak detection and tightness testing

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Abstract. Air tightness testing has importance in industrial environments where in compressed air systems leaks account for a high percentage of energy loss. These losses can effectively be reduced by locating and repairing of leaks. Furthermore, tightness is a criterion for the quality of different kinds of seals and joints. For leak detection and tightness testing acoustic methods (passive and active) can be applied. Variations of the technology enable access to different problems. The methods for leak detection can be graded up by the estimation of leak sizes and energetic losses. Similarly, slot size and length of tightness leaks are responsible for energetic losses in buildings (window and door seals) or for dysfunctions in technical systems such as cabins, heat exchangers and others.

Leaks can be found easily by means of traditional ultrasound leak detectors which operate in a narrow frequency band (e.g. 40 kHz). However, this simple technology is inadequate for quantitative estimations of leak and tightness losses. Therefore, new theoretically based approaches have been developed and experimentally exemplified. Sound will be created by passing of air through leaks (for high and low pressure as well). Compressed air exits an orifice generating a turbulent jet, which emits a broadband sound. Acoustic leak finder devices can localize these leaks. However, quantification of their size remains a crucial task (with respect to energy loss and priority of repair). From the point of view of aero-acoustical theory a quantification of fluid parameters of leak jets can only be achieved by evaluation of a broad frequency band (20 kHz to 100 kHz). A new testing procedure and evaluation algorithm for finding and quantification of leaks will be presented.

Tightness of many technical systems can be tested by means of actively transmitted (ultra-)sound. Again, quantification remains a demanding task. The sound field strongly depends on depth, width and geometry of an orifice and is affected by diffraction, reflection, transmission and interference. The method is discussed with respect to the quantification of leak size. It is shown which demands are to be met on the sound source and the generated acoustic fields.

1. Introduction

The paper deals with new approaches for the evaluation of acoustical effects caused by air losses by leakages. A second area of consideration is the tightness evaluation by means of actively transmitted ultrasound. The results demonstrate some general problems and difficulties but also the potential of ultrasound methods. Conventional testing equipment and technology can be used to find leakages. However, quantification is strongly limited and disputable from the scientific point of view.

Leakages in pressurized air systems are responsible for energetic losses to a remarkable extent. So, estimations concerning leakage losses are of economic and societal importance [1-3]. The reduction of leakage losses will contribute to the current low carbon activities. Turbulences in fluids are acoustical sources. That means that leaks can be acoustically found and have a certain acoustic signature, respectively. This idea will be discussed and elaborated in this paper. Ultrasound technologies are traditionally important in industrial maintenance. Leakage can be found easily with inexpensive equipment. One of the prominent applications is the use of ultrasound for the sound location (finding the acoustical source of a leakage). The technology for the "passive" detection of leakages (the acoustical source is the fluid turbulence), which can be found on the market, is relatively simple [see e.g. [4-6]]). Similarly, the tightness of cabins, hatches, cleanrooms (penetration of water, energetic loss by air gaps and other) can be proved by using of an active ultrasound transmitter. In both cases, relatively ultrasound frequencies are used (relatively narrow bands around 40 kHz). There are some providers on the market offering testing equipment basing on relatively simple technologies. A pragmatic reason for the simple technology is the availability of cheap sensors. Some disadvantages are accepted by the users. A further important feature for leakage testing is the transformation of the (narrow-band) ultrasound to audible frequencies [7]. The ultrasound signal is heterodyned to the audible range giving just qualitative information. Any spectral information is lost. This heterodyned signal is used to estimate (quantify) the loss by leakages. It should be emphasized that there is no physical relationship for this kind of quantification. However it may (empirically) work in some very special situations.

A theoretically based approach for leakage loss estimation will be given in this paper. It will be shown that a quantification of losses can be made (within certain limits of accuracy). Most important from the technological point of view is the use of broad band sensor (microphone for high frequencies). This is caused by the fact that aero-acoustical noise has a broad frequency distribution. Furthermore, the acoustic radiation is anisotropic which requires modifications for the testing procedure.

