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International Journal of Naval Architecture and Ocean Engineering 8 (2016) 301−311
http://www.journals.elsevier.com/international-journal-of-naval-architecture-and-ocean-engineering/

Determination of global ice loads on the ship using the measured full-scale motion data

Jae-Man Lee [a], Chun-Ju Lee [b], Young-Shik Kim [b], Gul-Gi Choi [c], Jae-Moon Lew [d,*]

[a] Daewoo Shipbuilding & Marine Engineering Co.,Ltd (DSME), Geoje, Gyeongsangnam, South Korea
[b] Korea Research Institute of Ships and Ocean Engineering (KRISO), Daejeon, South Korea
[c] Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea
[d] Chungnam National University (CNU), Daejeon, South Korea

Received 22 September 2014; revised 19 November 2014; accepted 24 February 2016
Available online 13 June 2016

Abstract

This paper describes the whole procedures to determine ice-induced global loads on the ship using measured full-scale data in accordance with the method proposed by the Canadian Hydraulics Centre of the National Research Council of Canada. Ship motions of 6 degrees of freedom (dof) are found by processing the commercial sensor signals named Motion Pak II under the assumption of rigid body motion. Linear accelerations as well as angular rates were measured by Motion Pak II data. To eliminate the noise of the measured data and the staircase signals due to the resolution of the sensor, a band pass filter that passes frequencies between 0.001 and 0.6 Hz and cubic spline interpolation resampling had been applied. 6 dof motions were computed by the integrating and/or differentiating the filtered signals. Added mass and damping force of the ship had been computed by the 3-dimensional panel method under the assumption of zero frequency. Once the coefficients of hydrodynamic and hydrostatic data as well as all the 6 dof motion data had been obtained, global ice loads can be computed by solving the fully coupled 6 dof equations of motion.

Full-scale data were acquired while the ARAON rammed old ice floes in the high Arctic. Estimated ice impact forces for two representative events showed 7−15 MN when ship operated in heavy ice conditions.

Keywords: Global ice load; Ship motions of 6 degrees of freedom; Motion Pak II; GPS; Band pass filter; Resampling

1. Introduction

Traditionally, global ice impact forces on ships have been measured by strain gauging the structure. That approach involves treating the ship as an elastically deformable structure. Its structural deformations are measured by strain gauging strategic hull-girder beams throughout the ship. Measuring structural strains can be an effective method for measuring global loads, however installing the gauges can be a time-consuming (and expensive) process.

Recently, a novel approach for determining global loads on ships was put forward by the Canadian Hydraulics Centre of the National Research Council of Canada (NRC-CHC). The method assumes the ship is a rigid body and uses its whole-ship motions to determine external ice forces. The whole ship motions in six-degrees of freedom are measured using an instrument called the MOTAN. Specially developed MOTAN software is used to process those motions and calculate global impact loads. To date, the MOTAN has been used on three icebreakers with satisfaction (Johnston et al., 2003).

Following the method proposed by the NRC-CHC, an algorithm and an analysis tool (hereinafter "program") to estimate global ice load based on the ship motion data were developed. The analysis program was used to calculate the

* Corresponding author.
E-mail address: jmlew@cnu.ac.kr (J.-M. Lew).
Peer review under responsibility of Society of Naval Architects of Korea.

http://dx.doi.org/10.1016/j.ijnaoe.2016.03.006

global ice load on the ship that processes the measured ship motion signals, linear accelerations and angular rates by a commercial sensor, Motion Pak II (Motion Pak II User's Guide).

This paper describes the whole procedures to compute the global ice loads of a ship. Linear velocities were computed by the measured linear acceleration by Motion Pak II and the linear displacements were obtained by the integration of the linear velocities without drift. Angular accelerations and the angles were computed by the differentiation and the integration of the measured angular rates using Motion Pak II during the full scale sea trials of Korean research vessel ARAON rammed ice floes in the high Arctic. To eliminate the noise of the measured signals, a band pass filter (Vegte, 2001) that passes between 0.001 and 0.6 Hz were developed and the cubic spline interpolations were applied to resample the measured data. The measuring rates were 100 Hz, however, the time interval of the resample data were 0.005 s to get more accurate 6 dof motions without any drift during the integration of the signals. Linear velocities were obtained by the integration of the measured Motion Pak II data and the linear displacements were obtained by integration of the computed linear velocities. Angular accelerations as well as angular displacements were obtained by the differentiation and the integration of the filtered angular rates. Hydrostatic coefficients were computed by the hull form data and the hydrodynamic data, added mass and damping coefficients, were computed by the three-dimensional panel method under the assumption of zero-frequency. Once the 6 dof motion data and all the coefficients of the equations of the motion were found, global ice loads were computed in a straightforward way using the developed program.

When a ship rams in the ice floes, ship motions must be affected by the ice loads acting on the ship. When a ship collides with the large and hard ice floes, the ship motions should be varied significantly than that of small and soft ice floes. In order to calculate the effect of load by ice on ship, an ice load analysis algorithm was developed using an obtained ship motion data as well as the computed hydrodynamic forces of a ship. An ice load analysis program based on LabVIEW using the ship motion data during a full-scale ice-breaking test was then developed.

2. Equations of motion to determine global ice loads

The ice-breaking vessel considered in this study operates at a low speed when breaking ice. The global ice loads can be computed as follows.

$$\mathrm{F}^{Ice} = \{\mathrm{M}\}\ddot{\eta} + \{B\}\dot{\eta} + \{C\}\eta \tag{1}$$

Where

$$\mathrm{F}^{Ice} = \left[F_x\, F_y\, F_z\, M_x\, M_y\, M_z\right]^2$$

$$\eta = [x\, y\, z\, \Phi\, \theta\, \psi]^2$$

$$\{\mathrm{M}\} = \begin{bmatrix} m - X_{\dot{u}} & 0 & -X_{\dot{w}} & 0 & mz_G - X_{\dot{q}} & 0 \\ 0 & m - Y_{\dot{v}} & 0 & -mz_G - Y_{\dot{p}} & 0 & mx_G - Y_{\dot{r}} \\ -Z_{\dot{u}} & 0 & m - Z_{\dot{w}} & 0 & -mx_G - Z_{\dot{q}} & 0 \\ 0 & -mz_G - K_{\dot{v}} & 0 & I_x - K_{\dot{p}} & 0 & -I_{xz} - K_{\dot{r}} \\ mz_G - M_{\dot{u}} & 0 & -mx_G - M_{\dot{w}} & 0 & I_y - M_{\dot{q}} & 0 \\ 0 & mx_G - N_{\dot{v}} & 0 & -I_{zx} - N_{\dot{p}} & 0 & I_z - N_r \end{bmatrix}$$

$$\{\mathrm{B}\} = \begin{bmatrix} X_u & 0 & X_w & 0 & X_q & 0 \\ 0 & Y_v & 0 & Y_p & 0 & Y_r \\ Z_u & 0 & Z_w & 0 & Z_q & 0 \\ 0 & K_v & 0 & K_p & 0 & K_r \\ M_u & 0 & M_w & 0 & M_q & 0 \\ 0 & N_v & 0 & N_p & 0 & N_r \end{bmatrix}$$

$$\{\mathrm{B}\} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & Z_z & 0 & Z_\theta & 0 \\ 0 & 0 & 0 & K_\Phi & 0 & 0 \\ 0 & 0 & M_z & 0 & M_\theta & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$Z_Z = -\rho_w g A_{WP}$$

$$Z_\theta = \mathrm{M}_Z = \rho_w g \iint_{A_{WP}} x dA$$

$$K_\Phi = -\rho_w g \nabla (z_G - z_B) - \rho_w g \iint_{A_{WP}} y^2 dA = -\rho_w g V GM_T$$

$$M_\theta = -\rho_w g \nabla (z_G - z_B) - \rho_w g \iint_{A_{WP}} x^2 dA = -\rho_w g V GM_L$$

