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New model to determine forces at on-bottom slender pipelines

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ABSTRACT

The present paper proposes a numerical model to determine horizontal and vertical components of the hydrodynamic forces on a slender submarine pipeline lying at the sea bed and exposed to non-linear waves plus a current. The new model is an extension of the Wake II type model, originally proposed for sinusoidal waves (Soedigdo et al., 1999) and for combined sinusoidal waves and currents (Sabag et al., 2000), to the case of periodic or random waves, even with a superimposed current. The Wake II type model takes into account the wake effects on the kinematic field and the time variation of drag and lift hydrodynamic coefficients. The proposed extension is based on an evolutional analysis carried out for each half period of the free stream horizontal velocity at the pipeline. An analytical expression of the wake velocity is developed starting from the Navier–Stokes and the boundary layer equations. The time variation of the drag and lift hydrodynamic coefficients is obtained using a Gaussian integration of the start-up function. A reduced scale laboratory investigation in a large wave flume has been conducted in order to calibrate the empirical parameters involved in the proposed model. Different wave and current conditions have been considered and measurements of free stream horizontal velocities and dynamic pressures on a bottom-mounted pipeline have been conducted. The comparison between experimental and numerical hydrodynamic forces shows the accuracy of the new model in evaluating the time variation of peaks and phase shifts of the horizontal and vertical wave and current induced forces.

1. Introduction

Submarine pipelines at intermediate and shallow waters are subjected to wave and current induced forces. An essential step for pipeline design is the accurate evaluation of the hydrodynamic forces.

The analysis of hydrodynamic loads acting on cylindrical structures such as submarine pipelines is usually related to the diffraction parameter, defined as the ratio between the diameter of the cylinder, D, the wave length, L, and, in particular, the Keulegan–Carpenter number, $KC = u_m T/D$, and the Reynolds number, $Re = u_m D/\nu$, where u_m represents the peak of the free stream horizontal wave velocity at the transversal axis of the pipeline, T is the wave period and ν is the kinematic viscosity (Sumer and Fredsoe, 1997). The values of KC and Re are referred to sinusoidal waves. For slender submarine pipelines the range of interest is $D/L<0.2$ and $KC>4$ (Sarpkaya and Isaacson, 1981); in this range, the incident flow separates from the pipeline producing a vortex shedding regime in the near field. The flow separation induces drag and lift hydrodynamic forces which become relevant in comparison with the inertia ones.

A widespread and practical tool for predicting in-line hydrodynamic forces induced by waves and currents on slender cylinders is the Morison model (Morison et al., 1950), where the horizontal velocity and acceleration components are referred to the undisturbed incident flow field at the axis of the pipeline and the hydrodynamic force coefficients (drag and inertia) are considered time constant. The in-line horizontal force component is obtained as the linear superimposition of two forces: a drag force, generated by the resistance of an obstacle to the incident flow, and an inertia force depending on the acceleration of the oscillatory flow. The transverse vertical force component, or lift force, is generated by the increased flow velocity across the pipeline induced by the blocking of the flow. The lift force is generally calculated by a similar expression of the Morison drag force but differs substantially for the evaluation of the lift hydrodynamic force coefficient.

A great deal of research has addressed the calibration of the Morison coefficients for a wide range of values of KC and Re, adopting different external roughness and geometrical configurations of cylinders. For bottom-mounted submarine pipelines, values of Morison hydrodynamic coefficients have been evaluated for different wave and current conditions based on field investigations (Grace and Zee, 1981; Lambrakos et al., 1987) and small and large scale laboratory experiments (Sarpkaya and Rajabi, 1980; Norwegian Hydrodynamic Laboratories, 1985; Cheong et al., 1987; Veritas Offshore Technology, 1988; Bryndum et al., 1983, 1992; Benassai, 1993; Neill and Hinwood, 1998; Chevalier et al., 2000; Aristodemo et al., 2006; Tomasicchio et al., 2007). Some authors (Sarpkaya, 1981; Bearman et al., 1984; Sarpkaya and Wilson, 1984; Chaplin and Subbiah, 1997; Sarpkaya, 2001) proposed, for limited KC and Re ranges, additional terms in the basic Morison

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equations in order to minimize the differences between the experimental and the simulated forces.

However, the reliability of the Morison scheme is limited by the constant value of the hydrodynamic drag, inertia and lift coefficients, which is not able to represent accurately the time variation of the flow field. Although the horizontal force component can be determined with acceptable accuracy, a refined evaluation of the peaks, phases and shapes of the lift force, highly dependent on the evolution of the vortices around the cylinder, cannot be achieved by the Morison scheme and its successive modifications.

An improved model to determine the hydrodynamic forces induced by wave and current conditions is the Wake model proposed by Lambrakos et al. (1987); the equations for the hydrodynamic forces take into account the vortex effects around the pipeline and the time dependence of the drag and lift hydrodynamic coefficients. The limitations of this model derive from the evaluation of the wake velocity and the numerical strategy used for determining the hydrodynamic coefficients. For sinusoidal waves, the more recent Wake II type model (Soedigdo et al., 1999) improved the description of the wake correction into the ambient flow. Sabag et al. (2000) proposed a version of the Wake II type model valid for the case of sinusoidal waves interacting with a uniform current.

The present work proposes an extension of the Wake II type model to the case of periodic and random waves, even with a superimposed current. The new Wake II type model is developed by using a numerical integration of the start-up function for representing the time variation of drag and lift hydrodynamic coefficients and adopting analytical modeling of the wake velocity. An extensive laboratory investigation in a large wave flume adopting various wave and current conditions has been conducted to calibrate the empirical parameters in the formulae for the drag and lift coefficients and the inertia forces.

