ARRAY MEASUREMENTS IN WIND TUNNELS WITH OPEN TEST SECTIONS

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ABSTRACT

Acoustically optimized wind tunnels usually have an anechoic chamber around an open test section. For array measurements in this type of tunnels the acoustic array is typically placed outside the flow field - beside or above the test section. The sound emitted from sources in the flow has to propagate through a turbulent shear layer to reach the microphones. During their passage through the shear layer the sound waves interact with turbulent structures. The higher the frequency of the wave, the more significant the effect of the shear layer is. In the present paper these interaction of sound waves with a turbulent shear layer is investigated. It is analyzed which effects can occur when sound waves propagate through a turbulent shear layer and how these effects can influence the results of array measurements. Experiments with a test source in a wind tunnel with open test section are performed. It is shown that turbulent structures in the shear layer lead to systematic phase fluctuations. These phase fluctuations have a certain spectrum and a distinct spatial correlation. Beside these effects the spectral broadening of tones due to the propagation trough the shear layer is investigated.

1 INTRODUCTION

The microphone array measurement technique is a good tool to investigate sound sources quantitatively and qualitatively. In the last few years, a lot of effort was put into the development of this technique for aeroacoustical applications to investigate sound sources of ground vehicles or to learn more about the mechanisms of airframe noise. Mainly, there are three different possibilities to conduct these measurements:

- Fly-over or drive-by measurements, respectively, using full-scale – vehicles
- In wind tunnels with closed test sections, using wind tunnel models
- Last not least: in open – jet wind tunnels with open test sections, also with models

The present paper only highlights the last item which deals with problems concerning measurements in open - jet wind - tunnels, particularly, the effects of sound propagating through the turbulent wind - tunnel shear - layer. The focus lies on the unsteady phase impact and the frequency broadening.

Because experiments are conducted with wind tunnel models, high frequencies above the audible range up to 50 kHz are of special interest, depending on the model – scale.

Interactions e.g. refraction in the mean flow field are not discussed here. Information about this can be found in [1] and [2].

2 EXPERIMENTAL SETUP

All experiments were conducted in the 1M wind tunnel of the German Aerospace Center (DLR) in Goettingen. This closed circuit wind tunnel with open test section achieves a maximum free stream velocity of $U_\infty = 65$ m/s. The picture in fig. 1 shows the test facility, including a close – up view of the nozzle exit. 'Seiferth – wings' are mounted to prevent low frequency instabilities inside the wind tunnel. It is supposed that this kind of passive flow control increases the level of turbulence of the shear layer and induces high frequency disturbances into the shear layer. In the foreground of the picture there is the used simple microphone array with 20 transducers which are outside the flow, about 1m in front of the shear layer. The electret condenser microphones (LinearX M51, USA) are equally spaced (distance 10cm) in a line parallel to the mean flow direction. Each microphone is mounted in an aluminium tube to avoid effects due to acoustical reflections. In the core flow the test source is installed. Inside the aerodynamically shaped wooden body a high - fidelity tweeter (Vifa XT300, Denmark) is installed. The tweeter is connected to an amplifier that is supplied by a signal generator. One can choose a sine, a white noise or a mixture of both as signal for the sound source. Preliminary tests have shown that an aerodynamic fairing made of a fine metal grid covered with silk influences the sound waves only marginally.

The used data acquisition system is able to acquire up to 32 channels with a sampling frequency of 102.4 kHz. The 20 microphone signals and the electrical signal from the signal generator were recorded.

