STYRELSEN FÖR

VINTERSJÖFARTSFORSKNING

WINTER NAVIGATION RESEARCH BOARD

Research Report No 94

Teemu Heinonen

NOTCH TOWING OPERATIONS: FULL SCALE MEASUREMENTS AND OBSERVATIONS

Finnish Transport Safety Agency

Finnish Transport Agency

Finland

Swedish Maritime Administration

Swedish Transport Agency

Sweden

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In this report no 94, the Winter Navigation Research Board presents the results of the research project NotchTowing. Full-scale measurements of the forces acting on the towing line were made on board ice breaker Kontio in the spring 2016. In total 21 towing events were recorded.

Apart from the forces acting on the towing line, also contributing factors for the load levels and suitability of different merchant vessel types to notch towing were investigated. The results can be used to develop recommendations for notch towing operations and for ship design and rule development purposes.

The Winter Navigation Research Board warmly thanks Teemu Heinonen for this report.

Turku

October 2017

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Notch Towing Operations:

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1. Introduction and objectives

The Finnish-Swedish Winter navigation board financed Aker Arctic to perform full-scale measurements on notch towing operations.

In difficult ice conditions, especially with ice compression, the merchant ships are occasionally unable to follow the icebreaker with their own propulsion power. Therefore it is necessary for the icebreaker to tow the merchant vessel. It is believed that notch-towing operations will increase in the future as the merchant vessels' engine powers tend to decrease due to emission regulations.

The towing operations require skilled crews and can be somewhat risky as high forces act in the towing line and also there is a risk of collision. However, relatively little is known about the forces acting during the notch towing operations.

The purpose of this study is to investigate the notch towing operations: gather full-scale data of the forces acting in the towing line and find contributing factors for high/low loads and investigate how different merchant vessels apply for notch towing.
The findings can be used for ship design/rule development and also for recommendations & guidelines for towing operations.

Measurements were performed onboard Finnish icebreaker Kontio during winter 2016 at the Bay of Bothnia. Kontio was chosen as the measurement ship because it usually has a high number of towing operations during the icebreaking season. In addition, Kontio along with its sister ship Otso are normally the first ships to start the icebreaking season and the last ones to return which will further increase towing events.

The measurement equipment were installed to IB Kontio on 9.3.2016. Aker Arctic's personnel were onboard the vessel during 9.-19.3.2016 performing measurements. After this, the measurement equipment was left onboard to log autonomously. Totally 21 towing events were recorded during the measurement period.

2. Notch towing

In notch towing operations the icebreaker tows the assisted vessel. Towing is performed in situations when the assisted vessel gets stuck in ice or otherwise cannot keep reasonable speed during the assistance. The icebreaker reverses to the assisted vessel and the towing cables are attached to the bollards of the assisted vessel. The bow of the assisted vessel is inside a notching fork of the icebreaker. Usually the icebreaker requests that the assisted vessel uses full power during the towing operation in order to have sufficient assistance speed. Normal assistance speed in the Baltic Sea for Finnish icebreakers is above 10 knots.

The towing arrangement of icebreaker Kontio and more details on how towing is performed are presented in chapter 3.1.

Figure 2-1: In the upper figure the Finnish icebreaker Urho tows a merchant vessel outside Oulu, winter 2014. In the lower figure IB Kontio is towing a general cargo vessel during the 2016 measurement campaign.

3. Icebreaker Kontio

Measurements were performed onboard Finnish icebreaker Kontio. IB Kontio is built by Wärtsilä Helsinki shipyard in 1987. The main parameters of the vessel are presented in Table 3-1. The vessel has a conventional diesel-electric propulsion with two shaftlines, two fixed-pitch propellers and two rudders.

Table 3-1: Main parameters and propulsion parameters of IB Kontio.

L [m]	99.0
B [m]	24.2
T_{max} [m]	8.0
P_D [MW]	2 x 7.8
$T_{B,ahead}$ [ton]	160.5
$V_{80\ cm\ level\ ice}$ [kn]	~11.5
$V_{OW,ahead}$ [kn]	~18

Figure 3-1: Icebreaker Kontio moving in channel.

