14th Australasian Fluid Mechanics Conference
Adelaide University, Adelaide, Australia
10-14 December 2001

Stationary and Oscillating Cylinders in the Presence of a Free-Surface

J. Carberry[1], J. Sheridan[1] and D. Rockwell[2]

[1]Department of Mechanical Engineering
Monash University, Clayton, Victoria, 3800 AUSTRALIA

[2]Department of Mechanical Engineering and Mechanics
Lehigh University, Bethlehem, PA, 18015, USA

Abstract

The effect of a free-surface, on both stationary and oscillating cylinders has been studied by simultaneously measuring the structure of the near wake and the forces on the cylinder. As the stationary cylinder approached the free-surface three different wake modes were observed: closer to the surface periodic vortex shedding did not occur and the two wake modes differed significantly from the fully submerged Kármán wake, while for the third mode at deeper submergence depths the response of the wake to the Kármán instability appeared to be amplified. For both the stationary and oscillating cylinders the presence of the free-surface caused the wake to become non-symmetric and there was a net negative lift force on the cylinder.

Introduction

Unbounded flow past a stationary cylinder results in periodic shedding of vortex structures from the cylinder and the formation of the characteristic Karman street. However, when the flow is bounded by a surface the structure of the wake and the forces on the cylinder can be significantly altered. Bearman & Zdravkovich [1] found that as a cylinder approached a solid surface there was a change in the pressure distribution around the cylinder: the front stagnation point rotated towards the surface and there were corresponding changes in the separation points. The non-symmetric pressure distribution resulted in a net force acting to push the cylinder away from the solid surface. At larger gaps between the surface and the cylinder there was periodic vortex shedding, despite a slightly non-symmetric pressure distribution, while at smaller gaps periodic shedding was suppressed. Price *et al* [8] showed that as the gap varied the flow could be characterised into distinct regions depending primarily on the suppression or nature of vortex shedding. They also found that the close proximity of the cylinder caused separation of the solid surface boundary layer, where the location of separation, and the extent of the boundary vorticity, varied with the gap between the cylinder and the solid surface.

The case of a cylinder underneath a free-surface is similar to the solid surface case. As for the solid surface, a rotation of the stagnation and separation points, a non-symmetric pressure distribution and a net negative lift force are observed as the cylinder approaches the free-surface, [7]. In contrast to a solid surface, vorticity is not generated along a flat free-surface, however the low pressure regions generated by flow over the body can cause surface deformation and the generation of free-surface vorticity. The level of surface deformation varies with the Froude number Fr, where $Fr = U/(g\,D)^{1/2}$. Thus, as shown by Sheridan *et al* [11], the structure of the wake varies not only with the depth of the cylinder below the surface, h/D but also with the Froude number. The structure of the cylinder's wake underneath a free-surface has a number of characteristic features. Flow visualisation of polystyrene beads and numerical simulation by Miyata *et al* [7] indicated that the lower shear layer has a distinct downwards angle, while quantitative PIV measurements by Sheridan *et al* [11] and subsequent flow visualisation [6], identified two distinctly different wake states which occurred when the cylinder was close to the free-surface. A feature of the wake states identified by Sheridan *et al* [11] for $0.22 \le Fr \le 0.97$ was the significant surface deformation at higher Fr. Interestingly, the wake states depended on both Fr and h/D. However, neither the Froude number based on the cylinder's diameter, or an alternative Froude number based on the cylinder's depth, allowed the identification of a critical value at which the wake transitioned between the two states.

Whilst separate studies have shown that the presence of a free-surface can cause changes in the wake structure or changes in the forces on the cylinder, a systematic link between changes in the wake and the forces on the cylinder is yet to be established. In this paper the link between the changes in the structure of the wake and the forces on the cylinder as the cylinder approaches the free-surface is investigated using simultaneous force and velocity field measurements. The experiments were undertaken at a relative low Fr, where the free-surface tends to remain flat. In many respects a free-surface at low Fr is the simplest boundary condition, as for all but the smallest values of h/D, there is no generation of vorticity at the free-surface.

