On the validity of the use of standard stability models for pipeline laid on seabed, on the case of a tidal-turbine export cable

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Résumé

Le choix d'une route optimale pour le câble d'export depuis une hydrolienne est fortement contraint par l'environnement bathymétrique, la nature des sols et la forte dynamique de site. Il devient alors complexe pour les développeurs d'identifier une solution fiable sans surcoût démesuré. Pour cause, les sites hydroliens présentent une forte dynamique fluide (courant et houle) et un sol rocheux interdisant l'ensouillage. Le routage du câble doit faire en sorte d'éviter, entre autres, les zones où le câble risque d'être déplacé par les sollicitations couplées de la houle et du courant. Historiquement, les méthodes permettant d'estimer la stabilité d'une structure posée sur le fond marin ont été développées pour des cylindres rigides (pipelines ou émissaires en acier) dans la zone d'atterrage, dominée par les sollicitations cycliques de la houle. Le projet STHYF a pour but de faire le point sur les limitations des méthodologies existantes, et de proposer une méthodologie dédiée au routage de câble d'export sous-marins. Ce papier présente une comparaison des différents modèles identifiés pour calculer les efforts hydrodynamiques qui s'exercent sur un câble posé sur le fond marin, dans le cas d'un courant et d'une houle régulière superposés. La méthode de Morison, une reconstruction des efforts par série de Fourier, et un modèle Wake2 adapté sont confrontés à des résultats expérimentaux, afin de sélectionner le modèle le plus adapté à une méthodologie d'estimation de la stabilité des câbles d'export, lors du design d'une ferme.

Abstract

Routing the export cable from a tidal site is highly constrained by bathymetry, soil nature, and local strong dynamics. It is then difficult for developers to identify a trustworthy and cost-effective route. Indeed, tidal sites are characterized by high fluid dynamics (current plus often waves), and a rocky seabed forbidding cable-burying. Cable route needs to avoid zones where the cable is likely to be displaced by coupled current plus wave solicitations. Historically, method for on-bottom structures stability have been developed for rigid cylinders (rigid pipes) in the landing zone, where wave-induced cyclic solicitations dominate over current flow dynamics. Part of STHYF project's aims is to identify common technologies for predicting on-bottom stability and to propose a stability assessment methodology that is specifically dedicated to export cables routing. This paper presents a comparison of the different models that are currently available for computing efforts on a cylinder lying on a seabed, in the case of superimposed current plus regular waves. Experimental measurements act as a reference for comparing force timeseries obtained with a Morison method, with a Fourier analysis method, and with a modified Wake2 model. The results of the comparison will orient towards the method for calculating hydrodynamic efforts that is best suited to a methodology for export cable stability assessment, at the design stage

Keywords
on-bottom stability ; hydrodynamics ; tidal turbine ; export cable ; cable routing

Nomenclature

Parameter	Notation	Definition
Current ratio	α	$\frac{U_c}{U_w}$
Current velocity	U_c	–
Drag coefficient	C_D	–
Horizontal force	F_H	–
Keulegan-Carpenter	KC	$\frac{U_w T}{D}$
Lift coefficient	C_L	–
Pipe diameter	D	–
Pipe roughness ratio	k_p^*	–
Reynolds number	Re	Steady current: $\frac{U_c D}{\nu}$ Regular waves: $\frac{U_w D}{\nu}$
Seabed roughness ratio	k_{SB}^*	–
Vertical force	F_V	–
Wake velocity	U_{wk}	–
Water density	ρ	–
Wave period	T	–
Amplitude of wave horizontal velocity	U_w	–

1. Introduction

The development of tidal turbines includes a hard task that is managing the export cable route and installation. This is particularly critical, as tidal turbines sites are chosen for their strong dynamics, and more specifically for their strong currents. Combined with the fact that the seabed at those locations is very poor in sediments and mostly rocky, many challenges arise for cable installation. To reduce the costs of installation and procurement, export route shall be as short as possible, but the need for stabilization devices (mattresses) shall be minimized. Hence the need, at the design stage of a tidal

farm, for a methodology able to assess cable stability all along its route, to estimate the need for stabilizers or cable deviation.
STHYF project includes the development of a methodology dedicated to assessing export cable stability over a route. The crux of this methodology is the choice of a suitable model for efforts calculation, that is fast enough to be run in a few seconds over the whole cable route, but precise enough to give a correct idea of whether a given situation presents a risk for cable slipping or not. This article presents a comparison between the available hydrodynamic models and appoints the best model to be fitted in such a methodology. All the pure mechanical aspects such as cable/soil friction, mechanical properties and boundary conditions are studied in STHYF project but are not presented here.

