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Overview of the POINT SAND model

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Overview of the POINT SAND model

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ABSTRACT:

The report (Uittenbogaard et al., 2000), presents the mathematical background as well as some simulation examples of what is called the POINT SAND model. As a function of time as well as vertical co-ordinate, the POINT SAND model simulates the currents, waves and sand transport while using turbulence closures. The intention of this model is that it will be used, improved and extended by Dutch researchers for developing and testing sand-transport formulations in a joint research effort.

There was a need for an overview of the model’s essential properties with more clarification of the general numerical procedure, the limitations and the assumptions of the implemented hydrodynamic and sand-transport processes. This addendum to the previous report is devoted to these aspects.

REFERENCES:

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Summary

As a function of time as well as vertical co-ordinate, the POINT SAND model simulates the currents, waves and sand transport while using turbulence closures.

The POINT SAND model contains the state-of-the-art formulations of sand-transport processes and particularly a novel direct simulation of wave-current-turbulence interactions. The novel direct simulation of wave-current-turbulence interactions in the same code allows for an unambiguous inter-comparison between sand-transport properties in a wave tunnel or in a free-surface wave channel or even in the field.

Our sensitivity analysis, based on an analytic solution for the depth-integrated sand flux in a steady flow, demonstrates that this flux is very sensitive to the simulated hydrodynamic properties. Consequently, continuous and careful validation of the code for turbulence, currents and for waves remains essential while developing new closures for sand transport processes. Therefore the code is extended with built-in and user-selected test cases.

The code’s most prominent limitations are periodic non-breaking waves and sheet-flow conditions rather than flows over sand ripples. These restrictions are mainly due to the one-dimensionality of the code. These limitations, however, can be partially elevated by additional modelling i.e. with lesser explicit simulation of these involved hydrodynamic processes.
I Introduction

The report (Uittenbogaard et al., 1999) or the corrected edition (Uittenbogaard et al., 2000), presents the mathematical background as well as some simulation examples of what is called the POINT SAND model.

Since the first release of the POINT SAND model it appeared that the precise purpose as well as its limitations was not understood by everybody. Particularly, deviations from sand flux observations were addressed as deficiencies of the POINT SAND model rather than due to the implemented state-of-the-art formulation for sand transport processes proper.

In addition, there was a need for an overview of the model's essential properties with more clarification of the limitations and the assumptions of the implemented hydrodynamic and sand-transport processes. This addendum to the corrected detailed description (Uittenbogaard et al., 2000) is devoted to these aspects and it attempts using minimal mathematics.
2 Objectives of the POINT SAND model

The POINT SAND model contains the state-of-the-art formulations of sand-transport processes and particularly a novel direct simulation of wave-current-turbulence interactions. The model offers various user-controlled options for checking the convergence and dependence of the results on particular choices or options such as turbulence models, orbital motions with or without vertical velocity component, numerical solution procedures etc.

The same code is used for simulating, in time, the vertical distribution of suspended sand in an oscillatory horizontal flow in a wave tunnel but also due to the horizontal and vertical orbital velocity, possibly superimposed on a turbulent current, in free-surface wave channel or in the field with different wave and current directions. Irrespective of the application in a wave tunnel or a free-surface wave channel, the same intra-wave sand transport formulations are used. These sand transport process formulations have been reported and demonstrated by others. With respect to the sand-transport process formulations, the POINT SAND model is not superior to published 1DV models but our model is just more flexible.

The novel direct simulation of wave-current-turbulence interactions in the same code allows for an unambiguous inter-comparison between sand transport properties in a wave tunnel or in a free-surface wave channel or even in the field, provided the bed is horizontal and the waves are stationary and do not break.

The source code of the POINT SAND model is offered to Dutch researchers. Its main purpose being an efficient aid in focussing ongoing research towards improving our understanding of intra-wave sand-transport processes by avoiding repetitions in individual code development. It is our intent to implement future improvements of sand transport formulations in the POINT SAND model so that this upgraded model may serve as reference to the state-of-the-art of modelling intra-wave sand transport in research context. Chapter 5 presents a list of the assumptions and limitations of the model and it is hoped that researchers will attempt to remove most of them.
3 Motivation of using the POINT SAND model

In The Netherlands various institutes as well as university groups are involved in research on sand transport in coastal seas under the combined action of turbulent currents and surface waves. Most of them join the Nederlands Centrum voor Kustonderzoek (NCK, Netherlands Centre for Coastal Research) and in this context mutually co-ordinate their research goals and exchange their findings.

A somewhat similar stimulation is pursued by the so-called Delft Cluster initiative of the Dutch government. Moreover, cooperation among various European researchers is funded by the EC through MaST programmes.

At research institutes and universities different numerical tools are in use for simulating sand transport either in a constant-flow channel, or in the so-called wave tunnel (oscillatory parallel flow) or in a free-surface wave channel or in the field, the latter two involve also vertical orbital motions by surface waves.

The mutual comparison of simulations using different numerical codes for sand transport is hampered by doubts about the accuracy and the convergence of numerical methods, differences in turbulence closures and/or their implementation, different domain sizes (water depth or just wave-boundary layer), input definitions such as for state parameters or the definition as well as the implementation of erosion formulations, the definition of grain-size dependent settling velocity etc.

On the one hand, small differences in input and numerical approximations are a trademark of flow simulations. On the other hand, the consequences for the output in terms of depth-integrated sand flux can be tremendous. Most of the remaining part of this section, therefore, is devoted to demonstrate the various error sources for estimating the depth-integrated sand flux. We begin with the sensitivity of horizontal sand fluxes to input conditions without numerically introduced deviations.