The hydrostatic restoring force and moment coefficient matrix (C) can be obtained from the given ship characteristics, while the hydrodynamic added mass and the damping coefficients ($X_{\dot{u}}$ and X_u etc. in M and B) are computed by the three-dimensional panel method assuming a motion of frequency of zero.

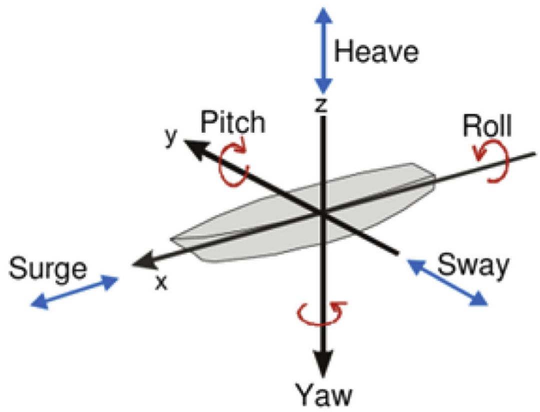

Fig. 1. Coordinate systems of whole ship motions.

In order to determine the global loads on the ship, 6 dof motion data ($\ddot{r}$, $\dot{r}$, r) shown in Fig. 1 should be known. The required motion data have been obtained by processing the measured linear accelerations and angular rates by Motion Pak II during the sea trials.

2.1. Determination of global ice load

Through hydrodynamic force analysis and processing the measured data from the sea trials, the longitudinal (F_x), lateral (F_y) and vertical (F_z) force components at the point of impact can be calculated when the external ice force is applied to the ship. The following equation can be used to determine the resultant global ice impact forces.

$$F = \sqrt{(F_x)^2 + (F_y)^2 + (F_z)^2} \quad (2)$$

Where

F = global ice impact force
F_x = longitudinal ice impact force component
F_y = lateral ice impact force component
F_z = vertical ice impact force component

In order to compute the ice loads on the ship, an ice load analysis algorithm that applies to solve the equation of motions was developed. Global ice load was estimated by using ARAON's motion data through the ice load analysis program.

2.2. Signal processing

A full-scale validation study of the present algorithm was performed using the data acquired on the ARAON. Acceleration, velocity, and displacement of 6 dof motion are needed as the input data to the ice load analysis program.

The sea trials were conducted in the high Arctic in 2011 to obtain the 6 dof motion data. The full-scale data were recorded from the commercial sensor Motion Pak II. In Motion Pak II, only acceleration and angular rates were measured. The measured raw data cannot be applied directly because of the noise and the staircase signals due to the low resolutions of the sensor. The authors developed the signal processing algorithm to eliminate the noise and resample the measured signal to have shorter intervals than measured values. First of all, a band pass filter (Vegte, 2001) was applied, a band pass filter has the

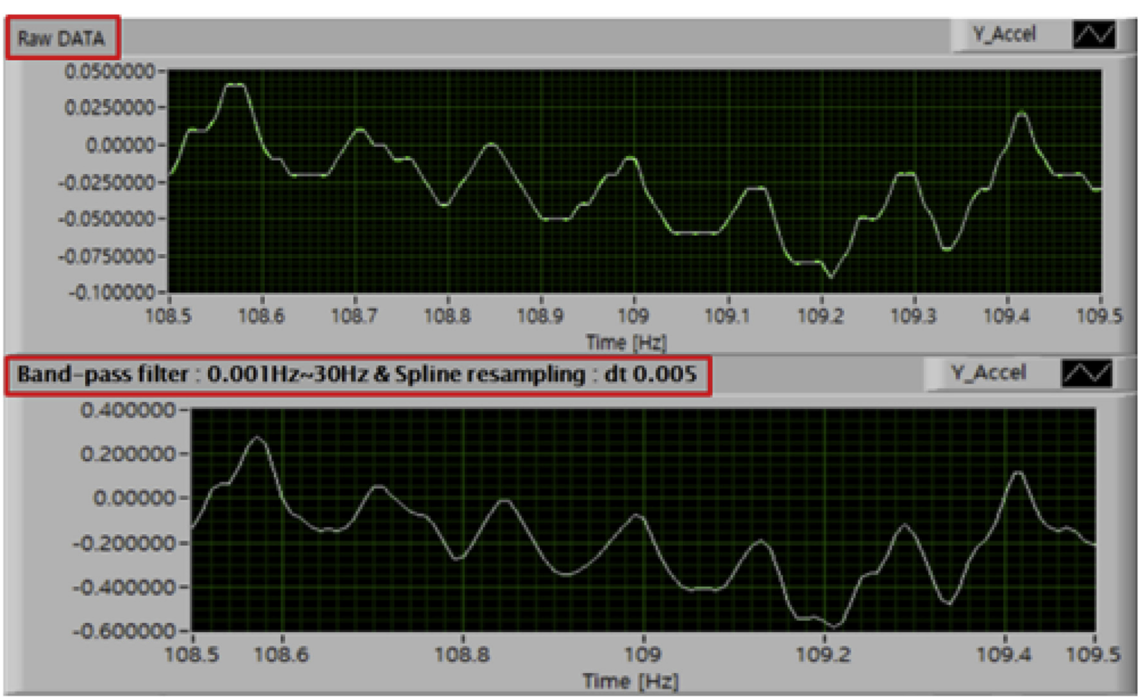

Fig. 2. Results of developed signal processing (Sway).

advantage to pass frequencies within a certain range and attenuate frequencies outside that range from the FFT analysis of the experimental values. To compute the ice loads in the present study, the measured time domain signals were converted into frequency domain data using Discrete Fourier Transform (DFT). Then, the energy was set to zero beyond the specific frequency to remove the noise and the signals were transformed using Inverse Discrete Fourier Transform (IDFT). Lastly, the obtained data were used to compute the global ice loads of a ship. The low and high frequency in the present analysis was set to be 0.001 and 0.6 Hz. Then, resample of the data using cubic spline interpolations were applied in the data processing process.

Figs. 2 and 3 show sample results of the data processing process. While the top figure shows the measured raw data using the Motion Pak II sensors with the sampling rates of 100 Hz, bottom figure shows the filtered and resampled data using a band-pass filter and cubic spline interpolations with the sampling rates of 200 Hz. The filtered signals show smooth curves without noise, therefore, it is thought that a band pass filter was properly designed for the signals. The staircase signals were obtained due to low resonance of the a/d converter of the sensor. To make the signals integrable or differentiable and to estimate the physical dynamic quantity more easily by converting large interval signals to dense signals, a spline interpolation was applied and then resampled from 0.01 s to 0.005 s.

