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Coherent flow noise beneath a flat plate in a water tunnel experiment

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ABSTRACT

Results from a combined experimental and numerical study on the properties of flow noise on the reverse side of a flat plate excited by a turbulent boundary layer flow are reported. Particular focus is given to the coherence between wall pressure fluctuations, plate vibrations, and interior flow noise. The plate was immersed in water and laterally attached to a streamlined model inside the HYKAT cavitation tunnel at HSVA Hamburg (Germany). The flow velocity in the tunnel was $U = 7$ m/s. Simultaneous measurements of wall pressure fluctuations, structural vibrations, and interior flow noise as well as a numerical response and eigenvalue analysis provide evidence that evanescent plate modes excited by wall pressure fluctuations play a crucial role in flow noise generation. Flow noise in the (quiescent) water inside of the model is found to have large coherence lengths and pronounced amplitudes for distinct frequencies below $f \approx 300$ Hz.

1. Introduction

Flow induced noise originating from a moving body which is surrounded by a turbulent boundary layer flow is not only of large relevance for many applications, but also of fundamental scientific interest [1,2]. Propagating away from the moving body this flow induced sound may be perceived as unwanted noise in the far field. Examples arise from aircraft noise [3], ship noise [4], and wind turbine noise [5]. If there are fluid filled spaces inside the body, pressure fluctuations can generate additional noise therein. This is known, for instance, as cabin noise of aircrafts [6] and cars [7] as well as in sonar applications [8]. In the latter case flow induced noise is generated by the motion of a sonar antenna through quiescent water and contributes to sonar-self-noise [9].

The fluctuations of velocity and pressure generated inside an (incompressible) turbulent boundary layer flow act on an underlying mechanical wall structure [10]. The fluctuations behave as a random field with a small coherence area and a slow propagation component in the flow direction. Wall pressure fluctuations beneath a turbulent boundary layer are of particular interest due to their dominant role in turbulent sound generation and have therefore been subjected to numerous experimental and theoretical investigations in the past [11–19]. Various semi-empirical models of the temporal and the space–time correlations behaviour of wall pressure fluctuations have been developed in order to understand the underlying physical processes but also to cope with applicational needs [20–25].

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Inside of a fluid-filled (moving) body pressure fluctuations can only propagate as sound waves and the wall structure plays a crucial role in the generation of this interior flow noise [26]. In principle turbulent pressure fluctuations can be transmitted locally through a wall structure into the fluid on the reverse side, but typically the mechanical wall structure responses to excitations from the turbulent boundary layer. This response reflects the modal character of the mechanical wall structure [27].

The vibroacoustical response to turbulent boundary layer excitation has been studied in detail, for instance, for flat plates (see e.g. [1,28,29]). Here, the Finite-Element Method [30–32] has played a crucial role. A particular focus of recent work in vibroacoustic response to turbulent excitations is given to the improvement of predictive methodology [33–36]. Fluid–structure interaction between boundary layer flow and wall structure can furthermore be considered to be of importance for the generation of flow-induced noise [37].

In this work the vibroacoustic response of a flat plate to a turbulent boundary layer excitation and the hydroacoustic pressure field in the vicinity of the vibrating plate are investigated. The plate is entirely immersed in water and flow-induced noise is measured on the reverse side of the plate, i.e. in the (quiescent) interior of a model surrounded by the turbulent boundary layer flow. In order to understand the relevant sources of flow-induced noise in the experiment particular focus is given to the coherence between wall pressure fluctuations, plate vibrations, and interior flow noise. Vibroacoustic properties and hydroacoustic response of the plate are determined by a numerical simulation based on the Finite-Element method.

2. Experimental setup

The experiments are performed with a streamlined model in the HYKAT cavitation tunnel at HSVA, Hamburg. The model has a symmetrical outer shape in flow direction and is made of coated wood. Inbetween a curved nose and tail the model contains a flat plate region which is inclined in vertical direction. The shape of the model is based on a towed body which was designed for flow noise measurements at open sea [38]. A schematic drawing of the starboard side of the towed body is depicted in Fig. 1(a). The outer shape of the lower part of wooden model and towed body is identical (below dashed line), except that fins have been omitted in the tunnel model. Furthermore an additional extension of 100 mm in vertical direction has been added to the tunnel model in order to reduce the influence of upper tunnel wall turbulence on the measurement region. The tunnel model (without vertical extension) has a maximal length and width of 5212 mm and 930 mm, respectively, and a height of 900 mm. The width of the model reduces to 393 mm at the bottom which results in a tilt angle within the flat plate region of 16.6° in spanwise direction. The location of the model (front view) inside the cavitation tunnel of height 1600 mm and width 2800 mm is indicated in Fig. 1(b). The inclination of the model as well as the vertical extension (online: green) can be seen.

On the port side the tunnel model is closed while on the starboard side a flat plate made of perspex is mounted flush to the model. The plate has a size of 2446 mm $\times$ 766 mm in streamwise and spanwise direction, respectively, and a thickness of $d=25$ mm. The location of the flat plate can be clearly seen in Fig. 1 (a) (online: blue). Different types of sensors are mounted on and positioned behind the flat plate. The positions of the sensors are concentrated in an area inside the flat plate, as indicated in Fig. 1(a) (online: green). This area is symmetric to the flat plate (dashed line: axis of symmetry) and is located at a distance of 655 mm from the leading edge of the plate. A detailed view of the measurement area and the sensor positions is given in Fig. 2. The accelerometers (ACC, online: red) of Type B&K 5958 are mounted on the inside of the plate. One flush-mounted hydrophone (FMH, online: blue) of type RESON TC4050 is located on the symmetry axis in order to measure wall pressure fluctuations.

Inside of the model a linear hydrophone array aligned in streamwise direction is positioned on the symmetry axis at a distance of $y=20$ mm in normal direction from the inner wall of the plate. The array consists of 16 equidistant hydrophones of type RESON TC4013 which have a spacing of 11.5 mm. It is mounted by elastic damping elements onto a (heavy) support in order to decouple the array from the wooden model as well as from the plate. The measurement distance between hydrophone array and plate was chosen in order to capture also near-field effects of the hydroacoustic pressure field. Here, a

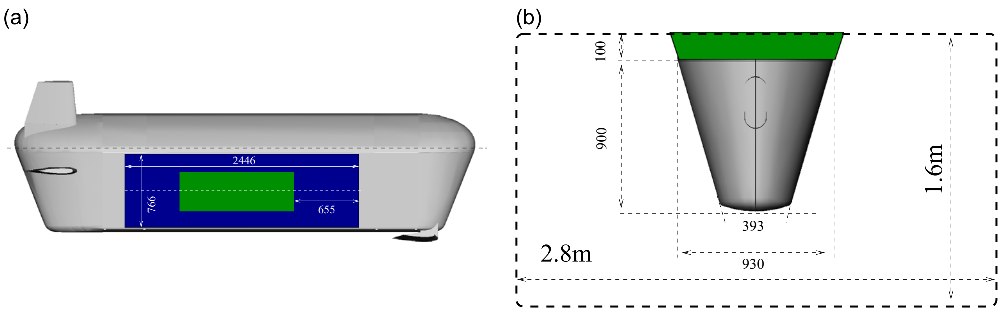

Fig. 1. (a) Schematic plot of the towed body (for open sea experiments [38]) with the flat plate region (blue) and position of the measurement region (green) inside of the flat plate area. (b) Schematic front view of the wooden model inside the HYKAT cavitation tunnel of HSVA, Hamburg. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)