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ADVANCES IN MICROPHONE ARRAY MEASUREMENTS IN A CRYOGENIC WIND TUNNEL

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ABSTRACT

The prediction of full-scale airframe noise based on small-scale model measurements via the phased microphone array technique is well known and in common use in closed test sections. Since conventional wind tunnels cannot generally achieve full-scale Reynolds numbers, measurements are often performed in cryogenic and pressurized wind tunnels which are capable of higher Reynolds number flows. Thus, the characteristics of the moving fluid are adapted to the scale of the model.

At the DLR Institute of Aerodynamics and Flow Technology the microphone array measurement technique was further developed to perform measurements in a cryogenic wind tunnel at temperatures down to 100 K. To this end, a microphone array consisting of 144 microphones was designed and constructed. In order to use a microphone array in a cryogenic environment, coming to grips with cold hardiness and ensuring long term stability of the array fairing and the electronic devices, especially the microphones, are the primary challenge.

Measurements of the radiated noise from a single rod configuration have been conducted. The results showed very good agreement between theory and measured sound radiation. A Reynolds number dependency of the measured and predicted sound power can be shown.

1 INTRODUCTION

Measurement techniques based on microphone-arrays are well-known and common practice on scaled models in wind tunnels with closed test section [1]. Usually, full-scale Reynolds numbers are not achieved. To increase the Reynolds number measurement are performed in cryogenic and pressurized wind tunnels. Previous measurements have been successfully carried out in a pressurized environment by Hayes [2] and in a mild cryogenic pressurized environment (≈ 230 K) by Stoker [3]. In the present work acoustic measurements have been performed in cryogenic environments (100 K < T < 300 K) using a single rod configuration. Furthermore, a systematic study of Reynolds and Mach number influence on the radiated sound of a single rod configuration has been carried out.

2 MEASUREMENTS

The measurements have been performed at the cryogenic wind tunnel at DLR's Cologne site (Kryo-Kanal Koeln, KKK). The KKK is a continuous flow low-speed wind tunnel with a 2.4 m × 2.4 m closed wall test section. Via injection of liquid nitrogen, the wind tunnel can be operated in the range of 100 K < T < 300 K at Mach numbers up to 0.38. This corresponds to a maximum Reynolds number of $Re_{0.1\cdot\sqrt{S}} = 9.5\cdot10^6$ based on the cross section S.

The microphone array consists of 21 electret microphones arranged along a line and spaced at logarithmic distances relative to the central microphone (for detailed description see Ahlefeldt and Koop [4]).

For the test setup, a single rod was used as an aeroacoustic noise source; the single rod placed in a homogeneous flow is well-known and recognized as an aeroacoustic source [5-7]. Figure 1 shows the test setup. The array is mounted onto the sidewall and the rod is located in the center of the test section. The figure (on the right) shows the microphone array and the cylinder in the (x,z)-plane.

