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CHALLENGES OF ICE MODEL TESTS WITH MOORED STRUCTURES: EFFECT OF MEASURING TECHNIQUES ON THE RESULT AND RECONSTRUCTION OF ICE LOADS

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ABSTRACT
The ice model tests aimed at studying of moored structure dynamics in ice conditions differ significantly from the physical simulation of static or quasi-static interaction processes of fixed structures with ice. One of the main distinguishes is that the ice loads acting on the moored structure cannot be directly measured. However, they can be reconstructed using parameters of the structure and the mooring system response on the ice action. In this case, determination of the ice forces and moments values is mathematically ill-posed inverse problem. In the paper, some peculiarities of the external action "reconstruction" procedure have been considered. Analytical solution of motion equation of flexible mounted structure under action of harmonic force gives dependencies of the body kinematic parameters on relation of natural frequency of the compliant body to the acting force frequency. The performed analysis has shown that external load acting on the compliant structure can be correctly determined using given system parameters and measured kinematic characteristics of the structure motion if only frequencies of harmonic components of the external forces are less than natural frequency of the compliant structure. As an example, the paper studies a motion of moored conical structure under drifting ice action. The scenario has been realized in the Ice Tank of Krylov State Research Centre, St. Petersburg, Russia. The recovered ice loads have been compared with model tests results of the fixed structure having the same geometry and in similar ice conditions. Horizontal components of the global ice load in both tests modes are in good agreement, at the same time the discrepancies in others components values may be caused by spatial motion of the structure. Since the mathematical model is based on very general differential equations of solid body motions in space, it can be adapted to other floating bodies as well.

INTRODUCTION
Moored ice-resistant platforms for freezing offshore seas should be designed based on careful studies of their behavior in ice-infested waters. Dynamics of a moored structure can be studied analytically and experimentally using model tests in ice basins. Model tests performed for investigating dynamic behavior of moored structures are essentially different from the tests modeling static and quasi-static processes of interaction between fixed platform models and ice: the ice loads acting on the moored structure cannot be directly measured.
There are several approaches to determination of global ice action on the moored structure using model tests results. First one has been realized on ice model tests of a SPAR platform at the HSVA Ice Basin (Bruun et al. 2009). A special measuring system was used during the tests of the SPAR model in moored mode. Together with other parameters (such as motions in 6 degrees of the model freedom, its velocities and accelerations, mooring tensions and mooring

system restoring loads, ice drift velocity), "the ice loads against the hull" were measured. However, the authors have justly noticed that "…the measured ice load for the moored test comprise ice load, any damping load (viscous damping) and inertial load of the upper part of the hull."

According to another approach, the ice loads can be reconstructed by solution of differential equations of solid body motion using measured kinematic parameters of the structure and the mooring system response on the ice action. This way has been used both for processing of ice model tests results with moored structures (Karulin et al. 2004) and for analysis of ice loads acting on full-scale ice-going ships (Krupina and Chernov, 2010; Ringsberg et al. 2014). In this case the estimation of ice-induced forces and moments is mathematically an ill-posed inverse problem (Tichonov and Arsenin, 1979). It should be kept in mind that the “reconstructed” ice load is a certain equivalent of an external ice effect causing the same response of the dynamic system (moored structure) under study. From a formal standpoint this value is not the actual load acting on the object. Therefore, the term “global ice load” in this case should be used cautiously.

Main purpose of analytical investigations presented in the paper was an assessment of validity of the ice loads "reconstruction" procedure based on the ice model tests with compliant structure models. For solution of this task, a simplified problem of one-dimensional translational motion of an elastically fixed material body under action of external exciting periodic force is considered. Analytical solution of the motion equation gives dependencies of the body displacement, velocity, acceleration, as well as of lagging between the acting force and the body displacement on relation of natural frequency of the compliant body to the acting force frequency. The performed analysis has indicated main condition for applicability of the external force "reconstruction": frequencies of harmonic components of the external forces should be less than natural frequency of the compliant structure.

As an example, the ice loads acting on a moored platform model have been reconstructed using the described procedure and compared with direct measurements of ice loads acting on the similar platform model during ice tests in fixed mode. Both types of the model tests have been performed in Ice Basin of the Krylov State Research Centre (KSRC). It can be seen that there is a rather good agreement between the levels of horizontal forces from ice ridges estimated by these two methods, considering different geometric dimensions of ice ridges. However, vertical loads on platforms when the ice ridge was pushed against the model exceeded the forces measured in towing tests, which could be explained by the influence of model dynamics in space.

PROBLEM STATEMENT

The problem addressed here is motion of a floating structure with anchor mooring system induced by loads from a drifting ice feature. It is assumed that no wind, current or wave effects are present. Waves are eliminated by continuous ice cover. Platforms of such type (TLP, SPAR) were investigated in Ice Model Basin of the KSRC (Bezzubik et al. 2004). One of these platforms with its mooring system is schematically shown in Figure 1. In the model tests, each bundle of mooring lines was substituted with a single equivalent line that represented the entire bundle in terms of the stiffness parameters

Two Cartesian systems of coordinates are used for describing the structure motion (Figure 2): fixed coordinate axes $O\xi\eta\zeta$ and moving coordinate axes – $O'xyz$ fixed in the platform. In the initial instant of time under equilibrium conditions both systems coincide. $O'z$ – axis crosses the platform’s center of gravity.

