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# KINEMATICS AND HYDRODYNAMICS OF UNDULATORY FIN MOTION OF SEAHORSE

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## Abstract

Increasing interest in applications of biomimetic systems in modern engineering and technology makes the investigations of bioflows an important topic in the modern fluid mechanics. This includes, for example, biomechanical studies of locomotion of different life-forms in water. Numerous scientists studied fish locomotion from different points of view. The present work focuses on seahorses which, due to their anatomy with a low ratio of areas of the active propulsive parts (fins) and passive parts (body), represent an interesting object in biofluidmechanics able to manoeuvre with use of small actuators. In the literature there is a lack of reliable information on the locomotion of seahorses regarded from the fluid mechanical point of view. Hence, in the present work the locomotion of seahorses caused by synchronous movements of dorsal and pectoral fins is analysed. Fin kinematics is analytically revealed. Flow induced by seahorses is studied by means of Particle Image Velocimetry (PIV). From experimental data characteristic undulatory movement of the dorsal fin of seahorse can be stated. High variety of fin activation patterns is observed with fin frequencies varying between 20 and 60 Hz depending on seahorse's activity. Dorsal fin kinematics can be described fairly well by a sinus wave equation with parabolically changing amplitude. Obtained PIV results show the characteristic flow pattern around mowing fins.

## Introduction

Bioflow investigations become an interesting topic in fluid mechanics. Understanding the motion of biological flow gives basics in controlling complicated processes like mixing, transport phenomena or even locomotion of Autonomous Underwater Vehicles. In the recent years fish undulatory propulsion was analysed from various aspects (Blake, 1983, Bone, 1978, Hertel, 1966, Lindsey, 1978, Webb, 1975, Webb and Weihs, 1983). Undulation refers to a wave of motion travelling down the fin length, whereas flapping denotes oscillatory motion of the fin with little or no travelling wave (Arreola and Westneat, 1996). Analysis of undulatory propulsion reveals four typical modes: anguilliform, tunniform, carangiform and subcarangiform (Lauder and Tytell, 2005, Lindsey, 1978, Graham and Dickson, 2004). The first locomotion type (anguilliform) represents the fishes which undulate large portions of body during propulsion with nearly a full wavelength at any given time (Gillis, 1996). Tunniform mode basing on tunas, involves a high aspect ratio tail with little lateral oscillation of the body (Graham and Dickson, 2004). Carangiform locomotion involves up to one half wave on the body and the last one subcarangiform more than one half wave but less than one full wave (Webb and Blake, 1985). Fish propulsion was examined by using hydrodynamics and theoretical models. Several scientists tried to understand how fishes interact with their fluid environment (Lauder and Tytell, 2005). In the last decade many improvements in the new technologies were done in order to measure fluid flow directly. Digital Particle Image Velocimetry (DPIV) enables detailed bioflow visualization. Several DPIV investigations were carried out with continuous laser giving detailed flow analysis. However, some studies apply pulsed laser with a maximal temporal resolution of 15 Hz (Lauder and Tytell, 2005, Raffel et al., 1998).

Seahorses among different underwater organisms, due to their anatomy with a low ratio of areas of the active propulsive parts (fins) and passive parts (body), represent an interesting object in biofluidmechanics able to manoeuvre with use of small actuators. Several studies on seahorses were carried out from different point of view. However, in the literature there is a lack of reliable information on the locomotion of seahorses regarding the fluid mechanics. Pioneering work of seahorse locomotion was done by Breder and Edgerton (1942). They analyzed fin movement by using stroboscopic light high speed motion picture camera. In their work wave direction was described. Lighthill and Blake (1990) and Daniel et al. (1992) gave theoretical fundamentals of the biofluid dynamics of swimming according to the undulatory and oscillatory fin movement. Lourie et al. (2004) and Kuiter (2001) contributed to the biological classification of all known seahorses. Moreover, Sfakiotakis et al. (2001) and Consi et al. (2001) modelled the kinematics of a dorsal fin of seahorse. Ashley-Ross (2002) studied mechanics of the dorsal fin of *Hippocampus*. Furthermore, Kowalczyk and Delgado (2007) presented numerical studies of undulatory, oscillatory and combined fin-like movement. However, in order to make a further progress towards a better understanding of flow induced by seahorses more detailed fluid mechanical studies are needed. Thus, in the present work fin motion pattern of seahorse is described. The major aim of the present work is to understand the mechanics of fin locomotion. Fluid flow generated by seahorse is analysed by means of Particle Image Velocimetry.

