FLOW CONTROL IN WATER USING PULSED LASER

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ABSTRACT

Controlled investigations of laminar–turbulent transition require the introduction of well-defined disturbances with prescribed amplitude, frequency, wavelength, and waveform. Classical excitation techniques, such as oscillating wires, are limited in spectral bandwidth and may introduce an undesired bias to the mean flow due to their intrusive nature. To overcome these limitations, the present study investigates pulsed laser excitation as a non-intrusive method for controlled disturbance generation in water flows. While the feasibility of laser-based excitation has previously been demonstrated in air, its applicability to liquid flows remains largely unexplored. The present work systematically examines the interaction between pulsed laser energy deposition and a water boundary layer, focusing on disturbance characteristics and controllability. Different materials, laser pulse energies, and excitation frequencies are evaluated to assess their influence on disturbance amplitude and repeatability. The methodology is applied to the controlled investigation of transition mechanisms in laminar separation bubbles (LSBs). Measurements demonstrate that laser-induced perturbations produce a clearly detectable and reproducible impact on the transition process over an LSB. The excitation allows targeted modification of instability growth without introducing mechanical interference into the flow. The results indicate that pulsed laser excitation constitutes a versatile and broadband disturbance generation technique for hydrodynamic stability experiments in liquids. This approach expands the experimental toolbox for transition research and provides new opportunities for controlled studies of instability amplification and transition control in separated flows.

INTRODUCTION

Flow control has been a central topic in aerodynamics for several decades, as the ability to manipulate boundary-layer development and separation directly determines aerodynamic performance, efficiency, and operational stability Gad-el Hak (2001). By modifying near-wall flow structures, lift can be increased, drag reduced, and stall behavior favorably influenced. While passive flow-control concepts rely on fixed geometric modifications, active flow control offers distinct advantages because actuation can be applied selectively, temporally modulated, and adapted to changing flow conditions, thereby minimizing undesired influence on the baseline configuration.

A broad spectrum of active control strategies has been developed. Steady or pulsed air jets, synthetic jets, plasma actuators, and mechanical exciters are commonly used to introduce disturbances or streamwise vortices that enhance momentum exchange and delay or suppress separation. Despite their effectiveness, these techniques typically require internal actuators, supply lines, or structural modifications of the model. The integration of such devices constrains geometric flexibility, restricts the available disturbance locations, and may introduce unintended bias to the undisturbed base flow. In fundamental transition experiments, mechanical disturbance generators such as vibrating ribbons or wires additionally suffer from limited spectral bandwidth and restricted control of disturbance shape and amplitude.

Laser-based excitation represents a fundamentally different, non-intrusive approach. In compressible air flows, pulsed laser energy deposition near the surface has been demonstrated to generate localized temperature and density perturbations that evolve into instability wave packets and can trigger laminar-turbulent transition Kähler & Scholz (2003); Kähler & Dreyer (2004); Heitmann *et al.* (2010). In high-speed boundary layers (e.g., Ma = 6), this technique has been successfully employed to generate controlled wave packets for detailed transition studies. The principal advantage lies in the absence of mechanical components within the model and the high spatial flexibility of the excitation location. Furthermore, the position, amplitude, frequency, and waveform can be easily aligned.

In contrast to compressible gas flows, the applicability of laser-induced disturbance generation in liquids remains largely unexplored. The fundamentally different thermophysical properties of water (higher density, very low compressibility, and strong optical absorption depending on wavelength) raise questions regarding the disturbance generation mechanism, its repeatability, and its controllability. Such a technique would be particularly valuable for investigations of laminar separation bubbles (LSBs). LSBs are highly sensitive to upstream disturbances, and controlled excitation of Tollmien–Schlichting waves is essential for systematic studies of instability growth, nonlinear breakdown, and transition location. Conventional mechanical exciters provide only limited flexibility in spatial positioning and disturbance characteristics, restricting parametric investigations. However, Lang *et al.* (2004) demonstrated that Tollmien–Schlichting waves can be excited by means of an oscillating wire in such flows, thereby allowing for targeted control of a laminar separation bubble.