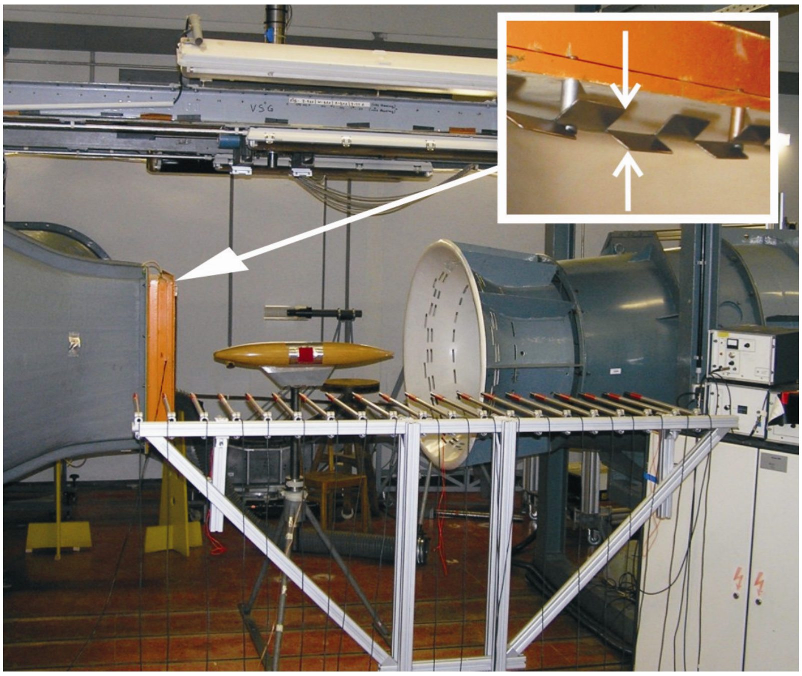

Fig. 1: Test section of the wind tunnel, in the foreground the microphone array, inside the flow the aerodynamically shaped sound source. The exit of the nozzle is equipped with Seiferth wings.

3 DATA PROCESSING AND RESULTS

3.1 Frequency broadening

When a sound wave passes a turbulent wind – tunnel shear – layer, several effects can occur. In this section the influence on a 30 kHz tone of the velocity of the mean flow U_∞ as well as the position of the receiving microphone is considered.

At first the influence of the flow velocity U_∞ is discussed. For this experiment the setup which is presented in the previous section is used, but only the signal of the microphone which is face to face positioned to the source is evaluated. fig. 2, left, shows the frequency spectra for several main flow velocities. It illustrates mainly two cognitions: both the ground noise level and the width of the frequency peak increases with flow velocity. The first fact is due to the increasing ambient noise level of the wind tunnel facility and is as expected, but the broadening of the peak is not obvious in advance. The shear layer seams to be able to redistribute energy which is in the 30 kHz peak to neighbouring frequencies. The tone appears outside the flow as a distribution in the frequency spectrum around the main peak. The simple explanation for this is that by increasing the velocity the turbulence level in the shear layer becomes stronger. The sound emitted by the source strikes a structure within the shear layer. Now this structure acts itself as source of sound that moves irregularly due to the turbulence in the shear layer. The frequencies which are emitted by the irregularly moving source have a Doppler – shift, which is randomly fluctuating This effect is well known under the name

'Doppler broadening' and mostly discussed in physics of spectroscopy or astrophysics. Refer to the citations [3], [5]. Doppler broadening is nothing else than an irregular Doppler shift. Thus, the broadening increases with the turbulence level in the shear flow.