3.1 Towing arrangement in IB Kontio

The towing arrangement in IB Kontio is following:

- Towing winch (Rauma Repola TW600H) is located at winch room at the stern part of the vessel. The nominal pull force of the winch is 60 ton and the nominal hauling speed is 0.27 m/s.
- Towing winch has a hydraulic brake and during towing the hydraulic brake is locked. The maximum brake hold power is 220 ton. However, the brake load is set usually lower so that it starts to slide at considerably smaller loads. This is done in order to reduce the loads and therefore reduce the risk of breaking of the towing line. The brake power can be adjusted from the bridge during the towing and normally the brake is set to start sliding at ~100 ton load.
- The winch operates a 60 mm diameter steel main towing cable/line. The brake load of the main cable is ~225 tons.
- The main towing line goes through a large roller fairlead (Figure 3-3 & Figure 3-4) which keeps the towing line in suitable angle for the winch and prevents the towing line from being in contact with the winch room walls.
- At the end of the main towing line is a strop in which a large single block/pulley is attached. A secondary towing line (40 mm) runs through this block and the secondary towing line is attached to the bollards of the towed vessel through two chocks. The breaking load of the secondary towing line is 112 tons and it is designed to fail before the main towing line as it is in angle. The secondary line should go through two chocks located at the sides of the center line, otherwise it is possible that the main towing line could fail instead of the secondary line.
- At the very stern of the icebreaker is located a towing fork. The bow of the towed vessel is fitted inside the towing fork. However, depending on the size and the bow shape of the towed vessel, it is possible that a small gap is left between the towing fork and the bow of the towed vessel. This is typical especially with vessels with bulbous bows which cannot fit inside the towing fork. In addition, if the assisted vessel is heavy, a small distance is required in order to improve manoeuvrability: the stern of the icebreaker has to be free as the steering is done with rudders located at the stern. On the other hand, the downfall of the gap between the vessels is that it allows the merchant vessels bow to hit/push other “cheek”/side of the towing notch. This will start to turn the icebreaker and makes steering difficult.
- Typically the towing is handled by two persons: the helmsman who steers the vessel and the officer who handles the propulsion power and the winch.


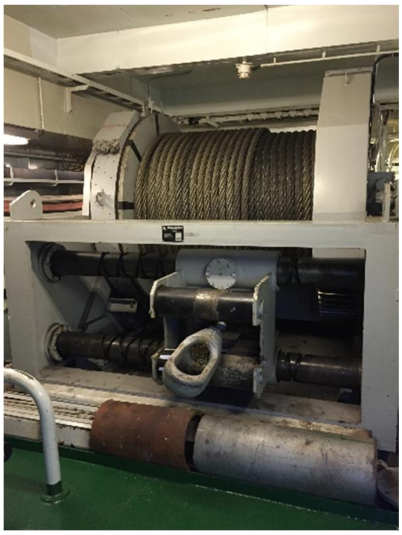

Figure 3-2: Left picture: the winchroom is located at the right side of the picture. The roller fairlead of the towing line is located at the left side. Right-side picture: The towing winch.

Figure 3-3: The main towing line coming through the roller fairlead. The secondary towing line goes through the orange block.

