ICE LOAD MEASUREMENT BY TACTILE SENSOR IN MODEL SCALE TEST IN RELATION TO RUBBLE ICE TRANSPORT ON ARCTIC OFFSHORE STRUCTURES (RITAS)

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Because of the presence of rich natural resource in the Arctic and also its strategically important location, an increasing interest has long been placed on the study of ice load on various types of Arctic structures (e.g., fixed or floating offshore structures and icebreakers). Ice load varies both spatially and temporally. Ice load measurements can be roughly categorised into two groups, i.e., field measurements and model scale measurements in ice tanks. In literatures, lots of ice load measuring techniques have been developed. Conventional ice load measurements mainly focus on the total ice load’s history whereas less attention has been paid on its spatial variation. However, the spatial variation of the ice load is equally important. This paper describes one of the approaches to measure the ice load’s spatial and temporal variation with model scale tests, i.e., ice load measurements with tactile sensor. This paper aims at documenting briefly the application of tactile sensor in measuring ice load. Focus is given to tactile sensor’s application in the test campaign ‘Rubble Ice Transport on Arctic offshore Structures (RITAS)’ in which the interaction mechanism of level ice and wide sloping structure interactions with the presence of rubble accumulation is studied. According to the measurements made within this test campaign, different load components and the relevant interaction mechanism were discussed. Particularly, ice load contributions from the ice rotating and rubble accumulation process were highlighted. Based on previous experience and this test campaign, the advantages and disadvantages of the ice load measuring ability of tactile sensor were summarized and discussed. It was concluded that tactile sensor is beneficial in displaying ice load’s relative spatial distribution while its magnitude should be treated with caution in pertinent ice load measuring tests. A measurement system which combines both tactile sensor and the conventional measuring technique (e.g., measuring by load cell) tends to offer a better understanding on the ice load’s spatial and temporal variation.

1. INTRODUCTION

Ice is a rather brittle material, strong in compression whereas weak in tension. The magnitude of ice load largely depends on the corresponding ice feature’s dominant failure modes and failure processes. Studying ice and structure interactions requires a good understanding on ice mechanics, which is still a rather young science (Sanderson, 1988). It is quite often that higher credit is given to field or physical model measurements. Those developed numerical or theoretical models are usually explanatory tools of the gathered data. Studying the spatial distribution of ice load is such a forefront that rather limited data of high quality is available. For vertical structures, the incoming ice usually fails in a crushing failure mode. Based on the gathered data, Sanderson (1988) illustrated the perplexing ‘pressure-area’ curve which puzzled generations of ice engineers. The spatial variation of ice load is crucial for the understanding of the ‘pressure-area’ curve. For an ice-going ship, the major ice load is concentrated around an ‘ice belt’ of the ship near the waterline where strengthening of the structure is a common design practice (Izumiyama et al., 1999a). Better understanding of ice load’s spatial distribution around a ship hull is important for a safe and economic design. For sloping sided offshore structures, the incoming level ice fails sequentially from breaking, rotating to submerging (Frederking and
Timco, 1985; Lu et al., 2014). Current offshore structure design practice does not differentiate such failure process in a procedural manner. Instead, all the ice load contributions from these failure processes are conservatively added up together to yield the final design load (API_RP2, 1995; ISO/FDIS/19906, 2010). In order to study the interaction between all these failure processes, an understanding of the ice load’s spatial and temporal variation is pivotal. Among all these ice load’s spatial distribution measurements, we focus on the scenario of level ice interacting with sloping sided structures.

Ice load measurements can be roughly categorised into two groups, i.e., field measurements and model scale measurements in the ice tank. However, measuring the spatial variation of ice load in the field is suffering from low resolutions due to all kinds of practical reasons. Model scale conditions are relatively more controllable. Different attempts have been made to measure the ice load’s spatial variation in model scale. These include: installing several spatially aligning load cells behind their corresponding independently movable segments (Aksnes, 2011; Timco, 1991); and also the method of mounting a tactile sensor on the considered sloping surface (Lu et al., 2014; Lu et al., 2013c). This paper will further focus on the ice load measurement in model scale with tactile sensor.

