Design and Execution of Model Experiments to Validate Numerical Modelling of 2D Ship Operations in Pack Ice

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Abstract— This paper describes the design and execution of experiments to validate a Graphics Processing Unit based numerical modelling of ship operations in 2D pack ice. Using a polypropylene vessel and floes, ship-floe and floe-floe interactions are modelled in a model basin and recorded on camera. The video is processed using Image Processing Techniques to track individual floes (and the vessel) to calculate their position and velocity over time. These results are compared with those of a numerical simulation using identical initial conditions. Conclusions are drawn on the accuracy of the numerical model and several points of improvement are identified.

Index Terms— Ship-ice interaction, 2D Model Experiments, Image Processing.

I. INTRODUCTION

A ship travelling through pack ice induces a complex pattern of ship-ice floe and floe-floe interactions. Therefore, a proprietary numerical model of a ship operating in pack ice is being developed within the project Sustainable Technology for Polar Ships and Structures (STePS^2). Using the power of Graphics Processing Unit (GPU) computer technology, this model is designed to simulate a ship transiting through pack ice in hyper-real time [1], thereby enabling the study of ice loads in realistic scenarios.

The model is to be supported by and validated with field trials and model experiments. This paper describes a series of pilot experiments to validate the generic model functionality and to identify points of improvement.

II. GPU MODEL

This numerical model uses GPU computer technology, which enables it to do a very large number of parallel calculations and is especially suited to model ship-ice and ice-ice interactions.

The program uses event mechanics to simulate a vessel transiting through pack ice [1]. This approach enables the program to calculate a large number of interactions faster than real-time because each collision is seen as an event, of which the outcome is directly calculated from the input parameters, without calculating each step in between. This saves time and resources, enabling the model to do many calculations in a very short time.

Important to the design of the validation experiments is the understanding of the model input, mechanics and output. These are described in the following paragraphs.

A. Model Input

The model can simulate all transit scenarios in which both the ice floes and the vessel are modelled as convex polygons with less than twenty sides [1]. For numerical reasons, the bodies are not allowed to be in initial contact with each other and all objects and processes are two dimensional.

The floes in the model have three degrees of freedom: movement in x-and y-direction and rotation around the z-axis. The ship is restricted to one degree of freedom, movement in x-direction (forward movement). Fig. 1 shows the 2D concept and the axis used.

B. Model Mechanics

The movements of the floes and the vessel, position and velocity in the 2D space, are updated with every time step. Energy is lost by a simple drag model and by ice crushing impact forces [1]. Due to the strictly two dimensional character of the model, rafting and rubbling are excluded.

The vessel propulsion is modelled in two ways. Either, a constant speed can be given to the vessel. or a simple propulsion system can be used to simulate ship behaviour in pack ice. The net thrust from this system is combined with a water resistance model to settle on a open water speed. Due to the collisions with the ice floes, the actual speed in the pack ice will settle at a lower speed.

C. Model Output

The model produces a graphical output of the ship transiting through the ice. Also, it is able to track the positions and velocities of all the bodies involved at every time step.
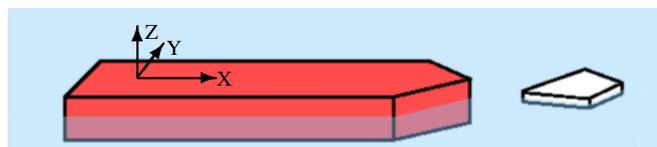

Fig. 1.   Schematic view of the 2D concept used in the model.

III. Model Experiments

The model experiments are used to validate the numerical model by closely reproducing its 2D mechanics. This is done by executing and measuring simplified ship-floe and floe-floe interactions at model scale and under controlled conditions.

The main goal is divided into five subgoals:

  A To develop a repeatable method of creating ship-floe and floe-floe collisions in the lab.

  B To develop a reliable method to register and measure positions and rotations over a given period of time.

  C To develop a method to analyse and quantify the results.

  D To develop a method to compare the results to a numerical simulation.

  E Validate the numerical model and make recommendations.

