Two phenomena: Honji instability, and ringing of offshore structures

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Abstract Honji instability and ringing of offshore structures are two different phenomena. Honji instability occurs at a circular cylinder in transverse periodic finite motion in a water tank. It is superposed on the streaming flow induced by the cylinder’s boundary layer. Its oscillation period is half of the period of the cylinder oscillation. Finite volume calculations of the filtered Navier-Stokes equations visualize the three-dimensional instability, where fluid particles transported by the circumferential roll pairs exhibit a periodic mushroom-like pattern. Force is the same with and without the Honji instability. The large eddy simulation calculations for high Reynolds number support a drag coefficient in accordance with the Stokes-Wang solution below separation and conform with experimental measurements of the damping force on a harmonically oscillating cylinder. Ringing of offshore structures are vibrations which appear at natural frequencies and concern fatigue. It is generated by a higher harmonic force oscillating with frequency being 3-4 times the fundamental wave frequency. Together with a strong inertia load in phase with the incoming wave’s acceleration, a secondary load cycle appears in strong seas when the wave crest leaves the structure; this occurs about 1/4 wave period after the main force peak, it starts when the wave crest is about one cylinder radius behind the cylinder, lasts for about 15-20 percent of the wave period and has a magnitude up to 11% of the peak-to-peak total force. It is a gravity effect and appears in strong irregular seas when $kA > 0.18$ and $u_m/\sqrt{gD} > 0.4$ ($k$ wavenumber, $A$ amplitude, $u_m$ maximal wave induced velocity, $g$ acceleration of gravity, $D$ cylinder diameter). © 2011 The Chinese Society of Theoretical and Applied Mechanics. [doi:10.1063/2.1106201]

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I. HONJI INSTABILITY

Honji performed laboratory experiments with a circular cylinder in transverse periodic motion in a water tank. Besides the classical streaming flow induced by the cylinder’s oscillatory boundary layer, Honji investigated a three-dimensional instability of this flow. The instability appeared when the oscillation amplitude was sufficiently large, and below a certain level. Honji was able to track the successive motion of fluid particles. He visualized how the particles, initially located on the body boundary, became detached from the body’s boundary layer.

The three-dimensional flow structure exhibits repeatedly, in the cylinder’s length direction, pairs of rolls extending along the cylinder circumference (Fig. 1). The pattern oscillates in time. It appears and disappears with a cycle of period being half of the oscillation period. Fluid particles transported by the roll pairs exhibit a periodic mushroom-like pattern (Figs. 2, 3).

The motion is governed by two dimensionless parameters, the Keulegan-Carpenter number $KC = \pi d_0/D$ and the Stokes number $St = fD^2/\nu$, where $d_0/2$ denotes amplitude of the motion, $D$ is cylinder diameter, $f = 1/T$ frequency, $T$ is period and $\nu$ is kinematic viscosity. The Reynolds number is given by the product of $KC$ and $St$. The Stokes number is in many publications referred to as the beta-number and is also used here ($St = \beta$).

Honji found that the three-dimensional roll and mushroom patterns formed in the range between a lower and an upper $KC$-value, depending on the Stokes number, in the range 70 < $St$ < 700. In his investigation, upper $KC$-value was: 3.9 (at $St = 70$) decreasing about linearly to $KC = 2.7$ (at $St = 200$), decreasing then about linearly to $KC = 2.2$ (at $St = 700$). Lower $KC$-value was: 2.7 (at $St = 70$) decreasing about linearly to $KC = 1.4$ (at $St = 200$), decreasing then about linearly to $KC = 1.3$ (at $St = 700$). Below the lower $KC$-value there were no three-dimensional instability, and above the upper value the flow became turbulent.

Calculations visualize the oscillatory three-dimensional instability, the lateral roll-pair pattern and mushroom form of the instability. The filtered Navier-Stokes equations are integrated by a finite volume method implemented in a modified version of CDP2.5.1,3,4 The flow is solved in a frame of reference fixed to the moving geometry where the fictive acceleration force is accounted for by a source term in the code. As a result the calculation grid is fixed. Beyond the laminar regime, a large eddy simulation (LES) closure is used with a dynamic Smagorinsky model. The cylinder (of diameter $D = 2R$) has height $H = 3D$ and $4D$. The $z$-axis corresponds to the cylinder axis with $z = 0$ midways on the cylinder, $x$-axis is along the translation direction, and $y$-axis is orthogonal to the $x$-, $z$-plane, in a right hand fashion. A computational domain of $(30D,10D,3(4)D)\) in

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Fig. 1. The cycle of the $z$-velocity $w$ in $x = 0$ plane, at the total $z$-direction of the cylinder. $KC = 2.07, \beta = 197$.\(^3\)

Fig. 2. 'Mushroom' vortices corresponding to the Honji instability in $x = 0$ plane, along the total $z$-direction of the cylinder. $KC = 2.07, \beta = 197.3$.