2. Acoustical Evaluation of Leakages

2.1 Theoretical Background

The noise caused by flowing of pressurized air (or other gases) through leakages has a broad frequency characteristic and is generally stochastic. The acoustic noise depends on different factors: size and shape of the leakage, surface topology of the material of the leakage, difference of the pressure, flow velocity and profile. From the point of view of an industrial tester the distance and even the angle relative to the leakage have to be considered. The basic theory of aero-acoustical flow has been given by *Lighthill* in 1952. The acoustic sources of turbulent flow noise can be described by monopoles, dipoles or quadrupoles with pronounced directional patterns. The acoustic properties (sound intensity) of the turbulent flow (exit velocity v of the leakage jet) depend on Mach's number.

A quantitative description of leaks can be given by means of the rate of the leakage q_l in m^{3}Pa/s (volume stream dm/dt resp. dV/dt or mass stream, according to DIN EN 1330-08 and ASTM E1002-11 [8]. A general equation can be formulated under isochor and isotherm conditions.

$$q_L = \frac{\Delta(p \cdot V)}{\Delta t}, \; q_L = \frac{d(p \cdot V)}{dt} = p\frac{dV}{dt} = \frac{p}{\rho} \cdot \frac{dm}{dt} = R_s \cdot T \cdot \frac{dm}{dt} \qquad (1)$$

$$\frac{dV}{dt} = \dot{V} = \int_A d\dot{V} = \int_A v(A) \cdot dA \approx \bar{v} \cdot A \tag{2}$$

ρ is the density, T the absolute temperature T, R_s the specific gas constant. The maximum velocity is smaller than the sound velocity. Only a certain part of the orifice A_{th} contributes to the acoustic effects. Therefore, the volume stream can be written as

$$\dot{V} = \mu \cdot c \cdot A_{th} \tag{3}$$

with μ as correction factor for the flow through the orifice.

2.2 Experimental Results and Quantification

According to the theoretical considerations, a measuring instruction has been developed. Acoustical signals of leakages are measured up to 100 kHz bandwidth. Averaging has been essential due to the stochastic character of the noise. Averaging of power spectra improved the data quality and reliability in a drastic manner (which could be meaningful for the improvement of industrial applications). Some impressive results are given in the following figures which show typical spectra and angular dependencies.

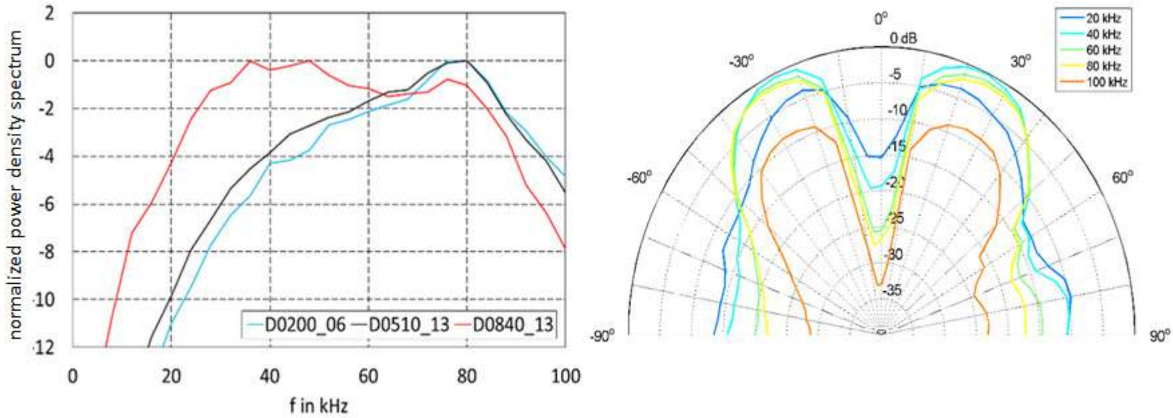

Fig. 1.frequency characteristics (left) and directivity (right) of leakages at different frequencies (flow direction 0°). This anisotropy has to be considered for the manual testing procedure and the data evaluation.

