Estimation of underwater flow noise by wave number decomposition

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Introduction

Pressure fluctuations of high-Reynolds-number turbulent boundary layers are of fundamental scientific interest with a large relevance for many applications. In an incompressable flow pressure couples non-locally different regions of a boundary layer and pressure fluctuations play an important role for the mechanisms underlying turbulence. In applications compressibility often cannot be neglected as pressure fluctuations can give rise to sound productions in a turbulent boundary-layer, generated e.g. at a wall of a moving vehicle. On the other hand compressibility can even be of crucial importance, such as in underwater applications. Properties of pressure fluctuations beneath a turbulent boundary layer are reviewed e.g. in [1, 2, 3, 4].

Sound is by far the least attenuated type of wave in the sea and therefore preferably used for signal transmission (e.g. for SONAR) in underwater applications. Measurements of turbulent boundary layers in a Reynolds number regime relevant to underwater applications have to be performed at sea (or partly in water or cavitation tunnels). The sea is a noisy environment and the mean sound level can exceed by far the level of turbulent pressure fluctuations, or vice versa, depending predominantely on the Reynolds number and the ambiant noise level at sea.

Kf-Decomposition

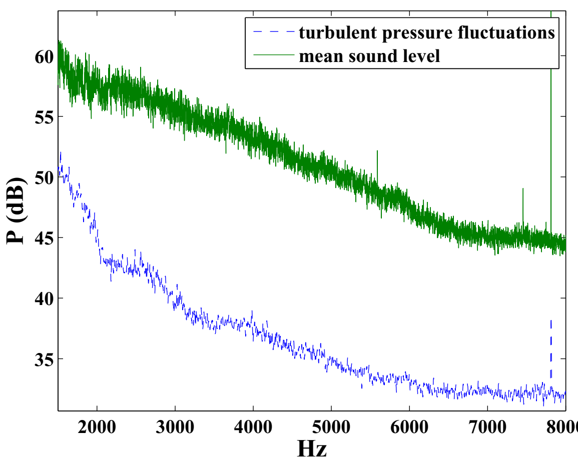

Figure 1: Comparison of mean sound level with estimated flow noise obtained from wave number - frequency decomposition at a relatively low towing speed corresponding to a Reynolds number of momentum thickness $Re_\Theta \approx 2000$

A typical example for the first situation can be seen in Fig. 1 (a). The power spectra result from measurements of pressure fluctuations performed with an underwater towed system at relatively low towing speed corresponding to a Reynolds number of the momentum thickness of about $Re_\Theta \approx 2000$. It can be seen from this measurement that the mean sound level at a hydrophone is much higher than the level of pressure fluctuations of the boundary layer. It is therefore crucial to discriminate both processes in order to separate the turbulent pressure fluctuations from sound. Pressure was measured in this experiments with an equally-spaced array of hydrophones and the turbulent pressure fluctuations are estimated with the use of a wavenumber-frequency filter. This filter enables a separation of sound from turbulent pressure fluctuations in certain regions of the kf-space. The wave number - frequency spectrum corresponding to the power spectra shown in Fig.1 is depicted in Fig.2. Due to the dispersion relation of sound waves projected onto a linear array only the (dark blue colored triangluar) acoustic region in the kf-spectrum can physically be attributed to sound. Spectral components of other noise sources, such as e.g. flow noise, do not necessarely underlie such restrictions and can therefore contribute to the low wave speed non-acoustic region in the kf-spectrum.

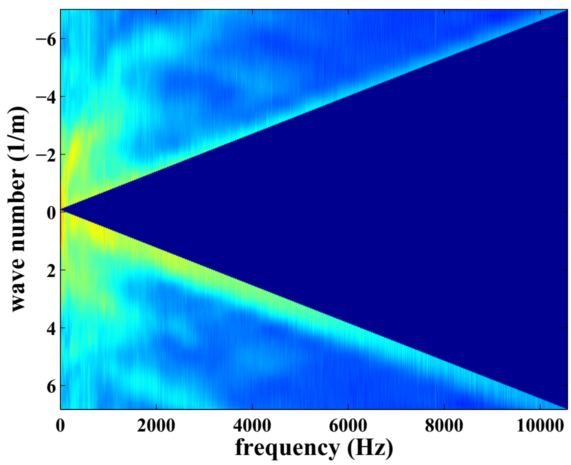

Figure 2: Wave number - frequency spectrum from measurements at $Re_\Theta \approx 2000$ (acoustic regime is filtered out).