A. To develop a repeatable method of creating ship-floe and floe-floe collisions

The experiments are carried out in a transparent acrylic tank, located in the marine laboratory of Memorial University of Newfoundland's Engineering and Applied Sciences Faculty. The tank measures 7.9 meter in length, 1.47 meters wide and 0.97 meters deep and the walls are constructed out of acrylic glass to enable an all-round view, as is shown in Fig. 2.

The ship and the floes are constructed out of polypropylene, with a density of 905 kg/m^3, which is close to the average ice density. Polypropylene is a relatively hard material, which makes the collisions completely elastic, guarantees rigid body behaviour and is wear resistant. Although natural ice does not share these properties, polypropylene is close to the boundary conditions of the numerical model, which (at the moment) still assumes rigid body behaviour and completely elastic collisions. Finally, the material is easy to machine and can be reused many times, which makes is an ideal material for tank testing.

Due to the two dimensional restriction of the numerical model, the vessel and floes do not change shape over their depth. The floes are 12.7 mm thick (1/2 inches) and randomly
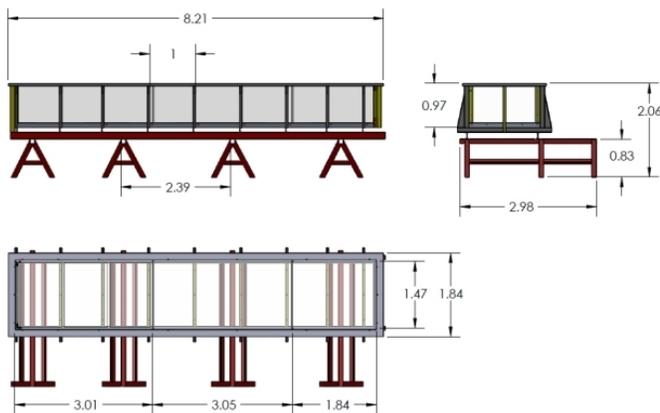
shaped into convex polygons with three to six sides. The vessel itself is made out of a 50.8 mm thick (2 inches) sheet of polypropelyne, has a overall length of 0.91 m (36 inches) and a beam of 0.178 m (7 inches). A small cargo hold is machined into the vessel to reduce the weight and increase the freeboard. This is enables the ship to go faster without taking green water and reduces the chance of floes taken aboard. Fig. 3 shows the vessel with her main dimensions.

The vessel is controlled using an overhead carriage, which is connected to the beam of the vessel using an aluminium rod. The carriage is suspended and moved by a wire loop, mounted over the centerline of the tank. The wire is driven by a variable speed motor, which, which is controlled by a DC controller. This layout is shown schematically in Fig. 4. Unfortunately, the overhead carriage is not stiff enough to restrict all the vessel's movements in sway and yaw direction. Therefore, the criteria used in the model (the vessel only moves in x-direction) is not entirely met. However, the error introduced is relatively small, as is shown in subsection E.

B. To develop a reliable method to register and measure positions and rotations over a given period of time

The movements of vessel and the floes in the tank are recorded on camera during the entire experiment. This camera is located under the tank and looks up through the acrylic bottom of the tank. This way, the camera is easier to access and less likely to get damaged than in an overhead position. On the other hand, the camera's view is limited to one segment of the tank, due to the structural support of the acrylic tank. However, this is not a problem at the current scale of the experiments.

Also, due to the camera placement under the tank, some refraction takes place when the light travels from the water, through the acrylic glass to the air. Theoretical refraction calculations have been performed and showed that due to this specific combination of water, acrylic and air only a neglectable refraction occurs.

The floes and ship are outfitted with targets, so they can be tracked using image processing software. A "bow tie" target is designed which differs a little from the typical cross-pattern, as is seen in Fig. 5. This design is chosen because it presents a single large coloured surface (a cross-pattern design has two), which makes it easier to find the target and remove computational noise. Also, the design makes it possible to

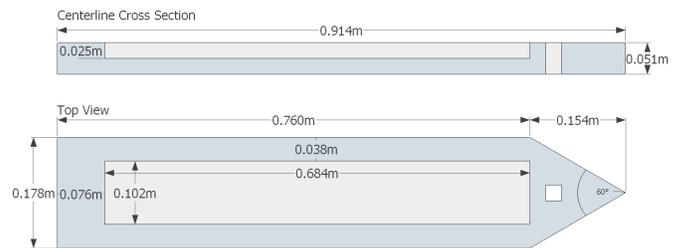Fig. 2.   Drawing of the acrylic tank, dimensions are in meters.

