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# Whole-Ship Motions and Accelerations at the Stern of the CCGS *LOUIS S. ST-LAURENT* October 2000 Ice Trials

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# Abstract

The MOTAN inertial measurement system was used to determine whole-ship motions and accelerations at the stern of the *LOUIS S. ST-LAURENT* during the October 2000 ice trials. A total of 43 ice impact events were recorded during the trials, most of which involved second-year and multi-year floes. Impact speeds ranged from 2 to 16 kt. Since the objective of the October 2000 Trials was to examine propeller-ice interaction, data from the MOTAN sensor, which was installed near the ship's centre of gravity, were used to compute the whole-ship motions at the ship's centre propeller, in the stern. During the 43 events, maximum accelerations in heave, sway and surge were 1.1 m/s², 1.9 m/s² and 1.0 m/s² respectively, at the centre propeller. The events produced a maximum roll of 7.6°, compared to maximum a pitch and yaw of 1.8° and 1.5°, respectively. Maximum accelerations in roll, pitch and yaw were 2.8 deg/s², 1.8 deg/s² and 1.5 deg/s² respectively. Results showed no apparent relation between impact speed and the measured whole-ship motions. Very few of the impact events qualified as symmetrical, head-on impacts where ship motions are primarily in heave and pitch; roll and yaw motions were a significant component of most of the impact events.

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# Whole-Ship Motions and Accelerations at the Stern of the CCGS *LOUIS S. ST-LAURENT*; October 2000 Ice Trials

## 1.0 Introduction

This project was undertaken to narrow the data gap relating to whole-ship motions and global accelerations measured in ice, since there are so few measurements in that area. MOTAN, an inertial measurement system, was used to measure the ice-induced whole-ship motions and global accelerations of the *LOUIS S. ST-LAURENT* during 43 events. The trials took place in Wellington Channel (75°N, 93°W), Eastern Canadian Arctic, from 12 to 25 October 2000. Most of the events involved second-year and multi-year ice, however five events were logged in nilas and thin first-year ice. This report provides a detailed discussion of the whole-ship motions recorded during nine events. A summary of the translational and rotational displacements and accelerations measured during the 43 events is also presented.

Because propeller-ice interaction was the theme of the *LOUIS S. ST-LAURENT* trials in October 2000, MOTAN was used to compute the whole-ship motions and global accelerations at the stern of the vessel. The MOTAN software used the angular rotational rates and accelerations measured where the sensor was installed, near the centre of gravity, to make the transformation to the centre propeller of the triple screw arrangement. All whole-ship motions documented in this report were referenced to the centre propeller.

## 2.0 Background

One of the first full-scale programs to measure ship accelerations during ice ramming operations was conducted in 1977, using the CCGS *LOUIS S. ST-LAURENT*. During the 1977 trials, a gyro-stabilized accelerometer package was used to measure local accelerations in heave, surge and sway, and the pitch and roll angles. Since that time, full-scale trials have been conducted with the CCGS *RADISSON*, M.V. *Kigoriak*, M.V. *Robert Lemeur*, M.V. *Arctic*, M.V. *Kalvik* and the USCGS *Polar Sea* and *Polar Star* (summarized in Fleet Technology, 1997). Since the primary focus of those trials was to determine local and global ice-induced loads, ship accelerations were not always reported, or if they were, may not have been accurate. This project was undertaken to provide reliable data on ship accelerations in ice, for which little information is currently available.

# 3.0 Description of the MOTAN Inertial Motion Measurement System

MOTAN is a two-part package that consists of a physical sensor unit and a computer program to process measurements from the sensor unit (Figure 1). The original MOTAN system was developed at the Canadian Hydraulics Centre in 1986, to measure the motion of model-scale ships and floating structures in a wave basin (Miles, 1986). Favorable performance of the MOTAN system at model-scale led to the concept of using the package at full-scale to measure the ship response during icebreaking operations (Johnston et al., 2000).

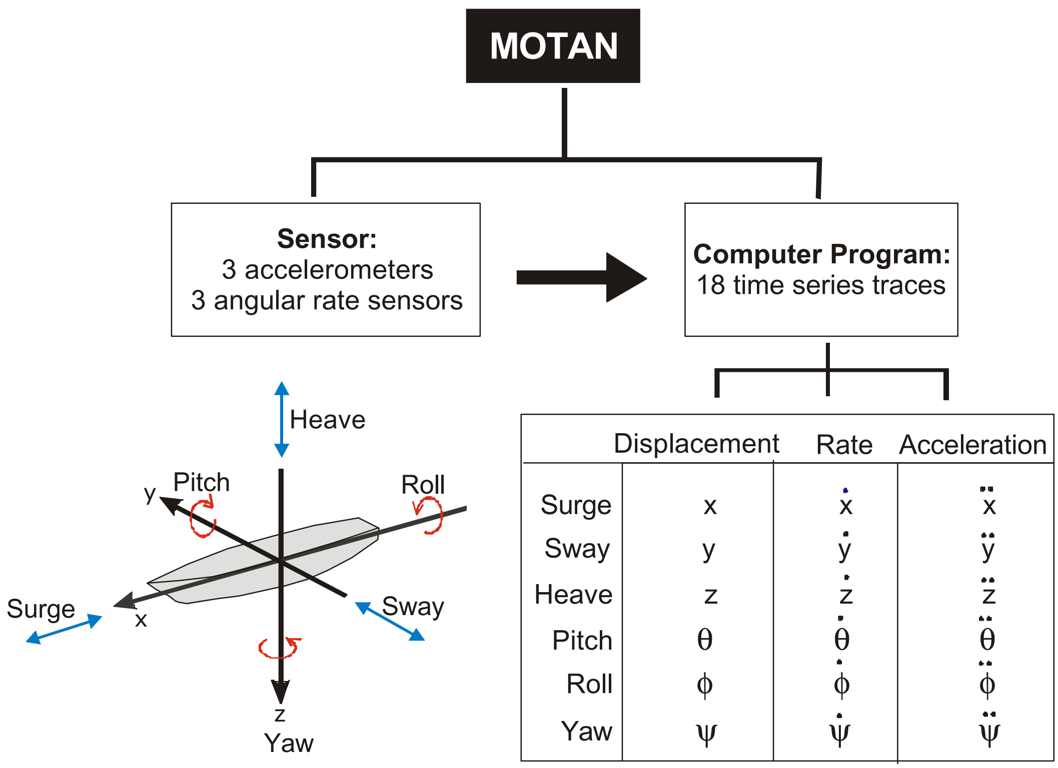



**Figure 1 Schematic of MOTAN package**

## *3.1 MOTAN Sensor Unit*

The MOTAN sensor unit is 260 mm long, 160 mm wide, 100 mm high and weighs 1.88 kg (Figure 2). It has three accelerometers and three angular rate sensors, arranged in a strapdown configuration. The accelerometers measure the total acceleration (including the earth's gravity components) and the rate sensors measure the three-dimensional angular rotational rate of the ship. Measurements are resolved along the instantaneous positions of the x', y' and z' body axes of the ship. A standard data acquisition system is used to record the six analog voltage signals from the sensor.


**Figure 2 MOTAN sensor unit**

### *3.2 MOTAN Computer Software*

The six analog signals from the MOTAN sensor are processed using computer software that was developed at the Canadian Hydraulics Centre (CHC). The accelerations and rotational rates measured by the sensor are used to determine rigid body motions of the ship from the equations of motion in Newman (1977). Whole-ship motions output by the MOTAN software are referenced to an inertial frame (x, y and z) that moves with the same average horizontal velocity as the ship, relative to the earth. The processed data represent the pure rigid-body motions of the ship in the six degrees of freedom shown in Figure 1.

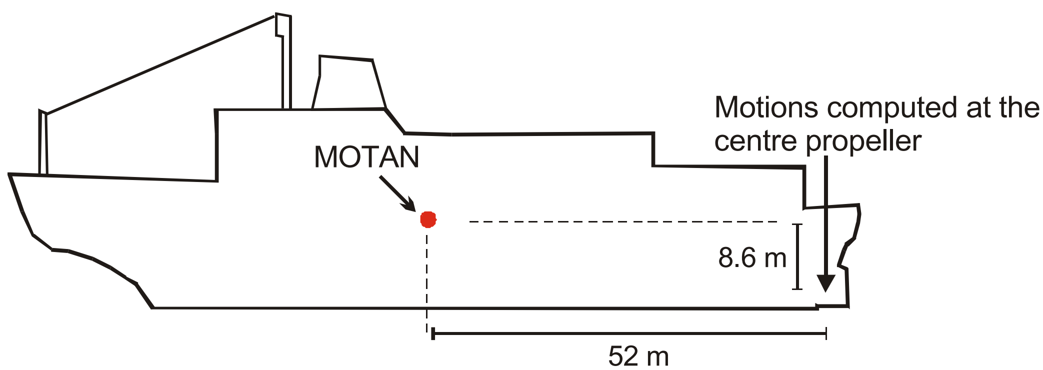
The MOTAN software outputs 18 digital files (Figure 1) to describe the rigid body motions of the vessel in six degrees of freedom. Output includes displacement, velocity and acceleration for translational (surge, sway and heave) and rotational motions (roll, pitch and yaw). One of the most advantageous aspects of the MOTAN system is that whole-ship motions can be computed at any location on the vessel, regardless of where the MOTAN sensor itself is located. This approach requires having knowledge of the positional vector (from the unit to the point of interest), and making the reasonable assumption that the icebreaking ship is a rigid body.

