Physical mechanism of ice induced self-excited vibration

Yihe Wang[1], Qianjin Yue[2]

[1,2] State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian, China

ABSTRACT

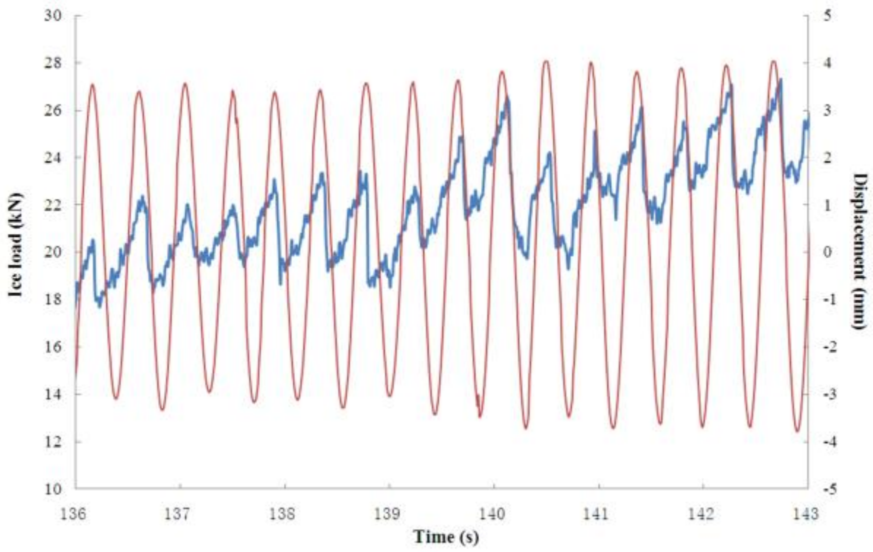
Steady state vibrations of vertical offshore structures induced by crushing failure of level ice were observed on several jacket platforms in Bohai Sea, China. Further analysis of the field data indicates that dynamic ice force is controlled by the structure's motion, in other words, the steady state vibration is self-excited. Yue et al (2009) proposed the physical mechanism of ice induced self-excited vibration based on the mechanical behavior of ice under uniaxial compression in the ductile-brittle transition region. As a matter of fact, the key feature of ice induced self-excited vibration is the loose simultaneousness between the unloading of the ice force and the swing back of the structure. A physical mechanism is presented in this paper to explain this simultaneousness between the unloading of the ice force and the swing back of the structure based on the work of Yue et al (2009).

Keywords: physical mechanism; self-excited vibration; ice induced vibration; ductile-brittle transition; micro crack

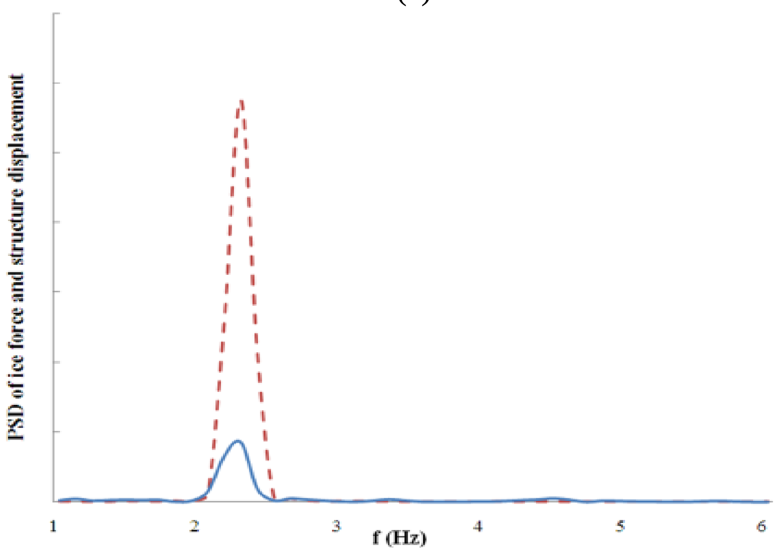
INTRODUCTION

Vertical structures are often placed in high latitude sea areas where ice is infested. Under certain condition, these structures vibrate during the interaction with moving ice sheet. Ice induced vibration of structures was first observed on the drilling oil platforms in Cook Inlet, Alaska (Payton 1966; Blenkarn 1970). After that, some measurements in situ and experiments in the laboratories were conducted to investigate the ice induced vibration.