The present work is organized as follows: in the second and third sections the original Wake II type models for sinusoidal waves and for sinusoidal waves plus current and the analysis of their limitations are presented; afterwards, the experimental investigation to determine wave and current forces on a on-bottom pipeline is illustrated in Section 4; the new Wake II type model is described in Section 5; then, the method to calibrate the empirical parameters involved in the new model is illustrated in Section 6; finally, some numerical simulations obtained by the new model are reported in Section 7, showing the time variation of the flow field and the comparison between the simulated and observed horizontal and vertical force components.

2. The Wake II type model

The Wake II model determines the wave induced hydrodynamic forces acting on a submarine pipeline lying at the horizontal sea bottom; it was proposed by Soedigdo et al. (1999) for sinusoidal waves, and by Sabag et al. (2000) for sinusoidal waves interacting with a positive uniform current. In the latter case, the external flow field is induced by the linear superimposition of a sinusoidal wave with a positive uniform current. The ambient velocity time variation is divided in two different phases. In phase A the total ambient velocity is assumed as the linear superimposition of the velocity induced by wave and current. In phase B the total ambient velocity is equal to the wave velocity minus the positive current velocity. The time shift of the two phases is identified by a zerocrossing analysis of the time variation of velocity.

The Wake II model takes into account the time variation of the drag and lift force coefficients. A modified velocity is defined taking into account the interaction between the pipeline and the wake flow. The wake generated by the presence of the pipeline is superimposed onto the ambient flow to give an effective velocity of the motion. In fact, in an oscillatory flow the correction due to the wake velocity can significantly increase the effective velocity during each half period.

The wake velocity correction was obtained with a closed form solution to the linearized Navier–Stokes equations for an oscillatory flow. With the hypothesis that the time dependence of eddy viscosity in the wake is oscillatory, the wake velocity, u_w, affecting the pipeline for sinusoidal motion, is given as (Soedigdo et al., 1999):

$$u_w(t) = \frac{\sqrt{\pi} erf\left[\frac{1}{2}C_2 \sin^n(\omega t + \phi)\right] u_m C_1}{C_2} \tag{1}$$

and, for sinusoidal motion interacting with a positive current, the wake velocity is equal to (Sabag et al., 2000):

$$u_{wk}(t) = \frac{\sqrt{\pi} erf\left[\frac{1}{2}C_{2k} \sin^n(\omega_k t + \phi_k)\right] C_{1k}}{C_{2k}} u_k \qquad \text{for } k = \mathrm{A, B}. \tag{2}$$

In Eq. (1) the values of the parameters C_1, C_2, n and ϕ are determined on the basis of experimental observations for KC ranging from 10 to 70 (Lambrakos et al., 1987) and ω is the wave frequency. The phase angle ϕ depends on KC for sinusoidal waves (Soedigdo et al., 1999) and on the ratio u_c/u_m for sinusoidal waves and currents (Sabag et al., 2000), where u_c is the positive current velocity.

In Eq. (2), $u_A = u_m + u_c$ and $u_B = u_m - u_c$ are the peak velocities in both the phases A and B. The parameters C_{1A}, C_{1B}, C_{2A}, C_{2B}, n, ϕ_A and ϕ_B are determined depending on the local Keulegan–Carpenter number, $KC_A = u_A T_A / D$ and $KC_B = u_B T_B / \mathrm{D}$, ω_A and ω_B are the wave frequencies in phases A and B dependent, respectively, on the periods $T_A = T + 4\Delta t$ and $T_B = T - 4\Delta t$ (Sabag et al., 2000). In particular, Δt is the time shift between the time variation of the ambient velocity induced by the sinusoidal wave and of the ambient velocity due to the combined action of sinusoidal waves and a uniform positive current. A sketch of the free stream horizontal velocity for combined sinusoidal wave and current is illustrated in Fig. 1.

The velocity field is represented through the effective velocity, u_e, evaluated as the sum of free stream velocity and wake velocity. For sinusoidal flow, it is defined as:

$$u_e(t) = u_m \cos(\omega t) + u_w(t) \tag{3}$$

and for sinusoidal flow interacting with a positive current as:

$$u_{ek}(t) = u_m \cos(\omega t) + u_c + u_{wk}(t) \qquad \text{for } k = \mathrm{A, B}. \tag{4}$$

Relationships for calculating the hydrodynamic forces are similar to the Morison's equations. In particular, the drag force is:

$$F_D(t) = \frac{1}{2} \rho D C_D(t) u_e(t) |u_e(t)| \tag{5}$$

where ρ is the water mass density and $C_D(t)$ is the hydrodynamic drag coefficient. The lift force is:

$$F_L(t) = \frac{1}{2} \rho D C_L(t) u_e^2(t) \tag{6}$$

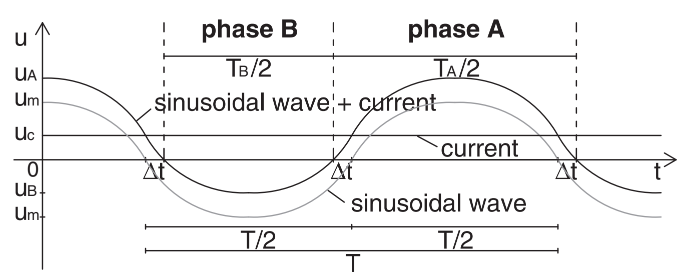

Fig. 1. Free stream horizontal velocity for combined sinusoidal wave and current.