Although not discussed in this report, the whole-ship motions output by the MOTAN software can be used to calculate the global forces produced during symmetrical, head-on impacts in ice. Currently, the CHC has developed software to compute the total vertical impact force from the heave and pitch ship motions that are output by MOTAN (Johnston et al., 2000). Work in that area is ongoing.

## 4.0 MOTAN Installation on the *LOUIS S. ST-LAURENT*

The MOTAN sensor was installed on the CCGS *LOUIS S. ST-LAURENT* when the ship was near Resolute, Cornwallis Island (74°W, 94°N). Stability information obtained from the Canadian Coast Guard was used to install the MOTAN near the ship's centre of gravity. That location was selected because non-rigid body vibrations are minimized there, and it is a convenient reference point about which to calculate whole-ship motions. MOTAN was installed on a bulkhead in the engine casing area, 5.36 m forward of the longitudinal centre of gravity, 1.48 m port of the centreline and 3.24 m above the vertical centre of gravity of the ship. After the unit was connected to a data acquisition system, baseline readings were taken from the instrument (when the ship was stationary).

Since propeller-ice interaction was the theme of the October 2000 trials, the whole-ship motions and global accelerations measured by the MOTAN were calculated at the ship's centre propeller. The MOTAN software used a mathematical transform to convert the angular rotational rates and accelerations measured where the sensor was installed (near the centre of gravity) to whole-ship motions at the centre propeller of the triple screw arrangement. The transformation required knowing the distance from the MOTAN sensor unit to the centre propeller (the MOTAN was 52 m forward, 8.6 m above and 1.48 m port of the centre propeller, Figure 3).




MOTAN located 5.3 m forward of longitudinal centre of gravity (LCG), 3.24 m above vertical centre of gravity (VCG) and 1.48 m port of centreline

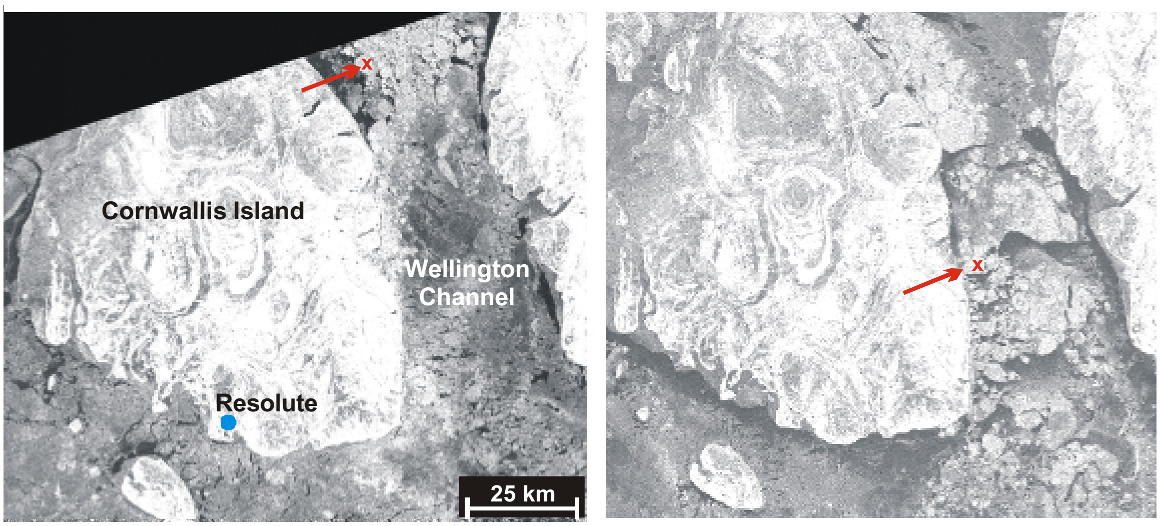
**Figure 3 Location of the MOTAN unit with respect to the centre propeller**

The MOTAN sensor unit was activated from a hand-held, remote trigger on the bridge. Impacts were typically logged for 15 minutes in order to capture several backing and ramming cycles. A sampling frequency of 50 Hz was used to provide a complete description of the time-series behavior. The raw data signal from the MOTAN was passed through a signal processing unit, where the signal was amplified (using a gain of 5) and a 5 Hz low pass filter was applied. Ship motions are in the low frequency range (around 3 Hz based upon Glen et al., 1981).

## 5.0 Ice Conditions during the Trials

The ice trials took place from mid to late October. Because the *LOUIS S. ST-LAURENT* was the only Canadian Coast Guard icebreaker stationed in the Arctic, it was necessary for the ship to remain close to Resolute, which was a convenient area for base operations. Given the operational requirements of the ship, Wellington Channel was the most logical place to find ice of adequate thickness for the trials. As expected, the recently formed first-year ice did not pose much resistance to the ship. The ship was quickly within the proximity of second-year and multi-year ice floes in Wellington Channel.

Figure 4 shows two images acquired by the Canadian RADARSAT satellite on two different days. When the Trials began on 12 October 2000, most of the old ice was located along the northeastern coast of Cornwallis Island. The two images in Figure 4 were used to illustrate that the thin first-year ice in Wellington Channel did not pose much impedance to the polar pack, which quickly moved south. Arrows were used to show the location of what is believed to have been the same floe in the 11 October image (Figure 4-a) and the 18 October image (Figure 4-b). The images show that the pack ice moved about 50 km south within one week. By 18 October 2000, the second-year and multi-year floes were in close proximity to Resolute, a convenient located for the trials. Most of the 43 events logged from 12 to 25 October 2000 involved old ice (second-year and multi-year floes). Five events were recorded in thin first-year ice as the vessel transited to the more substantial floes of old ice.




(a) 11 October 2000 (b) 18 October 2000

**Figure 4 RADARSAT images acquired during trials (arrows show location of same floe on two different days)**

## 6.0 Events Logged with the MOTAN during the Ice Trials

This report presents detailed information on nine events logged during the trials. Those nine events were used to provide a representation of the type of impact events that occurred during the October 2000 trials, and their associated ice conditions. Since space does not permit a discussion of the entire array of whole-ship motions (listed in Figure 1), time-series traces of the heave, pitch and roll are presented for each of the nine events. Records of the measured pitch and heave were included in the discussion because those two motion components are used to compute the total vertical impact force, as noted in Johnston et al. (2000). When available, digital records of the ship speed were also included, to provide more information about the ship's response during the event. The maximum accelerations in sway, surge and heave are tabulated for each of the nine examined events.

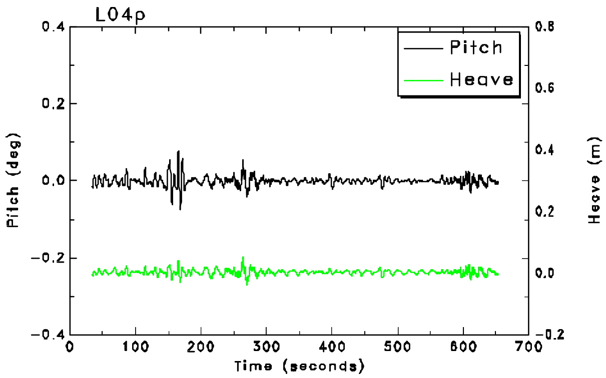
It should be noted that, because the *LOUIS S. ST-LAURNENT* is a rigid icebreaker, the angular displacements, rates and accelerations do not have a positional dependence, i.e. rotational motions would be the same at the ship's bow, centre of gravity and stern. In comparison, the translational motion components in heave and sway do have a positional dependence; they would be higher at the ship's bow than near the centre of gravity. It is expected that accelerations in heave and sway would be lower at the stern than near the centre of gravity. All data in this report are referenced to the centre propeller.

### *6.1 Event L04*

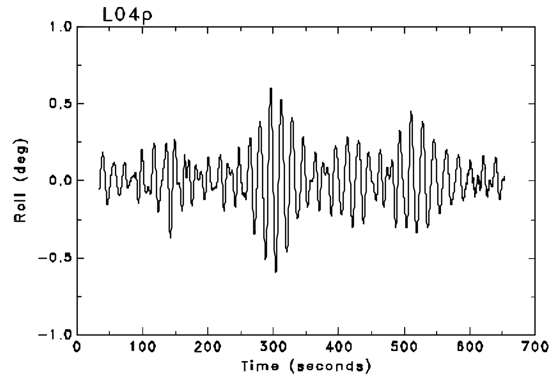
Event L04 was recorded on the afternoon of 17 October while the vessel transited nilas and thin first-year ice (Figure 5, 74°36.67 N, 93°19.63 W). Although the ice cover consisted of both thin first-year ice and rubbled ice floes, the vessel did not impact any substantial ice during the Event L04. Digital records of the ship speed were not available for this event, however periodic glances at the bridge's monitor showed that the ship maintained a speed of about 8 kt during Event L04.