The present work therefore investigates pulsed laser excitation as a method for controlled disturbance generation in water boundary layers. The study aims to characterize the disturbance mechanism, assess controllability in terms of amplitude and frequency, and evaluate its suitability for targeted excitation in LSB flows. By establishing a non-intrusive and spatially flexible excitation technique for liquid flows, this work seeks to expand the experimental toolbox for hydrodynamic stability and transition research.

To this end, the study is structured in two parts. First, the fundamental interaction between pulsed laser irradiation and different solid surfaces submerged in water is investigated in a quiescent environment. This allows the characterization of the disturbance generation mechanism, its dependence on material properties, pulse energy, and excitation frequency, as well as an assessment of repeatability and controllability. In the second part, the characterized excitation technique is applied to a laminar separation bubble developing on a hydrofoil profile. The influence of laser-induced disturbances on instability amplification and transition behavior is analyzed in order to evaluate the suitability of the method for controlled hydrodynamic transition experiments.

EFFECT OF LASER IMPINGEMENT: DISTURBANCE GENERATION

In a first step, preliminary experiments were conducted in quiescent water to investigate the fundamental parameters and mechanisms of laser-induced disturbance generation at solid–water interfaces, independent of external flow effects. These measurements serve to characterize the actuation process itself before applying it to boundary-layer and separation-bubble flows.

SETUP

The experiments were conducted in a rectangular glass tank ($29\,\mathrm{cm} \times 19\,\mathrm{cm} \times 20\,\mathrm{cm}$) filled with approximately 6 L of distilled water at room temperature. The water was seeded with hollow glass microspheres (9–13 μm) for Particle Image Velocimetry (PIV). Flat plates made of different materials were mounted inside the tank at a distance of approximately 50 mm from the front wall.

PIV illumination was provided by a continuous-wave Nd:YAG laser ($\lambda = 532\,\mathrm{nm}$). The illumination light sheet induced weak thermally driven convection, resulting in background velocities of 5×10^{-4} to $3 \times 10^{-3}\,\mathrm{m\,s^{-1}}$. A LaVision Imager Pro HS camera recorded the measurement plane at 200 Hz with a resolution of 2016×2016 pixels.

Disturbances were generated using a second pulsed Nd:YAG laser ($\lambda = 532\,\mathrm{nm}$) forming a light sheet directed perpendicular to the plate surface. Laser and camera were synchronized via an external trigger controlling flashlamp, Q-switch, and image acquisition. Each actuation pulse was followed by 17 frames for time-resolved PIV analysis. Measurements were repeated 200 times. Pulse energies ranged from (1.15 ± 0.10) mJ to (68 ± 3.2) mJ at actuation frequencies of 1–10 Hz, corresponding to energy densities of approximately 30–2,000 $\mathrm{J\,m^{-2}}$.

To investigate material-dependent laser–water interactions, plates with different optical absorption and thermal conductivities were tested. The materials included aluminum, aluminum oxide, black-anodized aluminum, black polymer, nickel, silicon carbide, graphite, and acrylic glass. All samples had smooth surfaces to minimize roughness effects.

RESULTS

Raw images obtained after laser actuation indicate localized material ejection from the surface, suggesting either ablation or particle detachment induced by the pulsed laser. To assess whether the laser pulse generates not only surface effects but also a measurable flow disturbance, the velocity field was evaluated at a distance of approximately 1 mm from the impact location. Figure 1 shows the temporal evolution of the induced velocity for selected materials. For graphite (subfigures a and b), only small disturbances are observed at a pulse energy of 13 mJ. Increasing the pulse energy to 23 mJ at a repetition rate of 1 Hz results in a pronounced increase in disturbance amplitude (note the different ordinate scaling), indicating a strong dependence of the induced velocity on pulse energy. In contrast, measurements for aluminum oxide (subfigures c and d), performed at nearly constant pulse energy but different repetition rates (5 Hz and 10 Hz), show nearly identical velocity responses. Within the investigated parameter range, the disturbance amplitude therefore appears largely insensitive to repetition rate. These results demonstrate that laser-induced disturbances in water can be generated in a controlled and reproducible manner, with the disturbance strength primarily governed by pulse energy and material properties. The analysis shows that aluminum is a well suited material for this purpose.