Top figure of Fig. 4 shows the samples of the raw data of the surge accelerations with noise. The second figure shows the filtered accelerations through the data processing process. Once the filtered signals are obtained, numerical integrations were carried out to get the surge velocities (the third) and displacements (bottom).

Fig. 5 shows the results of the pitch drawn in the same way of Fig. 4. Using the measured pitch rates (top), the filtered signals (the second) were obtained. Pitch accelerations (the third) and the angles (bottom) were found by the integration and differentiation of the filtered signals. From the results as shown above, it was thought that the developed signal processing procedure, a band pass filter with spline resampling, developed in this thesis was satisfactory to make the data integrable and differentiable by removing the noise and discontinuous points.

2.3. Analysis of ice loads

Once the 6 dof motion signals were obtained through the signal processing, global ice loads of a ship can be computed by solving the linear equation of motion, Eq. (1). The authors developed the GUI program to compute the global ice loads as shown in Fig. 6. The components of the global ice loads of Eq. (2) can be easily plotted on the screen. If the hydrodynamic and hydrostatic coefficients of the equation of motions were computed beforehand, the global ice loads of a ship can be computed in real-time using the measured data by the Motion-Pak II data.

3. Analysis of full-scale ice loads of ARAON

3.1. Characteristics of Korean ice breaking research vessel, ARAON

The full-scale motion data were obtained from a trial run of ARAON during sea trials of the Arctic Chukchi Sea in 2011. The Motion Pak II sensor providing RS-232 outputs has been installed at the point near longitudinal and vertical centre of

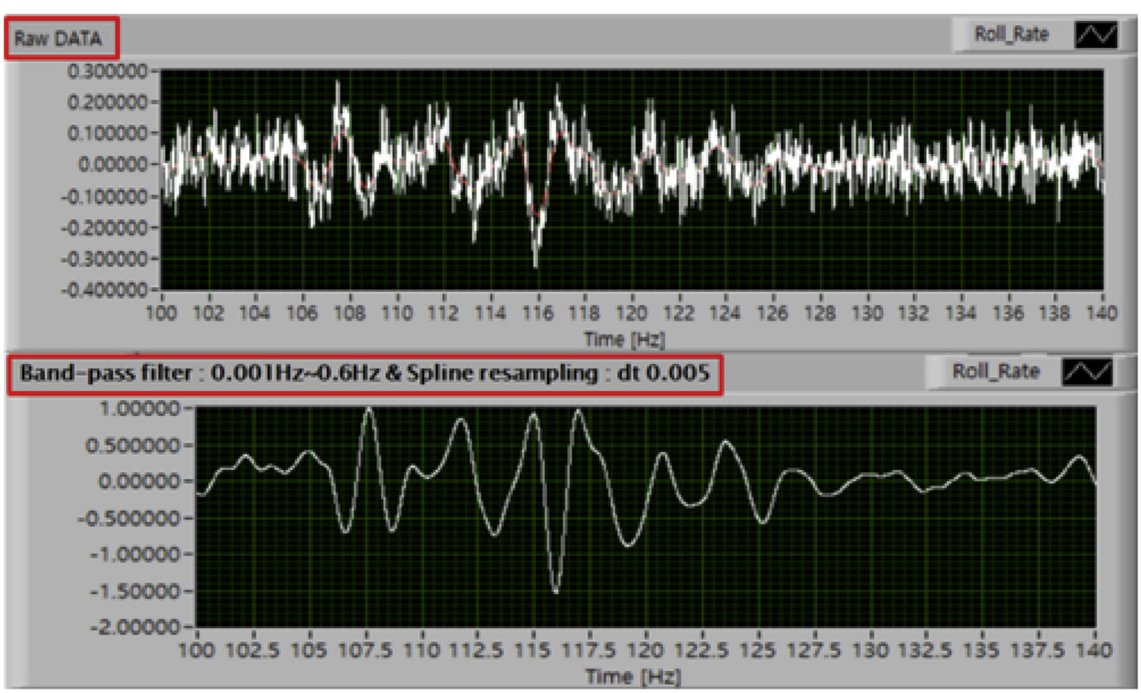

Fig. 3. Results of developed signal processing (Roll).

