POAC '03 Trondheim

Proceedings of the 17th International Conference on
Port and Ocean Engineering under Arctic Conditions
POAC '03
Trondheim, Norway, June 16-19, 2003

CONTINUOUS EM AND ULS THICKNESS PROFILING IN SUPPORT OF ICE FORCE MEASUREMENTS

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ABSTRACT

Coincident, continuous ice force and thickness measurements are presented which have been performed in 2002 on a lighthouse located in drifting sea ice in the Bay of Bothnia near Luleå, Sweden. Level and ridged ice thickness has been profiled both by means of upward-looking sonars (ULS) and electromagnetic induction (EM) sounding. Preliminary results indicate some correlation between forces and overall ice thicknesses, although no careful analysis considering varying ridge properties and different failure modes has been carried out yet. Both, EM and ULS data were well capable of yielding the required ice thickness data, although they have to be interpreted differently. However, EM measurements underestimated the maximum depth of ridge keels by as much as 50%. This might be due to disadvantageous sea water properties in the Bay of Bothnia.

INTRODUCTION

In the framework of EU projects LOLEIF (Validation of Low Level Ice Forces on Coastal Structures) and STRICE (Measurements on Structures in Ice) continuous full-scale measurements of ice forces acting on the base of lighthouse Norstrømsgrund in the Bay of Bothnia were performed in the winters of 1999 to 2003. The observations aimed at a better understanding of ice-structure interaction processes. The interpretation of ice forces largely depends on an accurate knowledge of ice thickness. Consequently, ice thickness was synchronously measured by means of upward looking sonar (ULS) (e.g. Strass and Fahrbach, 1998) and electromagnetic induction (EM) sounding (e.g. Kovacs and Holladay, 1990; Haas et al., 1997).

So far, most studies have related ice forces only to the prevailing level ice thickness which was sporadically measured at a few locations. The current data set allows to compare the

measured total ice force with the overall ice thickness distribution, including the thickness and frequency of pressure ridges.
Supposedly, with pressure ridges the excited forces strongly depend on the thickness of the consolidated layer, as ice blocks underneath are only weakly bonded to the overlying ice. The comparison of EM and ULS measurements could possibly resolve this problem, as the methods are sensitive to different "apparent" thicknesses of the ice. ULS always picks the deepest, protruding points of the ice underside, as the earliest received sonar signals have been reflected from there first. Therefore, thickness retrievals are always an estimate of the maximum thickness. On the other hand, EM induction sounding averages over a certain area of some meters in diameter, thus underestimating ridge thicknesses (Kovacs and Holladay, 1990; Haas et al., 1997). More important, as the measurements are dependent on the electrical conductivity of the ice, EM sounding is also dependent on the porosity of the blocky ridge keels. Therefore, EM retrievals will yield thicker ice the more consolidated a ridge is. Here, the measurements could resolve this topic by comparing the forces with both, ULS and EM thickness retrievals.

In this paper, we present an example for the acquired force and thickness data and discuss some of the problems involved in correlating forces with ice thicknesses obtained from different techniques. The unique data set is then used to compare ULS and EM soundings from the 2002 season with each other. This enables a better understanding on the character of both techniques.

MEASUREMENTS

Measurements were carried out at lighthouse Norstrømsgrund, located within the seasonal drift ice of the northern Bay of Bothnia of the Baltic Sea, close to the city of Luleå in Sweden. The lighthouse is located in 12 m deep water, and has a 23 m diameter basement extending to 6 - 7 m below sea level. 9 rigid force panels (1.2 m wide, 1.6 m high, measurement range 2000 kN + 50% overload) were mounted at water level, were the lighthouse has a diameter of 7 m, extending 1.5 m below the water level. They were arranged from the North over the East to the South, in order to cover the directions of the usually strongest ice drift events (Fig. 1). Forces were recorded with a sampling frequency of 1 to 30 Hz.

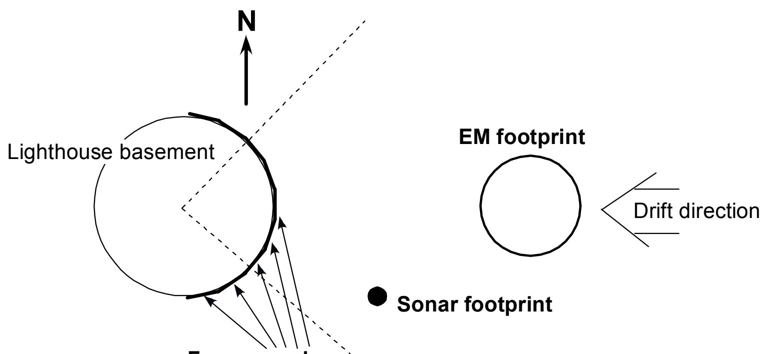

Figure 1: Sketch of the instrument setup showing the cross section of the lighthouse basement equipped with force panels as well as the locations of EM and ULS thickness measurements.