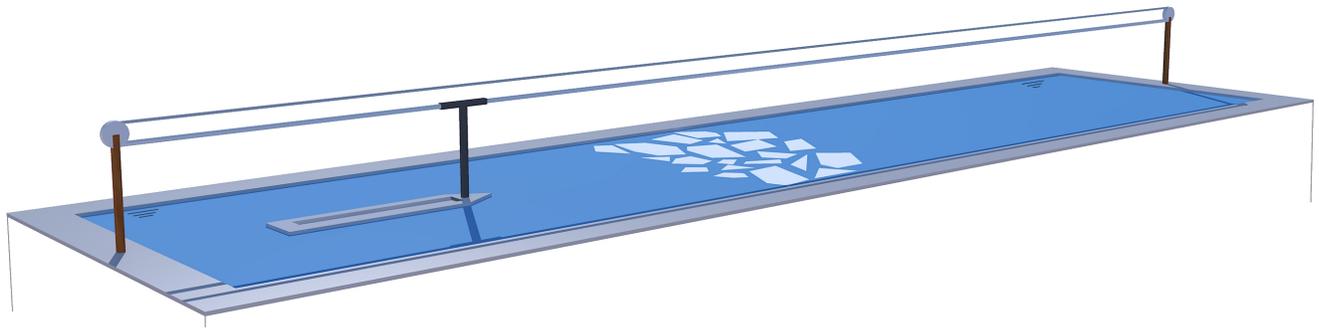Fig. 3.   Design drawing of the vessel used in the experiments.

Fig. 4. Schematic experiment layout, showing the vessel, some floes and the towing carriage above the tank.

recognise the direction of the floe and thus calculate the rotational velocity during the experiment.

C. To develop a method to analyse and quantify the results

The method used to analyse the data is based on image processing techniques. In each and every frame of the video, the computer program searches for the coloured targets by filtering out all other colours. The exact location and orientation of the target is calculated and saved for each frame in the video. The velocities are calculated by comparing the change in target position between frames, with a frame rate of 30 frames per second.

The camera footage, Fig. 6 shows one frame, is processed using a Matlab script. First of all, the user interface enables the user to crop and rotate the video. By doing this, all the parts of the image outside of the tank boundaries are removed and the sides and top of the image can be used as a reference frame to determine the exact location of the floes and the vessel. Also, the user is able to determine which part of the video is processed and which colours are tracked.

The processing starts with separating the colour information (rgb or red, green and blue) into separate matrices. Next, a colour threshold is used to find the colour targets. This threshold sets the value of the pixel to 255 if the colour is within the threshold and to 0 if it is not. Combining the information of all three images (red, green and blue) gives Fig. 7(a). The white areas are within (all) the thresholds, the coloured images are within one or two rgb values and the black areas are outside the thresholds. This colourful image is used to calibrate the threshold, as the colours show which part of the image has to be altered. Finally the image is converted into a binary image, Fig. 7(b), for further processing.
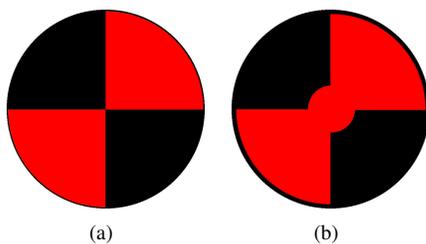
Using the build-in functions *filling* and *area* are used to respectively fill gaps in the "bow tie" and remove noise (small areas which fall within the threshold). The result is shown in Fig. 7(c). Using this image, the centroid and orientation of the "bow tie" is calculated and saved. Next, the following frame is analysed in the same way.

The colours most suitable for this tracking method are blue, yellow and red. Green is also usable, although it is quite close to the shade of blue. Using this method, two targets of the same colour cannot be tracked at the same time, because the program will just average the two and place the centroid between targets. However, for the first validation of the model, tracking only four targets (the ship and three floes) suffices.