## Materials and methods

Seahorses (*Hippocampus reidi*) are kept in a laboratory scale aquarium (see Figure 1). They are fed daily with mysis shrimps. Fin movement and flow induced by seahorses are analyzed using optical in-situ techniques.

Figure 1 Aquarium with seahorses

## Fin kinematics

The major aim of the present work is to describe the fin kinematics. In order to study the fin motion, images are acquired with a high speed CCD camera (NAC HotShot 1280) during seahorses feeding time. In the present work the dorsal fin is analyzed at different positions: in the front of the fins, angular and on the side. Every experiment is repeated several times. From the recorded images the fin motion patterns, fin frequency and also the diversity of fin activation modes is examined. Based on the experimental results a dorsal fin kinematic model is proposed.

## Particle Tracking Velocimetry

Fin motion is evaluated with use of OPTIMAS (Media Cybernetics, L.P.). Particle Tracking Velocimetry (PTV) is based on comparing two images with known time spacing. The characteristic points (fin ray bases) for which the velocity is to be determined are marked manually on both images. The difference in position of the markers represents the displacement of fin rays, which for the known time interval between images can be recalculated as fin velocity $u_F$. The procedure is repeated for different image sequences. Data obtained from OPTIMAS are further analysed with TECPLOT (Amtec Engineering).

## Particle Image Velocimetry

A frequency-doubled cw Nd:YAG laser with a wave length of 532 nm and a cylindrical lens is used as light source. The plane of the Nd:YAG laser light sheet is arranged perpendicular to the camera optical axis. Images are acquired by a high–speed CCD camera (Mikrotron GmbH) allowing a maximum speed of 520 frames/s. In the present case, the images with size of 1060x1024 pixels are taken with a speed of 25 frames/s. The frames from the CCD camera are transferred and recorded on a PC. Hollow glass spheres with a diameter of 2–20 µm (Dantec Dynamics) and a density of 1.1 g/cm$^3$ are implemented to visualize the flow pattern. The optical system with Nd:YAG laser is shown in Figure 2.

The calculation of the fluid velocity is carried out using software PIVview2C (PIVTEC GmbH) (Raffel et al., 1998). The cross–correlation mode is used to extract particle displacement. PIV investigations are carried out by the multiple–pass interrogation algorithm which increases the data yield due to the higher number of matched particles and reduces the bias error (Westerweel et al. 1997). In the present study, the interrogation window size is chosen as 48x48 pixels and the grid size is 23x23 pixels. Sub–pixel displacement of the correlation peak is obtained by a 3–point Gauss fit. This 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). Subsequently, velocity data from PIVview2C are further processed with TECPLOT (Amtec Engineering).

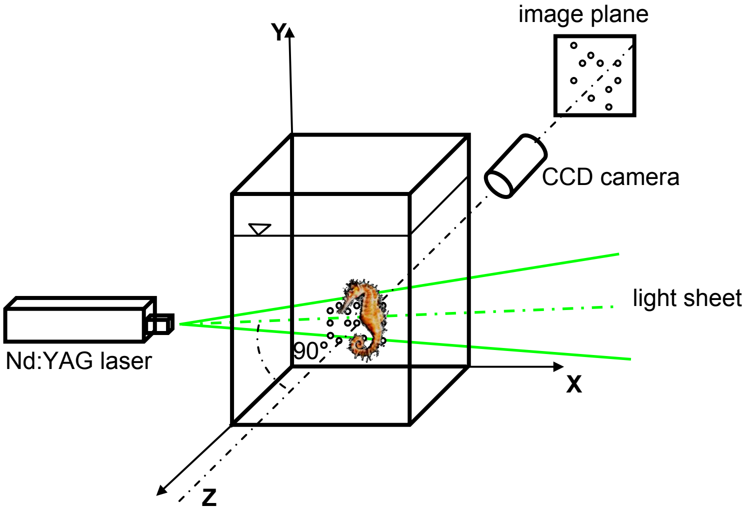

Figure 2 Optical system with Nd:YAG laser

### Results and Discussion

In this section, fin kinematics and flow induced by seahorses are presented. Three different fins (pectoral, dorsal and anal) initiate the motion of seahorses.