The thin first-year ice caused minimal ship motions, as shown by the pitch, heave and roll time-series in Figure 6. The ship had maximum heave of 0.1 m, while pitch and roll angles were less than 1° during the event. Translational accelerations were less than 1.0 m/s², as summarized in Table 1.

**Figure 5 Nilas and thin first-year ice associated with Event L04**




**(a) pitch and heave**




**(b) roll**

**Figure 6 Pitch, heave and roll during Event L04**

**Table 1 Select Displacements and Accelerations during Event L04**

| Event | Date | Scenario | Event Time | Maximum Amplitude at Centre Propeller | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Displacement | | | Acceleration | | |
| | | | | Heave (m) | Pitch (deg) | Roll (deg) | Heave ($m/s^2$) | Sway ($m/s^2$) | Surge ($m/s^2$) |
| L04 | 17 Oct | Tn FYI | 13:02:27 - 13:13:56 | 0.1 | 0.1 | 0.6 | 0.8 | 1.0 | 0.2 |

### *6.2 Event L09*

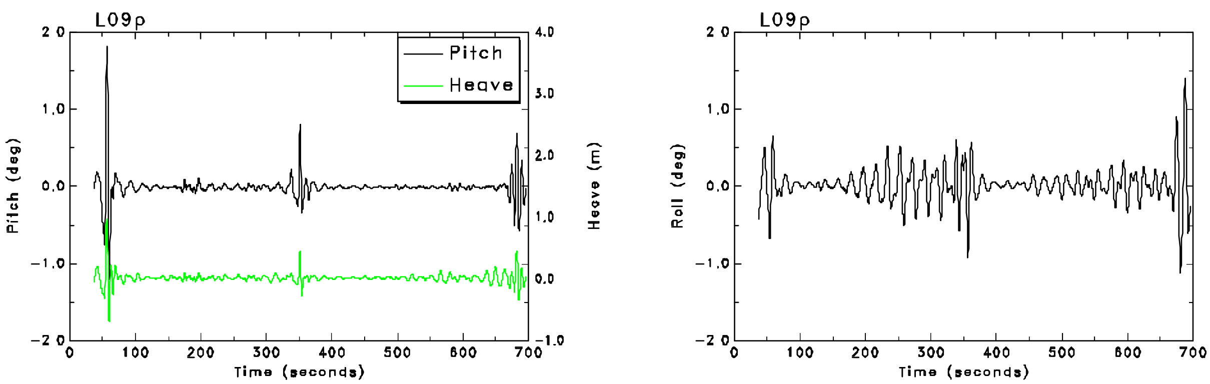
Event L09 resulted when the ship rammed a ridged, second-year ice floe in Wellington Channel (Figure 7-a, 74°37.75 N, 93°19.23 W). The same floe was also involved in the three previous events (L06, L07 and L08). Event L09 was selected for discussion because it produced the largest ship motions of the four events. Digital records of the ship speed were not available, however periodic glances at the bridge monitor indicated that the ship speed was about 6.6 kt during Event L09.

The time-series traces shown in Figure 8 show two complete ramming cycles (at elapsed times of 50 s and 332 s), and one partial ram at the end of the record. Observations noted that the most dramatic pitch occurred about 50 s after the start of the record, when the ship first impacted the floe. A large radial crack developed seconds later, propagating away from the ship's starboard side (Figure 7-b). At 124 s the ship began to reverse and the bow gradually slid off the ice. The second ram of the record occurred at about 332 s, when there was a hard impact that shoved the ship in the starboard direction. Bridge observations showed that the ship pitched at about 350 s, and there was a hard impact on the ship's port side at 357 s.

Figure 8 shows the pitch, heave and roll time-series from MOTAN, which corroborate the bridge observations. The first impact produced the greatest pitch and heave motions, 1.8° and 1 m respectively. A maximum roll of 1.4° occurred during the Event L09. Maximum accelerations in surge, sway and heave were 1.0 $m/s^2$.

(a) second-year ice floe (b) radial crack extending from vessel

**Figure 7 Second-year ice associated with Event L09**




(a) pitch and heave (b) roll

**Figure 8 Pitch, heave and roll associated with Event L09**

**Table 2 Select Displacements and Accelerations during Event L04**

| Event | Date | Scenario | Event Time | Maximum Amplitude at Centre Propeller | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Displacement | | | Acceleration | | |
| | | | | Heave (m) | Pitch (deg) | Roll (deg) | Heave (m/s²) | Sway (m/s²) | Surge (m/s²) |
| L09 | 18 Oct | MYI | 9:45:43 - 9:58:06 | 1.0 | 1.8 | 1.4 | 1.0 | 1.0 | 1.0 |

### *6.3 Event L12*

Event L12 was logged on 19 October in nilas and thin first-year ice as the ship transited to a more substantial old ice floe in Wellington Channel, identified by the Ice Service Specialist from remotely acquired imagery. The photo in Figure 9 shows the thin first-year ice in which the event was logged (74°42.31 N, 92°57.72 W). A portion of the rubbled floe that the ship bypassed on its port side (about 151 s after the record began) can be seen on the left side of the photo. The ship maintained a relatively constant speed of 5 to 7 kt throughout the event (Figure 10-b). Table 3 illustrates that Event L12 produced minimal ship motions; translational accelerations at the centre propeller were equal to, or less than 0.1 m/s².

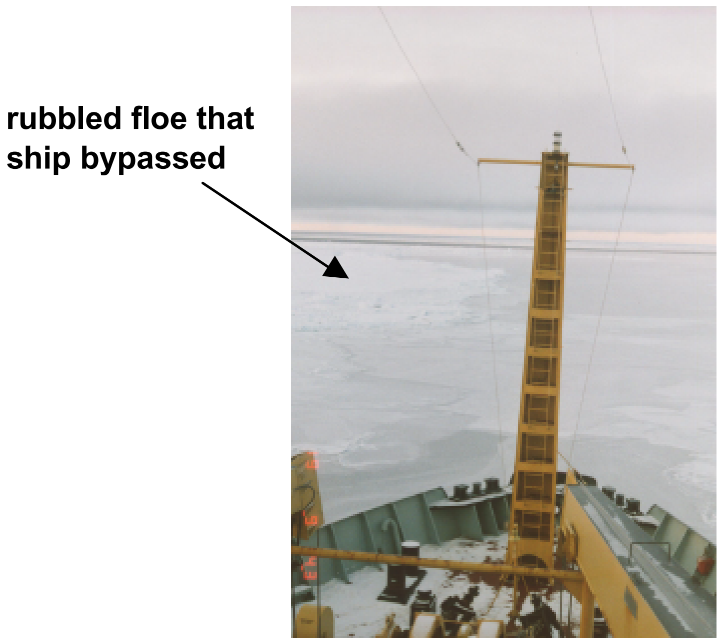
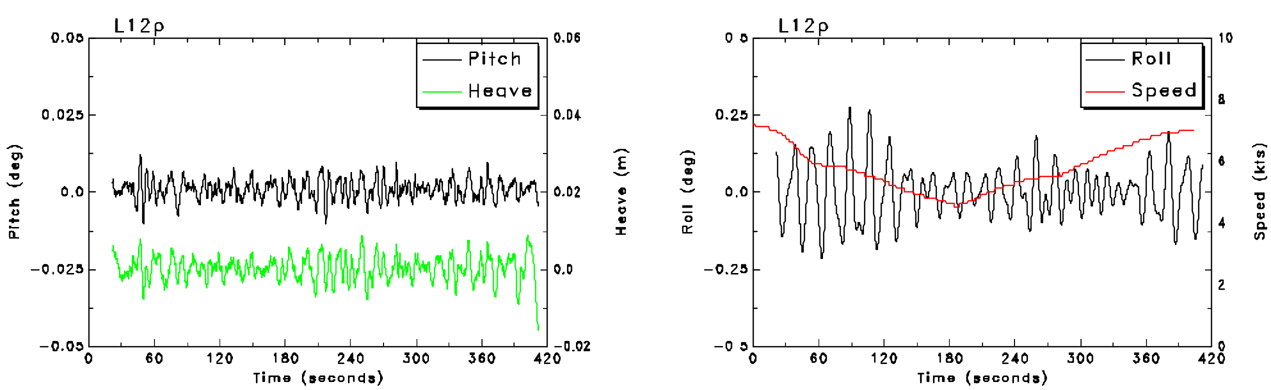