Carberry *et al* [3] have shown that a fully submerged cylinder that is forced to oscillate transverse to the free-stream exhibits at least two different wake states depending primarily on f_e/f_o, where f_e is the frequency of oscillation and f_o is the Kármán frequency of the stationary wake. As f_e/f_o passes through unity a characteristic jump in the phase and amplitude of the lift force is observed over a wide range of Reynolds numbers and oscillation amplitudes, [2, 12, 10, 3, 4]. Carberry *et al* [3] showed that the jump in the lift force corresponds to a change in the mode and phase of vortex shedding, and the two distinctly different wake states for f_e/f_o below and above the jump were defined as the low- and high-frequency states respectively. The low-frequency wake state is characterised by the formation of long attached shear layers resulting in the 2P mode of vortex shedding and the lift force on the cylinder is approximately out-of-phase with the cylinder's oscillation. In the high-frequency state the wake is much narrower and the resulting 2S mode of vortex shedding is similar to the Kármán wake of a stationary cylinder. As the wake transitions from the low- to high-frequency state there is a phase shift of approximately π and the lift force of the high-frequency state is approximately in-phase with the motion of the cylinder.

The case of transverse cylinder oscillations underneath a free-surface is interesting as the depth of the cylinder varies during the oscillation. It is not known how the presence of the free-surface alters the wake states of an oscillating cylinder, or if the apparently robust jump in the phase and amplitude of the lift force that is observed over a wide range of flow parameters for the fully submerged cylinder also occurs for the free-surface case.

Experimental Method

The experiments were performed in a free-surface water channel at Lehigh University. The cylinder, 25.4 mm in diameter and with an aspect ratio of 12.5, was mounted horizontally underneath the free-surface and fitted with end plates to promote parallel shedding. The free stream velocity U was constant at 0.083 mm/s giving a Reynolds number Re = 2100 and a Froude number, $Fr = U/(g\,D)$ of 0.166. Two different scenarios, a

stationary cylinder and a cylinder oscillating transverse to the flow, were examined. In both cases h, the depth of the cylinder was measured from the undisturbed free-surface to the top of the cylinder, where for the oscillating cylinder this measurement was taken from the top of the cylinder's motion. For the stationary cylinder a range of cylinder depths were considered, $0.079<h/D<3.0$, where D is the diameter of the cylinder, while for the oscillating cylinder $h/D = 3/16$.

The motion of the oscillating cylinder was given by:

$$y(t) = A \sin(2\pi f_e t) \quad (1)$$

where A, the amplitude of oscillation was equal to $A/D = 0.5$, and the frequency of oscillation was varied between $0.76 \le f_e/f_o \le 1.05$. In all cases the wake was locked-on to the sinusoidal oscillation of the cylinder and the non-dimensionalised lift force can be represented by:

$$C_L(t) \approx C_L \sin(2\pi f_e t + \phi_{lift}) \quad (2)$$

where C_L is the amplitude of the lift force and ϕ_{lift} is its phase with respect to the motion of the cylinder. The results for a cylinder oscillating at $h/D = 3/16$, were compared with the results for a fully submerged cylinder. The time varying lift force on the cylinder was measured by strain gauges mounted on a support sting. For the oscillating cylinder the inertia force due to the vertical acceleration of the cylinder's mass was subtracted from the lift force. The near wake velocity field was measured using a laser scanning version of high-image density PIV [9]. The images were recorded on high resolution 35 mm film and digitised at 106 pix/mm resulting in velocity fields with approximately 3500 vectors. The mean vorticity fields were calculated from 2-4 complete oscillation cycles, where each cycle contained 8 images.

