Free surface effects and the utility of a skim plate for experiments in a water towing tank at steady and unsteady model velocity

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Abstract
A towing tank is utilized to investigate the flow field around a two-dimensional submerged foil model operating near the free surface. Free surface effects are analyzed for steady and unsteady model velocity. The model’s submergence depth and angle of attack are varied. Tests are conducted for the model facing upside-up and upside-down. The surface deflection is recorded and the experimental results are utilized to validate an analytic model that is deployed to predict wake wave patterns at arbitrary model velocity. The flow mechanism leading to load alterations when the foil is in the vicinity of the free surface is explored in detail using experimental and analytic results. The imposed wave-induced velocity perturbations alter the effective angle of attack experienced by the foil. Flow separation is delayed when the model is facing upside-up and promoted when facing upside-down. For test cases with unsteady sinusoidal model velocity, forward traveling waves are generated, leading to a time-varying change in the inflow condition of the submerged foil. Increasing the model’s submergence depth alleviates free surface effects. A skim plate is installed in-between the free surface and model. It shows similar wave alleviating effects as obtained when increasing the model submergence depth by locally blocking wave-induced velocities. The skim plate position is varied in the longitudinal direction to determine its most advantageous position. Surface wave effects at unsteady model velocity are alleviated most effectively when the skim plate protrudes upstream of the model.

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1 Introduction

Towing tanks are a well-established mean for the experimental investigation of watercraft and their components (e.g., ships, submarines, or hydrofoils). In addition, it is a viable alternative to study the aerodynamic characteristics of land- and airborne bodies such as cars, trains, and airfoils (Schmidt et al. 2017; Tshepe et al. 2019; Kirk and Jones 2019). A towing tank may be the preferred choice over a wind tunnel if high Reynolds numbers or realistic boundary
conditions (i.e., quiescent fluid and moving body) need to be obtained. Furthermore, unsteady experiments are conducted with more ease due to the increased time scales in water compared to air. Especially in recent years, there is a notable increase in experimental studies concerning surging airfoils (time-dependent variation in freestream velocity) (Smith and Jones 2020; Zhu et al. 2020; Müller-Vahl et al. 2020; Kirk and Jones 2019; Medina et al. 2018). Many of these studies are carried out in a towing tank or water tunnel due to the relative simplicity of generating the desired motion profile while achieving high non-dimensional parameters such as Reynolds number Re, reduced frequency $k$, and relative velocity amplitude $\alpha$. However, several challenges need to be overcome to obtain high-quality and unbiased experimental data (Jentzsch et al. 2021). Among these challenges, free surface effects may affect the hydrodynamic characteristic of the towed object near the free surface such that the desired transferability to aerodynamic forces is in question. Some researchers report utilizing a skin plate placed atop or just below the free surface to alleviate free surface effects in a towing tank (Stevens et al. 2016; Corkery et al. 2018). For a vertically mounted wing, this plate also acts as a symmetry plane and thus doubling the effective aspect ratio AR. Studies discussing the effectiveness of such devices are absent. Furthermore, any guidelines regarding the proper sizing and installation of a skin plate have not been reported either. Overall, the available literature is very limited.

When an airfoil is tested in water rather than in air, it essentially becomes a hydrofoil. The basic shape of both foils is similar but they do differ in geometric details such as camber or thickness depending on the desired characteristic and application. Hydrofoils are utilized to lift the boat out of the water in order to reduce the hull drag leading to an increase in speed and fuel efficiency. Therefore, hydrofoils usually operate near the free surface. The steady lift coefficient $C_L$ shows a dependence on the submergence depth ratio $h/c$ and submergence depth Froude number $Fn_h = u/\sqrt{gh}$ where $h$ stands for submergence depth, $c$ for the chord length, and $u$ for the velocity of the hydrofoil (see Fig. 1). Generally, the lift coefficient $C_L$ is reduced due to the presence of the free surface and shows the largest deviations in between $1 < Fn_h < 5$ (Hough and Moran 1969). At low Froude numbers $Fn_h < 0.4$ the lift coefficient $C_L$ can reach values higher than the lift coefficient $C_L$ obtained in an unbounded fluid, where surface effects are absent. In such a case, the free surface acts as a rigid wall, and the foil experiences similar effects as a wing in ground proximity. Based on Airy’s linear wave theory, it can be shown that foil-generated surface waves become prominent for $Fn_h > 0.4$ (Faltinsen 2006). Above this threshold value, the submergence depth of the foil is less than $\lambda = 2\pi u^2/g$, which corresponds to the wavelength of the transversal waves in the wake. The orbital particle motion caused by the waves alters the effective velocity and angle of attack experienced by the foil section (van Walree 1999). Alterations of the effective angle of attack due to incident sea waves are reported in Faltinsen (2006) and Filippas et al. (2020). Wilson (1983) shows that the zero-lift angle $\alpha_0$ is affected considerably for low submergence depth ratios $h/c$ and low chord-based Froude numbers $Fn_c = u/\sqrt{gc}$ on a thin symmetrical hydrofoil of aspect ratio $AR = 6$. At a Froude number of $Fn_c \approx 1.2$, the zero-lift angle $\alpha_0$ is shifted by $\Delta \alpha_0 \approx 2.4^\circ$ at $h/c = 0.25$ and $\Delta \alpha_0 \approx 0.5^\circ$ at $h/c = 1$ due to the asymmetry below and above the foil. The change in zero-lift angle is negligible for $Fn_c > 3$ according to this study. Based on the experimental and numeric studies carried out by Hough and Moran (1969) and van Walree (1999), free surface effects on a hydrofoil are insignificant as long as $h/c > 5$ because the Froude number of a hydrofoil usually operates at is $Fn_h > 3$. A hydraulic jump may occur at low submergence depth Froude number $Fn_h$ and low submergence depth ratio $h/c$. In such event, the pressure distribution around the hydrofoil is affected considerably and the minimum pressure coefficient $C_p$ may even be observed at the trailing rather than the leading edge (Parkin et al. 1956). While all these studies analyze the interaction between the submerged foil and self-induced free surface effects, the waves generated by a test rig that is required to mount the model have to be taken into account as well. The surface wave deflection may be altered significantly depending on the test rig design.

Although wake waves have been extensively studied for various objects with a constant velocity, the reporting is limited for unsteady model velocities. The practical relevance is limited to ships de- or accelerating or performing a turning maneuver. However, knowledge about the wave system at unsteady model velocity is particularly crucial for
towing tank tests such as when investigating surging models. Especially at sinusoidal motion profiles, a complex wave system forms that changes in space and time. Due to the cyclic variation in velocity, waves are generated that pass the model when the instantaneous model velocity is low, and thus potentially affecting the flow over the submerged model. The resulting wake system depends on the parameters of the prescribed motion profile (i.e., mean velocity $U_0$, frequency $f$, and relative velocity amplitude $\sigma$).

Towing tanks represent a viable alternative to wind tunnels to investigate the aerodynamic behavior of submerged models. However, asymmetric boundary conditions due to the deflection of the free surface may alter the forces acting on the submerged model. Waves introduce a fluid particle motion that change the effective angle of attack and pressure. Wake waves at unsteady (sinusoidal) model velocity have not been investigated in the past. This paper discusses the effect of free surface waves on a submerged airfoil at relatively low submergence depth ratios ranging from $h = 1.3c$ to $h = 2.5c$ at steady and unsteady model velocity. The applicability of a skim plate as a tool to alleviate surface wave effects is discussed.

The general properties of Airy’s linear wave theory are discussed in Sect. 3.1. A mathematical description of the pressure patch method is provided that is utilized to model the resulting steady and unsteady wake waves analytically. The analytic solution is compared to experimental results to demonstrate the validity of this approach (Secs. 3.1.1 and 3.1.2). Changes in pressure and effective angle of attack due to the wave-induced particle motion are addressed in Sect. 3.2 at steady (Sect. 3.2.1) and unsteady (Sect. 3.2.2) model velocity. In Sect. 3.3, the effect of utilizing a skim plate is discussed and the effectiveness assessed through surface pressure measurements on the submerged foil model. The effectiveness of a fixed-size skim plate is discussed when varied in the longitudinal direction relative to the submerged model.