The platform position in space at any instant in time is determined by six coordinates: linear coordinates of the pole – point O' – in the fixed coordinate system $(\xi_{O'}, \eta_{O'}, \zeta_{O'})$, and three ship (Euler) angles– ψ , θ , φ. The angle ψ defines yaw, angle θ defines trim, and angle φ refers to heel of the platform.

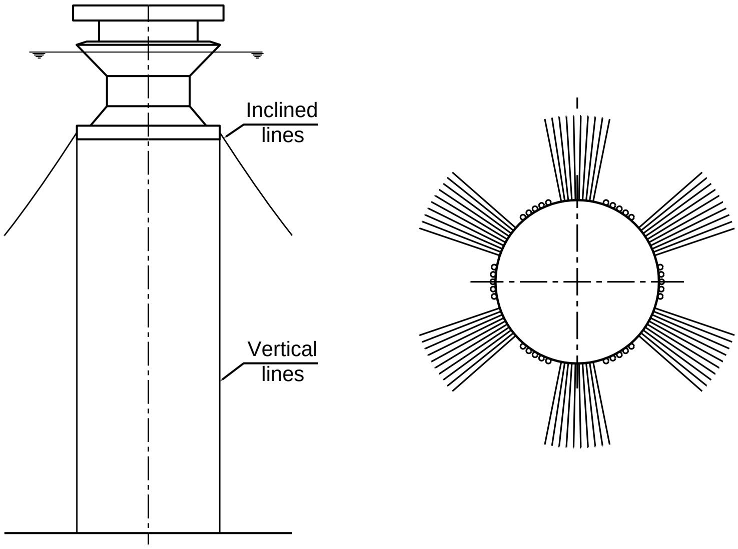


Figure 1. Outline of the moored platform (on the left) and its mooring system (on the right)

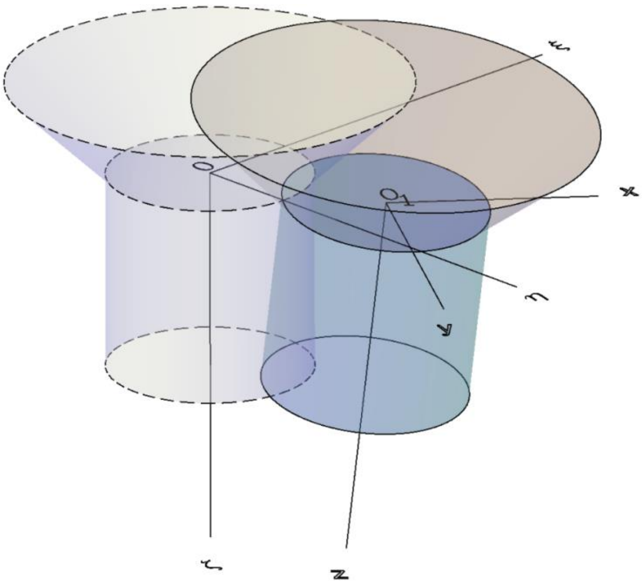


Figure 2. Coordinate systems

The motion of moored platform as a solid body under the drifting ice effect can be described by Euler equations having the following vector form in the body-fixed axes:

$$m[\dot{\vec{V}} + \vec{\Omega}\times\vec{V} + \dot{\vec{\Omega}}\times\vec{r}_G + \vec{\Omega}\times(\vec{\Omega}\times\vec{r}_G)] = \vec{F} ,$$
$$\Theta^0 \cdot \dot{\vec{\Omega}} + \vec{\Omega}\times\Theta^0 \cdot \vec{\Omega} + m\vec{r}_G \times(\dot{\vec{V}} + \vec{\Omega}\times\vec{V}) = \vec{M} \qquad (1)$$

where: m is the body mass; r_G is radius vector of platform's CoG in body axes;

$\Theta^0 = \begin{pmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{pmatrix}$ is inertia tensor of solid body;

$\vec{V}$ is linear velocity vector of point O', pole of body axes; $\vec{\Omega}$ is angular velocity vector of the pole in body axes; $\vec{F}$ is resultant vector of external forces; $\vec{M}$ is resultant moment of external forces with respect to the pole of body axes.