Table 3.1 presents an example of the sensitivity of the depth-integrated horizontal sand flux in a stationary turbulent flow. This example is based on the analytic solution presented in detail in Appendix E of (Uittenbogaard et al., 2000). This table shows the powers in the proportionality relation between the depth-integrated horizontal sand flux and the tabulated inputs for the given representative flow and sand condition. The analytic solution in Table 3.1 is based on solutions for the vertical profiles of mean horizontal velocity and mean sand concentration with constant settling velocity using a parabolic profile for eddy viscosity/diffusivity, the latter is an approximation in its own. Without going into details, this table illustrates the great sensitivity of the depth-integrated sand flux on input parameters for a given analytic solution.
Table 3.1 Powers in local proportionality relation between input parameters and depth-integrated sand flux

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Magnitude</th>
<th>Dim.</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>density of water ($\rho_w$)</td>
<td>1000</td>
<td>kg.m$^{-3}$</td>
<td>4.3</td>
</tr>
<tr>
<td>water depth (H)</td>
<td>1</td>
<td>m</td>
<td>0.15</td>
</tr>
<tr>
<td>mean velocity (U)</td>
<td>2</td>
<td>m.s$^{-1}$</td>
<td>4.5</td>
</tr>
<tr>
<td>ratio zero-velocity level and $z_0$</td>
<td>9</td>
<td>-</td>
<td>0.25</td>
</tr>
<tr>
<td>bed roughness length ($z_b$)</td>
<td>4.10$^{-5}$</td>
<td>m</td>
<td>0.59</td>
</tr>
<tr>
<td>turbulence Prandtl/Scmidt number ($\sigma_f$)</td>
<td>0.7</td>
<td>-</td>
<td>-2.9</td>
</tr>
<tr>
<td>density of sand ($\rho_s$)</td>
<td>2650</td>
<td>kg.m$^{-3}$</td>
<td>-3.3</td>
</tr>
<tr>
<td>sand grain diameter ($d_{so}$)</td>
<td>2.10$^{-4}$</td>
<td>m</td>
<td>-4.3</td>
</tr>
</tbody>
</table>

The origin of this great sensitivity can be appreciated by the following physical argumentation based on energy considerations. Sand grains in water sink with a bulk velocity $w_s$ related to Stokes solution of low-Reynolds flow along a single sphere in infinite volume of laminar fluid but corrected for deviations such as larger Reynolds number as well as for the shape and the size distributions of the sand grains.

In horizontal flows, a steady profile of sand suspended in the flow exists due to the supply of potential energy from turbulent motions by increasing the grain’s vertical position through upward mixing. The upper limit of the supply of potential energy is determined by the production of turbulence, the latter is proportional to the mean velocity cubed. Therefore the sand concentration at some position above the bed is roughly proportional to the mean velocity cubed.

Similar energy arguments apply to the release of sand from a sand bed into the flow so that the near-bed sand concentration is also roughly proportional to the mean velocity cubed. Particularly, the generally applied formulation of Zyserman and Fredsoe (1994), also implemented in the POINT SAND model, for the near-bed concentration of suspended sand shows at the onset of erosion a dependence to the mean velocity with a power 3.5, rather than 3.0, but this power decreases to zero for very fast flows, or smaller grain sizes. Consequently, even the powers change significantly depending on e.g. grain size: for 100 μm sand and all other conditions the same, the sand flux is then proportional to the mean velocity with power approx. 2.5.

Notice that the previous qualitative arguments refer to the vertical sand transport processes proper i.e. for exactly given hydrodynamic and turbulence conditions in a stationary flow. Nearly all theoretical research, however, is supported by numerical solutions of the flow and sand-concentration profiles. Even for steady flows the following considerations show, in addition to Table 3.1, an increased uncertainty due to numerical errors.

For steady turbulent flows, the numerical simulation is complicated severely by the following well-know ingredient of modelling turbulence in steady boundary layers along plane walls. Prandtl’s concept of mixing length yields

$$V_T = K u_* Z$$  \hspace{1cm} (3.1)
for the eddy viscosity $\nu_t$ depending on Von Kármán constant $\kappa \approx 0.4$, bed-friction velocity $u_\ast$ and distance $z$ with respect to some level $a z_0$ below the fluid-bed interface with bed-roughness length $z_0$ and $\alpha \approx 9$. The consequences of (3.1) for the horizontal sand flux are twofold. Firstly, the mean velocity near the bed is logarithmic. Secondly, the near-bed vertical profile $e(z)$ for sand concentration is proportional to $z^\beta$. Here, $\beta$ is the so-called Rouse parameter and $\beta = \nu_0 \sigma_t / \kappa u_\ast$ holds with settling velocity $\nu_0$ and $\sigma_t$ is the turbulence Prandtl/Schmidt number. The latter being the ratio between eddy viscosity and eddy diffusivity.

The consequence of the classical but well-established empirical law (3.1) is that both the mean velocity profile as well as the mean sand concentration profile are nearly singular. The strict reader is asked for some tolerance in the latter mathematically poor but intuitively clear definition.

In a steady current along a horizontal bed, the horizontal sand flux profile is the product of the nearly singular mean velocity and the nearly singular mean sand concentration profiles. The latter product thus suggests that the numerical solution of the horizontal sand flux is overly sensitive to numerical errors.

Until this point we considered horizontal sand transport in steady flows and we addressed the sensitivity for variations in input, as illustrated by Table 3.1, and numerical solutions nearly singular profiles.

In the following we consider additional sources for horizontal sand flux as well as the numerical aspects when simulating these contributions. Apart from modulating the bed shear stress, most contributions of surface waves to horizontal sand transport originate from so-called second-order effects. In many cases second-order effects by surface waves are due to the correlation

$$\overline{\hat{h}(t) \bar{v}(t)}$$

between some horizontally oscillatory flow or sand property $\hat{h}(t)$ and some vertically oscillatory flow or sand property $\bar{v}(t)$, both with zero time averages. The respective amplitudes $\hat{h}$ and $\bar{v}$ can be substantial. In most cases, however, $\hat{h}(t)$ and $\bar{v}(t)$ are nearly in quadrature i.e. they are $\pm 90^\circ$ out of phase in time except for some small deviation $\phi$ in phase angle so that (3.2) becomes

$$\overline{\hat{h}(t) \bar{v}(t)} = \frac{1}{2} \hat{h} \bar{v} \sin \phi.$$  \hspace{1cm} (3.3)

Formulations of the type (3.3) are regarded as some second-order effect of surface waves. The problem of estimating (3.3) numerically is not so much in computing the amplitudes $\hat{h}$ and $\bar{v}$, which are usually substantial, but lies in estimating the small deviation $\phi$ from $\pm 90^\circ$ phase differences.

Some numerical schemes have dominant diffusive properties which then affect mostly the amplitudes $\hat{h}$ and $\bar{v}$. Other numerical schemes invoke phase errors that affect $\phi$, the magnitude of the latter is usually just a few degrees so that phase errors largely distort (3.3)
and may even change its sign. Obviously, the latter frustrates the analysis e.g. for onshore or offshore sand transport.