## 2 Setup and instrumentation

The towing tank facility utilized to carry out the experiments is described in Sect. 2.1. It is one of the largest towing tanks in Europe and was built in 1903. The test rig, skim plate, and foil model that are towed through the water basin are described in Sect. 2.2.

### 2.1 Towing tank facility

The experiments are conducted in the large water towing tank at Technische Universität (TU) Berlin (Fig. 2). The water basin measures 250 m in length, 8.1 m in width, and the average water depth is 4.8 m. The basin depth is not constant along the entire length and drops from 3.4 m to 5.2 m at a longitudinal position of 60 m. Wave breakers are installed at one end of the water tank and along one side of

![Towing tank and carriage train at Technische Universität Berlin](image)

Fig. 2 Towing tank and carriage train at Technische Universität Berlin
the basin. It accelerates wave dissipation and reduces waiting times in between test runs. A preparation area is utilized to install the test rig, skim plate, and model, and has a length of 17 m, width of 2.1 m, and depth of 2.4 m. It is drained using an electric pump and is decoupled from the main water basin using a bulkhead. A carriage train with a weight of about 25 tons moves on two rails that are mounted along the walls of the towing tank. The rails are leveled with the water surface to retain a constant distance between the free surface and the measurement platform. The test rig and model are mounted to a truss that can be traversed in the vertical direction to change the submergence depth of the model. The maximum permitted loads in longitudinal (drag) and vertical (lift) direction are 1 and 2 tons, respectively. The application of side loads is avoided to prevent damaging the truss. Therefore, foil models are limited to tests with horizontal alignment. The carriage train is powered by eight 55.5 kW DC-motors and computer-controlled to generate velocity profiles of arbitrary shape. The maximum acceleration is limited to 1 m s\(^{-2}\) and the maximum velocity that can be reached is 12.5 m s\(^{-1}\). The carriage train velocity is recorded using a rotary encoder with a resolution of 10 000 ticks per meter in combination with a frequency-to-current signal converter (WAS4 PRO Freq) by Weidmueller.

### 2.2 Test rig setup, skim plate, and foil model

A test rig is used to mount two-dimensional models with a maximum span of \( s = 1.0 \text{ m} \) to the measurement platform (Fig. 3). Two splitter plates with a size of \( 1.25 \text{ m} \times 1.0 \text{ m} \times 0.035 \text{ m} (l \times w \times t) \) are attached to both sides of the model to provide a quasi-two-dimensional flow field. The splitter plates are attached to four steel frameworks that consist of multiple welded steel plates with a thickness between 5 mm and 8 mm. All welded plates are oriented at an angle to each other but at zero incidence with respect to the longitudinal carriage train motion. The foil model is mounted onto angular steel mounts with a welded pin of 50 mm diameter at either side. The pins are inserted into bearings located on the outer part of either splitter plate such that the angle of incidence can be changed continuously. The point of rotation is located at \( x/c = 0.5 \). Additional end plates on the outer side are utilized to connect the pins with the test rig such that the angle of attack is fixed in place. The model’s submergence depth \( h \) is controlled by traversing the truss, and thus the entire test rig in the vertical direction. The submergence depth of the model to the free surface is measured from the upper side of the foil at an angle of attack of \( \alpha = 0^\circ \). The submergence depth \( h \) ranges from 1.3\( c \) to 2.5\( c \), where \( c \) is the chord length of the model.

A flat plate serves as a generic surrogate to investigate the effect of free surface waves onto a submerged foil model moving at steady and unsteady velocity. The foil has an aspect ratio of \( AR = 1.9 \), where the span measures \( s = 0.95 \text{ m} \) and the chord \( c = 0.5 \text{ m} \). The foil’s leading edge is elliptical and the trailing edge is blunt. The length of the semi-major axis of the elliptical leading edge is \( a = 0.06 \text{ m} \) and the thickness of the model is \( t = 0.03 \text{ m} \). The foil is a composite of coated wood and aluminum. To increase the structural integrity, two aluminum plates (0.01 m and 0.005 m thick) are affixed on top and bottom of the wood core. Multiple pressure sensors are embedded into the model. The pressure tubing length connecting the pressure sensor and tab is \( l_{\text{tube}} = 0.15 \text{ m} \) for all sensors. All pressure tabs incorporated into the model are on one side of the foil only. Thirteen pressure tabs are located at midspan and distributed along the chord. Two-dimensional flow around the model at steady velocity is confirmed at pre-stall angle of attack by utilizing two spanwise pressure tabs. Detailed information regarding the spanwise measurements is provided by Jentzsch et al. (2021).

Differential pressure sensors made by Honeywell (26PCBFA6D) with a range of ±35 kPa and accuracy of 0.25% full scale are used together with custom-made amplifiers. The pressure reference side is connected to atmospheric pressure outside of the water. A pressure calibrator (KAL 84) can be connected to the tubing of the reference side to carry out a static sensor calibration. The other side of the differential pressure sensor is connected to the pressure tab via a silicon tube to record the surface pressure of the submerged foil. The tubing and sensor cavity are carefully filled with water. A triple-axis accelerometer (ADXL335) installed within the model is calibrated in situ, which is utilized to set the model’s angle of attack.

The free surface wave deflection is measured using one ultrasound sensor (Balluff BUS0052) while towing the model and test rig. All time-resolved signals such as pressure, model velocity, acceleration, and surface deflection are acquired with a data acquisition system with 32 synchronized channels at a sampling rate of \( f_s = 10\,000 \text{ Hz} \). The system consists of an NI 9188 mainframe by National Instruments equipped with eight analog input modules (NI 9215-BNC).

A skim plate can be installed above the model. The skim plate is 2.44 m long, 0.96 m wide, and 0.02 m thick. The position can be traversed in longitudinal and vertical direction. The submergence depth of the skim plate below the undisturbed free surface is \( h_{\text{sp}} = 0.2c \). Three different longitudinal positions are tested within this study (i.e., front, center, and aft). In the center position, the skim plate protrudes equally over the leading and trailing edge. Measured from this position, the skim plate is moved either 0.8\( c \) to the front or 1.16\( c \) aft, which is the maximum translation possible in either direction for the given setup. A principle sketch showing the relative position of the submerged model and skim plate is provided in the inset in Fig. 3.
3 Results

Experiments that are conducted in an open channel water tunnel or towing tank are prone to the generation of water waves that travel on the density discontinuity of the two fluids (i.e., water and air). The general properties of water waves are discussed in Sect. 3.1. Often, the experimental investigation of air- and land-borne vehicles (i.e., airfoils, trucks, or trains) is performed in facilities where the working fluid is water rather than air in order to increase the Reynolds number. Assuming that the effects of compressibility are negligible, an important requirement for the transferability of results to extract the pure aerodynamic coefficients is that results are not affected by the boundary

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conditions of the facility. A violation thereof exists if the model submergence is not sufficient such that free surface effects are apparent. The deflection of the free surface introduces a pressure and velocity perturbation. These perturbations attenuate with depth depending on the corresponding wavenumber and water depth. Knowledge regarding the wavenumber spectrum, including the correct amplitudes and phase, is required to obtain the perturbation values at the corresponding model submergence depth. However, it is a challenging task to obtain this information experimentally. The resulting wave field is a superposition of multiple waves generated by various sources distributed in three dimensions. Thus, an analytic approach is utilized to model the steady and unsteady wave pattern with pressure patches as described in Sect. 3.1. The applicability of the analytic approach to model the free surface deflection caused by the moving test rig and model is validated with experimental results obtained at steady (Sect. 3.1.1) and unsteady velocity (Sect. 3.1.2). These results are utilized in Secs. 3.2.1 and 3.2.2 to conceptually show how the free surface deflection alters the effective angle of attack as well as pressure at various submergence depths. Especially tests conducted at unsteady velocity exhibit large deviations depending on the submergence depth of the model. A skim plate is utilized to alleviate free surface effects. Surface pressure measurements on the foil model are obtained with and without skim plate installed at various submergence depths and at steady and unsteady model velocity (Sect. 3.3). The skim plate’s position is varied in longitudinal direction relative to the foil model to examine the effects of relative location.