Resultant vectors of the external force and moment on the platform model are defined by corresponding vector sums:

$$\vec{F} = \vec{F}_{HS} + \vec{F}_{HD} + \vec{F}_{ML} + \vec{F}_{ICE},$$
$$\vec{M} = \vec{M}_{HS} + \vec{M}_{HD} + \vec{M}_{ML} + \vec{M}_{ICE} \qquad (2)$$

where

$\vec{F}_{HS}, \vec{M}_{HS}$ are resultant vectors of hydrostatic forces and moments acting on the platform;

$\vec{F}_{HD}, \vec{M}_{HD}$ are resultant vectors of hydrodynamic forces and moments acting on the platform;

$\vec{F}_{ML}, \vec{M}_{ML}$ are resultant vectors of the mooring lines forces and of moments of these forces relative to the pole of body axes;

$\vec{F}_{ICE}, \vec{M}_{ICE}$ are ice force and ice moment induced on platform by ice feature.

Thus, it can be concluded that:

- It is impossible to measure the ice load in such experiments because the forces and moments include inertial and damping components.
- Equation system (1) can be used to “reconstruct” the magnitudes of global ice loads on the platform in the body axes if the initial data inputs are available: mass and inertial characteristics of platform model, kinematic parameters of the model motion in 6 degrees of freedom (displacements, velocities and accelerations), as well as the necessary forces in accordance with (2).

For judging the reliability of obtained results it is required to consider some specific aspects of the procedure for “reconstruction” of external effects applied to an elastically fixed structure.

MOTION OF AN ELASTICALLY FIXED SOLID BODY

For analyzing the specific procedure used for reconstruction of the ice load applied to moored structure let us consider a simplified problem of one-dimensional translational motion of an elastically fixed material body. The schematic diagram is given in Figure 3.

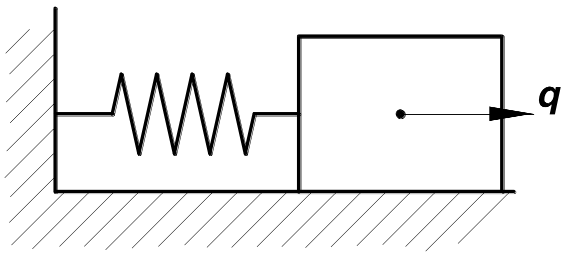


Figure 3. One-dimensional translational motion of an elastically fixed material body

Let us assume that the body is subjected to the following forces:

- elastic force from the spring side;
- resistance force from some environment;
- external exciting periodic force.

Let us also assume that:

- restoring force from the spring side is proportional to displacement;
- resistance force is proportional to velocity of body displacement;

- external exciting force can be represented as one or a number of harmonics of different frequencies;
- body displacements with respect to the initial equilibrium position are characterized by the coordinate q.

The equation of motion for this problem is as follows:

$$a\ddot{q} + b\dot{q} + cq = Q(t) \quad (3)$$

where
a is body mass;
b is body resistance coefficient;
c is spring stiffness coefficient;
$Q(t)$ is exciting force defined as $Q(t) = H \cdot sin\, \omega t$
H is amplitude of exciting force;
ω is circular frequency of exciting force.
It is convenient to write equation (3) as:

$$\ddot{q} + 2h\dot{q} + k^2 q = \frac{H}{a} \cdot \sin \omega t \quad (4)$$

where $h = \frac{b}{2a}$ and $k^2 = \frac{c}{2a}$.
Then, the solution of equation (4) can be written as:

$$q = e^{-ht}(C_1 \sin k_* t + C_2 cos k_* t) + \frac{H}{a\sqrt{(k^2-\omega^2)^2+4h^2\omega^2}} \sin(\omega t - \gamma) \quad (5)$$

where:

$k_* = \sqrt{k^2 - h^2}$, $\tan \gamma = \frac{2h\omega}{k^2-\omega^2}$,

C_1 and C_2 are constants defined by initial conditions.

The solution for displacements (5) consists of two summands: aperiodic and harmonic parts. Let us ignore the decaying component of motion and consider the harmonic periodic part of the solution.
For the interest of space we omit here the cumbersome formulas for velocity and acceleration. Let us analyze these quantities and phase shift angle between the exciting force and body displacement coordinate q in function of the ratio between the natural frequency of spring-mounted body k and the exciting force frequency ω.
Calculations for the case study used the values obtained from experimental studies of the platform shown in Figure 1:

$a = 200$ kg; $b = 2$ N·s/m; c $= 50$ N/m; $H = 20$ N.

Figure 4 shows the plots of body displacement, velocity, acceleration versus the ratio between the model natural frequency and the exciting force frequency, and the angle of phase shift between the exciting force and displacement is given in Figure 5 The results for relative values in plots are presented in non-dimensional form. The following quantities were used for the normalization:

- for displacement – “zero” frequency amplitude
- for acceleration – acceleration amplitude at maximum frequency;
- for velocity – maximum amplitude.

The values used in the analysis are close to real values obtained in modeling of the moored platform (Bezzubik et al. 2004).