2. Context

2.1 Problematic

In the objective of cable stability assessment at design stage, the efforts calculation method on which the global stability methodology relies shall:

- be fast to run,
- present a robust convergence pattern, and
- be applicable to as many potential cable situations as possible.

Some parameters make this application specific: the sea bottom is very rough, inducing a highly turbulent boundary layer; the cable is close to the seabed, inducing a high flow dissymmetry ; steady current velocity and oscillating wave-induced velocity are of the same order of magnitude (none is negligible against the other, and the resulting non-linear interactions significantly impact the global fluid dynamics).

2.2 Existing solutions

2.2.1 DHI experimental database

The Danish Hydraulic Institute (DHI) carried out a vast experimental campaign directed by the Pipeline Research Council International Inc (PRCI). Within this basin test campaign, whose results were partly published and analysed in 1986 in [1], more than 1000 individual tests have been conducted, leading to a huge database of force coefficients as well as useful timeseries. The part of these tests suiting to our problematic (steady current and/or regular waves) consists in the following. A flume, in which a steady current can be set up, is equipped with a horizontal plate that can move back and forth following the direction of the basin current, to represent wave-induced flow oscillation on an artificial sea-bottom. The horizontal plate is equipped with a tube that is perpendicular to the flow, standing for a cable or a pipe lying on the seabed. The global set-up is drawn on Figure 1.

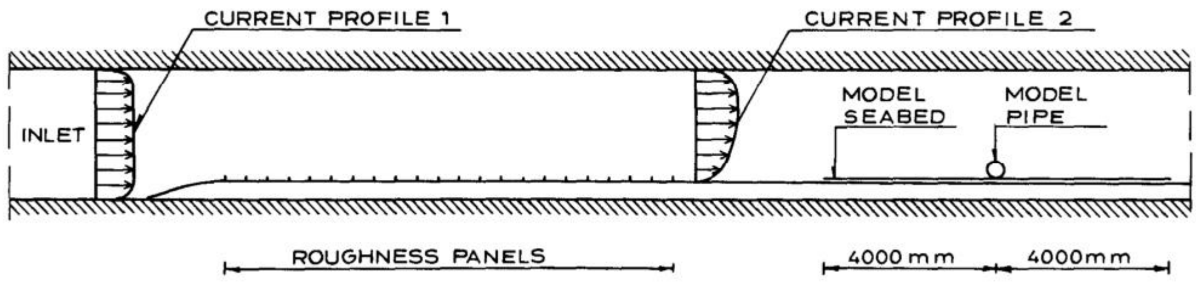

Figure 1: DHI experimental set-up ([1], p.41)

Most tests were conducted with a pipe of diameter $D = 0.2m$. The sea bottom and cable surface can be of three different relative roughnesses : $k_p^*, k_{SB}^* \in \{10^{-3}; 10^{-2}; 5 \cdot 10^{-2}\}$ relatively to cable diameter. The ranges of the main parameters tested within this campaign are listed in Table 1.

Table 1: range of tested parameters ([1], p.50)

Parameter	Test range
KC	2.5 - 160
α	0 – 1.6
Re	Steady current: 0.3 – 2.4 (x 10^5) Regular waves: 0.5 – 3.6 (x 10^5)

The measurements of the experimental campaign are partly compiled in [1]. It takes the form of figures showing time series of horizontal and vertical forces applied on the pipe, as well as flow oscillating velocity and acceleration around the cylinder.

2.2.2 Morison theory

Morison equations are the traditional preference for calculating efforts on submarine structures. They are recalled below, where U is the total surrounding flow velocity $\left(U(t) = U_c(t) + U_w(t)\right)$.

$$F_H(t) = \frac{1}{2}\rho D C_D U(t)|U(t)| + \frac{\pi}{4}\rho D^2 C_M a(t) \quad \text{(eq1)}$$

$$F_L(t) = \frac{1}{2}\rho D C_L U^2(t) \quad \text{(eq2)}$$

C_D, C_M and C_L can either be estimated from experimental results, derived from known graphs or directly calculated, for some well-known cases.

This method is easy and fast, and is adapted for many cases in hydrodynamics. However, it cannot reproduce complex physical phenomena (even when assuming a dependency of C_D, C_L and C_M in Re and KC), as in the case of a cylinder near a seabed in a surrounding flow where the constant and fluctuating components are of the same order of magnitude. This fact is particularly well highlighted in [1] and [2].

2.2.3 Fourier analysis

The forces and their origin being of cyclic behaviour, it is possible to expend the efforts into Fourier series, as done within [1] or [3]. This method can give an accurate estimation of the efforts on a pipe lying on the seabed, provided that coefficients are available up to the adequate order. However, Fourier approach is only valid for ranges of parameters covered by a coefficients database including pipe dimensions and roughness values. Due to the absence of physics in Fourier approach, coefficients cannot be safely extrapolated for cases that are even slightly out of the available database.