### 3.1 Free surface wave profile

When towing an object through the water basin of a towing tank waves are generated due to the pressure disturbance at and below the air–water interface. The two restoring forces are gravity and surface tension. Surface tension effects need to be considered for capillary waves that are of small wavelength \( \lambda \lesssim 0.1 \text{m} \) and often referred to as ripples. Due to their short wavelength compared to the submergence depth of the model in this study, changes to the hydrodynamic characteristic of the foil are negligible. For simplicity, capillary waves are neglected in the following. For all larger wavelengths, gravity is the dominant restoring force such that these waves are often referred to as gravity waves.

The particles under a wave prescribe an orbital motion being elliptical in finite depth (shallow water and intermediate regime) and circular in deep water. A velocity and pressure oscillation is associated with the wave motion. Airy’s wave theory (i.e., deep water approximation) is utilized to visualize the oscillatory perturbations in velocity \( u' \) and \( w' \) as well as pressure \( p' \) under a monochromatic wave in Fig. 4 (Kundu et al. 2016).

The magnitude of the perturbations introduced by the wave decline exponentially with depth in deep water. Additionally, Fig. 4 highlights that a submerged body such as a foil experiences an induced angle of attack \( \alpha_{\text{ind}} \) and a change in pressure depending on its submergence depth but also relative position to the wave in the longitudinal direction. However, the wavefield generated during a test run in a towing tank may become complex. A broadband range of wavenumbers is excited depending on towing speed. The interaction between the submerged model and free surface is altered by the foils loading, which depends on the angle of incidence. Further, multiple wave-generating sources exist (i.e., test article and test rig) and their waves interact with each other. At unsteady towing velocity, an unsteady wake is generated and the steady assumption may not be applicable anymore.

A suitable approach to model complex wake wave systems is the pressure patch approach. This method was first introduced by Havelock (1908). It is a computationally inexpensive method to predict resulting wake waves in order to highlight wave features in the far-field (Benzaquen

![Fig. 4](image_url)
et al. 2014; Li and Ellingsen 2016; Li 2018; Colen and Kolomeisky 2021). An external pressure source with arbitrary shape and magnitude is imposed onto the free surface and the resulting free surface deflection is solved analytically. Li et al. (2019) utilize this method to predict the wave field generated by a moving ship with shear currents of arbitrary direction. A complete set of derivations and formalism including the effect of shear currents is presented by Li and Ellingsen (2015). Their approach and formalism are adopted for the purpose of this study while omitting the effect of shear flow. In the following, only the most important equations utilized to model wake waves within this study are provided.

The pressure patch shape and magnitude are modeled with an arbitrary function. Ship hulls are often modeled with an elliptical super-gaussian (Eq. 1) where \( m = 3 \). Equations 1 and 2 are utilized to model the test rig and foil model (see Fig. 3) as external pressure sources in a very simplified manner by creating gaussian pressure patches that correspond to the actual length scales of the surface piercing parts and the submerged foil. Nine external pressure sources are utilized to model the experimental setup. The test rig is simulated using eight pressure sources. Four sources are used to model the most inward surface of the steel frameworks and another four sources to model the skin plate mounting struts. The exponent in Eq. 1 is chosen as \( m = 5 \) to create a fairly sharp pressure drop at the border of the pressure patch. The submerged foil is modeled using the same equation but with \( m = 2 \) to create a smoother pressure distribution. The magnitude of each pressure patch is chosen to scale with the dynamic pressure \( q_\infty \) of the instantaneous velocity \( q_\infty = 1/2 \rho u(\phi)^2 \). Additionally, a scaling factor \( S_\text{exp} \) is applied (Eq. 2) such that the resulting wave amplitudes from the pressure patch approach align with the experimentally determined amplitudes. Equation 3 is added to account for waves generated by a submerged body such as the foil model.

\[
\begin{align*}
    p_{\text{ext}}(r, t) &= p_0^* e^{-\frac{2\pi^2}{m}} \int\left(\frac{2\pi}{L}\right)^{\frac{2\pi}{B}} \int d^2k (2\pi)^2 \frac{\hat{p}_\text{ext} k \tanh (kH)}{(\omega_+ - i\epsilon)(\omega_- - i\epsilon)} e^{ikr} \\
    p_0^* &= q_\infty \cdot S_\text{exp} \\
    \Xi &= \frac{\cosh(k(z + H))}{\cosh(kH)}
\end{align*}
\]

Equation 3 is added to account for the instantaneous pressure patch alignment with the experimental pressure distribution. The magnitude of each pressure patch is chosen to scale with the dynamic pressure \( q_\infty \) of the instantaneous velocity \( q_\infty = 1/2 \rho u(\phi)^2 \). Additionally, a scaling factor \( S_\text{exp} \) is applied (Eq. 2) such that the resulting wave amplitudes from the pressure patch approach align with the experimentally determined amplitudes. Equation 3 is added to account for waves generated by a submerged body such as the foil model.

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    p_0^* &= q_\infty \cdot S_\text{exp} \\
    \Xi &= \frac{\cosh(k(z + H))}{\cosh(kH)}
\end{align*}
\]

The surface deflection generated by a pressure source moving at constant velocity is readily obtained by Eq 5. The phase velocities \( \omega_+ \) and \( \omega_- \) correspond to the wave components traveling in directions of \( k \) and \( -k \) with \( \omega_\pm = k \cdot U \pm \sqrt{gk \tan (kH)} \). The term \( i\epsilon \) is necessary to circumvent the poles in the complex plane with \( \epsilon \) a small number approaching zero, also known as the radiation condition. Results at steady velocity are discussed in Sect. 3.1.1.

Equation 6 is utilized to obtain the solution for unsteady model velocities as presented in Sect. 3.1.2. Implementing this equation results in ring waves created by a finite impulse pressure excitation in the laboratory reference frame. These ring waves spread out over time. All contributions at every time step since \( t = 0 \) are summed up over time, taking into account the distance the pressure source has traveled. Thus, any arbitrary motion profile can be constructed as a sum of finite impulses at different times and locations (Eq. 7).

\[
\begin{align*}
    \zeta'(x, y, t) &= \frac{1}{\rho} \int \int \frac{d^2k}{(2\pi)^2} \frac{\hat{p}_\text{ext} k \tanh (kH)}{(\omega_+ - i\epsilon)(\omega_- - i\epsilon)} e^{ikr} \\
    \zeta(x, y, t) &= \frac{1}{\rho} \int \int \frac{d^2k}{(2\pi)^2} \left\{ -k\hat{p}_\text{ext} \tanh (kH) \sin \sqrt{gk \tan (kH)t} \right\} e^{ikr} \\
    \zeta_{\text{total}}(x, y, t) &= \sum_{i=0}^{t} dt \zeta(x, y, t)
\end{align*}
\]

Obtaining the surface deflection allows to calculate the velocity and pressure perturbations at arbitrary submergence depth in xy-space. These findings are utilized to conceptually show how the pressure coefficients of a submerged foil model are affected by the free surface as presented in Sect. 3.2.

### 3.1.1 Steady velocity

Tests are carried out in the towing tank at constant velocity. A steady wake pattern forms, which moves with the model and test rig. The wave amplitudes are recorded along the centerline of the model using a single wave gauge. Multiple test runs are conducted and the wave sensor is repositioned after each measurement. The time-averaged data are
acquired over 100s excluding the acceleration and deceleration phases.

Figure 5 shows experimental results for three different angles of attack $\alpha$ at a submergence depth of $h = 1.3c$ and a towing velocity of $U_0 = 1.0 \text{ m s}^{-1} \left(Re_0 \approx 440\,000\right)$ corresponding to a depth-based Froude number of $Fr_h \approx 0.4$. The wave amplitude $\zeta$ in the vicinity of the model is affected by changing the model’s angle of attack. Thus, an interaction between the submerged foil model and free surface is apparent. Therefore, a reciprocal action from the free surface to the model is expected. These results suggest that the model’s submergence depth is not sufficiently deep for this test configuration to be free from surface wave effects.

The analytic solution showing the wake in the xy-space generated by the submerged model at $\alpha = 0^{\circ}$ and test rig is depicted in Fig. 6. A comparison of the analytic and experimental results in the vicinity of the model and along its centerline (i.e., $y = 0$) is provided in Fig. 5. Good agreement is achieved for an angle of attack of $\alpha = 0^{\circ}$ from any upstream point until the trailing edge of the model, which corresponds to $x = -0.25\text{m}$. For $x < 0.25\text{m}$ results differ when multiple wake waves superpose and interfere with each other. The deviations are caused by the simplified setup of pressure patches that generate the wake waves (as described in Sect. 3.1). Additionally, the superposition of the wake waves yields a pattern with many ripples over a short distance, as is seen in Fig. 6. The ultrasound sensor that transmits a signal in form of a beam is not suitable to accurately detect these small-scale features. Furthermore, the spatial resolution (i.e., measurement locations) selected with the wave gauge is not sufficiently high to capture these ripples of short wavelength.