$(x, y, z)$, extended periodically in all directions, has the following discretization: $\Delta z/D = 0.05$; there are 128 points in the angular direction; in the radial direction the grid cell nearest to the cylinder is $\Delta r/D = 0.0005$. The total number of grid cells is $0.8 - 1.1 \times 10^6$. The time step is $T/1 000$.

Putting the perturbation velocities in the plane $x = 0$ on the form $(v, w) = (\partial \psi/\partial z, -\partial \psi/\partial y)$, the stream function $\psi$ may be integrated, and $\psi = \text{const}$ gives the lines corresponding to the traces measured in the original experiments by Honji.

Wave lengths ($\lambda$) of the Honji mushrooms are, with $KC = 2.07, \beta = 197$ and cylinder height $H/D = 3$ [$\lambda/D = 0.6$ (Ref. 3), 0.63 (Ref. 1) and $\sim 0.6-0.7$ (Ref. 5)], and with cylinder height $H/D = 4$ [$\lambda/D = 0.67$ (Ref. 3), 0.63 (Ref. 1) and $\sim 0.6-0.7$ (Ref. 5)]. The height of the mushroom is $0.65R$, the outer width $0.62R$ and inner width $0.4R$ (Figs. 2-3).

The force on the cylinder is obtained by integrating the fluid pressure plus the tangential shear stress over the cylinder surface. Consider the in-line force which is decomposed by terms in phase with the acceleration and velocity. Its sectional variant reads

$$F(t) = \frac{1}{4} \pi \rho D^2 C_m + \frac{1}{2} \rho D C_d |U| U,$$

where $\rho$ denotes density, $U = U_m \sin(2\pi t/T)$, $C_m$ is inertia coefficient and $C_d$ is drag coefficient. The classical Stokes-Wang solution for viscous flow at an oscillating circular cylinder obtains the inertia and drag coefficients by $(KC << 1, \beta >> 1)\(^6,7\)$

$$C_m = 1 + 4(\pi \beta)^{-1/2} + (\pi \beta)^{-3/2},$$

$$C_d = \frac{3\pi^3}{2KC} \left[ (\pi \beta)^{-1/2} + (\pi \beta)^{-1} - 1/4(\pi \beta)^{-3/2} \right].$$
Two phenomena: Honji instability, and ringing of offshore structures

Fig. 4. $C_d$ vs. $KC$. Calculations with $\beta = 11240$ using LES-closure\(^3\) (large red squares); measurements of harmonically oscillating cylinder with $\beta = 61400$ (large blue circles)\(^9\); U-tube measurements with $\beta = 11240$ (small black circles)\(^8\).

A surprising result of the laminar calculations is that the force is the same before and after the appearance of the Honji instability,\(^3\) in disagreement with Sarpkaya’s U-tube measurements.\(^8\) Sarpkaya has maintained that presence of the Honji instability along the cylinder boundary causes a drag force which is higher than predicted by the Stokes-Wang solution.

Laminar and LES calculations\(^3\) support a drag coefficient in accordance with the Stokes-Wang solution (3), for $KC < 2$, for a range of $\beta$-numbers ($197 < \beta < 11240$). In this $KC$-range there is no flow separation. This result agrees with experimental measurements of the damping coefficient of a harmonically oscillating cylinder with $\beta = 61400$.\(^9\) This result differs with experiments obtained in U-tube experiments,\(^8\) however, both in the laminar range and the turbulent range. Flow separation causes the drag coefficient to increase, for $KC > 2$. The LES simulations with $\beta = 11240$ give a drag coefficient, in agreement with the harmonically oscillating cylinder with $\beta = 61400$, which is significantly smaller than drag coefficient obtained in U-tube experiments with $\beta = 11240$, in the same range of the Keulegan-Carpenter number ($2 < KC < 4$) (Fig. 4).