Today, the widest database of Fourier coefficients for calculating efforts on a cylindrical body lying on a seabed is the one available in the DHI report [1]. The range of validity of this database is the test range of the experimental campaign.

2.2.4 Wake2 semi-empirical model

S. Sabag [4] extended I. Soedigdo [5] and K. F. Lambrakos [6] works, into a model called Wake2 that is specifically dedicated to calculating the hydrodynamic forces on a pipe or a cable lying on a seabed, in presence of a current and regular waves. This semi-empirical approach, the formulation of which is derived from Morison equations, introduces two sources of non-linearities. The major difference with Morison formulation is that Wake2 takes the velocity of the cable wake into account, thus introducing a memory effect of the fluid. When the flow reverses, the cable is subjected to an effective velocity composed of the undisturbed upstream velocity, and of its own wake. The second major non-linearity introduced in Wake2 formulation is known as the start-up effect [6]: the force coefficients vary with time. This dependence of force coefficients with flow history enables the possibility to catch force peaks that are perceptible at the beginning of flow velocity cycles. S. Sabag Wake2 model is calibrated for a KC range between 10 and 40.

F. Aristodemo later proposed a version of that model dedicated to irregular waves in [7], but only valid for a summation of sinusoidal components, such as defined by standard irregular wave spectrum (Jonswap spectrum alike).

3. Models compared within STHYF project

3.1 Morison-based model

Along with the effort timeseries measured during the experimental campaign, the DHI report shows the reconstruction of the efforts by Morison-type equations. The coefficients are derived by comparison with the experimental results, via a Least Square Analysis.

3.2 Fourier

A Fourier model has been implemented within STHYF project, following DHI Fourier theory. The coefficients (resp. phases) used in this model are interpolated within the datasets of coefficients (resp. phases) given in the report, that have been partly digitalized. The five first non-even terms of the Fourier series are considered.

3.3 Wake2

S. Sabag et al., in [4], calibrated Wake2 model against experimental data obtained within the Pipeline Field Measurement Program (PFMP, [8]). The campaign covered Keulegan-Carpenter numbers up to 40, and Reynolds numbers up to $8 \cdot 10^5$. As DHI test range is much wider than PFMP range, some cases treated in the DHI report were used to test Wake2 model robustness outside its range of validity. It appeared that some modifications were needed in Wake2 formulation.

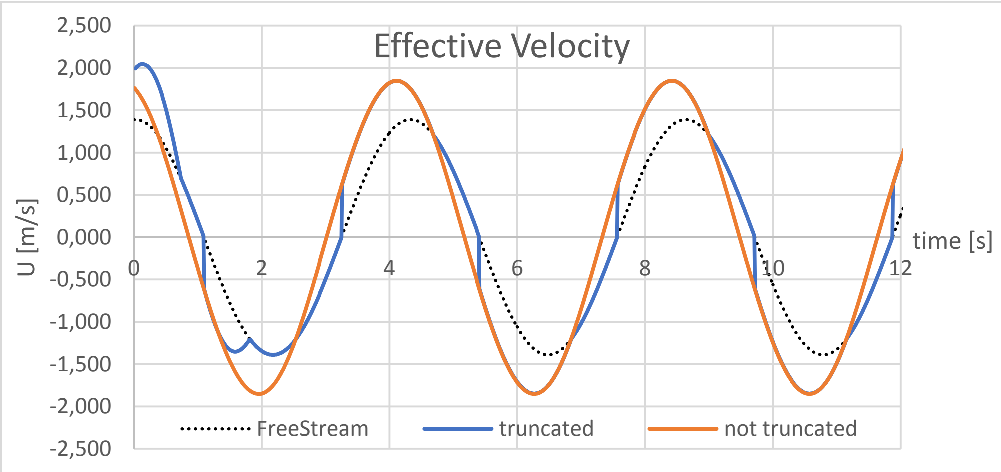

Figure 2: Example of effective velocity around cylinder calculated with and without a truncation of U_{wk} , on an arbitrary case

Most important modifications of S. Sabag formulation for Wake2 to be able to predict DHI force timeseries are (see [4] for more details on the definition of parameters):

1) the link between (φ_A, φ_B) and local Keulegan-Carpenter numbers is changed from an empirical fit ([4], [5]) to a more general polynomial relation defined by F. Aristodemo;