### Fin kinematics

A high variety of fin activation patterns is observed. Namely, modulation by differential activation of fins, modulation by changing fin orientation, modulation by changing the direction of fin movement and modulation by changing the spatial pattern are found.
Figure 3 presents different fin activation. Here a 0/1 system is demonstrated, where 0 means that the fins are not active while 1 signifies fin activity. Various fin modulation modes are observed, e.g. in MM1 all analyzed fins are active (dorsal, pectoral left and pectoral right). In the second case MM2, only pectoral right fin is active. However, it was discovered that in every fin modulation at least one of pectoral fin (left or right) is active.

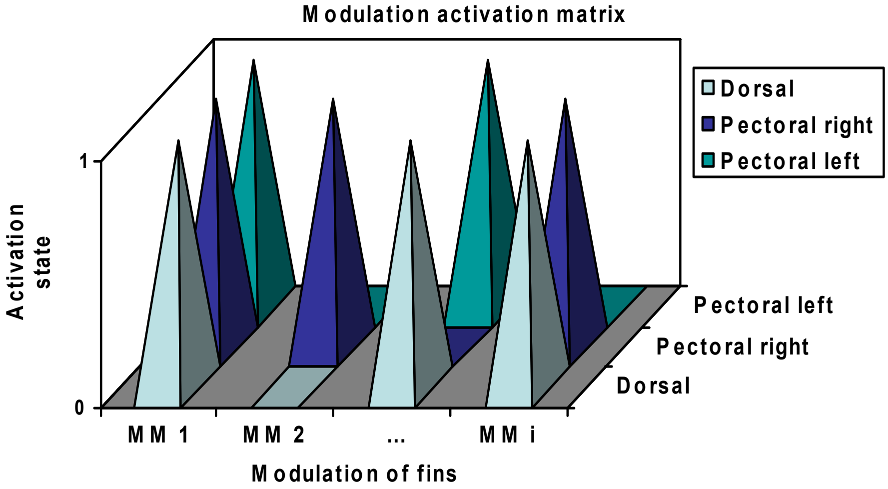

Figure 3 Modulation by differential activation of fins

Analysis of the modulation by changing the fin orientation shows that seahorses have the ability to tilt all fin rays by the same angle (inclination) or even differently (rotation).

Moreover, present studies indicate the possibility of seahorses to change the direction of fin movement. Rostrocaudal and in reverse order orientations are discovered, respectively.
Further modulation including changing spatial pattern is displayed in Figure 4. Various fin frequencies are observed varying between 20 and 60 Hz depending on the seahorse's activity. For seahorses staying in one place the lowest frequency is observed. In contrast the highest frequency is noted for actively moving seahorses. Moreover, for different measurement time as well as for several examples different wavelength and various amplitudes are discovered.