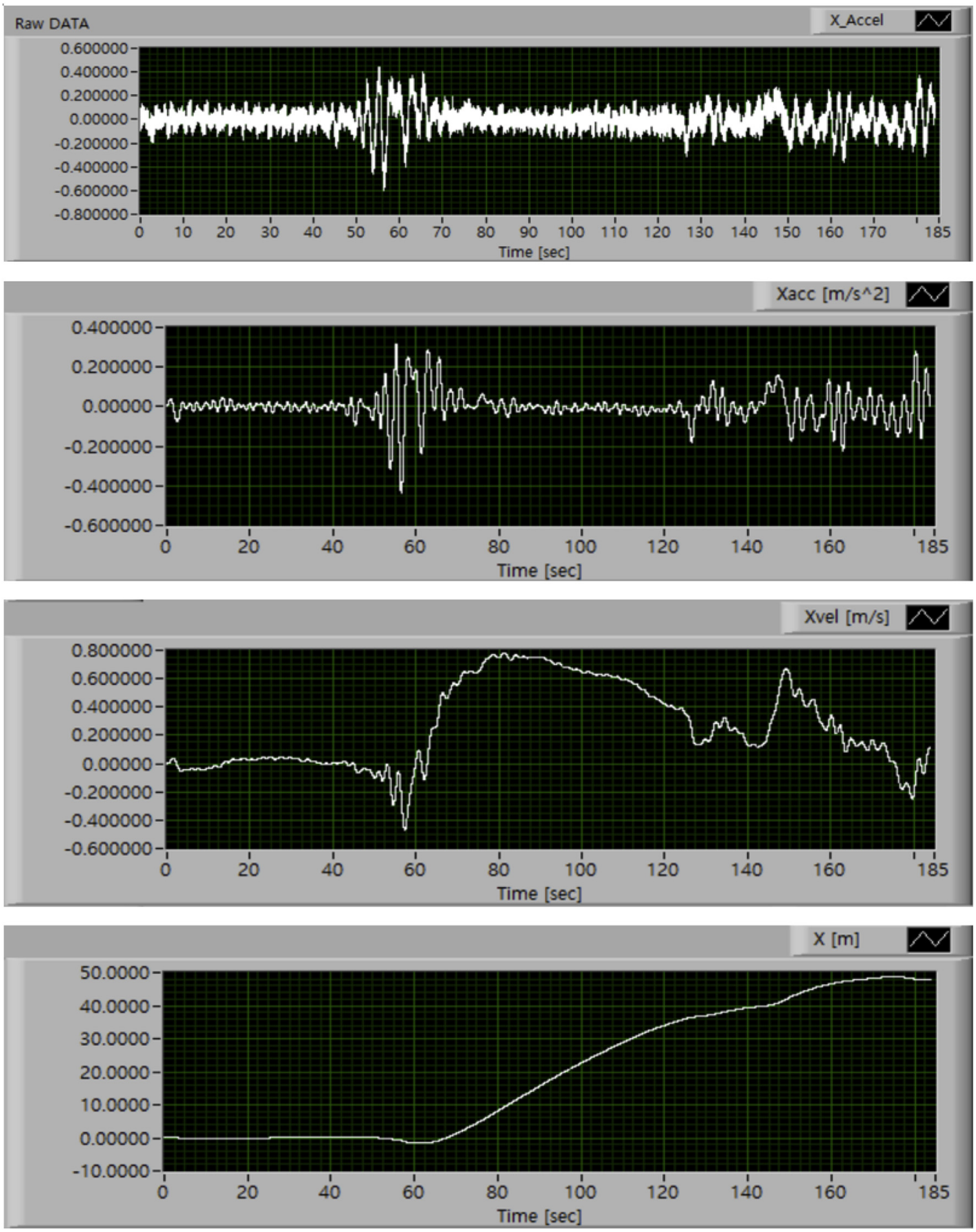

Fig. 4. Measured and filtered surge accelerations (top and the second) and computed surge velocities and displacements (third and bottom).

gravity of the ship as show in Fig. 7. The data measuring system using the commercial sensor are shown in Fig. 8. The principal characteristics of ARAON are summarized in Table 1 and the brief hull form of ARAON with hydrostatic data are shown in Fig. 9. The longitudinal and transverse radius of gyration to find the inertia matrix of the ship were applied 0.25Lpp and 0.3B in the computations, followed by the inclining test results.

3.2. Test ice loads of the Chukchi Sea in 2011

In the Arctic Ocean, thawing of ice occurs from June to August and freezing occurs from October; freezing starts when the surface of sea water loses energy to the atmosphere and temperature drops to around −1.89 °C.

This sea trial was conducted during the mid-summer, and most of the first-year ice was melting. Many melting ponds

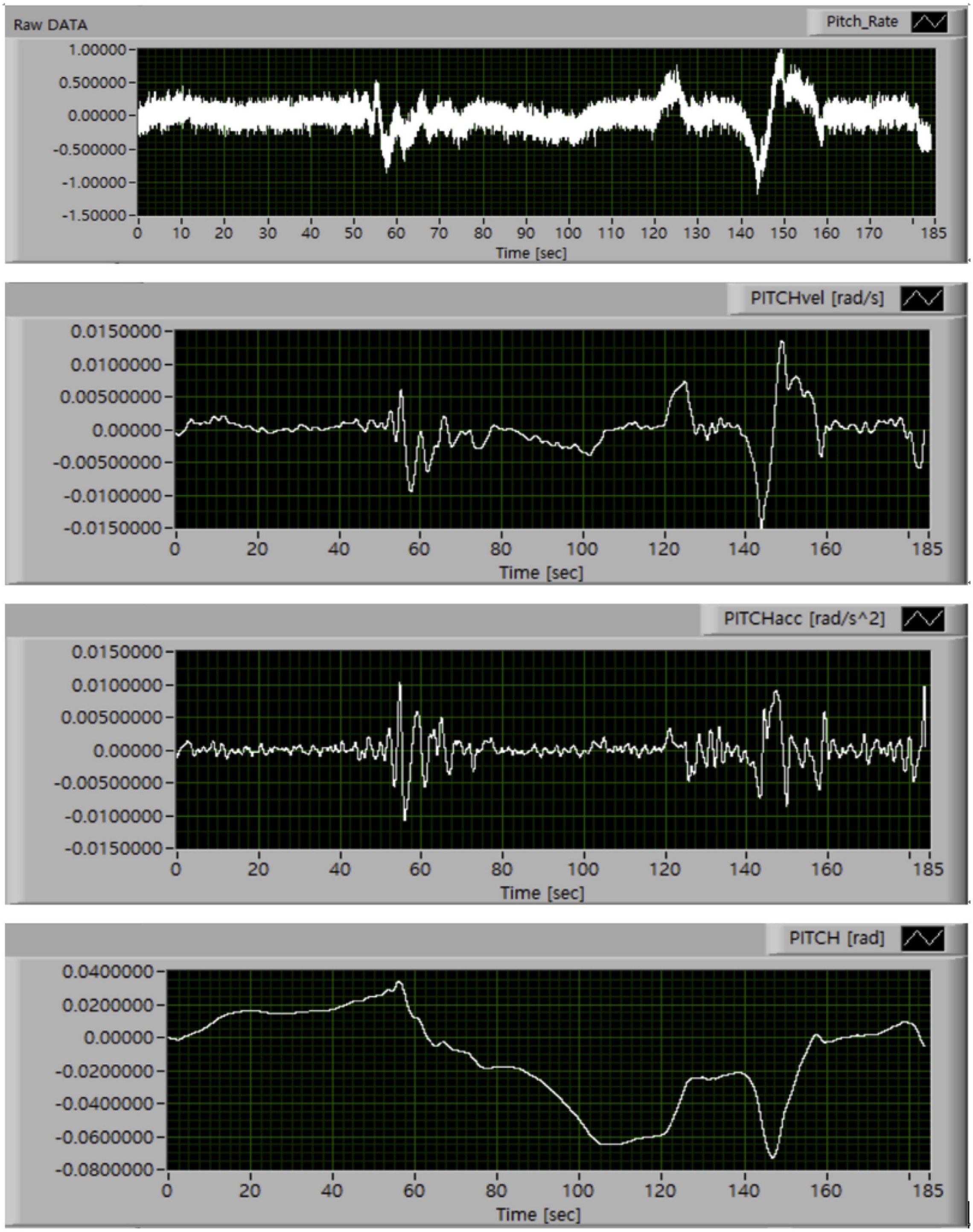

Fig. 5. Measured and filtered pitch rates (top and the second) and computed pitch accelerations and angles (third and bottom).

were observed on ice floes together with second-year ice of 2−4 m and ice ridges of 7−12 m.

Old Ice #1 in Fig. 10 is the first test ice floes during the Arctic navigation using ARAON on August 11, 2011; its width, length, and thickness were 45 m, 100 m, and 1.3−3 m, respectively, and second-year ice was largely distributed. The thickness of the starting part of the ice floe was 1.3 m, and it thickened toward the middle, which was 3 m (Fig. 11) (Jeong and Choi, 2012). (see Fig. 12)

We evaluated apparent conductivity of the sea ice to measure sea ice thickness, using drilling equipment (2-inch ice auger) and an electromagnetic induction instrument (EM31-MK2). These results are shown in Figs. 11 and 13.

