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Fault detection in vibration systems: Identifying damaged moorings

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ABSTRACT

Offshore platforms are anchored to the ocean floor using moorings to prevent excessive drifting, and these moorings need to be monitored for damage, an expensive process. Is it possible to detect a change in moorings stiffness by measuring the motion of the platform under random wave forcing? The platform's response is strongly dependent on the wave spectrum and direction of forcing, this forcing is random, and the measurements are indirect, so it seems unlikely. To examine the feasibility we examine a *much simpler* but analogous spring-plate-table system with table rotation mimicking wave action. We find that by using a modal analysis of the underlying system one can unscramble the plate's response and thus determine spring stiffness changes under random forcing, however, as one would expect, the forcing has to have components in an 'active' frequency and direction range. In principle the same type of analysis can be used for real moorings.

Whilst the spring-plate-table system model was developed with moorings in mind, such fault detection issues often arise under circumstances in which direct fault detection is impossible but the basic underlying system is 'known'. The simple spring-plate system examined here is perhaps the simplest non-trivial example of this situation.

1. Introduction

Offshore oil platforms (and also risers) need to remain connected to the well head and so are moored to the ocean bottom to prevent excessive drift under the action of oncoming waves and currents, see Fig. 1. The moorings provide a structural support for the platform which will be compromised if any of the moorings break or are weakened. Although designed to survive extreme wave events, recent data suggests that they regularly fail early in their lifetime through a number of mechanisms (Morandini et al., 2009). Fault detection is therefore of critical importance. Monitoring strategies attempt to catch the early signs of failure, with current industry practice being to deploy unmanned vehicles or divers to undertake visual inspection every five years, alongside shallow water inspections on a yearly basis (Morandini et al., 2009) (Renard et al., 2006). We propose methods for (continuously) detecting faults by observing the changed movement of the platform under random wave forcing. Primarily taut leg platforms will be the focus but the procedures used may be applicable to other moorings types and other forms of external forcing.

Vibrations in the form of sound waves or light rays have been used in the mining industry for the detection of ore bodies, in engineering to determine the presence of cracks in metal and bubbles and other flaws in plate glass, and in medicine to determine abnormalities in human anatomy, see (Sen and Stoffa, 2013), (Duan et al., 2016), (Deng and Liu, 2011). In these classical inverse problem circumstances the vibrational source is prescribed and the aim is to determine some physical property associated with the underlying system. The moorings problem is also an inverse problem but is different in that the vibrational forcing (waves) is not controllable but the response of the platform/moorings system is almost completely known. An additional difficulty is that the response of the platform/moorings system is strongly direction and frequency dependent, so any crude statistical approach will fail; we will make use this sensitivity to detect the fault.

In general terms the vertical vibrational movement of the platform, of mass M, can be described by an equation of the form

$$M\ddot{\mathbf{z}} + \mathbf{D}\dot{\mathbf{z}} + \mathbf{K}\mathbf{z} = \mathbf{F}(t),$$

where $\mathbf{z}$ is the vertical displacement of locations on the platform, $\mathbf{F}(t)$ represents the vibrational forcing due to waves, $\mathbf{K}$ is the effective mooring stiffness and $\mathbf{D}$ is the damping coefficients. The aim to determine the change in $\mathbf{K}$ by observing $\mathbf{z}$ when $\mathbf{F}(t)$ is random with zero mean. In the case of a taut leg platform the moorings are cables anchored some distance from the platform and the effective stiffness for vertical motions is provided by the vertical component of the cable tensions, see Fig. 1.

Aside of course it is the non-vibrational horizontal components of

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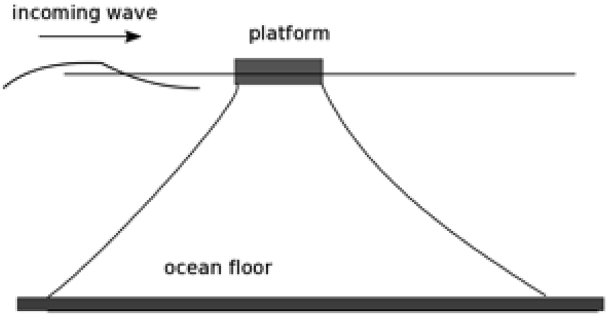

Fig. 1. A long wave hits a moored platform causing it to pitch, roll and translate vertically. Can the vibrations induced be used to determine changes in the mooring stiffnesses?

cord tension that act to restore the platform to a central location and some information concerning mooring stiffness can be obtained by observing this translational movement, however here we consider vibrational vertical movements caused by waves; the system is assumed to be linear so such quasi-steady forcing with associated translational motion can be filtered out. Also, although an equation of the above type can be used to describe induced horizontal vibrations, it seems unlikely that the forcing and platform response will be consistent enough to enable stiffness calculations of the type described here to be successful. There are other moorings types and the applicability of the procedures used here will depend on the circumstances of forcing and restraint, see Section 4.