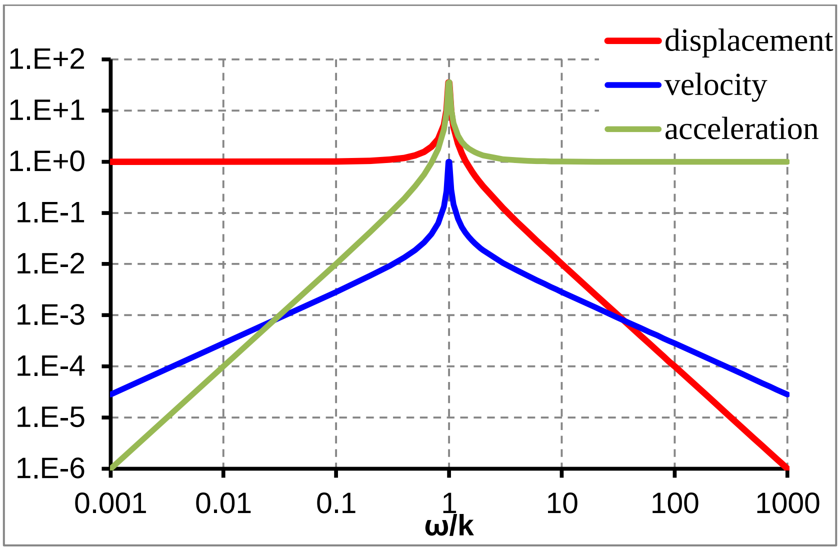


Figure 4. Relative displacement, relative velocity and relative acceleration vs. ratio between natural frequency and exciting force frequency

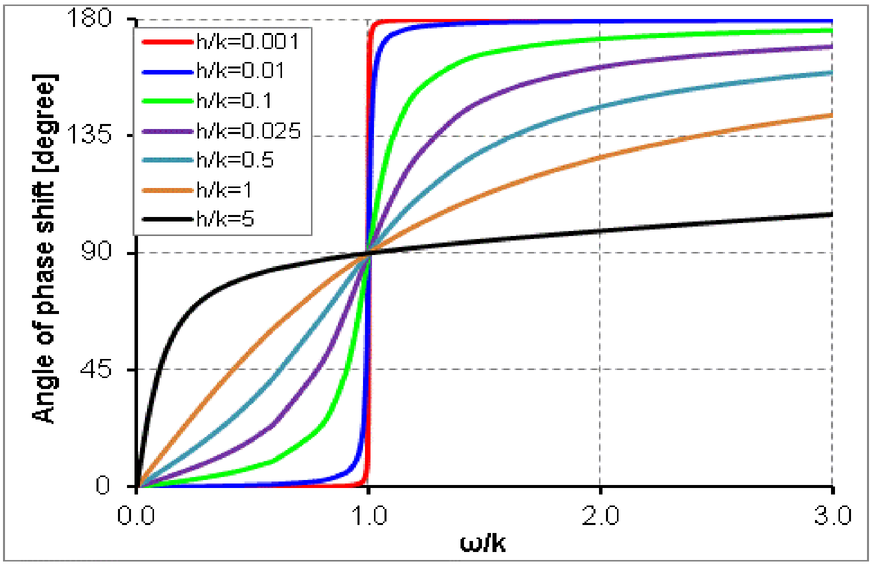


Figure 5. Angle of phase shift between exciting force and displacement vs. ratio between natural frequency and exciting force frequency

From analysis of the above curves it is seen that there is a significant dependence on the ratio between natural frequency and exciting force frequency. According to Yablonsky (1984) forced oscillations with a frequency lower than the natural body frequency are referred to as low-frequency oscillations. The forced oscillations with the frequency higher than the natural body frequency are referred to as high-frequency oscillations.

It should be noted that

- displacement amplitude in the range of low-frequency oscillations is close to 1, growing as the exciting force frequency approaches the body natural frequency (well-known resonance phenomenon), with the curve dropping to 0 in the range of high-frequency oscillations;
- velocity amplitude grows with approach to the resonant frequency;
- variation of acceleration amplitude is opposite to the displacement amplitude pattern featuring close to 0 values at low-frequency oscillations with a resonant peak of the curve then falling to 1 in the range of high-frequency oscillations.

The relationship for the exciting force/displacement phase shift angle is no less complicated. Its special variation pattern is most vividly seen for the system without resistance:

- at low-frequency oscillations the phase of displacement coincides with the phase of exciting force;
- at high-frequency oscillations there is 180° phase shift between the displacement and exciting force, i.e. these processes are opposite in phase.

Let us use this simplest example and try to reconstruct the external exciting force using the system's known parameters (equation coefficients) and the known kinematic parameters of body motion (displacement, velocity and acceleration). Also, let us use exact solutions of equation (4) as motion kinematic parameters. Assumption is made that the exciting force is the sum of two harmonics:

$$Q(t) = H_1 \cdot sin\, \omega_1 t + H_2 \cdot \cos \omega_2 t \qquad (6),$$

where H_1 and H_2 are amplitudes of exciting force harmonics;
ω_1 and ω_2 are circular frequencies of exciting force.

