

Large-scale PIV measurements of the boundary layer beneath a towed structure

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ABSTRACT

We present measurements of the developing boundary layer beneath a towed structure. As a validation, we initially tow a flexible (but flat) structure across stagnant water. This results in a comprehensive visualization of the classical case of a developing boundary layer: an initial laminar part, followed by a transition to a turbulent boundary layer. Repeated experiments ($N = 100$) show that the transition position is highly variable: for some cases, the boundary remains completely laminar, while for others it already transitions as soon as $Re_x = 1.5 \times 10^5$ (equivalent to a downstream distance of 1 m of the total length of 5 m). By binning the results according to the transition point, average velocity fields can be obtained for various transition points. The growth of the boundary layer in each region matches with the established predictions ($\sim x^{1/2}$ and $\sim x^{4/5}$). After this validation, the experiments are repeated with surface waves, to investigate whether these waves affect the growth and transition behavior of the boundary layer.

1. Background

Our study is part of an ongoing effort to understand the hydrodynamic forces that act on large, thin, flexible floating structures (Pot et al., 2025; Uksul et al., 2025). Examples of such structures range from floating solar panel arrays to ice floes.

2. Facility and methods

The experiments are carried out in Towing Tank No. 2 at the Department of Maritime and Transport Technology of Delft University of Technology. This towing tank, measuring 85 m in length and 2.75 m in width, provides a well-regulated environment for hydrodynamic studies. During the experiments, the water depth h was maintained at 1.22 m and the water temperature - while not actively controlled - was recorded to be 18 °C.

The floating, flexible structure used in this study has a rectangular planform with a length of $L = 5$ m, a width $B = 1.02$ m, and a thickness $t = 4.8$ mm. It is made of closed-pore neoprene foam with a density of 145.42 kg/m^3 .

The structure is secured by mooring lines to a carriage (see Figure 1a). The carriage tows the structure with a velocity of 0.145 m/s . A single wave probe ("WP" in the figure) monitors the structure or wave elevation. Optical access is available through a single, relatively small window in the side wall of the facility. Using mirrors, including a large one mounted on the bottom, a 3 mm thick light sheet is created in the midplane of the towing tank (Figure 1b) using a Litron Bernoulli Nd:YAG. Two LaVision Imager sCMOS CLHS cameras, equipped with 200 mm Nikon lenses, are mounted so that they each capture a field of view of $9 \times 8 \text{ cm}^2$ (27 px/mm resolution), giving a total 'wall-normal' height of the domain of 16 cm. For seeding, hollow glass spheres ($10 \text{ }\mu\text{m}$ diameter, Sphericul, Potters Industries) are dispersed in the water. The seeding density is a compromise between quiescent initial water conditions (which requires approximately 30 minutes between runs), yet without excessive settling.

Images pairs are recorded at a frequency of 25 Hz, with a ΔT of $2800 \text{ }\mu\text{s}$. Synchronisation between lasers and cameras is performed using a LaVision PTU, synchronized with a dedicated Arduino Micro that controls the towing, wave generation, and wave probe logging.

The images are processed using commercial PIV software (LaVision DaVis 10) utilizing multiple passes, with a final window size of 48×12 with 50% overlap. The velocity fields from the two cameras are stitched to form a single vector field. The latter was facilitated by an overlap between the two camera views, and a linear transition between the two vector fields in the overlap region was used to avoid (minor) discontinuities due to differences in the vector fields.

3. Results

A typical result is shown in figure 2. These composite figures are created by stacking a single column from each of the subsequent vector fields. Assuming 'frozen' flow, the boundary layer can then be visualized as it passes through the measurement domain. The image is comprised of 260×1800 velocity measurements, with the long axis representing the downstream (spatial/temporal) axis.

Note the aspect ratio of the figure, which is stretched for visualization purposes. For this particular case, the transition to a turbulent boundary layer occurs approximately halfway the structure ($x \approx 2.5 \text{ m}$, $Re_x \approx 360000$). Besides the change in growth rate, the appearance of wall-normal fluctuations is clearly visible (Fig. 2, bottom).