The previous introduction, using (3.3), to numerically solving intra-wave sand transport is abstract and therefore we present the following illustration, crucial for simulating sand transport. If the oscillatory flow is due to surface waves the time-averaged sand flux near, but at some distance \( z \), above the bed can be approximated by

\[
\bar{u} \bar{c} = \bar{\bar{u}}(z) \bar{c}(z) + \bar{u} \bar{c} \approx \bar{\bar{u}}(z) \bar{c}(z) + \beta \bar{u}^S \bar{c}(z) \quad ; \quad \bar{u}^S(z) = \frac{1}{z^0} \int_0^z \bar{u}^S(z') \, dz' ,
\]

(3.4)

where \( \bar{u}^S \) is the wave-induced Stokes drift \( \bar{u}^S(z) \), averaged from bed to level \( z \). The tilde refers to perturbations by orbital motions with zero mean; the overbar in (3.4) denotes long-time averaging or averaging over a single repetitive wave period. In (3.4), horizontal turbulence transport has been neglected. The essential steps in achieving (3.4) read

\[
\bar{c} \approx -\bar{Z}(z,t) \frac{\partial \bar{c}}{\partial z} \quad ; \quad \bar{u} \bar{c} \approx -\bar{\bar{u}} \bar{Z} \frac{\partial \bar{c}}{\partial z} \quad ; \quad \bar{u} \bar{Z} \approx \int_0^z \bar{u}^S(z') \, dz' ,
\]

(3.5)

with \( \bar{Z}(z,t) \) the deviation in vertical displacement by orbital motions, of a fluid element from its time-averaged level \( z \). In (3.5), the first approximation is due to mass conservation of sand with a dominant mean vertical concentration profile. For the last expression in (3.5) we refer to Appendix B of (Winterwerp and Uittenbogaard, 1997) and here we omitted additional terms that depend on the vertical gradient of the mean horizontal velocity.

The Stokes drift \( \bar{u}^S(z) \) is due to the gradient in the vertical profile of the horizontal velocity amplitude as well as of the mean flow which makes \( \bar{u} \) in the forward and upward motion different from \( \bar{\bar{u}} \) in the downward and backward motion. The latter temporal asymmetry is essentially by the following part of the momentum equation for the horizontal orbital velocity:

\[
\text{at } z: \quad \frac{\partial \bar{u}}{\partial t} + \bar{u} \frac{\partial \bar{u}}{\partial x} + \bar{\bar{w}} \frac{\partial \bar{u}}{\partial z} + \bar{w} \frac{\partial \bar{u}}{\partial z} + \frac{1}{\rho} \frac{\partial \bar{p}}{\partial x} + ... + T_x = 0 ,
\]

(3.6)

with \( \bar{\bar{w}} \) the vertical velocity component, \( \rho \) the density of water, \( \bar{p} \) the pressure and \( T_x \) the wave-current interaction (WCI) force that we explain below. The vertical distribution of the non-hydrostatic pressure fluctuations in (3.6) invokes a vertical profile for the amplitude of \( \bar{u} \). The two terms in (3.6) that depend on \( \bar{\bar{w}} \) affect the temporal asymmetry of \( \bar{u} \) and this asymmetry is the origin of the Stokes drift \( \bar{u}^S(z) \), being a wave-averaged property.
About the role of $T_x$ as WCI force

Finally, we explain the meaning of the force $T_x$ in (3.6) which is the consequence of splitting the flow into wave-averaged and wave-resolving motions. For the latter, (3.6) is defined and designed for strictly orbital velocity i.e. with zero average. As soon as the solution of (3.6) creates an orbital velocity with non-zero average this implies a change in wave-averaged momentum that should be transferred to the mean flow (equation). The main reason that a wave-averaged momentum is developed is the wave-averaged of the term $\bar{w} \partial \bar{u} / \partial z$, although $\bar{u} \partial \bar{u} / \partial x$ and the omitted friction terms contribute as well. The phase lag between $\bar{w}$ and $\partial \bar{u} / \partial z$ deviates from $\pm 90^\circ$ by the presence of the mean flow profile $\bar{w} \partial \bar{u} / \partial z$ as well as by bed friction. In virtue of (3.2) and (3.3), the average of $\bar{w} \partial \bar{u} / \partial z$ yields a small but non-negligible mean value that depends on the z-level. Without $T_x$, the solution of (3.6) would yield an orbital velocity with an increasing drift component. This drift is actually the manifestation of the time-integrated wave momentum, induced mainly by $\bar{w} \partial \bar{u} / \partial z$. Presently, there exists no general analytic expression for the time-average of $\bar{w} \partial \bar{u} / \partial z$. In the POINT SAND model, therefore, this time average is obtained numerically by adjusting the z-dependent force $T_x$ such that the time-averaged orbital velocity is or becomes (nearly) zero, in accordance with its definition. If the time-average of the orbital velocity is zero then the force $T_x$ must represent the WCI force. In principle, the numerical recipe of obtaining $T_x(z)$ is irrelevant, provided it yields its objective i.e. a zero time-averaged orbital velocity.

Notice that it is the decomposition of the flow into mean and orbital motions that introduces the WCI force. Is sole function is the exchange of mean momentum between orbital motions and the mean flow. Consequently, the WCI force appears with opposite sign in the mean momentum equation, see Figure 3. The WCI force dissappears in the sum of the mean-momentum and orbital-momentum equations, yielding the total momentum equations. The latter statement again creates confusion because how can the mean flow profile then be altered if the WCI force drops out in this summation? The answer is that the WCI force is z-dependent, see the relevant figure in Appendix F of (Uittenbogaard, et al., 2000). If the WCI force were z-independent, similar to the horizontal hydrostatic pressure gradient, then the velocity profile would remain logarithmically. In case of initially zero flow, force $T_x$ creates a mean horizontal velocity profile $\bar{u}(z)$, called boundary-layer streaming. Figure 1 illustrates the latter phenomenon where $\bar{u}(z)$ is due to a monochromatic surface wave propagating in positive x-direction (in co-ordinates fixed to the channel) in a free-surface wave channel closed at both ends i.e. with zero depth-integrated flow. Figure 1 is opposite to Figure 4.6 in (Kloppman, 1994) because there the monochromatic wave (case WMN) propagates in negative x-direction yielding negative streaming velocity.

