Measurement of Turbulent Air Noise Distortion in Loudspeaker Systems

Wolfgang Klippel, wklippel@klippel.de

Robert Werner, r.werner@klippel.de

Abstract

Air leaks in the dust cap and cabinets of loudspeakers generate turbulent noise which highly impairs the perceived sound quality as rub and buzz and other loudspeaker defects do. However, traditional measurement techniques often fail in the detection of air leaks because the noise has a large spectral bandwidth but a low power density and similar spectral properties as ambient noise generated in a production environment. The paper models the generation process of turbulent air noise and develops a novel measurement technique based on asynchronous demodulation and envelope averaging. The technique accumulates the total energy of the leak noise radiated during the measurement interval and increases the sensitivity by more than 20 dB for measurement times larger than 1s. The paper also presents the results of the practical evaluation and discusses the application to end-of-line testing.

1. INTRODUCTION

The generation of sound in loudspeaker systems requires the compression of air and generates high air pressure within the enclosure. If the enclosure is not perfectly sealed air at high velocity is expelled at those leaks causing turbulences which generate characteristic air noise. The signal contains spectral components all over the audio band and beyond. In passive loudspeaker systems those leaks usually occur at the dust cap, at the surround or somewhere in the cabinet. Modern active loudspeaker system using a sealed enclosure and active filtering to extend the bandwidth to lower frequencies are much more prone to air noise than passive system because the pressure inside the box is significantly increased and electronic components such as switches and connectors require careful sealing. In vented-box systems high air velocity in the port generates a similar noise signal.

The generated high-frequency components of the turbulent air noise are highly audible and are not acceptable like other irregular loudspeaker defects (e.g. rubbing coil, buzzing parts, loose particles, …). Despite the high impact on perceived sound quality air noise is difficult to measure, especially in a production environment. Traditional measurement techniques based on spectral analysis fail because the power density is small and usually masked by microphone and ambient noise. Special techniques developed for rub and buzz measurement are also not sensitive enough because higher-order harmonics are not a reliable symptom for air leakage noise due to its random characteristic.

It is the target of the paper to develop a new measurement technique for air noise generated by turbulences at leaks and ports. In the first step the physics of the sound generation process is investigated and modeled by a signal flow chart. This modeling reveals unique properties of air noise which are exploited in a new measurement method. Finally the paper reports on the practical evaluation on various kinds of vented and sealed loudspeaker systems.

2. SYMBOLS

c	speed of sound
$e(t)$	modulation envelope
$e_{\max}$	peak value of averaged envelope
f	frequency
f_0	excitation frequency
$H_{\text{det}}(j\omega)$	deterministic filter transfer function
$H_{\text{post}}(j\omega, r_{\text{i}}\|r_s)$	post-filter transfer function between source point r_{s} and receiving point r_{i}
$H_{\text{pre}}(j\omega)$	pre-filter transfer function
$H_{\text{stoch}}(j\omega)$	stochastic filter transfer function
MOD_{abs}	absolute modulation level
MOD_{rel}	relative modulation level
$n(t)$	random noise signal
$\text{N}(p_{box})$	static nonlinear system

p_0	reference sound pressure (absolute hearing threshold)
$p(t,r_i)$	sound pressure at the receiving point r_i
$p_a(t)$	ambient noise
$p_{box}(t)$	sound pressure in box
$p_{det}(t)$	deterministic sound pressure component
$p_{lin}(t)$	linear sound pressure component
$p_{mod}(t)$	modulated air noise
$p_{stoch}(t)$	stochastic sound pressure component
$q_{mod}(t)$	modulated air volume flow
$r(t)$	non-harmonic components in stochastic signal
$R(\tau)$	auto correlation function
t	time
T	period length
$u(t)$	voltage at speaker terminals
δ	DIRAC impulse
ρ_0	density of air
τ	time lag
ω	angular frequency

3. SOUND GENERATION AT AIR LEAKS

3.1. First Experiments

To understand the physical mechanisms generating the characteristic turbulent noise at air leaks a 4 inch woofer has been mounted in a one liter enclosure with a defined 2 mm hole at the rear side. While exciting the loudspeaker with a sinusoidal tone at 35 Hz the sound pressure was measured close to the leak by using a sensitive half inch condenser microphone.

Fig. 1 shows the recorded sound pressure waveform with the open and sealed leak. The sound pressure of the sealed box reveals the fundamental component of 35 Hz and some harmonics distorting the waveform. The time signal of the leaky box contains additional distortion generated at particular sections of the waveform where the sound pressure is close to the positive and negative maximum. Fig. 1 also shows a second solid line which represents a repeated measurement of the leaky enclosure performed under identical conditions. Obviously, the distorted intervals have a differing stochastic fine structure but occur at the same section of the waveform and have a deterministic envelope.

Fig. 2 shows the amplitude spectrum of the sound pressure signals presented in Fig. 1 generated by a loudspeaker enclosure with and without leak. The harmonic components at low frequencies are almost identical and are caused by motor and suspension nonlinearities. However, the leak generates about 20 dB more broad-band distortion (black curve) above 1 kHz than the sealed enclosure (grey curve). Those components do not only contain higher-order harmonics at multiples of fundamental frequency 35 Hz, but fill all lines of the spectrum.

3.2. Signal Analysis

The following section describes the observations made from a signal theoretic perspective.

A loudspeaker device under test is excited by a stimulus $u(t)$, and the sound pressure

$$p(t, r_{\mathrm{i}}) = p_{\mathrm{lin}}(t) + p_{\mathrm{det}}(t) + p_{\mathrm{stoch}}(t) + p_{\mathrm{a}}(t) \qquad (1)$$

is measured at a particular location r_i. It comprises a linear component $p_{\mathrm{lin}}(t)$ which is coherent with the input signal u(t) as well as a deterministic distortion component $p_{\mathrm{det}}(t)$, a stochastic distortion component $p_{\mathrm{stoch}}(t)$ and ambient noise $p_{\mathrm{a}}(t)$ which are incoherent with the input signal $u(t)$.

Both the deterministic and stochastic components will vanish if the voltage of the stimulus at the terminals is attenuated while the ambient noise signal $p_{\mathrm{a}}(t)$ is completely independent of the stimulus. The motor and suspension nonlinearities dominate the deterministic distortion component $p_{\mathrm{det}}(t,r_{\mathrm{i}})$ and are accepted as regular distortion mainly defined in the design process and may be even desirable in particular applications. Some loudspeaker defects such as hard mechanical clipping or wire beating on the diaphragm also generate deterministic distortion. The waveform has a reproducible pattern containing only higher-order harmonics where the amplitude and phase of each component has a defined relationship to the fundamental component. Thus repeating the measurement with the same stimulus and averaging the measured sound pressure responses will increase the deterministic component and the sensitivity of the measurement.

