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Erhöhung der maximalen Auftriebskräfte am Schiffsruder durch aktive Strömungskontrolle

Maximum lift enhancement on a ship rudder model by active flow control

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Aktive Strömungskontrolle, Strömungsabriss, Fluidischer Oszillator, PIV, Auftriebserhöung
Active flow control, stall, fluidic oscillator, PIV, lift enhancement

Summary

This paper shows a method for active flow control on a ship rudder. The experimental setup and methods are explained and described. It is shown that it is possible to delay the flow separation on a ship rudder to a greater angle of attack using pulsed jets. With this, it is possible to achieve higher maximum lift and thus greater steering forces. The described method is validated on booth, a down-scaled down and a near full-scale rudder model. The fluid dynamic effects are investigated by particle image velocimetry and a force balance.

Introduction

Global shipping is a major contributor in greenhouse gas emissions. Reducing these emissions is a main challenge of current applied hydrodynamic research. Alongside with developments in propulsion technology, the fluid dynamic optimisation of ships and its control exhibit great potential in this field. Especially the rudder is in the focus of many investigations, as Liu and Hekkenberg 2017 show. One promising approach to this problem is the application of Active Flow Control (AFC). This technology is already well investigated in aviation application for its potential in delaying flow separation, noise reduction and thrust vectoring, like shown in Collis et al. 2004. Flow Separation is the detachment of the flow along a surface from that surface, accompanied by a reversed flow downstream of the separation point. Delaying flow separation on a ship rudder is useful to enhance the maximum achievable steering forces using a given rudder size. With this it would be possible to realise the same manoeuvrability with a smaller rudder surface. This in turn leads to a smaller over all fuel consumption because of the smaller drag created by the rudder being in the propeller wake during the whole mission. Greenblatt et al. 2019 introduces the different approaches of AFC which may be used to achieve this goal. In this study, an AFC system based on pulsed jet actuators is developed. To implement the pulsed blowing, a fluidic oscillator is used. A fluidic oscillator is an analogue device to create a periodic flow without the need of electric or moving parts. The pulse jet oscillator is capable of creating pulsed flow on two outlets, with a square-wave like temporal modulation of the flow rate of each outlet. Its basic principles are shown in Arwatz et al. 2008. AFC with pulsed blowing shows promising results in aviation as discussed Lin et al. 2016 as well as in Schlösser and Bauer 2020. By adding momentum to the boundary layer, it is energised, which helps to prevent the flow from separating. Additionally, the lower part of the boundary layer is enriched with high momentum fluid from outside the boundary layer, due to the effect of the pulsed creation of vortical structures in the near wall flow. While Johnston and Nishi 1990 show this effect for constantly driven vortex generator jets, the research of Eroglu and Breidenthal 2001shows this mixing behaviour for pulsed actuation. As a result, the flow stays attached to the suction side of the lifting body. As a side effect, the necessary flow rate is reduced, since the fluidic oscillator operates two exits alternately. The usage of a pulse jet oscillator to create pulsed blowing eliminates the need for electric or mechanical components like fast switching valves or other complex parts. The research of Seifert et al. 2016 shows, that it is possible to apply this technology for transportation aside from the field of aviation.

In the following section a system for active flow control with a pulse jet oscillator is introduced. The technology is adapted for usage in maritime environment. The flow field around the actuated rudder is analysed and the potential for enhancing the rudders lifting forces is investigated.

The results shown in this paper shall be understood as preliminary data from ongoing experiments and analysis. It is aimed at demonstrating the potential of AFC in a maritime environment. The results do not exploit the whole available parameter space, but instead are intended to explore beneficial combinations of selected parameters.

Rudder model and actuation system

The rudder model used in this study is based on a commercial design by Damen Marine Components. This model was scaled down to a chord length of 300mm and a span of 420mm for the experiments.