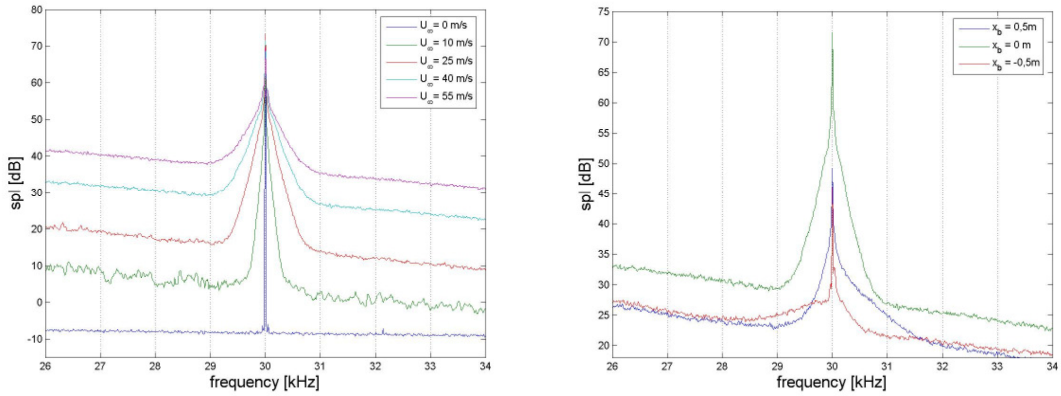

Fig. 2.: Spectral broadening. Left: the influence of the main flow velocity. Right: spectra for three different positions of the microphones, all at $U_\infty = 40$ *m/s.*

Besides the velocity dependence the position of the observer influences the shape of the frequency distributions as well. In fig. 2, right, spectra for three different positions of the receiver are plotted. Thereby $x_b = -0.5$ m means that the microphone is arranged upstream and $x_b = 0.5$ m means the microphone is located downstream of the source, with the microphone in $x_b = 0.0$ m as reference which is face to face to the source. If the observer is located downstream (blue line in the figure) the distribution is skewed to higher frequencies, if it is upstream the distribution is skewed to lower frequencies (red line). It appears that the sound waves interact with randomly fluctuating structures inside the shear layer which move downstream on average. Thus, there is a component of their movement toward the observer (downstream microphone) or away from the observer (upstream microphone). So the Doppler broadening becomes unsymmetrical for observers which are not looking perpendicularly through the shear layer.

Performing microphone array measurements for special applications where high frequency resolution and accuracy is required this effect should be taken into account.

3.2 Unsteady phase fluctuation

This chapter describes the unsteady phase fluctuations of a sound wave which passes a turbulent shear layer. During the propagation the wave could take unsteady acceleration or deceleration. This leads to an unsteady phase relation between the source signal emitted from inside the flow and the signal of the receiver outside the flow. It is obvious that this effect also decreases the correlation between the signals of two microphones positioned outside the flow. This is an important issue for beamforming on a sound source trough a shear layer. The reduction of correlation means a loss of quality doing array measurements.

In the present study these phase fluctuations between the source signal and the receiver signal are evaluated. For this purpose an experiment is performed where the source emits a test tone with frequency f_{test}. Then the spectral cross density $S_{xy}(\omega)$ between the two signals is computed as follows:

$$S_{xy}(\omega) = F\{y(t)\} \cdot [F\{x(t)\}]^{*}. \tag{1}$$

Here $x(t)$ is the time series signal from a microphone and $y(t)$ is the electrical sine signal, directly from the signal generator. $F\{\,.\,\}$ denotes the Fourier transform and $[\,.\,]$ the complex conjugate. The goal is to catch unsteady effects, so this calculation is done window wise by computing $S_{xy}(\omega)$ for short time intervals. If one uses broad windows the unsteadiness will vanish, because the averaging is done over a longer time interval. Because an acceptable time resolution is desirable, narrow windows of 1024 samples are used here. That corresponds at the given sampling frequency of the acquisition system to a window wise average time of 1/100 sec. The windows overlap is 50% which leads to a time series of Fourier coefficients at a rate of 200 per second. This can be considered as an artificial sampling frequency of the Fourier coefficient of $f_{\text{sampling,Fourier}}$ = 200 Hz. For the present analysis only the Fourier coefficient which corresponds to the test-tone frequency is taken into account. This coefficient contains the phase shift between source and microphone. The data for two test cases with different test-tone frequencies are presented here. Both were recorded at a mean flow velocity of 40 m/s. The selected test - tone frequencies are $f_{test} = 10\,\text{kHz}$ and $f_{test} = 30\,\text{kHz}$, emitted by the source. The receiving microphone is installed face to face with the source, and the acoustic sound - "beam" propagates perpendicular trough the shear layer. Fig. 3 shows that the coefficients are more or less randomly distributed around a centre of gravity which is outside of the origin of the coordinate plane. The distributions look a little bit like a ball of wool. Phase ϕ as well as amplitude (distance to the origin) fluctuations occur. The higher the frequency the stronger phase and amplitude fluctuate. The average amplitude for the 10 kHz test case is higher what is basically due to the frequency-dependent response of the source and of the microphone.

