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ANALYSIS OF THE FLOW INDUCED BY THE UNDULATORY FIN MOTION OF SEAHORSE

Emanuela Botello-Payro, Lucia Diez-Robles, Cornelia Rauh, Antonio Delgado
Institute of Fluid Mechanics, Technical Faculty, Friedrich-Alexander University Erlangen-Nuremberg, Cauerstraße 4, D-91058 Erlangen, Germany

Seahorse locomotion, undulatory fin motion, PIV

Abstract

The transfer of bio-mechanical knowledge on technical applications is essential in bionics-research making for example biological flows induced by under-water life-forms to an important topic in biology and fluid mechanics. The present study focuses on seahorses which due to their anatomy have a very low ratio between the area of their active moving fins and the passive transported body. Nevertheless, they are able to stabilise their locomotion precisely. The understanding gained from the investigation of the induced flow fields combined with the resulting locomotion of the seahorse have a great potential for future technical developments like for example under-water vehicles, which can be adopted in oil platforms. The locomotion of seahorses and the flow caused by the undulating motion of the fins is analysed using laser-optical measuring techniques (2 dimensional – 2 component PIV). For illumination an Nd-YLF laser (Litron LDY 303) is used with a light wave length of 527 *nm*. The images have been recorded with a high-speed camera (Photron Phantom v12). The time distance between the images is $5\ ms$. The images have been evaluated with the PIVview2C software (PIVTEC GmbH) in a cross-correlation mode. The PIV investigations have been carried out using the multiple-pass interrogation algorithm which is included in the PIVview2C software.

1 Introduction

The locomotion of life-forms in water has recently gained increasing interest in fluid mechanics and bionics. The ability to transfer knowledge about fluid mechanical phenomena to technical applications could for example enable improvements of water and underwater micro-vehicles. Diverse studies have been carried out in order to understand fish locomotion. The maximum swimming speed possible for fishes has been already studied by Werdle and Videler (1980). Walker (2004) compared the kinematics and the performance of the manoeuvring system of several bone fishes. Sunfish has been investigated regarding its mobility by Drucker and Lauder (2001). Moreover, the propulsion system of fishes with an anatomy differing from seahorses has been examined by Sfakiotakis et al. (1999). Seahorses in opposite to other fishes do not possess a streamline like body. Still they are able to overcome this disadvantage with small, high frequently moving fins and perform locomotion in all directions of space.

To understand the interaction of fishes with their fluid environment Particle Image Velocimetry (PIV) studies have been conducted. Müller et al. (1997) visualised the water flow in the wake of swimming fishes. Fluid flows generated by tails, fins and the body of swimming fishes have been examined by Anderson et al. (2000) and Lauder and Drucker (2002), respectively.

Although several fluid mechanical studies have been carried out with fishes there is a lack of reliable information about locomotion of seahorses. Compared to other underwater organisms seahorses have a low ratio between the area of the active propulsive parts (fins) and passive parts (body). They are able to manoeuvre and stabilise their levitating body not only by means of their swim-bladder but also with the aid of small high frequent actuators (fins). Their translational motion is propelled by synchronous kinematics of dorsal and pectoral fins. First investigations on seahorse locomotion were performed by Breder and Edgerton (1942). They implemented stroboscopic light and a high speed motion camera to analyse the fin movement. Moreover, cinematography investigations of Blake (1976) enabled some analysis on translational motion of seahorses. Biological classification of all known seahorses has been given by Lourie et al. (2004). Theoretical fundamentals of the fluid dynamics according to the undulatory and oscillatory fin movement were described by Lighthill and Blake (1990). Sfakiotakis et al. (2001) and Consi et al. (2001) modelled experimentally the kinematics of the dorsal fin by using a moving membrane. Kowalczyk and Delgado (2007) analysed fin-like movement by means of numerical simulation.

Despite these efforts, seahorse locomotion, the flow they induce by their fins and the spectacular ability to manoeuvre and stabilise their whole body with small actuators is not completely understood. Therefore there is a need for further fluid mechanical investigations in this area.

In the present study, the stabilisation effect of the flow on the seahorse body induced in the vicinity of the fins and the seahorse body has been investigated with 2 Dimensional - 2 Component Particle Image Velocimetry (2D-2C PIV).

2 Experimental method

Seahorses (*Hippocampus reidi*) are kept in an aquarium with a size of 120*cm* x 60*cm* x 60*cm*. They are fed daily with mysis shrimps. All optical measurements have been performed in artificial sea water at a temperature of 23°C and a density of 1.0261 g/cm^3. For this study adult female seahorses have been chosen.

The flow has been investigated with a classical 2D-2C PIV in-situ method. For illumination an Nd-YLF laser (Litron LDY 303) is used with a light wave length of 527 *nm* and a pulse rate of 10 *kHz*. The laser beam is expanded to a light sheet with a cylindrical lens. Hollow glass spheres with a diameter of 10 *µm* have been used as tracer particles. The images have been recorded with a high-speed camera (Photron Phantom v12). The time distance between the images is 5 *ms* and the image size is 1280pixel x 800pixel. Figure 1A shows a picture of the used setup.