For the present study, a new double-chamber actuation system is developed. The system consists of two independent chambers inside the leading edge of the model. A single fluidic oscillator is used to power both chambers, with each chamber connected to one outlet of the oscillator. The rudder model and oscillator are 3D printed from PLA and post-processed with epoxy resin and coating. Connections between the oscillator and rudder model as well as to the supply pump are realized using flexible tubing and CAMLOCK joints. A simple bypass system is used to adjust the volume flow rate. For each experiment, the volume flow rate is kept constant. Flowrate and pressure are monitored with inline sensors during the experiments. Different combinations of jet position and jet geometry were tested in a preliminary study and the most promising setup is analysed further.

The actuation jets are placed a short distance upstream of the detachment point of the flow in baseline configuration. Different distances from the detachment pint were tested beforehand to find efficient positions for AFC. Additionally, the span wise placement and the slot geometry were varied to find beneficial combinations. The present study focuses on the most promising combination of these parameters. The final jets were chosen to have an inclination of 30° to the surface. For the slots a 28mm by 1mm opening was chosen.

Experimental setup

PIV measurements where conducted in the towing tank of the University of Rostock with a total length of 37m, 5m width and a water depth of 2,7m. Considering acceleration and deceleration of the towing cart, a usable distance of 30m is achieved for the measurements. An underwater stereo PIV System made by LaVision is used to measure a 2D-3C velocity field. Double images are captured with a temporal resolution of 12,5Hz. For seeding the water polyamide particles with a diameter of 100µm are used. Fig. 1 shows a raw image from the PIV setup. The rudder is illuminated with a light sheet from downstream. Because of this configuration the rudder is casting a shadow on its bottom side. This shadow is present in all further analyses but it is outside of the area of interest.

Alongside to the PIV system a piezo-electric fore balance from Kistler is used to measure the lift and drag forces on the rudder. Additionally, the force balance is used to detect remaining waves and other flows inside the towing tank to determine the required settling time between the runs.

The small-scale experiments shown in this paper were conducted with a towing velocity of 0.5 m/s and a corresponding Reynolds number of 1.5e+5.

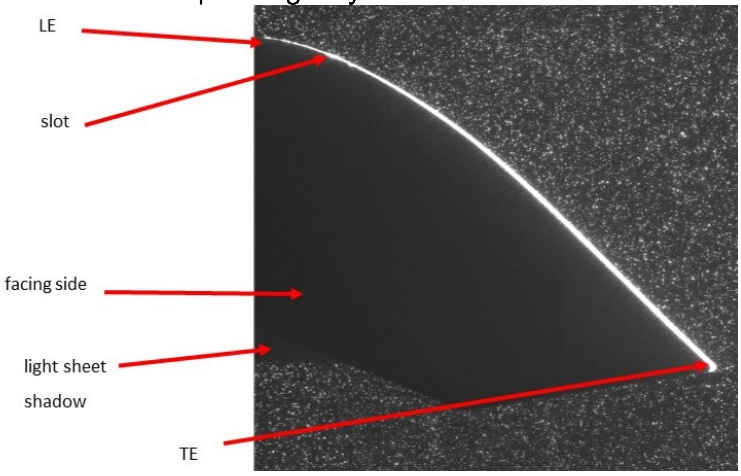

Fig. 1 Experimental Setup - raw-image. Tailing edge (TE), leading edge (LE)

Results

In Fig. 2 the standard deviation for a run without actuation (baseline) is shown. Two points are marked for further analysis. Point 1 lies outside the separation bubble and is used to represent the undisturbed outer flow of the setup. Point 2 lies inside the separation bubble at the area of highest measured fluctuation. Additionally, Fig. 3 shows the divergence of the flow in a similar manner. The same two points outside and inside the separation bubble were chosen for further analysis.