**Figure 9 Nilas and thin first-year ice associated with Event L12**




**(a) pitch and heave** **(b) roll**

**Figure 10 Pitch, heave and roll during Event L12**

**Table 3 Select Displacements and Accelerations during Event L12**

| Event | Date | Scenario | Event Time | Maximum Amplitude at the Centre Propeller | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Displacement | | | Acceleration | | |
| | | | | Heave (m) | Pitch (deg) | Roll (deg) | Heave (m/s²) | Sway (m/s²) | Surge (m/s²) |
| L12 | 19 Oct | FYI | 9:43:29 - 9:50:41 | 0.0 | 0.0 | 0.3 | 0.1 | 0.1 | 0.0 |

### *6.4 Event L17*

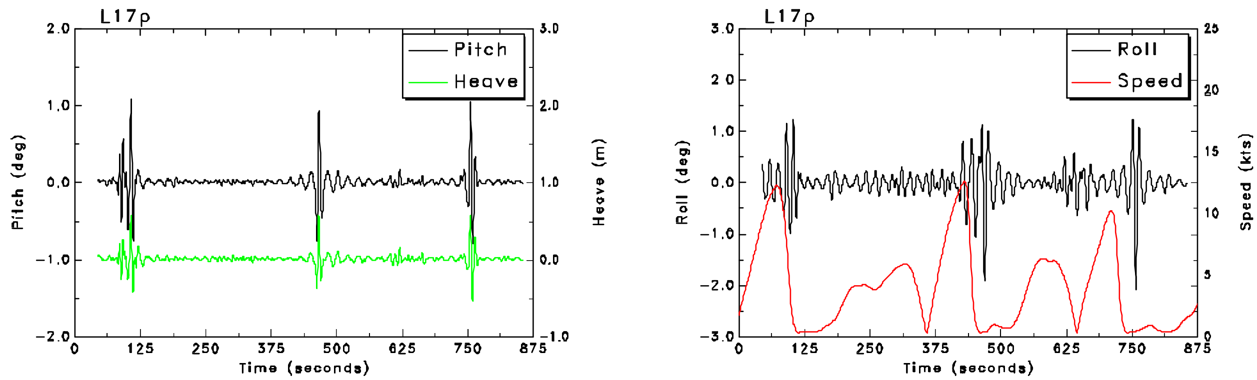
Event L17 resulted when the ship repeatedly rammed an old ice floe in Wellington Channel (Figure 11, 74°38.25 N, 93°19.52 W). The cusp of ice that the ship overturned as it entered the floe indicated that the ice was about one metre thick (Figure 11-b), yet the ice towards the interior of the floe was about 3 m thick. Three distinct rams were captured during Event L17, as shown in Figure 12. A ramming speed of about 10 to 12 kt was used for each of the rams. The ship was able to penetrate about only one ship length into the ice, before coming to a halt.

MOTAN showed that the third ram caused the greatest ship response (impact at 750 s, Figure 12), even though it used a lower impact speed than the previous two rams (Figure 12-b). The maximum heave, pitch and roll of 0.6 m, 1.1°, 2.1° occurred during the third impact. Maximum translational accelerations at the centre propeller ranged from 0.9 to 1.5 m/s². Observations made from the bridge noted that pitching occurred at 96 s, 482 s and 740 s. It was also noted that accelerations from the second impact (482 s) were clearly felt on the bridge.

**(a) bow print after ramming cycle**

**(b) ice thickness at floe edge, note the black metre stick used for scale**

**Figure 11 Multi-year floe associated with Event L17**




**(a) pitch and heave** **(b) roll**

**Figure 12 Pitch, heave and roll associated with Event L17**

**Table 4 Select Displacements and Accelerations during Event L17**

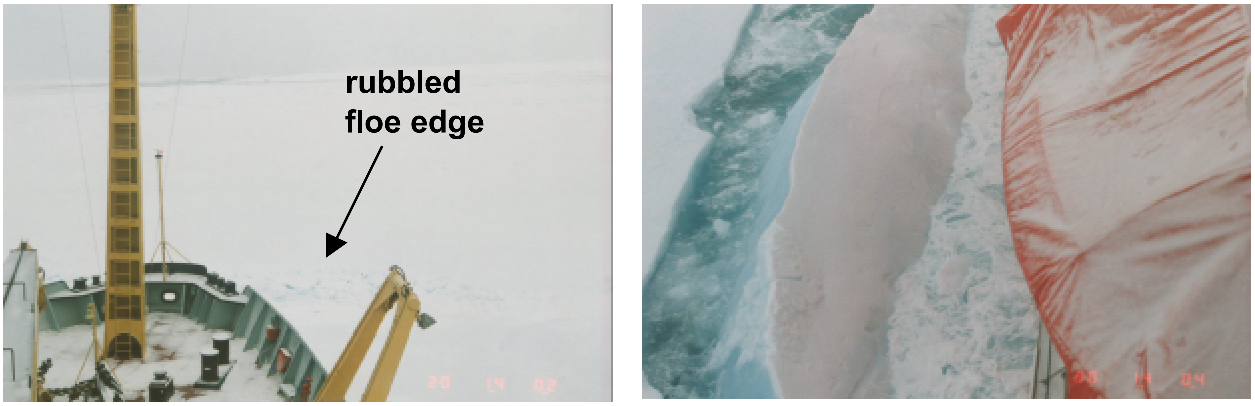
| Event | Date | Scenario | Event Time | Maximum Amplitude at Centre Propeller | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Displacement | | | Acceleration | | |
| | | | | Heave (m) | Pitch (deg) | Roll (deg) | Heave (m/s²) | Sway (m/s²) | Surge (m/s²) |
| L17 | 19 Oct | MYI | 13:57:19 – 14:12:19 | 0.6 | 1.1 | 2.1 | 1.0 | 1.5 | 0.9 |

### *6.5 Event L19*

Event L19 was recorded on the afternoon of 20 October. The second-year floe that caused Event L19 (74°29.56 N, 93°27.78 W) was also involved in events logged earlier that morning. As the ship approached the second-year floe, it passed through one metre thick ice. Figure 13-b shows that the ship had a speed of about 13 kt as it transited the thinner, level ice at the periphery of the floe (elapsed time of 136 s). Observations showed that the thin ice fragmented easily.

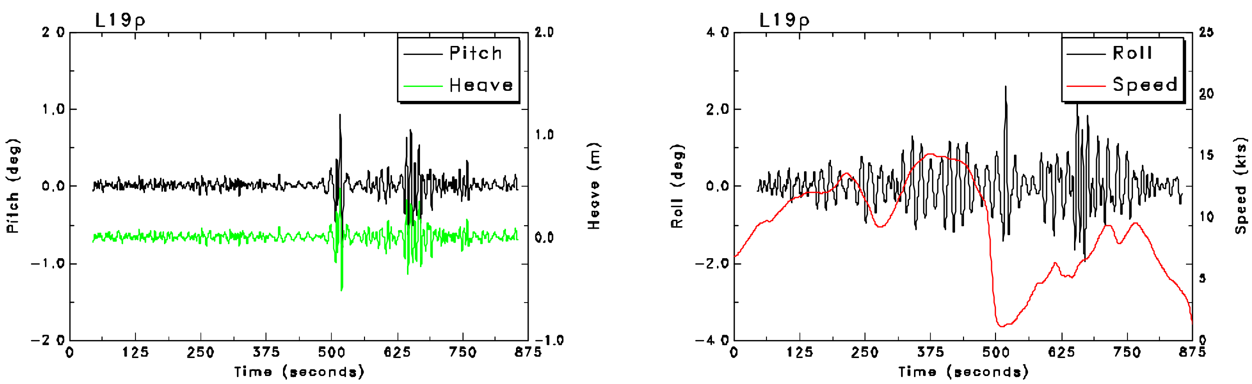
As the ship approached the main floe, its speed decreased to 10 kt. Observations noted that a considerable amount of sway occurred at 246 s. The ship impacted rubble at the edge of the main floe at an elapsed time of 505 s, and came to a halt. The ice thickness was about two metres at the rubbled periphery of the floe (Figure 13-b). Once in the main floe, the ship continued forward, when at 636 s, a second major blow was felt on the bridge. By an elapsed time of 756 s, the ship had exited the two metre thick ice, and re-entered one metre thick ice.

Time-series traces of the heave, pitch and roll indicated that the largest ship motions occurred at 505 s, upon contacting the rubbled exterior of the floe. Event L19 was primarily a roll event (2.6°) that produced a maximum heave of 0.5 m. Table 5 shows that Event L19 caused maximum translational accelerations from 0.5 to 1.3 m/s².