The images have been evaluated with the PIVview2C software (PIVTEC GmbH) in a cross-correlation mode developed by Raffel et al. (1998). The PIV investigations have been carried out using the multiple-pass interrogation algorithm which is included in the PIVview2C software. This method provides a high data yield due to the higher number of matched particles and reduces the bias error (Westerweel et al. 1997). In this study, the interrogation area size has been chosen as 32pixel x 20pixel. Sub-pixel displacement of the correlation peak is obtained by a three-point Gauss fit, which selects the four closest neighbours of a correlation maximum and fits a three-point Gaussian curve for each of the major axes (Willert and Gharib, 1991). The evaluated data have been post-processed in TECPLOT (Amtec Engineering).

The measurements of the flow fields have been done in a separated compartment (40*cm* x 40*cm* x 50*cm*) of the aquarium (see right top edge of Figure 1A). In this compartment the seahorses showed their natural behaviour and made different typical swimming manoeuvres like stagnation (swimming without changing the position in space) and horizontal locomotion to right and left. During the measurements the compartment has been closed from all sides. The aquarium itself closed the front side and a movable plate the back side. The measurements have been performed whilst the seahorse resides between the movable plate and the light sheet plane with his dorsal fin oriented towards the light sheet plane as sketched in Figure 1B. The distance between the plate and the light sheet plane has been kept constant at 7 *cm* during the investigations of the flow induced by the dorsal fin and at 3.5 *cm* for the pectoral fin. Hence it was possible to keep the distance between the investigated fins (dorsal and pectoral) and the light sheet plane for all measurements nearly constant. This distance usually varies between 0 and 4 *mm*. It is a challenge for systems

where the flow induced by animals is investigated to keep this distance exactly constant and to achieve good data where only the flow induced by the fins is measured. Hence it is advantageous to perform measurements where the fin is close and behind the light sheet plane and not directly in the laser light. Due to the shadow caused by the fin the flow would not be completely visible. Additionally the seahorse body and the fins were placed behind the light sheet plane in order to measure only the fluid flow induced by the fin and not an overlapping flow induced by the fin and body motion.
The flow induced by the anal fin has not been investigated in this study due to the difficult spatial accessibility of this fin.