Turbulent air noise from ports and leaks, loose particles and a rubbing voice coil contribute to the stochastic distortion $p_{\mathrm{stoch}}(t)$ but the fine structure of the waveform is not reproducible and the amplitude of the stochastic distortion component cannot be increased by averaging.

3.3. Modeling

The air leakage distortion is directly related to the sound pressure in the enclosure

$$p_{\mathrm{box}}(t) = F^{-1}\{H_{\mathrm{pre}}(j\omega)\} * u(t) \qquad (2)$$

which can be predicted by convolving the voltage $u(t)$ at the loudspeaker terminals with the transfer function $H_{\mathrm{pre}}(j\omega)$ transferred into time domain. The transfer function has a low-pass characteristic for sealed enclosures and a band-pass characteristic for vented enclosures. For high positive values of sound pressure the velocity of the outwards moving air particles at the leak is high, generating turbulences and air leak distortion. Much less noise will be generated for negative sound pressure sucking the air particles to the leak and causing more turbulence inside the enclosure. The generation of turbulent air noise distortion $q_{\mathrm{mod}}(t)$ can be modeled by a modulation process

$$q_{\mathrm{mod}}(t) = N(p_{box}) \cdot n(t) \qquad (3)$$

where random noise signal $n(t)$ is multiplied with the output of a static nonlinear system

$$N(p_{\mathrm{box}}) = n_0 + n_1 p_{\mathrm{box}} + n_2 p_{box}^2 + \ldots \qquad (4)$$

where the coefficient n_1 generates an asymmetrical characteristic versus sound pressure p_{box}. The random noise has a white spectral characteristic where the auto-correlation function

$$R_{nn}(\tau) = \mathrm{E}\{n(t)n(t+\tau)\} = \delta(\tau) \qquad (5)$$

vanishes for any time delay $\tau \neq 0$.

The propagation of the generated air noise distortion at the source point r_s to the sound pressure distortion

$$p_{\text{mod}}(t, r_{\text{i}}) = F^{-1}\left\{H_{\text{post}}(j\omega, r_{\text{i}}|r_{\text{s}})\right\} * q_{\text{mod}}(t) \qquad (6)$$

at any receiving point r_{i} in the far field may be modeled by a second linear post-filter using the Green function

$$H_{\text{post}}(j\omega, r_{\text{i}}|r_{\text{s}}) = -\frac{j\omega\rho_0}{2\pi}\frac{\exp(-j\omega|r_{\text{i}} - r_{\text{s}}|/c)}{|r_{\text{i}} - r_{\text{s}}|}. \qquad (7)$$

with the air density ρ_0, speed of sound c and the distance $|r_{\text{i}}-r_{\text{s}}|$ between source and receiving point. This transfer function describes the distortion source by a monopole radiating the volume velocity $q_{\text{mod}}(t)$ at the wall boundary into the half-space. It causes a time delay and attenuation of the distortion signal but will not affect the waveform of the signal. This approximation is only valid under free-field condition or within the critical distance where the direct sound dominates the room reflections. However, propagation in a reverberant environment beyond the critical distance will smear temporal variation of the envelope and reduce the modulation index significantly.

4. MEASUREMENT TECHNIQUE

4.1. Previous Approaches

The detection of leaks in material structures is an important measurement task in many industrial applications and thus a variety of measurement techniques has been developed [1]. In many cases the application is related to quasi-static pressures in installations and enclosures carrying fluid material.

Genereally there are two approaches for the task of leak detection. On the one hand the flowing material is detected to identify and localize the source, on the other hand secondary effects such as pressure decay, acoustical emissions and changes of volume or temperature are used for this purpose. The most simple techniques exploiting pressure decay are usually very time consuming and require devices to generate, apply and measure quasi-static pressure variations.

The main goal of detecting leaks in loudspeaker system is to prevent audible acoustical emissions in terms of signal distortion due to turbulent flow noise. Therefore acoustical measurement techniques are preferred. Especially in the context of loudspeaker measurement systems all required tools for acoustical and electrical measurement are available.

The effects of small structural leaks on the variation of small signal parameter of the transducer or the enclosure (e.g. box resonance, loss factor) are usually negligible. Garcia et al. [2] stated a method for telecommunication devices with relatively small air volume measuring only impedance and electrical impulse response for comparison with reference curves. In most cases purely electrical techniques do not provide comparable sensitivity to acoustical measurements which offer a variety of different realizations.

Marziale et al. [3] introduced an automatic analysis based on frequency groups in the audio band. For this method empirical and thus application specific references have to be determined in advance. Peacock [4] describes a related method using a sensor array to identify and localize leaks in a fluid tank for off-line diagnostics. Another microphone array technique is suggested by Greene [5] for detecting acoustic leaks. To improve the signal separation towards ambient noise an adaptive filtering approach has been developed by Savic [6]. Yonak [7] suggests a leak detection and localization system measuring the photo-acoustic sound emission of an indicator gas initiated by a carbon dioxide laser.

Zaschel [8] shows that the separation of deterministic and stochastic components is beneficial for the early identification of defects. Klippel [9] suggested an adaptive filter to separate the regular distortion component from the irregular deterministic distortion component. G. Moshier [10] exploits ultra-sonic frequency components in the turbulent noise for leak detection.

4.2. A New Demodulation Technique

A new approach presented here exploits some properties of the modulated noise which are only visible in the time domain. The envelope of the turbulent air noise has a characteristic periodic pattern which corresponds with the periodicity of the stimulus. Instead of averaging the original random time signal it is the idea to average the deterministic envelope of the noise. In the first step this requires detecting the envelope by performing a demodulation of the measured noise. Since the primary noise signal $n(t)$ (“carrier”) at the leak is not accessible an asynchronous demodulation has to be applied.

4.3. Envelope Detection

The radiated sound pressure signal $p(t)$ measured at the receiving point r_i is passed to a linear filter extracting the stochastic signal component

$$p'_{stoch}(t) = F^{-1}\{H_{stoch}(j\omega)\} * p(t) \qquad (8)$$

and suppressing the fundamental as well as other deterministic distortion components (harmonics).