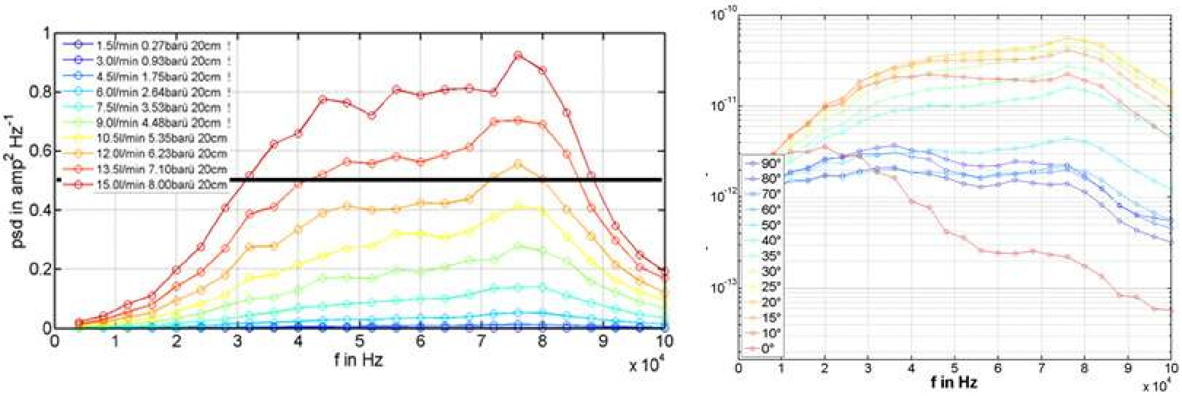

Fig. 2. Left: leakage (round orifice: D = 0.25 mm, L = 12.7 mm) at different pressure, right: angular dependence of the acoustical signal of this orifice (p = 7 bar, q ~ 0,5 Nl/min., dist. = 1 m)

Most important for numerical evaluations are spectral parameters such as spectral density and spectral centroid (and other).

$$f_{sc} = \frac{\sum f_i \cdot psd(f_i)}{\sum psd(f_i)} \qquad (4)$$

The evaluation of leakage loss of pressurized air uses a patented algorithm which is sketched in figure 3.

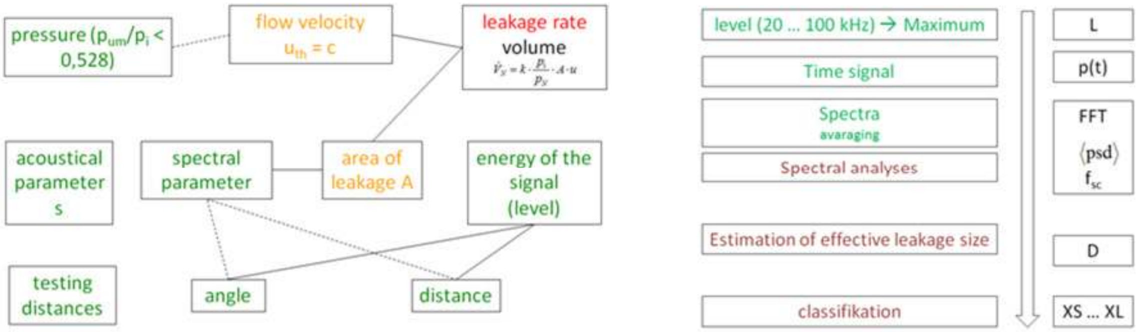

Fig. 3. Functional chain of the physical influence on the acoustics of leaks and schematic representation of the flow chart of the data treatment

3. Tightness Evaluation with Active Transmitters

Tightness evaluation of a "volume" can be (qualitatively) done by means of ultrasound by placing a sound source in the "closed" volume or behind a wall (the "volume" is not necessary for the function of the method). It should be useful to achieve an isotropic/homogeneous sound field (essential for quantification). This can be complicate for ultrasound frequencies. The method appears relatively simple. However, this is not the case particularly for quantifying testing.

3.1 Background

The transmission of sound trough any kind of gaps or through walls is influenced by different physical processes (diffraction, scattering, reflexion, interference). All these effects occur (to a different extent) depending on the real practical situations. Diffraction becomes important if the ratio between gap size and wavelength is small. For small gaps (smaller than the constructive and destructive wavelength) interference can be dominant. The transmission loss can exhibit positive and negative values as well. It obvious, that simple interpretation may fail in many practical cases. The method is not available in such cases (without theoretical/numerical considerations).

3.2 Simulations

Various gap scenarios have been constructed in order to simulate the practical case of transmitter-receiver arrangements (as in the practical use). The simulations have been done with the freely available toolbox "k-wave" [9 and 10]. The results demonstrate clearly that the interpretation remains demanding even when simulations would support the experimental results. On the other hand, the simulations demonstrate the potential for the extension of the method e.g. for the use in energy saving tasks such as the tightness of buildings (windows).