EFFECT OF LASER IMPINGEMENT ON LAMINAR SEPARATION BUBBLE

The experiments investigating the impact of laser actuation on the flow were conducted in the water towing tank of the Institute of Fluid Mechanics and Aerodynamics at the University of the Bundeswehr Munich. The tank has a cross section of approximately $\approx 0.9 \times 0.9\,\mathrm{m}^2$ and a length of 8 m.

SETUP

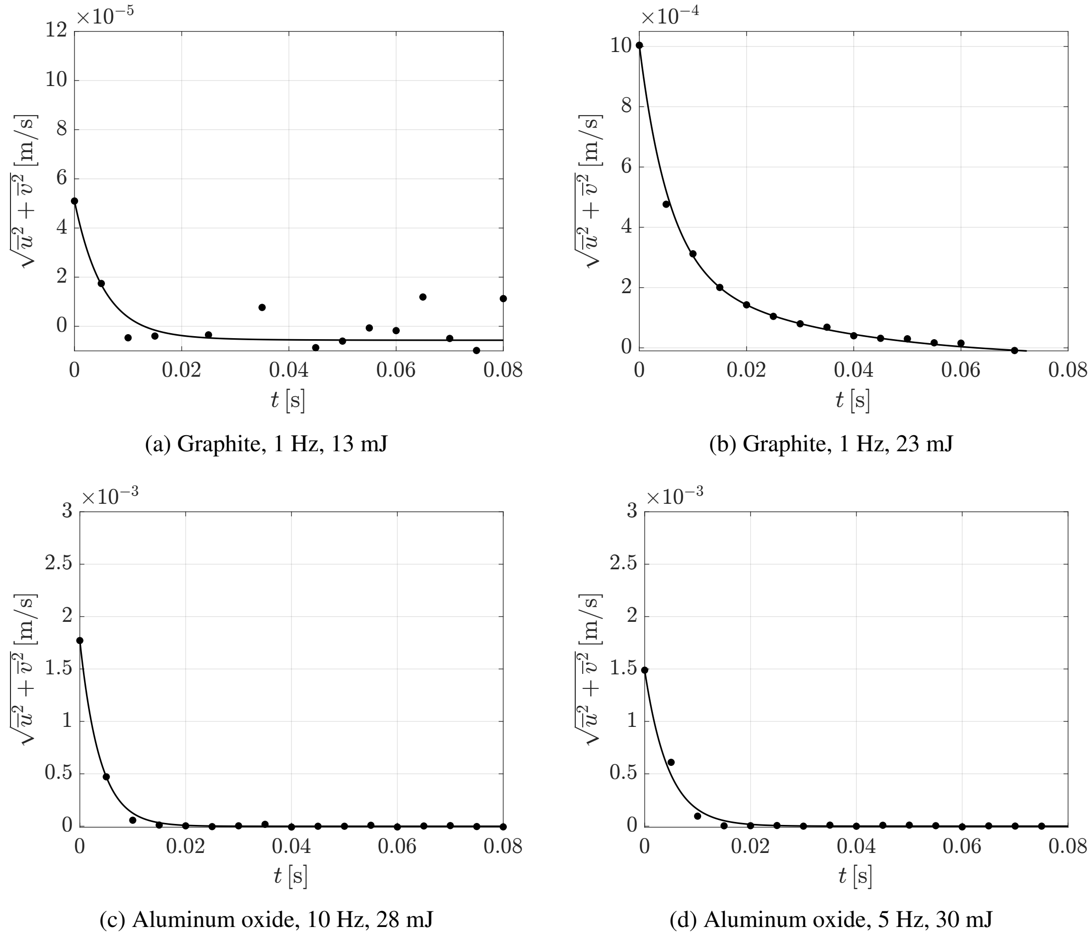
An SD7003 airfoil with a span of 750 mm and a chord length of $c = 250\,\mathrm{mm}$, resulting in an aspect ratio of 3, was used for the investigation at an angle of attack of $\alpha = 6^\circ$ (Dierl *et al.* (2024)). The water level was slightly above 750 mm. A glass plate was installed above the airfoil to suppress waves on the water surface and to provide proper optical access for high-speed imaging from above (Dierl *et al.* (2024)).