Having the analytic solution available allows calculating the corresponding fluctuation values $w'$ and $p'$ at the submergence depth of the model not only along the centerline but also in the entire xy-space. These qualitative results are utilized in Sect. 3.2.1 to conceptually show how the effective angle of attack and pressure on the submerged model are altered. It shall be noted that these analytic results intend to conceptually demonstrate how the free surface interacts with the submerged model. The intention is not to correct the experimental results, which is beyond the capability of the pressure patch approach.

### 3.1.2 Unsteady velocity

As opposed to the steady velocity case, the wake waves at unsteady velocity are not stationary with respect to the model. The sinusoidal velocity profile is defined by Eq. 8 where $U_0$ denotes the mean velocity of the model, $\omega$ the angular frequency, and $\sigma$ the relative velocity amplitude. When performing an oscillatory (sinusoidal) motion, waves of various wavelengths, and thus different phase velocities $c_{ph}$, are generated, which depend on the instantaneous towing velocity. The resulting wake is a superposition of all waves shed at different time instances and depends on the parameters of the sinusoidal motion (i.e., $U_0$, $f$, and $\sigma$). Therefore, the resulting wake wave pattern changes as a function of time. Similar to the measurements at a steady velocity, the wave deflection is measured using one wave gauge that is repositioned in the longitudinal direction after...
each test run. The recordings are synchronized with the carriage train velocity. The unsteady waves exhibit a repetitive cyclic behavior in accordance with the periodic velocity profile. Therefore, each measurement is phase averaged.

\[ u(t) = U_0(1 + \sigma \sin(\omega t)) \]  

(8)

Figure 7 shows the variation of the wave amplitude \( \zeta \) along the centerline of the model for phase angles in the range of \( 0^\circ \leq \phi < 360^\circ \) in a model fixed reference frame. The results of two different angles of attack are presented, obtained at \( U_0 = 1.0 \text{ m s}^{-1} \) (\( Re_0 \approx 440 000 \)), \( f = 0.155 \text{ Hz} \) (\( k \approx 0.24 \)), and \( \sigma = 0.5 \). The y-axis in Figs. 7b, c, and d represents the instantaneous phase angle and corresponding model velocity as shown in Fig. 7a. The x-axis contains the longitudinal coordinates at \( y = 0 \) in the model reference frame. The location of the model’s leading and trailing edge is confined between \(-0.25 \text{ m} \leq x \leq 0.25 \text{ m}\), which is identical to the region highlighted in Fig. 5.

Experimental results obtained at an angle of attack of \( \alpha = 0^\circ \) (Fig. 7b) agree well, at least qualitatively, with the analytic solution (Fig. 7c). However, quantitative differences in the wave amplitude \( \zeta \) are apparent. The wave amplitude is underestimated by the pressure patch approach, especially upstream of the model. Similar to the steady results presented in Sect. 3.1.1, a change in angle of attack to \( \alpha = +8^\circ \) (Fig. 7d) affects the deflection of the free surface. Therefore, a reciprocal action between submerged model and free surface is apparent. Independent of the angle of attack \( \alpha \), all results (experimental and analytic) show a free surface deflection upstream of the model and test rig.

The solution of the analytic approach corresponding to Fig. 7c is utilized to plot the wave deflection \( \zeta \) in the \( xy \)-space. Four different phase angles \( \phi \) are presented (Figs. 8a–d) to visualize the evolution of the unsteady wake in space at different time instances. Contrary to steady model velocities, the wake angle that forms is not fixed at \( \Phi \approx 19.47^\circ \) and changes as a function of time.
The mean velocity of the model for this particular test case is \( U_0 = 1.0 \text{ m s}^{-1} \), yet the phase velocity \( c_{ph} \) of some waves shed in the first half of the motion cycle (i.e., \( 0^\circ < \phi < 180^\circ \)) is larger than \( U_0 \). These waves eventually pass the model, which explains the wave deflections upstream of the model and test rig. As a consequence, tests with unsteady sinusoidal velocity always generate waves that travel ahead of the model. Therefore, the water upstream of the model is set in motion before the model arrives. It may affect the inflow conditions experienced by the submerged model leading to a change in the effective angle of attack and introduces pressure fluctuations, which is discussed in detail in Sect. 3.2.2. Waves shed at higher velocity do not only travel faster but also exhibit larger wave amplitudes due to the increased pressure perturbation exerted onto the free surface. When passing the model while the instantaneous velocity and therefore the dynamic pressure \( q_d \) is low, these waves affect the flow field around the model even more than it would be the case for any (quasi-) steady scenario.

### 3.2 Wave-induced angle of attack and pressure offset

The geometric angle of attack \( \alpha_g \) of a foil is defined as the angle between the foils chord line and the freestream velocity vector. When towing a model through the basin of a towing tank wave tanks are generated, setting the water particles into an orbital motion. The particle motion is superposed onto the towing velocity leading to a possible alteration of the effective angle of attack. Additionally, a pressure variation associated with the wave’s motion may be experienced by the submerged model. Free surface effects may lead to discrepancies between results obtained in a towing tank and wind tunnel.

The wave-induced angle of attack at steady velocity is revealed experimentally and discussed in Sect. 3.2.1. At unsteady velocity, the complexity is increased due to the time dependence of the wake. These results are presented and discussed in Sect. 3.2.2. Complementary results are provided in both sections utilizing the pressure patch approach as discussed in Sect. 3.1. Once the free surface deflection at the air–water interface is obtained analytically, the vertical velocity component at arbitrary depth is readily derived by applying the linearized kinematic boundary condition at the free surface (Eq. 9) (Arzhanikhin and Kotelnikov 2016). Thereafter, the scaling factor \( \Xi \) (Eq. 3) is multiplied to Eq. 9 to obtain the effective wave profile at arbitrary submergence depth. The scaling factor takes into account the attenuation of each wavenumber at the given depth, yielding the effective vertical velocity (Eq. 10). The validity of this approach can be verified using Airy’s linear wave theory with the definition of \( \zeta \) provided in Sect. 3.1.

\[
\begin{align*}
\frac{\partial \zeta}{\partial t} \bigg|_{z=0} &= \frac{\partial \phi}{\partial \zeta} \bigg|_{z=0} \\
\frac{\partial \zeta}{\partial t} \bigg|_{z=h} &= \frac{\partial \phi}{\partial \zeta} \bigg|_{z=h} \cosh(k(z + H)) \cosh(kH)
\end{align*}
\]

The induced angle of attack is calculated based on Eq. 11. For measurements at a steady velocity, the freestream velocity is constant and replaced by \( u = \text{const} \). Similarly, the induced vertical velocity is constant relative to the model such that \( w'(x)_{z=h} \). For tests with an unsteady model velocity, the time-varying freestream velocity is used to obtain the instantaneous induced angle of attack \( \alpha_{ind}(\phi) \). Wave-induced perturbations in longitudinal direction \( u' \) are neglected in calculations since \( u' << u(\phi) \). This approximation for the induced angle of attack is valid for a single point in the flow field. Additional effects such as virtual camber of the foil occur if the vertical velocity perturbation along the chord is not constant (Sedky et al. 2020). Since the induced angle of attack calculations are based on the pressure patch approach that highlights effects conceptually, no correction is applied to account for chordwise varying vertical velocities.

\[
\alpha_{ind}(x, \phi)_{z=h} = \tan^{-1} \left( \frac{w'(x, \phi)_{z=h}}{u(\phi)} \right)
\]

### 3.2.1 Steady velocity

Free surface effects are analyzed for the steady velocity case. The leading parameter (i.e., wave-induced effective angle of attack or hydrostatic pressure offset) responsible for biased aerodynamic results is determined. Experimental data are presented and compared to the solution of XFOIL (Mark Drela 2000) as well as the analytic pressure patch approach to reinforce the observations made. Subsequently, the obtained knowledge of the underlying flow mechanisms is applied to the more complex unsteady velocity case as discussed in Sect. 3.2.2. The gained knowledge is useful in developing a fundamental understanding regarding the working principle of a skim plate that has not been widely utilized nor investigated for the application in towing tank tests.