Results and Discussion

Stationary Cylinder

The mean lift force, $C_{L\,mean}$ on a fully submerged cylinder is zero, however as the cylinder approaches either a solid or free-surface the cylinder experiences a net lift force away from the surface. In these experiments, at Fr = 0.166, $C_{L\,mean}$ became significantly negative as the cylinder's depth becomes less than $h/D = 3.0$, Figure 2. For $h/D \ge 3.0$ the lift forces on the cylinder do not vary significantly as h/D is increased further and the cylinder is effectively fully submerged. At $h/D = 3.0$ $C_{L\,mean}$ is not exactly equal to zero which was attributed mainly to experimental drift of the strain gauges. Within the region where the cylinder's wake is affected by the free-surface, or the free-surface region, three distinctly different wake states were observed. The wake modes and lift forces corresponding to these states are described in the following sections. It is expected that the extent of the free-surface region and the bounds of a given wake state will vary with Fr, however the nature of this variation is not known.

Mode I Wake: $0.5<h/D\le3.0$: Figure 1a

The first wake state as the cylinder moves from being fully submerged into the free-surface region occurs for cylinder depths of $0.7\le h/D\le3.0$. Many of the features of this wake state are similar to the fully submerged Kármán wake and the wake is effectively a modified Kármán wake. Vorticity of alternating sign is shed periodically from the cylinder, Figure 1a and the modified Kármán wake is termed a Mode I wake. The wake of the fully submerged cylinder at Re = 2100 has a very long formation length and in general, the vortex shedding is less organised than for Re well above or below 2100. The corresponding lift force on the cylinder has relatively small amplitude fluctuations, which are subject to "die out" intermittently as the vortex shedding becomes disorganised. As h/D is reduced below 3.0 the vortex shedding becomes more organised. Figure 2 shows that the lift force is larger in amplitude and, as shown in the force insert of Figure 1a, the lift is strongly periodic resulting in a sharp well defined Strouhal peak. Closer examination of the instantaneous vorticity fields and lift traces indicated that an increase in the amplitude of the lift force corresponds to a systematic decrease in the wake's formation length as h/D decreases from 3.0 towards 0.7. This relationship was also observed for instantaneous wakes and lift forces as the wake varied during an experiment at a constant value of h/D.