A total of 100 repetitions were performed. The transition to a turbulent boundary layer showed

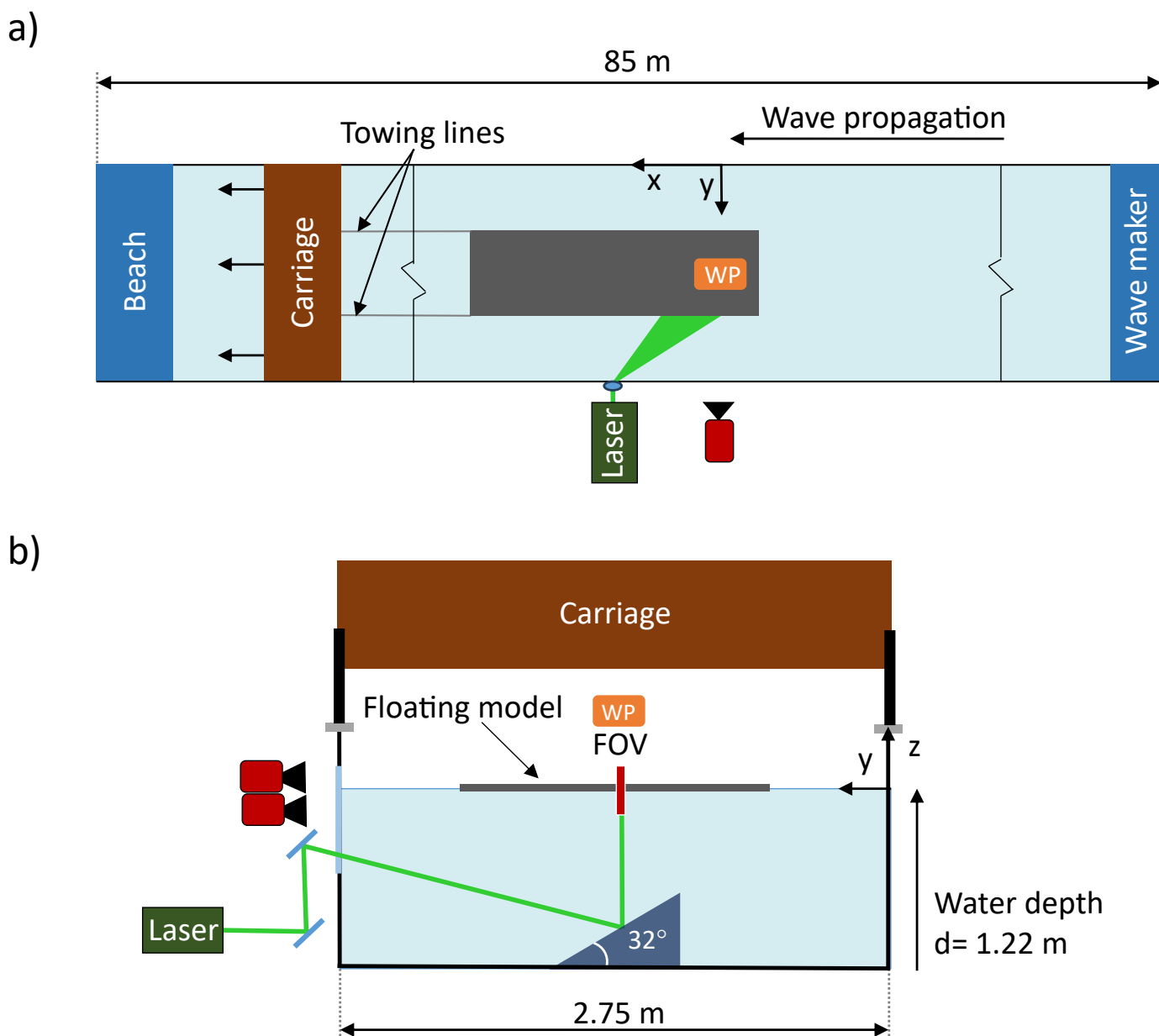


Figure 1. (a) Top view of the facility, which shows the flexible structure (grey) being towed by the carriage (brown).
 (b) Side view, showing the location of the field-of-view. This region is illuminated by a laser and observed by two stacked high-resolution cameras.