It can be seen from Fig. 2 that in the low-frequency regime the non-acoustic region appears structured. Those structures result from mechanical (mainly bending) waves which are excited by turbulent pressure fluctuations. Above a certain frequency those structures are well separated from the acoustic region in the kf-spektrum (here above $f \approx 1500$ Hz). Flow noise can generally be considered as wave number white above such high frequencies and therefore the level can be estimated. The result of an estimation procedure applied to the kf-spectrum is shown in Fig. 1.

Scaling behavior

Wave number - frequency filtering allows (partly) to separate flow noise from underwater sound and therefore enables an investigation of flow noise properties independent of environmental conditions (at least in a certain frequency regime).

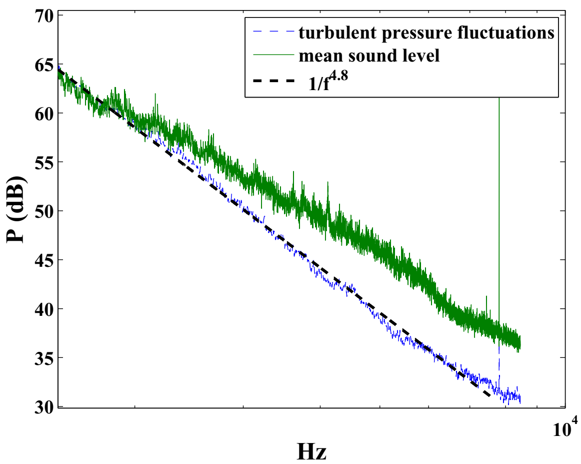

Figure 3: Scaling behavior of flow noise at $Re_\Theta \approx 2800$.

A characteristic properties of flow noise is the spectral scaling behavior. Typically, a scaling law of about $P \approx 1/f^{4-5}$ has been suggested from previous measurements and theory in the high frequency regime (see e.g. [3] and ref. therein). Our experiments confirm those results, as can be seen from Fig.3. Here, the towing speed was higher compared to that of the measurements shown in Fig.1 yielding a Reynolds number of about $Re_\Theta \approx 2800$. Within the investigated frequency regime the flow noise spectrum decays with $1/f^{4.8}$ which is within the range of previous results. Note, that for this Reynolds number the sound level is dominated by flow noise below $f \approx 2000$ Hz in contrast to the case of lower towing speed. Most relevant for underwater applications is the strong increase of flow noise level with speed. Our results confirm the theoretically known $P \propto v^6$ law (see e.g.[4] for a recent overview and ref. therein), as may be seen from Fig. 4. Here, the dependence of flow noise level with towing speed is depicted for $f = 3000$ Hz. Wave number - frequency filtering does not only allow the investigation of spectral but also statistical properties of flow noise. Recent experiments on statistics of pressure fluctuations in a high Reynolds number turbulent boundary layer have revealed a non-gaussian probability distribution function which displays a relatively independence on Re_Θ in the investigated high Reynolds number regime [5]. Non-gaussian statistics have been studied in high Reynolds number turbulence also for lagrangian acceleration of fluid particles [6], velocity differences [7], and pressure gradient [8], and have been addressed theoretically by a 'superstatistic' approach [9]. In our experiments we have revealed a

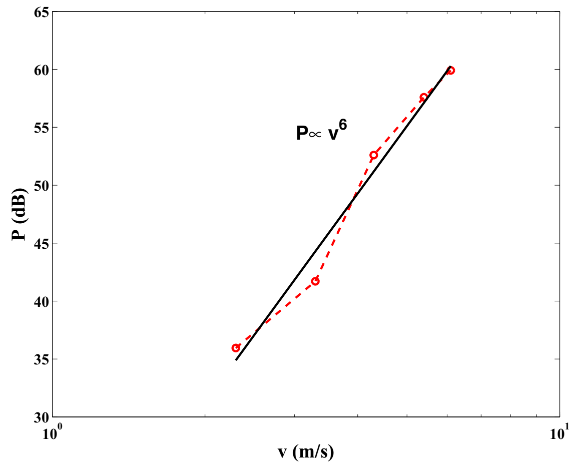

Figure 4: Speed dependence of flow noise at 3000 Hz

transition between gaussian and non-gaussian behavior. It is found that the transition occurs within a Reynolds number regime $Re_\Theta \approx 2000 - 3500$. In this regime the boundary layer is turbulent and, as shown in Fig.4, the level of turbulent pressure fluctuations significantly increases by a scaling law.

Summary

Results on pressure fluctuations of turbulent boundary layers are presented which are obtained from underwater towing experiments. With the help of wave number - frequency filtering properties of flow noise have been investigated independently from the environmental conditions. Our results experimentally confirm scaling behavior of flow noise but also provide evidence for the relevance of non-Gaussian behaviour in underwater applications.

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