Surface pressure measurements on the foil model are conducted at a steady velocity of \( U_0 = 1.0 \text{ m s}^{-1} (Re_0 \approx 440 \text{ 000}) \). Various angles of attack are tested. Since only one side of the symmetric model is equipped with pressure tabs, the model is tested upside-up and upside-down to check for symmetry. Angles of attack denoted with the subscript ‘+’ refer to measurements conducted with the pressure tabs on the top
surface facing toward the free surface. The subscript ‘−’ refers to the configuration where the model is flipped such that the pressure tabs are located on the bottom of the model facing toward the towing tank floor. For each configuration (i.e., model upside-up and upside-down), a positive change in the angle of attack is achieved by pitching the model in the opposite direction such that the pressure tabs are located on the suction side of the model. The steady pressure coefficients \( C_p = (p_x - p_{atm+bud})/q_{\infty} \) are obtained by time averaging the pressure reading of each sensor over a time interval of 100s excluding the acceleration and deceleration phases.

Figure 9 shows the pressure coefficients \( C_p \) measured along the chord for various angles of attack at a submergence depth of \( h = 1.3c \). Solid lines represent measurements with model upside-up \((\alpha_+)\) and dashed lines with model upside-down \((\alpha_-)\). Comparing the coefficients at an angle of attack of \( \alpha = \pm 8^\circ \) (red), a large deviation between both configurations is noted. For the configuration with model upside-up, a suction peak at the leading edge is apparent, reaching minimum pressure coefficients of less than \( C_p = -3 \). When flipping the model, no distinct suction peak is determined. The minimum \( C_p \)-value is \( C_p \approx -1.2 \). It indicates a premature onset of flow separation compared to the model facing upwards. Reducing the angle of attack to \( \alpha_- = 7^\circ \) (green) shows much better agreement to \( \alpha_+ = 8^\circ \). The pressure reading matches well at the leading edge but differences are apparent in between 0.1 \( \leq x/c \leq 0.6 \). An exact match of the pressure coefficient curves at an angle of attack of \( \alpha_+ = 8^\circ \) is not achieved. It could be caused by not finding the appropriate angle of attack iteratively or the pressure readings could be affected by the free surface. In Fig. 5, it was shown that the free surface elevation is affected differently for model upside-up and model upside-down.

The pressure coefficients obtained at an angle of attack of \( \alpha = \pm 0^\circ \) are also presented in Fig. 9 (blue lines). Since the foil model is symmetric, these measurements combined yield the pressure distribution of the foil on the suction and pressure side. If symmetry is unaffected and if the effective angle of attack is zero, both curves would collapse onto each other. However, the pressure coefficients obtained on the bottom surface (blue dashed) yield lower pressure coefficients compared to the values measured on the top surface (blue solid). It suggests that the model is producing a negative lift at \( \alpha = 0^\circ \). The angle of attack is changed to \( \alpha_- = -2^\circ \) with model upside-down to achieve a good match with the pressure readings obtained with model upside-up at \( \alpha_+ = 0^\circ \). These results indicate that the zero-lift angle \( \alpha_0 \) is shifted by approximately \( \Delta \alpha \approx 2^\circ \) due to non-symmetric boundary conditions introduced by the free surface.

Evidence that the shift in the effective angle of attack is induced by the free surface is obtained by keeping the angle of incidence \( \alpha \) fixed but varying the submergence depth of the model. Thereby, any differences in the pressure readings obtained are solely precipitated by the change in the distance of the model to the free surface. Ground effects are neglected since at deepest submergence the ground is still \( \Delta h \approx 8c \) distanced to the model. Figure 10 shows pressure coefficient deltas \( \Delta C_p \) at an angle of attack of \( \alpha_+ = 8^\circ \). The pressure coefficients obtained at the deepest submergence of \( h = 2.5c \) serve as reference values since free surface effects
are the least pronounced at this depth. These pressure coefficients are subtracted from those obtained at a submergence depth of \( h = 1.3c \) and \( h = 1.9c \). The overall differences in pressure coefficient increase the shallower the submergence depth of the model. Further, the highest difference in the pressure coefficient is obtained at the leading edge in the suction peak region. The deltas decrease gradually toward the trailing edge of the model where the data of all submergence depths collapse onto each other. It reinforces the conclusion that changes in the flow field imposed by the free surface are dominated by the effects of an induced angle of attack \( \alpha_{\text{ind}} \) rather than wave-induced pressure offset.

The change in effective angle of attack introduced by the free surface becomes apparent when comparing these findings to results obtained with XFOIL. It is an open-source tool based on a panel method algorithm. The geometric foil parameters from the experimental study are embedded into XFOIL and the pressure coefficients calculated neglecting the effects of viscosity. The trailing edge of the foil geometry passed to XFOIL is sharpened in order to satisfy the Kutta condition. The reference case in this scenario is the data obtained at \( \alpha = 8^\circ \), which then is subtracted from the results obtained at \( \alpha = 8.55^\circ \) and \( \alpha = 8.2^\circ \), respectively, and plotted in Fig. 10. These angles of attack are chosen to match the same suction peak delta at the leading edge as for the experiments. The overall trend of the delta plots obtained experimentally and numerically is similar. The highest deltas are observed at the leading edge and gradually decrease toward the trailing edge. However, in the experiment, the deltas originate from the deflection of the free surface and its effects onto the submerged model attenuate with increasing submergence depth. Numerically, these similar trends are obtained by changing the geometric angle of attack of the foil. Alterations in the effective angle of attack due to the presence of the free surface are verified via XFOIL. According to XFOIL, the difference in effective angle of attack between shallowest (\( h/c = 1.3 \)) and deepest submergence (\( h/c = 2.5 \)) tested is rather small for the test case presented and yields \( \Delta \alpha \approx 0.55^\circ \). However, it elucidates the underlying flow mechanism, which is detected with more ease at steady rather than unsteady velocity. Additionally, it highlights that wave-induced changes in the effective angle of attack dominate over the changes introduced by the perturbation pressure \( p' \).

The analytic approach is utilized in order to verify these findings conceptually. The results obtained in Sect. 3.1.1 are used to determine the wave-induced vertical velocity \( w' \) at different model submergence depths. Results are discussed based on a model’s angle of attack of \( \alpha = 0^\circ \) because this test case is validated experimentally. It reveals the impact of the wave-induced effects of the test rig that superpose to the free surface effects when the angle of attack of the model is changed. Equation 11 is then utilized to calculate the effective angle of attack under the wave. Figure 11 shows a case study of different submergence depths and the corresponding induced angle of attack along the centerline of the model (i.e., \( y = 0 \)) below the wave. Changes in the angle of attack and pressure coefficient \( C_p \) at a velocity of \( U_0 = 1.0 \text{ m s}^{-1} \) are small. This is expected since the Froude number is \( F_{nh} \approx 0.4 \) at \( h = 1.3c \), which is the threshold value at which surface waves at steady velocity become negligible. For \( F_{nh} < 0.4 \), often the biplane approximation is applied, in which the free surface is replaced by a rigid surface such that the foil experiences effects similar to a wing in ground proximity. These results also suggest that the pressure patch approach underestimates the wave-induced effects when compared to the solution obtained with XFOIL or the experimental results provided in Fig. 9. However, the overall trends are consistent. Increasing the submergence depth of the foil alleviates free surface effects. Further, the attenuation is not linear since the submergence depth is changed in equidistant steps but the deltas obtained are not constant. The results presented in Fig. 11 also show that changes introduced by the wave motion are not constant along the chord. As a result, the induced angle of attack \( \alpha_{\text{ind}} \) may be underestimated when utilizing the flow field information of a single point. Note that at higher \( F_{nh} \), deviations along the chord reduce due to the increased wavelength of the waves generated.