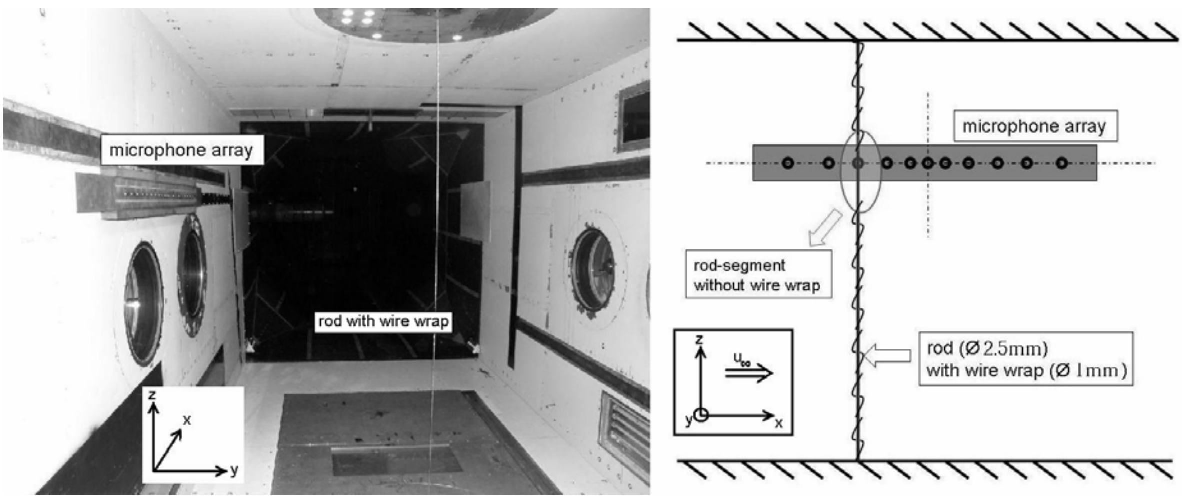

Fig 1. Left: Photo of the test section with array mounted on the side wall and the rod situated in the center, view in flow direction. Right: drawing of the measurement setup.

The rod has a diameter of d = 2.5 mm and is mounted from floor to ceiling (2.4 m) of the test section. The rod is wrapped with wire of 1 mm diameter to eliminate coherent structures. At about the height of the microphone array, the cylinder is not wrapped for a length of 171 mm in order to get coherent structures in this region.

Measurements were carried out with a wide range of operational flow parameters. The temperature was varied in 6 steps in the range of 100 K < T < 300 K. Mach-number was varied in 8 steps in range of 0.1 < Ma < 0.3. Range of Re was $5\cdot10^3 < Re_d < 8\cdot10^4$, where Re_d is the Reynolds number based on the rod diameter d = 2.5 mm and the free stream velocity of uniform flow.

Microphone signals were simultaneously sampled with an A/D conversion of 16-bit at a sampling frequency of 150 kHz by a data acquisition system located outside the test section. The recording time for each measurement was 20 s. To reduce influence of the low frequency wind-tunnel noise, a high-pass filter with a cut-off frequency of 500 Hz was used. To obtain the source maps, conventional beamforming in the frequency domain including diagonal removal was applied [8]. The sound power level is obtained by integrating over the whole grid region (which is only affected by a single source) normalized by a source map of a reference monopole with known source strength situated at the source position [9, 10].

The temperature-dependent speed of sound c_0 in the fluid is of primary interest to the beamforming process. Therefore, the array pattern is temperature dependent, since the change in c_0 acts like a frequency shift. In addition, the contraction of the array fairing causes a change in the position of each microphone; allowance can be made for this from the known thermal expansion of the used aluminium alloy [11].

In terms of frequency-response for the individual microphones mounted in the array, a comparative calibration with a 1/4” GRAS condenser microphone was carried out in a semi-anechoic chamber prior to the measurement. Additionally, the electret microphone used was compared to prototype 1/4” Brüel&Kjær cryogenic condenser microphones to obtain the temperature dependent frequency-response.

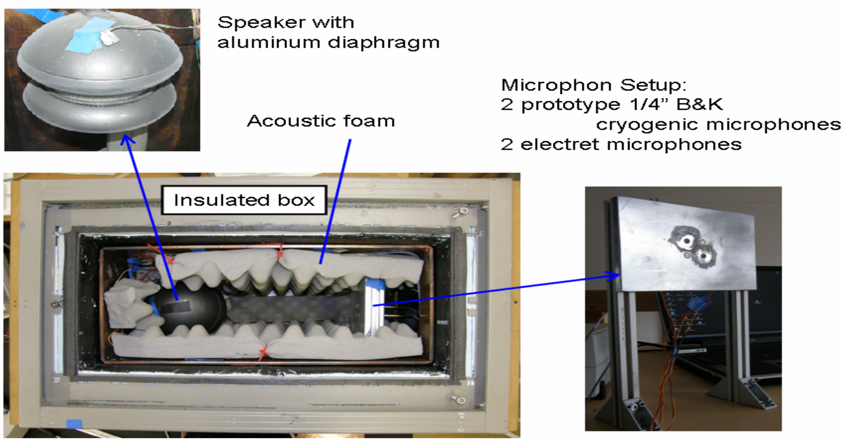

Fig 1. Measurement setup for the determination of the temperature dependent frequency-response. The electret microphone used in the array was compared to prototype 1/4” Brüel&Kjær cryogenic condenser microphones using an insulated box.