The upper half of the airfoil was manufactured from aluminum, while the lower half was made of acrylic glass, see Dierl *et al.* (2024). The laser actuation was performed on the aluminum surface. The towing velocity was set to $0.24\,\mathrm{m/s}$, leading to $Re \approx 60{,}000$. The water temperature was in the range of $16-19^\circ C$.

Hollow glass microspheres with diameters of $9-13\,\mu\mathrm{m}$ were used as tracer particles to visualize the flow using time-resolved planar Particle Image Velocimetry (2D2C PIV). A photo of the setup is shown in Fig. 2.

Illumination for the PIV measurements was provided by a continuous-wave Nd:YAG laser with a wavelength of $\lambda = 532\,\mathrm{nm}$ (Coherent OPSL Genesis Taipan with a maximum power of 8 W). The laser beam was guided into the water through a sealed tube containing the required optical components. The tube was positioned sufficiently far downstream of the airfoil so that any disturbances of the flow could be considered negligible. A LaVision Imager Pro HS high-speed camera was aligned with the measurement plane and operated at a recording rate of 1,000 Hz with an exposure time of $200\,\mu$s. The field of view in chordwise direction covered approximately 75 mm, corresponding to about $0.3\,c$ in the range $x/c \approx 0.17 \ldots 0.47$.

A second pulsed Nd:YAG laser (Quantel Evergreen 200) with the same wavelength of $\lambda = 532\,\mathrm{nm}$ was used to generate the laser-induced disturbance on the model surface. Synchronization of the laser with the camera was achieved using an external sequencer (Hardsoft V750), which provided trigger



(a) Graphite, 1 Hz, 13 mJ

(b) Graphite, 1 Hz, 23 mJ

(c) Aluminum oxide, 10 Hz, 28 mJ

(d) Aluminum oxide, 5 Hz, 30 mJ

Figure 1: The flow velocity induced by the laser pulse as a function of time after the pulse. Consider the different *y*-axis scalings of the subplots.

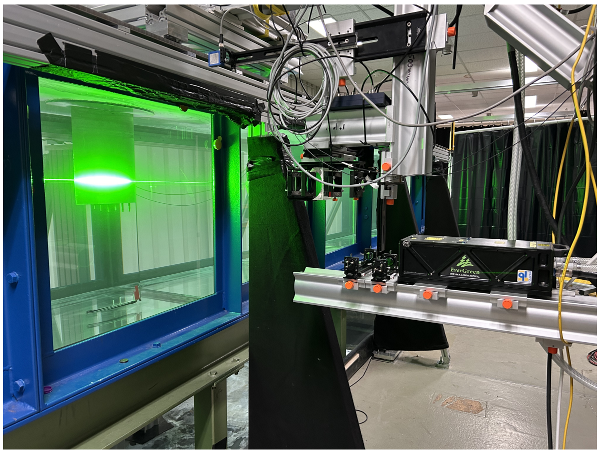


Figure 2: Experimental setup. The cw illumation laser is visible in this picture. Due to the reflection on the aluminum surface of the airfoil it appears larger in this region as it really is. The pulse laser as well the optics for flow control are visible outside of the tank (pulse laser not active).

signals for the flashlamp, the Q-switch, and the camera. The measurement sequence was initiated by a photo sensor when the towing carriage passed a predefined position, ensuring reproducible experimental runs. All equipment was mounted on the carriage. Laser actuation was performed in most runs at 5.7 Hz, corresponding to the vortex shedding frequency determined in previous experiments, see Dierl *et al.* (2024). Actuation was applied with the pulsed laser either focused on a point or on a line in order to generate 0D and 1D disturbances.

RESULTS

The obtained velocity fields were transformed from the initial cartesian coordinate system to an airfoil-aligned coordinate system, see Fig. 3.