Old Ice #2 in Fig. 12 was the ice floes of the second test during the Arctic navigation using ARAON on August 12, 2011. This was level ice with a width of 55 m, length of 110 m, and thickness at 1 m−1.69 m except around the 30 m area in Fig. 13. The two test ice floes were second-year ices,

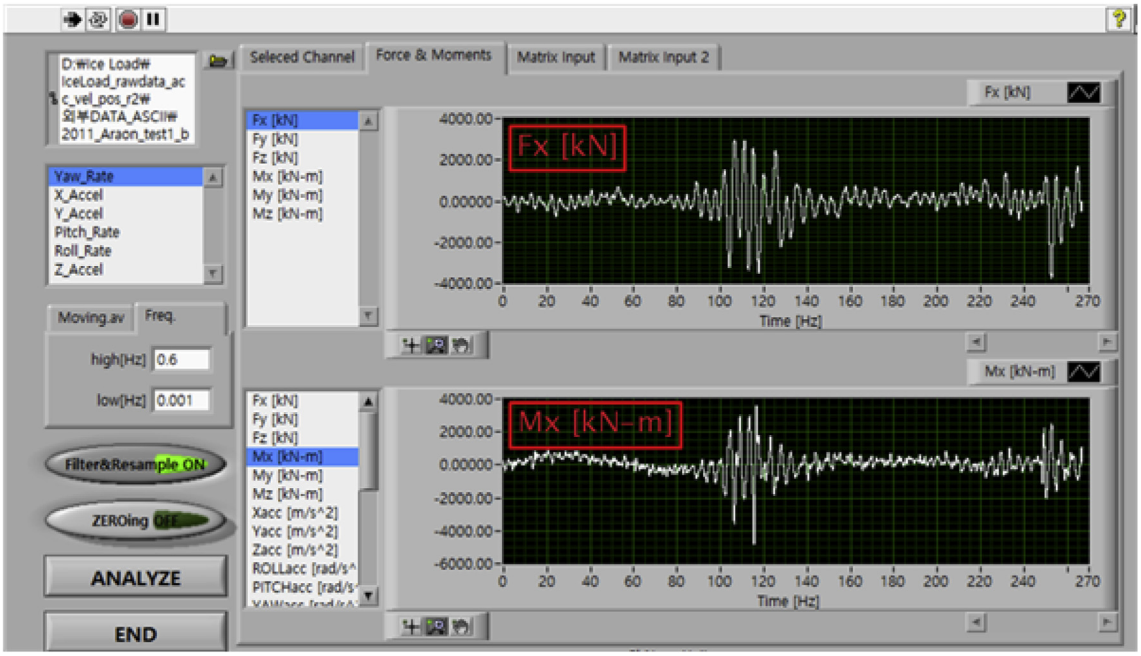

Fig. 6. Results of ice load analysis.

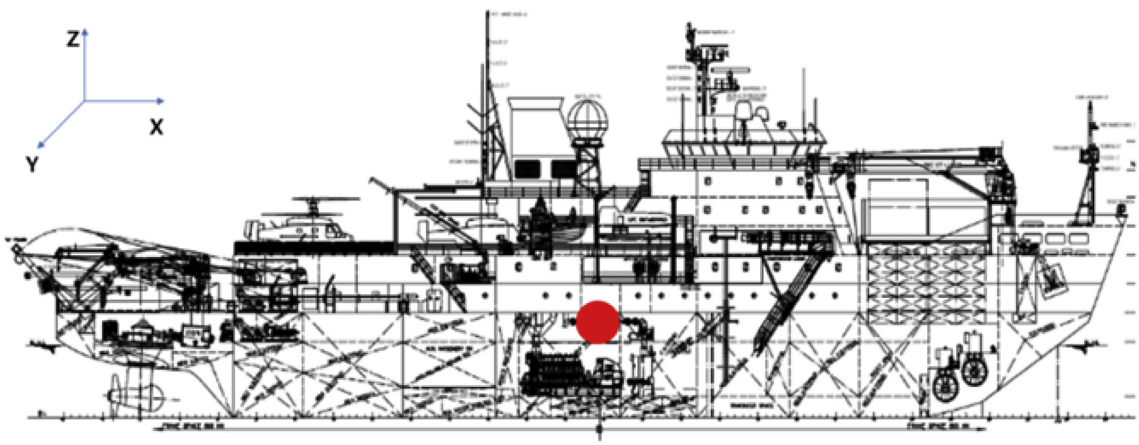

Fig. 7. Location of Motion Pak II.

and many melting ponds were distributed on their surfaces (Jeong and Lee, 2012).

3.3. Results of the global ice load analysis of ARAON

Figs. 14 and 15 show the 6 dof motion and the analyzed ice load of ARAON of old ice floe #1 and #2, respectively.

Ice thickness of the floe #1 in Fig. 11 shows double peak shape. First peak value was around 2.8 m and the second one was 3.2 m, respectively. In general, ice loads increases as the ice thickness increases, therefore, it was thought that the computed ice loads show similar trends. However, Fig. 14 shows somewhat different results. Comparing the motion data of ARAON and the calculated global ice load, all of the motions showed large fluctuations and the first high ice load was approximately 11 MN between 45 and 75 s. It is thought that ARAON approached the first thicker part of the test ice floe of thickness 3 m as shown in Fig. 11. Although the Araon passed through the thickset part of the ice floe after 100 s, computed ice load showed only 10 MN which is less than the former. One reason is the ice crack during the earlier ice breaking and the other is ice drift. It's because the old ice floe #1 was relatively small size and furthermore, the edges of ice floe were not bounded. Thus, ice load showed low peak value because of reduction of ice resistance. From the results, it is believed that all of the 6 dof motion affected the ice loads.

Fig. 15 shows ship motions and the ice loads on test ice floe #2. Considering the ice thickness of the ice floe #2 in Fig. 13 and the results of Fig. 14, ice thickness of the floe #2 is less than that of the floe #1. All the 6 dof motions at the ice floe #2 showed relatively small compared to those of the ice floe #1. The highest ice load was about 8 MN around 50−70 s and it is