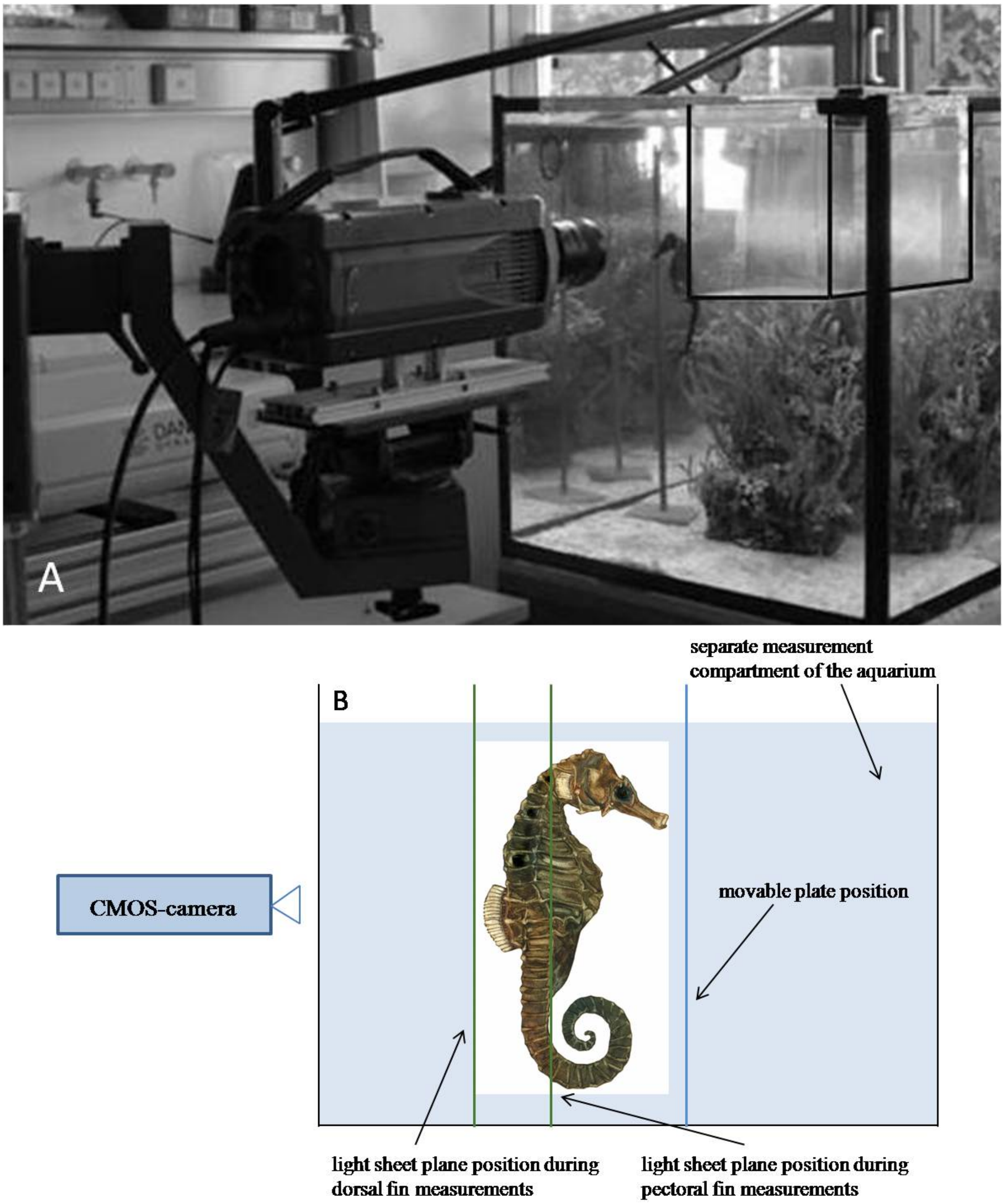

Figure 1(A) 2D-2C PIV setup consisting of an Nd-YLF laser, light sheet arm, cylindrical lens and a high-speed camera; (B) Sketch of the experimental procedure

Additionally, numerical simulations of the fin motion are conducted. The fin simulations have been performed with a commercial code CFX-12. The mesh consists of 27958 tetrahedrons and the simulation-time amounts 1.365 s. Equation 1 which has been used for the fin simulations approximates the motion of a fin at a frequency of 54 *Hz.* The fin dimensions are the following: length 2 *cm*, width 4 *mm* and depth 0.2 *mm*.

$$y(x,z,t) = \underbrace{1.134}_{A(z)} \cdot z \cdot \sin(\underbrace{314.16}_{\omega[1/s]} \cdot t - \underbrace{610}_{k[1/m]} \cdot x) \qquad (1)$$

3 Results and discussion

In the following section the typical flow patterns induced by the dorsal and pectoral fin are presented and analysed when the seahorse is in stagnant, balanced position.

Figure 2 illustrates the typical flow profile induced by the dorsal fin during seahorse stagnation in a vertical position. The distance between the undulatory dorsal fin and the light sheet plane is about 4 *mm* (see Figure 2). It can be observed that two downwards directed counter rotating vortices are induced.

Figure 3 indicates the typical flow profile induced by the pectoral fin whilst the seahorse is in stagnant position. This experiment has been performed when the seahorse head was placed behind the light sheet plane in a straight position. The distance between the pectoral fin and the light sheet plane is about 3 *mm* (see Figure 3). In this case two upwards directed counter rotating vortices have been observed. The seahorse carries a pair of pectoral fins and for both fins two upwards directed counter rotating vortices are induced.

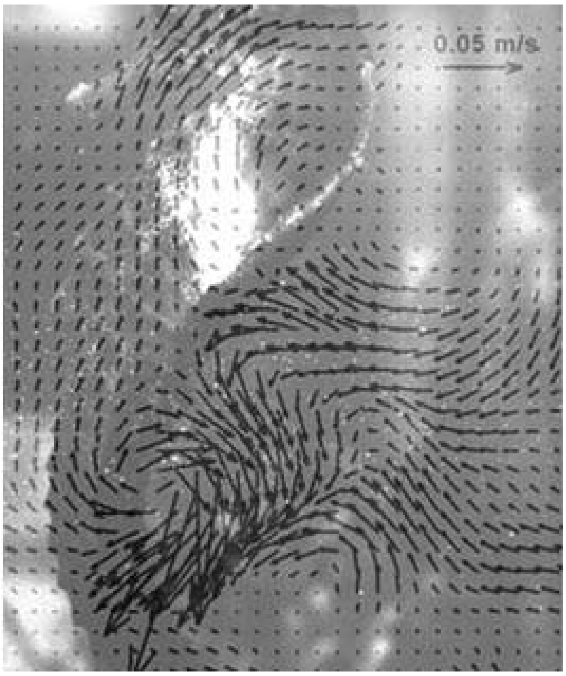

Figure 2 Flow induced by the undulatory motion of the dorsal fin

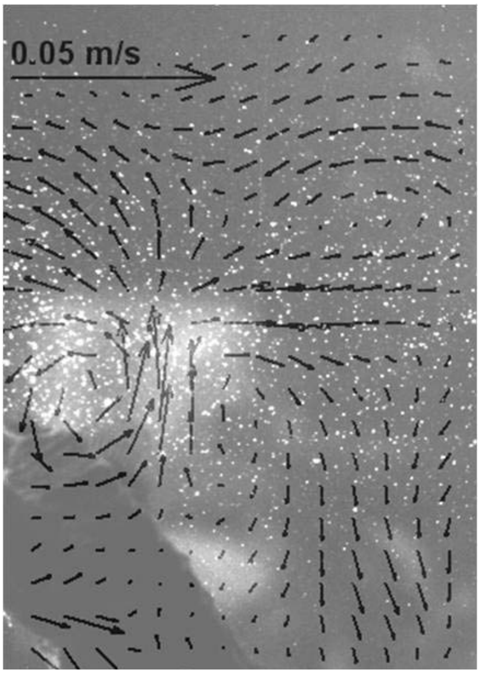

Figure 3 Flow induced by the undulatory motion of the pectoral fin

This flow profiles induced at the dorsal and pectoral fins are characteristic for all performed measurements in this study at the constant conditions described in chapter 2 during seahorse stagnation.