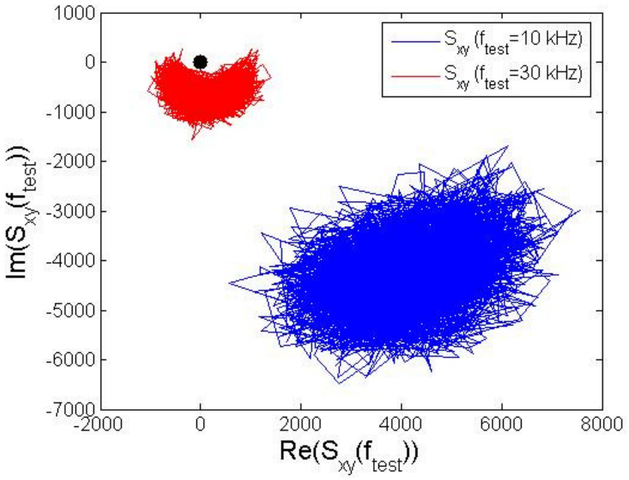

Fig. 3: The Fourier coefficients for two different test-tone frequencies f_{test}

By using the equation:

$$\varphi = \arctan\left(\frac{\operatorname{Re}(S_{xy}(\omega))}{\operatorname{Im}(S_{xy}(\omega))}\right) \tag{2}$$

one obtains the phase between the signals $x(t)$ and $y(t)$. Finally, one subtracts the mean component $\overline{\varphi}$ and achieves the fluctuating component of the phase:

$$\varphi'(t) = \varphi(t) - \overline{\varphi}\,. \tag{3}$$

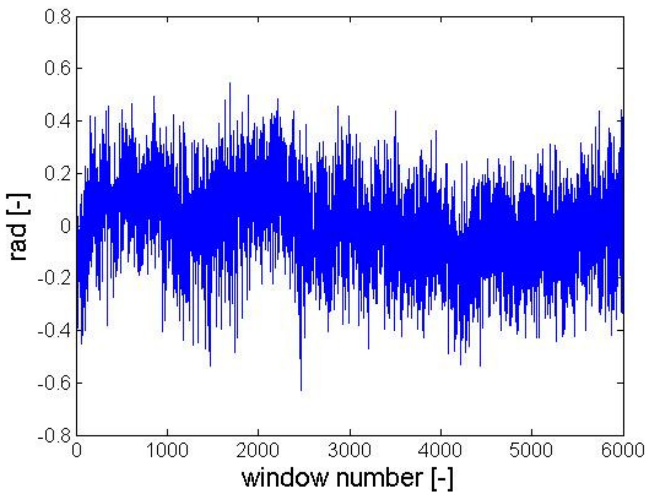

Fig. 4: Time series of the phase fluctuation $\varphi'(t)$, for f_{test} = 10 kHz

Fig. 4 shows the time series of $\varphi'(t)$ for a 30 sec measurement. Because of the artificial sampling frequency of 200 Hz one gets 6000 values for φ'.

In the next step frequency spectra of the time series of these phase fluctuations are estimated. The results for $f_{test} = 10\,\text{kHz}$ and $f_{test} = 30\,\text{kHz}$ for various main flow velocities are shown in fig. 5.