D. To develop a method to compare the results to a numerical simulation

The starting position of all the floes, taken at the time of first ship contact, is manually converted into an .ice-file. This file type is used as the input for the numerical simulation and contains all the positions and initial velocities of the bodies (vessel, floes and sides).

The numerical model processes the input file and provides the position and velocities for each floe and the vessel over time, both in a graphical way (a video) and a numerical way. The position and velocity vectors are compared with those from the experiment, creating a plot with overlaying
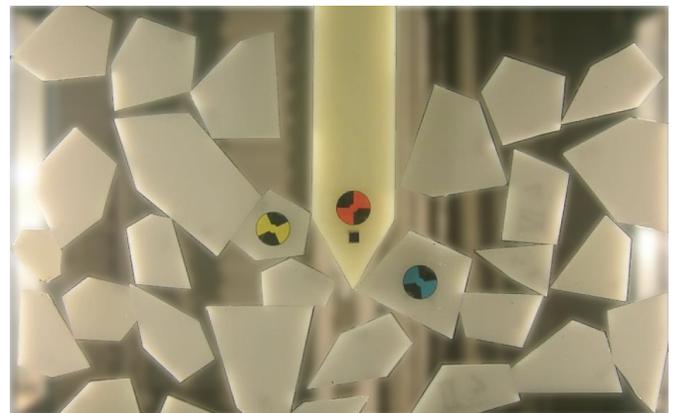

Fig. 5. Cross design (a) and Bow Tie design (b).

Fig. 6. Bottom-up view of floes and a ship, outfitted with "bow tie" targets.

(a) RGB Thresholding

(b) Binary Image with noise

(c) Final Image

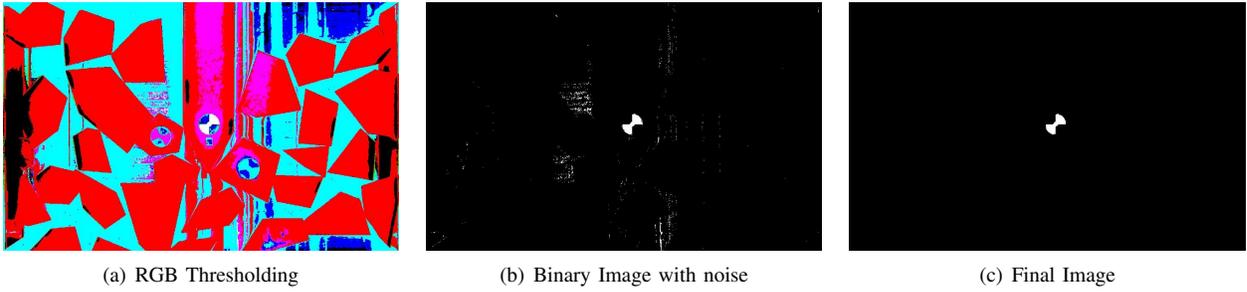Fig. 7. Three stages of thresholding. First selecting areas based on rgb-colour, coverting them to an binary image and removing the noise.
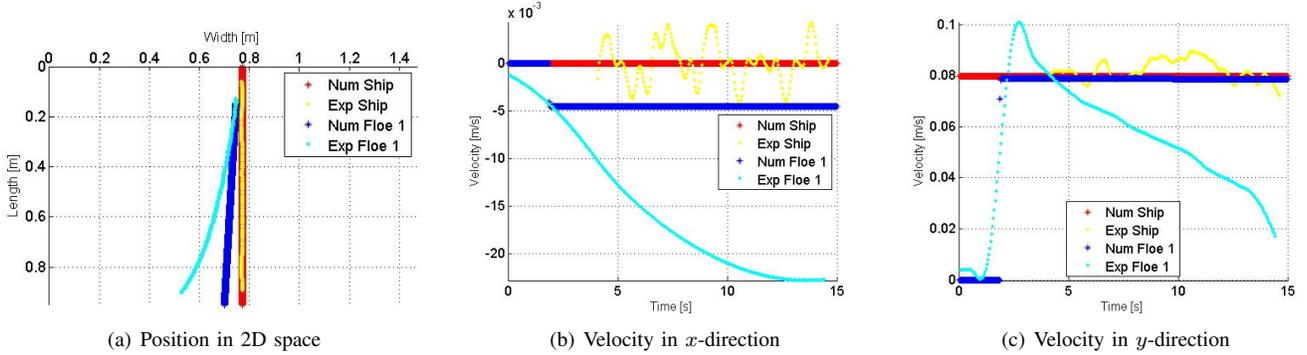

(a) Position in 2D space

(b) Velocity in x-direction

(c) Velocity in y-direction

Fig. 8. Comparison between the numerical model (Num) and experimental data (Exp) of a one ship and one floe situation.