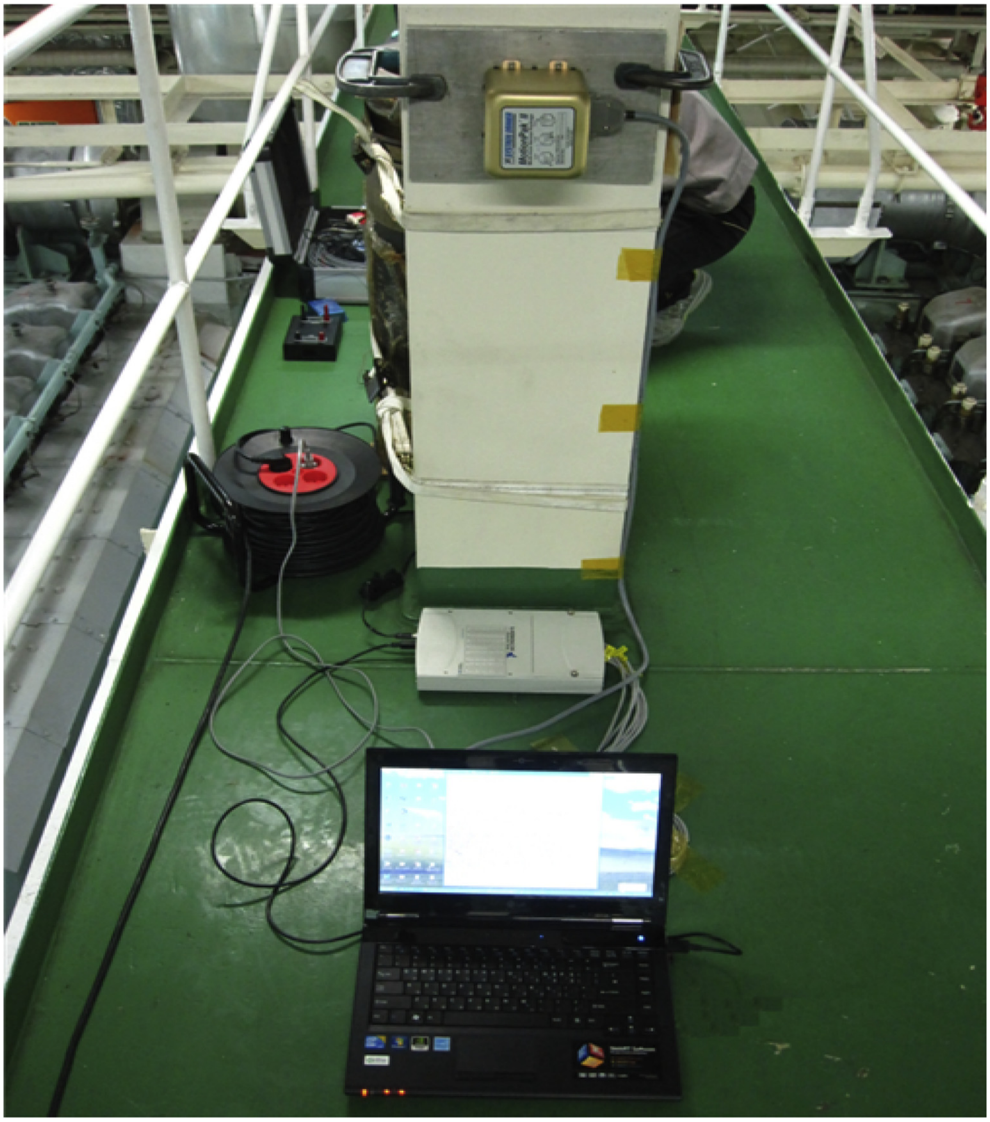

Fig. 8. Data acquisition system using Motion Pak II.

thought that the forces caused by the 6 motions mainly affect the ice loads. Also, the ice load showed another peak value about 7 MN around 150 s. Accordingly, the 6 dof motions of ARAON showed large fluctuations as shown in Fig. 15. This indicates that the examination of the overall ship motion is essential to estimate the ice loads.

Table 1
Principal characteristics of ARAON.

Principal characteristics	Dimension
L_{PP}	95 m
B	19 m
T	6.8 m
Displacement	7699 ton
GM_T	2.123 m
GM_L	83.734 m
LWL	102.585 m
LCG	46.457 m
KG	7.61 m

Maximum global ice load by the ice load analysis program was about 11 MN on test ice floe #1 and about 8 MN on test ice floe #2. Comparing with 17.3 MN analyzed by the LOUIS ice trial of Canada in 2003, the same order was obtained. Therefore, the global ice load analysis algorithm and the developed program by the authors were verified with reasonable accuracy.

Figs. 16 and 17 show the time history of the components of ice loads as well as total ice loads of a ship for old ice floe #1 and #2, respectively. Note that the scales of the components are different from the total ice loads. From the results, it is found that the vertical components are the main cause of the ice loads. When the ice loads increase, the components of the vertical force also show significant change.

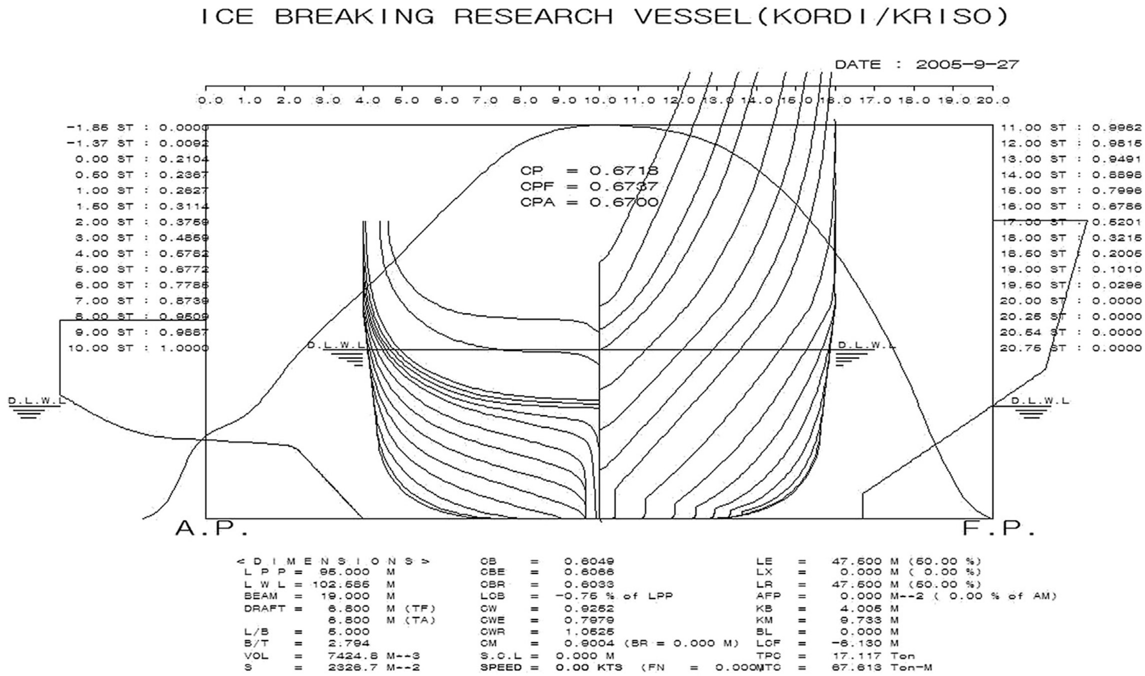

Fig. 9. Hull form of ARAON with hydrostatic data.

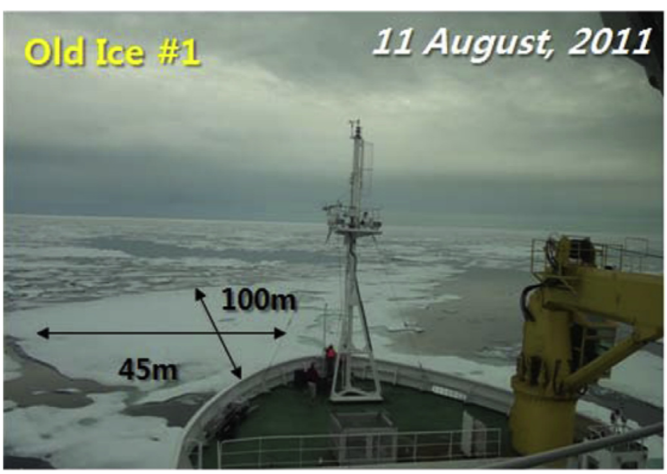

Fig. 10. First old ice floes during the field test (August 11, 2011).

