Study of Vibration Control of Platform Structures

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Abstract

This paper discusses the vibrations induced by sea ice in off-shore oil platform structures. The mitigation of these vibrations through passive controls, specifically the tuned mass damper (TMD), is also explained. A single-degree of freedom model of the JZ20-2 MUQ oil platform under excitation was designed and validated using Simulink. Simulation of the actual platform structure in the Bohai Bay was used with a large-scale model of the passive control TMD for testing. This set-up is referred to as a half-experimental with half-simulation test. Experiments were conducted by applying four different forcing patterns with and without the TMD attached to the system. The four force types were a harmonic input, a determined ice-force, a random ice-force, and the ice-force time history function. These excitations were based upon the actual measured ice-force on the JZ20-2 MUQ oil platform structure in the Bohai Bay. They were first set to the natural frequency of the tuned mass damper and then other frequencies were applied to verify the assumed natural frequency. The results of the testing with and without the TMD were then compared to see the effectiveness of the TMD. Mitigation of vibrations from ice forces was shown through a reduction in displacement of the structure. There is still no reduction of acceleration in the structure with the passive control TMD; necessitating further testing, possibly with active or semi-active controls.

Introduction

The growing need for more energy sources in recent years has driven the research for safe and reliable methods for the extraction of oil from below sea water, in areas susceptible to freezing. This has led to the construction of off-shore oil platform structures in the Bohai Bay in order to gain access to the oil reserves. The problem realized here is that ice forms in the sea around the bases of these structures. Forces are then transferred to the structure upon the breaking of this ice against the base. These vibrations can cause equipment malfunction, damage to the structure, and discomfort to workers on the platform structure.
Various techniques have been applied to mitigate vibrations caused by the ice breaking against the structures. For example, conical legs have been implemented, in place of standard vertical legs, to transform the breaking force of the ice from crushing to bending as the ice is lifted at the base. This force is much lower; however with the addition of these conical legs the force becomes periodic and is related to the breaking length of the ice. There is also no verification that conical legs are effective in reducing vibrations that occur in the platform structures. It was also found by Peyton (1966) that at high ice speeds the breaking ice-force could be at the same frequency as the natural frequency of the structure. This could cause an extreme amplification of the dynamic motion of the platform, which would increase the potential for severe damage to the structure and equipment (Yue and Liu 2003).

In the past structures have been built in the Bohai Bay without consideration of the susceptibility these platforms have to ice-induced vibrations. Several of these structures were destroyed and in effect, new highly expensive structures that were overly rigid were designed. Although there was a notable decrease in vibration, human discomfort and equipment malfunction were still an issue. Until recently the effects of ice-induced vibrations were studied, but no research to mitigate them was employed (Yue and Liu 2003, Jin and Hu 1998, Li and Yue 2002, Li, et al. 2003).

In order to prevent such problems from occurring, various forms of vibration mitigation have been explored. Vibrations in structures caused by wind and earthquakes have already been well researched; however, it is found that ice-induced vibrations do not act in the same manner as either of these. Rather, ice-induced vibrations are periodic and have “saw tooth like” excitations. They do share common characteristics with both earthquake and wind-induced vibrations. Past research has shown, however, that ice-induced vibrations act in more the same way, respect to frequencies for example, as wind-induced vibrations. So, it is most beneficial to focus research on the vibration mitigation systems put to use in the area of wind-induced vibration mitigation.

**Background**

Research to find an effective vibration mitigation system has revealed that the use of a passive control tuned mass damper may be most effective and economical. The concept of tuned mass dampers as a vibration mitigation system has been around since the early twentieth century, mainly for tall buildings susceptible to high winds or seismic activity (Den Hartog 1956). A TMD is a device with a mass, springs, and a damper, usually installed on the top of structure. In order to achieve the most efficient energy absorbing capacity, the TMD tunes its natural frequency with the natural frequency of the structure, but has a phase shift. Passive control TMDs do not need an external energy source, are highly reliable, and are easy to maintain.