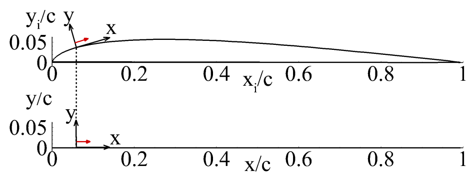


Figure 3: Transformation of the velocity field in wall-normal and wall-tangential coordinates. Upper figure: initial coordinate system. Lower figure: transformed coordinate system.

For each configuration (variation of the laser power of the actuation laser, variation of the actuation frequency, and point- or line-wise actuation), between two and five experimental runs were conducted. In addition, the duration of the actuation was varied. As a reference, experimental runs without any actuation were performed. Furthermore, runs were carried out in which the actuation laser was active in the first and third window (see the side windows of the channel in Fig. 2). In additional runs, the actuation laser was active over the entire path, only interrupted by the lateral support struts between the side windows (see Fig. 2). These configurations allow a clear assessment of whether and to what extent the pulsed laser has an influence on the flow, as well as which disturbances occur even without laser actuation. All measurements have in common that they were started approximately 2 m after the beginning of the towing process. This ensures that a fully developed flow state is present, see Dierl *et al.* (2024).

Figure 4 first shows the mean flow field without actuation. The upper part displays the full field of view, while a detailed view of the reattachment region is shown below. The formation of the laminar separation bubble, including reattachment at $x/c \approx 0.39$, is clearly visible. The mean flow field differs significantly when pointwise laser actuation is continuously applied at the position $x/c = 0.072$ with a pulse energy of 16 mJ and a frequency of 5.7 Hz, see Fig. 5. In this case, the laser actuation is only interrupted by the struts (width of 100 mm) visible in Fig. 2. The actual location of the actuation is not visible; for the sake of higher spatial resolution in the downstream region, it was omitted in the recording. The frequency of 5.7 Hz corresponds to the natural vortex shedding frequency in the present case, see Dierl *et al.* (2024). Compared to the unactuated case, it is clearly visible that the size of the recirculation region is significantly reduced and that reattachment occurs earlier. The laser actuation thus clearly demonstrates a measurable effect.

The question now arises as to which parameters govern the effectiveness of the laser actuation. For this purpose, various parameters were varied and the boundary layer thickness at the position $x/c = 0.25$ was evaluated. The results of this analysis are presented in Fig. 6. In contrast to the previously shown mean flow field, a sliding average of the boundary layer thickness as a function of time is now considered. In addition, the results represent an average over multiple experimental runs, with the exact number specified in the figure caption. Furthermore, the laser actuation was applied in an alternating manner, which is indicated in the figures by the blue shaded regions. At the beginning of the measurements, the flow can be regarded as fully developed, since the profile had already been traversed over approximately eight chord lengths (Dierl *et al.* (2024)).

Subfigure (a) shows the temporal evolution of the boundary layer thickness for actuation applied at $x/c = 0.072$ with a pulse energy of 16 mJ and a repetition frequency of 5.7 Hz. This case is similar to that shown in Fig. 5, where the laser actuation, however, was applied continuously. Figure 6 (a) demonstrates that the actuation also produces a noticeable effect in this configuration. Following activation, the flow responds only gradually (decrease in boundary layer thickness at $t = 0$ s and $t = 7$ s). After deactivation at $t = 3$ s and $t = 10$ s, the boundary layer thickness increases again with a certain delay. The effect is clearly discernible. According to XFOIL simulations (Drela (1989)), the separation point under the present flow conditions is located at $x/c \approx 0.08$; the actuation position $x/c = 0.072$ is thus situated upstream of the separation point.

When the actuation position is shifted to $x/c = 0.12$, while keeping all other parameters unchanged, the result shown in Fig. 6 (b) is obtained. In this case, the effect of the actuation is no longer observable or only very weakly pronounced. If the actuation frequency is reduced to half of its original value, i.e. 2.85 Hz, no influence of the actuation can be identified, see Fig. 6 (c). In contrast, doubling the original frequency to 11.4 Hz leads to a clearly observable effect, see Fig. 6 (d).