2) Formulation of wake velocities for each half-cycle is changed from the equations in [4] to the following :

$$\begin{cases} U_{wk_A} = U_B \cdot \sqrt{\pi} \cdot \mathrm{erf}\left(\frac{1}{2} C_{2A} \cos(\omega \cdot t + \varphi_A)^n\right) \frac{C_{1A}}{C_{2A}} & (eq3) \\ U_{wk_B} = U_A \cdot \sqrt{\pi} \cdot \mathrm{erf}\left(\frac{1}{2} C_{2B} \cos(\omega \cdot t + \varphi_B)^n\right) \frac{C_{1B}}{C_{2B}} & (eq4) \end{cases}$$

3) the truncation of U_{wk} is removed, as shown on Figure 2 where effective velocity (sum of free-stream velocity and wake velocity) is plotted against time in a regular-waves-only case. The truncation has no obvious physical meaning and introduces discontinuities in the effective velocity, that propagates in acceleration and forces calculations.

4 Choice of the most relevant model for STHYF methodology

4.1 Comparison of force time series

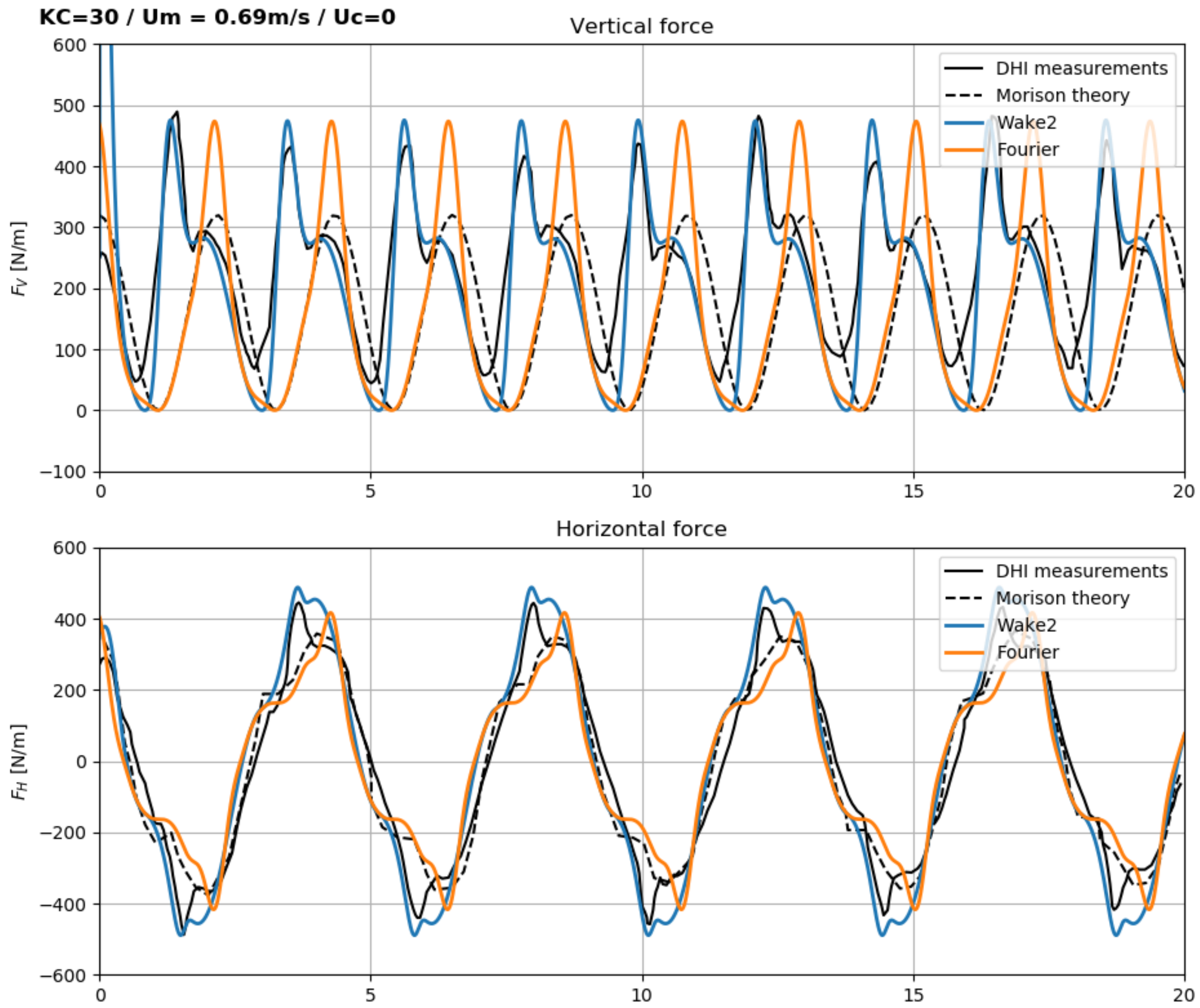

Figure 3: Comparison of horizontal and vertical forces timeseries (KC=30, α=0)