Using a sinusoidal stimulus with known excitation frequency f_0 this filter can be realized as an inverse comb-filter with the transfer function

$$H_{stoch}(j\omega) = \prod_{k=1}^{K} \left(1 - \delta(\omega - 2\pi k f_0)\right) \qquad (9)$$

which attenuates the fundamental frequency f_0 and all higher-order harmonics only.

The filtered signal $p'_{stoch}(t)$ displayed in Fig. 5 reveals the random noise and the deterministic envelope more clearly than the original time signal $p(t,r_i)$.

The squared envelope signal

$$e(t)^2 = F^{-1}\{H_{det}(j\omega)\} * p_{stoch}(t)^2 \qquad (10)$$

is detected by squaring the time signal $p_{stoch}(t)$ and applying a linear comb-filter with the transfer function

$$H_{det}(j\omega) = \prod_{k=1}^{L} \delta(\omega - 2\pi k f_0) \qquad (11)$$

which selects only the demodulated component at the fundamental frequency f_0 and the low–order harmonics ($L < 10$).

4.4. Time Averaging

For modulated air noise the envelope signal $e(t)^2$ in Fig. 6. reveals the same periodicity as the sinusoidal stimulus.

To suppress unmodulated noise caused by the production environment or the microphone the envelope time signal is divided in adjacent segments with the same period length $T_0=1/f_0$ as the stimulus and averaged over N periods by

$$\overline{e(t)^2} = \frac{1}{N}\sum_{i=0}^{N} e(t+iT_0)^2 \text{ for } 0<t<T. \qquad (12)$$

Finally the peak value of the averaged envelope signal

$$e_{\max} = \max_{0<t<T_0}\left\{\overline{e(t)^2}\right\} \qquad (13)$$

is detected within one period.

4.5. Characteristic Measures

Due to the quasi-stationary character of the modulation envelope during stationary sinusoidal excitation the described averaging technique can be applied to derive easy interpretable level measures for the qualitative and quantitative evaluation of turbulent leak noise. Focusing on the amplitude e_{max} of the averaged, squared modulation envelope $\overline{e(t)^2}$ as shown in Fig. 7 an absolute as well as a relative measure is determined.

4.5.1. Absolute Modulation Level

To evaluate the absolute level of turbulent leak noise the envelope peak value e_{max} can be expressed in terms of a sound pressure level using the absolute hearing threshold p_0 as the reference value:

$$\text{MOD}_{\text{abs}} = 10\lg\left(\frac{e_{\max}}{2p_0^{\,2}}\right)\text{dB}. \qquad (14)$$

4.5.2. Relative Modulation Level

As stated before the generation of turbulent leak noise is modeled as an amplitude modulated process. This unique feature can be exploited to derive a second relative measure.

A relative modulation level

$$\mathrm{MOD}_{\mathrm{rel}} = 10\,\lg\left(\frac{e_{\max}}{\tilde{r}^{2}}\right)\mathrm{dB}. \qquad (15)$$

is introduced which describes the ratio between the maximal value of the squared envelope e_{max} corresponding with the harmonic components in Fig. 8 and reference value

$$\tilde{r}^{2} = \sqrt{\frac{1}{T_0}\int_0^{T_0} r(t)^2\,\mathrm{d}\,t} \qquad (16)$$

of all stochastic signal components

$$r(t)^2 = F^{-1}\{H_{\mathrm{stoch}}(\omega)\} * p_{\mathrm{stoch}}^{2}(t) \qquad (17)$$

corresponding with the dashed horizontal line also presented in Fig. 8. The MOD_{rel} measure is easily interpretable on an absolute scale. Measuring random noise which is not modulated by f_0 generates low values of MOD_{rel} which are close to 0 dB.

5. AMBIENT NOISE IMMUNITY

A two-channel measurement has been suggested in previous work [11] for detecting ambient noise corrupting end-of-line testing. A second microphone located in the far field is used for predicting the impact of ambient noise on the measurement in the near field of the test object. The described method can also be applied in the present case. However, comparing the absolute and the relative modulation level gives additional cues for detecting ambient noise.

While the absolute modulation level MOD_{abs} reflects the power density of any broad band noise the qualitative information provided by the MOD_{rel} measure is a reliable indicator for modulation.

Figure 9 illustrates this statement by showing the demodulated sound pressure signal of a corrupted and a valid measurement performed by a test microphone located in the near-field of the loudspeaker and a second ambient noise microphone at remote location. The lower black curve represents the uncorrupted near-field demodulation spectrum and reveals high harmonics which are reliable symptoms of the noise modulation process. The lower gray curve shows that the remote ambient noise microphone detects unmodulated noise only. The upper curves show the demodulated sound pressure spectra in case of significant ambient noise affecting the test and ambient noise microphones. Both spectra have the same high absolute values of MOD_{abs} and reveal no harmonics at multiples of f_0 generating low relative levels MOD_{rel} (close to 0dB). This information is sufficient for detecting invalid measurements corrupted by ambient noise reliably.

6. PRACTICAL EVALUATION

To validate the developed measurement technique and to evaluate the derived measures two standard applications have been chosen – a closed box and a vented box system. For providing reproducible conditions holes of different diameters were drilled in the enclosures to simulate leak defects caused by manufacturing errors or loose joints. Other leak geometries were also investigated with comparable results.

The measurement was performed with the KLIPPEL QC System, a measurement system for quality control of electro-acoustic devices using an ICP driven 1/4" electret condenser microphone in the near field of the test objects [12]. Figure 10 shows the measurement setup schematically.

6.1. Sealed Box System

Sealed box systems with a single full-range driver are a very basic, but also very common application. Especially small and cost-effective multimedia speakers have to cope with high sound pressure within the box on account of high membrane excursion to provide proper low frequency reproduction. Thus air leakage is very critical for this application.

The test object was a 9 cm woofer in a cubic enclosure ($V \approx 1$ liter) with a 2 mm diameter leak. As a first experiment the generation of turbulent flow noise depending on the stimulus voltage was examined. As shown in figure 11 the measured distortion does not rise continuously with the stimulus level, but very abruptly at a certain threshold. The absolute level MOD_{abs} rises slightly with the applied voltage above this threshold.

As stated before the MOD_{rel} is a good qualitative indicator for the presence of modulated noise indicating exactly the voltage where the modulated air noise sets in. The relative modulation saturates fast with rising voltage.

A second experiment shows the influence of the averaging applied during signal processing. Therefore the measurement was performed with varying stimulus duration as shown in Fig. 12.