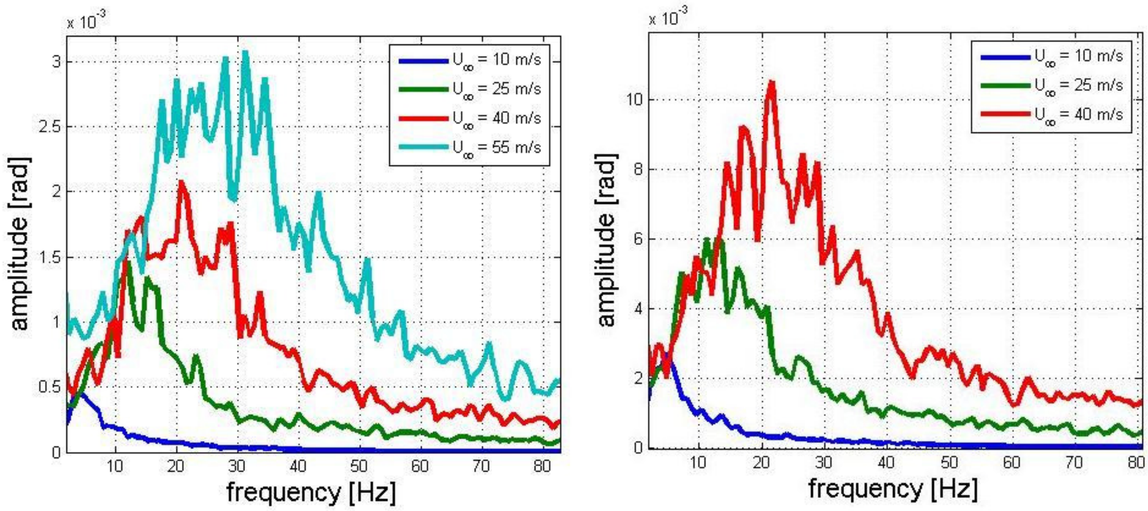

Fig. 5: Frequency spectra of the phase fluctuation $\varphi'(t)$ for different flow velocities.
Left: $f_{test} = 15$ kHz. Right: $f_{test} = 30$ kHz.

The figure illustrates that there is a distinct frequency distribution in the spectra. There is a maximum in the region around 10 – 40 Hz which seems to be velocity dependent. However, the frequency of the test tone f_{test} does not play an important role. Due to the fact that the frequencies of the phase fluctuations are quite low, large-scale structures must be responsible for it. This is the motivation to consider the Strouhal number of the observed phase fluctuation with the nozzle diameter $l = 1.05\,\text{m}$ as characteristic dimension:

$$Sr = \frac{l \cdot f_{\varphi}}{U_{\infty}}. \tag{3}$$

Where f_{φ} is the frequency maximum of the spectra in fig. 5. The result for $f_{test} = 10\,\text{kHz}$ is shown in Fig. 6. Within the measuring accuracy the Strouhal number is constant around the mean value of Sr = 0.48, in comparison with the Strouhal number Sr = 0.2 one can find in literature (e.g. [4]) for the frequency of vortex shedding behind a cylinder.

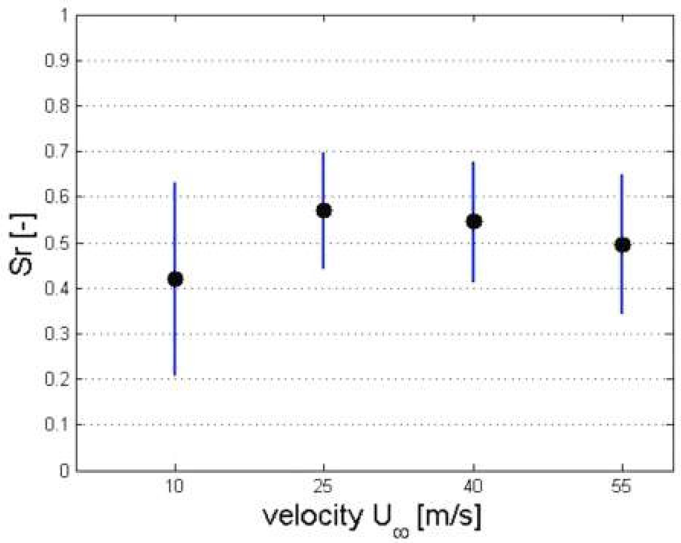

Fig. 6: Strouhal number of the phase fluctuations vs. flow velocity.