The first case of comparison is in the middle of the validity range of Fourier and Extended Wake2 models. Figure 3 shows the horizontal and vertical forces as computed via Morison theory, via Fourier series, and via the Extended Wake2 model, to be compared with the timeseries as measured during DHI experimental campaign. Morison theory fails to reproduce the lift force, and provides a correct global trend for horizontal forces. However, it does not reproduce the horizontal force peaks that may be critical for stability estimation. Fourier series also give a correct overall shape for the horizontal force, despite an inversion of the shape around the extremum. This method catches well the intensity of lift force peaks, but it is absolutely not in phase with the measurements and the shape of the lift timeseries is not reproduced. Wake2 model gives results that are very close to DHI measurement, for both horizontal and vertical forces. Amplitudes, shapes and phases are very well calculated.
A second comparison is made on a case that is out of the range of calibration announced by S. Sabag in [4] ($KC = 60$), but it in the range of Fourier coefficients given by the DHI. Again, Morison theory is not able to reproduce vertical force correctly, but predicts a relatively close horizontal force shape (exclusive of local sharp peaks preceding every main sinusoidal-like peak). Fourier theory does not provide the two-peaks shape of the lift force and extremum are phase-shifted. It predicts a shape of horizontal force timeseries that is globally correct but locally quite far from the measurements. Extended Wake2 model gets the correct shape for both horizontal and vertical forces, but the smaller

and sharper secondary peaks appearing right before the main peaks happen a bit too early to be able to reproduce the forces extrema.

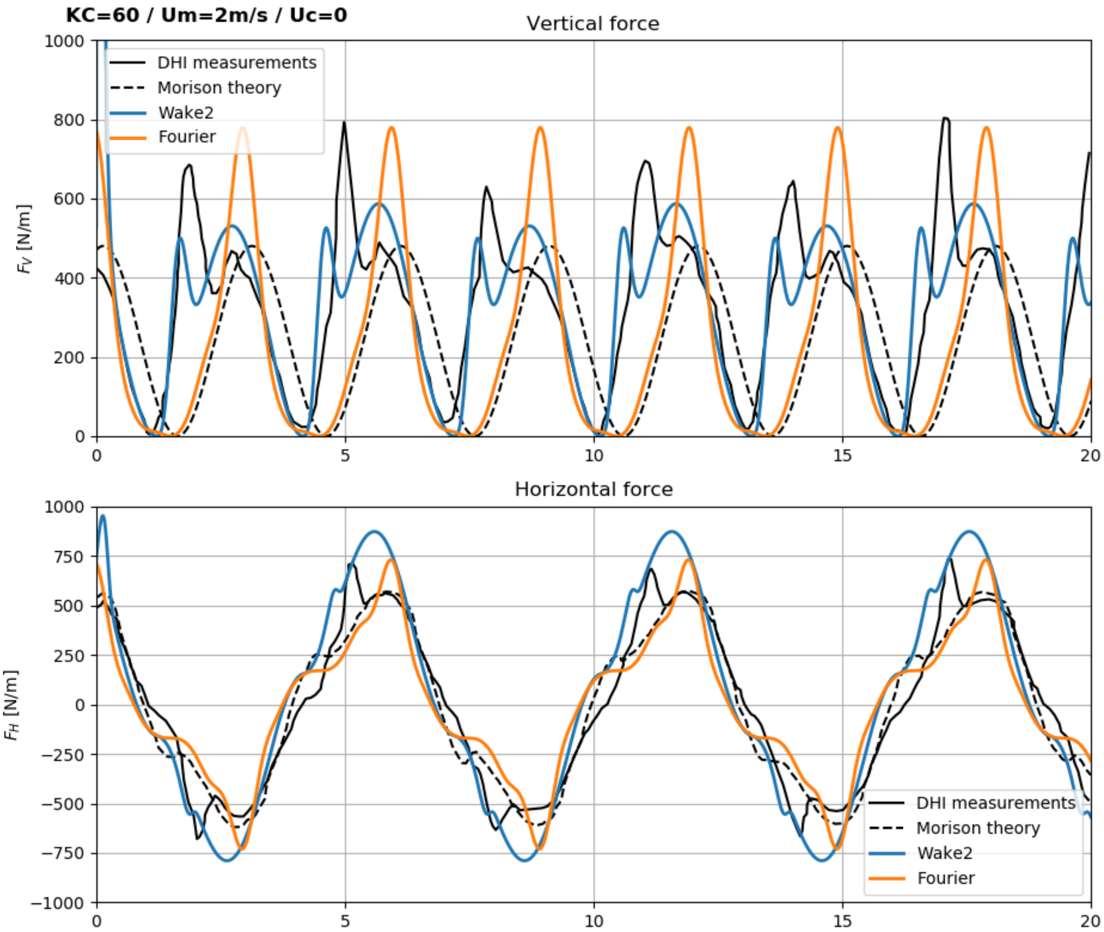

Figure 4: Comparison of horizontal and vertical forces timeseries (KC=60, α=0)

The same conclusions can be drawn when KC is much higher than what Wake2 was calibrated for (KC numbers up to 100 have been tested).