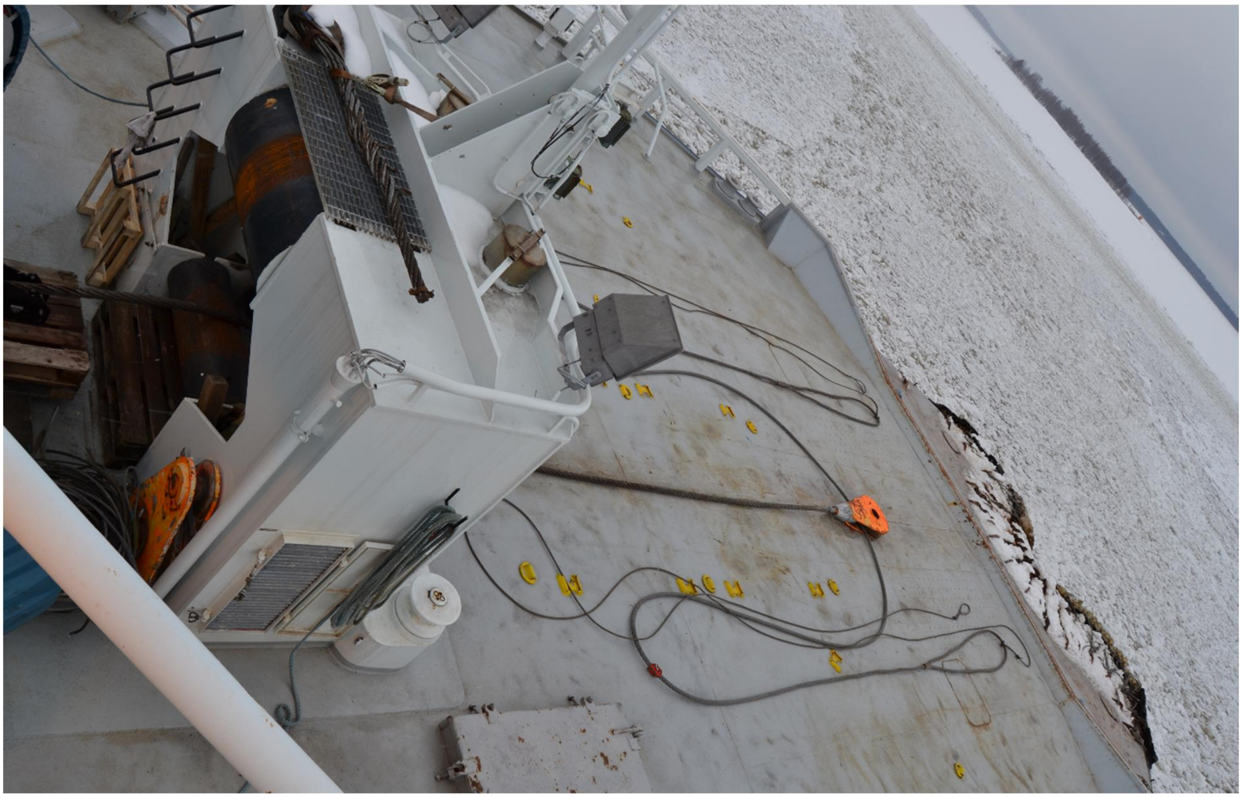

Figure 3-4: The main towing line coming through the roller fairlead. The secondary towing line goes through the orange block. The towing fork is located at the very stern.

Figure 3-5: The bow of the cargo vessel is fitted inside the towing fork of icebreaker.

Figure 3-6: A relatively large loaded 6000 DWT general cargo vessel being towed. A small gap is left between the tow vessels in order to allow the stern of the icebreaker to turn/move. However, the gap also allows the assisted vessel to push the sides of the towing fork which will rotate the icebreaker.

4. Measurements

The towing line force was measured with a 250 ton running line monitor which was installed between the winch room and the roller fairlead of the towing cable. The cable runs through the running line monitor and compresses against the instrumented wheels inside the monitor. The monitor was calibrated against a regular force transducer before the measurement campaign by the manufacturer.
In addition to the towing line force measurements, navigational data and propulsion data of the icebreaker were measured. Also a small portable GPS was installed to the bow of towed merchant ship. A summary of the measured quantities are presented in *Table 4-1* and *Table 4-2*. In addition to the measurements, the towing operations were videotaped. Measured quantities from different sources were joined together based on the timestamp.