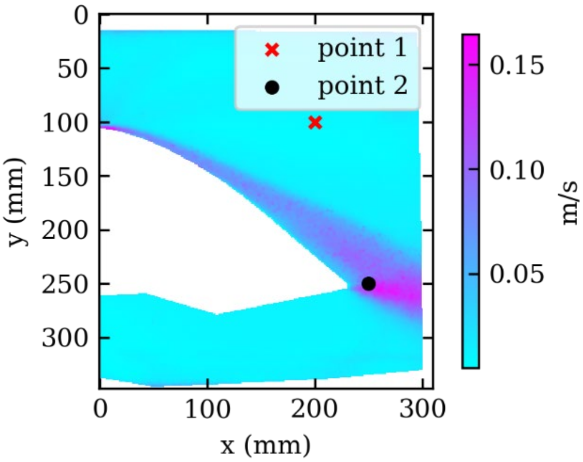

Fig. 2 Standard deviation of the streamwise component measured by PIV. Towing velocity of 0.5 m/s, baseline case without actuation. Points indicate position for analysis of statistical significance

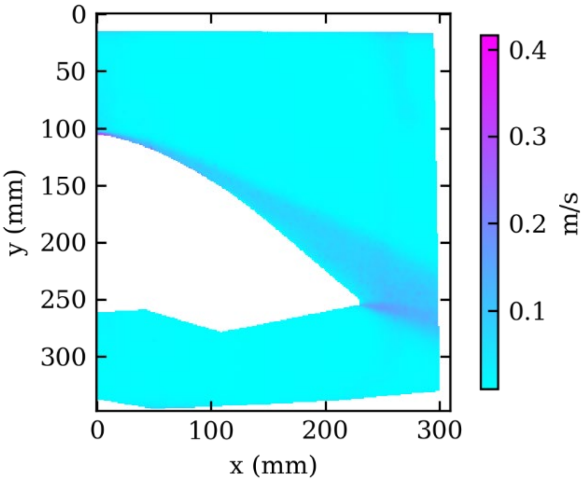

Fig. 3 Divergence of the flow field measured by PIV. Towing velocity of 0.5 m/s, baseline case without actuation.

To analyse the influence of measuring time and flow development, Fig. 4 shows the convergence and standard derivation of the flow as a function of the number of snapshots. For the undisturbed flow a steady state is achieved after a few seconds. The flow inside the separation bubble requires more time to reach a quasi-steady state. This is because the circulation around the rudder and with it the recirculation bubble on the rudder both need some time to fully form. In the case of AFC, the required time to reach this steady state is much smaller, this is an indication for the suppression of the highly unsteady flow separation. Overall, the flow fields show a stable and converged behaviour during a large fraction of the measurement time, as compared to the time required to reach this state.