This paper starts by briefly documenting the application of tactile sensor in ice engineering. The main idea and experience with tactile sensor’s application is summarised. Afterwards, our focused scenario (i.e., ‘level ice interacts with sloping sided structures’) is introduced. Based on all these previous experiences, tactile sensor’s application in measuring the ice load’s spatial variation is conducted under the project RITAS to study level ice and wide sloping structure interaction mechanism with the presence of rubble accumulation.

2. A BRIEF DOCUMENTATION OF THE APPLICATION OF TACTILE SENSOR IN ICE ENGINEERING

2.1 Application of tactile sensor in indentation test

To the authors’ knowledge, the application of tactile sensor in measuring ice load can be dated back in 1990th in the so called ‘indentation test’, particularly in relation to the Japan Ocean Industries Association (JOIA) project (e.g., (Sodhi et al., 1998; Takeuchi et al., 2001)). The indentation test is a method to study the interaction between level ice and vertical sided structures (see Figure 1). In this interaction scenario, the incoming level ice fails in a variety of failure modes (Timco, 1987) of which, the crushing failure mode is of concern. Ice load in this failure mode depends largely on the interaction speed, ice thickness and ratio between the structural widths to the ice thickness. If the interaction speed is slow, ice usually behaves rather ductile; on the other hand, it fails in a brittle manner during high interaction speed. In these two different situations, the incoming intact ice has different contact scenarios with the vertical surface. The ‘non-simultaneous failure’ concept has been proposed to explain the riddle of the observed ‘pressure-area relationship’ curve (Ashby et al., 1986; Sanderson, 1988). Instead, based on a series of tests, Sodhi et al. (1998) argued further that the key reason behind the ‘pressure-area relationship’ is due to the different failure modes (i.e., ductile or brittle) under different interaction speed. Of all these theories, it is of great importance to measure the actual contact area between level ice and structure. To achieve this, a tactile sensor system has been utilised in addition to the traditional load cell measuring technique.

Among these applications of tactile sensors, Izumiyama et al. (1998) systematically studied the applicability of tactile sensor in ice engineering. The major findings of these authors’ study in relation to tactile sensor can be summarised here as: 1) the sensor shows a consistent measurement of dynamic load in the range from 0.1 Hz to 35 Hz (the upper limit is mainly due to the vibration of the structure instead of the limit of tactile sensor); 2) static loading tests have been conducted on several areas of equal size; and spatial consistence of the measurements were obtained; 3) however, a nonlinear relationship exists between the applied load and the measured raw data (in relation to the sensors’ voltage change). i.e., the measurement does not have the same accuracy in all loading ranges; 4) the measured value further shows a dependence upon the loaded area. i.e., the same load applied upon areas of different sizes yields different measured values. The first two findings are beneficial to ice
load measurements whereas the last two findings set some limits on the reliability of the absolute values measured by tactile sensor. Despite of this limitation, these authors conclude in their paper that:

“It is the authors’ feeling that the pressure sensing system used in this study will be a good tool for ice engineering researches”

Figure 1 Application of tactile sensor (i.e., sensor film) in an indentation test (originally from (Izumiyama et al., 1998))

In application of tactile sensor in combination with load cells, Sodhi et al.(1998) found that the measurement by tactile sensor is only half of that measured by the load cells. Despite of the questionable reliability of the measured load magnitudes, Sodhi et al. have taken full advantages of the sensors’ ability in recording ice load’s spatial variation. Based on the measured spatial distribution of the ice load, these authors successfully visualised the evolution of the contact area between the ice and the structure with varying interaction speed. In a different paper, Sodhi (2001) normalised tactile sensor’s measurement to the values measured by load cells. It turned out that rather satisfactory matching is obtained.