Based on the above assumptions let us reconstruct the exciting force $Q(t)$ using the system's known parameters and the known kinematic parameters of body motion:

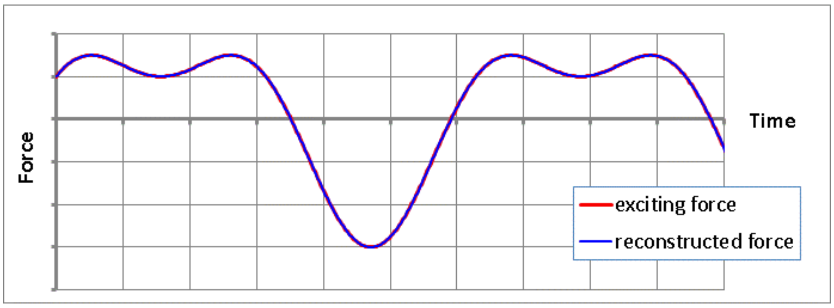
$$Q(t) \; = \ddot{q} + 2h\dot{q} + k^2 q \qquad (7).$$

The obtained results are presented in Figure 6 for the following cases:

1. $k \; = \; 5 \cdot \omega_2 = 10 \cdot \omega_1$ – natural frequency is considerably higher than the exciting force harmonics;
2. $\mathrm{k} \; = \; 0.625 \cdot \omega_2 = 1.250 \cdot \omega_1$ – natural frequency is higher than the first harmonic frequency but lower than the second harmonic frequency of exciting force;
3. $\mathrm{k} \; = \; 0.375 \cdot \omega_2 = 0.750 \cdot \omega_1$ – natural frequency is somewhat lower than the first and second harmonic frequencies of exciting force;
4. $k \; = \; 0.125 \cdot \omega_2 = 0.500 \cdot \omega_1$ – natural frequency is considerably lower than the first and second harmonic frequencies of exciting force;
5. $k \; = \; 0.625 \cdot \omega_2 = 1.250 \cdot \omega_1$ – natural frequency is higher than the first harmonic frequency but lower than the second harmonic frequency of exciting force, however in this case the exciting force is reconstructed with a reduced acceleration value at the second (higher) harmonic frequency (reduction coefficient is 0.25).

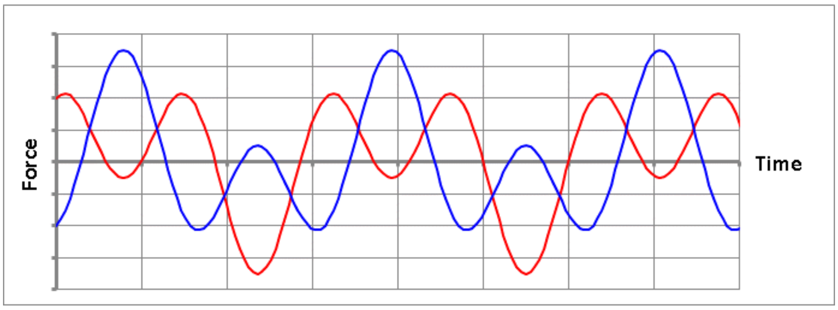
Analysis of the exciting force "reconstruction" procedures described above shows that it is possible to correctly determine the force applied to an elastically fixed body, given known system parameters and kinematic parameters of body motion, only when the frequencies of harmonic components of external forces are lower than the natural frequency of the elastically fixed body. It should be noted that this conclusion is valid not only for determination of external forces acting on the moored platform, but also for the bodies fixed with force measuring instruments (dynamometers) of finite stiffness during investigations.

Case No. 1

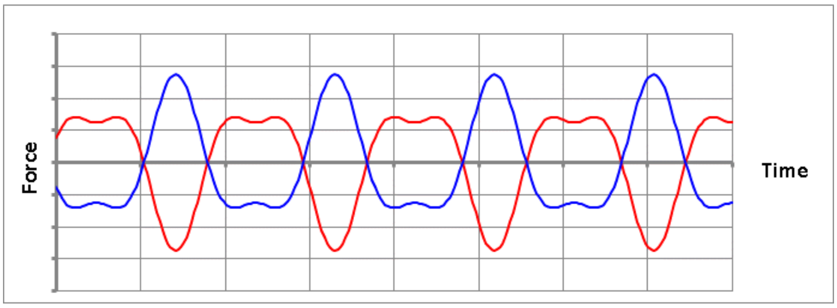


(both curves coincide)

Case No. 2



Case No. 3



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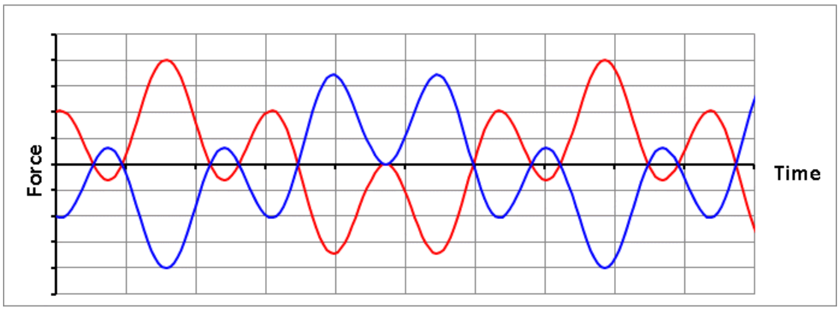