(a) rubbled periphery of second-year floe (b) two metre thick ice cusp

Figure 13 Second-year floe associated with Event L19




(a) pitch and heave (b) roll

Figure 14 Pitch, heave and roll during Event L19

Table 5 Select Displacements and Accelerations during Event L19

| Event | Date | Scenario | Event Time | Maximum Amplitude at Centre Propeller | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Displacement | | | Acceleration | | |
| | | | | Heave (m) | Pitch (deg) | Roll (deg) | Heave (m/s²) | Sway (m/s²) | Surge (m/s²) |
| L19 | 20 Oct | MYI | 13:55:24 - 14:10:24 | 0.5 | 0.9 | 2.6 | 1.1 | 1.3 | 0.5 |

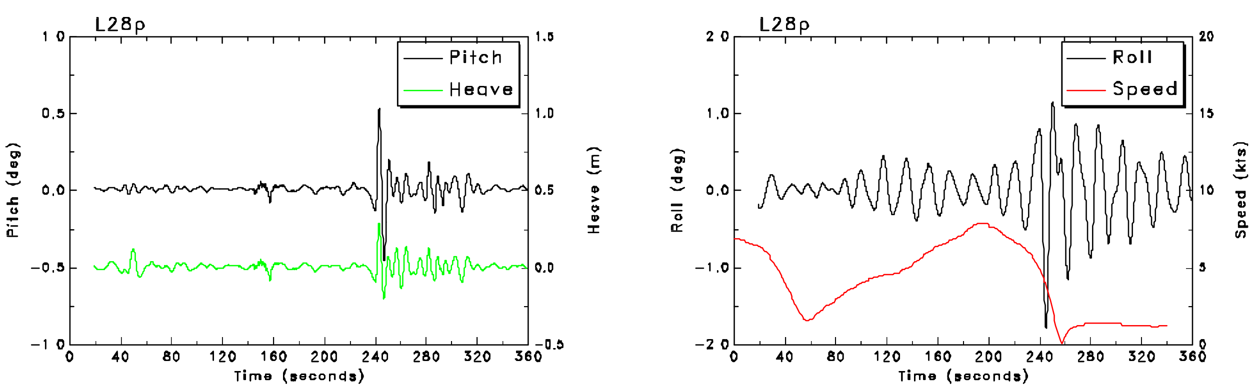
## 6.6 *Event L28*

Event L28 was logged on the afternoon of 22 October. The event was the third in a series oblique impacts that targeted ice floes embedded in the rubble field in Figure 15-a (74°34.71 N, 94°21.80 W). Events L26 and L27, the two previous events, also occurred when the ship obliquely impacted the old ice at speeds of 5 and 7 kt, respectively. Event L28 was selected for discussion, because it produced larger whole-ship motions than either Event L26 or Event L27.

Field observations indicated that the oblique impact of Event L28 occurred at 236 s, as the ship impacted an old ice floe on its starboard side, at a speed of 8 kt. The maximum heave, pitch and roll experienced during Event L28 were 0.3 m, 0.5° and 1.8° respectively. As might be expected from an oblique impact, the highest accelerations were in sway (1.1 m/s², Table 6), whereas accelerations in heave and surge were 0.8 and 0.2 m/s² respectively.


**(a) rubbled old ice** **(b) hummocked multi-year ice**

**Figure 15 Old ice floes used for oblique impacts of Events L26, L27 and L28**




**(a) pitch and heave** **(b) roll**

**Figure 16 Pitch, heave and roll during Event L28**

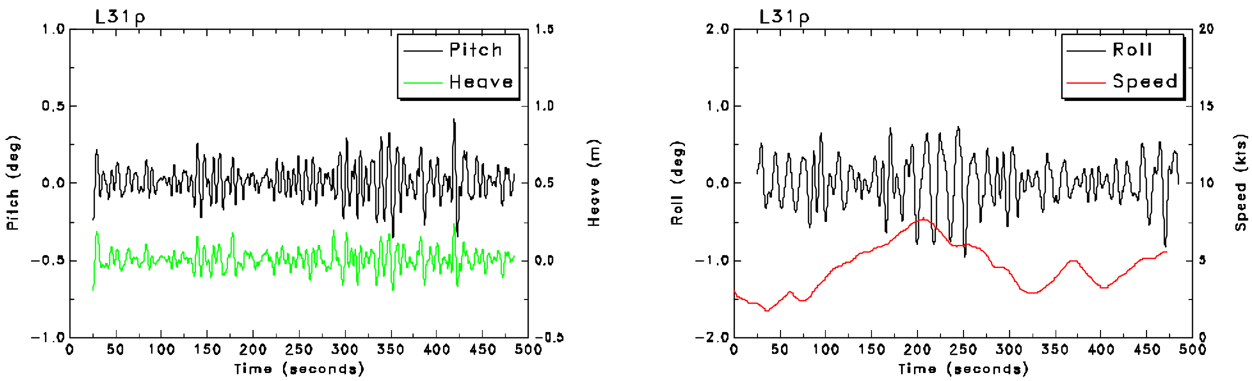
**Table 6 Select Displacements and Accelerations during Event L28**

| Event | Date | Scenario | Event Time | Maximum Amplitude at Centre Propeller | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Displacement | | | Acceleration | | |
| | | | | Heave (m) | Pitch (deg) | Roll (deg) | Heave (m/s²) | Sway (m/s²) | Surge (m/s²) |
| L28 | 22 Oct | Ru MYI | 13:18:55 - 13:25:13 | 0.3 | 0.5 | 1.8 | 0.8 | 1.1 | 0.2 |

## *6.7 Event L31*

Event L31 was logged as the ship moved between two pieces of ice created by a radial crack propagating into the second-year floe, from the ship's bow (Figure 17, 74°37.71 N, 93°21.80 W). During the event, the ship swayed, as it was pushed from either side of the two floes. As such, ship motions during Event L31 were similar to those resulting from an oblique impact. Observations made from the bridge indicated that at an elapsed time of 4 s, the ship began to advance into the bow print made during a previous ram. Sway was noted at 84 s, 127 s and 186 s, and by 298 s the ship was being pushed from side-to-side as it transited through the lead. The ship exited the open lead at 319 s, and penetrated another part of the floe. The ship motions associated with Event L31 were quite small. The event produced a maximum heave of 0.2 m, pitch of 0.4° and roll of 1.0° (Figure 18). Table 7 shows that accelerations were minimal in heave, sway and surge (0.3, 0.4 and 0.2 m/s² respectively).


**Figure 17 Level ice associated with Event L31**




**(a) pitch and heave** **(b) roll**

**Figure 18 Pitch, heave and roll during Event L31**

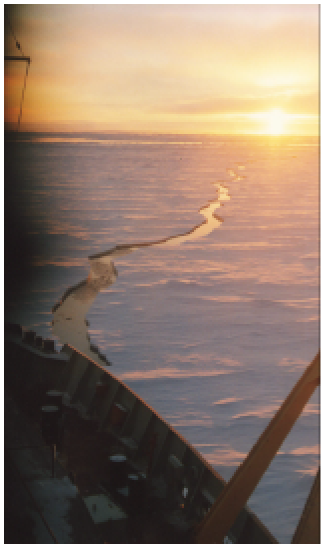
**Table 7 Select Displacements and Accelerations during Event L31**

| Event | Date | Scenario | Event Time | Maximum Amplitude at Centre Propeller | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Displacement | | | Acceleration | | |
| | | | | Heave (m) | Pitch (deg) | Roll (deg) | Heave ($m/s^2$) | Sway ($m/s^2$) | Surge ($m/s^2$) |
| L31 | 22 Oct | MYI | 14:18:28 – 14:26:58 | 0.2 m | 0.4 | 1.0 | 0.3 | 0.4 | 0.2 |

### *6.8 Event L34*

Figure 19 shows the very different ice conditions that characterized Event L34: (a) an open lead caused by a crack propagating in thin first-year ice and (b) ridged and rubbled old ice (74°37.71 N, 93°21.88 W). The ship gradually increased speed from 0 to about 14 kt as it moved from thin first-year ice into the cushion of crushed ice, formed during a previous ram (at an elapsed time of 56 s). At 139 s, the ship purposely veered to the starboard side to expose the port shaft's propeller to ice, which had been instrumented to measure impact forces. That maneuver produced a notable increase in pitch and heave (Figure 20-a), and an associated reduction in ship speed. At 141 s, 178 s and 252 s the ship impacted rubble on its starboard side that forced the ship to port. Motions subsided at 354 s, when the ship entered an open lead.

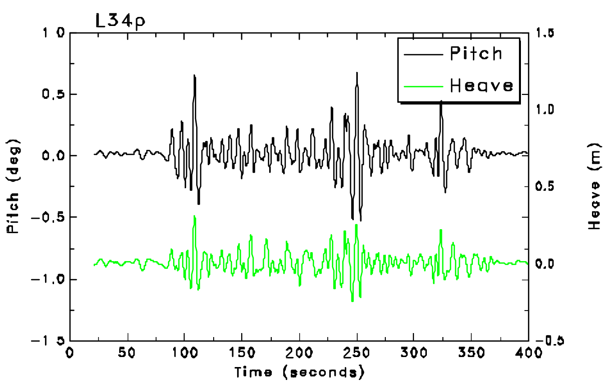
During Event L34, the rubbled ice caused a heave, pitch and roll of 0.3 m, 0.7° and 1.7° respectively. Table 8 shows that Event L34 produced maximum accelerations from 0.3 to 1.2 $m/s^2$ in heave, sway and surge. The most significant accelerations were measured in sway.