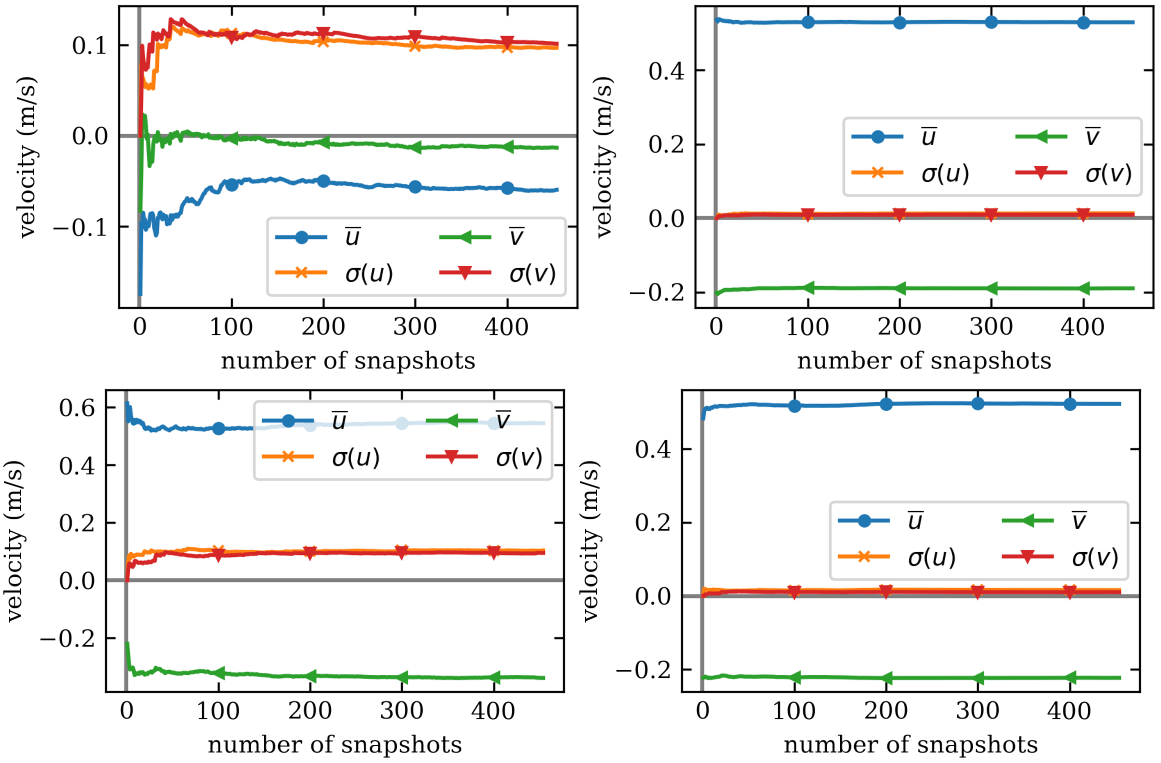

Fig. 4 Convergence of mean and standard deviation of velocity at selected points as indicated in Fig. 2 as measured by PIV. Left: inside separation bubble, right: undisturbed inflow. Towing velocity of 0.5 m/s, baseline case without actuation. Bottom row the same for flow with AFC

Fig. 5 shows a comparison between the mean velocity field of the baseline case and of the case with AFC. The baseline shows a separation bubble with recirculation. Here, the flow is fully separated from the rudder. In case of the AFC this flow separation is completely supressed.

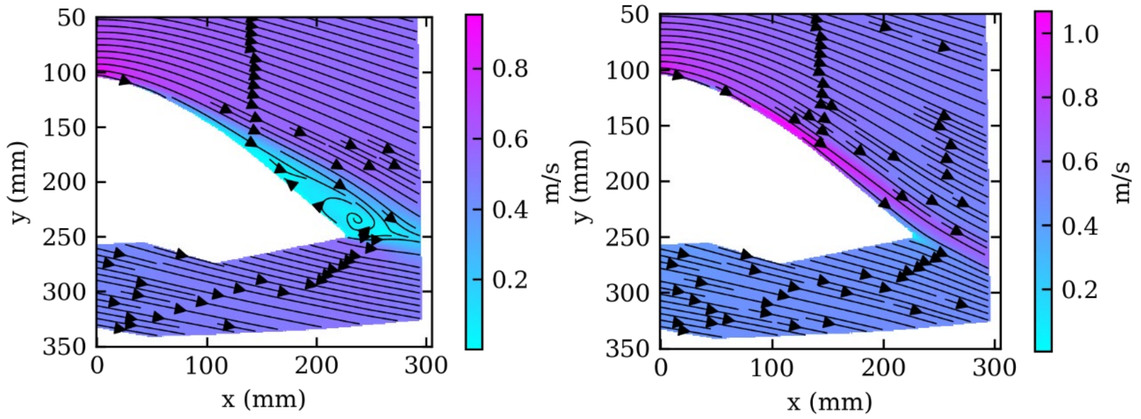

Fig. 5 Mean velocity magnitude and corresponding streamlines of the flow field measured by PIV. Towing velocity of 0.5 m/s, baseline case without actuation (left) and actuation at 30 l/min (right).