3 RESULTS

Figure 2 shows the sound power level for different Mach numbers at T = 290 K and T = 100 K as a function of both frequency and Strouhal number. Each spectrum shows a peak at the rod's vortex shedding frequency. For higher frequencies smaller peaks arising from higher harmonics can also be identified. A comparison of the plots at the two temperatures shows a downward frequency shift at 100 K which is due to the lower free stream velocity u_∞. At T = 290 K the peak in sound power shifts to lower Strouhal numbers as the Mach number increases, where the Reynolds number also increases. On the other hand, at T = 100 K the peak is hardly shifted at the various Mach numbers. This corresponds to the well-known Strouhal–Reynolds number relationship [15].

The relative bandwidth of the peak in the Strouhal number plots seems to be approximately constant, so that the peak level gives a good indication of the quantitative tonal component of the radiated sound power. In terms of the following analysis the peak level will be used.

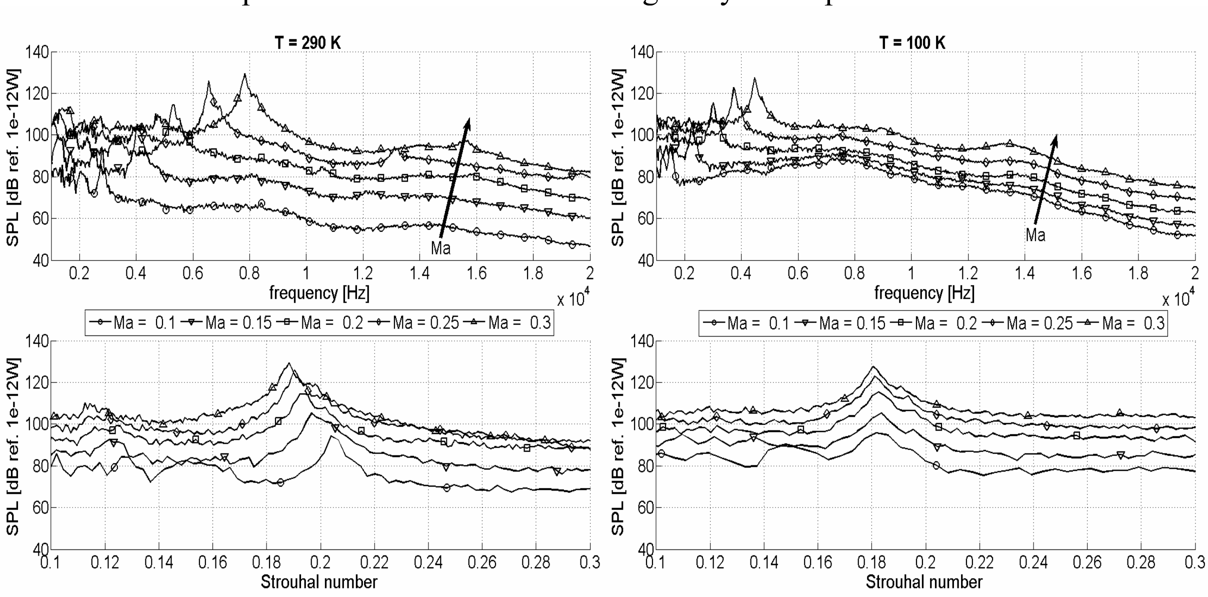

Fig. 2. Sound power level for several Mach numbers at T = 290 K (right) and T = 100 K (left). Displayed is the sound power level [dB, ref. $1{\cdot}10^{-12}$ W] versus frequency and versus frequency normalized with free stream velocity and cylinder diameter i.e. the Strouhal number. Note that the frequency range for the two plots is different, so that only the first peak can be seen in the Strouhal number plots.