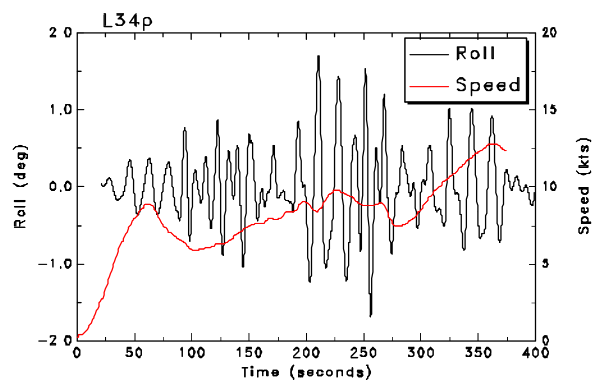
(a) crack propagating in front of vessel

(b) rubbled ice

**Figure 19 Ice conditions during Event L34**




(a) pitch and heave




(b) roll

**Figure 20 Pitch, heave and roll during Event L34**

**Table 8 Select Displacements and Accelerations during Event L34**

| Event | Date | Scenario | Event Time | Maximum Amplitude at Centre Propeller | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Displacement | | | Acceleration | | |
| | | | | Heave (m) | Pitch (deg) | Roll (deg) | Heave (m/s²) | Sway (m/s²) | Surge (m/s²) |
| L34 | 22 Oct | Lead/Tn FYI/Ru MYI | 15:37:52 - 15:44:53 | 0.3 | 0.7 | 1.7 | 0.9 | 1.2 | 0.3 |

### *6.9 Event L42*

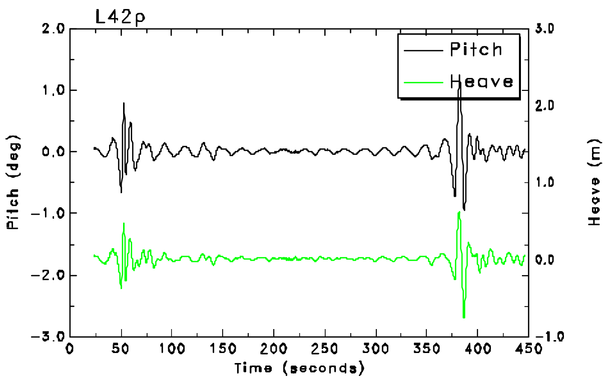
Event L42 was the most dramatic of the 43 events logged during the ice trials. The event occurred when the ship impacted the ridged multi-year floe shown in Figure 21 (74°33.89 N, 93°20.01 W). Figure 22 includes two complete ramming cycles, both of which involved the same area of the ridged ice floe. The first ram occurred at an elapsed time of 50 s. The ship then reversed, in preparation for the second ram, which occurred at 408 s.

Although a higher speed was used for the first ram (8 kt) than the second ram (6 kt), ship motions were greater during the second ram (408 s). That is because, as the ship impacted the floe and rode-up onto it, the ice beneath the ship collapsed suddenly. The ship lurched to the port side, causing significant accelerations and a maximum attendant roll of 7.6°. Persons on the bridge lost their footing and were thrown to the port side (as did the dinnerware in the dining quarters, much to the cook's dismay!).

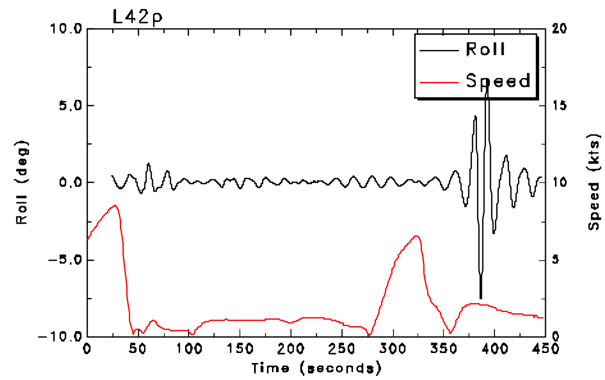
Records from MOTAN confirm that Event L42 was primarily a roll event (Figure 22). A maximum heave and pitch of respectively 0.8 m and 1.1° were measured during Event L42. Table 9 shows that the event produced a maximum acceleration of 2.0 $m/s^3$ in sway, which made it the most noteworthy of all the events logged during the October 2000 trials. Accelerations in heave and surge were 1.1 $m/s^2$ and 0.6 $m/s^2$ respectively.

**(a) bow imprint after ram #1** **(b) floe edge demolished by ram #2**

**Figure 21 Ridged multi-year floe associated with Event L42**




(a) pitch and heave




(b) roll

**Figure 22 Pitch, heave and roll during Event L42**

**Table 9 Select Displacements and Accelerations during Event L42**

| Event | Date | Scenario | Event Time | Maximum Amplitude at Centre Propeller | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Displacement | | | Acceleration | | |
| | | | | Heave (m) | Pitch (deg) | Roll (deg) | Heave (m/s²) | Sway (m/s²) | Surge (m/s²) |
| L42 | 23 Oct | Ri /MYI | 11:23:16 - 11:31:33 | 0.8 | 1.1 | 7.6 | 1.1 | 2.0 | 0.6 |

## 7.0 Summary of Whole-ship Motions and Accelerations

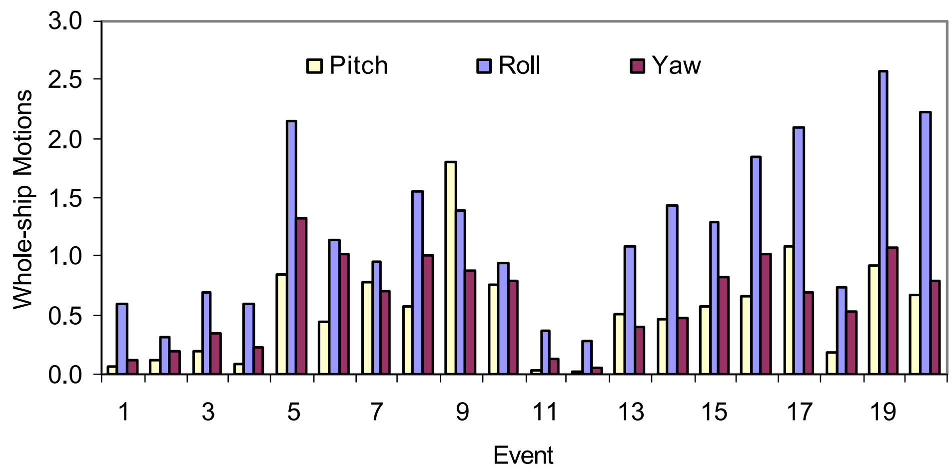
Table 10 summarizes the maximum amplitude of whole-ship motions measured during the October 2000 trials. Events that produced the greatest ship response are shown in the shaded portions of Table 10. Event L42, the most dramatic of the 43 events, resulted from the ship ramming a ridged multi-year ice floe at 6 kt. It produced a maximum sway of 1.5 m, roll of 7.6° and a sway acceleration of 2.0 m/s². Although this report did not discuss the rotational accelerations in detail, Event L42 also resulted in the highest accelerations in roll and pitch (2.8 deg/s² and 1.8 deg/s² respectively).

Events L09, L17 and L39 also produced significant ship motions. During Event L09 the ship rammed an old ice floe at 7 kt, which caused the greatest heave (1.0 m), pitch (1.8°) and surge acceleration (1.0 m/s²) of the 43 events. Event L17 occurred when the ship rammed an old ice floe at a speed of 12.5 kt, which produced a maximum surge of 1.9 m. Event L39, with a speed of 13 kt, used the highest impact speed of the trials to produce a maximum yaw of 1.5°, and yaw acceleration of 1.5 deg/s².