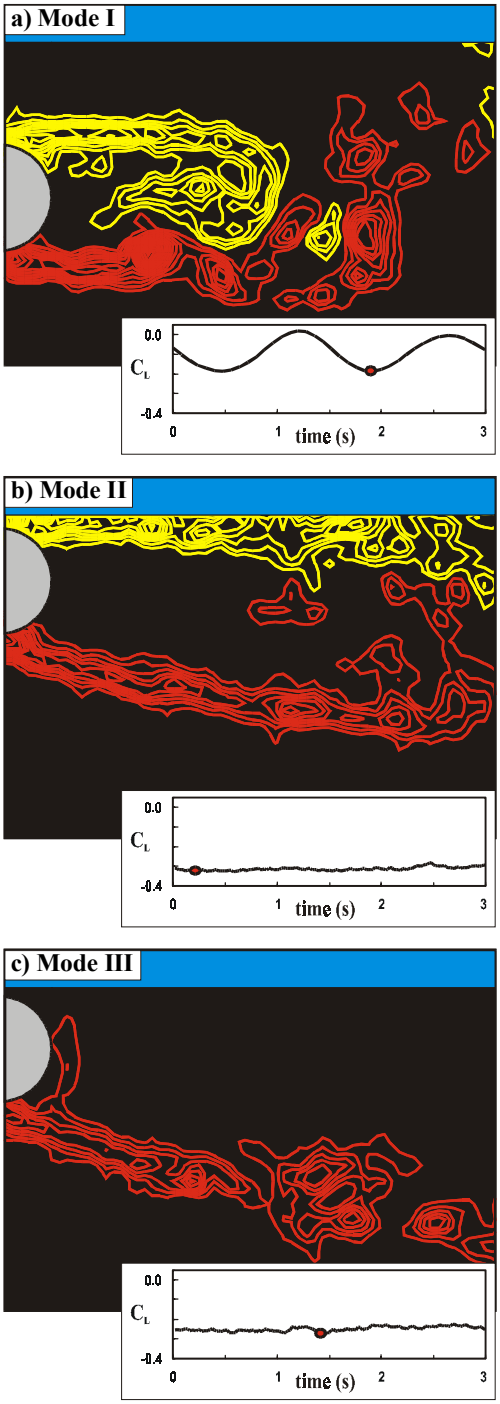

Figure 1 Instantaneous vorticity fields showing the variation of wake mode with cylinder depth: a) Mode I, h/D = 1.0, b) Mode II, h/D = 0.125, c) Mode II, h/D = 0.079. The lift traces corresponding to the images are shown in the force inserts , where the small circle indicates the time at which the image was acquired.

Although the mode I wake in Figure 1a appears relatively symmetric, the net negative lift force on the cylinder, shown in Figure 2 indicates that there is an asymmetry in the generation and distribution of vorticity. Interestingly the non-symmetry in the mode I wake appears to enhance the Karman instability, with

more organised vortex shedding occurring closer to the cylinder and an increase in the fluctuating forces on the cylinder.

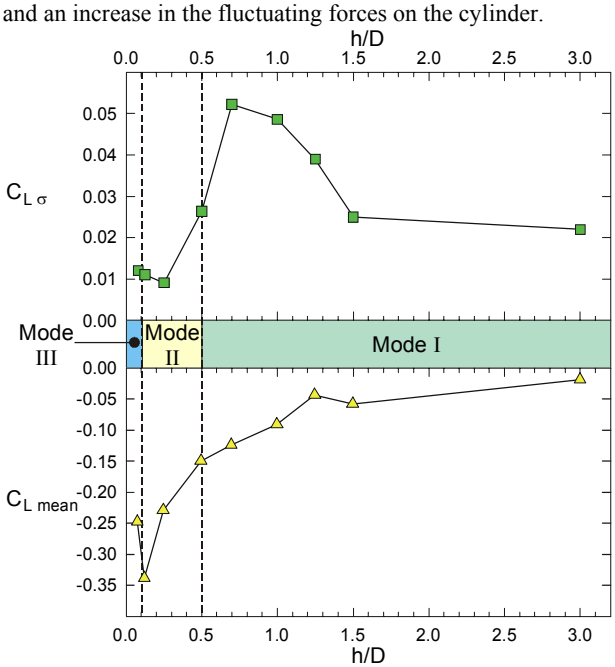

Figure 2 Variation of the mean and standard deviation of the lift force coefficient with cylinder depth, h/D. The standard deviation of the lift force $C_{L\,\sigma}$ is used to represent the amplitude of the lift force, as for h/D < 0.5 the lift force is neither sinusoidal nor periodic.

Mode II Wake: 0.125≤h/D≤0.5: Figure 1b

As h/D decreases past 0.7 $C_{L\,mean}$ continues to decrease, however, as shown in Figure 1b there is a dramatic change in the wake mode, and a sharp drop in the amplitude of the lift force. The mode II wake is characterised by long shear layers with no distinct periodic shedding events. As shown by the force insert in Figure 1b the lift trace is no-longer periodic and there are no strong peaks in the corresponding lift spectra. Examination of the lift traces indicates that the major contributions to the standard deviation of the lift force, $C_{L\,\sigma}$ are associated with fluctuations in $C_{L\,mean}$. At h/D = 0.5 the wake appears to be switching between mode I and mode II as there are times when the lift trace is strongly periodic and other times when the fluctuating component of the lift is very small.

In Figure 1b the attached shear layers are significantly longer than for either the Mode I or fully submerged cylinder wakes, the upper negative shear layer is parallel to the free-surface while the positive shear layer has a distinct downwards angle. The high velocity fluid in the upper shear layer separates from the cylinder but remains attached to the free-surface. The mode II wake is similar to the wake state observed by Sheridan *et al* [11] for 0.22≤Fr≤0.60, where a jet of high speed fluid separates from the upper surface of the cylinder and remains attached to the free-surface. Unlike the wakes observed for Fr ≥ 0.35, the mode II wake at Fr = 0.166 does not result in free-surface waves or the generation of free-surface vorticity, and is similar to the wake observed by Sheridan *et al* [11] at Fr = 0.22. At Fr = 0.166 the values of h/D over which this wake is observed are much smaller and the positive shear layer forms a greater angle at separation.