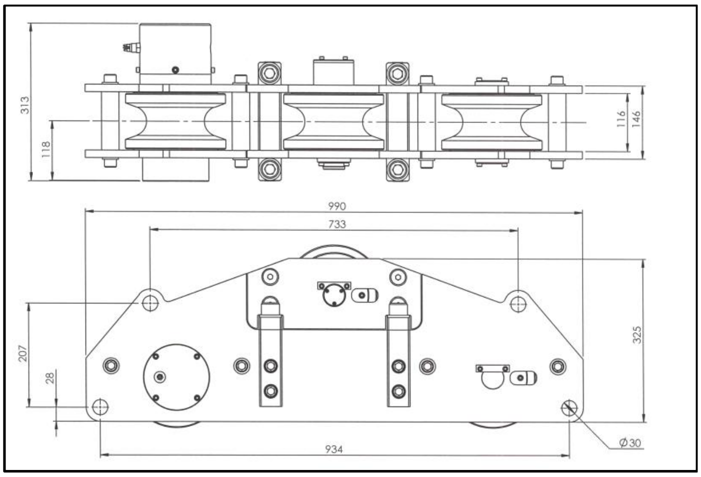

Figure 4-1: The running line monitor consists of the three wheels which result a small angle to the cable. As the cable tightens, it compresses against the upper wheel which is instrumented.

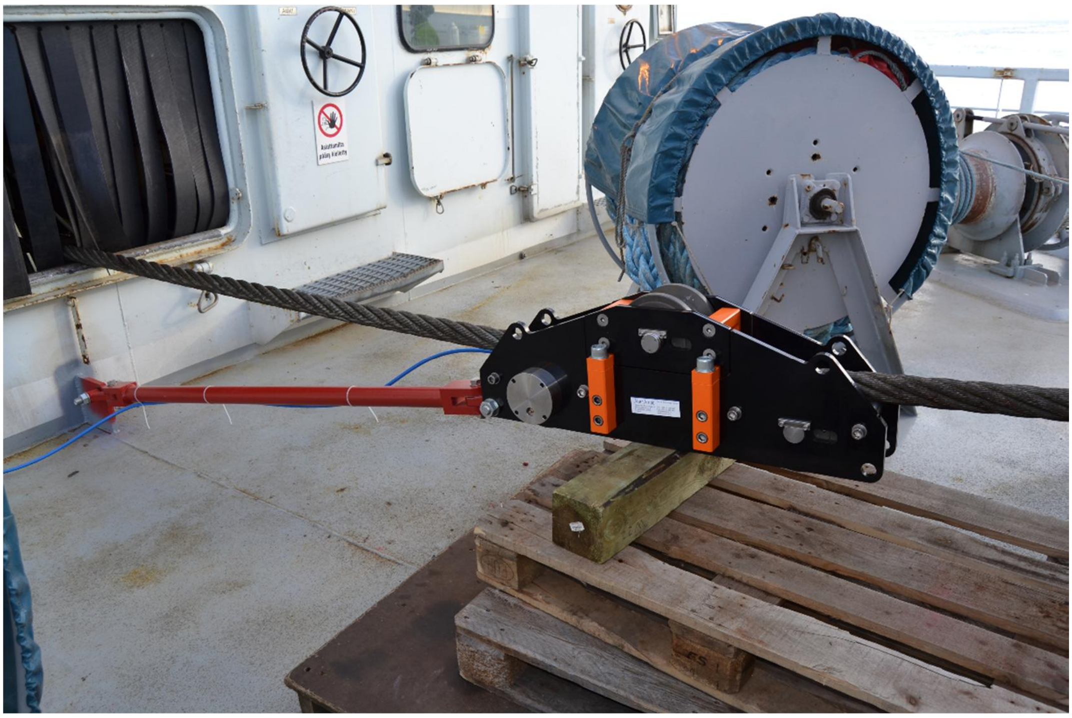

Figure 4-2: The running line monitor was installed next to the winch room with a jointed bar.

Table 4-1: Measured quantities from the icebreaker.

Quantity	Where/system	Frequency [Hz]
Towing line force	Running line monitor	130
Towing line length	Running line monitor	130
Propulsion power	ABB panel	1
Lever reference	ABB Panel	1
Propeller RPM	ABB Panel	1
Propulsion motor torque	ABB panel	1
Rudder angle	Ship System/Consilium	1
Position	Consilium ECDIS	1
Speed over ground	Consilium ECDIS	1
Course over ground	Consilium ECDIS	1
Heading	Consilium ECDIS	1
Relative wind speed	Consilium ECDIS	1
Relative wind direction	Consilium ECDIS	1

Table 4-2: Measured quantities of the assisted vessel.