Figure 5 shows the comparison between force timeseries in a case with current ($\alpha = 0.4$). Morison-based force calculation gets the overall tendencies but cannot reproduce the shape of the measured timeseries as accurately as Wake2. Fourier timeseries are quite close to Morison timeseries most of the time, but completely diverges around main lift force peaks and corresponding horizontal force peaks. Wake2 model is able to reproduce most of the small particularities of the timeseries and often gives a correct estimation of peaks magnitude. It is reminded here that there is no need for any Wake2 coefficient to be triggered when introducing a current superimposed to the wave velocity.

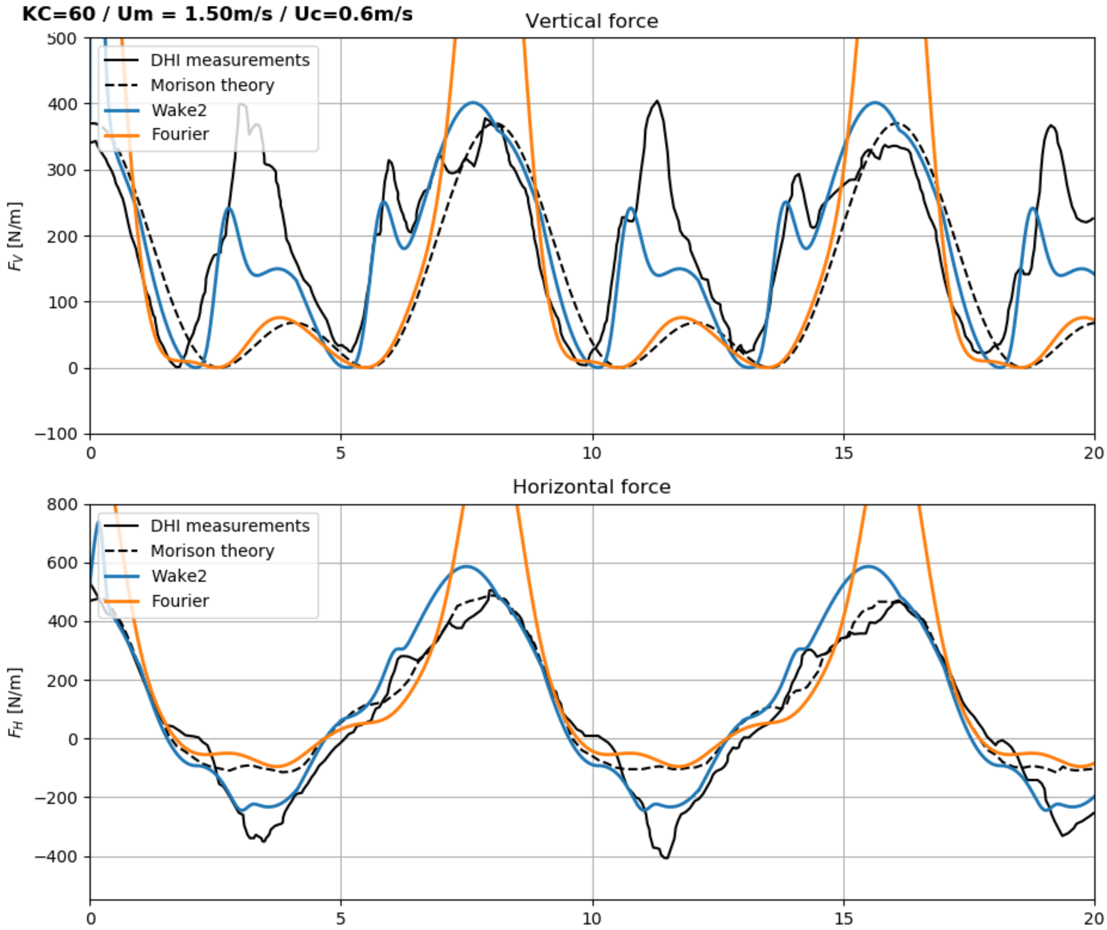

Figure 5: Comparison of horizontal and vertical forces timeseries (KC=60,α=0.4)

4.2 Analysis of timeseries comparison

4.2.1 Morison theory

Morison theory is not adapted when non-linearities need to be taken into account, especially for lift force where non-linearities are critical for stability.