Apparently, our particular choice (Uittenbogaard et al., 2000, eq. 3.40) for the numerical procedure is confused as being some approximation to the yet unknown analytic WCI force but that is not the case. Notice that even if the analytic expression for the WCI force is known and implemented in (3.6) then numerically-induced phase or amplitude errors, as discussed previously, would still invoke a drift in the simulated orbital velocity. In other words, still some compensating z-dependent correction ($T_x$) would be required in addition to the analytic formulation of the WCI force. This ends our explanation about the role of $T_x$. 
in the orbital and mean momentum equations and we continue with the consequences for sand transport.

We desire simulating rather than modelling the sand flux (3.4) and then the momentum equation (3.6) must be solved accurately. Particularly, the subtle phase difference between \( \hat{w} \) and \( \bar{u} \), which are nearly in quadrature, are essential for two reasons. Apart from oscillatory turbulence mixing, it is \( \hat{w} \) that invokes \( \bar{c} \) and thus \( \hat{w} \) affects the correlation \( \overline{\hat{u}\hat{c}} \). Note that the first expression in (3.5) is valid only if the vertical orbital-velocity component is at least comparable to the settling velocity of sand grains. Particularly, the vertical orbital motions play a significant role on the temporal concentration profile if their velocity amplitude at the top \( z = \delta \) of the wave-boundary layer is at least of the same order-of-magnitude as the settling velocity \( \omega_s \). For sufficiently long waves, compared to water depth \( H \),

\[
\frac{\hat{w}(\delta)}{\omega_s} = \mathcal{O}\left(\frac{\sigma_z}{\beta k^3 H}\right)
\]  

(3.7)

holds with \( \hat{\zeta} \) the amplitude of surface elevation. For \( \beta \) less than unity and for typical wave conditions, (3.7) is of order unity showing the significance of vertical orbital motions which are not reproduced in a wave tunnel with a rigid lid. Finally, not only is the temporal correlation yielding \( \overline{\hat{u}\hat{c}} \) affected by the ratio (3.7) but also by the turbulence response in the wave-boundary layer. It is established that the turbulence response and its consequences for temporal erosion is due to a secondary flow instability that is not yet objectively incorporated in eddy-viscosity type of turbulence models.

We summarise as follows. The previous presentation demonstrates that surface waves contribute to the time-averaged sand flux (3.4) firstly by the occurrence of a vertical orbital velocity and secondly by the creation of small changes in phase lags between oscillating flow properties. Notice that in a wave tunnel just the horizontal orbital-velocity component is reproduced while the vertical orbital-velocity component remains zero. If the plungers of the tunnel create a temporally symmetric flux then \( \hat{u} \), without \( \hat{w} \), is also temporally symmetric so that in a wave-tunnel the sand flux \( \overline{\hat{u}\hat{c}} \) is zero as opposed to (3.4) for a free-surface wave channel.

Consequently, (3.4) shows that the translation from sand flux observations in a wave-tunnel, i.e. with a rigid lid, to the sand flux in a wave channel or in the field with a mobile water surface is not straightforward.

One of the purposes of the POINT SAND model is to make such a comparison between wave tunnel and wave channel possible while using the same formulations and solution procedures for vertical and horizontal sand transport processes. The POINT SAND model, therefore, includes a subprogram that solves the horizontal and vertical orbital velocity components of surface waves propagating in turbulent shear flows for a given set of wave height, wave period, phase and wave direction. Compared to existing 1DV models for constant flows or wave tunnels only, the POINT SAND model is unique in this respect. Particularly, the POINT SAND model uses the solution procedure for vertical sand transport in a wave-tunnel but, of course, the horizontal and vertical transport by orbital motions is added in case of simulating sand transport in a free-surface water channel.
An undesired modelling aspect, contributing to the sensitivity of input variables, is due to discontinuities (steps) in the piece-wise approximation of the Shields parameter as a function of dimensionless grain diameter, for details see (Uittenbogaard et al., 2000, eq. 6.12). This Shields parameter determines erosion through the non-linear formulation of Zyserman and Fredsøe (1994). In oscillating flows such discontinuities can be passed repetitively and then convergence, through time step reduction, in the simulated sand flux is even impossible. Similar discontinuities were noted for the piece-wise approximation to the settling velocity as a function of grain diameter, for details see (Uittenbogaard et al., 2000, eq. 6.4).

Before reliable conclusions can be drawn from the comparison between wave tunnel and wave channel simulations, the POINT SAND model must be thoroughly validated against wave-current experiments, such as those reported in (Klopman, 1994). Consequently, the POINT SAND model must offer options for investigating the sensitivity of the wave channel simulations to numerical procedures, various closures for turbulence etc.

Finally, the POINT SAND model offers a first but limited step towards the field where sand transport occurs in tidal currents with surface waves that are mostly perpendicular to the coast. The POINT SAND model allows the mean current, induced by tides and wind, as well as the spectral components of the surface waves to have arbitrary directions.

The previous list of arguments, extensive but by far not complete, shows that before concluding that e.g. some bed erosion formulation is generally applicable, many uncertainties in the experimental as well as numerical simulation of hydrodynamics, turbulence and concentration properties require careful considerations. The latter investigation is so complex that it easily exceeds the scope of work that can be handled by a single research group so that most research groups stick to their particular numerical model, usually dedicated to one flow aspect, which then slows down the progress in finding better sand transport formulations. The next section summarises the contents of the POINT SAND model for performing this involved task.
4 General description of the POINT SAND model

4.1 Introduction

This section presents the general contents of the POINT SAND model as well as a substantially more thorough explanation of the solution procedure then presented in Appendix A of (Uittenbogaard et al., 1999). In addition, this section addresses most questions, discussions and misunderstandings that emerged since the first release.

4.2 Flow configurations

The POINT SAND model is designed for simulating sand transport in the following typical flow configurations:
1. Constant-flow channel (free surface);
2. Confined wave tunnel (rigid lid);
3. Field conditions without surface waves (wind-driven and tidal currents, varying water depth, varying flow direction);
4. Combined wave-current channel (free surface, waves parallel to flow); or
5. Field conditions with surface waves (wave propagation irrespective of flow direction).

4.3 Modelling turbulence but resolving waves and time-dependent currents

In all cases the flow solved explicitly by the POINT SAND model is time-averaged or, in case of surface waves, phase-averaged over turbulent motions. The net-effect of the turbulent motions on the simulated flow and sand transport are additional momentum and mass fluxes which are represented by turbulence models. Thus the resolved flow is either due to currents and/or waves.