(a) Position in 2D space

(b) Velocity in x-direction
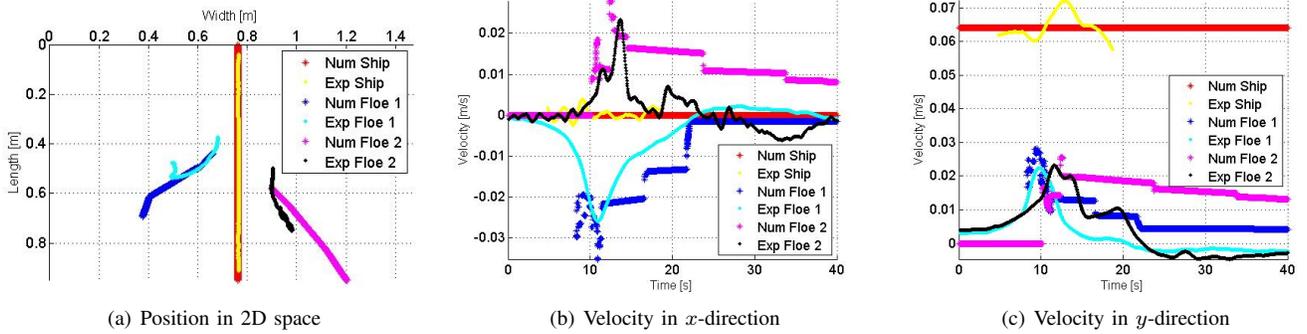

(c) Velocity in y-direction

Fig. 9. Pack ice comparison, numerical model (Num) and experimental data (Exp).

directions and velocity profiles. A situation with one floe and the vessel is shown in Fig. 8 and a pack ice simulation is shown in Fig. 9. Both figures display the position (a), velocity in x-direction (b) and velocity in y-direction (c). The experimental data contained some noise and is filtered. Also, due to the resolution of the camera and the thresholding method, a change in centroid of just a couple of pixels will induce irregularities in velocity.

Also, the ship in the experiment is able to sway a little, which is visible on the graphs. However, these disturbances are relatively small compared to the floe velocities.

Finally, the graphical output of the numerical model enables the comparison with the experiment data by placing both videos next to each other, as is shown for four frames in Fig. 10.

E. Validate the numerical model and make recommendations

The model is validated in a qualitative way, visually comparing the data from the experiment with the numerical simulations. Conclusions can be drawn because the data sets are obviously different. As the model improves, a more quantitative comparison method will be developed whereby position and velocity differences are measured.

Based on the comparison of four experiments with only one floe and the vessel and one experiment with thirty floes and one vessel the following conclusions are drawn:

1) The hydrodynamics of the floes (water drag, added mass and wave damping) are insufficient in the numerical model. This shows in the numerical simulation through floes (in open water, see Fig. 8) loosing little velocity over time compared to the experiments. Since the model is used to model pack ice, open water behaviour is of less importance than collisional behaviour. However, it

does influence the speed at which the floes collide and thus influences the "chain of events".

2) The numerical model, in pack ice situations (Fig. 9), shows positions and velocities at the early stage of the simulation which are closer to the experimental values. This leads to the conclusion that the collisions are modelled more realistically. However, over time the average velocity of the floes in the numerical model is still higher than the velocity of the floes in the experiment.

3) In the experiment, it is noticeable that the surface tension makes floes stick together, influencing their motions and speeds. It is clearly seen how the floes follow a different trajectory in Fig. 9(a) and 10. This is not incorporated in the model (because in large scale, it is neglectable) but is important in the scale used for the experiments.