It appears that in the free jet of the wind tunnel fluctuations occur which have a typical frequency like the fluctuations in the wake flow behind a cylinder. But at this point it is not clear what kind of structures inside the wind - tunnel shear - layer are responsible for the observed phase fluctuation.

3.3 Velocity of turbulent structures in a shear layer

So far the results indicate that the structures which are responsible for the phase fluctuations are moving downstream in the shear layer. In the following the velocity of this movement is evaluated. For this purpose again an experiment with a test tone is performed. The sketch in fig. 7 shows the principle of the test: Two microphones A and B of known distance record the signal which is emitted from the source inside the flow. It is assumed that there are phase impacting structures in the shear layer which move downstream with a certain velocity. At first this structures influence $\varphi_1^{'}(t)$, and a certain time later $\varphi_2^{'}(t)$. By cross correlating these two sets of data one gets the time which a phase-disturbing structure inside the shear layer requires to travel from position a to position b. Time and distance between a and b gives the mean velocity u_{shear} of these structures.

In [2] it was found out that the narrower the window is the higher the calculated velocities u_{shear} are. This physical relation is not presented here in detail, but it is needful to give a short explanation here:

Window-wise calculation of $\varphi^{'}(t)$ always means filtering in the time domain. As already mentioned, if the window width is broad, short-time fluctuations will not be captured because they vanish due to a long averaging time over one time interval. In the case of a narrow window width the averaging time is short and quick phase fluctuations are detected, but a higher noise level is the drawback which decreases the correlation and complicates the evaluation. In the present investigations the computations were done for different window –

widths. Afterwards, a extrapolation 'limes $\text{width} \rightarrow 0$' was done to find the maximum of u_{shear}.

The result for two different test frequencies at four different free stream flow velocities is shown in fig. 8. Note that u_{shear} is made non-dimensional by U_∞. Within the measurement accuracy this value is considered to be constant and has a value of about $u_{shear}/U_\infty = 0.7$ for all test cases. It is found that u_{shear}/U_∞ increases slightly with the test-tone frequency. The possible explanation for this could be the different ratio between the wavelength of the test-tone and the extension of the phase – disturbing structures. The sound waves interact stronger with structures of a size which is similar or larger than the wavelength. If the wavelength is much larger then the dimension of the structure, there will be only a very weak interaction. Hence, the test-tone with higher frequency is more likely to interact also with smaller structures. If the structures with different size move with different velocities a shift in the evaluated mean velocity is plausible. Finally, the result here means that larger structures must be slower than smaller ones.