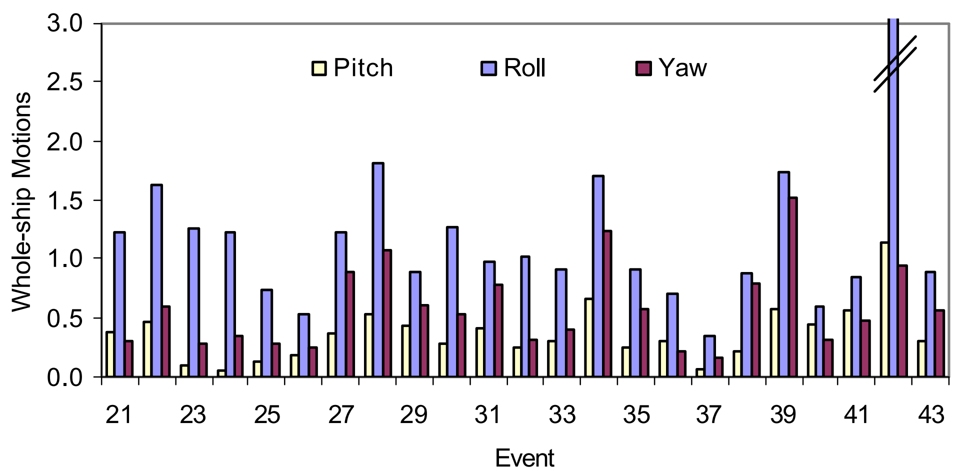
**Table 10 Summary of Maximum Whole-ship Motions during Ice Trials**

| | Maximum amplitude | Event | Ice Conditions | Impact speed |
|---|---|---|---|---|
| **Heave** | 1.0 m | L09 | MYI | 7 kt |
| **Sway** | 1.5 m | L42 | Ridged MYI | 6 kt |
| **Surge** | 1.9 m | L17 | MYI | 12.5 kt |
| **Roll** | 7.6° | L42 | Ridged MYI | 6 kt |
| **Yaw** | 1.5° | L39 | MYI | 13 kt |
| **Pitch** | 1.8° | L09 | MYI | 7 kt |
| **Heave acc** | 1.1 m/s² | L42 | Ridged MYI | 6 kt |
| **Sway acc** | 1.9 m/s² | L42 | Ridged MYI | 6 kt |
| **Surge acc** | 1.0 m/s² | L09 | MYI | 7 kt |
| **Roll acc** | 2.8 deg/s² | L42 | Ridged MYI | 6 kt |
| **Pitch acc** | 1.8 deg/s² | L42 | Ridged MYI | 6 kt |
| **Yaw acc** | 1.5 deg/s² | L39 | MYI | 13 kt |

Figure 23 plots the roll, pitch and yaw for all 43 events logged during the trials. Typically, roll was much larger than either pitch or yaw. Most of the events produced a considerable amount of yaw, particularly those events that classified as oblique impacts (L28 and L34). Pitch was usually the smallest of the three rotational displacements, however that is to be expected since substantial forces are required to lift the bow even a fraction of a degree. Results showed that since most of the events logged during the October 2000 trials had a yaw component, very few of those events classified as symmetrical head-on rams, where motions that were restricted to pitch and heave motions, predominantly.




**(a) Event L01 to Event L20**




**(b) Event L21 to Event L43**

**Figure 23 Summary of Whole-ship Motions for all Events logged during the Trials**

The histogram shown in Figure 24 shows the maximum heave, surge and sway for events that involved second-year and multi-year floes. The surge motions, which ranged from 0.2 to 2.0 m, had the widest distribution. The second widest distribution occurred in sway, with displacements of 0.2 to 1.6 m. Heave motions ranged from 0.2 to 1.0 m.

Figure 25 shows the maximum accelerations in heave, surge and sway produced when the ship rammed the old ice floes. Events typically produced surge accelerations from 0.2 to 0.4 m/s², sway accelerations from 1.0 to 1.2 m/s² and heave accelerations from 0.8 to 1.0 m/s².

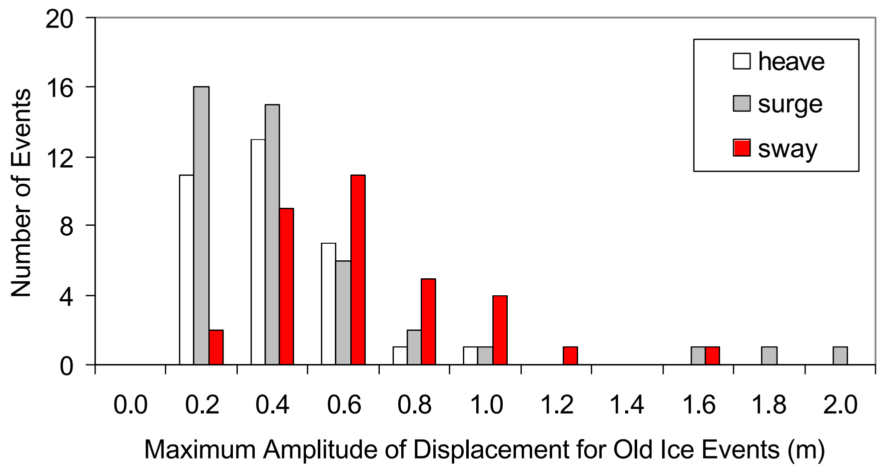



**Figure 24 Distribution of heave, surge and sway at centre propeller**

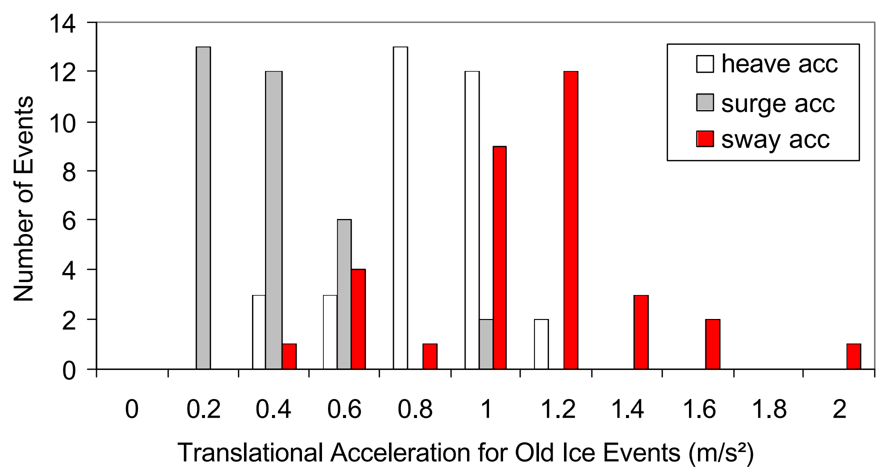
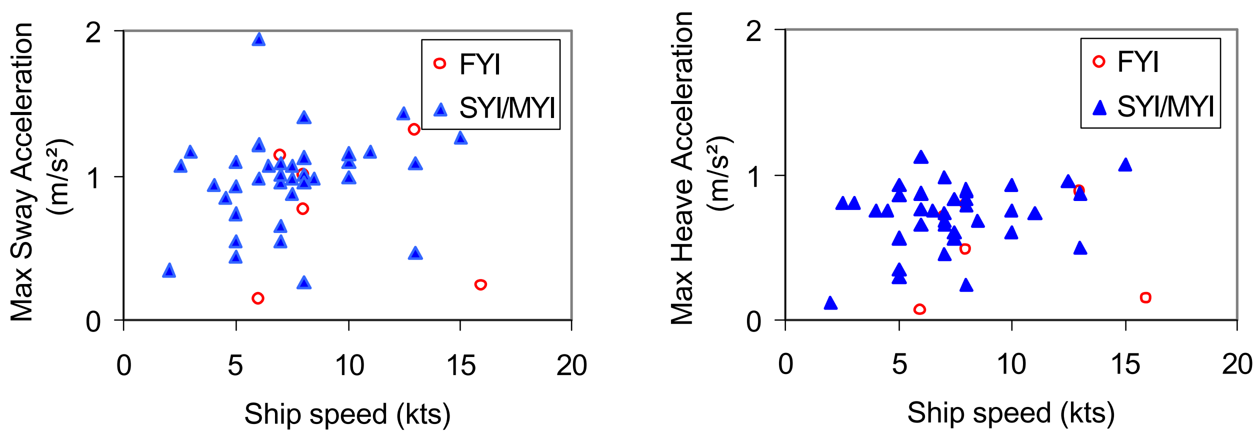



**Figure 25 Distribution of heave, surge and sway accelerations at centre propeller**

Each of the whole-ship motion components (displacement, rate and acceleration) were plotted against ice impact speed, to determine if there was a correlation between the ship speed and the response that the impact produced. Figure 26 shows two of those cross-plots, (a) sway acceleration and (b) heave acceleration. Data were categorized based upon the type of ice they involved; first-year ice (FYI) or second-year and multi-year ice (SYI/MYI). Neither plot in Figure 26 showed a clear relation between impact speed and the associated ship accelerations, regardless of the type of ice involved in the impact. Similar results were found for the other ship motion components.