4.2.2 Fourier analysis

The reconstruction of force timeseries *via* Fourier method, using the coefficients extracted from experimental results by the DHI, does not give satisfactory results. It is surprising, as Fourier theory is supposed to work at its best in such cases, where the origin of the physics is of pure sinusoidal nature. A problem is suspected either in the database of coefficients or in the definition of the phases conventions. An extensive work of graph digitization and Fourier treatment would be needed for being able to reproduce DHI Fourier coefficients and phases database. Even so, force calculations from Fourier data would only be fully valid for the cases already validated against measured data. In other words, Fourier analysis is not pertinent in a methodology for export cable stability assessment, at the design stage.

4.2.3 Wake2 model

Looking closer at what happens for lift force, in the case of Figure 4 for instance (where KC=60 and α=0), Figure 6 shows freestream velocity and effective velocity as calculated within Wake2 model, the lift force timeseries as in Figure 4, and the lift coefficient timeseries. The lift coefficient, thanks to the start-up function, is time-dependent and shows regular peaks. These peaks allow to decompose time in two kinds of periods: when lift coefficient is flat (where C_L is equivalent to a steady-flow lift coefficient) and when lift coefficient undergoes a peak.

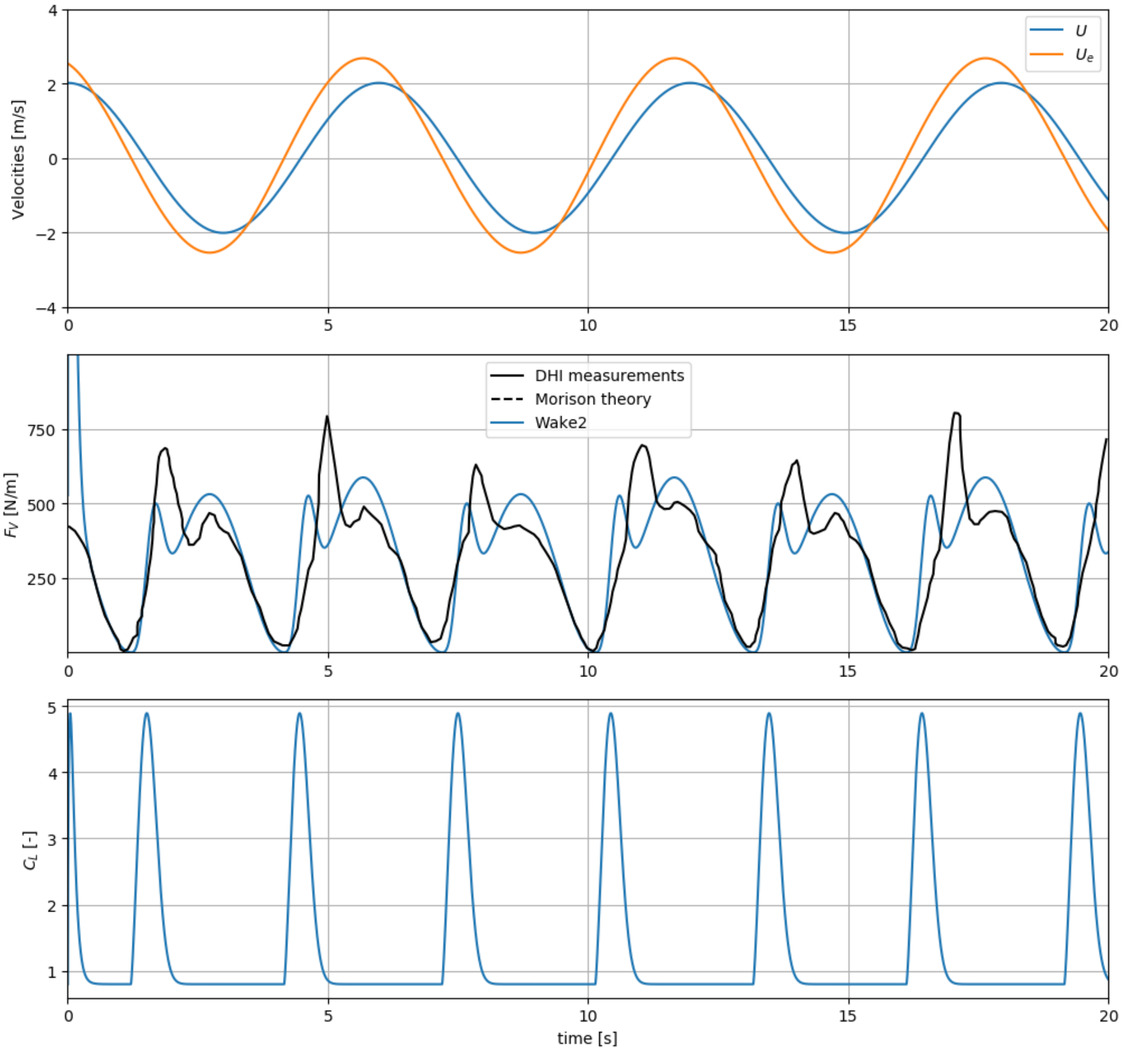

Figure 6: Analysis of lift force computation by Wake2 (KC=60, α=0)