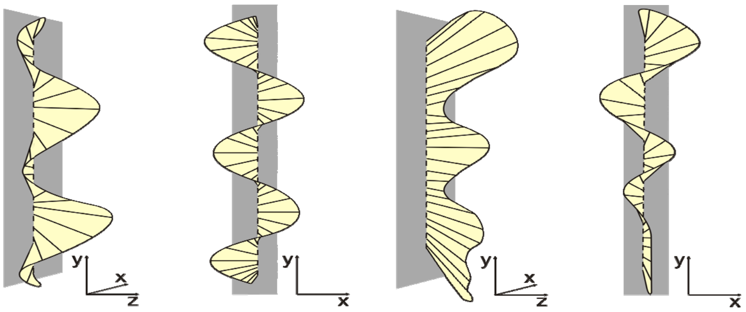

Figure 4 Modulation by changing the spatial pattern

Figure 5 gives a summary of different fin activation patterns. Similar as in Figure 3 0/1 system is used. In this case four different fins modulation modes are presented: differential activation of fins (DAF), changing the spatial pattern (CSP), changing fin orientation (CFI) and changing the direction of fin movement (CDM). Above modulation modes are studied for dorsal, pectoral right and pectoral left fins. For the first modulation mode (DAF) all the analyzed fins are active. In case of CSP, only pectoral right fin is active, whereas different combinations are observed in CFI and CDM modes. However, it can be observed that in every mode at least one of pectoral fin is active.

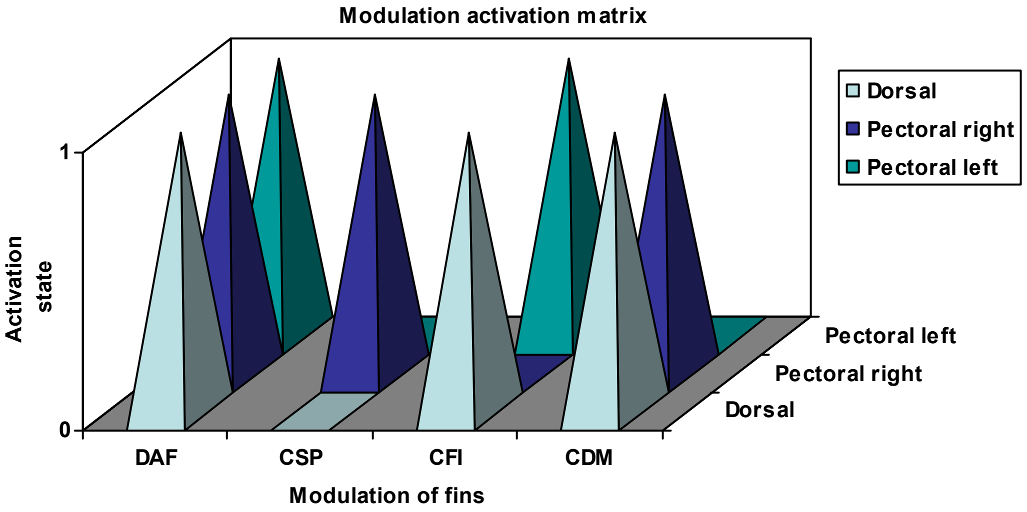

Figure 5 Variability of fin activation patterns

From the experimental data a fin motion model is derived. Dorsal fin kinematics is described using the sinus wave equation (1)

$$y\,(x,t) = A\sin(\omega t - kx), \tag{1}$$

where *A* is the amplitude of the wave, *t* time, *x* the oscillating variable and $k$ the wave number given by formula (2)

$$k = \frac{2\pi}{\lambda}. \tag{2}$$

Here $\lambda$ is the wavelength, $\omega$ the angular frequency described with equation (3)

$$\omega = \frac{2\pi}{\mathrm{T}} \tag{3}$$

and T the period of the wave. For the present study the amplitude is given by the parabolic equation (4)

$$A = -cx^2 + a. \tag{4}$$

Here, *a* is the half width of the dorsal fin and *c* is described by formula (5)

$$c = \frac{a}{b^2}, \tag{5}$$

where *b* is the half length of the dorsal fin.

Taking into account the characteristic dimensions of the fins (length - 2.52 cm, width - 0.54 cm, maximal amplitude - 0.42 cm), dorsal fin kinematics is described by the equation (6)

$$y(x,z,t) = \left(-0.1323x^2 + 0.21\right)\sin\left(352.81t - \left(\frac{6.14}{-0.2317x + 0.8719}\right)x\right)1.852z. \tag{6}$$

It should be pointed out, that the present model is analyzed for a specified frequency $f = 56\ Hz$. The fin pattern reconstructed by the above model (6) with characteristic undulatory form is shown in Figure 6.