Case No. 5

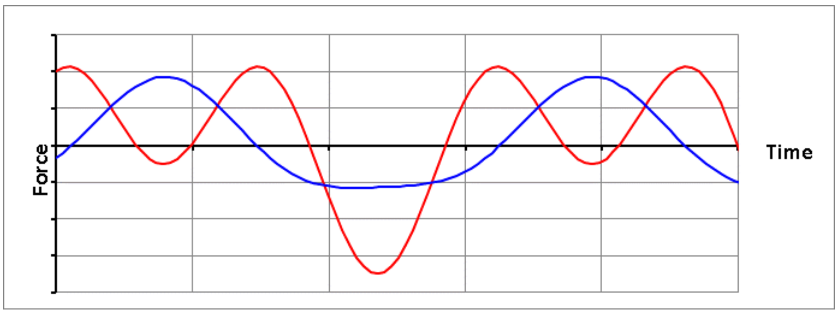

Figure 6. Time curves of exciting (red line) and reconstructed (blue line) forces for calculation procedures of cases 1-5

Analysis of the exciting force “reconstruction” procedures described above shows that it is possible to correctly determine the force applied to an elastically fixed body, given known system parameters and kinematic parameters of body motion, only when the frequencies of harmonic components of external forces are lower than the natural frequency of the elastically fixed body. It should be noted that this conclusion is valid not only for determination of external forces acting on the moored platform, but also for the bodies fixed with force measuring instruments (dynamometers) of finite stiffness during investigations.

When ice effects on moored structures are studied in ice model basins, interactions between platform model and ice cause ice failure. In case of brittle ice failure (and this is the process that they try to model in ice basins) the force induced by ice on the model decays in time rather quickly. Therefore the spectrum of interaction forces contains relatively high-frequency harmonics (time of force decay at failure of a cantilever beam made of model ice is only several centiseconds; the force spectrum contains some components whose frequency reaches up to 10 Hz). These relatively high-frequency harmonics of the exciting force can be lost during “reconstruction” of the ice load, considering that the natural frequencies of platform model fixed with a mooring line system may be in the range of several hertz to tenths of hertz. It is for this reason that the authors use the term “reconstruction” in describing such procedure for determination of external effects, implying that the spectral composition of obtained time functions is incomplete. Certainly, there is also an issue of correctly measuring the body accelerations. In the above the body was assumed to be absolutely rigid and accelerations at any point of the body were determined as accelerations of absolute motion of the pole and rotations around the pole. It is different in reality: models, and more so full-scale platforms, are elastic bodies with compliant structures. Therefore, measurements of body accelerations are affected by the following two processes:

- additional accelerations due to various modes of natural oscillations of the body as an elastic object;
- reduction of harmonic amplitudes in the high-frequency spectrum of measured accelerations due to the fact that accelerometers are fitted to an elastic compliant part of the body under study.

These considerations should be taken into account when choosing the accelerometer location to measure and record accelerations of the body.

RESULTS OF RECONSTRUCTION OF ICE LOAD ON MOORED PLATFORM BASED ON EXPERIMENT DATA

The Ice Basin of the Krylov State Research Centre conducted model experiments for investigating ice interaction with the moored ice-resistant platform shown in Figure 1. Detailed description of the ice model tests and simulated ice conditions is given in Bezzubik et al. (2004).

During the tests all parameters necessary for the ice load “reconstruction” were measured. Figure 7 shows by way of example the tension time histories of most loaded forward mooring lines measured in the course of model experiments intended for studying ice ridge effects on the platform. The time histories of model’s longitudinal displacement and model’s trim angle are given in Figure 8.

It should be noted that velocities and accelerations in all six degrees of freedom were determined by differentiation of respective displacements. Time histories in Figure 9 show results on numerical differentiation. As demonstrated above, the amplitude of displacements falls to zero in the high-frequency range. Thus, in the process of numerical differentiation the high-frequency part of the velocity and acceleration spectrum is lost and does not manifest itself in the results.