Quantity	Where/system	Frequency [Hz]
Position	Portable GPS	1
Speed over ground	Portable GPS	1
Course over ground	Portable GPS	1

In addition to the measurements, information of the assisted vessel was gathered. Following data was obtained:

- Ship name
- Ship type
- Ice class
- Built year
- Propulsion power [kW]
- Length [m]
- Breadth [m]
- Design Draft [m]
- Current Draft [m] (if available)
- Loaded/Ballast?
- DWT
- Bow type
- Max. open water speed [kn] (if available)

4.1 Limitations of the force measurements

It should be noted that the towing line force measurement was done behind the roller fairlead of the towing line. It is likely that due to friction the fairlead affects the force acting in the towing in line in situations when the cable is in contact with the rolls of the fairlead.

5. Test conditions

The measurements were done at the Bay of Bothnia where Kontio was assisting traffic to Oulu, Tornio, Kemi and Raahe.
Ice conditions during the winter 2016 were average: level ice thicknesses were around 50 cm with some ridging. Landfast ice was present near the shores while moving sea ice present at the center of the Bay of Bothnia. Majority of the assistance happened in channels. Ice thickness and channel thickness measurements were not possible. The ice conditions were estimated on a scale easy/hard. However, as there was only little variation on the ice conditions, the towing force results have not been compared to the ice conditions.

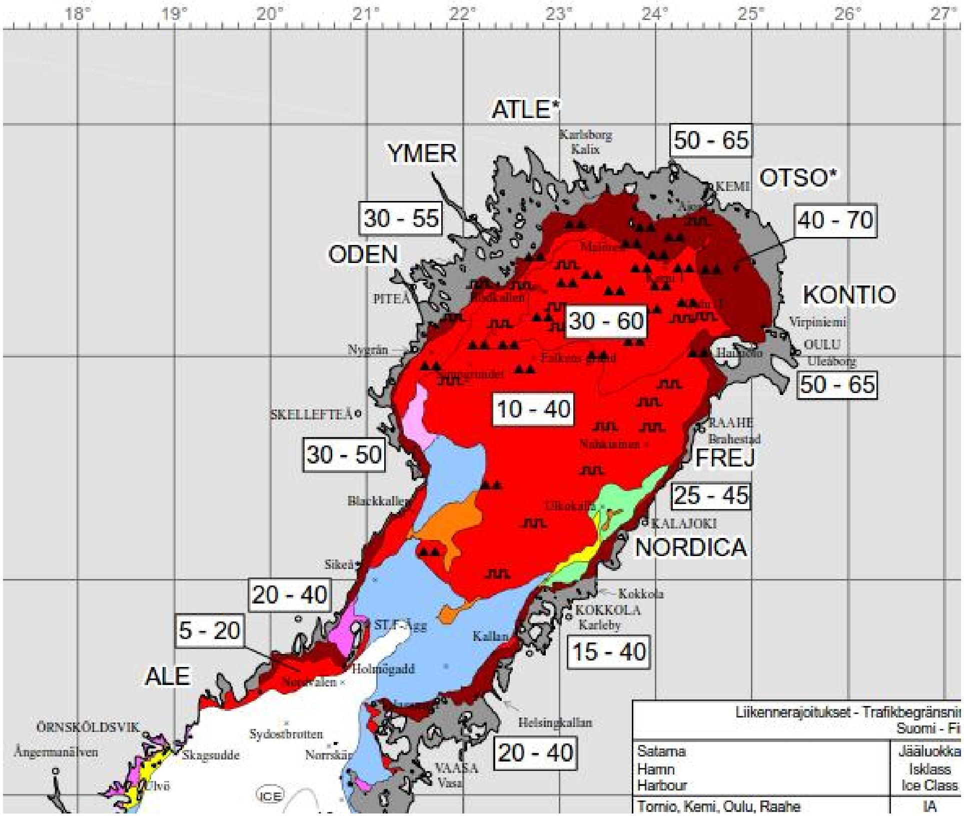

Figure 5-1: Ice chart of the Bay of Bothnia, 14.3.2016.