The absolute peak level of the modulated distortion (MOD_{abs}) is not influenced by the measurement time due to steady-state conditions. The averaging mainly influences broad-band noise which is not correlated to the stimulus frequency and is represented by the reference value Eq. (16) for relative modulation level calculation Eq. (15). While the envelope amplitude stays constant, the reference “noise” floor decreases due to averaging which leads to an increase of MOD_{rel} with the measurement time.

Using steady state single tone excitation and coherent signal processing it is important to characterize the influence of stimulus frequency on the generation of leak noise. The measurement results in Fig. 13 confirm the assumption that the excitation frequency has almost no influence for closed systems, as long as it is below the system’s resonance frequency (here 200 Hz) implying constant excursion amplitude. The pressure difference at the leak is directly connected to the air compression caused by the membrane displacement of the driver.

As a further variable the influence of measurement distance in a reverberant environment was determined varying the distance between the leaky surface of the enclosure and the measurement microphone. As expected the absolute modulation level MOD_{abs} shown in Fig. 14 is inversely proportional to the distance to the (point) source and falls by 6 dB with doubled distance. More important are the results for relative modulation MOD_{rel}. In an ideal anechoic environment (with negligible air attenuation) the relative measure is expected to be constant by theory. In the measured reverberant environment diffuse reflections interfere with the direct signal influencing the modulation ratio. Therefore MOD_{rel} falls with the distance until the reverberant signal is dominant and the modulation envelope is covered.

6.2. Vented Box System

Although ventilated speaker systems use relatively large ports to provide acoustic mass they are not less susceptible to leak defects. The sound pressure within the box becomes maximal at the port resonance but drops significantly for lower and higher frequencies. The impact of excitation frequency on the measured modulated distortion values is shown in Fig. 15.

The port resonance of the used speaker is around 40 Hz while the driver resonance is at 75 Hz. The maximal relative and absolute modulation level is measured close to the port resonance as expected. At very low frequencies the acoustic short circuit sets in and the modulation levels drop abruptly to a minimum (noise floor) which equals the values at frequencies close to and above the driver resonance.

A second concern is the behavior of the port itself close to its resonance frequency. In this frequency range the port generates the main sound pressure output and the volume velocity within the port becomes maximal. Sharp edges, grills and the port geometry itself may cause significant port noise which is also modulated by the stimulus and may mask symptoms from small leaks. To investigate both types of air noise independently the port and the leak were sealed alternately and measured vs. stimulus voltage.

Fig. 16 shows a systematic difference in symptoms generated by vents and leak noise. The port noise level rises less abruptly and stays below the level of leak noise. Of course these results are not to generalize because they strongly depend on the geometry of the test object and the leak defect.

6.3. Measuring Large Speaker Systems

All measurements so far have been performed with a microphone facing the leaky surface of the test object. According to figure 17 the main energy of turbulent air noise is located at higher frequencies of the signal spectrum. Thus shadowing is expected to be a practical problem measuring large objects with a limited amount of locally fixed sensors.

Figure 17 shows the measurement results of MOD_{rel} vs. input voltage for a large vented subwoofer using an arrangement of four microphones placed around the enclosure. The port was sealed during measurement to prevent the emission of port noise. Comparing the measured values shows that one microphone is the closest to the leak while two microphones do not have a direct transmission path being on the opposing side of the enclosure. The measured distortion values for these measurement positions are above the reference curve but not significantly high.

7. DISCUSSION

The sensitivity of the new measurement depends on the following factors:

7.1. Excitation Frequency

Air leakage noise depends on the sound pressure peak value in the enclosed air below the dust cap or in cabinet. In sealed enclosures any tone below resonance frequency may be used as stimulus because it generates almost the same air pressure in the enclosure. In a vented box system the most critical stimulus is a tone just above port resonance.

7.2. Excitation Amplitude

Sufficient stimulus amplitude is also a critical factor because the turbulences require a critical air velocity depending on the geometry of the leak.

7.3. Measurement Time

It is a unique benefit of the new demodulation technique that doubling the measurement time will increase the sensitivity by 3dB. For a 100 Hz excitation tone and a measurement time of 1 s the signal-to-noise ratio of the averaged envelope is 20 dB higher than the leakage noise detected by spectral analysis or high-pass filtering as used in conventional rub and buzz analysis. Averaging of the original noise signal is not useful and will even more reduce the sensitivity.

7.4. Other Causes for Modulated Noise

Ports of vented loudspeaker systems may also generate modulated noise which is similar to the noise generated by air leaks. It is recommended to check the sealing of the enclosure after closing the port with a plug. If this is not possible or desired the amplitude and frequency of the excitation tone should be chosen carefully. A rubbing voice coil will also produce a stochastic component which can be similar to air leakage noise.

7.5. Microphone Position

A direct propagation path of the high-frequency leak noise components to the test microphone is required. Since the wavelength of those components is smaller than the dimensions of most enclosures there is not much diffraction at the edges and noise radiated to the opposite side of the enclosure will be attenuated significantly. Multiple microphones (usually four) placed in the near-field of the enclosure provide a reliable check of any leak on the surface of a large enclosure. Microphones placed in a larger distance detect more diffuse sound part which reduces the modulation index. For remote detection of air leaks in line arrays or fixed sound installations a microphone array with a larger directivity index is recommended.

7.6. Microphone Noise

The new demodulation technique can cope with noise generated by the microphone, preamplifier and other electronic components which may completely mask the air noise. However, to detect leaks within shortest measurement time it is recommended to use highly sensitive microphone capsules.

7.7. Ambient Noise

Any external noise generated by air conditioning system, machines or other sources in a production environment usually do not produce a significant Relative Modulation Level MOD_{rel} (modulation symptoms) because it is very unlikely that those sources perform a modulation with the same frequency as used in the stimulus. Thus a clear distinction between ambient and leak noise is possible.

However, if the ambient noise exceeds the leak noise by more than 20 dB the measurement time should be larger than 1s which is usually not acceptable in manufacturing. It is recommended to provide additional attenuation of the ambient noise by placing the loudspeaker in a small measurement chamber or at the corner of the production site where the walls are covered with a relatively thin layer of absorber material.

8. CONCLUSION

The generation of turbulent air leakage noise can be modeled as a modulation process and is the basis for a new measurement principle which is subject of patent protection [11]. Asynchronous demodulation of the measured noise and averaging of harmonic components of the envelope is a powerful technique for detecting air leaks reliably at a sensitivity superior to the human ear. New modulation measures MOD_{abs} and MOD_{rel} are introduced to describe the stochastic signal components which have a deterministic envelope. Those measures exploit the spectral information between higher-order harmonic components which has been not used by traditional analysis used for rub and buzz detection.