Mode III Wake: h/D < 0.125: Figure 1c

At very small cylinder depths a third wake state is observed. In the mode III wake separation of the upper shear layer from the cylinder is delayed and the thin jet of fluid above the cylinder separates from the free-surface. The generation of net positive vorticity is particularly obvious for the mode III wake in Figure 1c, and $C_{L\,mean}$ is large and negative. The reason for the small increase in $C_{L\,mean}$ at h/D = 0.079 is not known. As for the mode II wake, the lack of organised vortex shedding from the mode III wake results in small non-periodic fluctuations of the lift force, and the lower shear layer has a characteristic downwards angle. The angle of the lower shear layer for both the mode II and III wakes appears to increase with decreasing h/D. Thus the major factor which differentiates between the mode II and mode III wakes is whether the fluid above the cylinder remains attached to, or separates from, the free-surface.

The jet in the mode III wake was so thin that it was not fully resolved by PIV measurements, but it was clearly visible in flow visualisation. For the majority of the time the thin jet of fluid remained attached to the cylinder and there was a systematic upstream movement of the low speed fluid directly behind the cylinder. The migration of fluid upstream caused the attached jet to become unstable and separate from the cylinder. The free jet persisted for short periods of time and tended to "flap" at angles of between 45 and 60 degrees to the free-surface. The two positions of the jet are similar to those shown in Figure 4 of Sheridan *et* al [11]. The short periods of time during which the jet separated from the cylinder appeared to be linked to a general downstream movement of the low speed flow behind the cylinder.

The separation of the fluid above the cylinder from the free-surface is indicative of the generation of positive free-surface vorticity, and therefore of free-surface deformation. However, significant deformation of the free-surface was not detected. The free-jet wake mode observed by Sheridan *et al* [11] at higher Fr occurred at larger h/D values. In this case the high velocity fluid formed a strong, apparently stable free jet and there was a clear depression of the free-surface behind the cylinder. At their very smallest h/D values they found that their jet remained attached to the cylinder and appeared very similar to Figure 1c.

Oscillating Cylinder

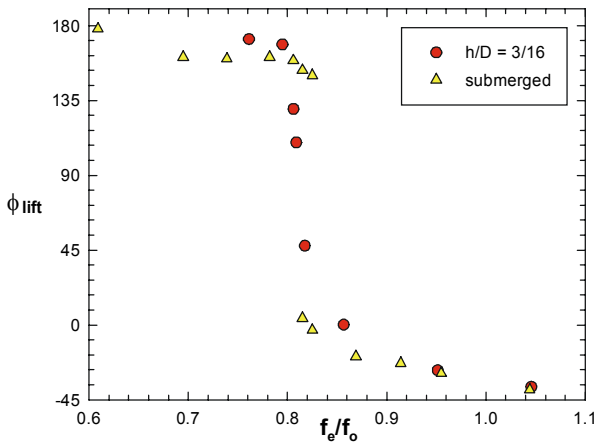

Figure 3 Variation of ϕ_{lift} with f_e/f_o at A/D = 0.5 for a cylinder oscillating below a free-surface, h/D = 3/16 and a fully submerged cylinder.

The low- and high-frequency wake states of a fully submerged cylinder occur over a wide range of Re and A/D, and the transition between the two states corresponds to a jump in the phase and amplitude of the lift force. As the depth at which the cylinder oscillates is reduced to h/D = 3/16 the characteristic jump in the lift force still occurs around, or just before, $f_e/f_o \approx 1$. As shown in Figure 3 the variation of ϕ_{lift} with f_e/f_o is very similar for both the fully submerged and free-surface cases. At h/D = 3/16 ϕ_{lift} has a number of intermediate values during the jump, indicating that the nature of the transition between the low- and high-frequency states is altered by the free-surface. For all values of f_e/f_o at h/D = 3/16 $C_{L\,mean}$ was negative, indicating that the wake is non-symmetric. Therefore although the variation of the ϕ_{lift} with f_e/f_o indicates that the wake can be described in terms of the low- and high-frequency states, as we shall demonstrate, the presence of the free-surface does alter the structure of the near wake.