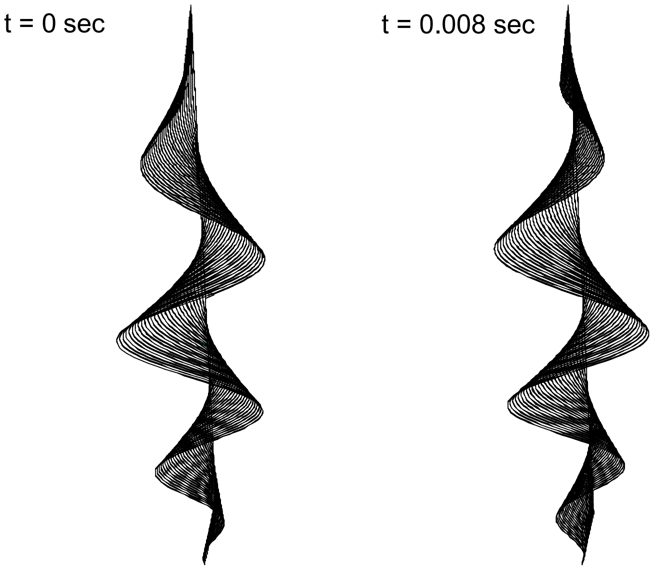
t = 0 sec
t = 0.008 sec

Figure 6 Dorsal fin pattern at different times

## Particle Tracking Velocimetry

PTV studies were carried out for various cases at different times. PTV data prove that the fin velocity changes significantly with time. As shown in Figure 7, the velocity profile at 0.008 s differs from that at 0.016 s. For the first case velocity alters between 0.08 m/s and 0.18 m/s while for the second one it changes between 0.09 and 0.23 m/s. Fin direction is different for both cases.

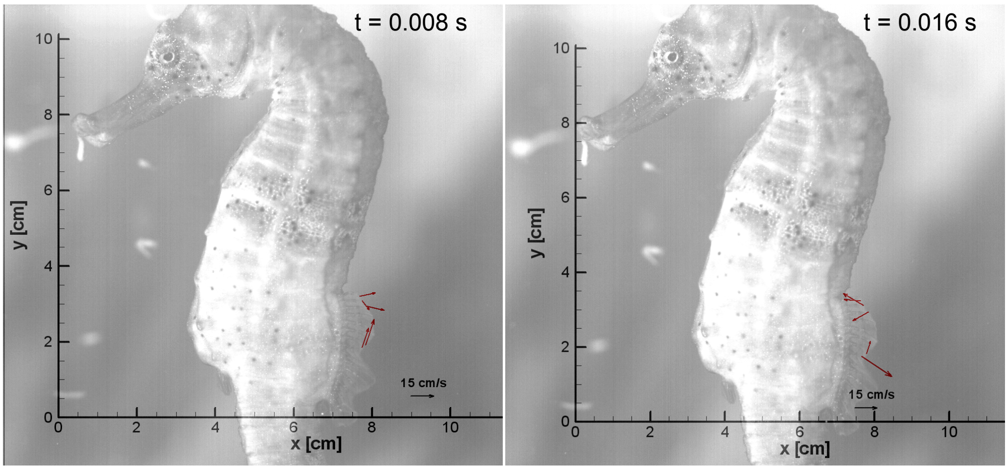

Figure 7 Fin velocity at different times $t_1$=0.008 s, $t_2$=0.016 s

By means of the wall binding equation (7) the pressure force ($F_p$) was computed. The obtained results show that $F_p$ changes between $F_p = 0.007\ N$ and $F_p = 0.046\ N$.

$$
\begin{aligned}
u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} &= -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\eta}{\rho}\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right] \\
u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} &= -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\eta}{\rho}\left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right]
\end{aligned} \qquad (7).
$$

## Particle Image Velocimetry

PIV investigations indicate characteristic flow patterns around moving fins (see Figure 8).