Simulations of oscillating cylinders with $KC$ exceeding 4, and $\beta = 11000$ (and $Re > 45000$) are currently pushed forward by using the computational strategy documented in Ref. 3, investigating the flow field, flow separation characteristics and the force picture.

II. RINGING OF OFFSHORE STRUCTURES

Ringings of offshore structures are unwanted structural vibrations which appear at one or more of the natural frequencies of the structure. Such vibrations were discovered in model tests during the construction phase of the Heidun tension leg platform (TLP) and the Draugen gravity based structure (GBS) (Fig. 5) where the latter is a monopile standing on the sea floor. Both platforms are located in Norwegian waters. Both constructions had to be reinforced in order to keep an acceptable safety level in relation to fatigue. Model tests of the structures showed that resonant ringing vibrations were triggered in steep irregular waves, in the form of a resonant build-up during a wave period, at frequency being 3-4 times the fundamental wave frequency (Fig. 6). Column diameters at the water line of the Heidrun and Draugen platforms are 30 m and 16 m, respectively.

Ocean wave laboratory tests of the Draugen monopile undertaken by Saga Petroleum in 1995 showed that the typical load leading to resonant ringing vibrations occurs for wave slope $kA$ as low as 0.18 and nondimensional wave period as low as $T \sqrt{g/D} = 1.06$ ($k$ wavenumber, $A$ amplitude, $T$ wave period, $g$ acceleration of gravity, $D$ cylinder diameter.)\(^{10}\) For steeper waves ringing occurs for even shorter period (discussed below). This wave range is of interest in regard to fatigue analysis of offshore wind turbines which are supported by fixed, slender vertical cylinders in shallow water.

Wave loads leading to ringing were investigated in moderate scale ocean wave laboratories\(^{11,12}\) and small scale wave tanks.\(^{10,13,14}\) All investigations have concluded on a consistent force picture of the nonlinear force. Together with a strong inertia load in phase with acceleration of the incoming wave, a secondary load cycle appears when the wave crest leaves the structure, when the incoming wave is sufficiently steep.

It is the rapid appearance of the secondary load cycle that generates the resonant vibrations. If one performs measurements in a wave tank, one may gradually increase the amplitude of a focusing wave, at the po-
sition where a vertical cylinder is mounted. When the amplitude reaches a certain level, the secondary load cycle appears in the force recordings. Alternatively, the cylinder may be mounted by stiff strings. At the same amplitude level the cylinder starts to vibrate at the resonance frequency of the cylinder as found in early measurements of the ‘ringing-problem’.

This process is illustrated in Fig. 7. A vertical cylinder of diameter $D = 2R = 11.9$ cm is mounted in a wave tank of length 24.6 m, width 0.5 m and depth 0.6 m. The cylinder position is 13.12 m from the wave maker. Incoming waves are made in the form of a focusing wave giving a large wave event at the cylinder position. The height of the wave event is changed gradually, from a small to a large value. In regard to the appearance of the secondary load cycle, it is the intermediate elevations which are of primary interest, not the largest ones (the breaking events).

Three similar focusing waves of three different amplitudes are illustrated in Fig. 7a. For each of these waves we identify the maximal wave elevation ($\eta_m$) and the local trough-to-trough period ($T_{tt}$). We then estimate the wavenumber ($k$) and wave slope ($kA$) of the event by solving the two equations

$$k\eta_m = kA + (kA)^2/2 + (kA)^3/2$$

and

$$(2\pi/T_{tt})^2 = gk[1+(kA)^2],$$

where $g$ denotes the acceleration of gravity, according to a procedure documented in many laboratory events and theoretical calculations.\(^\text{15}\) In the three large events in Fig. 7a the local wave slope is $kA = 0.205, 0.280$ and $0.308$. The trough-to-trough period for the highest two waves becomes $T_{tt}\sqrt{g/D} = 7.94$ (0.87 s). With regard to the scale, $\beta = D^2/\nu T \simeq 16 \, 300$ in these examples.