4.4 The outer loop

The option to make the flow time dependent in the second and third flow configuration (Section 4.2) caused misunderstandings, therefore, we address this subject immediately. In the first three flow configurations, the flow velocity vector is by definition horizontal i.e. in the momentum equations for the two horizontal velocity components the vertical velocity as well as the horizontal gradient of the mean or orbital velocity vector are neglected. Further, the flow is driven by the horizontal gradient of the hydrostatic pressure. We define this flow
as the *mean flow* and in the POINT SAND model it is solved in the so-called *outer loop*. All this is represented by the upper box in Figure 2 where \( U(z,t) \) represents one of the two horizontal velocity components. The mean flow is thus a horizontal velocity vector solved as a function of time and of co-ordinate \( z \) along the entire water depth i.e. from bed to upper surface and at arbitrary depth-dependent i.e. \( z \)-dependent flow direction.

For the mean flow, the user may specify a time-dependent depth-averaged velocity vector (magnitude as well as direction) and also a time-dependent water depth. In addition, the simulated mean flow responds in time as well as along the water depth to the forcing by some given time-dependent wind vector. In all cases the horizontal gradient of the hydrostatic pressure is adjusted internally such that the user-specified depth-averaged velocity vector is maintained.

The user can select periods ranging from those of tidal motions to periods of short surface waves; the latter creating ambiguity. Notice that in all cases, the *mean flow* remains horizontal, by definition. This is the reason why the first three flow configurations are solved in the POINT SAND model with exactly the same input and solution procedures that we define generally as the *outer-loop*. Presently, the wave tunnel is the most relevant flow configuration and its flow is simulated by the *outer-loop* of the POINT SAND model, similar to solving tidal currents, because the resolved flow in the wave-tunnel configuration is strictly horizontal, see Figure 2.

After solving the horizontal flow, see Figure 2, the most recent bed shear stresses are determined and the turbulence conditions are adjusted accordingly yielding the most recent mixing coefficients. Subsequently, the vertical sand transport equation is solved i.e. with settling velocity and vertical mixing by turbulence. In this sand-transport equation, the horizontal gradients of velocity and of sand concentration are omitted i.e. horizontal advection and horizontal mixing is omitted by the assumption of uniformity. Erosion conditions are determined by the bed-shear stress using the Zyserman and Fredsoe formulation that is prescribed at \( 2d_{50} \) above the fluid-bed interface.

Another point of ambiguity is that the user can also define time-varying water depths for the horizontal flow solved in the *outer-loop*. Such water-depth variations are meant for slow tidal motions only, such as in the third flow configuration (see Section 4.2), where the velocity vector essentially remains horizontal. With varying water depth in the *outer-loop*, mass conservation of sand is not guaranteed although for sand transport, with its rapid adjustment in the erosion-diffusion-settling balance, we regard this mass-closure error negligible under tidal conditions.

For avoiding confusion, notice that later in this section sand transport by the action of surface waves is described. Under wave conditions, the mass conservation for suspended sand is guaranteed by including horizontal and vertical orbital velocity components and their respective horizontal and vertical gradients. Therefore, the user must not attempt to mimic free-surface waves by coupling water-depth variations to time-dependent depth-averaged flow velocity for the horizontal flow solved by the scheme of Figure 2.
The outer loop is solved with time steps (TIMEST in Figure 2) that are a fraction of the period of the oscillatory horizontal velocity. In case of steady flow it is just quick convergence that matters rather than accurate temporal resolution so that the time step can be taking significantly larger, typically the time characteristic for turbulent mixing along the water depth.

4.5 Coupled outer and inner loops for wave-current and wave-turbulence interaction

Most freely propagating surface waves are shorter than tidal waves and have significant horizontal gradients of velocity, a significant vertical-velocity component as well as a pressure usually deviating from the hydrostatic pressure. Moreover, free-surface waves are better specified by their direction of propagation and their wave amplitude per wave period rather than by their depth-averaged velocity vector. All these aspects of free-surface waves differ so much from those of purely tidal or wave-tunnel oscillations that the POINT SAND model has a more extended set of equations for the wave-related pressure and orbital velocity vector. Per given wave period or angular frequency \( \omega \), this set is solved in the inner-loop as a function of depth co-ordinate and time, see Figure 3 where (3.6) is recognised.

Figure 3 shows several inner-loop boxes, each representing the inner-loop subprogram of Figure 5. The latter will be explained later. Each inner-loop box in Figure 3 represents the solution of the orbital motions per wave period over a single time step and as a function of the depth co-ordinate \( z \). In other words, per inner-loop box in Figure 3 a single spectral component of a user-defined wave spectrum is solved. Figure 3 shows that a sequence of spectral components with increasing angular frequency \( \omega \) is solved over a single time step. The reason of this particular sequence is that waves with longer periods usually are more energetic and affect the shorter waves significantly more than vice versa. The interaction is due to the perturbation of the horizontal and vertical orbital motions of a particular spectral component by itself as well as by all other spectral components. The sequence in a single inner-loop time step thus uses the shortest, in wave length, orbital motions from the previous time step but the most recent orbital motions of all longer components. In principle, iteration until convergence is required e.g. by up-and-down sweeps from low to high and conversely from high to low frequencies. Although this iteration can easily be included in the system it is not yet implemented, assuming sufficiently small inner-loop time steps.

The user can switch on the entire inner-loop procedure by setting the number NUMWAV of steps per outer-loop time step (TIMEST) larger than zero; the inner-loop time step then equals TIMEST/NUMWAV.

After such a small inner-loop time step, the strain rates induced by all spectral components are collected. The sum of these strain rates and of the mean flow (outer-loop box) serve as input to the turbulence model. Compared to Figure 2, the turbulence model is called after every inner-loop time step so that orbital modulation of the turbulence is computed.
Likewise, after each inner-loop time step all horizontal and vertical orbital velocity components are mutually summed and converted into mass-conserving advection terms exploiting the horizontal periodicity of the orbital motions. This net mass-conserving advection by the waves is used in the sand transport equation where the settling velocity is included as well. Presently, the minor horizontal diffusion of sand is not taken into account. Consequently, the sediment fluctuations due to the orbital motions and turbulence modulations are simulated. It is this explicit simulation of concentration fluctuations that allows the computation of the wave-induced correlation \( \overline{u'c'} \) in (3.4), without using the approximations of (3.5).