7. Results and analysis

The test results are presented below. The time histories and results in tabular form are presented in Appendixes A & B.

Following limitations should be noted when investigating the results:

- Even though the maximum engine power of the assisted vessel is known, it is not known if the vessel actually uses the maximum power. It is not uncommon that the towed vessel saves fuel and does not use full power even though the icebreaker advices to do so. In addition, it is not known if the full power is even available. This can be the case especially with older vessels.
- The measurement system was not initially designed as an autonomous longterm logging system. Some of the video footage of the latter part of the winter is not available due to technical problems.
- GPS measurements of the towed vessel and the propulsion measurements required active use and some of the data from the latter part of the winter is not available depending on the activities of the crew.

7.1 General results of the towing operations

Totally 21 towing operations were measured. Statistics of the towed vessels are presented in Table 7-1. All vessels were general cargo ships with Finnish-Swedish ice class of 1A. During the measurement campaign a typical vessel to be towed was a ~5450 DWT cargo vessel in ballast with engine power of ~2900 kW and 0.53 kW/DWT.
Statistics of the towing time and speed are presented in Table 7-2. It can be seen that the towing speed is relatively high. Statistics of the towing forces and the propulsion power of the icebreaker are presented in Table 7-3. The maximum measured towing force was 241.1 ton which is above the nominal breaking load of the towing cables. However, the cables have not failed. On the other hand, the cables failed with a lower load on another towing operation. More discussion of the failure and maximum peaks in chapter 7.5. The average used propulsion power of the icebreaker was about the half of the available power. However, full power was used occasionally during the towing operations.

Table 7-1: Statistics of the towed vessels.

Loaded	Ballast	Average DWT	Engine Power [kW]	Power/DWT [kW/DWT]
9	12	5394	2626	0.50

Table 7-2: Statistics of the towing time and speed.

Max. Towing time	Average Towing time	Max. Towing Speed [kn]	Average Towing Speed [kn]
06:05:00	02:34:00	14.3	9.7

Table 7-3: Statistics of the towing force and propulsion power of the icebreaker.

Max. Towing Force [ton]	Average Max. Towing Force [ton]	Average Towing Force [ton]	Average Towing Force St. dev. [ton]	Average Propulsion Power [MW]
241.1	123.3	36.8	15.5	7.8

7.2 Towing force compared to the size and power of the towed vessel

It is quite natural that the vessel size would affect the towing forces. Mainly the mass and breadth of the towed vessel are interesting. However, the breadths of the towed vessel varied only little and all of the towed vessel were clearly narrower than the icebreaker so the breadth did not influence to the forces.

The comparison between the towing forces and deadweight of the assisted vessels is presented in Figure 7-1 and Figure 7-2. Some correlation is visible but also lot of scatter. This is due to the fact that the DWT represents the maximum cargo capacity of the vessel but the actual loading condition of the vessels varies.