This paper focuses on the study of off-shore oil platforms and the effects of sea ice vibrations on them, specifically in the Bohai Bay. Development and validation of the simulation model used during testing with the large-scale tuned mass damper will be described. The process of mitigating vibrations from platform structures with a TMD
will also be explained. The conclusion of the paper will compare the passive control experiment results and the simulation.

Simulation Model Development and Validation

The model designed at State Key Lab of Structural Analysis of Industrial Equipment, Dalian University of Technology, China to test vibration mitigation with a TMD is an innovative approach to study in the area of vibration mitigation of off-shore platform structures. The system is unique in that it uses a half-experimental with half-simulation arrangement. The necessity of this system arises because of the expense and unavailability of full-scale testing. It has been established that conducting testing on a device with a simulation input can be beneficial to testing (Dyke and Jansen 1999). This experiment allows for testing of the effectiveness of the TMD with a simulated response of the platform structure.

The basic model set-up includes the TMD, the “moving table,” the dSPACE control system, the hydraulic actuator, the sensors for the TMD response, and the virtual model of the platform structure. The TMD, shown in Fig.1, consists of a moving mass connected to two reaction walls via twenty-four coil springs. The outer dimensions of the TMD are 1.8X1.1X0.7m and the damping coefficient (friction) of the damper is 0.04. The moving mass is a variable, but testing was done with a weight of 810 kg. With this mass and damping coefficient, the natural frequency of the damper is found to be 1.27 Hz. A damper filled with liquid is attached to the moving mass and uses frictional force to mitigate vibration from the system under periodic frequencies. Frictional force also occurs along the tracks which the moving mass slides on during random excitation. An input force is simulated to act upon the platform structure and applies the corresponding displacement to the “moving table” via a hydraulic actuator. This force is only applied as a displacement in order to safely conduct testing. Applying a direct force could be too dangerous if the results are not already known. Sensors are attached to the tuned mass damper and moving table, which supply the dSPACE control system with the response of the TMD. A representation of the experimental set-up is shown in Fig.2.
The sensors attached to the damper and the base are unique in that they are able to read displacement, velocity, or acceleration. Each sensor has switches which allow for the choice of the response read. In testing, displacement and acceleration were the variables desired. The problem that occurs with these sensors is that they are not as precise as sensors designed to read one specific response.

The responses collected by the sensors placed on the TMD and base are converted from analogue to digital signals via an Analog Digital converter (ADC) and input to the computer system. This information is then analyzed in the dSPACE computer program and fed back to the actuator connected to the TMD. This process is called hardware-in-the-loop simulations (HILS). The result of experimentation with this system gives seven outputs, which can be evaluated in Matlab: simulated structure acceleration, simulated structure displacement, expected actuator displacement, actual actuator displacement, TMD acceleration, TMD velocity, and TMD displacement. The first three of these outputs are simulated with the Simulink model and the last four are actually collected experimental data. A diagram of the Simulink model with seven outputs is shown in Fig.3.

The experimental system can be modeled mathematically as a simple two degree of freedom system. From this model, we can find the equation of motion of the structure (1) and the equation of motion of the structure with the tuned mass damper (2) to be of the forms:

\[ m_1 \ddot{x}_1 + c_1 \dot{x}_1 + k_1 x_1 = F_{inc}(t) \]  
\[ m_2 \ddot{x}_2 + c_1 \dot{x}_1 + k_1 x_1 = F_{inc}(t) - m_2 \ddot{x}_2 \]
In the second equation the right side of the motion equation represents the external force input and the inertial force of the TMD. The left side of the equation is obviously then the mass, the damping, and the stiffness terms.