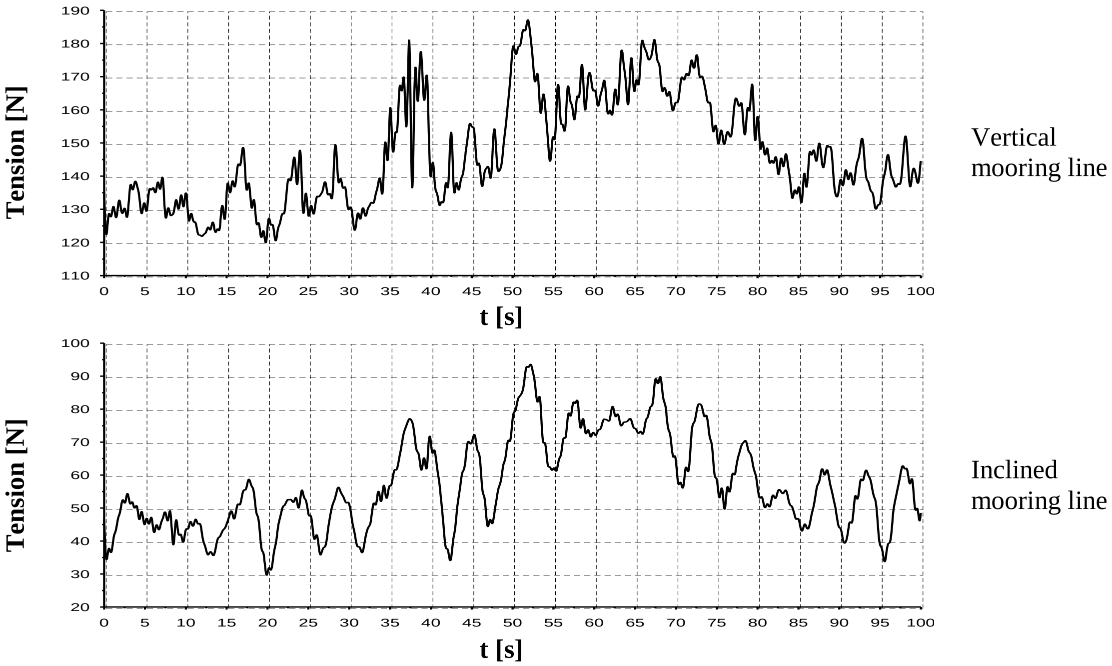

Figure 7. Time-histories of two most loaded mooring lines tension

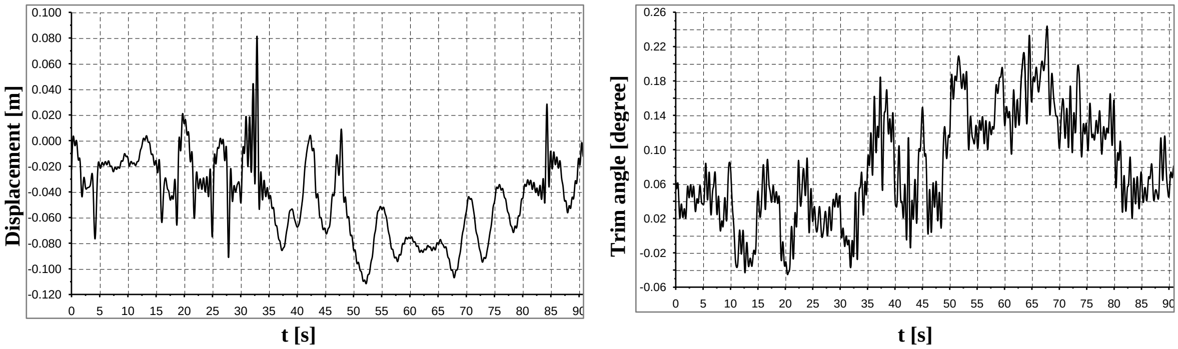

Figure 8. Time histories of model's longitudinal displacement (in the left) and of model's trim angle (in the right)

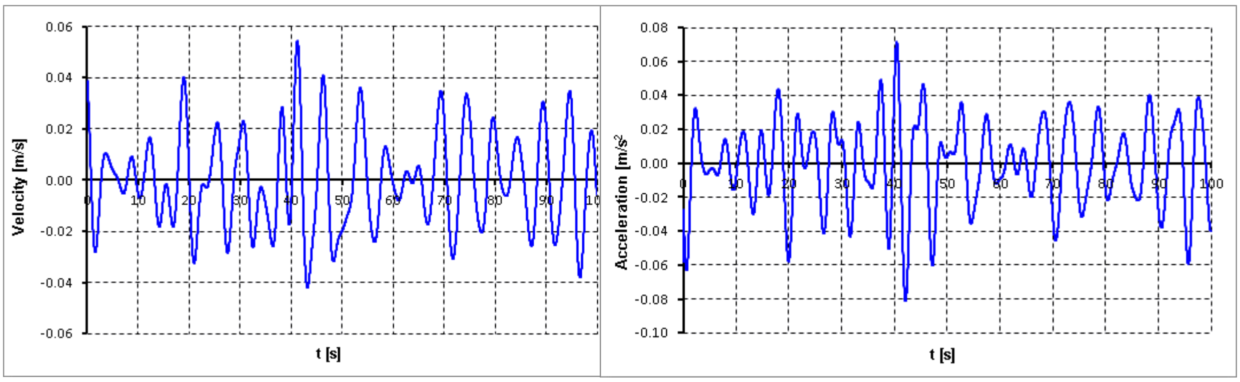

Figure 9. Time histories of model's longitudinal velocity longitudinal acceleration (after numerical differentiation)

In Figure 10 are given reconstructed values of the global ice load on the platform model due to interaction with an ice ridge. These figures also show the corresponding time histories recorded during model tests of the same platform when it was rigidly fixed to the towing carriage.