2.2 Application of tactile sensor in ship model test

An ice going vessel differs the conventional ship design from mainly three aspects, i.e., a hull shape that is efficient in breaking the ice, a strengthened hull and sufficient power to transit in ice (Riska, 2011a; Riska, 2011b). In order to gain sufficient power requirement estimations, usually the global ice resistance should be calculated and measured in model scale. However, in order to determine the local ice pressure on the hull for detailed design, the measurement of ice load’s spatial distribution on the ship hull is thus necessary. In practice, it is common to strengthen the shell plating of the ship hull along the waterline area and this is the so called ‘ice belt’. In model tests, usually a highly idealised and rather simple test scenario is designed to measure the potential local pressure. e.g., Riska (1991) utilised a flat panel to impact the ice blocks with different angle and observed a line-like pressure distribution. Moreover, the same author conducted full scale measurements with the same system and observations with a transparent window installed within the ‘ice belt’ area. Though there has been authors attempting to construct ship hulls which are composed of independent segments so as to measure the ice load’s spatial distribution with load cells (e.g., (Aksnes, 2011; Liukkonen and Nortala-Hoikkanen, 1992)), quite low spatial resolution was encountered.

As a flexible ice load measuring tool, Izumiyama et al.(1999a) successfully installed a series of tactile sensors onto the ship hull along the waterline to measure the ice load (see Figure 2). Thanks to tactile sensor’s capability in measuring the ice load’s spatial variation with a rather high resolution (i.e., the smallest sensing area is 5.4 mm × 5.4 mm), these authors were able to conclude that a similar ‘line-like’ pressure as in the field observation is also measured. Even though it is questionable to rely on the ice load magnitudes measured by tactile sensors, the comparative values measured by them are convincing indicators in terms of the spatial distribution of the maximum ice load. Based on these comparative values, these authors further found that the ice load could be dominant even up to a depth of 30% of the ship draft. A similar application of tactile sensor on the ship hull in model tests was made in a following publication (Matsuzawa et al., 2006).
2.3 Compilation of previous experience with the application of tactile sensor

Based on the previous brief literature review regarding the application of tactile sensor in ice load measurements, it can be summarised that the advantages of tactile sensor includes:

- Tactile sensor manages to survive and yield satisfactory results in harsh testing environment (i.e., cold temperature, water environment, et al.);
- Dynamic load can be consistently measured at least in a frequency range from 0.1 Hz to 35 Hz;
- Static load can be consistently measured irrespective of the measuring location as long as the loading area’s size remains the same;
- It is of great value to measure the spatial distribution of ‘ice load’. The measured values, though is questionable, are good comparative values to identify the location where are mostly suffering from ice load; and are indicative values to illustrate the spatial and temporal variations of the development of ice load.

However, utilisation of tactile sensor is suffering from several disadvantages which include:

- There exist a nonlinear relationship between the applied load and the measured values. i.e., in different ice load ranges, the accuracies are different;
- The measurement is sensitive to the size of the loading area.

These experiences have in a way prepared us for our application of tactile sensor in RITAS project as described in the following.

3. APPLICATION OF TACTILE SENSOR IN LEVEL ICE AND WIDE SLOPING STRUCTURE INTERACTIONS

3.1 Interaction mechanisms and the pertinent research question

Wide sloping structures have many applications in ice infested waters. Due to the relatively limited ice clearing capability of a wide sloping structure, the presence of rubble greatly influences the whole interaction mechanism (Serré et al., 2013a). The interaction mechanism between level ice and wide sloping structures could be categorised into three different stages (Lu et al., 2014). A brief interaction mechanism is shown in Figure 3. The first stage is the ice breaking stage (see Figure 3⃣). In this stage, the incoming ice fails against the structure and a large ice breaking load is expected to be detected at the waterline. The second stage is the ice rotating stage see (Figure 3⃣⃣). As the broken ice block is travelling downwards, the corresponding ice rotating load is supposed to be measured below the waterline. The third stage is the rubble accumulation stage which occurs simultaneously with the previous two stages and is shown in both Figure 3⃣ and ⃣⃣.
The research questions for the current problem are simple. They are:

- Where exactly are these loads spatially located?
- What are the comparative values of these loads?
- How would these loads evolve with time?