For a fully submerged cylinder both the Kármán wake of the stationary cylinder and the low- and high-frequency states of the oscillating cylinder are symmetric about the horizontal axis. However, as seen in Figure 1, close to the free-surface the wake of a stationary cylinder becomes strongly non-symmetric. In Figure 4(a & b) the mean vorticity fields for two different cylinder positions are shown. The prominent central image of the cylinder is at the mid-point of the oscillation, while background images at the top and bottom of the oscillation demonstrate the extent of the cylinder's motion. The mean vorticity field of a fully submerged oscillating cylinder is shown in Figure 4a for a wake that is in the high-frequency state, where vortices are shed in the Kármán or 2S mode. The structure of the fully submerged mean vorticity field is similar to the mean field for 2S shedding from a submerged elastically mounted cylinder, [5]. In both cases the mode of vortex shedding is similar to the Kármán shedding from a stationary cylinder, although the cylinder's oscillation causes a significant decrease in the length of the recirculation region.

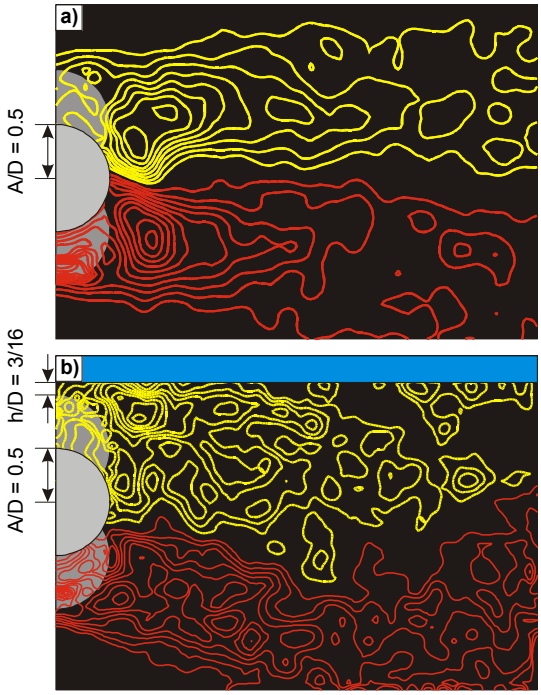

Figure 4 Mean vorticity fields for an oscillating cylinder which is a) fully submerged and b) where the depth of the cylinder at the top of the oscillation is h/D = 3/16. In both cases the amplitude of oscillation is A/D = 0.5 and the wake is in the high-frequency state where f_e/f_o = 0.815 and 0.951 in a) and b) respectively.

When the depth of the oscillating cylinder is reduced to h/D = 3/16 the high-frequency wake mode is still 2S, however the distribution of vorticity during the shedding cycle appears to be non-symmetric and the vortex structures are generally less organised. The mean vorticity field in Figure 4b shows that on average the lower shear layer has a distinct downwards angle and the wake is clearly non-symmetric, with a corresponding net lift of $C_{L\,mean}$ = -0.29. The mean vorticity field of the oscillating cylinder in Figure 4b has similar non-symmetric characteristics to the instantaneous vorticity fields of the mode II and III wakes shown in Figure 1(b & c). In Figure 4b the averaging of the vorticity removes the periodicity of the wake, allowing examination of the mean effect of the free-surface, while for the mode II and III wakes in Figure 1(b & c) the general structure of the wake is essentially non-periodic. Interestingly, despite the physical differences between a stationary and oscillating cylinder, in both cases the lower shear layer has a characteristic downwards angle and $C_{L\,mean}$ is negative.