3.2.2 Unsteady velocity

The steady lift coefficient \( C_L \) of a hydrofoil is a function of the depth based Froude number \( F_{nh} \) and submergence depth ratio \( h/c \) of the foil. Depending on \( F_{nh} \), the lift coefficient compared to the \( C_L \) obtained in an unbounded fluid domain
may be increased if \( F_{n_h} \lesssim 0.4 \) (biplane approximation) or decreased if \( F_{n_h} \gtrsim 0.4 \) due to the imposed effects of the free surface. Independent of the submergence depth ratio \( h/c \), largest deviations occur near \( F_{n_h} \approx 1.5 \) according to the studies carried out by Hough and Moran (1969) and van Walree (1999) (see Fig. 1). In the range of \( 0.4 < F_{n_h} < 1.5 \) the gradient of \( d(C_L(h/c))/dF_{n_h} \) is large such that small changes in \( F_{n_h} \) may introduce large changes in the lift coefficient \( C_L \). Hydrofoils usually operate at Froude numbers \( F_{n_h} > 3 \) such that these large gradients in the low Froude number range are not of importance (Faltinsen 2006). When experiments are performed in a towing tank, especially for the investigation of aerodynamic properties, the submergence depth Froude number \( F_{n_h} \) is rather small. For example, in the large towing tank that is utilized for the investigation presented, the maximum velocity reached (steady and unsteady) is \( U_0 = 5.0 \text{ m s}^{-1} \). With a foil chord of \( c = 0.5m \) and a minimum submergence depth of \( h = 0.65m \), the maximum Froude number obtained during this study is \( F_{n_h} \approx 2 \).

In the case of unsteady surge experiments, the airfoil performs a sinusoidal motion and the instantaneous Froude number becomes a function of \( \phi \) such that \( F_{n_h}(\phi) \). Therefore, even under quasi-steady conditions (i.e., low reduced frequency \( k \)) the resulting forces acting on the foil are changing dynamically if the foil is not submerged sufficiently deep. Figure 12 shows the instantaneous Froude number \( F_{n_h}(\phi) \) as a function of the phase angle \( \phi \) for two different mean velocities (i.e., \( U_0 = 1.0 \text{ m s}^{-1} \) and \( U_0 = 2.5 \text{ m s}^{-1} \)) and a relative velocity amplitude of \( \sigma = 0.5 \) at three different submergence depth ratios. The black line at \( F_{n_h} \approx 0.4 \) denotes the limit below which free surface effects become negligible and the free surface acts as a rigid wall. Therefore, according to the findings as presented in Fig. 1, large deviations in the forces acting on the foil are expected due to the change in Froude number even under quasi-steady conditions. At high reduced frequencies \( k \), the wake becomes unsteady, leading to the observed effects of waves passing the model. Upstream traveling waves as discussed in Sect. 3.1.2 alter the inflow condition such that the foil may experience an additional pitch motion. Unsteady loads induced by sea waves, which are experienced by a hydrofoil translating at steady velocity, are described by van Walree (1999) and Faltinsen (2006).

In the following, unsteady results for two test cases are presented and discussed (i.e., model upside-up at \( \alpha_+ = 8^\circ \) and upside-down at \( \alpha_- = -7^\circ \)). These angles of attack are chosen because the static polar at \( Re_0 \approx 440000 \) yield a close match at steady velocity as presented in Fig. 9. Experimental data at \( U_0 = 1.0 \text{ m s}^{-1}(Re_0 \approx 440000) \), \( f = 0.155 \text{ Hz} \) \( (k \approx 0.24) \), and \( \sigma = 0.5 \) at shallow submergence depth of \( h = 1.3c \) are presented in Fig. 13. The phase averaged pressures obtained with ten pressure tabs distributed along the chord are presented. Comparing both configurations (i.e., Figs. 13a, b), significant discrepancies are detected at unsteady model velocities.

Figure 13a shows the phase averaged pressure for the model upside-up at \( \alpha_+ = 8^\circ \). A noticeable pressure undulation of all sensors is detected in the phase angle range of \( 160^\circ < \phi < 300^\circ \). It occurs at all pressure tab locations simultaneously without significant phase shift. The magnitude of the undulation is declining toward the trailing edge of the foil because the surface pressure close to the leading edge is affected by the superposing effects of the induced angle of attack and wave-induced pressure changes. The surface pressure closer to the trailing edge is not susceptible to changes in the effective angle of attack as long as the flow remains attached. No convective behavior of the local pressure minima at \( \phi \approx 200^\circ \) and \( \phi \approx 280^\circ \) is observed. Therefore, it is precluded that flow separation and the shedding of a vortex are causing this pressure undulation. Further, the difference in the pressure coefficient between different pressure tab locations remains almost constant throughout the entire motion cycle. Only the pressure coefficient \( C_p \) obtained at \( x/c = 0.04 \) shows a sudden pressure coefficient decrease starting at \( \phi \approx 180^\circ \). Steady and quasi-steady experiments, which are not presented, reveal that the surface pressure at this \( x/c \)-location is affected considerably by the occurrence of a laminar separation bubble whose location and extend is Reynolds number dependent. Even though the reduced frequency for the surge motion is \( k \approx 0.24 \) and marks a high degree of unsteadiness, the flow remains nominally attached throughout most parts of the motion cycle.
On the contrary, flow separation is observed for the model upside-down at $\alpha = 7^\circ$ (Fig. 13b). Up to approximately $\phi \approx 150^\circ$ the flow remains attached. The phase averaged pressure coefficients obtained closest to the leading edge (i.e., $x/c = 0.01$ and $x/c = 0.02$) reach pressure coefficient values of $C_p \approx -3.6$. A sudden increase in the pressure coefficient at both tab locations is observed at $\phi \approx 150^\circ$. For $\phi \geq 180^\circ$, the four following pressure tab readings show the occurrence of a successive pressure minimum. It is identified as the footprint of a vortex that rolls up at the leading edge.
size, and convects downstream. The remaining pressure sensors closer to the trailing edge do not experience a vortex-induced pressure drop. It indicates that the vortex detaches from the foil surface. Flow reattachment occurs for $\phi > 270^\circ$ once the acceleration of the model is turning from negative to positive (see Fig. 13c).

In order to assess if these results obtained at a submergence of $h = 1.3c$ are influenced by free surface effects, the submergence depth of the model is increased to $h = 2.5c$ while keeping all other parameters fixed. Any differences occurring by changing the model’s submergence depth are tied back to free surface effects. The effect of submergence is studied for model upside-up at $\alpha_+ = 8^\circ$ and upside-down $\alpha_- = 7^\circ$ since flow topological differences (i.e., attached and separated flow) at shallow submergence depth of $h = 1.3c$ are identified even though steady measurements are in good agreement. The phase averaged pressure coefficient of only one representative pressure tab location at $x/c = 0.01$ is presented in Fig. 14 to increase the readability of the plot. Results at shallow ($h = 1.3c$) and deep ($h = 2.5c$) model submergence are provided.

Blue lines depict the phase averaged pressure for the model upside-up. Up to a phase angle of $\phi \approx 160^\circ$, the phase averaged pressure coefficient for both submergence depths is akin. However, apart from minor deviations in the pressure coefficient magnitude, a different trend in the pressure coefficient gradient $dC_p/d\phi$ is observed between $60^\circ < \phi < 160^\circ$. At shallow submergence, the phase averaged pressure curve exhibits an inflection point that is not apparent at deep submergence. Furthermore, the pressure undulation in the range of $160^\circ < \phi < 300^\circ$ observed at a submergence depth of $h = 1.3c$ is absent when increasing the submergence depth to $h = 2.5c$. For model upside-up free surface effects are significant in the second half of the motion cycle. The largest deviation in the pressure coefficient is $\Delta C_p \approx 0.6$ at $\phi \approx 200^\circ$. Based on these findings and the results presented in Fig. 13a, it is concluded that for nominally attached flow, free surface effects alter the magnitude of the phase averaged pressure. These changes are imposed by affecting the effective angle of attack and perturbation pressure.