This technique supplements the standard R&D measurements and is also perfectly suited for automatic testing at the assembling line. The objective assessment can be combined with subjective evaluation of the demodulated signal using closed headphones to protect the operator’s ear against excessive level of the fundamental component as illustrated in Fig. 10. This auralization technique is more sensitive than a conventional stethoscope and provides additional clues for loudspeaker diagnostics. First experiments with this tools show that the air noise increases the “sharpness” of the sound and generates an unnatural “roughness” of the sound related to the envelope signal.

An interesting subject of further research is the localization of air leaks by using multiple microphones extending the demodulation technique to multi-channel processing to exploit the time difference of arrival.

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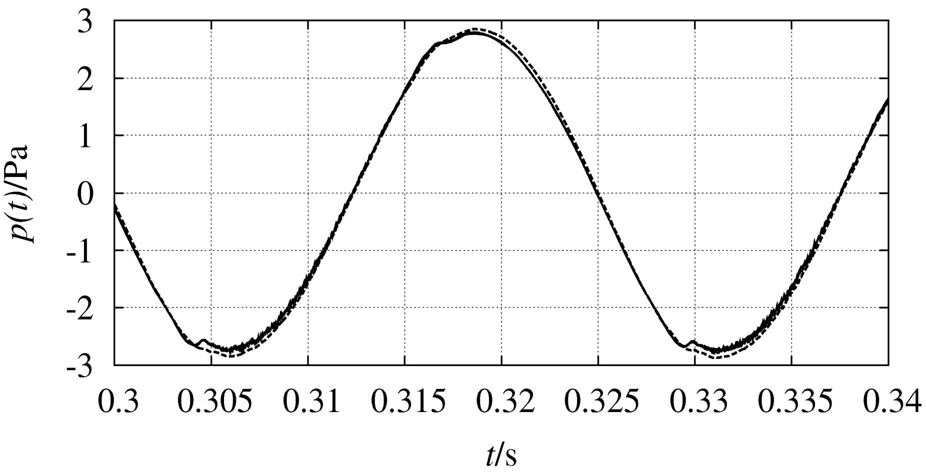

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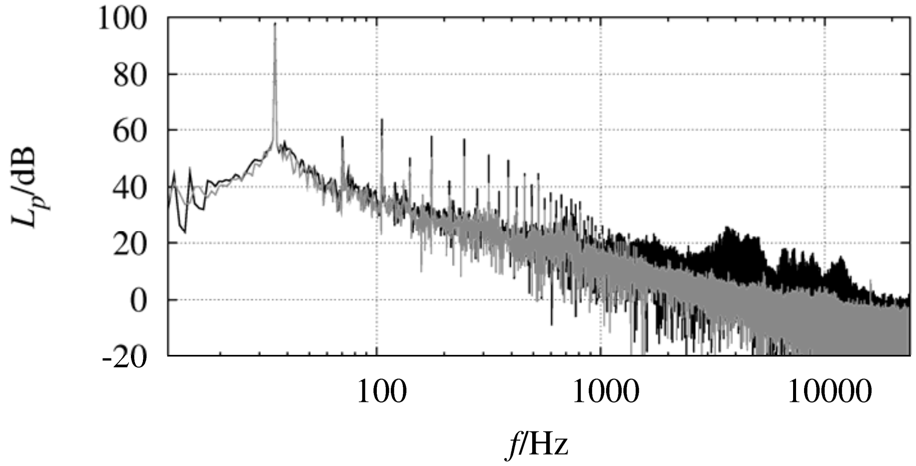

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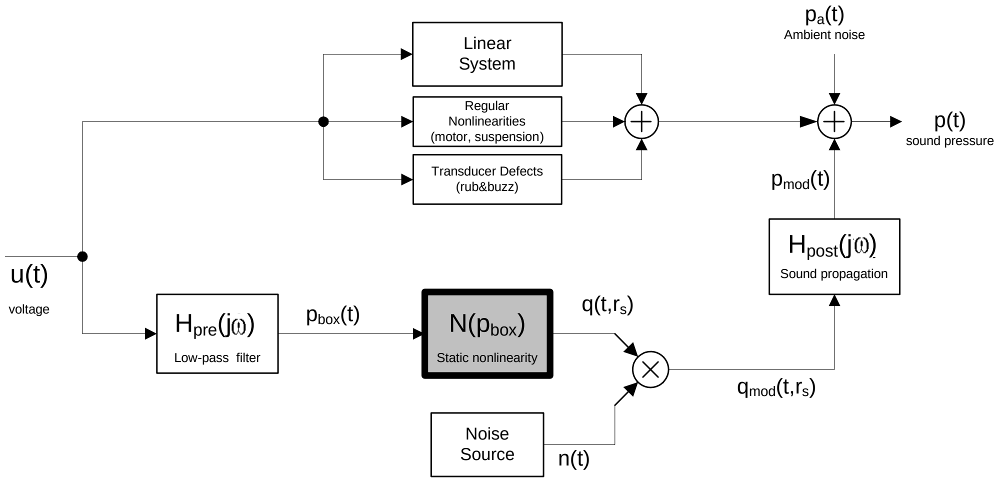

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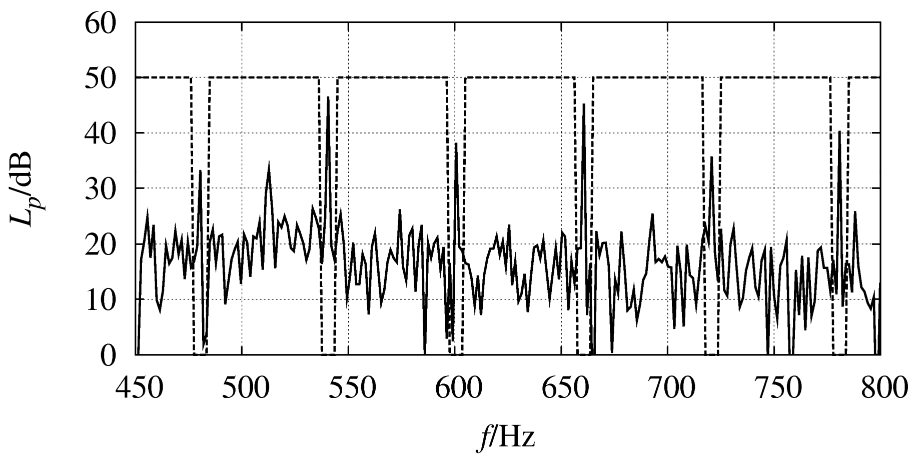