Conclusions

As the depth of a stationary cylinder below a free-surface is decreased three different wake states are observed. The modification of the Kármán wake by the free-surface in the mode I wake state results in a shorter formation length and an increase in the $C_{L\,\sigma}$. The mode II wake, with high velocity fluid moving underneath the free-surface, and the mode III wake with a thin jet of fluid separating from the free-surface are similar to the wakes observed by Sheridan *et al* [11] at higher Fr. However, at lower Fr the free-surface appears flat and significant levels of positive free-surface vorticity are not detected. Periodic vortex shedding does not occur for the mode II and mode III wakes and $C_{L\,\sigma}$ is very small. For both the stationary and oscillating cylinders, the presence of the free-surface causes a non-symmetry of the wake, the lower shear layer has a characteristic downwards angle and $C_{L\,mean}$ is negative. However, as the frequency of the oscillating cylinder passed though unity the characteristic jump in the phase and amplitude of the lift force was observed for both the fully submerged and free-surface cases.

Acknowledgments

Primary support for this research program was provided by the Office of Naval Research Grant N00014-94-1-0815, P0006, monitored by Dr. Thomas Swean, and by the Australian Research Council through the ARC Large Grant A89702238. In addition, supplemental support was provided by NSF Grant CTS-9803734. Ms. Carberry acknowledges support through an Australian Postgraduate Award.

References

[1] Bearman, P. W. & Zdravkovich, M. M., 1978, "Flow around a circular cylinder near a plane boundary", *J. Fluid Mech.*, **89**, 33-47.

[2] Bishop, R. E. D. & Hassan, A. Y., 1963, "The Lift and Drag Forces on a Circular Cylinder in a Flowing Fluid", *Proceedings of Royal Society, London, Series A*, vol. **277**, 32 – 50.

[3] Carberry, J., Sheridan, J. & Rockwell, D. 2001a, "Forces and wake modes of an oscillating cylinder", *Journal of Fluids and Structures*, **15**, 523-532

[4] Carberry, J., Sheridan, J. & Rockwell, D. 2001b, "A comparison of forced and freely oscillating cylinder", *Proceedings of he 14th Australasian Fluid Mechanics Conference, Adelaide, Australia, December 2001*

[5] Govardhan, R. & Williamson, C. H. K., 2001, "Mean and fluctuating velocity fields in the wake of a freely-vibrating cylinder", *Journal of Fluids and Structures*, **15**, 489-501

[6] Hoyt, J. W. & Sellin, H. H. J., 2000, "A comparison of tracer and PIV results in visualizing water flow around a cylinder close to the free surface", *Experiments in Fluids* **28**, 261-265

[7] Miyata, H., Shikazono, N. & Kanai, M., 1990, "Forces on a circular cylinder advancing steadily beneath the free-surface", *Ocean Engng,* **17** (1/2), 81-104.

[8] Price, S. J., Smith, J. G., Leong, K. & Paidoussis, M. P., 2000, "Flow visualization around a circular cylinder near to a plane wall", *Proceedings of the 7th International Conference on Flow Induced Vibration, Lucerne, Switzerland 2000,* Ed. Ziada & Staubli, Balkema, Rotterdam, 105-112.

[9] Rockwell, D., Magness, C., Towfighti, J., Akin, O. & Corcoran, T., 1993 "High image-density particle image velocimetry using laser scanning techniques", *Experiments in Fluids* **14**, 181-192

[10] Sarpkaya, T., 1995, "Hydrodynamic Damping, Flow-Induced Oscillations, and Biharmonic Response", *ASME Journal of Offshore Mechanics and Artic Engineering*, Vol. **177**, 232-238

[11] Sheridan, J., Lin, J.-C. & Rockwell, D., 1997, "Flow past a cylinder close to a free surface", *J. Fluid Mech.*, **330**, 1-30.

[12] Staubli, T. 1983b, Untersuchung der oszillierenden Krafte am querangestromten, schwingenden Kreiszylinder. Dissertation ETH 7322.