When lift coefficient remains constant, the shape of the lift force timeseries is directly driven by effective velocity (lift force expression in Wake2 model is the same as in (eq. 2), except that flow velocity U is replaced by effective velocity U_e). Right before effective velocity reaches any extremum, lift coefficient peaks induce force peaks clearly identifiable on both Wake2 and measurements force timeseries. Hence, it is possible to dissociate the contributions of computed wake velocity and start-up function behaviour.

Two noticeable points are highlighted by force timeseries analysis, over the range of parameters tested during the comparisons:

1) The higher the KC, the earlier the sharp peaks due to the start-up function (compared to the measurements). And if start-up-function peaks happen further from effective velocity extrema, then the related force peaks magnitudes are lowered. Figure 6 shows that sharper peaks happen

earlier and are smaller when computed by Wake2 model than when measured. This point reflects the need for a small delay of the start-up function increasing with KC.

2) Effective velocity extrema magnitudes are probably a bit overestimated, as implied by the small overestimation (10 to 15 percent) of the related lift force local extrema. This point needs to be further investigated

These two points imply that global shape and sharp force peaks can be calibrated in a separate manner. This is particularly interesting as for further calibration of the model, and is very promising about Wake2 model ability to be applicable to a wide range of applications.

4.3 Choice of the model best suited to the methodology

Morison theory obviously fails at predicting the efforts on a cable lying on the seabed. It cannot take all the complicated physics into account, and that is reflected on the calculated timeseries.
Fourier approach gives better results but every new situation (change in diameter or roughness of the cable, velocity or turbulence characteristics of the flow, etc…) requires to digitalize a new set of coefficients and phases (if data exists). If data does not exist, then a numerical or experimental campaign is needed to build a new dataset. This is very time- and cost-consuming. In addition, the formulation is highly sensitive, especially regarding the influence of components phases on the timeseries behaviour, even at the highest considered orders. The Fourier approach is not robust enough for being suitable to a methodology with which new cases need to be computable in a short time window.
Wake2 results are much closer to experimental timeseries, for every testcase. All the results were obtained by using a single set of coefficients inside Wake2 model. It gives a fairly good adequation in terms of efforts magnitudes (even for the most energetic components), but above all it gives a correct time correlation between horizontal and lift forces. Time-correlation between force peaks is particularly needed when the objective is to estimate the risk for cable movement. A small phase difference between horizontal and lift force peaks may produce a very different behaviour of the cable, at identical peak amplitudes. The most important observation is that Wake2 model is able to reproduce the major non-linearities, which can be obtained accurately with a very small calibration work.
For these reasons, Wake2 model seems to be the most suitable to be introduced in a cable stability methodology. An experimental campaign is planned at Ifremer Boulogne wave and current facilities, with the objective of providing more comparison cases and extending the calibration range of the model. For instance, one of the extended parameters consists in taking a small gap between the cable and the seabed into account. Moreover, a numerical model is being developed within STHYF, with the objective of providing a large number of results outside the range of the already available data, as presented in [9]. In particular, measurement features are used to clearly identify the source of non-linearities among the surrounding wake velocity and the hydrodynamic coefficients.

5. Conclusion

Wake2 model is reliable and robust for fitting well with experimental horizontal and lift forces on a variety of situations, without any need for coefficient interpolation or estimation. We are very confident on its relevancy to extend its actual range of application with little calibration effort. It has proven to be perfectly fitted to a use in the methodology for cable stability assessment. Morison-based method fails to predict the efforts on the cable. In particular, the lift force features some components that are not in phase with the squared velocity, but play a significant role, and that cannot be predicted

by Morison theory. Fourier analysis is rather heavy to use ; it needs a lot of data to run and, even with data available, it is very sensitive to parameters variation. A strong effort of model adaptation is anticipated for every new situation, that is not acceptable for a use in such a methodology.
To be sure that Wake2 model can be used for tougher cases, computations need to be compared to results obtained on a wider range of parameters (KC, seabed roughness, current ratio). These results on a wider range will be obtained by CFD computations and a dedicated experimental campaign.

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