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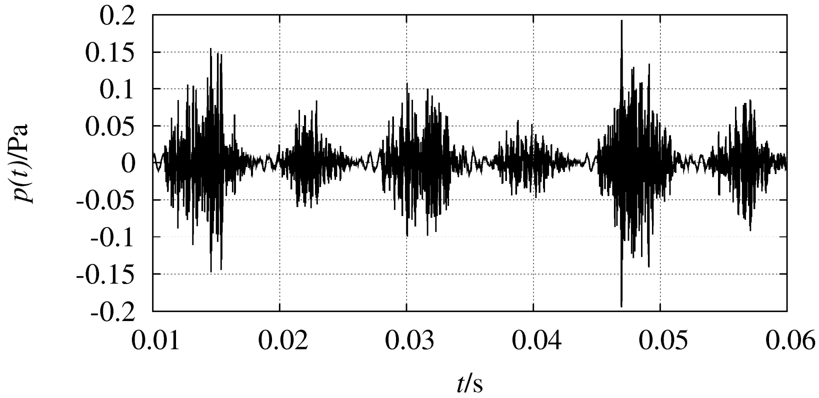

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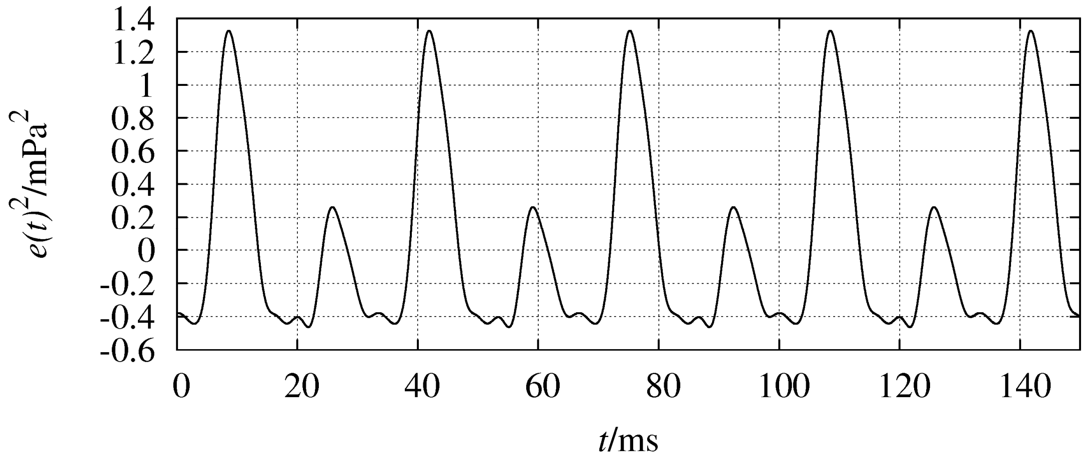

Fig. 6: Squared envelope signal $e(t)^2$ after demodulation

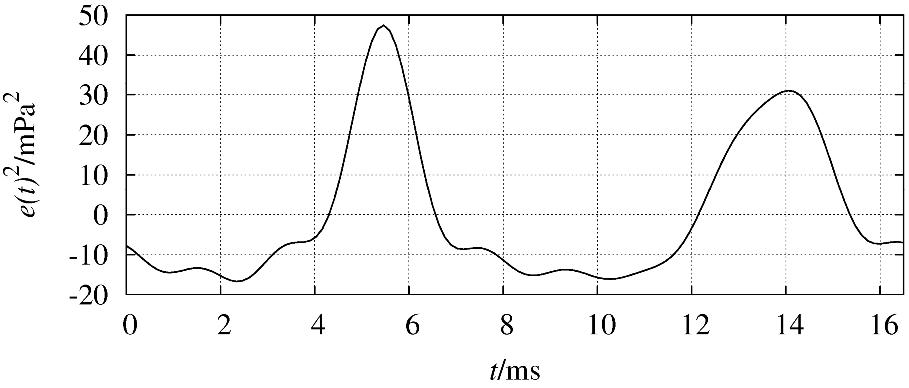

Fig. 7: Averaged squared modulation envelope $\overline{e(t)}^2$

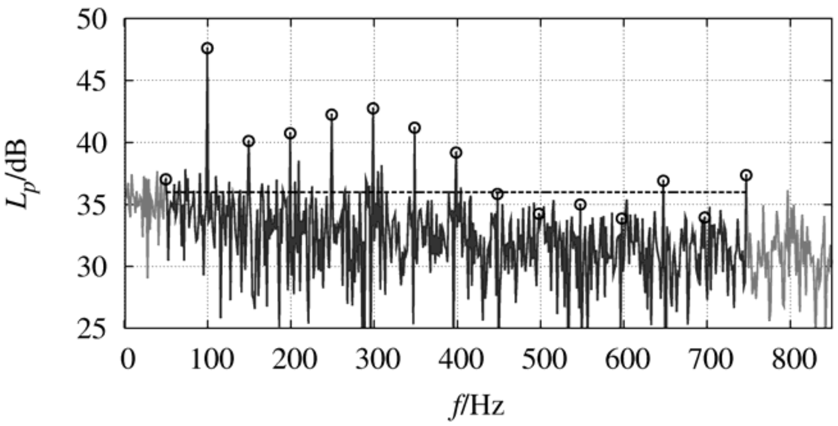

Fig. 8: Demodulated sound pressure spectrum revealing modulation symptoms (circles) representing the modulation envelope; reference value $\tilde{r}^2$ (dashed line)

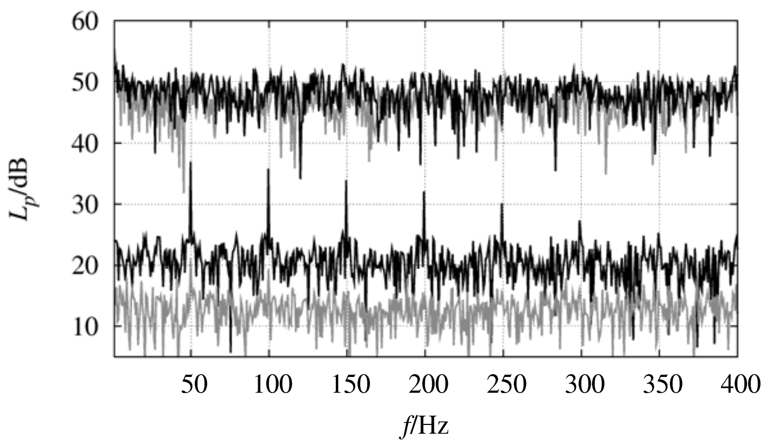

Fig. 9: Demodulated sound pressure spectra $F\{p_{stoch}^2(t)\}$ simultaneously measured in the near (black curves) and far field (gray curves) of the test object; lower curves: silent environment, upper curves: ambient noise corruption