IV. CONCLUSIONS AND RECOMMENDATIONS

The numerical model shows the general trends which are also visible in the experimental data. Especially in the pack ice scenario, it shows realistic behaviour. However, there are some points where the model needs improvement and where the data collected in this research can prove useful in improving the model. First of all, the open water behaviour of the numerical model is not accurately predicted, resulting in a unrealistically high open water velocity of the floe. The collisions, however, tend to be modelled more realistically and follow the general trend seen in the experiments. Finally, due to the (small) scale of the experiment, surface tension is an important parameter in the floe behaviour, while it is not incorporated in the model.

A. Recommendations for further research.

The next step should be a calibration of the numerical model. The critical points identified should be individually improved/calibrated using the data collected from these experiments or by designing dedicated experiments to investigate each particular parameter. One could think of calibrating the water drag, added mass and wave damping or collisions.

In the end, it is recommended to rerun the exact same simulation as described in this paper, using the calibrated model. This way, the differences due to the calibration are easy recognisable.

B. Recommendations for future improvement

If more and larger scale ship-floe and floe-floe collision experiments are executed in the acrylic tank, some improvements are recommended. First, the camera position does not allow a larger view from underneath the tank. Therefore, it could be considered to place the camera at the far end or above the tank. Also, for more accurate ship movements (which are more in line with the assumptions in the model) the overhead carriage should be improved to resist sway and yaw movements.

(a) t ≈ 4 sec

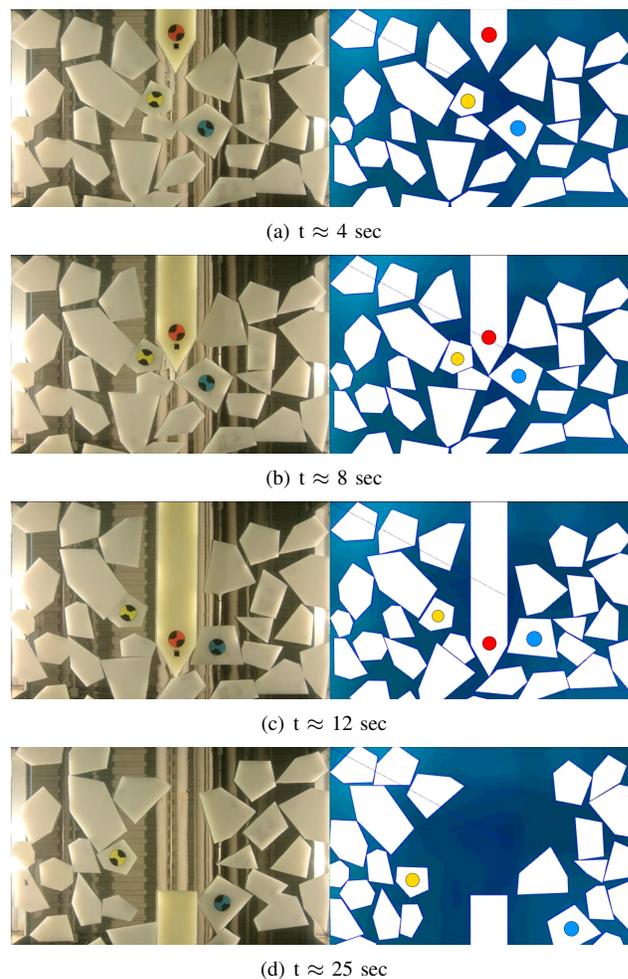(b) t ≈ 8 sec

(c) t ≈ 12 sec

(d) t ≈ 25 sec

Fig. 10. Comparison between the numerical simulation and the experiments of a single case. The bodies in the numerical model are manually given coloured dots for convenience.

From a numerical modelling point of view, the procedure to make an .ice file should be simplified. Presently, this task is elaborate and error sensitive. It is recommended to develop an automated method to read images and write the .ice-file.

Finally, as the model improves, a more quantitative method is needed to compare the trajectories between the experiment and the numerical data.

REFERENCES

[1] Claude Daly and Shadi Alawneh and Dennis Peters, and Bruce Quinton and Bruce Colbourne, "GPU Modeling of Ship Operations in Pack Ice", International Conference and Exhibition on Performance of Ships and Structures in Ice (ICETECH) 2012, Banff, Alberta, Canada.