Fig. 4. Principles and several applications of the acoustic evaluation of tightness by means of an ultrasound active transmitter

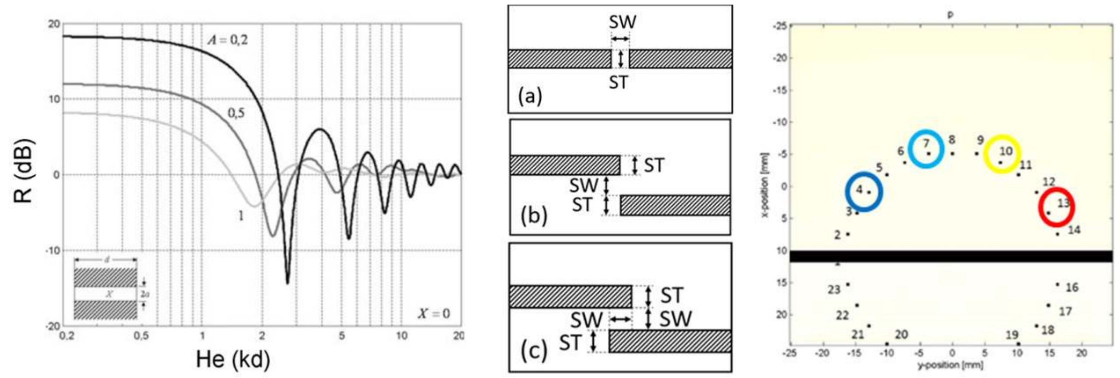

Fig. 5 . Left: Transmission loss R of a circular orifice as a function of Helmholtz-number (normalized - A = 2a/d, circular wave number k = 2 π/λ, Wavelength λ) [5], middle: Simulation of different gap geometries (a) „normal" parallel gap, (b) displaced gap, (c) overlapping displaced gap -width (SW) und gap thickness(ST)., right: microphone positions for the power density spectra in the next figure.

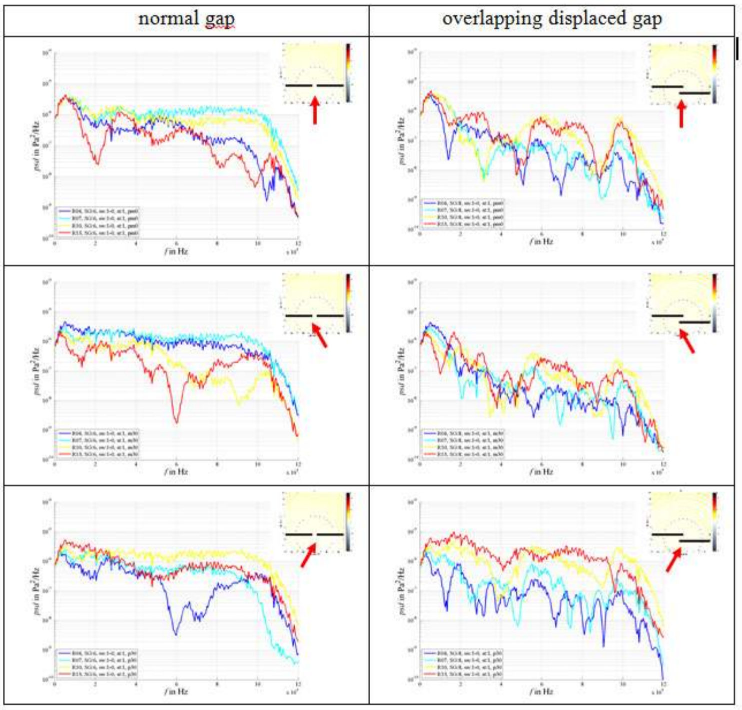

Fig. 6. Power density spectra at different receiver positions (colors according to the previous figure) for a gap distance of 1,85 mm and a gap width of 1.85 mm. The acoustic source is white noise (the wave direction is indicated by a red arrow).

Conclusion

Technology and procedures for leakage size estimation and for tightness evaluation have been revisited. The extensions have been physically justified. Proposals have been made for a redesign of testing equipment, procedures and algorithms. A classification system for leakage size has been proposed basing on aero-acoustic laws and empirical estimations.

Problems tightness evaluation by means of active ultrasound source has been investigated by means of simulations. It has been shown that the geometry of gap has a tremendous influence of the measured data. A simple recording and interpretation of acoustic data is worthless in many practical situations. However, the method has some potential provided the theoretical background is taken into account.

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