The comparison between the baseline flow field and the AFC flow field is shown in Fig. 6 for the stream-wise component and in Fig. 7 for the cross-stream component. In the case of the non-actuated flow a recirculation zone with low mean velocity is apparent. In the AFC case a region of faster fluid is present instead. The mean stream-wise velocity in this area exceeds the towing velocity for high actuation intensities. Also, the additional momentum of the fluid from the jets is also visible in the mean cross-stream velocity in Fig. 7. For high flow rates the accelerated flow is also visible downstream from the tailing edge of the rudder. Such high flow rates begin to show behaviour of active circulation control, where the lifting forces created by the actuated rudder can be higher than the theoretical forces of the rudder without a separated flow region.

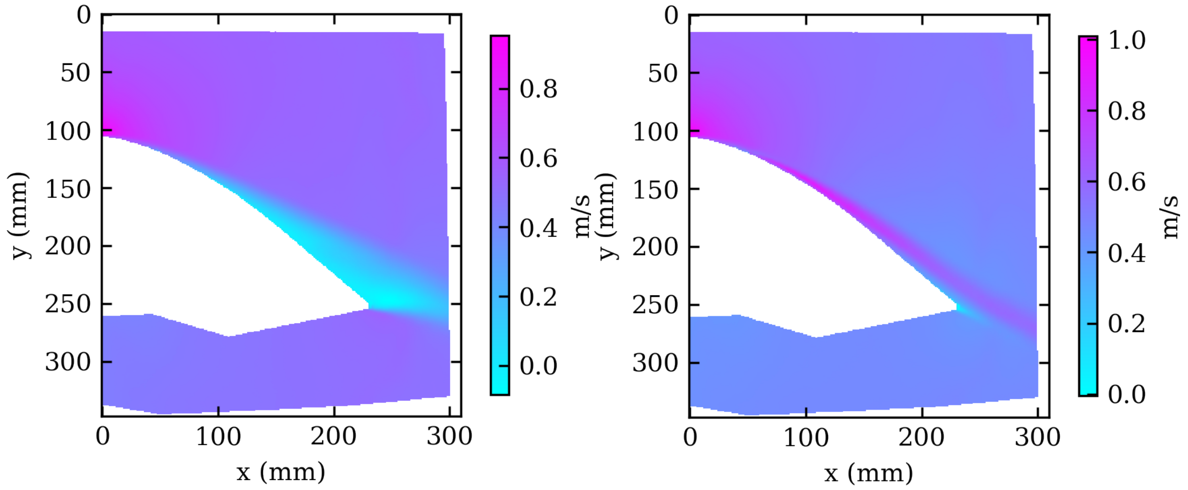

Fig. 6 Mean streamwise velocity measured by PIV. Towing velocity of 0.5 m/s, baseline case without actuation (left) and actuation at 30 l/min (right).