After the completion of NUMWAV inner-loop time steps, the net action of the orbital motions, in terms of WCI force, turbulent mixing and enhanced bed-shear stress, is transferred to the mean flow solver in the outer-loop. This completes the entire wave-current-sediment-turbulence interaction which is the novel aspect of the POINT SAND model allowing for an inter-comparison of sand transport in a rigid-lid wave tunnel and a free-surface wave channel.

Yet many subtle aspects in the entire wave-current-sediment-turbulence simulation require more explanation. Below we begin with the rather involved time management of the POINT SAND model.

### 4.6 Time management

In line with the definition of the mean flow, a single outer-loop time step (TIGHT) covers at least one or more wave periods \( T_1, T_2 \) etc., see Figure 4. In the inner-loop subprogram (Figure 5) the zero-crossings of the surface elevation of each spectral component is recorded and after each wave period, the WCI force of that spectral component is upgraded. Under non-stationary conditions or when two or more spectral components are computed, the upgrading of the WCI force causes a jump such as depicted in the lowest diagram of Figure 4. Therefore, the adjustment of the WCI force is introduced gradually through a procedure described in (Jitlenbogard et al., 2000, eq. 3.42). It is this new WCI force, thus based on the most recent wave period, that forms the feedback to the orbital motions with the purpose of obtaining a zero time-averaged horizontal orbital velocity. Depending on the actual outer-loop time step (TIGHT) the most recent WCI forces of individual spectral components are collected i.e. all WCI contributions refer to the most recently completed wave cycle. With an ill-chosen outer-loop time step (TIGHT) such a summation of WCI forces of interacting waves introduces additional fluctuations that are communicated to the mean flow solver in the outer-loop. The consequence is that non-physical amplitudes of subharmonics could occur. Our experience for yielding minimal mean-flow modulations is growing but still it needs some expert judgement. The current advice is using the period of the longest subharmonic as outer-loop time step (TIGHT) when maximal three energetic spectral components are simulated with non-multiple periods. Tests with a spectrum of 12 spectral components with nearly equal wave amplitudes show a vanishing dependence of the results on outer-loop time step (TIGHT), likely due to the reduction of the modulation in WCI force by collecting so many spectral components.
4.7 The inner-loop subprogram

The following general aspects are of importance for appreciating the approximation and solution procedure for the orbital velocity components:

1. The equations are solved on a fixed Eulerian grid and all free-surface conditions are imposed at the still water level and at the lowest order of approximation;
2. The emphasis is on non-linearity due to wave-current-turbulence interaction;
3. There is a gradual introduction of wave-current, wave-turbulence and wave-wave interactions in solving the particular sequence: $\zeta \rightarrow \vec{p} \rightarrow \vec{w} \rightarrow \vec{u}$.

The first condition is suitable for infinitesimal waves only and it may be the most recommendable one for future improvements.

In addition, the first point also states that the POINT SAND model does not compute the orbital velocity up to the mobile water surface. In other words, the net wave-induced mass flux that occurs above the wave troughs is not simulated. This mass flux is equivalent to the depth integral of the Stokes drift which then equals the last expression of (3.5) but with its upper limit of integration equal to the mean-water level. This unaccounted net wave-induced mass flux is compensated by subtracting from the user-defined depth-averaged velocity the mathematical expression presented at the bottom of the diagram in Figure 5, see also (Winterwerp & Uittenbogaard, 1997, App. B). Instead, the wave-induced correlation $\overline{u \tilde{c}}_z$ is computed correctly, provided the sand concentration at the free surface is negligible which is the usual case. The derivations in (3.5) demonstrate that this wave-induced correlation $\overline{u \tilde{c}}_z$ is due to the depth integral of the Stokes drift from the bed up to level $z$. As long as sand does not reach the free water surface, the vertical displacement of the sand isolines is computed correctly. For determining the Stokes drift of sand-mass flux, these sand isolines replace the mobile water surface for the Stokes drift of water.

The second point states that most attention is given to incorporating correctly the influence of the vertical profile of the mean horizontal velocity in the solutions for orbital motions. In other words, lesser attention is paid to the subtle treatment of stress-free boundary conditions for waves on a laminar flow. From literature we do not know a numerical model that explicitly computes the surface-layer streaming in the weak viscous Stokes layer at the mobile surface. The surface-layer streaming is significantly weaker than in the bed-boundary layer where the strong no-slip condition holds and this condition introduces strong velocity gradients significantly larger than the boundary condition at the weakly rotating stress-free water surface (Phillips, 1980, p. 480). Our brief experience learns that even small numerical phase errors in the treatment of the stress-free water surface can invoke unexpected surface-layer streaming. A well-known example from nature is the dominant role of surface tension and increased viscosity of oil slicks on surface-layer drift.

The third point is born out of practice rather out of theoretical order estimates: we introduced as much non-linearity as needed for simulating Klopman’s (1994) wave-current observations.
These are the comments on the three general aspects and limitations of the hydrodynamics of the POINT SAND model. Below the subsequent steps in Figure 5 are explained.

For each spectral component, Figure 5 presents the sequence \( \zeta \rightarrow \vec{p} \rightarrow \vec{w} \rightarrow \vec{u} \) of equations solved in the inner-loop. In a separate routine (DEFWAV), the surface elevation \( \zeta(t;\omega) \) for the particular spectral component with angular frequency \( \omega \) is computed using wave period, phase and wave amplitude, as defined by input. During 10 wave cycles of the particular spectral component, the wave amplitude \( \zeta \) is gradually increased from zero to its input value. There is no feedback on surface elevation, neither by the mean flow nor by any inner-loop solution. In this context, all wave amplitudes are treated independently, despite anticipated interactions and coupling with \( \vec{w} \).

Another routine (AVERAG) detects every second zero-crossing of the surface elevation of the spectral component under consideration. When that happens, the vertical profile of the hydrodynamic pressure as well as the wave number magnitude (dispersion relation) are computed using the most recent mean-flow velocity profile, projected on the direction of wave propagation. The vertical profile of the pressure, scaled by \( \zeta(t;\omega) \), remains frozen over the subsequent wave cycle i.e. the pressure magnitude is adjusted in proportion to the actual surface elevation. Alternatively, this routine (AVERAG) also notifies the end of a wave cycle and then the averages for Stokes drift and WCI force are assigned, this is the last action in Figure 5.