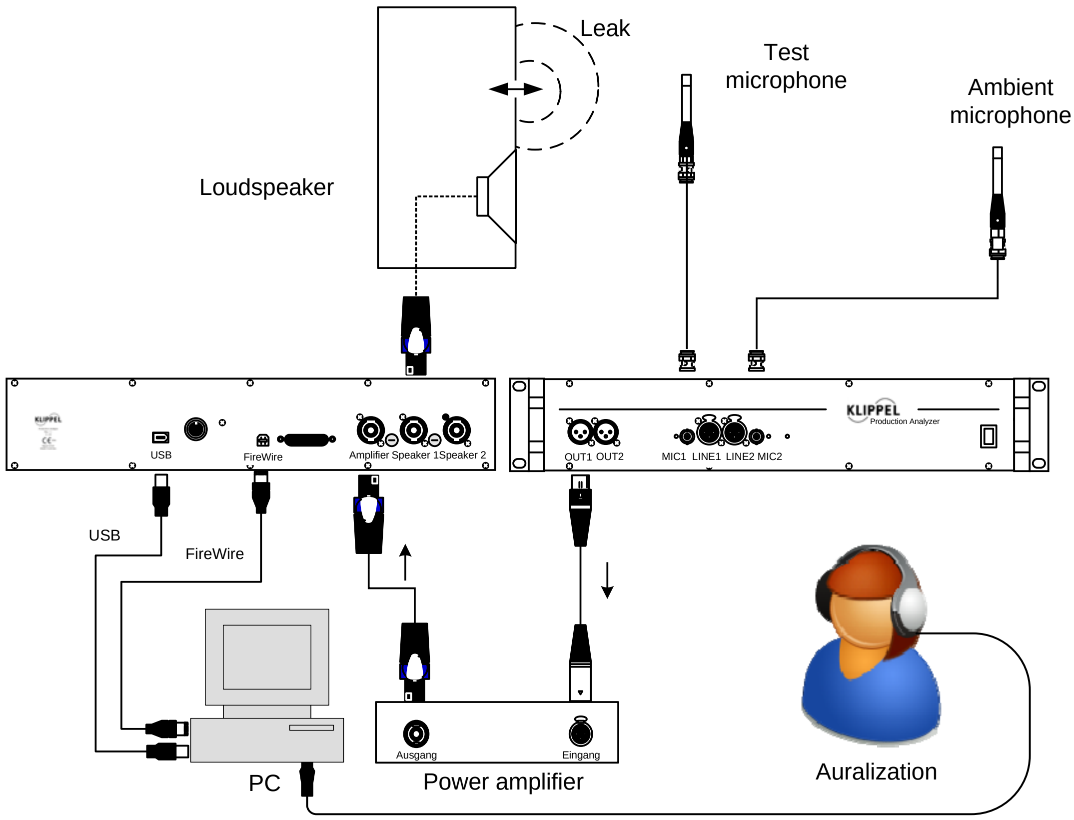

Fig. 10: Measurement setup with KLIPPEL QC System

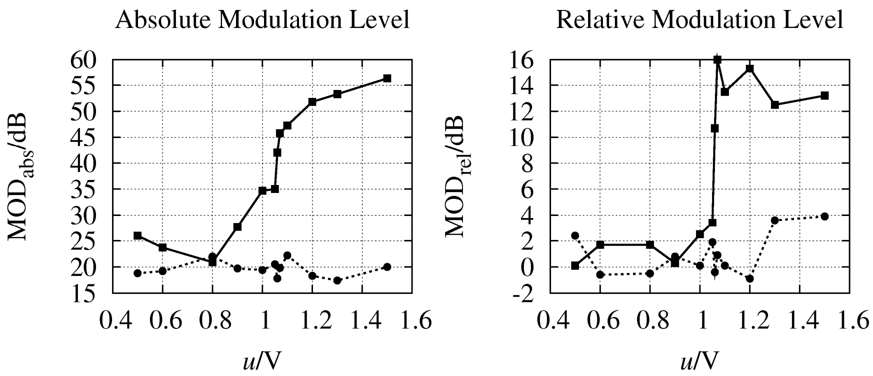

Fig. 11: Absolute and relative modulation level vs. excitation voltage, measured with (solid line) and without leak (dashed line) on a sealed box system

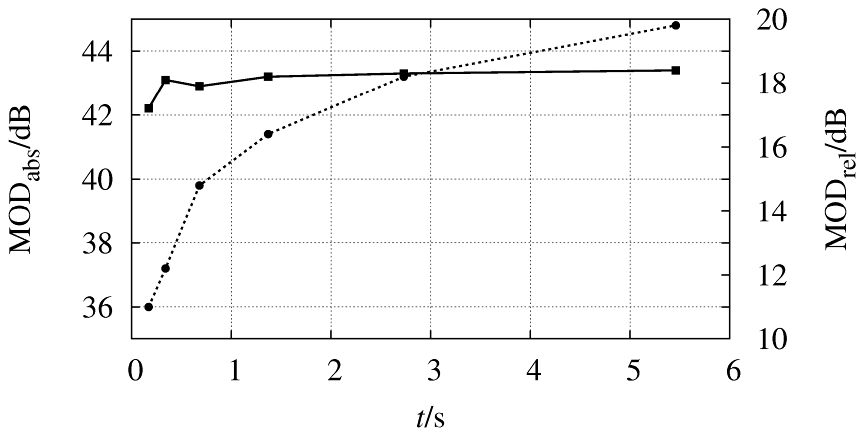

Fig. 12: Absolute (solid line) and Relative (dotted line) Modulation Level vs. measurement time for a closed box system