A special kind of ice induced vibration, in other words, steady state vibration which features the frequency "locked-in" was observed (Figure 1(b)). And many models and theories, among which there is a disagreement between forced vibration and self-excited vibration, have been proposed to describe ice induced, steady state vibration of cylindrical-leg structures. Fig 1(a) shows the time history of the displacement of the structure and the ice force in typical ice induced steady state vibration. Obviously the dynamic ice force is controlled by the structure's motion, and I have no doubt that the ice induced steady state vibration is self-excited vibration.



(a)



(b)

Figure 1. (a) Concurrent time history plot of ice force and vibrating displacement of structure, in which the smooth time history is displacement and the saw tooth curve is ice force; (b) Power spectrum density (PSD) of ice force and structure displacement (the dashed line is PSD of structure displacement and the units of ordinate is eliminated for clarity).

Blenkarn (1970) proposed the “negative damping” theory to explain the mechanism of ice induced self-excited vibration. Sodhi (1988) discussed the negative damping model extensively and noted some obvious flaws in the hypothesis, which is difficult to use to prove and explain the origin of ice induced self-excited vibration.

Self-excited vibration is an important branch in the theory of nonlinear vibration. In nature and engineering field, the physical mechanism of vortex induced vibration (VIV) and dry friction-caused self-excitation has been explained with regular shedding of vortex and the “stick-slip” effect respectively. Therefore, it is very important to identify the physical mechanism of ice induced self-excited vibration to predict its response.

PHYSICAL MECHANISM

Ductile to brittle transition

As shown in Figure 2, under uniaxial compression, sea ice exhibits different failure modes including ductile, ductile-brittle transition, and brittle failure due to different loading rates. Under low loading rate, the material is ductile, and exhibits strain hardening and strain softening, see Figure 2. Ascending and descending branches characterize its stress strain curve. And less cracks nucleate in the specimen which is loaded under low strain rates. The ductile strength or peak stress increases with increasing strain rate. On the other hand, at higher strain rates, ice is considered to be brittle when its stress-strain curve is pseudo-linear in shape and terminates suddenly owing to the onset of a mechanical instability. Ice exhibits brittle behavior and an ascending branch characterizes its stress-strain curve. Under the loading rate which is in the ductile to brittle transition region, much more cracks nucleate in the specimen.

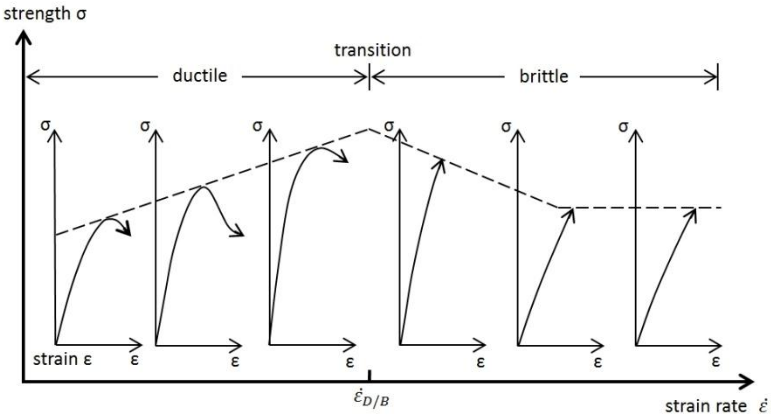


Figure 2. Schematic sketch showing the effect of strain rate on the compressive stress strain behavior of ice.

As a matter of fact, different physical mechanism of ductile failure and brittle failure leads to the ductile to brittle transition behavior. In the ductile region, the end point of the stress strain curve represents the moment when the nucleation of the last crack which links the cracks around it takes place, which leads to the final failure of the specimen. On the other hand, in the brittle region, the end point of the stress strain curve represents the moment when the wing cracks (Figure 3) propagate to a critical length, in other words, the linkage of the wing cracks takes place (Sanderson, 1988, Schulson, 2001).

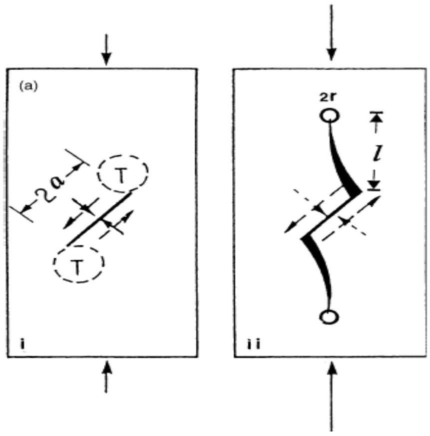


Figure 3. A wing crack in ice specimen.