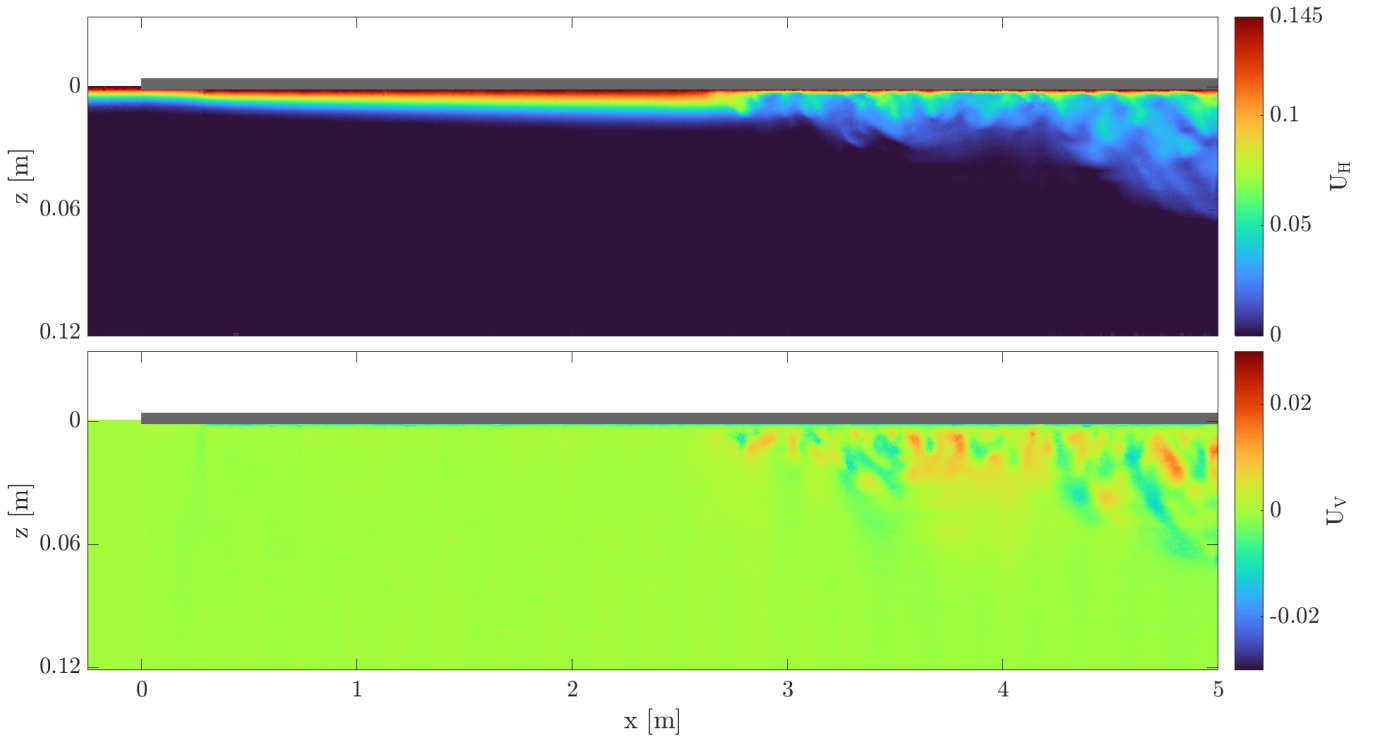


Figure 2. Composite image showing the spatial development of the boundary layer, obtained by stacking the velocity profiles at the center of the field-of-view (top figures: horizontal component, bottom vertical). The grey region represents the towed structure. The flow is from left to right when moving with this structure. For this case, the transition is around $x = 2.5$ m (equivalent to $Re_x \approx 360000$.)

remarkable variability: in approximately 25% of the cases, the boundary layer remained laminar over the entire length of the structure. For other cases, it transitions as soon as 1 m from the leading edge ($Re_x = 1.5 \times 10^5$). By averaging velocity fields for comparable cases (i.e. cases with a transition within a certain small range of Re_x), more statistical convergence can be achieved - the latter especially important for turbulent cases.

From the composite velocity data, the thickness of the boundary layer can be determined by finding the location where the velocity has decreased to 1% of the velocity of the moving structure; note that this is equivalent to the conventional δ_{99} definition in a moving reference frame. In figure 3, the thickness is shown as a function of the downstream distance x for various cases: a case that remains laminar throughout, a case that transitions halfway, and a case with a late transition. Also shown are the theoretical Blasius result ($\delta_{99} \sim x^{1/2}$) for a laminar boundary layer and the Schlichting correlation for turbulent boundary layers ($\delta_{99} \sim x^{4/5}$). Note that the latter is shown purely to guide the eye and no attempt has been made to precisely align the start of the turbulent region.