The velocity magnitude of the flow as well as the qualitatively estimated diameter of the vortices at the dorsal fin is higher than at the pectoral fin. The ensemble-averaged maximum velocity magnitude of the flow over 12 experiments is measured at about 0.1 *m/s* at the dorsal fin compared to about 0.06 *m/s* at the pectoral fins. Here a connection with the fin length can be drawn since the length of the dorsal fin is almost two times higher than the length of the pectoral fin. The deviations from the mean velocity values range from -5% to 20% for both cases. Although the most often observed fin frequency is at about 50 *Hz*, these deviations can be ascribed to the changing fin frequencies of the seahorses during the experiments.

These PIV investigations affirm that due to the undulatory motion of the dorsal and pectoral fin the surrounding medium is actuated and a flow is induced that compensates imbalances and keeps the whole seahorse body in equilibrium during stagnation. Hence, this function is not only carried out by the swim-bladder but also by the fin induced flow.

Since the fin undulation has a certain periodicity with respect to time, it is interesting to find out whether the flow structure is periodically as well. On the other hand it can be speculated that the surrounding flow shows also stationary properties since the seahorse is in stagnant motion. Therefore, the structures of the flow and the velocity magnitude have been observed with respect to time.

Figure 4 shows the flow field induced by the dorsal fin and the changes of this field during short time steps of 5 *ms* (e.g. t_0 and t_1). It can be observed that the position in space and the shape of the two vortices are almost constant and the velocity changes are small. The centre of the maximum flow velocity is unmodified in y-direction over the presented time domain and slightly changed in x-direction between the times t_1 and t_3 with 0.2 *cm* whilst the position of the seahorse remains unchanged.

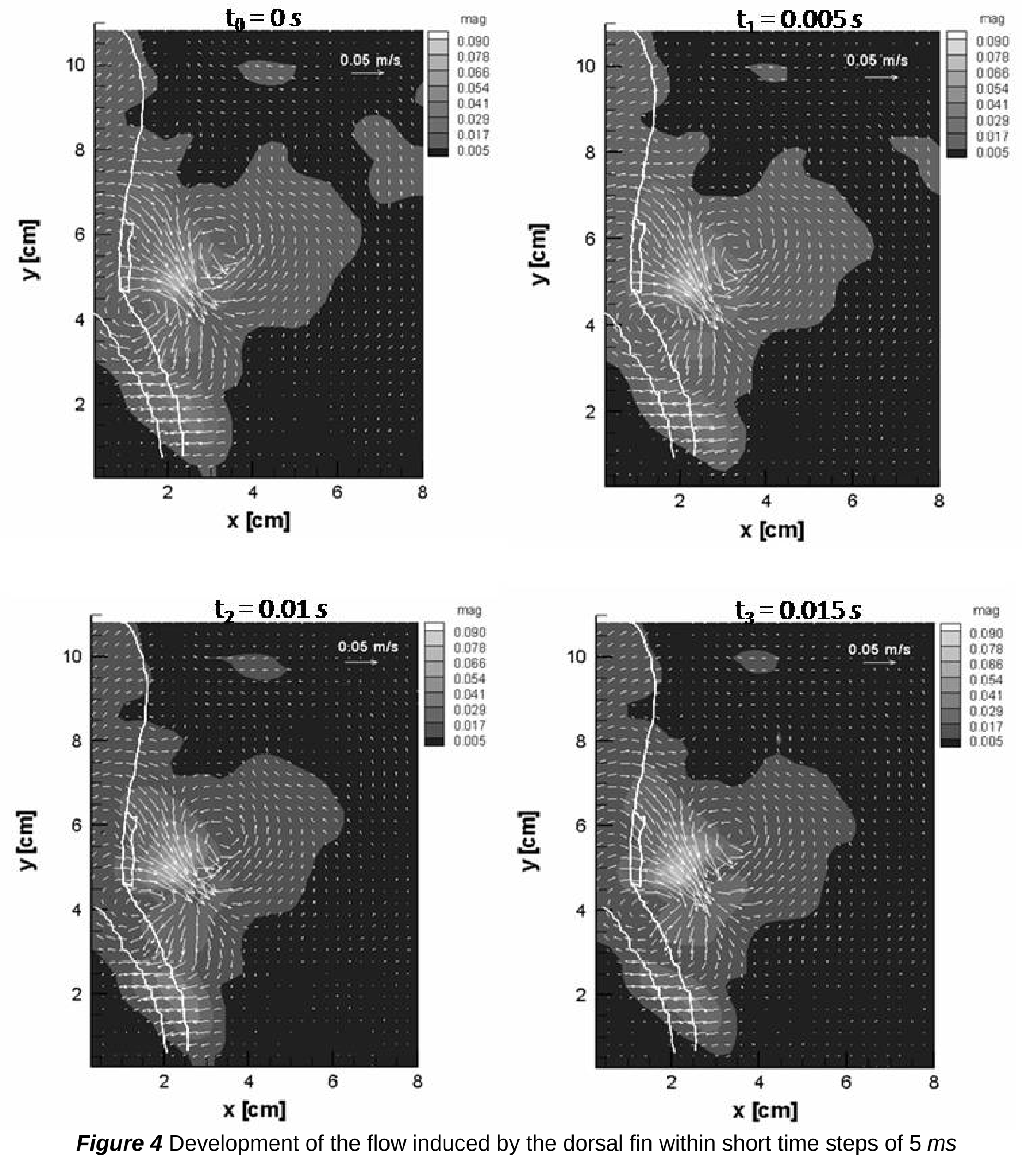

Figure 4 Development of the flow induced by the dorsal fin within short time steps of 5 *ms*