Whenever an effect of the actuation is visible, as is the case in subfigure (d), a delayed response and gradual adaptation of the boundary layer to the actuated or undisturbed inflow can be clearly observed. Investigations reported in Dierl *et al.* (2024) show that the flow requires approximately six convective length scales to develop when the profile is accelerated from rest.

After completing the experiments, it is natural to ask whether, and to what extent, the surface was affected by the laser irradiation. Since transition phenomena are highly sensitive to even minor disturbances, it is of particular importance to assess whether the laser actuation causes any damage to the irradiated material – i.e., the airfoil surface – or leads to a modification of its geometry. To this end, the surface was examined after the experiments using a Keyence laser-scanning microscope. The corresponding results are shown in Fig. 7. For the point actuation, surface depressions of approximately 30 µm are detected, which are below the registration sensitivity by human hands. The laser pulse energy was set to 16 mJ. Multiple depressions occur due to slight fluctuations in the position of the focused laser beam, which are attributed to small vibrations of the measurement equipment during carriage motion. The total number of applied laser pulses was on the order of $\mathscr{O}(10^3)$. So unwanted flow disturbances due to the laser damage do not take place.

SUMMARY AND CONCLUSION

The present study investigated pulsed laser actuation as a non-intrusive method for disturbance generation in water boundary layers and its application to a laminar separation bubble. In contrast to conventional mechanical or fluidic actuators, the laser-based approach enables spatially flexible excitation without introducing intrusive components or modifying the model geometry. The strength as well as the repetition frequency of the disturbance can be freely adjusted. Preliminary experiments conducted in quiescent water demonstrate that a pulsed laser generates localized flow disturbances that can be measured in the surrounding flow field. The results indicate that the disturbance amplitude is primarily governed by pulse energy and material properties, whereas the influence of repetition frequency is comparatively weak within the investigated parameter range. The disturbance generation was found to be reproducible and controllable, establishing a reliable basis for flow-control applications.

The application of the laser actuation to a laminar separation bubble on an SD7003 airfoil at $\alpha = 6^\circ$ and $Re \approx 60,000$ revealed a clear influence on the mean flow field. Continuous pointwise actuation at $x/c = 0.072$ with 16 mJ and 5.7 Hz significantly reduced the extent of the recirculation region and shifted the reattachment point upstream. This demonstrates the capability of the method to actively modify separation-bubble dynamics. A systematic parameter study showed that the effectiveness of the actuation strongly depends on both spatial and temporal characteristics. Actuation upstream of the separation point ($x/c = 0.072$) proved to be effective, whereas downstream actuation ($x/c = 0.12$) resulted in a significantly reduced or negligible effect. Furthermore, the actuation frequency was identified as a critical parameter. Reducing the fre-