The results for the model upside-down at $\alpha_- = 7^\circ$ are also presented in Fig. 14 and highlighted with red line plots. The pressure coefficient obtained for both submergence depths is identical up to $\phi \approx 160^\circ$. A deviation is observed for $160^\circ < \phi < 300^\circ$. Both curves coincide again for $\phi > 300^\circ$. At shallow foil submergence depth premature, flow separation at $\phi \approx 160^\circ$ is observed compared to the tests carried out at deep model submergence. The pressure coefficient at the foils leading edge increases from $C_p \approx -3.6$ to $C_p \approx -1.3$ during the process of flow separation. A similar trend is obtained at deep model submergence of $h = 2.5c$ but flow separation is delayed by $\Delta \phi \approx 30^\circ$. In comparison with the results obtained with the model upside-up, the occurrence of an inflection point within the first half of the motion cycle is absent. Further, a pressure undulation in the second half is not apparent since the critical angle of attack at which flow separation occurs is reached at earlier phase angles. After flow separation, the flow field is dominated by the vortex dynamics. Imposed changes in the effective angle of attack by the free surface are ineffective in the second half of the cycle. Hence, no pressure undulation is observed for $\phi > 180^\circ$ at this angle of attack and performed velocity profile.

One may question if the differences in the underlying flow physics (i.e., attached vs. separated flow) are due to the orientation of the model. While it is true that free surface effects are responsible for these discrepancies since the foil operates near static stall angle, flipping the model does not necessarily lead to flow separation and the roll-up of a vortex. Results at $\alpha_- = 3^\circ$ (model upside-down), which are not presented, show similar pressure undulation at similar phase angles $\phi$ as is the case for model upside-up. However, the gradient of the phase averaged pressure coefficient is adverse for the model upside-up compared to upside-down. Whether flow separation takes place or not depends on the effective angle of attack that is imposed during the unsteady motion. Changes in the effective angle of incidence at unsteady model velocity are elaborated in more detail in the following paragraph utilizing the analytic approach.

The findings obtained in the experimental study correlate well with the findings obtained by the analytic approach as presented in Fig. 15. The induced angle of attack $\alpha_{ind}$ and changes in pressure over one cycle of oscillation are calculated analytically at the leading edge location of the pressure sensor.

![Fig. 14 Effect of model submergence on the pressure signal measured at $x/c = 0.01$, $\alpha_+ = 8^\circ$ and $\alpha_- = 7^\circ$, $U_0 = 1.0 \text{ m s}^{-1}$ ($Re_0 \approx 440000$), $f = 0.155 \text{ Hz}$ ($k \approx 0.24$), and $\sigma = 0.5$](image-url)
model at $\alpha = 0^\circ$. This angle is chosen since it elucidates the underlying mechanisms with more ease. However, note that the majority of the induced effects are attributed to the test rig design. Model-induced effects are superposed once the angle of attack is altered. The angle of attack and pressure fluctuations introduced by the wave, calculated with the pressure patch approach, are rather small. However, conceptually it captures the physics and agrees with the experimental data. At shallow submergence depth of $h = 1.3c$, the induced free surface effects are largest. With increasing submergence depth, the magnitude of the imposed free surface effects attenuates due to the exponential decay with depth and dependency on the wavenumber. The induced free surface effects as depicted in Fig. 15 are discussed on the basis of the shallow submergence depth of $h = 1.3c$ because the occurring effects are more pronounced.

Within the first half of the cycle, changes in the induced angle of attack occur gradually. The induced angle of attack $\alpha_{\text{ind}}$ is monotonically decreasing until $\phi \approx 180^\circ$ reaching a local minimum. For the remaining $180^\circ$ of the cycle, the induced angle of attack imposed by the gravity waves is undulating reaching two more local maxima at $\phi \approx 250^\circ$ and $\phi \approx 315^\circ$ and a local minimum around $\phi \approx 275^\circ$. Pressure deviations $\Delta C_p$ introduced by the free surface are almost constant within the first $180^\circ$. A pressure undulation is observed in the second half of the cycle featuring three local extrema similar to the induced angle of attack $\alpha_{\text{ind}}$. However, the phase angles at which these extrema occur are different. The two local maxima are obtained at $\phi \approx 220^\circ$ and $\phi \approx 300^\circ$. The local minimum is apparent at $\phi \approx 265^\circ$. A superposition of both effects is experienced by the foil model and verifies the experimental findings. Wake waves that pass the model in the second half of the cycle introduce an unsteady change in the instantaneous induced angle of attack $\alpha_{\text{ind}}$ and pressure $\Delta C_p$. Especially for $\phi > 180^\circ$, when the instantaneous model velocity is low, wave-induced effects are dominant exhibiting an undulation similar to the experimental results.

Following intermittent conclusions for model upside-up and upside-down are drawn. When the model is oriented upside-up, the effective angle of attack is continuously decreasing for $\phi < 180^\circ$ leading to a stabilizing effect that delays flow separation and leads to the formation of an inflection point in the phase averaged pressure coefficient curve. For $\phi > 180^\circ$, the undulation of the pressure coefficient $C_p$ (see Fig. 13a) is the result of free surface effects that introduce changes in the effective angle of attack and pressure. Since the flow remains attached at this incidence, the largest differences are obtained at pressure tab locations closest to the leading edge. The surface pressure measured in the trailing edge region is not susceptible to large magnitude fluctuations introduced by a change in the effective angle of attack because of the Kutta condition that has to be satisfied for attached flow. Therefore, any undulation observed close to the trailing edge is caused by changes in the perturbation pressure only. Increasing the submergence depth from $h = 1.3c$ to $h = 2.5c$ alleviates the magnitude of free surface effects substantially (Fig. 15). The delay of flow separation for a hydrofoil operating close to the free surface and facing up is confirmed by findings presented by Ni et al. (2021) utilizing experimental and numerical data. However, their explanation for the delayed stall characteristics is the increase of the boundary layer’s momentum on the suction side due to the wave-induced velocities. While this may be true, Fig. 18 in their publication also suggests that the effective angle of attack is increased by increasing the submergence depth of the model. Comparing the streamlines of the foil at $\alpha = 21^\circ$ reveals that the stagnation point at the leading edge is moving aft when increasing the submergence depth. Additionally, comparing the lift coefficients at different submergence depths as depicted in Fig 1 shows that the lift coefficient is generally low when the model is close to the free surface possibly caused by a decrease in the effective angle of attack.

Contrary, for the model upside-down the induced angle of attack $\alpha_{\text{ind}}$ is acting in the adverse direction leading to a destabilizing effect promoting flow separation for $\phi < 180^\circ$. Therefore, as presented in Fig. 14 and compared to the model upside-up, no inflection point is apparent and the pressure coefficient is generally lower for the model facing upside-down. The critical condition at which flow separation occurs is reached at a lower geometric angle of attack compared to model upside-up (Fig. 14). Increasing the submergence
depth alleviates the free surface effects and consequently flow separation is delayed.

In summary, it is observed that free surface effects are most pronounced in the second half of the motion cycle for a sinusoidal velocity profile. Wake waves pass the model while the instantaneous model velocity is low. Changes in the effective angle of attack act in adverse directions or are at least altered in magnitude for non-zero angles of incidence for model upside-up and upside-down. A stabilizing effect for model upside-up is observed because the effective angle of attack is reduced and flow separation delayed. Concomitantly for model upside-down, flow separation is promoted. Contrary to the steady velocity tests as discussed in Sect. 3.2.1, at unsteady model velocity the wave-induced pressure offset is not negligible. These findings are verified through experimental and analytic results.

### 3.3 The utility of using a skim plate

Free surface effects are apparent in facilities where the top boundary is a layer of density discontinuity (e.g., air–water interface) rather than a rigid surface. Examples of such facilities are towing tanks and water tunnels with a free surface. In some experiments, it is reported that a skim plate is utilized to alleviate wave-induced effects (e.g., Stephens et al. 2016; Stevens et al. 2016; Corkery et al. 2018). In these experiments, the skim plate is placed onto the air–water interface. Within the current study, the amplitudes of waves generated during a test run exceed the thickness of the skim plate by an order of magnitude. Therefore, the skim plate is submerged below the air–water interface to ensure submergence at all times. Studies regarding the proper installation and size of a skim plate are not available. Furthermore, the effectiveness of such a device has not been validated. The idea of a skim plate is to change the boundary condition on the top of the submerged body by introducing a rigid wall similar to wind tunnel tests. It is believed to locally block water waves and prevent wave-induced particle motion and pressure fluctuations.