The acceleration in the region of interest (ROI) was calculated out of the velocity change between the times t_0 and t_3. The average acceleration in the ROI is 0.08 *m/s²*. Figure 5 shows the acceleration for all grid points in the region of interest.

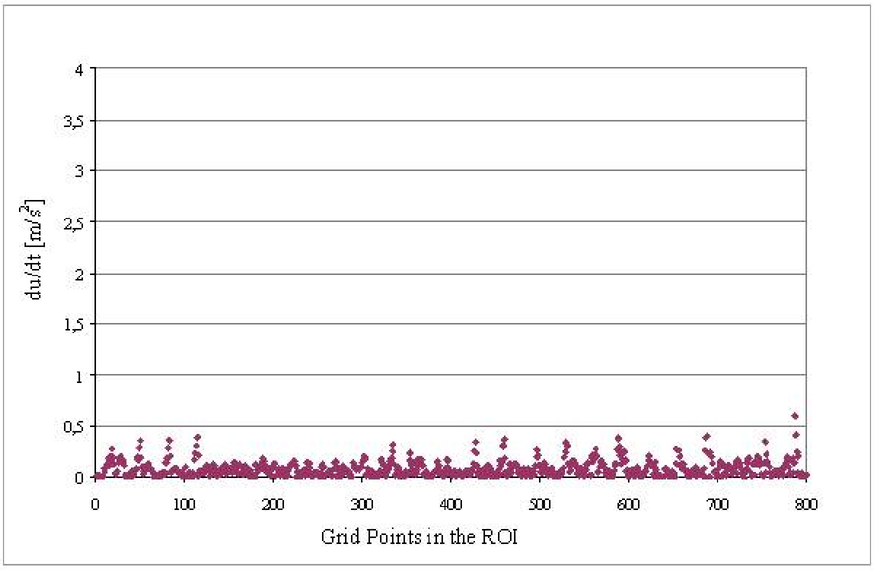

Figure 5 Velocity differences between t_0 and t_3 in the region of interest for the flow induced by the dorsal fin

Integrated in time this small acceleration leads to some changes in the flow structure as illustrated in Figure 6. Between the times t_0 and t_4 (200 *ms*) the flow structure still consists of the two counter rotating vortices and the centre of the maximum flow velocity moves relatively to the seahorse body by 1 *cm* downwards in y-direction and by 0.2 *cm* to the right in x-direction.

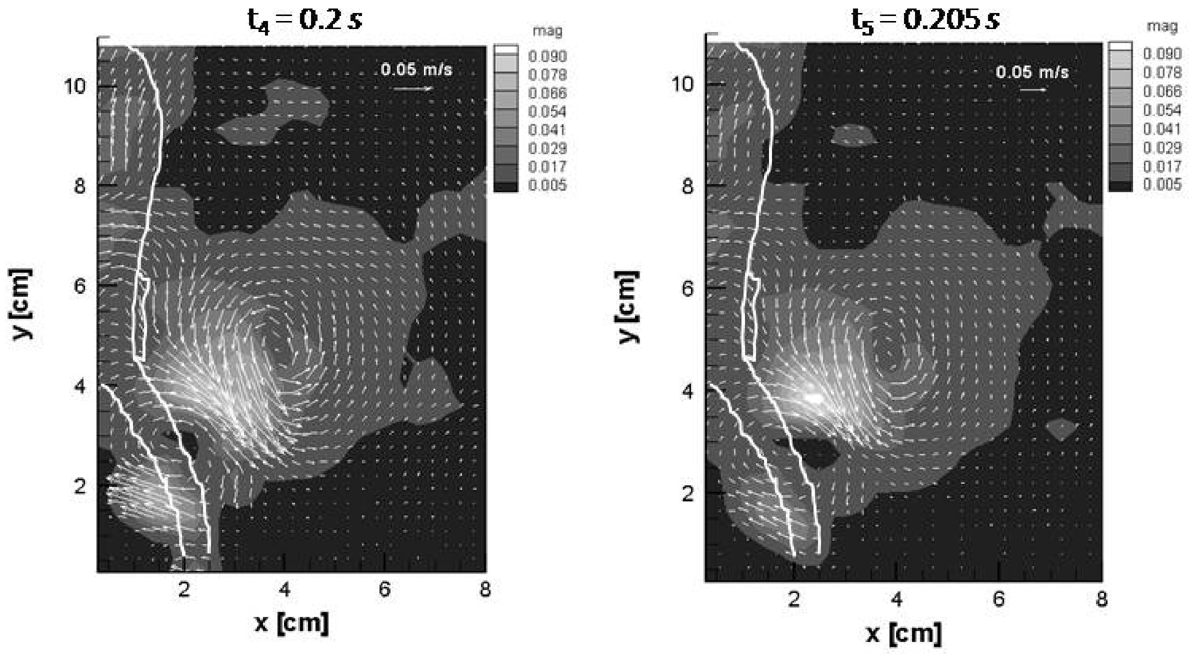

Figure 6 Development of the flow induced by the dorsal fin after a time period of 200 *ms* with respect to t_0 (see Figure 4)