Figure 3 Simulink Diagram of Simulation Model

Vibration Mitigation of Platform with the Tuned Mass Damper

Tuned mass dampers have been widely used for the suppression of vibration of wind-induced and seismic vibrations in tall buildings (Whalen 2002). Buildings such as the Centerpoint Tower in Sydney, Australia, the Citicorp Center in NY, and the John Hancock Tower in Boston have all implemented TMDs to reduce vibrations (McNamara 1977). However, the concept of using TMDs with ice-induced vibrations in off-shore platform structures has only recently been conceived. Tuned mass dampers are dynamic vibration absorbers, normally with a mass connected to the top of a structure by way of a spring-dashpot arrangement, which can tune itself to oscillate with the same frequency as the structure, but with a phase shift. Obviously, the mitigation of vibrations is optimized when the phase shift of the TMD is ninety degrees off from the structure. Vibrations are mitigated as relative motion takes place between the structure and the mass via the dashpot. This energy dissipation allows for the TMD to obtain some of the external force in place of the structure (Kwok 1995).
It is imperative that TMDs are properly tuned to the frequency of the structure in order to most effectively mitigate vibrations from ice forces. In order to accomplish this, effective damping must be found. This can be obtained by comparing the TMD as a single-degree of freedom (SDOF) system with the combined structure and TMD system with the same frequency and then solving for the effective damping. The response to dynamic ice forces depend on ice speed/thickness, surrounding environment, structure shape, size, mass, stiffness, and amount of energy dissipation available in the system (McNamara 1977).

**Experimental Procedure**

Testing in the lab with the HILS system was conducted to verify the effectiveness of the tuned mass damper at dissipating vibrations from the platform structure. In order to carry out experimentation with the correct input force frequency, the natural frequency of the structure must first be established. As stated previously, the TMD is most effective when it is tuned to have the same frequency as the natural frequency of the excitation. The natural frequency of the TMD is found by applying a scanning test. The Simulink model is used to apply this increasing force function to the system. Plotting the displacement verses time data or the acceleration versus time data allows for the natural frequency to be calculated. An example of the displacement versus time graph is shown in Fig.4. The natural frequency of the TMD was then calculated to be 1.27Hz. In order to verify this further, testing was carried out for various input forces at frequencies of 1.22Hz and 1.32Hz as well as 1.27Hz.

![Figure 4 Displacement vs. Time Plot of Scan Test Data](image1)

![Figure 5 Measured Ice-force Time History vs. Time](image2)

Input forcing functions used for experimentation were based upon an Ice-force Time History function collected by load panels on the JZ20-2 MUQ oil platform in the Bohai Bay. An example of the Measured Ice-force time history is shown in Fig.5. With this function a determined ice-force function and a random ice-force function were
derived mathematically. The two variables of these functions are frequency and amplitude. The determined ice-force function has a steady frequency and amplitude during testing and the random ice-force function varies these two variables according to a mathematical method.

Testing was then carried out by applying each of these input functions, as well as a standard harmonic function, with the Simulink model. For each function except the ice-force time history function the test was carried out with the three separate frequencies in order to verify the natural frequency of the structure; all other variables remained constant. The dSPACE control system in conjunction with Simulink and Matlab then allowed for the processing of data. Comparisons between the simulation model without the TMD and the actual experimental data were able to be plotted in Matlab.

**Results**

Collection of the data was done with the use of the program Matlab. All data was plotted as comparisons between simulation data without the TMD and experimental data with the TMD. Figs.6 to 8 show that the TMD is effective for reducing structural displacement under an applied harmonic input force. It is also evident that Fig.6 with an input frequency of 1.27Hz, the natural frequency of the structure, is most effective at reducing structural displacement as well as it is most closely in phase with the structural displacement. Similar results can be seen in Figs.11 to 13 for the Input Determined Ice-force function. It is clear that Fig.11, with the natural frequency input, is most effective for reducing structural displacement. Analysis of Figs.16 to 18 reveals that the TMD is effective for reducing displacement of the structure under a random ice-force. The reduction in displacement is not as significant as the periodic inputs of the harmonic force and the determined ice-force though. Again, the figures clearly show that an input frequency equal to the natural frequency is the most effective, verifying the value of 1.27Hz. These plots also illustrate the increased effectiveness of the TMD with increasing input force. For example, as the amplitude of structural displacement increases, the reduction of displacement with the TMD becomes larger. The Ice-force time history displacement comparison plot in Fig. 21 also demonstrates the effectiveness of the TMD.