An ULS was mounted on the basement at 6 - 7 m water depth, approximately 5 m away from the lighthouse in a south easterly direction. On a rig extending 10 m from the lighthouse to the East, an EM sensor and a laser distance meter were suspended at a height of about 2 m above water level. The system was identical to the one described in Haas (1998) and Haas et al. (1999). Ice thickness data were collected at 1 to 0.1 Hz. The time lag between forces and thicknesses due to the sensors spatial separation was accounted for by manually aligning the data.

Ice drift direction and speed were determined from video observations. For the following analysis, we extracted all drift and deformation events with ice drift direction between 45° to 135°, i.e. within 45° of the line between EM system and central force panel (Fig. 1).

RESULTS

Total forces versus ice thickness

In total, in 2002 only 9 events have been identified which fulfilled the requirements of a uniform, easterly drift of a confined ice field (Table 1). Figure 2 shows a time series of ice forces and associated ULS and EM ice thicknesses for a typical drift and deformation event. Here, ice drift speed was 0.2 m/s from 100°. For data ownership reasons we can only present relative forces. The forces show typical events of low-frequency, long-lasting static loads, with superimposed, up to five times stronger spontaneous loads due to crushing and/or bucking and bending failure. Note that ULS and EM data agree well with each other at level ice thicknesses of typically 0.2 to 0.3 m, but deviate by up to 50% in ridge zones. Both data sets can very well distinguish between level and ridged ice.

There is strong correlation between static ice forces and thickness in the example in Figure 2. However, peak forces due to crushing and bending failure blur a clear relationship, and can be very high in level ice and even higher than in ridges, too, as e.g. around 7:00 h in the example. Closer inspection reveals that in this case also in the virtually level ice some deformation zones existed, with about twice the level ice thickness due to rafting, but without clear keels.

At present, we have only performed a rough correlation analysis between forces and ice thicknesses, applying linear regressions between the variables. For these, 3- and 5-minute averages of time series like in Figure 2 have been used. Correlation coefficients obtained form these linear fits ranged from 0.81 to 0.06, both for EM and ULS ice thickness. This means that no clear relationship was found between force and thickness for the complete duration of the events.

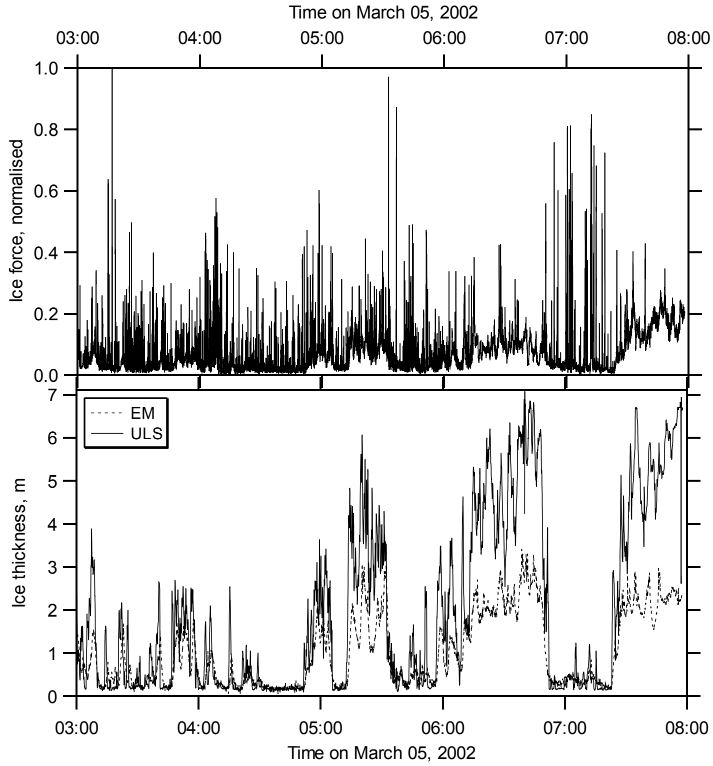

Figure 2: Typical five-hour time series of forces (top) and ULS and EM ice thicknesses (bottom) for a strong drift event on March 05, 2002.