We return to the top of Figure 5 and continue with the hydrodynamic pressure that is solved by its linearised Poisson equation i.e. for small wave amplitude but for arbitrary vertical profile of the mean horizontal velocity. The latter consideration emphasises our interest in wave-current interaction. The vertical pressure gradient then drives the momentum equation for the vertical orbital velocity in which there is just linear advection by the mean flow and damping by turbulence in the RHS. In the subsequent step or box in Figure 5, the horizontal orbital velocity component in the direction of wave propagation is driven by the horizontal pressure gradient but with non-linear advection and damped by vertical exchange of horizontal momentum through turbulence.

This completes the particular sequence: \( \zeta \rightarrow \vec{p} \rightarrow \vec{w} \rightarrow \vec{u} \) showing an increasing degree of wave-current interaction and wave-wave non-linearity which appears to be sufficient for simulating the wave-current experiments in (Klopman, 1994).

### 4.8 High-pass filtering of strain rates for turbulence production

This section explains why we apply a high-pass filter, depending on the wave period, that reduces the strain rates of orbital motions for momentum exchange and turbulence production. Unfortunately, such a filter is applicable only to wave channel or field conditions because the orbital motions are simulated individually but not in the wave tunnel. The probable consequence is that the POINT SAND model overestimates turbulence production in the wave tunnel.
The principle idea for introducing a high-pass filter reads as follows. Consider the interaction between turbulent eddies with a wide spectrum in time scales as well as length scales and a coherent velocity field with strain rates at some fixed frequency and fixed wave length. The latter obviously represents the strain rates induced by orbital motions and we call this strain field the source.

First consider eddies of sizes much larger than the wave length and also much slower than the period of the source. The source (field) spatially deforms the large eddies at scales smaller and also significantly faster than their size and turnover time. The contours of the large and slow eddies, visualised e.g. with dye, behave as some elastic balloon. The consequence is that the large and slow eddies are reversibly deformed by the source i.e. without exchanging energy with the source.

Next consider eddies with significantly shorter length scales as well as significantly faster turnover times than the wave length and period of the source. We may again visualise the contours of these small and fast eddies with e.g. dye. Now during the passage of the source the eddies are so short and fast that they deform significantly as if deformed steadily by the source. The contours of the small and rapid eddies rotate and elongate significantly by the imposed straining. This vortex stretching and thus a part of the local vorticity is thus correlated with the velocity fluctuations imposed by the source. From vector calculus follows that the mean of turbulence advection is the force

\[ \bar{F} = \bar{u} \cdot \nabla \bar{u} = \nabla \left( \frac{1}{2} \bar{u}^2 \right) - \bar{u}^T \omega' \]  

(4.1)

where the last term is called Lighthill’s vortex force. The described deformation of the small and rapidly responding eddies now contribute to this vortex force because the eddies are displaced by the comparatively slow deformation of the source. Therefore, sufficiently small eddies interact with the source field and transfer its momentum and consume energy through Lighthill’s vortex force.

We conclude from this qualitative description that only eddies smaller and faster than the source field interact with it.

Surface waves that significantly affect the bed-boundary layer and thus contribute to sand erosion have wave lengths larger than the water depth i.e. larger than the length scale of the most energetic eddies of 3D turbulence. Therefore, when comparing just wave lengths and length scales, all turbulent eddies in the channel flow would interact with the large-scale deformation imposed by surface waves. Comparing typical wave periods with time scales of the energetic eddies, however, the imposed wave deformation is significantly faster than the turnover time of the energetic eddies. Thus the comparison in terms of time scales is the most limiting criterion for determining which eddies interact irreversibly with the orbital motions. This conclusion can be substantiated by comparing the period \( \tau \) of sufficiently long surface waves to the time scale \( \tau^* \) of turbulence in a channel flow with rms turbulence level \( |u'| \):

\[ \frac{\tau}{\tau^*} \approx \frac{2 \pi |u'|}{\kappa Z (1-Z) \sqrt{g H}} \quad \text{using} \quad \tau^* \approx 2 \pi \frac{H \sqrt{H}}{g} \quad \text{and} \quad \tau^* \approx \frac{\kappa H Z (1-Z)}{|u'|} \quad \text{with} \quad Z = \frac{z}{H} \]  

(4.2)
showing a ratio substantially smaller than unity halfway the water depth ($Z=0.5$). Near the free surface or near the bed, the time scale ratio $\bar{\tau} / \tau^*$ may become larger than unity i.e. just the turbulent eddies in the boundary layer(s) respond to the orbital motions.

The previous arguments are mathematically translated by Figure 6 where the shaded parts of the energy spectrum contribute to turbulent eddies faster than the source and with time scales smaller than the period of the source. From these shaded areas follows a function depending on $\bar{\tau} / \tau^*$ that reduces the eddy viscosity, formulated in Figure 6, to an effective eddy viscosity. We call this reduction the high-pass filter function $f_{hp}(\bar{\tau} / \tau^*)$, see (Uittenbogaard et al., 2000, eq. 4.12). This function appears in the turbulence damping terms in the orbital momentum equations but obviously not in the momentum equation(s) of the mean flow, see Figure 3. The sand concentration acts passively to all mixing so that the high-pass filter function $f_{hp}(\bar{\tau} / \tau^*)$ does not appear in the sand transport equation.

All mean-flow strain rates but just the high-pass filtered part of the orbital strain rates contribute to turbulence production so that just in thin boundary layers the orbital motions significantly enhance turbulence and mixing.

For a spectrum of waves in a wave channel or in the field, the high-pass filter function $f_{hp}(\bar{\tau} / \tau^*)$ is frequency-selective and because each spectral component is solved individually their respective strain rates are known and can be reduced by $f_{hp}(\bar{\tau} / \tau^*)$.

The same arguments apply to slow oscillations and slow or rapid turbulent eddies in the wave tunnel. However, there a discrimination between active and inactive strain rates is not readily available in the simulation with a spectrum of oscillatory horizontal motions because a single depth-averaged velocity signal is constructed from a given series of harmonics. Presently, for turbulence production in simulations of the wave tunnel an adequate filter is lacking. For the time being, therefore, we conclude that in the wave tunnel turbulence production must be overestimated by the POINT SAND model and probably by other IDV models as well.

The next chapter summarizes in short-hand style the various aspects of the POINT SAND model.
5 Summary contents POINT SAND model

This chapter presents an overview of the options of the POINT SAND model as well as its assumptions and limitations.