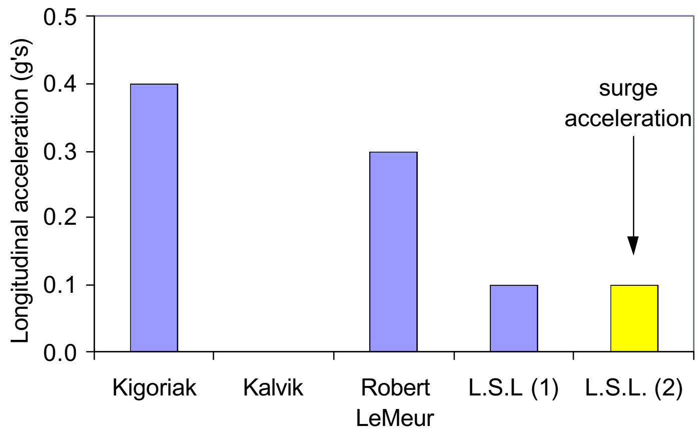

**(a) sway acceleration** **(b) heave acceleration**

**Figure 26 Cross-plot of impact speed and translational acceleration, at centre propeller**

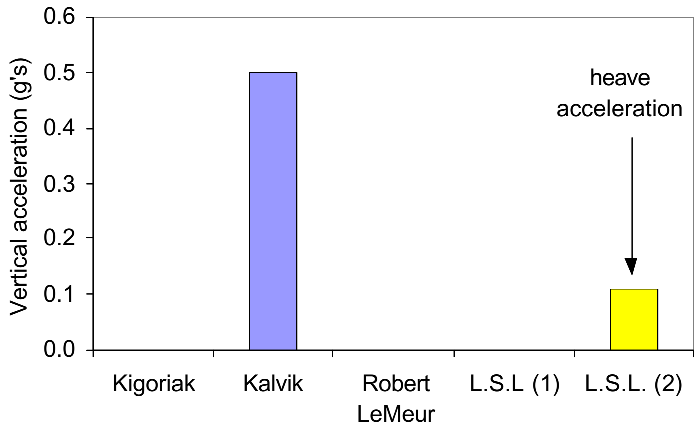
## 8.0 Discussion

Fleet Technology (1997) summarized full-scale data that were measured during icebreaking trials of the M.V. *Kigoriak*, M.V. *Robert LeMeur*, M.V. *Kalvik* and the 1977 trials with the CCGS *LOUIS S. ST-LAURENT*. During those trials, ship accelerations were measured from accelerometers that were installed in the ship's stern. Figure 27 shows the maximum longitudinal, vertical and transverse accelerations that were measured at the stern during those trials, expressed in units of gravity (g's). Note that the 1977 trials with the *LOUIS S. ST-LAURENT* were denoted as LSL (1) in the figure. The distributions in Figure 27 summarize the limited amount of information that is available on ship accelerations in ice.

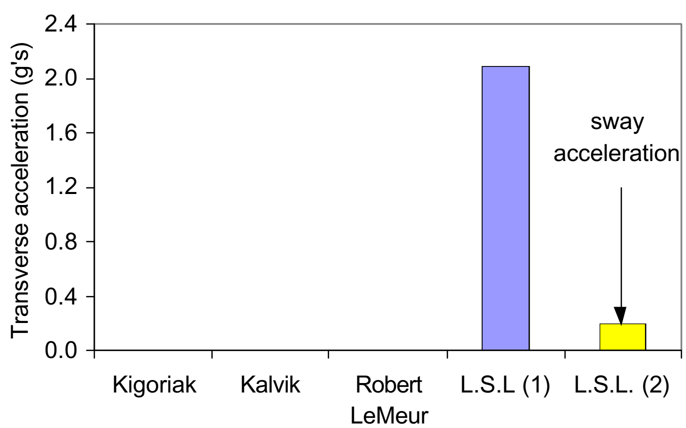
Accelerations processed using the MOTAN software were also included in Figure 27, denoted by LSL (2). It should be noted that the processed accelerations MOTAN provides are not the same as the unprocessed, raw accelerations measured during the other trials. MOTAN provides "pure" ship motions by (a) removing gravitational effects and (b) transforming the accelerations measured along a body-axis coordinate system (that moves with the ship, x', y' and z'), to an inertial frame of reference (x, y, and z) that moves with the same average horizontal velocity as the ship, relative to the earth.




**(a) longitudinal accelerations at the stern**




**(b) vertical accelerations at the stern**




**(c) transverse accelerations at the stern**

**Figure 27 Full-scale measurements of ship accelerations in ice (expressed in g's)**

That said, Figure 27 shows a comparison of the processed accelerations obtained during the October 2000 trials, and the ship accelerations obtained from other sources. There was good agreement between the longitudinal accelerations measured on *LOUIS S. ST-LAURENT* during the 2000 trials and those reported for the 1977 ice trials (Figure 27-a). During both trials, the maximum longitudinal acceleration at the stern was 0.10 g's. Longitudinal accelerations were substantially higher for the M.V. *Kigoriak* and M.V. *Robert Lemeur*. The difference is most likely a result of the ship displacements, and the aggressiveness with which the vessel was operated.

Figure 27-b shows that a maximum acceleration of 0.1 g's was measured in heave on the *LOUIS S. ST-LAURENT* during the October 2000 trials. The only other full-scale measurements of the vertical accelerations at the stern of a vessel were reported for the M.V. *Kalvik*. Measurements of the vertical accelerations on the M.V. *Kalvik* were about five times those measured during the October 2000 trials.

Figure 27-c shows that transverse ship accelerations in ice were only available for the 1977 trials involving the *LOUIS S. ST-LAURENT*. During those trials, the maximum transverse acceleration (at the stern of the vessel) exceeded 2 g's. In comparison, a maximum acceleration of 0.2 g's was measured in sway during the October 2000 trials; one order of magnitude less than reported for the 1977 trials. It should be noted that the transverse acceleration measured during the 1977 trials was, most likely, erroneous (Browne, personal communication).

## 9.0 Conclusions

This report documented the whole-ship motions and global accelerations measured on the *LOUIS S. ST-LAURENT* during the October 2000 trials. During those trials, 43 ice impact events were recorded, most of which involved second-year and multi-year floes. Five events were recorded in thin first-year ice. Impact speeds ranged from 2 to 16 kt. Cross-plots of the whole-ship motions and ship impact speed did not show any apparent relation between the ramming speed and the ship response that it produced, regardless of whether the event involved first-year, second-year or multi-year ice.

Since propeller-ice interaction was the theme of the field program, the MOTAN software was used to transform the accelerations and rotational rates measured by the MOTAN sensor unit near the centre of gravity (where it was installed), to the centre propeller (the point of interest). A maximum heave, sway and surge of 1.0 m, 1.5 m and 1.9 m respectively were measured at the center propeller. Maximum accelerations of 1.1 $m/s^2$, 1.9 $m/s^2$ and 1.0 $m/s^2$ were measured in heave, sway and surge (for the centre propeller).

A maximum roll of 7.6°, maximum pitch of 1.8° and maximum yaw of 1.5° was measured during the 43 events. Maximum accelerations in roll, pitch and yaw were 2.8 $deg/s^2$, 1.8 $deg/s^2$ and 1.5 $deg/s^2$. Very few of the impact events qualified as symmetrical, head-on impacts where ship motions are primarily in heave and pitch; roll and yaw motions were a significant component of most of the impact events.

## 10.0 Recommendations

Assuming the ship behaves as a rigid body, the MOTAN software enables the whole-ship motions to measured at one location, and computed at another, different location. During the October 2000 trials, the MOTAN sensor unit was installed near the ship's centre of gravity. Measurements from the sensor unit were used to compute the whole-ship motions at the ship's centre propeller. It is expected that accelerations in the ship's would be significantly higher than at the stern. A logical next-step would be to use MOTAN to process accelerations at numerous points along the vessel. Using this approach, accelerations at the bow could be compared to accelerations amidships, and at the stern.

The second recommendation pertains to the procedure used to determine ice impact forces from the whole-ship motions measured by MOTAN. Presently, the MOTAN software can be used to compute a vertical ice impact force for symmetrical head-on rams, where motions are predominantly in pitch and heave. Results from the October 2000 trials showed that very few of the impact events qualified as symmetrical, head-on impacts. That finding provides the impetus needed to expand the MOTAN software to take into account the entire suite of whole-ship motions when calculating global forces on ships in ice.

## 11.0 Acknowledgements

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**17.Abstract Résumé**


The MOTAN inertial measurement system was used to record whole-ship motions and accelerations at the stern of the *LOUIS S. ST-LAURENT* during the ice trials conducted in October 2000. A total of 43 ice impact events were recorded during the trials, most of which involved second-year and multi-year floes. Impact speeds ranged from 2 to 16 kt. Since the objective of the October 2000 Trials was to examine propeller-ice interaction, results from MOTAN, which was installed near the ship's centre of gravity, were transformed to the centre propeller, at the ship's stern. Maximum heave, sway and surge accelerations at the centre propeller were 1.1 $m/s^2$, 1.9 $m/s^2$ and 1.0 $m/s^2$ during the 43 events. The largest ship rotation was measured in roll (7.6° ), as compared to maximum pitch and yaw motions of 1.8° and 1.5°, respectively. Maximum rotational accelerations in roll, pitch and yaw were 2.8 $deg/s^2$, 1.8 $deg/s^2$ and 1.5 $deg/s^2$ respectively. Results showed no apparent relation between impact speed and the measured whole-ship motions.


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