Many issues complicate the fault detection moorings problem, see Section 4, however the primary difficulties are that: the forcing is random and unknown, the system's response is highly frequency and direction dependent, and the measurements are indirect. It was/is not clear if detection is possible ‘in principle’, so an analogous but much simpler system has been examined. The simpler system consists of a plate (platform) mounted by springs (cables) on a vibrating table (the waves), see Fig. 2. In the taut leg mooring situation it is the long waves (i.e. waves of length of the platform or larger) that cause the platform to move against gravity causing the platform to vibrate vertically and to pitch and roll. In our simpler system the rotating table applies this external forcing causing the rigid plate to translate, pitch and roll. The direction of the in-plane axis of rotation, as well as the amplitude and frequency of oscillation, may vary randomly to simulate waves impacting the platform at an arbitrary angle. The advantage of this plate model is that exact solutions are available so that the fault detection procedures used can be assessed. Typical inverse approaches in vibrations rely on modal analysis techniques to extract information from resonant peaks in the frequency domain, which can be used to reconstruct the mass, stiffness and damping of the system (Schmitz and Smith, 2011). This is the approach we will take here.

In Section 2 we solve the forward problem under deterministic forcing. We then use the results to address the inverse problem in Section 3, and we then use simulations to determine the efficacy of the method. Finally, in Section 4, we return to discuss the application to real moorings.

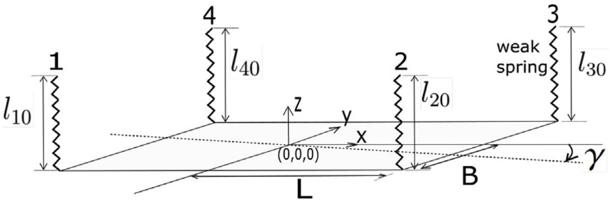

Fig. 3. Base table and uncompressed springs. γ is the axis of rotation (dotted line).

2. Forward problem

2.1. Table and plate geometry and dynamics

The situation to be examined is that of a plate attached to a vibrating table by supporting springs as shown in Fig. 2. The vibrating table causes the plate to vibrate. The centre of the table is chosen as the origin O through which passes the horizontal datum plane with axes x and y aligned with the sides of the table and with the z axis vertical.

We will begin by considering the oscillating table and initial spring positions in the absence of the plate, shown in Fig. 3.

The table oscillates about an axis passing through O and lying in the plane of the table at an angle γ clockwise to the x axis. The table has length 2L and width 2B. The equations describing the corner heights of the table Z_i above the datum plane at time t due to the table oscillation are given by

$$Z_1 = -e^{j\omega_f t}\sqrt{B^2 + L^2}\,\alpha_0 \sin\left(\gamma + \arctan\left(\frac{B}{L}\right)\right)$$

$$Z_2 = -e^{j\omega_f t}\sqrt{B^2 + L^2}\,\alpha_0 \sin\left(\gamma - \arctan\left(\frac{B}{L}\right)\right)$$

$$Z_3 = e^{j\omega_f t}\sqrt{B^2 + L^2}\,\alpha_0 \sin\left(\gamma + \arctan\left(\frac{B}{L}\right)\right)$$

$$Z_4 = e^{j\omega_f t}\sqrt{B^2 + L^2}\,\alpha_0 \sin\left(\gamma - \arctan\left(\frac{B}{L}\right)\right),$$

where ω_f is the angular frequency of rotation and α_0 the amplitude of rotation of the table, and where the small angle approximation $\sin\alpha_0 = \alpha_0$ has been used under the assumption that the forcing magnitude is sufficiently small.

There are four springs attached to the table corners, denoted i = 1.4. The i_{th} spring of initial length l_{i0} is attached to the table as shown. As we are most interested in the effect of mooring integrity on system behaviour, spring 3 is allowed to be weaker. Thus, the spring constants k_i are

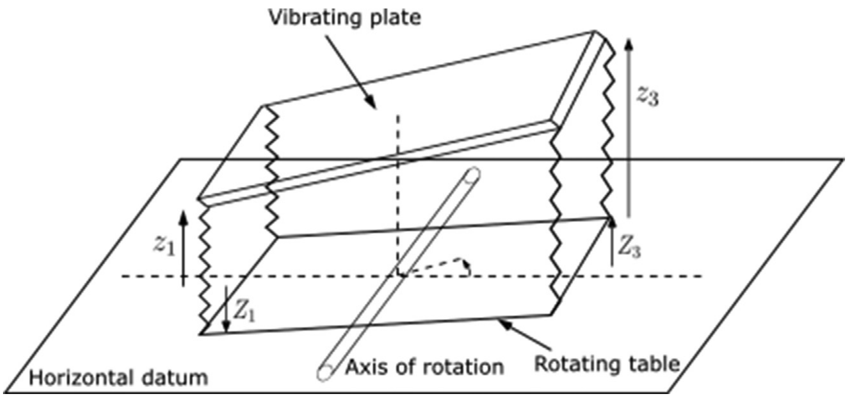

Fig. 2. The plate/spring/table system. Springs attach the corners of a plate to a table which can rotate about an axis in the plane of the table passing through the centre of the table. The suspended plate (platform) acts in response to a table which vibrates about its axis. In the illustrated case the axis of rotation (direction of incoming wave) is parallel to the plate edges but arbitrary in-plane orientations are considered. The (z_i, Z_i) ’s locate the (plate, table) relative to the horizontal datum plane through the centre of the table.