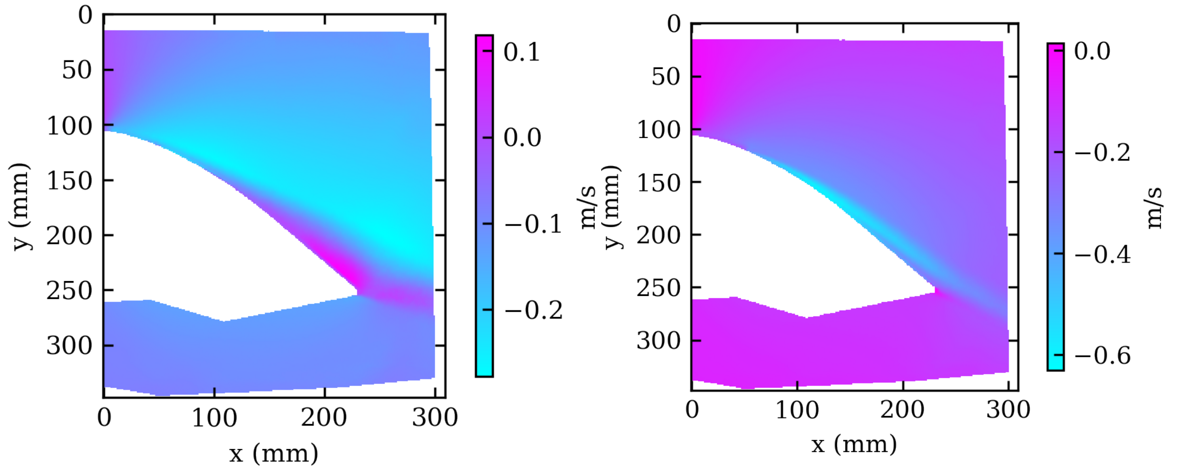

Fig. 7 Mean cross-stream velocity measured by PIV. Towing velocity of 0.5 m/s, baseline case without actuation (left) and actuation at 30 l/min (right).

All baseline measurements were conducted with masked jet slits to ensure an undisturbed baseline flow. The lift and drag coefficients for different AFC flow rates are shown in Fig. 8. It is possible to positively influence the flow around the rudder also with lower flow rates, as long as the jet velocity is as least as high as the towing velocity. The suppression of a partial trailing edge separation for a given angle of attack is also apparent in the drag coefficient.

Higher flow rates are capable of delaying the full flow separation to higher angels of attack. This way, this it is possible to archive a higher maximum lift force than without AFC. The small-scale experiments show, that with an appropriate combination of flowrate, jet position and geometry, a maximum lifting force above 120% of the baseline rudder are achievable. Higher angles of attack require higher flow rates to energize the boundary layer enough to keep the flow attached to the rudders suction side.