Ashby and Hallam (1986) gives a two dimensional model of the crack which is simplified to

$$\sigma_{11} \approx \frac{\sqrt{3}\delta K_{IC}}{\sqrt{\pi a}(1-\mu)\beta} \quad (1)$$

for uniaxial compression condition when δ, the ratio of the length of the wing cracks to the half length of the parent crack is much larger than 1, where K_{IC} is the fracture toughness, a is the half length of the parent crack, μ is the friction coefficient across the crack which decreases with increasing sliding speed, β is approximately 0.4.

According to Equation (1), the stress required to propagate the wing crack to a certain length decreases with increasing loading rate, which attributes to larger loading rates results in larger sliding speed.

Specifically, under low loading rates, as the load increases, the secondary creep strain rate increases, and the nucleation of cracks takes place when the stress state reaches a critical level or the delayed elastic strain reaches a critical level. When the stress reaches the maximum value, it is still not large enough to propagate the wing cracks long enough to linking each other. As a result of that, the ice specimen is still capable to bear further load. The cracks nucleate one by one constantly as the actual stress in the ice specimen increases, and the more cracks in the ice specimen, the more lower the actual stress is than the nominal stress, which leads to the descending branches of the stress strain curve. The trigger of the ending of the stress strain curve is the nucleation of the last crack which links the wing cracks around it. According to the physical mechanism of ductile failure discussed above, the ductile failure stress required to induce secondary creep, which is taking place at the loading strain rate, increases with the increasing loading strain rate, in other words, the ductile failure stress is characterized by strain rate hardening.

On the other hand, under high loading rates, after the nucleation of cracks in the ice specimen, the stress increases until it is large enough to propagate the wing cracks long enough to link each other which leads to the failure of the ice specimen. As mentioned earlier, the stress required to propagate the wing crack to a certain length decreases with increasing loading rate, which attributes to larger loading rates results in larger sliding speed, in other words , lower friction coefficient μ in Equation (1). Consequently the brittle failure stress decreases with increasing loading strain rate, which is called strain rate softening.

Actually, Schulson (2000) proposed a new physical mechanism of brittle failure of ice which features comb cracks in ice. This new physical mechanism does not contradict with what we discussed above, and Schulson (2000) also admits that the two physical processes both exist. Since this is not what we concern in this paper, I will not go into detail about it.

The ductile to brittle transition marks the point where the compressive strength reaches a maximum with respect to strain rate. The ductile to brittle transition point is nothing but the intersection point of the strain rate hardening curve and the strain softening curve of compressive strength. Under the ductile to brittle transition loading rate, the final failure stress is the stress required to yield the loading strain rate in the form of secondary creep, and also the stress required to propagate the wing cracks long enough to link each other, which means both of the above are equal.

Physical mechanism of ice induced self-excited vibration

Self-exited vibration is an important branch of nonlinear vibration, and every kind of self-excited vibration has its own physical mechanism.

According to the analysis of the field ice force data from JZ9-3 MDP-1 and MDP-2 in Bohai Sea, crushing ice forces could be classified into three modes, including quasi static loading, self-excited ice force and random dynamic ice force (Yue et al. 2009). It was found that ice induced self-excited vibration occurs under relatively low ice velocities (2~4cm/s according to the video data). Figure 4 and Figure 5 show the field test system and typical concurrent time history of structural displacement and ice force during ice induced self-excited vibration respectively.

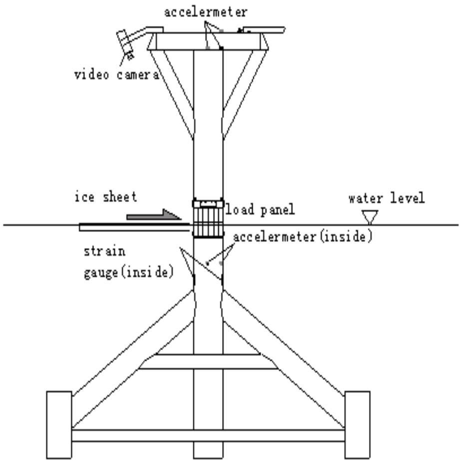


Figure 4. Field set-up on JZ9-3 MDP-1.

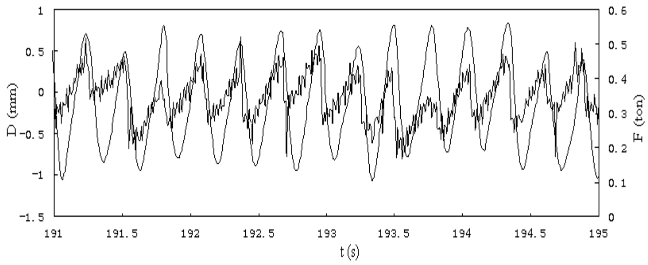


Figure 5. Concurrent plot of structural displacement and ice force during ice induced self-excited vibration, in which the smooth time history is displacement and the saw tooth curve is ice force.