4 PREDICTION

As a comparison for the acquired measurement results, theoretical assumptions for the sound radiation of a circular cylinder were investigated. From the averaged sound pressure of the expected aeolian tone, as shown by Phillips and by way of example adopted by Fujita and by Hutcheson [5–7], the qualitative radiated sound power can be simplified as follows:

$$P_\infty \propto \rho c_0^{-3} u_\infty^6 St^2 C_l'^2 \Lambda_d . \tag{1}$$

The classical dipole assumption includes a sixth order u_∞, Re and Ma dependency. Furthermore, the radiated sound pressure is a function of the fluctuating lift coefficient C_l', the correlation length normalized by the cylinder diameter Λ_d and the Strouhal number *St*. These quantities are dependent on the Reynolds number and can be obtained by using empirical data [12–14]. Furthermore, the dependence of the state of the surrounding fluid on temperature has to be taken into account. Important quantities are the density ρ_0, the speed of sound c_0 and the dynamic viscosity.

Following on from this, figure 3 shows good agreement in a comparison of the prediction model and the measured data. The mean variance is 2.1 dB(rms) and the maximum deviation is approximately 4.5 dB. The major deviations occur at higher Mach numbers and the two temperatures $T = 290$ K and $T = 100$ K. Effects which are unaccounted for – roughness of the cylinder and various boundary conditions – are mainly thought to be responsible for the deviance of the predicted and measured sound power.

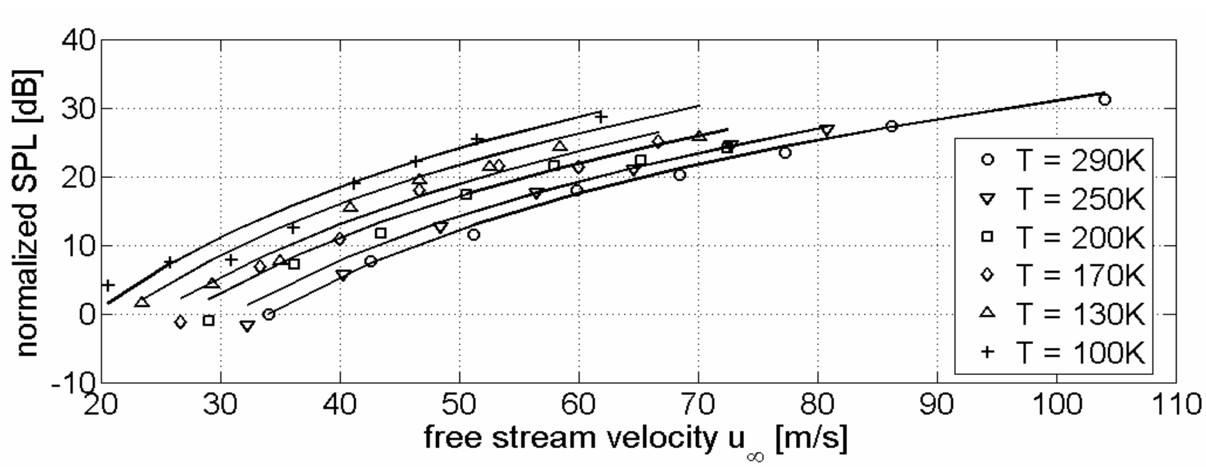

Fig. 3. Comparison of the results obtained from the prediction model (equation 1, (-)) with the measured data. Shown is the sound power level at various temperatures plotted versus the free stream velocity. Both data are normalized to sound power level at a Mach number of 0.1 and a temperature of T = 290 K.

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