Similar investigations as for the dorsal fin have been performed for the pectoral fins. The flow induced at one pectoral fin is depicted within short time steps of 5 *ms* (e.g. t_0 and t_1) in Figure 7. The structure of the vortices has been found stable and the position of the velocity maxima was not changing with respect to the x- and y-coordinates whilst the position of the seahorse head was unchanged. The accelerations in the region of interest were calculated out of the velocity changes between the times t_0 and t_3 in the ROI. The average acceleration in the ROI is 0.1 m/s^2. Hence, after 305 *ms* (e.g. t_0 and t_4) the two vortices still exist, they are slightly bigger than at the beginning and have an oval shape as illustrated in Figure 8. It can be observed that the centre of the maximum flow velocity moves relatively to the seahorse body by 1.25 *cm* upwards in y-direction and remains unchanged in x-direction. During the experiments it has been observed that seahorses tend to change their position after a certain time period, which explains the unsteady character of the flow.

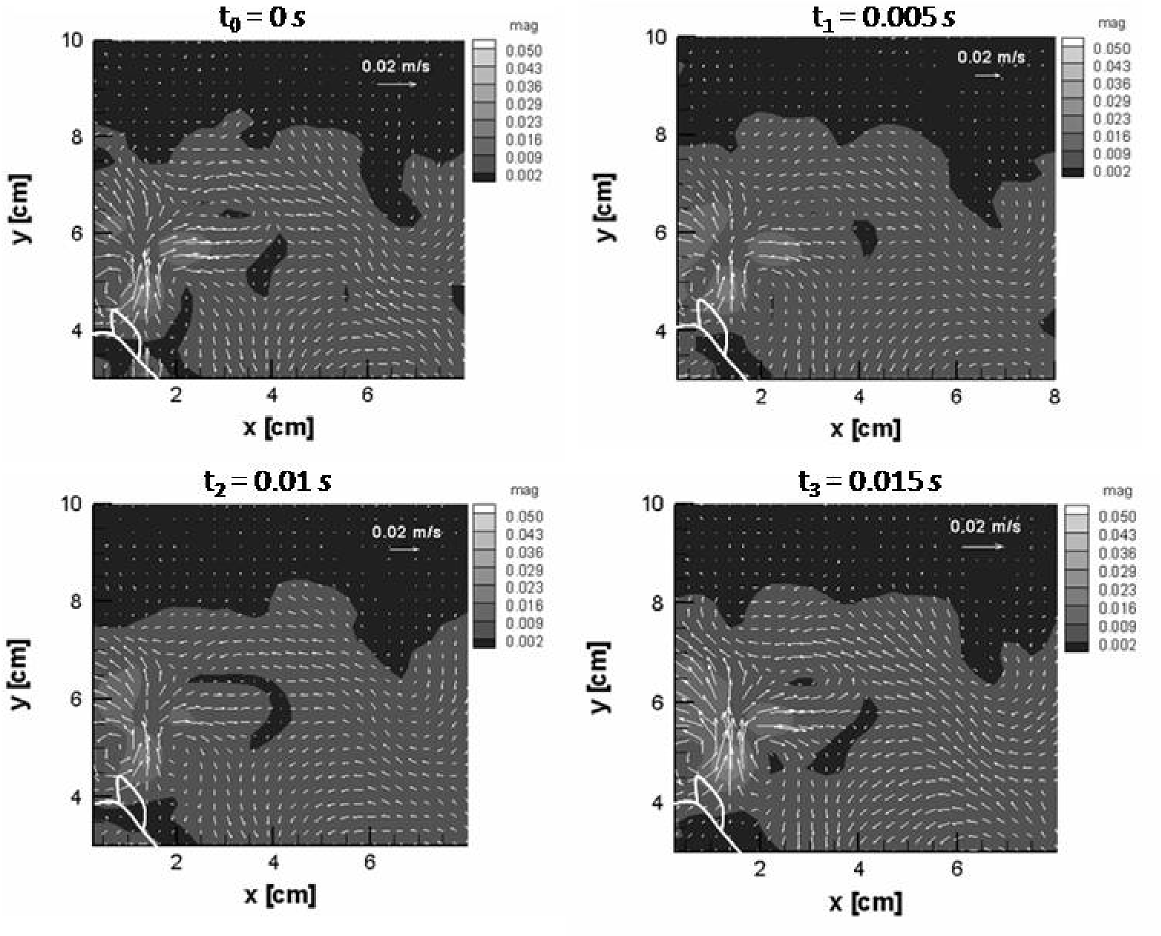

Figure 7 Development of the flow induced by one pectoral fin within short time steps of 5 *ms*