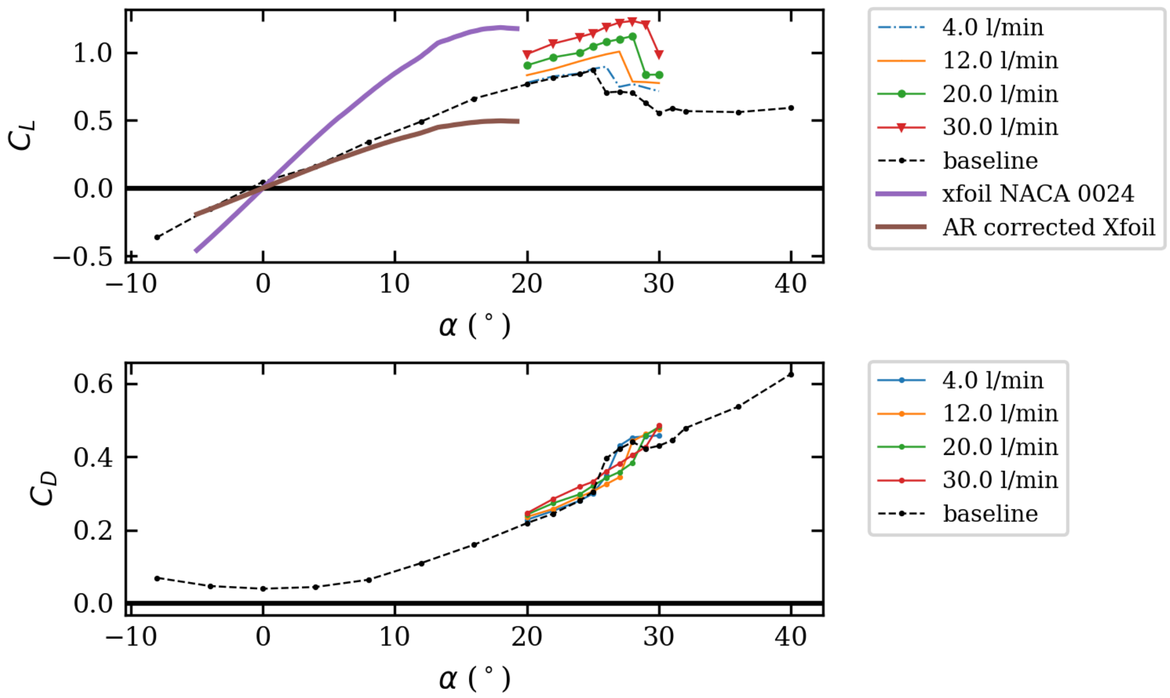

Fig. 8 Lift and drag coefficient vs angle of attack for various actuation intensities. Towing velocity of 0.5 m/s.

The small-scale experiments were validated by full-scale experiments in cooperation with the Hamburgische Schiffbau-Versuchsanstalt (HSVA). A rudder similar to the small-scale rudder was built by the HSVA. The internal and jet geometry were scaled accordingly. The full-scale rudder has a chord length of 0,97m and a span of 1,388m. This validation experiment took place in the large towing tank of the HSVA with a length of 300m. In this case only a selection of measurements were conducted. Oscillator feeding rates were chosen such that the jet exit velocity where comparable to measurements from the small-scale experiments. However, only the lower oscillator feeding rates from the small scale experiments were validated, because of limitations in the maximum achievable flow rates with the pumps.

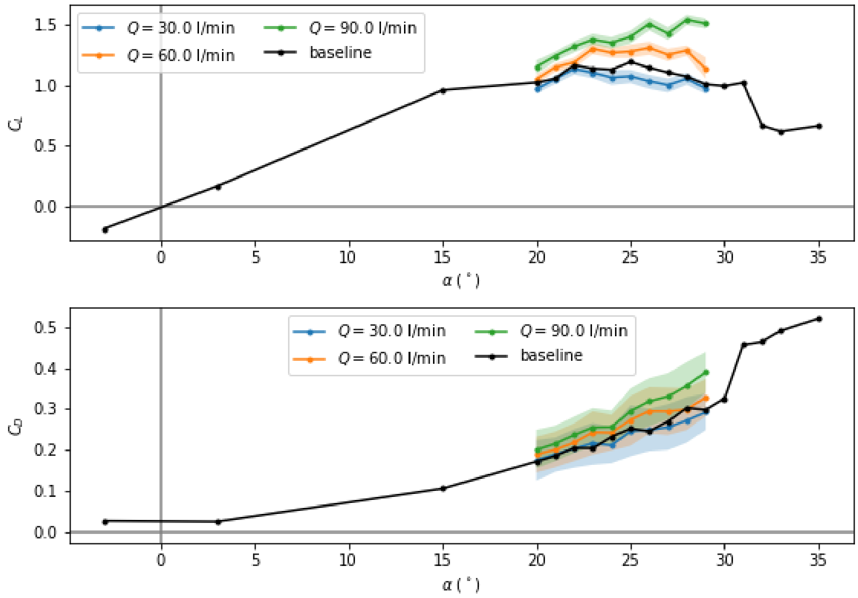

Fig. 9 Lift and drag coefficient vs angle of attack. Validation experiments at HSVA. Towing velocity 0.625 m/s

The outcome of these experiments is shown in Fig. 9. The measurements were conducted at a towing velocity of 0.625 m/s and a corresponding Reynolds number of 6e+5. All conducted full-scale experiments show a behaviour comparable to the small-scale experiments. With scaled jets and feeding rates it is possible to delay flow separation to higher angles of attack comparable to the ones from the small-scale experiments. A similar enhancement of the lift and drag coefficients are also achievable. These experiments on a full scale show, that up-scaling of AFC on a ship rudder is possible.

Outlook

In order to further use this technology in a maritime environment, it is planned to apply the same principle and method on a ship hull. Initially the flow control will be focused on the aft section of the Japan Bulk Carrier (JBC). The target here is the optimisation of the inflow condition for the propeller. Additionally, optimisations of course stability, manoeuvrability and drag reduction are goals of these studies.