For the scenario of level ice interacting with sloping structures, Timco (1991) has conducted measurements of ice load’s spatial distribution with a sloping structure which is composed of 6 independent segments (each is 15 cm in length). Load cells are installed behind each segment. Based on the measured values, this author concludes that the maximum ice load is detected around the waterline area. However, this segmented region is relatively large (e.g., approximately 5 times of the ice thickness). A delineation of the ice rotating load from the ice breaking load is thus difficult. In consideration of the above mentioned research questions and a desire of achieving higher spatial resolutions, tactile sensor was employed in our test plan (Lu et al., 2013c; Serré et al., 2013a; Serré et al., 2013b).

### 3.2 Application of tactile sensor in project RITAS

In April 2012, a series of model scale experiments on the interaction between level ice and an arctic offshore structure with a downward sloping surface was conducted in the large ice tank of HSVA. A series of research papers are published either fully or partially cover different aspects of this test campaign (i.e., (Astrup et al., 2013; Helgøy et al., 2013a; Helgøy et al., 2013b; Kulyakhtin et al., 2013; Lu et al., 2014; Lu et al., 2013b; Lu et al., 2013c; Serré et al., 2013a; Serré et al., 2013b)). In this paper, we mainly focus on the application of tactile sensor in this test campaign.

In this test campaign, tactile sensor was installed on a sloping surface of a structure confined by two transparent Lexan plates. The geometry of the test set-up and the location where tactile sensor is mounted are shown in Figure 4. During the tests, the Tekscan® sensor #5513 was utilized. It has an operating temperature ranging from -9°C to 60°C; the pressure measuring range was claimed to be within 0 to 175 MPa. All these specifications are compatible with the current application. Most importantly, this sensor has a rather long tail. This ensures that the handle which connects the tail to the computer can be positioned far away from the water.

This sloping structure has been tested in different ice conditions with different ice thickness and different interaction speed. A detailed test matrix can be find in relevant literatures (Lu et al., 2013c; Serré et al., 2013b). The application of tactile sensor in all these tests follows generally three important steps which are described below:

**Step 1: installation of tactile sensor**

As recommended by the manual (Tekscan, 2011), during the installation, great attention has been paid to make sure that the tactile sensor is waterproof and protected against ice abrasion. To achieve this, the sensor was first put in between two plastic films adhered by silicone gel so as to make it waterproof. Afterwards, a metallic adhesive layer was applied above the sensor serving as the abrasion 

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Figure 3 A brief interaction mechanisms between level ice and wide sloping structures
protection. This step is finished in the very beginning of the tests and no further repetition was made as long as the tactile sensor works properly.

Figure 4 (a) The buoyancy box (b) the schematic drawing of the test set-up with geometry (N.B, drawing not in scale) (c) tactile sensor

Step 2: calibration of tactile sensor
Due to the complexity of ice and structure interactions, the ice pressure covers a very wide range of possible values. In the current tests, based on the chosen sensitivity and saturation pressure, tactile sensor tends to capture the ice pressure that repeats most often, saying the pressure that would be around the mean ice pressure. However, for extreme values, the sensor is prone to underestimate the extreme values. Even though, the merits of using tactile sensor in the current test should not be degraded. Tactile sensor will anyhow produce the contact area (i.e. the load’s spatial variation) and comparative pressure irrespective of possible errors within its measured maximum values. The pertinent choice on tactile sensor’s sensitivity and saturation pressure are made in the literature (Lu et al., 2013c).

Step 3: validation of tactile sensor in each test
Before each test, the tactile sensor is again validated against several known weights so as to confirm its functionality (calibration check). In all the validations, errors between the measured results and the known weights were all within 15%. With all these three steps implemented, tactile sensor was successfully utilised in measuring the ice load (at least its spatial distribution). We present the major findings in the next section.