Tests are carried out at steady and unsteady velocities to quantify the effectiveness of a skim plate. For the steady test cases considered, the impact onto the foil’s surface pressure when installing the skim plate is generally small. A change in the effective angle of attack is observed with skim plate installed. It agrees well with the findings obtained at steady model velocity as discussed in Sect. 3.2.1 where small changes in the effective angle of incidence are observed when changing the model’s submergence depth. An increased effect is observed at unsteady model velocities due to the nature of waves passing the model as described in Sect. 3.1.2. Thus, the applicability of a skim plate is discussed based on unsteady measurements only. The velocity profile of the results presented is identical to those already discussed in the previous sections where $U_0 = 1.0 \text{ m s}^{-1}$ ($Re_0 \approx 440000, f = 0.155 \text{ Hz} (k \approx 0.24)$, and $\sigma = 0.5$).

The question arises if it is possible to alleviate surface effects at shallow submergence of $h = 1.3c$ where the effects are most prominent. Alleviating wave effects at shallow submergence is important because sufficiently deep submergence of the foil cannot be guaranteed in every setup (e.g., due to integration of measurement equipment or optical access).

Figure 16 shows the unsteady phase averaged signal of a pressure sensor located at $x/c = 0.01$ identical to Fig. 14 at an angle of attack of $\alpha_s = 8^\circ$. The pressure sensor close to the leading edge is chosen since the surface pressure in the suction peak is most sensitive to changes. The unsteady pressure coefficients of the baseline data without skim plate mounted in the shallowest (i.e., $h = 1.3c$) and deepest depth (i.e., $h = 2.5c$) are shown again for comparison. As discussed in Sect. 3.2.2, the results without the skim plate installed are influenced by the free surface showing large deviations between the two submergence depths tested, especially in the second half of the cycle. Installing the skim plate, irrespective of the longitudinal mounting position, eliminates the hump, which is apparent for the

![Figure 16](image-url)
baseline case at \( h = 1.3c \). The pressure hump has its pressure minimum at \( \phi \approx 200^\circ \). However, the configuration with the skim plate mounted aft (green line) exhibits a dip in the pressure coefficient curve in the same phase angle range of \( 180^\circ < \phi < 235^\circ \). The configurations front and center do not show such behavior. Further, moving the skim plate in the longitudinal direction introduces an offset.

Although a pressure offset is apparent for the unsteady pressure signals, comparing the phase averaged pressure signal of all configurations with the skim plate installed at \( h = 1.3c \) to the baseline configuration at deepest submersion \( h = 2.5c \) shows good agreement. It indicates that a skim plate is capable of alleviating free surface effects at shallow submersion. Results that are usually obtained at deeper depth can be replicated. It is postulated that the skim plate position front and center perform better compared to the installation aft since the former two do not show a pressure dip at the beginning of the second half of the motion cycle. Because forward traveling waves are generated each cycle, it is suggested that the skim plate needs to be positioned sufficiently front to be effective. Additionally, comparing the deep submersion test case at \( h = 2.5c \) (black dashed line) without skim plate installed to the front (red solid line) and center (blue solid line) configuration, data alignment is observed for partial phase angle sections. In the phase angle range of \( 0^\circ < \phi < 130^\circ \), the black dashed and blue solid lines collapse onto each other. In the range of \( 270^\circ < \phi < 360^\circ \), the black dashed and red solid line coincide. Consequently, since the phase averaged pressure obtained at \( h = 2.5c \) collapses partially with the configuration at shallow submersion and the skim plate mounted front or center, it indicates that the longitudinal position of the fixed size skim plate does matter. It is believed that the dimension of the skin plate will affect the wave-alleviating characteristics. However, no study has been performed to determine the optimal size. It is assumed that a larger skin plate will perform better, especially for tests with unsteady model velocity. Note that at deep submersion of \( h = 2.5c \) installing the skin plate has a negligible effect on the phase averaged surface pressure irrespective of the skin plate position (not shown). Therefore, it is concluded that free surface effects are negligible for the specific test case with the underlying velocity profile at \( h = 2.5c \).

Measurements at unsteady velocity are conducted for the model upside-down at \( \alpha_x = 7^\circ \), \( x/c = 0.06 \), \( U_0 = 1.0 \text{ m s}^{-1} \) \((Re_0 \approx 440000)\), \( f = 0.155 \text{ Hz} \) \((k \approx 0.24)\), \( \sigma = 0.5 \), and skim plate mounted front and in its front position or increasing the submersion depth to \( h = 2.5c \) delays the onset of the pressure drop as well as the location of the pressure minimum by approximately \( \phi = 20 - 30^\circ \). Even though deviations are apparent, the pressure reading at shallow submersion of \( h = 1.3c \) and skin plate installed agrees better with the results obtained at deep submersion where free surface effects are naturally reduced. The remaining discrepancies between the deep submersion test case (blue dashed lines) and the configuration where the skin plate is installed at shallow submersion (red solid line) may be reduced even further if a larger skin plate is utilized.

In summary, the application of a skin plate at shallow submersion shows similar effects on the instantaneous phase averaged surface pressure as increasing the submersion depth of the model. The skin plate locally blocks the gravity waves such that velocity perturbations are hindered to influence the flow field around the foil. Thus, the effects of the induced angle of attack are diminished. Additionally, a fixed-size skin plate is tested. Based on the results presented, it is assumed that a larger skin plate will be more independent of the longitudinal position and the overall performance to diminish the effects of gravity waves increases. It is expected that the proper size of the skin plate is dependent on the parameters of the foil model, submersion depth, and parameters of the velocity profile.

Fig. 17 Effect on flow separation for model upside-down at \( \alpha_x = 7^\circ \), \( x/c = 0.06 \), \( U_0 = 1.0 \text{ m s}^{-1} \) \((Re_0 \approx 440000)\), \( f = 0.155 \text{ Hz} \) \((k \approx 0.24)\), \( \sigma = 0.5 \), and skim plate mounted front.
4 Conclusion

When towing a submerged body through the basin of a towing tank, waves are generated by the submerged parts of the test rig and the model. A complex wave system forms due to the superposition of wake waves from these various wave-making sources.

The analytic pressure patch approach is a useful tool to model wake waves generated at steady and unsteady model velocity. It can be utilized to obtain wave-induced velocity and pressure fluctuation below the free surface of a complex setup and for arbitrary motion histories. The resulting unsteady wake pattern differs from the steady wake pattern and depends on the parameters of the velocity profile. During the sinusoidal motion, waves with large amplitude, phase velocity, and wavelength are generated in the first half of the cycle as long as the model velocity is high (i.e., above $U_0$). These waves travel faster than the model within the second half of the motion cycle and thus pass it. Therefore, these waves alter the inflow condition upstream of the model and locally affect the flow field around the model.

Free surface effects introduce pressure and velocity perturbations. At steady velocity, changing the foil submergence depth shows effects that are similar to changes in the effective angle of attack for a foil in an unbounded fluid. These findings are validated using experimental, numerical (XFOIL), and analytic (pressure patch approach) data. At steady velocity, changes in the effective angle of attack are the dominant effect that are imposed by the free surface. At unsteady velocity, free surface effects are more pronounced compared to (quasi-) steady experiments. The largest surface pressure coefficient deviations are introduced by the free surface in the second half of the cycle when the instantaneous dynamic pressure is low. For model upside-up, wave-induced effects are stabilizing the flow at unsteady model velocity. The wave-induced motion reduces the effective angle attack that the foil experiences and flow separation is delayed. On the contrary, wave-induced effects are destabilizing the flow when the model is facing downwards. Premature separation is observed when flipping the model upside-down due to the adverse wave-induced effects.

A skim plate is utilized to alleviate free surface effects. Installing a skim plate at shallow submergence depth achieves similar effects as increasing the submergence depth of the model. It locally blocks the wave-induced velocity fluctuations, and thus the magnitude of the wave-induced angle of attack $\alpha_{\text{ind}}$ is diminished. Due to the forward traveling waves at unsteady model velocity, it is postulated that the skim plate needs to protrude sufficiently upstream from the leading edge of the model. Thus, the skim plate is an effective tool to alleviate free surface effects and justifies the usability of a towing tank to investigate the aerodynamics of airfoils, wings, ground vehicles, or wind turbines.

Subjects for future studies are the influence of free surface waves and the applicability of a skin plate on finite wings at steady and unsteady model velocity. Obtaining detailed flow information experimentally is challenging. Therefore, a joint numerical and experimental study shall be conducted to gain a more in-depth understanding of the underlying flow physics.

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