For this phase of the project a scaled model of the JBC was built. The model is divided in three sections. Similar to the rudder approach, an insertable narrow section was designed with two chambers connected to small outlets. The system is again driven by a single oscillator. As a first experiment, the pulsed jets are placed only at the bottom of the ship hull. Different flow rates and oscillation frequencies where tested and the flow field was measured with 2D3C-PIV while the drag was measured using a force balance in similar manner to the rudder experiments.

A preliminary study was conducted with actuation at around two thirds of the ships length. In Fig. 9 a comparison between the un-actuated baseline flow and the actuated flow is shown.

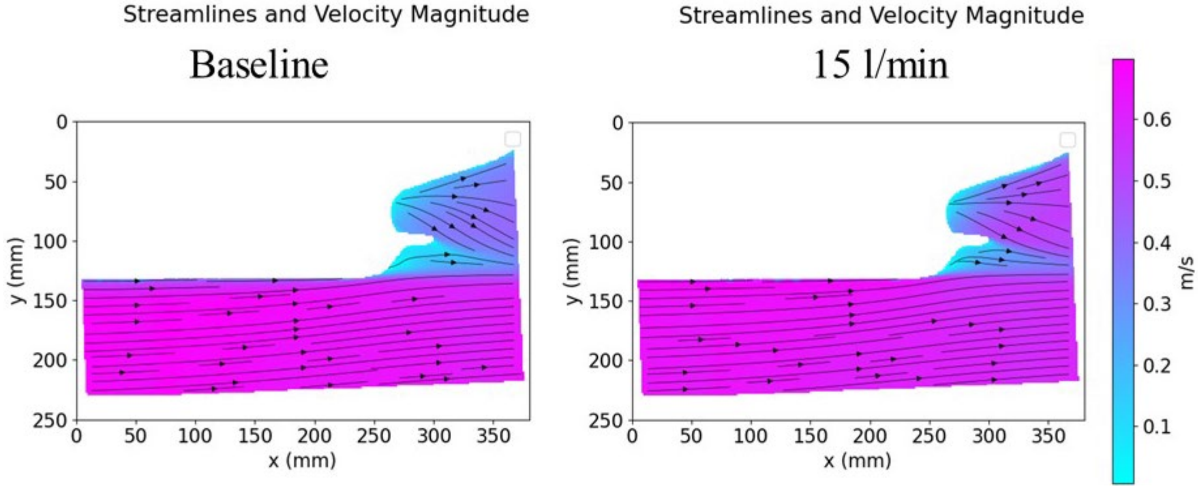

Fig. 10 Comparison of the flow field around the JBC model without (left) and with AFC (right)

The wake area of the ship is slightly influenced and the flow on the tailing edge is bend upwards towards the position where the propeller would be. However, this effect is achieved only by high flow rates.

The following activities will concentrate on identifying the best possible geometry and position of the jets at the lowest possible flow rates in order to develop an AFC system that allows the scaling to full scale with reasonable flow rates.

Conclusion

An approach for active flow control on a ship rudder was shown. By adapting methods developed for aviation it was possible to delay flow separation on a scaled-down ship rudder model. By feeding slotted jet exits by a fluidic oscillator along the rudder span it was possible to enhance the maximum lift coefficient significantly and thus the maximum achievable steering forces. By combining PIV measurements with force balance measurements, it was possible to show the beneficial effect of the pulsed jet actuation. The increase in lift was attributed to the reattachment of the flow and suppression of separation. The small-scale experiments were validated with large scale experiments in cooperation with the HSVA. These experiments proved the scalability of this approach. This is an important step in showing the potential for AFC in maritime environment and the possible impact of this technology on this sector. The knowledge gathered in these rudder experiments can serve as a foundation for upcoming experiments on the usage of AFC on a ship´s hull.

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