Linear equations obtained from the regression were very variable, too. The standard deviation of the coefficients of these equations were approximately 90% of the absolute values of the coefficients.

EM versus ULS ice thickness

Figure 2 suggests that EM and ULS ridge thicknesses differ quite much. To illustrate this further, Figure 3 shows a scatter plot of EM and ULS thicknesses with the respective linear regression for the same example of March 05, 2002. The correlation is very good, however, the EM data underestimate the ULS thickness by about 60%.

Table 1 lists the results of all EM and ULS comparisons thus obtained. EM and ULS data are generally very well correlated with correlation coefficients above 0.9. There is only a small improvement for 5-minute averages compared to 3-minute averages. The mean of all regressions results in relations between EM ice thickness Z_i(EM) and ULS ice thickness Z_i(ULS) of

$$Z_i(\mathrm{EM}) = 0.25 + 0.47\, Z_i(\mathrm{ULS}) \tag{1a}$$

for 3-minute averages and in

$$Z_i(\mathrm{EM}) = 0.24 + 0.49\, Z_i(\mathrm{ULS}) \tag{1b}$$

for 5-minute averages. Here, the standard deviation of the coefficients averaged from all nine events is only 25%. The equations show that in the present cases the EM thickness amounted to only 47 to 49% of the ULS thickness. This is clearly due to the dominating contribution of ridges to Equations 1. In fact, the none-zero intercepts for zero ULS thickness are artefacts from the wide range of thicknesses analysed, too, comprising both level and deformed ice. Actually, for level ice alone the agreement and correlation of EM and ULS thicknesses was very good.

DISCUSSION

The presented data have been gathered during a unique field experiment, combining continuous force measurements with ice thickness estimates from two different kind of sensors. While full analysis of force-thickness relations is pending, there is almost no difference between correlations of ice forces with ice thickness from the different sensors, although the EM data underestimate ridge thicknesses by as much as 50%.

In further analysis of the data a number of caveats have to be taken into account in the interpretation of results. Most of them are related to the experimental design, while some are also due to varying ice properties, and to Baltic ice properties in particular.

Although the locations of the force panels and thickness sensors have been carefully planned, they did not finally meet the requirements of really coincident measurements (Fig. 1). The reason for the misalignment is mainly of technical nature, as it was extremely difficult to mount the ULS underwater, and the EM rig on the slim lighthouse rising out of a rough and windy sea. The ULS positions were planned for the installation of two instruments, however, at least one was destroyed every year by the first grounded ice hitting the concrete basement.

Another problem in our comparisons results from the fact that the force panels were only extending to a maximum depth of 1.6 m below the water level. This means that the effect of deep keels could in fact not really be measured because the forces generated by the lower parts of the keels were not measured. This might also explain the good agreement between the comparisons of forces with both, EM and ULS data, respectively, as our results might only represent forces from the upper 1.5 m or so. The problem is amplified by partially strong wind induced or tidal sea level variations, which sometimes reduced the panel area below the water level even more, or could have risen sea level above the upper edge of the panels.

Data analysis also has to consider the variability of physical properties and strength of the ridges. Depending on the degree of fracturing of the ice within a ridge, or on the degree of consolidation, it is of course expected that ridges of the same thickness can exert different forces. Physical ridge properties depend for example on the original level ice thickness they have been formed from, the history of their formation, their age, and the history of thermodynamic conditions they have experienced since their formation (Høyland and Løset, 1999). There were also single ridges and extensive rubble fields with the same thicknesses.

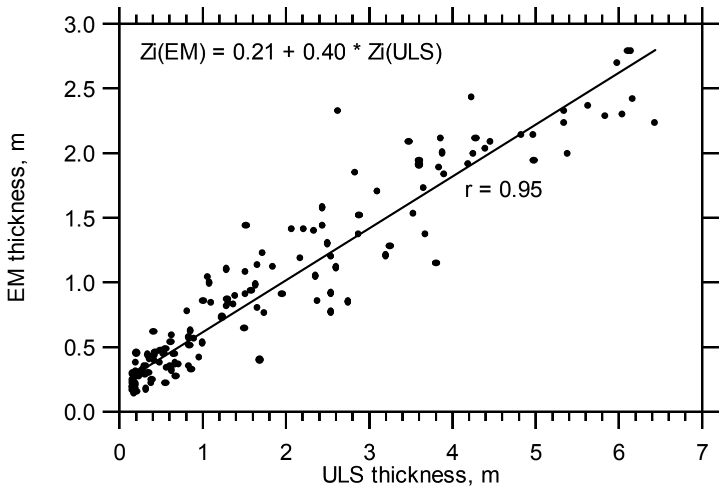

Figure 3: 3-minute average EM thickness versus ULS ice thickness on March 05, 2002. C.f. Figure 2.