4. RESULTS AND DISCUSSIONS

4.1 Measurements visualisation and discussion
During different tests, the sloping structure in Figure 4(a) was pushed through level ice in the ice tank. The spatial and temporal variation of the ice load is recorded by the installed tactile sensor. A real time ice load evolution can be exemplified as in Figure 5 (different colors represent different pressure magnitude). This measurement illustrates one circle of the ice load development (i.e. ice breaks at the waterline and rotates downwards afterwards). It takes approximately 3 seconds for such cycle to develop in Test 1210. It can be seen that, after the initial breaking of the incoming ice, the local pressure did not diminish instantly. Instead, the pressure keeps travelling down at a relatively smaller yet comparable magnitude.
4.2 Ice load’s spatial variation

With the measured data as presented in Figure 5, it is possible to study how the ice load is distributed in the vertical direction (i.e., Z direction or the short edge’s direction of the panel in Figure 5). Summing all the load recordings along the long edge’s direction in Figure 5, we are able to present the time averaged ice load’s spatial distribution as in Figure 6(a) and the maximum ice load’s spatial distribution as in Figure 6(b).

![Figure 6](image)

Figure 6 (a) Time averaged ice load and (b) the maximum ice load (in time history) variation in the vertical direction (i.e., short edge’s direction) of the sensor (the shaded area is the location of the un-deformed level ice).

Since both the elastic foundation beam and plate theory suggest that the tip deflection at flexural failure is minimal comparing to the thickness of the ice, it would be reasonable to assume the ice breaking load (i.e., the load required to bend the incoming intact ice) is within the un-deformed level ice’s thickness region (i.e., the shaded area in Figure 6). Note that inside this region, other interaction mechanisms such as the initial ice rotating and rubble effect also exist (Lu et al., 2013a). It is observed in Figure 6(b) that the maximum loads are mainly found within such shaded area. This agrees with our common sense and previous research assumptions that the ice breaking load is one of the decisive components of the ice load. However, as it is shown in the theoretical model (Lu et al., 2013a; Lu et al., 2013b), the ice rotating load would also become decisive when there is sufficient rubble accumulated in front of the structure. For the time being, it can be simply concluded that based on tactile sensor’s measurement, the maximum load often takes place around the un-deformed level ice’s thickness region. This is in agreement with the measurements conducted by Timco (1991) with a similar test set-up within a broken ice field. The numerical simulation conducted by Paavilainen and Tuhkuri (2013) also detected the maximum ice load slightly below the waterline for gentle sloping angles.
4.3 Ice load’s spatial and temporal variation

Among all important findings based on the measurements from tactile sensor, it is interesting to illustrate the ice load’s spatial and temporal variation as in Figure 7.

![Figure 7 Vertically spatial and temporal distribution of ice load (bins 3 and 4 in the red square is approximately where the undeformed level ice is).](image)

It can be seen from Figure 7 that generally most of the recorded loads in the vertical direction increase with time. This underlines the importance of rubble accumulation. Moreover, below the un-deformed level ice’s thickness region (i.e. below bin number 3 and 4), the recorded ice load also increases with time and may become even more significant than the process that occur within the un-deformed level ice’s thickness region. This further strengthens the point that the accumulated rubble together with the ice rotating process intensifies the ice load under the un-deformed level ice’s thickness region.

4.4 Discussion about the applicability of tactile sensor in this test campaign

Though Figure 6 and 7 were presented with absolute values of the ice load, caution should be made on the reliability of tactile sensor’s measurement since it does not have the same accuracy in all the measuring range. In this test campaign, the tactile sensor was calibrated to capture the mean ice load with a higher accuracy than the maximum ice load. Therefore, the measured absolute value of the mean ice load can be assigned a higher confidence. Furthermore, tactile sensor’s capability in measuring the ice load’s spatial distribution as in Figure 6 and 7 supplied valuable information in investigating the pertinent questions raised in Section 3.1.