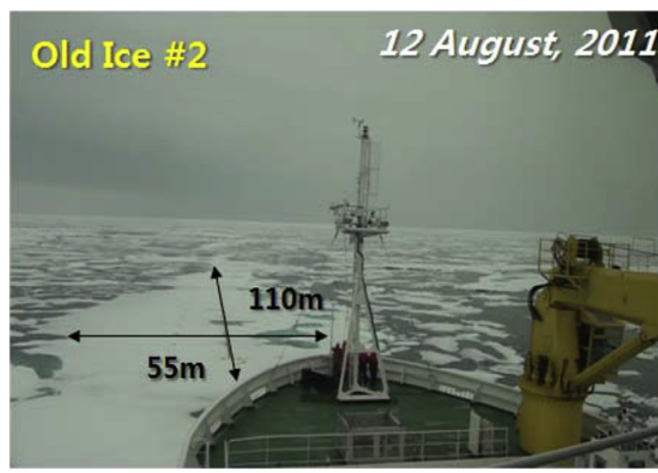

Fig. 12. Second old ice floes during the field test (August 12, 2011).

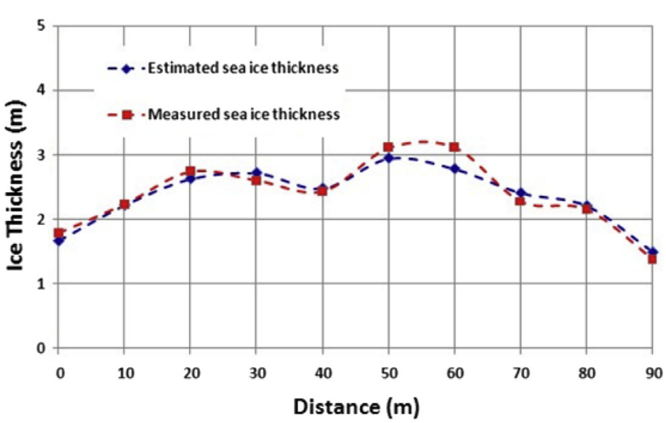

Fig. 11. Sea ice thickness profiles at ice floe #1.

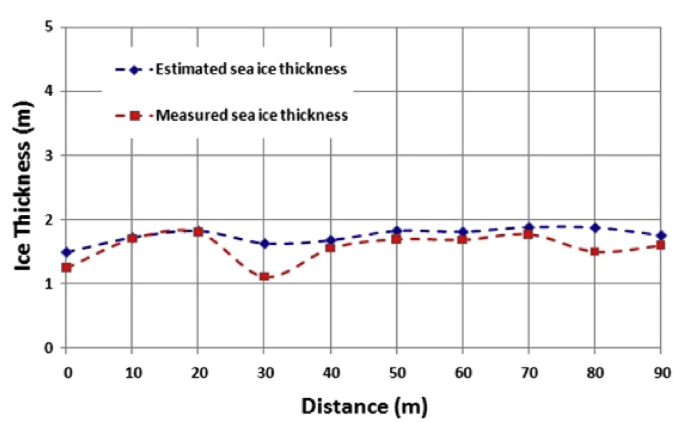

Fig. 13. Sea ice thickness profiles at ice floe #2.

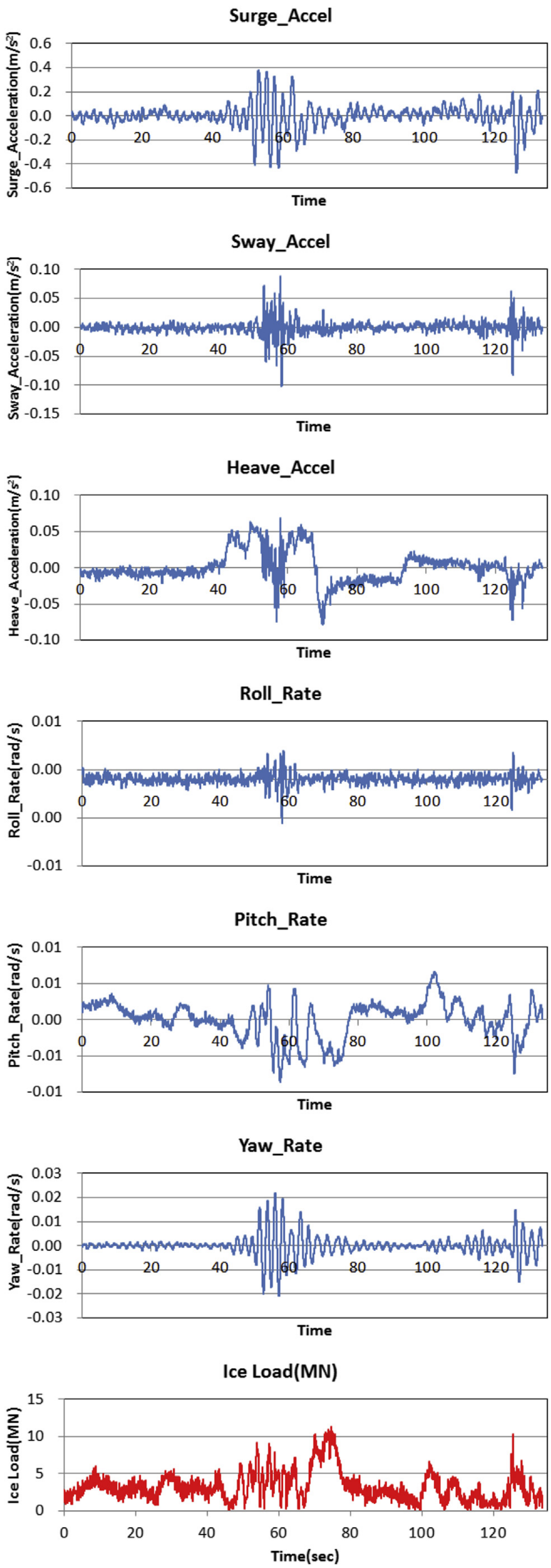

Fig. 14. Motions of ARAON during ramming old ice floe #1.