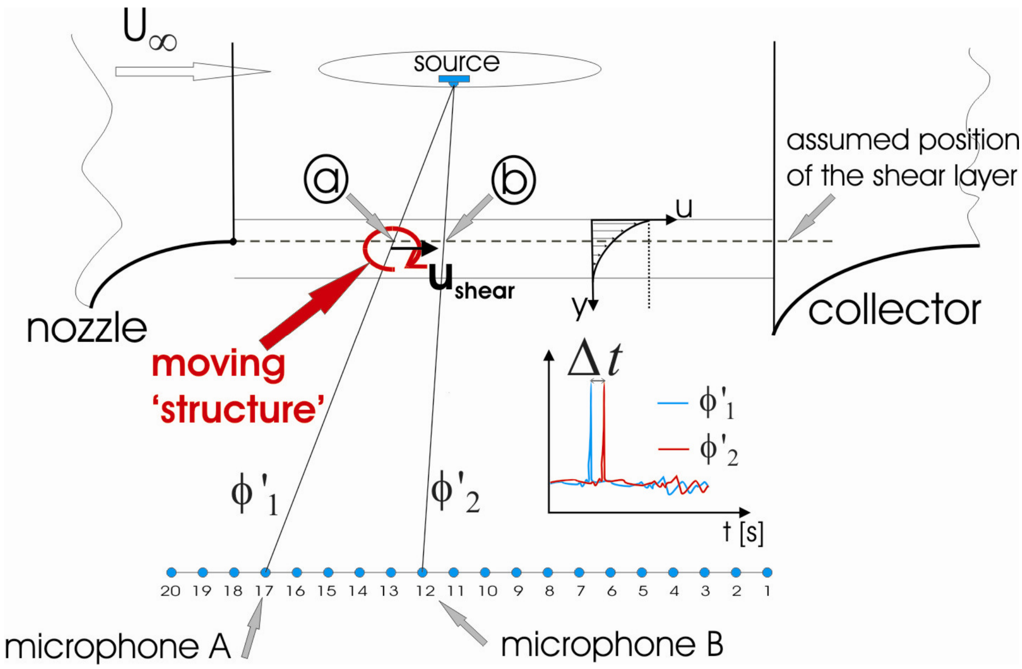

Fig. 7: Top view of the set up and the principle of the velocity measurement

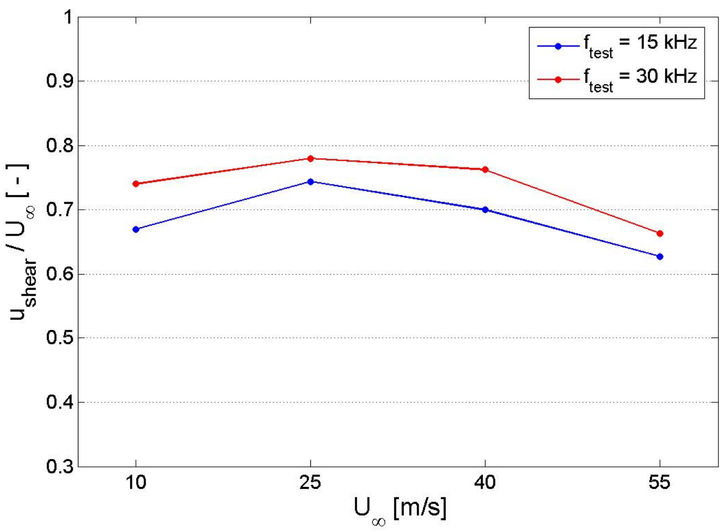

Fig. 7: The result for two different test frequencies and four free stream velocities.

3.4 Noise of the wind – tunnel shear – layer

In the following the noise which is generated by the shear layer of an open-jet wind tunnel is considered. It is evident that sound is generated by the turbulent flow in the shear layer. Here it is investigated how strong this effect is. For this purpose a microphone array evaluation (delay and sum- beamforming, [3]) is performed to search for sound sources. The resulting average noise – map over the frequency range 5 – 40 kHz is shown in fig. 9, left. Unfortunately, shear layer noise cannot be identified. Pressure fluctuations are not strong enough and the ambient noise level produced by the wind tunnel is too high. But in the area around the Seiferth - wings a raised array output level indicates a source. In the next step an array evaluation is done for a single focus – point for all frequencies between 0 and 25 kHz. The array output for every frequency is stored and the result is a frequency spectrum, focused on the positions a (position of the Seiferth - wing) and b (outside the flow) which is plotted fig. 9, right.