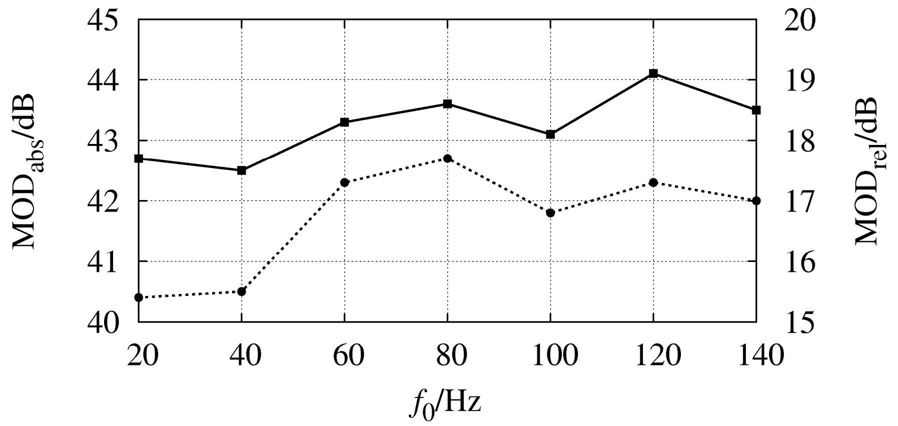

Fig. 13: Absolute (solid line) and relative (dotted line) modulation level vs. excitation frequency for a closed box system

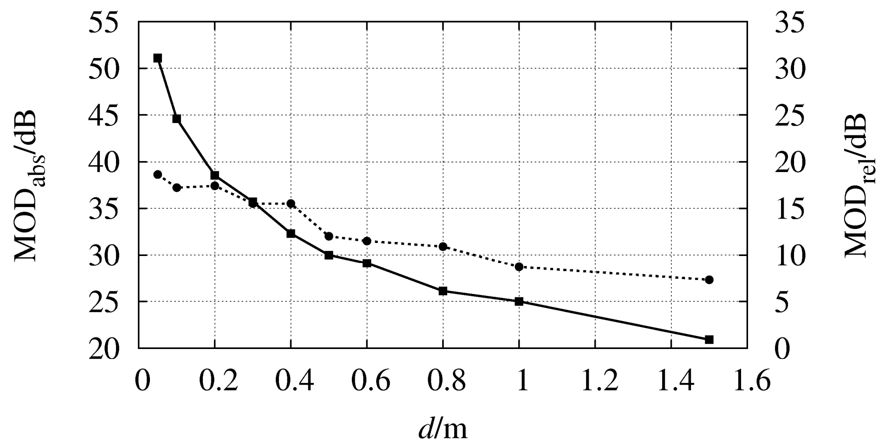

Fig. 14: Absolute (solid line) and Relative (dotted line) Modulation Level vs. measurement distance for a closed box system

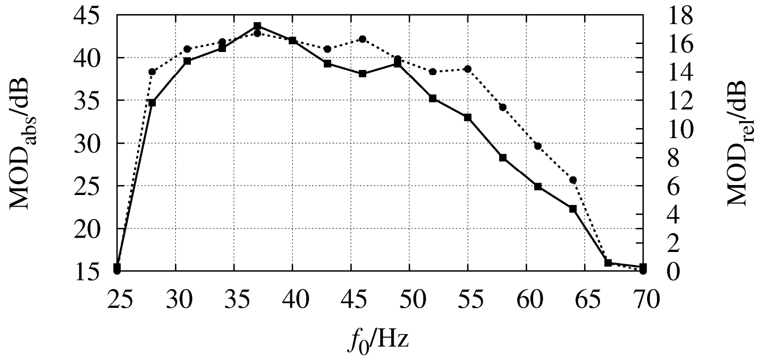

Fig. 15: Absolute (solid line) and Relative (dotted line) Modulation Level vs. excitation frequency for a vented box with leak

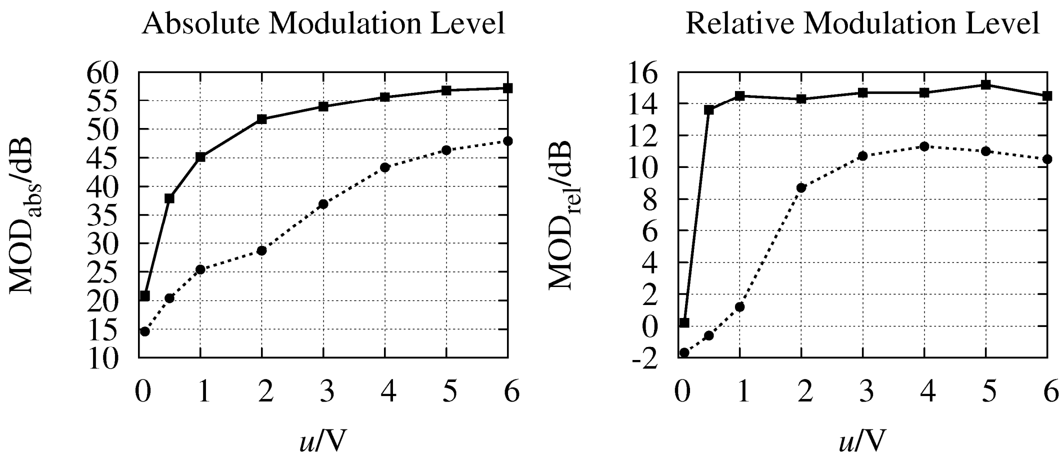

Fig. 16: Comparison of Absolute (left) and Relative (right) Modulation Level of isolated leak noise (solid line) and port turbulences (dashed line) measured at vented box system

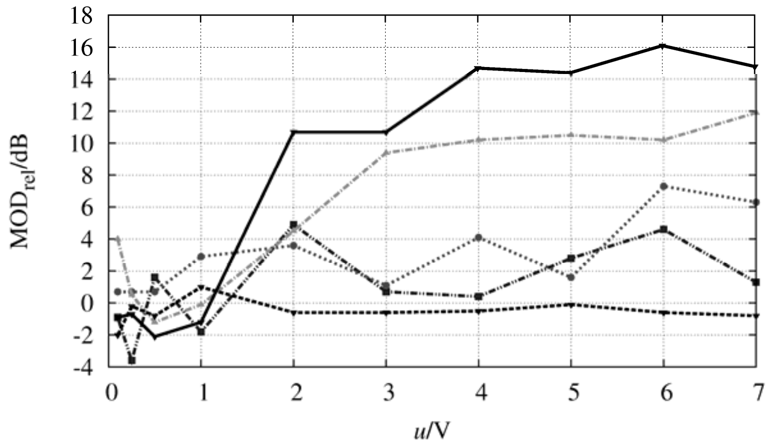

Fig. 17: Relative Modulation Level vs. excitation voltage at four different microphone positions around a large subwoofer with one leak and a reference curve without leak (lowest dashed line)