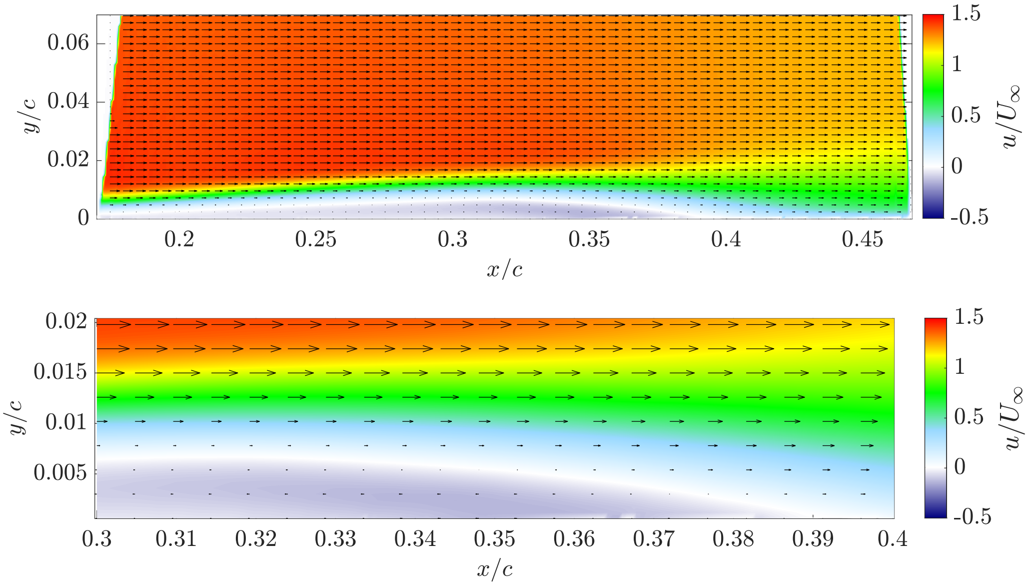


Figure 4: Mean velocity field without laser control. Top: complete field-of-view. Bottom: detail view of the reattachment region.

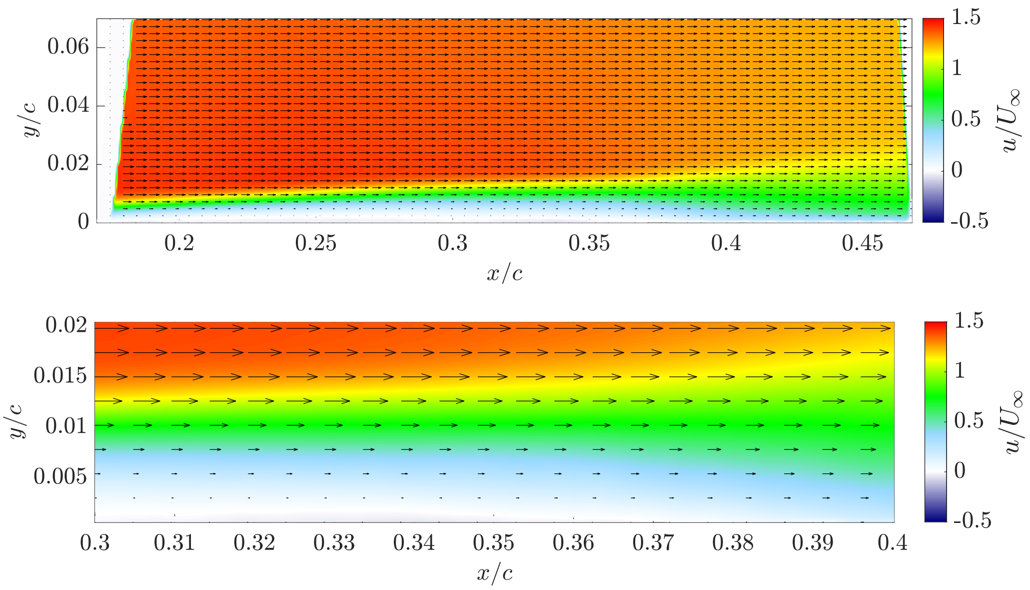


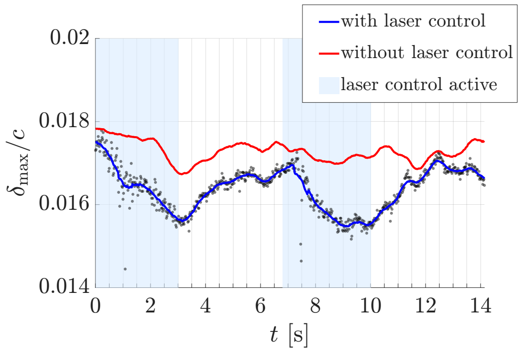
Figure 5: Mean velocity field with continuous laser control. Point-actuation at $x/c = 0.072$ with 16 mJ at 5.7 Hz. Top: complete field-of-view. Bottom: detail view of the reattachment region.

quency to 2.85 Hz eliminated the observable influence, while increasing it to 11.4 Hz enhanced the effect. These results prove that the laser-induced disturbances trigger characteristic instabilities.