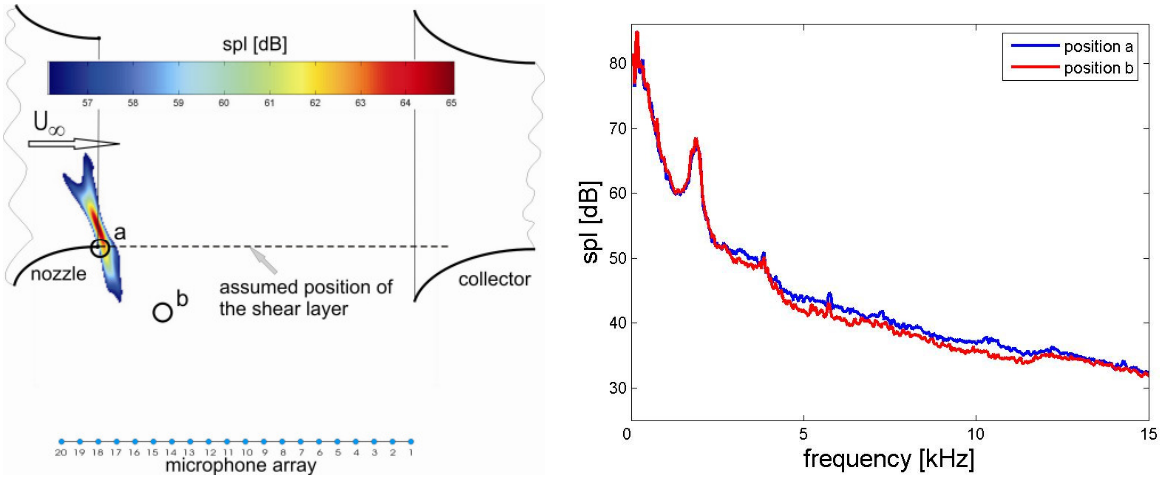

Fig. 8: Left: noise - map, top view of the test section with array. Right: focused frequency spectra for the positions a and b. Main flow velocity $U_\infty = 40$ *m/s.*

The spectrum illustrates that within the range from 6 to 12 kHz the array output for focus point *a* is raised slightly compared with the spectrum for focus point *b*. It can be seen that the Seiferth - wings are responsible for the generation of this broad band noise.

4 CONCLUSIONS

The present study shows that sound waves which propagate through the shear layer of an open test-section are influenced in different ways. It is found that a shear-layer sound interaction redistributes energy to neighbouring frequencies. For example, the peak of a tone is broadened and the broadening is proportional to the mean flow velocity. The direction under which the sound passes the shear layer influences the broadening. If the sound propagates perpendicular through the shear layer the broadening is symmetric, and it is skewed for non – perpendicular propagation. For an observer downstream of the sound source the broadening is skewed towards higher frequencies whereas the upstream observer signal is skewed towards lower frequencies. Performing microphone array measurements where high resolution und accuracy in the frequency domain is required, this effect has to be taken into account, since frequencies are detected which are not emitted by the source but induced by the shear layer.

The unsteady phase fluctuations of a sinusoidal wave propagating through the wind-tunnel shear layer were measured. The used technique captures phase fluctuations up to a frequency of 100 Hz. The frequency spectra of the phase fluctuations show maxima that depend on the mean flow velocity. Taking the diameter of the nozzle as characteristic dimension one obtains a Strouhal number of Sr = 0.48. These low-frequency phase fluctuations are considered to be responsible for a loss of correlation between the array microphone signals, what finally means a loss of quality of the array measurements.

A method is introduced to measure the velocity of the phase-disturbing structures in the shear layer. This method used a source in the flow which emits a test tone and two microphones outside the flow. The experiments show that the structures move downstream with a velocity of $u_{shear} / U_{\infty} = 0.7$. The frequency of the test tone f_{test} has a small effect on the velocity determination. It is concluded that smaller phase-disturbing structures must be faster than larger ones.

Beamforming was used to investigate the sound which is generated by the turbulent shear layer of the wind tunnel itself. The map shows a source at the nozzle exit where the Seiferth - wings are mounted. The focused spectrum computed for this region shows that the Seiferth - wings produce broad band noise in the range of 6 kHz to 12 kHz.

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