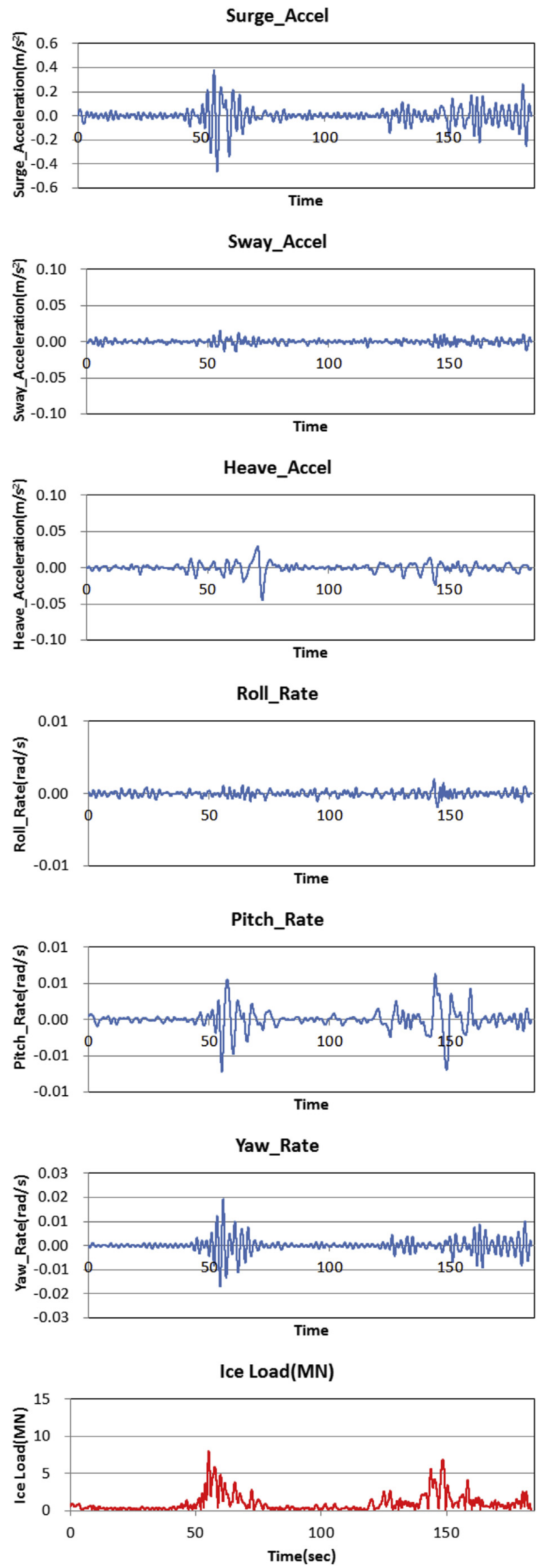

Fig. 15. Motions of ARAON during ramming old ice floe #2.

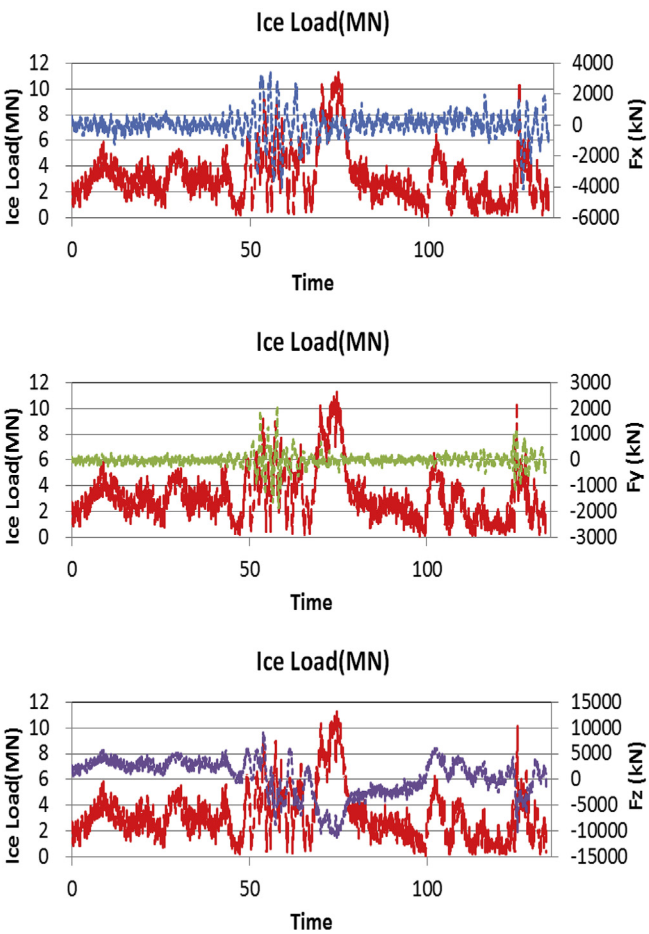

Fig. 16. Ice load & force of ARAON during ramming old ice floe #1.

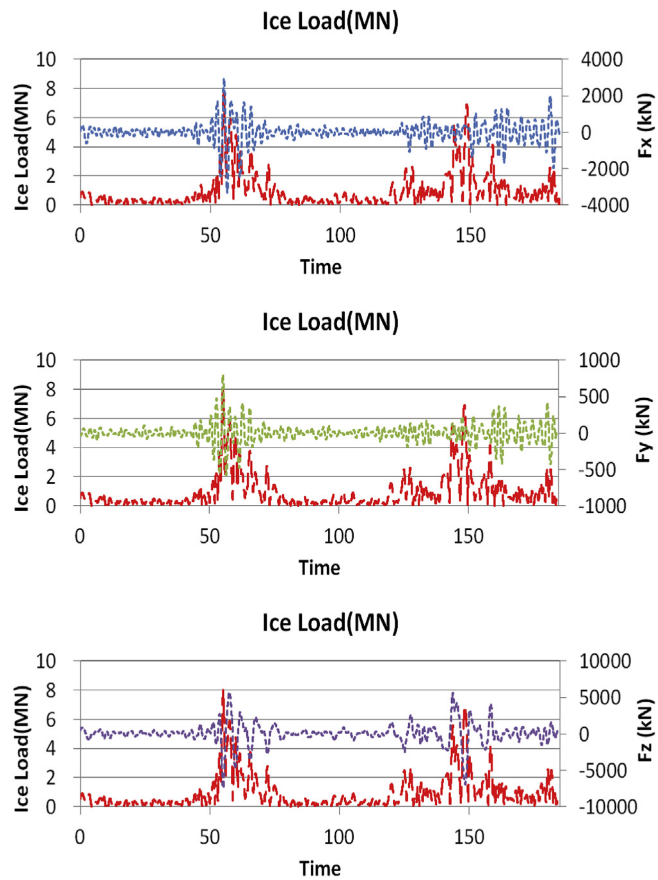

Fig. 17. Ice load & force of ARAON during ramming old ice floe #2.

4. Conclusions

The authors developed the ice load analysis program based on LabVIEW with signal processing of 6 degree of freedom motion data measured by commercial sensor, Motion Pak II. The developed system immediately analyzes ship motion data obtained during full-scale ice breaking or navigation and calculates ice loads. Using the compact system developed in the present study, it is possible to make comparisons between real-time ice load analysis and the results from field tests. Full-scale data are acquired while the ARAON rammed old ice floes in the high Arctic. Estimated ice impact forces for two representative events show about 8−11 MN when ships operate in heavy ice conditions.

In order to improve the accuracy of global ice load, precise motion data should be obtained above all. Further studies should be carried out to determine the optimum filtering method to remove noise, and in the process of spline resampling for the data processing of the measured data signals.

Acknowledgements

This paper was supported by research funds for the task “Ice performance test evaluation method and optimization technology (PNS184B)” of the Ministry of Trade, Industry and Energy's industrial original technology project “Polar class vessels' polar passage safe navigation technology and very low temperature ice performance test evaluation method”.

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