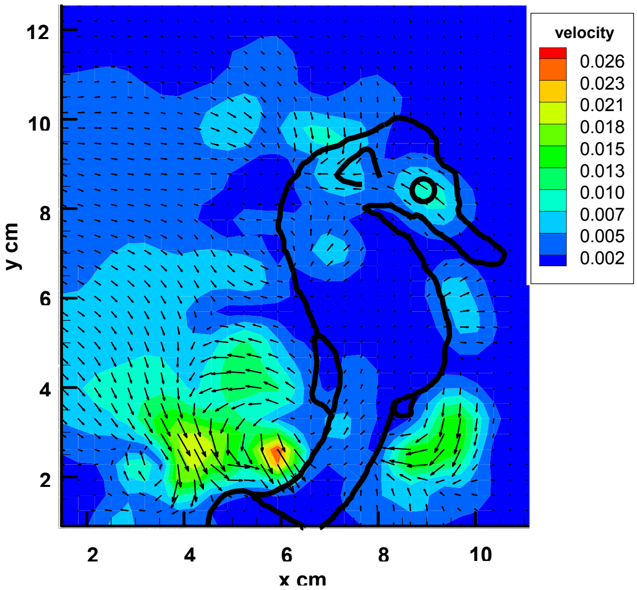

Figure 8 Velocity field around seahorse in m/s

The maximal velocity of $u_{max}$ = 0.026 m/s appears close to the dorsal fin. Lower velocity $u_{max}$ = 0.016 m/s is observed around the anal fin and the lowest one $u_{max}$ = 0.010 m/s near the pectoral fin. Further studies for different times indicate that the flow pattern and the range of velocity distribution are different. However, the tendency is similar as in the previous case. Characteristic undulatory movement of the dorsal fin of the seahorse is observed (see Figure

9). It agrees with the fin kinematics model presented above (equation (6)) and also with the results of the numerical simulation obtained by Kowalczyk and Delgado (2007).

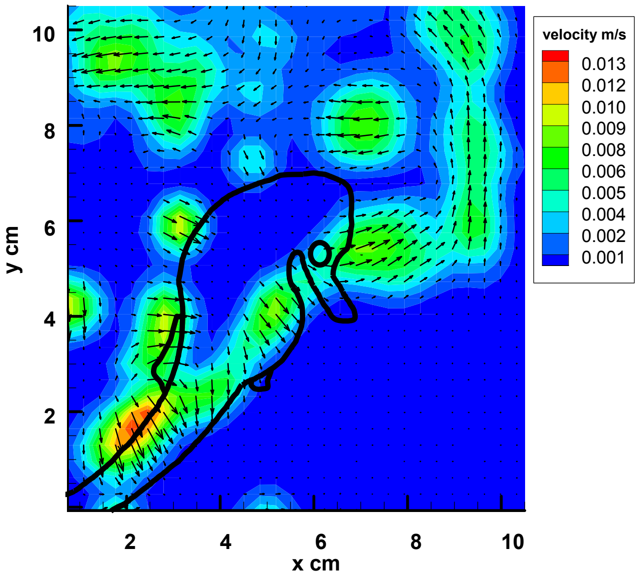

Figure 9 Undulatory fin movement of seahorses

## Summary

In the present work kinematics and hydrodynamics of undulatory fin motion of seahorses are investigated. PIV studies indicate a characteristic undulatory movement of the dorsal fin. It is observed that the fin pattern is modified significantly with time. Fin frequencies vary between 20 and 60 Hz depending on the seahorse's activity. A model equation describing the undulatory motion of the dorsal fin is proposed. The pressure force determined by means of the wall binding equation varies between $F_p = 0.007\ N$ and $F_p = 0.046\ N$.