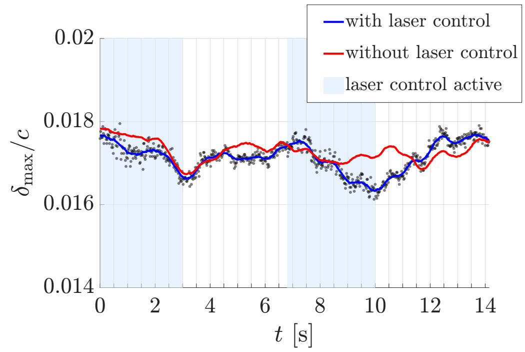
Time-resolved measurements of the boundary layer thickness revealed a delayed response of the flow to both activation and deactivation of the laser forcing. This behavior reflects the finite convective development time of the boundary layer and is consistent with previous observations that several convective length scales are required for the flow to adjust to changing conditions.

Finally, surface investigations using laser-scanning microscopy showed localized material removal in the form of depressions of approximately 30 µm after $\mathcal{O}(10^3)$ pulses at 16 mJ. Although these modifications are small, they indicate that laser-induced disturbance generation in liquids is associated with surface interaction effects that must be considered when applying the method to sensitive experiments.

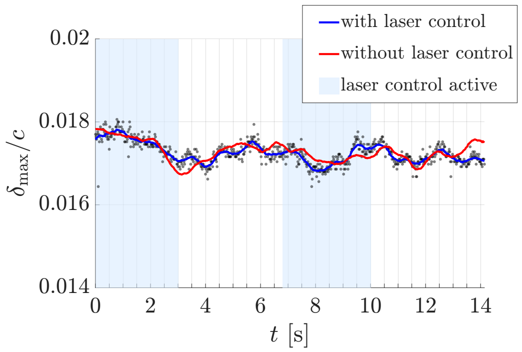
Overall, the results demonstrate that pulsed laser actuation provides a viable and flexible tool for controlled disturbance generation in water boundary layers. The method enables targeted excitation of instability mechanisms and offers significant advantages for experimental investigations of transition and separation phenomena. Future work should focus on a more detailed characterization of the underlying disturbance mechanisms, optimization of actuation parameters, and extension to the investigation of the three-dimensional effects generated by the laser disturbance.



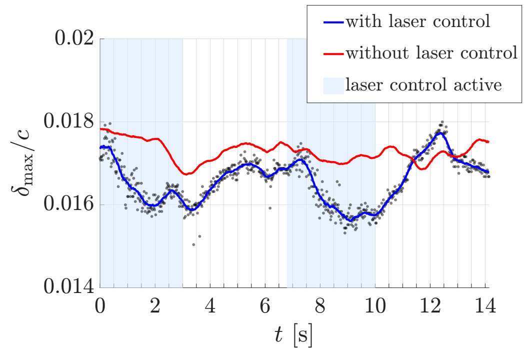
(a) Actuation at $x/c = 0.072$ with 16 mJ at 5.7 Hz. Mean over 5 runs.



(b) Actuation at $x/c = 0.12$ with 16 mJ at 5.7 Hz. Mean over 5 runs.



(c) Actuation at $x/c = 0.12$ with 16 mJ at 2.85 Hz. Mean over 2 runs.



(d) Actuation at $x/c = 0.12$ with 16 mJ at 11.4 Hz. Mean over 3 runs.

Figure 6: Boundary layer thickness at $x/c = 0.25$ as a function of time with alternating laser point-actuation.

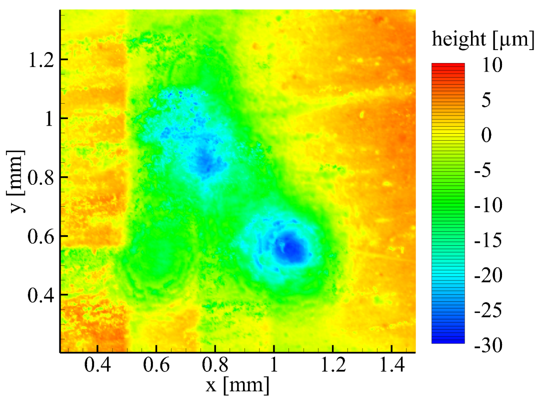


Figure 7: Model surface after pointwise laser actuation on the surface.

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