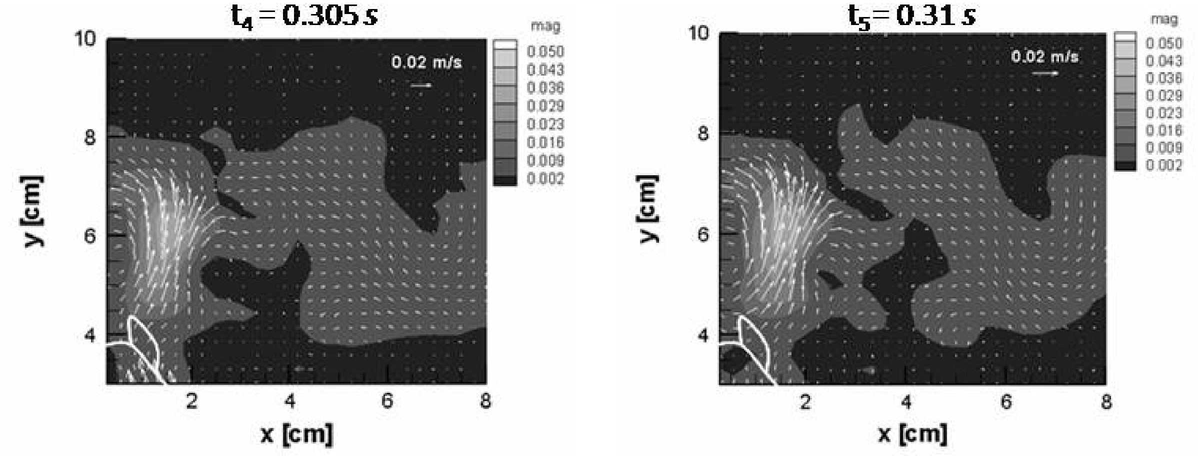

Figure 8 Development of the flow induced by the pectoral fin after 305 *ms* with respect to t_0 (Figure 7)

Out of these investigations it can be concluded that the two counter rotating vortices induced by the dorsal and pectoral fin during seahorse stagnation are not stationary. Still the vortex flow is laminar because of the small dimensions and low velocities, stable and non-periodic.

The distribution of the shear rate at the dorsal and pectoral fin might provide an insight on the stabilizing mechanisms of the flow induced by the dorsal and pectoral fin on the whole seahorse body whilst it stands in a stagnant position. Figure 9 shows the shear-rate distribution at the dorsal and pectoral fin.

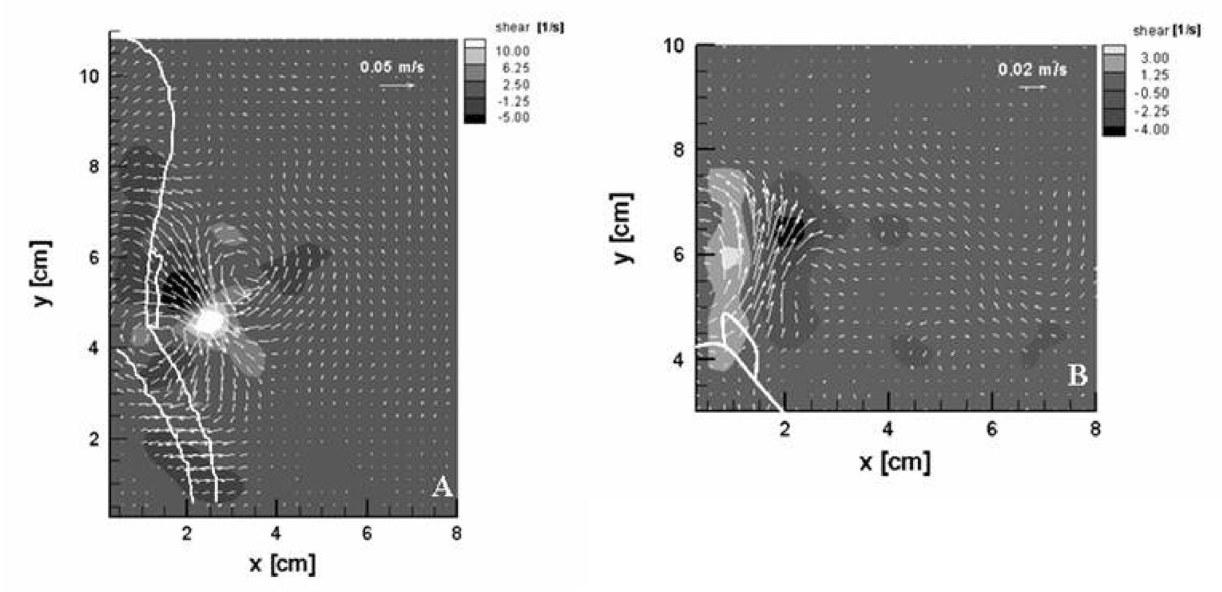

Figure 9 Distribution of the shear rate of the flow induced by the dorsal (A) and pectoral (B) fin of a seahorse in the region of interest

For both fins the distribution is similar since the region of maximum shear rate is located close to the seahorse body where the flow is deflected. The shear rate at the dorsal fin is greater than at the pectoral fin. Since the two symmetrical vortices induced at the dorsal and pectoral fin have opposite directions, it can be concluded that the momentum transfer from the fluid to the seahorse body preserves an equilibrium of forces not only in horizontal but also in vertical direction and hence stabilises the levitating body of the seahorse during stagnation. Additionally during stagnation no eddy shedding in the vicinity of the seahorse body has been observed. Hence it can be concluded that an efficient transfer of kinetic energy from the flow to the seahorse body takes place.