Based on the fact that ice induced self-excited vibration takes place when ice drifting velocity enters a special range (2~4cm/s according to field video data), and crushed ice fragments from ice induced self-excited vibration are quite smaller than that of brittle crushing, Yue et al (2009) proposed that ice induced self-excited vibration arises when ice sheet undergoes ductile-brittle transition failure.

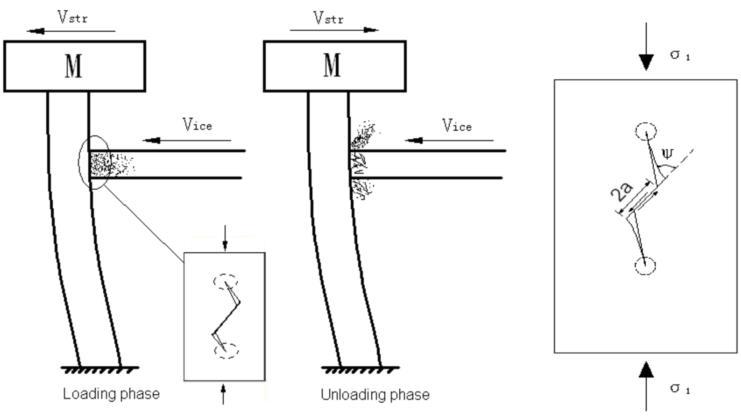


Figure 6. Sketch of ice induced self-excited vibration and wing-crack model.

As shown in Figure 6, one cycle of structure vibration is divided into two phases: loading phase and unloading phase. When structure moves in the same direction of ice drift (loading phase), relative speed between structure and ice sheet is low and makes ice loaded in ductile-brittle transition region, which means that lots of cracks form in the ice sheet but the ice force is not large enough to propagate the wing cracks long enough to link each other, which leads to unloading. As a result, most of kinetic energy of the ice sheet is stored as deformation energy of the structure.

Actually, the unloading phase is the key point of ice induced self-excited vibration. The fact that when the structure swings back, the ice sheet fails and is crushed, extruded upwards and downwards, leads to the loose simultaneousness between the unloading of the ice force and the swing back of the structure. Why would the ice sheet fail and be crushed when the structure swings back? The physical mechanism is explained as follows.

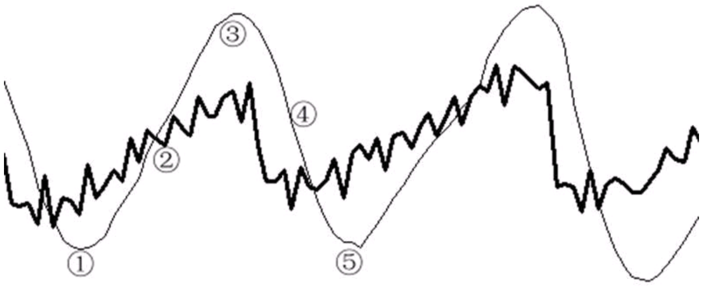


Figure 7. Detailed time history of ice force (saw-tooth) and structure's displacement (smooth).

Herein we divide one vibration cycle by five characteristic points as denoted in Figure 7. In the loading rate from Point 1 to Point 3, the actual loading strain rate is constantly changing due to velocity of the structure is constantly changing. The loading strain rate of Point 2 is approximately the ductile to brittle transition strain rate, and the ice force at Point 2 is lower than the force required to crush the ice sheet under the ductile to brittle transition strain rate as shown in fig 10, so the ice force will continue to increase. As the structure swings from Point 2 to Point 3, the loading strain rate increases into the brittle region. And the track line of the changing loading status of the ice sheet is shown by the red line in Figure 8. At Point 3, the loading strain rate is larger than that at Point 2, and the ice force is large enough to propagate the wing cracks long enough to link each other, which leads to the failure of the ice sheet, in other words, the entrance to the unloading phase. From Point 3 to Point 4, the damaged ice sheet is crushed and extruded, upwards and downwards, while the ice force decreases. After the extrusion or clearance of the crushed ice particles, at Point 4, the ice sheet contacts the undamaged ice sheet again, and the entrance to loading phase takes place.