Regarding the sensitivity of measurements with the loading area size, this test campaign was not able to avoid this problem. However, considering the fact that most of the time, the effective ice load behaves a ‘line-like’ distribution as shown in Figure 5. Significant variation in contact area is not expected. Therefore, we can have a higher confidence in the measured value irrespective of this unsolved disadvantage of tactile sensor.

In a continuing study of the measured data in RITAS project (Lu et al., 2014), the authors have utilised load cells’ measurement to compensate the inaccuracy of tactile sensor’s measurement in maximum ice load range. Recalling that former researchers have also utilised load cells’ measurements to ‘correct’ tactile sensor’s measurement (Sodhi, 2001; Sodhi et al., 1998), it is fair to say that a combination of both measuring technique (i.e., tactile sensor and load cells) is preferred.

5. CONCLUSION

In this paper, we briefly reviewed the application of tactile sensor in ice engineering. Particularly, the importance of measuring ice load’s spatial variation in different scenarios was highlighted. Based on previous experiences, the advantages and disadvantages of measuring with tactile sensor were
summarised. Such experience has prepared us to apply tactile sensor to study the interaction mechanism between level ice and wide sloping structure interactions in RITAS project. Based on tactile sensor’s measurements on ice load’s spatial and temporal distribution, it is concluded that:

- During the interaction, after the breaking of an initially intact ice, the recorded ice load does not diminish instantly. Instead, the ice moves down continuously with a relatively lower load magnitude (see Figure 5). This is considered due to the effect of ice rotating load in combination of the accumulated rubble effects;
- Based on the mean ice load’s (i.e., averaged in time) vertical variation, it is found out that equally large ice load can be detected beneath the un-deformed level ice’s thickness region (see Figure 6(a)). As discussed above, the contribution of this large ice load is mainly due to the combined effects of ice rotating load and the rubble accumulation;
- Generally the recorded maximum load acts at the un-deformed level ice’s thickness region (see Figure 6(b)). The ice breaking occurs mainly at the waterline region. This is in line with previous experiments and assumptions that the ice breaking load is one of the decisive loads during design.

With respect to the utilisation of tactile sensor in this test campaign, it is concluded that tactile sensor is beneficial in displaying ice load’s relative spatial distribution while its magnitude should be treated with caution. A measurement system which combines both tactile sensor and the conventional measuring technique (e.g., measuring by load cell) tends to offer a better understanding on the ice load’s spatial and temporal variation.

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REFERENCES


Astrup, O.S., Helgøy, H. and Høyland, K., 2013. Laboratory work on freeze-bonds in ice rubble, Part III: Shear box experiments, Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions, Espoo, Finland.


Helgøy, H., Astrup, O.S. and Høyland, K., 2013b. Laboratory work on freeze-bonds in ice rubble, Part II: Results from individual freeze-bond experiments, Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions, Espoo, Finland.


Lu, W., Serré, N., Høyland, K.V. and Evers, K.-U., 2013c. Rubble ice transport on Arctic Offshore Structures (RITAS), part IV Tactile sensor measurement of the level ice load on inclined plate, Proceedings of the 22nd International Conference Port and Ocean Engineering Under Arctic Conditions, Espoo, Finland, pp. 1-14.


Serré, N., Lu, W., Høyland, K.V., Bonnemaire, B., Borge, J. and Evers, K.-U., 2013b. Rubble Ice Transport on Arctic Offshore Structures (RITAS), part II: 2D scale-model study of the level ice action, Proceedings of the 22nd International Conference Port and Ocean Engineering under Arctic Conditions, Espoo, Finland.


Timco, G.W., 1991. The vertical pressure distribution on structures subjected to rubble forming ice, 11th International Conference on Port and Ocean Engineering under Arctic Conditions, St. John's, Canada, pp. 185-197.