When analyzing acceleration mitigation with the TMD, results are not as anticipated. There are clearly problems with the responses collected for Figs.9, 14, 19, and 22. This is most likely due to external sound vibrations read by the accelerometer during testing. The figures do reveal that the TMD is not effective for mitigating acceleration of the structure. There have also been complications with the force transducer, requiring it to be recalibrated; however, this process is still underway.

In the comparison of input forces to inertial forces, effectiveness of the TMD is shown by a ninety degree phase shift of the inertial force to the input force. This is most evident in the Harmonic input force and the Determined Ice-force, since they are periodic and tuned to the same frequency as the TMD. Plots of the Harmonic and Determined Ice-force input to inertial force are shown in Fig.10 and Fig.15, respectively. The effectiveness of the TMD decreases with the Random Ice-force input due to difficulties it
has with self-tuning to the random amplitude, shown in Fig. 20. It is generally effective for fundamental frequencies, which is desired. The Random Ice-force function acts most similar to the Ice-force Time History function so it is not surprising that the TMD is not very effective for the actual time history input function, shown in Fig. 23. These results are reassuring as to the effectiveness of the TMD for vibration mitigation; however, further studies are obviously necessary in order to increase effectiveness for real ice-forces on platform structures.

Figure 6 Harmonic Function Displacement Comparison w/ and w/o TMD (1.27Hz)

Figure 7 Harmonic Function Displacement Comparison w/ and w/o TMD (1.22Hz)

Figure 8 Harmonic Function Displacement Comparison w/ and w/o TMD (1.32Hz)
Harmonic Acceleration Comparison

Figure 9 Harmonic Function Acceleration Comparison w/ and w/o TMD (1.27Hz)

Harmonic Force Comparison (1.27Hz)

Figure 10 Harmonic Function Input vs. Inertial Force Comparison (1.27Hz)

Determined Ice Force Displacement Comparison (1.27Hz)

Figure 11 Determined Ice-force Displacement Comparison w/ and w/o TMD (1.27Hz)

Determined Ice-force Displacement Comparison (1.22Hz)

Figure 12 Determined Ice-force Displacement Comparison w/ and w/o TMD (1.22Hz)

Determined Ice-force Displacement Comparison (1.32Hz)

Figure 13 Determined Ice-force Displacement Comparison w/ and w/o TMD (1.32Hz)
Figure 14 Determined Ice-force Acceleration Comparison w/ and w/o TMD (1.27Hz)

Figure 15 Determined Ice-force Input vs. Inertial Force Comparison (1.27Hz)

Figure 16 Random Ice-force Displacement Comparison w/ and w/o TMD (1.27Hz)

Figure 17 Random Ice-force Displacement Comparison w/ and w/o TMD (1.22Hz)

Figure 18 Random Ice-force Displacement Comparison w/ and w/o TMD (1.32Hz)
Figure 19 Random Ice-force Acceleration Comparison w/ and w/o TMD (1.27Hz)

Figure 20 Random Ice-force Input vs. Inertial Force Comparison (1.27Hz)

Figure 21 Ice-force Time History Displacement Comparison w/ and w/o TMD

Figure 22 Ice-force Time History Acceleration Comparison w/ and w/o TMD

Figure 23 Ice-force Time History Input vs. Inertial Force Comparison
Conclusions

Testing with the passive control tuned mass damper in the hardware-in-the-loop simulation has revealed useful results to research conducted on vibration mitigation of off-shore platform structures. The effectiveness of the TMD in the State Key Lab of Structural Analysis of Industrial Equipment at Dalian University of Technology has been shown for structural displacement reduction. Acceleration of the platform structure is still not reduced by the current set-up of the system. Further testing is required, possibly with more accurate accelerometers. Semi-active or active control measures may also be required for acceleration reduction to be effected.

The continuing need for energy sources substantiates the continued quest for oil sources. This verifies the necessity of continued research in the area of vibration controls for off-shore oil platforms in order to increase the life-time of the structure and equipment as well as to prevent human discomfort.

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