Table 1: Linear correlation coefficients R obtained from linear regressions between EM and ULS ice thicknesses for all 9 ice drift events analysed.

Date	Duration, h	Drift speed, m/s	Drift direction, °	3-minute averages $R_{Zi(EM) vs Zi(ULS)}$	5-minute averages $R_{Zi(EM) vs Zi(ULS)}$
05.03.2002	7.8	0.23	100	0.95	0.97
09.03.2002	5.3	0.17	100	0.93	0.95
12.03.2002	0.8	0.10	80	0.94	0.93
20.03.2003	7.6	0.10	130	0.85	0.86
31.03.2002	20.4	0.04	83	0.79	0.81
01.04.2002	23.8	0.08	90	0.96	0.97
03.04.2002	23.5	0.03	90	0.93	0.94
04.04.2002	8.3	0.01	90	0.94	0.94
08.04.2002	4.7	0.02	113	0.89	0.90
Mean				0.91	0.92

As could be expected, correlation between EM and ULS thicknesses is very good. However, the agreement between absolute thickness measurements is rather poor, as the EM thicknesses of ridges are about 50% thinner than those determined with the ULS. The amount of this disagreement is surprising, as previous inter-comparisons have shown less differences between EM and "real" thickness (Kovacs and Holladay, 1990; Haas et al., 1997). On the other hand, a similar extensive comparison has never before been possible. However, we believe that the large disagreement is due to some peculiarities of the present study, which might not be so important under Arctic conditions with thicker ice and saltier water.

The brackish water in the Bay of Bothnia had only a salinity of 3 ppt. The detection of ice thickness changes with this low conductivity contrast between ice and water is at the limit of resolution of the EM31 instrument. Thus, as the overall ice volume of the lowest keel sections is small compared with the overall measurement volume inside the footprint sensed with the

EM sensor, it is much harder to detect deep keel sections than with more conductive sea water, e.g. in the Arctic.

Ridges and rubble fields were composed mainly of thin ice fragments only. The original level ice thickness hardly exceeded 0.4 m in 2002. The small and thin ice blocks did not consolidate much under the mild weather during the observation period. Therefore the porosity of the ridges, or the amount and connectivity of water between the ice blocks was very high and could well have amounted to 30 to 50%. This also contributed to the strong underestimate of EM ridge thicknesses.

CONCLUSIONS

We have presented continuous, coincident ice force and ice thickness data from the Bay of Bothnia, and have compared EM with ULS thicknesses. The data comprised both, level and ridged ice which were not yet analysed separately. The data suggests good correlation between total forces and ice thickness, although no systematic analysis has been performed yet. Different ice and ridge properties as well as different failure modes will have to be taken into account.

The long time series might have great value for ship design and ice navigation studies, as time integrals of forces correspond to the resistance experienced by a ship steaming through ice. Thus, the data might be used to quantify and model results obtained e.g. by Haas et al. (1999) when comparing ship performance with continuous along-track thickness data.

Comparison of EM and ULS thicknesses revealed that keel depths are underestimated by as much 50% by the EM measurements. While the amplitude of the disagreement might be surprising and might be a consequence of special, disadvantageous EM conditions in the Bay of Bothnia, the good correlation with the ULS and force data shows that an electromagnetically derived “effective thickness” could be very powerful to be used as environmental variable. The EM data yield accurate estimates of level ice thickness, and can well identify ridges to compute ridge spacing and depth distributions.

From an operational standpoint, the EM measurements seemed to be more convenient than the ULS measurements because they were easier to perform and process, and there was not a single system failure in four field seasons. In contrast, the ULS had a success rate of less than 50%.

ACKNOWLEDGEMENT

We are very grateful for the logistical support provided by L. Fransson and U. Stenman, Luleå Technical University, as well as for the numerous volunteers from the STRICE and LOLEIF projects running the lighthouse and maintaining the measurements continuously for several weeks during four field seasons. Staying on the lighthouse was kindly made possible by Swedish Sjöfartsverket and Swedish Polar Board through weekly helicopter supply. STRICE (“Structures in ICE”) was funded by EU project EVG1-CT-2000-00024. Compiling and presentation of the manuscript was also supported by EU project EVK3-CT-2003-00833 IRIS.

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