When the seahorse changes its position and moves horizontally to one side, it inclines its body accordingly to diminish the projection area. This measurement has been performed whilst the dorsal fin was slightly touching the light sheet plane and the body of the seahorse was behind it. Additionally during this action the structure of the flow at the dorsal fin changes (see Figure 10). It can be observed that the two counter rotating vortices induced by the undulation of the dorsal fin during stagnation pass over into a single stable vortex which is located at the left side of the dorsal fin during locomotion to the right.

Due to the fact that the vortex flow is developed only on one side of the fin and of the body, the seahorse achieves a stronger momentum into the sidewise direction of locomotion.

The effect of the undulatory motion of a fin on the surrounding fluid can be investigated in more detail by numerical simulations. Simulation results based on the real fin geometry and motion are presented in Figure 11.

Due to the sinusoidal motion of the fin the velocity distribution in the fin is periodic which causes an alternating vortex flow at the half width of the fin. The computed velocity magnitudes agrees well with the measured velocities. At the tip of the long side of the fin the flow is conveyed upwards similar to the flow profile observed during the PIV experiments at the pectoral fin.

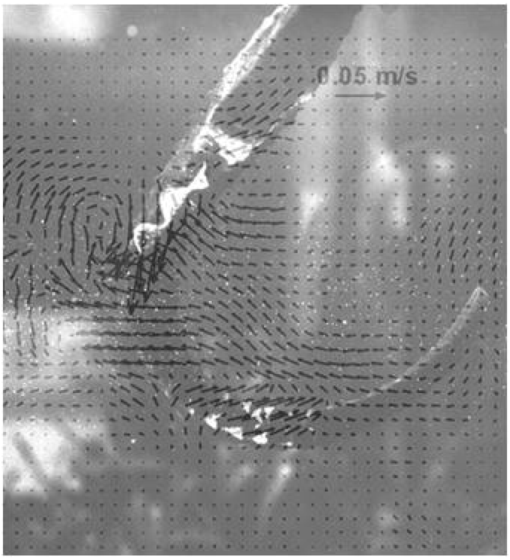

Figure 10 Flow profile consisting of one vortex located at the left side of the dorsal fin during a displacement of the seahorse to the right

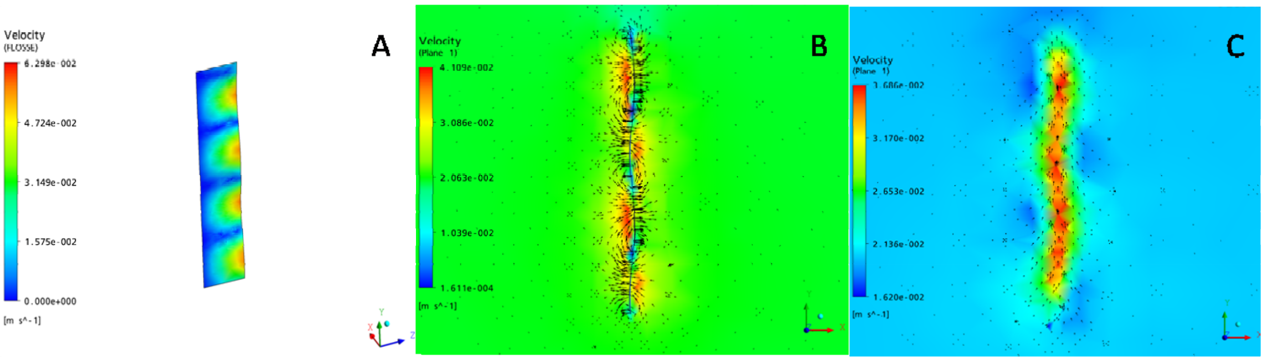

Figure 11 (A) Periodic velocity distribution at the dorsal fin; (B) Flow induced by the dorsal fin motion at half width of the fin (2 *mm*); (C) Flow induced at the tip of the long side of the fin

4 Conclusions

From the PIV investigations reported it can be concluded that seahorses create a flow in the vicinity of the fins and of the seahorse body by the action of their dorsal and pectoral fins which allows them to compensate imbalances and stabilize their upright equilibrium position and control their locomotion in water. To this end, a downwards directed counter rotating vortex flow is induced at the dorsal fin and an upwards directed counter rotating vortex flow at the pectoral fin during stagnation.

In order to execute locomotion to the right or to the left side seahorses incline their body accordingly and the two counter rotating vortices at the dorsal fin evolve to a single vortex which is located at the opposite side of the dorsal fin with respect to the direction of the locomotion.

Hence, the knowledge about fin kinematics and the flow induced by the fins can lead to the first steps for the development of underwater propulsion systems.

Acknowledgment

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