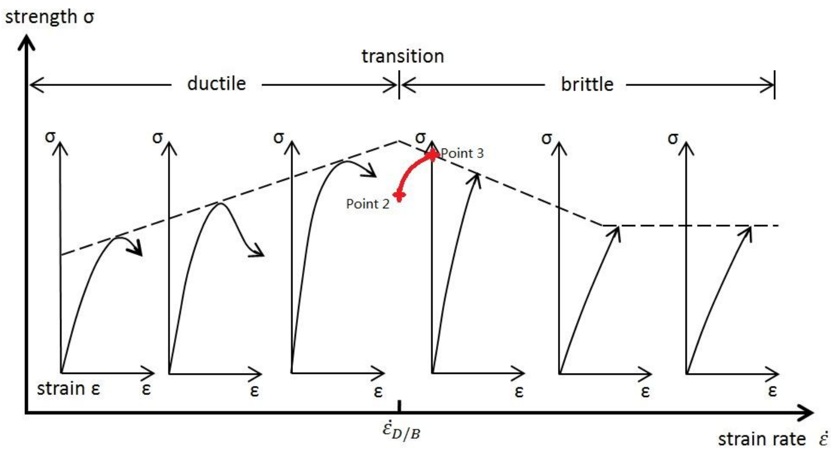


Figure 8. The loading status of the ice sheet from Point 2 to Point 3 in Figure 7.

Actually, during self-excited vibration the loading strain rate of Point 2 is not necessarily the ductile to brittle transition strain rate, it could be a little higher or lower than the ductile to brittle transition strain rate, in other words, the loading strain rate of Point 2 is in the ductile to brittle transition region.

VERIFICATION OF THE PHISICAL MECHANISM BASED ON FIELD DATA

The last section presented the physical mechanism of ice induced self-excited vibration and described the process in one complete cycle. It was pointed out that the loading strain rate in the loading phase when the velocity of the structure reaches its maximum, is approximately the ductile to brittle transition strain rate, which will be proved by field data in this section.

The strain rate of ductile–brittle transition under uniaxial compression is $\dot{\varepsilon} = 10^{-4} \sim 10^{-3} s^{-1}$ approximately. However, the strain rate of ice sheet could not be acquired directly from the field data, so approximate calculations have to be performed to obtain the strain rates. It is presumed that strain rate of ice sheet $\dot{\varepsilon}$ is a function of indentation velocity v_r, structure's width D and ice thickness h, moreover, in the case of high aspect ratio D/h, strain rate might be independent of ice thickness because h is much smaller than D, and strain state of ice sheet is invariant in the direction of ice thickness.

In order to calculate the approximate average strain rate of ice sheet during the loading phase of ice induced self-excited vibration, the equation by Michel & Toussaint (1977) was adopted.

$$\dot{\varepsilon} = \frac{v_r}{4D} \qquad (2)$$

Over 100 events of ice induced self-excited vibration from three structures were analyzed, the relative indentation velocities $v_{ice} - (v_{str})_{max}$ were substituted into v_r in Equation (2), in which v_{ice} is ice velocity and $(v_{str})_{max}$ is the velocity amplitude of structure at ice level, the strain rates of ice are plotted as histogram in Figure 9. It can be seen that all the strain rates data are in the range of $1.2 \times 10^{-3} \sim 2 \times 10^{-3}$, which is close to the ductile to brittle transition point of ice.

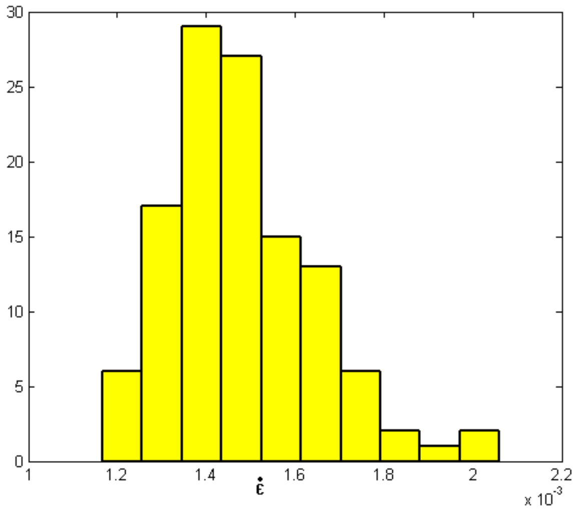


Figure 9. Histogram of strain rates in the loading phase of ice induced self-excited vibration.

CONCLUSION AND DISCUSSION

A physical mechanism is presented to describe the process of vibration and the fluctuation of the ice force during ice induced self-excited vibration. And the simultaneousness between the unloading of the ice force and the swing back of the structure is explained with the physical mechanism, which is proved by field data.

However, understanding of physical mechanism and the process of ice induced self-excited vibration is not enough. For offshore engineers, a quantified criterion must be developed based on the physical mechanism, to enable them to avoid ice induced self-excited vibration or reduce its action to structures.

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