**Input/control by user:**

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<th>Options</th>
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<td>five choices for layer distribution, time step, time for output, time series and of harmonic analysis</td>
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<tr>
<td>Advection scheme for sediment</td>
<td>1st order upwind or 2nd order central scheme</td>
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<tr>
<td>Turbulence models</td>
<td>laminar; k-L, k-L (Davies' version), k-ε</td>
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<tr>
<td>Bed friction</td>
<td>partial slip: Chezy, Manning, roughness length or no-slip with given viscosity.</td>
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<tr>
<td>Mean flow equations</td>
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<tr>
<td>Earth rotation</td>
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<tr>
<td>Water depth</td>
<td>constant, time series or harmonics</td>
</tr>
<tr>
<td>Tidal current vector (outer loop)</td>
<td>depth-averaged or at given fixed reference level: constant, time series or harmonics</td>
</tr>
<tr>
<td>Atmospheric forcing</td>
<td>constant or time series: wind vector, air pressure, cloudiness, air humidity</td>
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<tr>
<td>True orbital motions (inner loop)</td>
<td>inner loop time step, relaxation time for WCI force and reference to a file for amplitude, period, phase and direction of the spectral wave components</td>
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<td>Time series output</td>
<td>for given z-level over given time interval</td>
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<tr>
<td>Sediment properties</td>
<td>multiple fractions, d₅₀, ρₑ, σₑ, pick-up or bed concentration, initial sand profile</td>
</tr>
<tr>
<td>Water density</td>
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<tr>
<td>Surface waves</td>
<td>vertical and horizontal orbital velocity (z,t) over entire water depth only depending on bed friction, internal friction, horizontal current, solving pressure, arbitrary direction and phases, WCI force, boundary layer streaming</td>
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<tr>
<td>Sediment transport</td>
<td>(z,t) over entire water depth only, depending on settling velocity, hindered settling, orbital motions, diffusion, pick up or bed concentration</td>
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<td>As sum of spatially and temporally periodic waves; no wave breaking</td>
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</table>

The previous table shows the numerous aspects that needed to be resolved in the future and it is hoped that Dutch researchers will continue from here, using the available source code of this POINT SAND model.

Acknowledgements

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Figures
Mean current profile or streaming by a monochromatic surface wave propagating in positive U-direction in a free-surface channel closed at both ends (Klopman, 1994).
Diagram of the POINT-SAND model: time-varying currents, without surface waves.
Diagram of the POINT SAND model: time-varying currents and surface waves.

**POINT SAND MODEL**

**outer loop:**

\[
\frac{\partial U}{\partial t} + \frac{\partial}{\partial z} \left\{ (\nu + \nu_T) \frac{\partial U}{\partial z} \right\} = - \frac{\partial P}{\partial x} + \sum_{\omega} T_x
\]

**inner loop:** \( \omega_0 \)

\[
\frac{\partial \tilde{u}}{\partial t} + \tilde{w} \frac{\partial \tilde{u}}{\partial z} + \frac{\partial \tilde{U}}{\partial z} + \frac{\partial \tilde{p}}{\partial x} = - T_x
\]

**inner loop:** \( \omega_1 > \omega_0 \)

\[
\frac{\partial \tilde{u}}{\partial t} + \tilde{w} \frac{\partial \tilde{u}}{\partial z} + \frac{\partial \tilde{U}}{\partial z} + \frac{\partial \tilde{p}}{\partial x} = - T_x
\]

**after a single inner loop:**

- sum strain rates & vert. orb. velocity
- solve turbulence model
- solve sediment transport

1. collect WCI force
2. collect Stokes drift
3. bed shear stresses
4. low-pass filtering

**NUMWAV**

**T IMES T**

**W L DELFT HYDRAULICS**

Z2889.10

Fig. 3
Time Management

outer loop wave-averaged equations

period $T_1$

inner loop equations
inner loop equations

period $T_2$

inner loop eq's inner loop eq's inner loop eq's

signal

Smoothing: REL TIM

time

Time management of the POINT-SAND model
Flow diagram of the inner-loop solution procedure for surface waves.

\[ \begin{align*}
\text{Input:} & \quad \zeta; \omega \\
\text{Hydrodynamic Pressure:} & \quad \bar{p} = g \tilde{\zeta} \\
& \quad \frac{\partial \bar{p}}{\partial x} = -k \frac{\partial \bar{\zeta}}{\partial x} \quad \frac{\partial \bar{p}}{\partial t} = \omega \frac{\partial \bar{\zeta}}{\partial t} \\
& \quad \nabla \cdot \bar{p} = -2 \frac{\partial U}{\partial z} \frac{\partial \tilde{\omega}}{\partial x}
\end{align*} \]

\[ \begin{align*}
\text{Vertical Orbital Velocity:} & \quad \frac{\partial \tilde{\omega}}{\partial t} + U(z) \cdot \nabla \tilde{\omega} + \frac{\partial \bar{p}}{\partial z} = \frac{\partial}{\partial z} \left\{ 2(u + f \tilde{\nu}) \frac{\partial \tilde{\omega}}{\partial z} \right\}
\end{align*} \]

\[ \begin{align*}
\text{Horizontal Orbital Velocity:} & \quad \frac{\partial \tilde{u}}{\partial t} + \tilde{\omega} \frac{\partial \tilde{u}}{\partial z} + \tilde{\omega} \frac{\partial U}{\partial z} + \frac{\partial \bar{p}}{\partial x} = -T_x
\end{align*} \]

\[ \begin{align*}
\text{Averaging per cycle:} \\
T_x = \frac{\bar{u}(z;\omega_s)}{T} \\
\bar{u}(z;\omega_s) = \frac{1}{T} \int_{t_i}^{t_i+T} \tilde{u}(z,t;\omega_s) \, dt
\end{align*} \]

\[ \begin{align*}
\zeta U & \left\{ \frac{\partial}{\partial z} \right\} = \zeta \frac{\partial}{\partial z} \left( \bar{u} \right) + \frac{1}{2} \zeta^2 \frac{\partial U}{\partial z}
\end{align*} \]
The foundation of the high-pass filter function.

\[ \Gamma_T = \lim_{\tau \to \infty} \frac{d^1}{d\tau} \left\langle X^2 (\tau) \right\rangle = \left\langle u'^2 (x, t) \right\rangle \tau_L \]
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