The laminar case closely matches the theoretical prediction. It is noteworthy that a boundary layer already exists *before* the start of the structure at $x = 0$ m, which is caused by the stagnation pressure at the front of the moving structure. The structure acts as a forward facing step, as it is

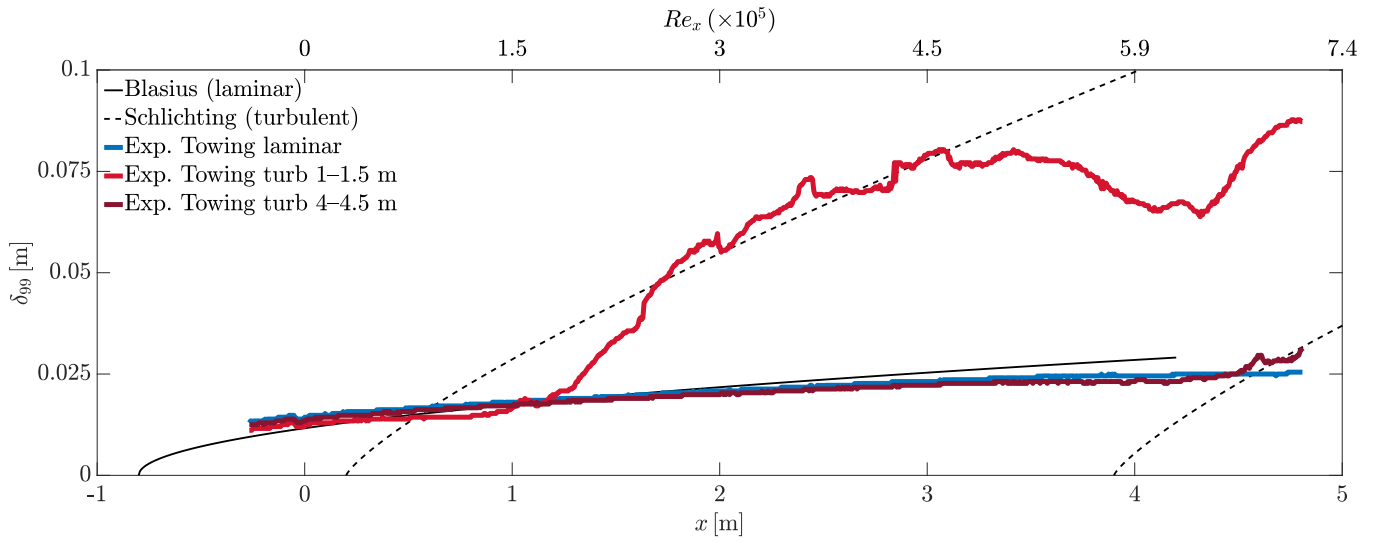


Figure 3. Streamwise evolution of the boundary-layer thickness as a function of x and local Reynolds number. Symbols show thicknesses extracted from the mean velocity fields for (i) runs that remained laminar over the full measurement domain and (ii) two representative transitional cases with transition onset between $x = 1.0$ – 1.5 m and $x = 4.5$ – 5.0 m. Theoretical laminar boundary-layer growth predicted by the Blasius solution and the Schlichting correlations are included for reference.

partially submerged. This forward facing step will likely also affect the initial laminar growth of the boundary layer (Hildebrand et al., 2025). The details of this local minimum in thickness at the leading edge are part of our current investigation, but it seems to be reproducible (the ‘dip’ is visible in all three realisations).

For the turbulent case, the increased growth rate is apparent. Note that only a single realization is shown, so we cannot expect a perfect match with the prediction for the *average* boundary layer thickness.

4. Outlook

While the results presented here mostly serve as a validation of our measurement technique, we have also obtained where the structure is towed over a wavy surface (wavelength $\lambda = 3.0$ m and wave height $H = 60$ mm, corresponding to a wave steepness of $H/\lambda = 0.020$). Currently, we are processing the data to investigate if these surface waves will impact the growth rate and/or stability of the boundary layer.

References

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