It can be seen that there is a rather good agreement between the levels of horizontal forces from ice ridges estimated by these two methods, considering different geometric dimensions of ice ridges. However, vertical loads on platforms when the ice ridge was pushed against the model exceeded the forces measured in towing tests, which could be explained by the influence of model dynamics in space.

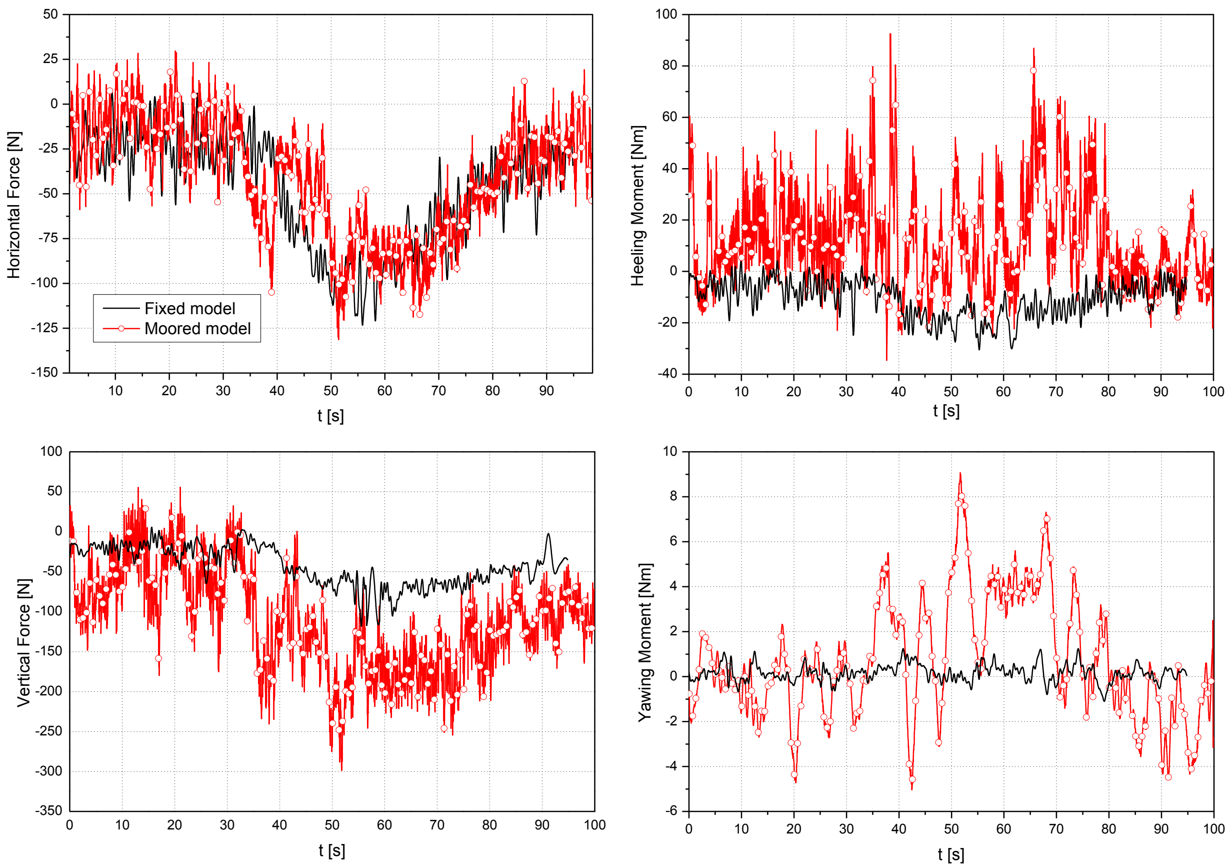

Figure 10. "Reconstructed" (moored model) and recorded (fixed model) time histories of model’s longitudinal force, heel moment, vertical force and yaw moment

CONCLUSIONS

In studying behavior of dynamic objects careful analysis of specific properties of their dynamics is required. It is necessary to take into account a possibility that the obtained information could be distorted being affected by the object itself. In the extreme cases this could make the results of research studies totally meaningless.

The performed analysis has shown that external load acting on the compliant structure can be correctly determined using given system parameters and measured kinematic characteristics of the structure motion if only frequencies of harmonic components of the external forces are less than natural frequency of the compliant structure. Relatively high-frequency harmonics of the acting external force may be lost after the "reconstruction" taking into account low natural frequencies of the moored structures, and a spectral content of the recovered time dependencies of the ice loads is incomplete.

Application of the mathematical model developed for the analysis of model test data indicates that this model enables us to solve the “reverse” problem and derive the “reconstructed” ice load on the moored platform model using tension forces in mooring lines and kinematic parameters of the platform motion measured in the experiment.
From comparisons of ice ridge loads on rigidly fixed and moored platform models it is seen that good agreement has been obtained between the values and variation patterns of the horizontal longitudinal force.

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