## Acknowledgement

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## Literature

Arreola V.I., Westneat M.W., 1996: Mechanics of propulsion by multiple fins: kinematics of aquatic locomotion in the burrfish (*Chilomycterus schoepfi*), Proceedings of the Royal Society, London, Vol. B 263, pp. 1689-1696

Ashley-Ross M.A., 2002: Mechanical properties of the dorsal fin muscle of seahorse (*Hipopocampus*) and pipefish (*Syngnathus*), Journal of Experimental Zoology, Vol. 293, pp. 561-577

Blake R.W., 1983: Fish locomotion, Cambridge University Press, Cambridge, UK

Bone Q., 1978: Locomotor muscle. Fish physiology VII. Locomotion, 361-424, Academic Press, New York

Breder C.M., Edgerton H.E., 1942: An analysis of the locomotion of the seahorse, *Hippocampus hudsonius,* by means by of high speed cinematography, Annals of the New York Academy Sciences, Vol. 43, pp. 145-172

Consi T.R., Seifert P.A., Triantafyllou M.S., Edelmannn E.R., 2001: The dorsal fin engine of the seahorse (*Hippocampus sp.*), Journal of Morphology, Vol. 248, pp. 80-97

Daniel T., Jordan C., Grunbaum D., 1992: Hydromechanics of swimming, Advances in Comparative and Environmental Physiology, Vol. 11, pp. 17-49

Gillis G.B., 1996: Undulatory locomotion in elongate aquatic vertebrates: Anguilliform swimming since Sir. James Gray, American Zoologist, Vol. 36, pp. 656-665

Graham J.B., Dickson K.A., 2004: Tuna comparative physiology, Journal of Experimental Biology, Vol. 207, pp. 4015-4024

Hertel H., 1996: Structure, Form and Movement. Reinhold, New York, NY

Kowalczyk W., Delgado A. (2007) Simulation of fluid flow in a channel induced by three types of fin-like motion, Journal of Bionic Engineering, Vol. 4, 165-176

Kuiter R.H., 2001: Seepferdchen, Seenadeln, Fetzenfische und ihre Verwandten Syngnathiformes, Verlag Eugen Ulmer GmbH&Co, Stuttgart

Lauder G.V., Tytell E. D., 2005: Hydrodynamics of undulatory propulsion, Fish biomechanics, Vol. 23, pp. 425-468

Lighthilll M.J., Blake R.W., 1990: Biofluiddynamics of basilistiform and gymnotiform locomotion. Part.1, Biological background and analysis by elongated-body theory, Journal of Fluid Mechanics, Vol. 212, 183-207

Lindsey C.C., 1978: Form, function and locomotory habits in fish. Fish physiology VII, 1-88, Academic Press, New York

Lourie S.A., Foster S.J., Cooper E.W.T., Vincent A.C.J.A., 2004: Guide to the identification of seahorses, Project seahorse and traffic North America. Washington D.C.: University of British Columbia and World Wildlife Found

Petermeier H., Kowalczyk W., Delgado A., Denz C., Holtmann F., 2007: Detection of microorganismic flows by linear and nonlinear optical methods and automatic correction of erroneous images artefacts and moving boundaries in image generating methods by a neuronumerical hybrid implementing the Taylor’s hypothesis as a priori knowledge, Experiments in Fluids, Vol. 42, pp. 611-623

Raffel M., Willert Ch. E., Kompenhans J., 1998: Particle Image Velocimetry. A Practical Guide, Springer - Verlag, Berlin Heidelberg

Sfakiotakis M., Lande D.M., Davies B.C., 2001: An experimental undulating-fin device using the paralell bellows actuator. Proceeding of the IEEE International Conference on Robotics and Automation, Seul, Korea, Vol. 3, pp. 2356-2362

Webb P.W., 1975: Hydrodynamics and energetic of fish propulsion. Bulletin Fisheries Research Board of Canada, Vol. 190, pp. 1-159

Webb P.W., Blake R.W., 1985: Swimming. Functional Vertebrate Morphology 110-128, Harvard University Press, Cambridge, MA

Webb P. W., Weihs D., 1983: Fish Biomechanics, Praeger Publisher, New York

Westerweel J., Dabiri D., Gharib M., 1997: The effect of a discrete window offset on the accuracy of cross-correlation analysis of digital particle image velocimetry. Experiments in Fluids, Vol. 23, pp. 20-28

Willert, C., Gharib, M., 1991: Digital Particle Image Velocimetry. Experiments in Fluids, Vol. 10, pp. 181-193