By increasing the wave height, the main force peak becomes skewed. This force is in phase with the acceleration of the incoming wave. The important feature of the strongly nonlinear force is the appearance of the secondary load cycle. This occurs about 1/4 wave period after the main force peak, when the wave is sufficiently steep, and is here pronounced for $kA$ exceeding 0.28. The secondary load cycle starts when the wave crest is about one cylinder radius behind the cylinder and lasts for about 15-20 percent of the wave period. It has a magnitude up to 11 % of the peak-to-peak total force. Its resultant acts approximately one cylinder radius below the mean water line. Figure 7b shows the force recorded on the upper transducer, at height 0.863 m above the tank floor, corresponding to the overturning moment. The lower transducer is 0.19 m above the tank floor.

The high-frequency force is obtained by filtering out the first two Fourier components in a Fourier representation of the force, over the periodic domain, with period 0.87 s. This force has two peaks, the first peak is in phase with the acceleration and the second peak is
the new peak, due to the secondary load cycle. For illustration, we make the high frequency part of the force dimensionless dividing by \( pgA^3 \). The curves in Fig. 7c show that the second peaks (the secondary load cycles) are \( F_{h1}/(pgA^3) \approx 0.1 \) (\( kA = 0.205 \)), \( F_{h1}/(pgA^3) \approx 0.45 \) (\( kA = 0.280 \)) and \( F_{h1}/(pgA^3) \approx 0.43 \) (\( kA = 0.308 \)), respectively. This illustrates the high nonlinearity in the appearance of the secondary load cycle; the peak of the secondary load cycle grows according to \((kA)^2\), from \( kA = 0.205 \) to \( kA = 0.28 \). The secondary load cycle becomes present when the wave slope exceeds a certain level, rather than a gradual process. The wave slope level where the secondary load cycle appears changes according to the wave period and is documented below.

Strong surface depression has been measured at quarter angles, symmetrically with respect to the central plane of the wave tank, at the rear side of the cylinder, indicating a considerable low-pressure during the occurrence of the secondary load cycle. This indicates that a suction causes the force. Pressure measurements on the submerged part of the cylinder surface showed the same feature.

Several investigations document the connection between the secondary load cycle and appearance of ringing. Of course, slamming forces in breaking wave events may also trigger such high frequency responses. However, at the intermediate range, where ringing is experienced, the effect of slamming is weak. Model scale tests with vertical cylinders show that the secondary load cycle has a stronger appearance in irregular waves than in periodic waves. The relevant nondimensional number combining the three physical quantities \( u_m \), \( g \) and \( D \) is the Froude number.

\[
Fr = \frac{u_m}{\sqrt{gD}}. \tag{4}
\]

The secondary load cycle was found to be pronounced when \( u_m/\sqrt{gD} \) exceeded 0.4. This threshold is indicated in Fig. 9. It is seen that \( u_m/\sqrt{gD} = 0.4 \) separates the occurrences of the secondary load cycle on vertical circular cylinders, and occurrences of ringing of models the Draunen GBS and Heidrun monopile, from events with no ringing. A line \( Fr = u_m/\sqrt{gD} = 0.38 \) shows in fact a more precise estimate between occurrence of secondary load cycle/occurrence of ringing and no observation of ringing. An important point with the plot in Fig. 9 together with the nondimensional number in Eq. (4) is that ringing is caused by a free surface gravity effect.

Measurements indicate that the secondary load cycle has a stronger appearance in irregular wave events than in periodic waves. Third order theories are developed under the assumptions of periodic incoming waves. They are asymptotically valid for \( kA \to 0 \) and compare excellently to experiments in periodic waves, for \( kA \sim 0.1 \). (There is a difference in the force phase of the third harmonic force in Ref. 16, but the magnitude of the force agrees with experiments.) Measurements show that the third harmonic force component divided by the amplitude in the cubic power, i.e. \( |F_3|/(pgA^3) \), reduces with increasing amplitude, and may become about the half of its value, when \( kA \) increases from 0.1 to 0.2, and \( kD \approx 0.3 \). This should be compared to the rather opposite growth illustrated in Fig. 7c. High order nonlinear potential calculations have been pushed up.
to \( kA = 0.145 \), in good agreement with experiments. \(^{16}\) Local breaking at the cylinder continues to be a challenge in potential flow calculations. New computational methods are needed in order to predict strongly nonlinear forces for subsequent response analysis of offshore structures. The obvious range of interest is indicated in Fig. 9, with \( kA > 0.18 \) and \( u_m/\sqrt{gD} > 0.4 \).

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