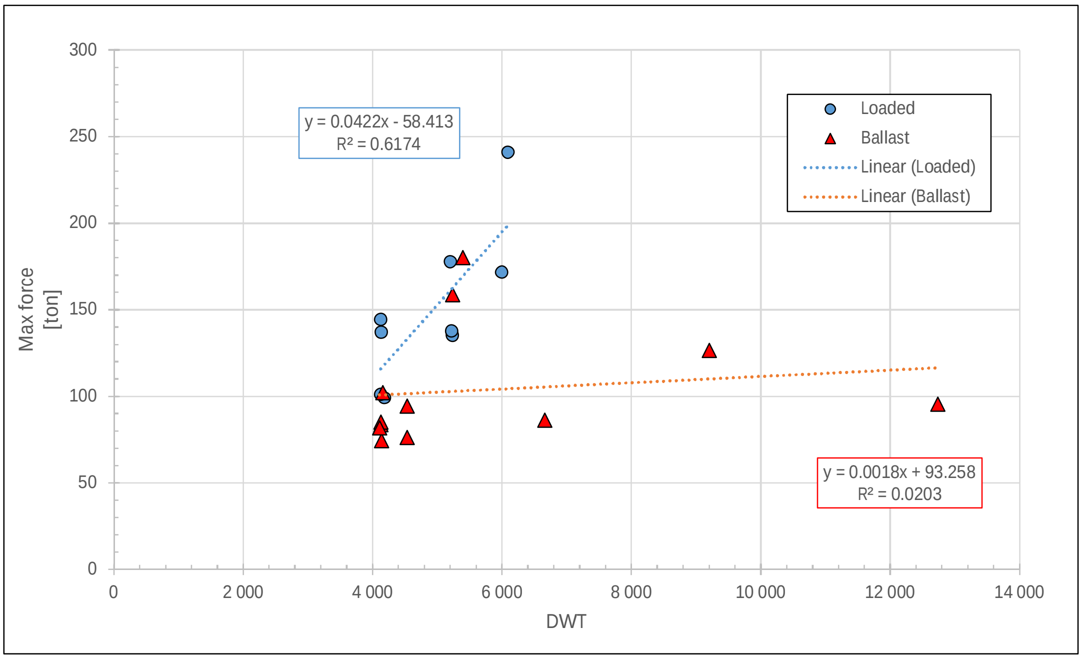

Figure 7-1: Maximum towing force versus DWT of the towed vessel.

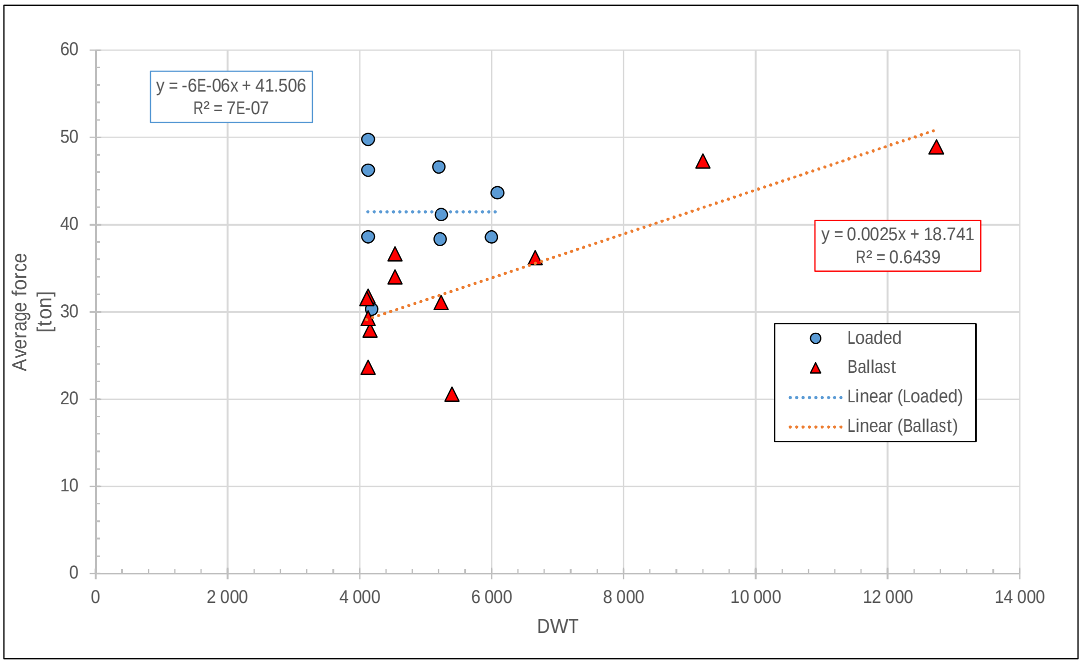

Figure 7-2: Average towing force compared to towed vessel DWT.

In order to have a better understanding of the actual mass of the towed vessels, the displacement has been estimated roughly based on the main dimensions of the vessels:

*Estimated displacement [ton] = 0.72 * Length [m] * Breadth [m] * Current Draft [m] * 1 [ton/m³]*

The 0.72 represents the block coefficient and the same coefficient has been used for all cases as all of the towed vessels are relatively of same size and type.

The comparison between the towing forces and estimated displacements are presented in Figure 7-3 and Figure 7-4. Clear correlation is visible.

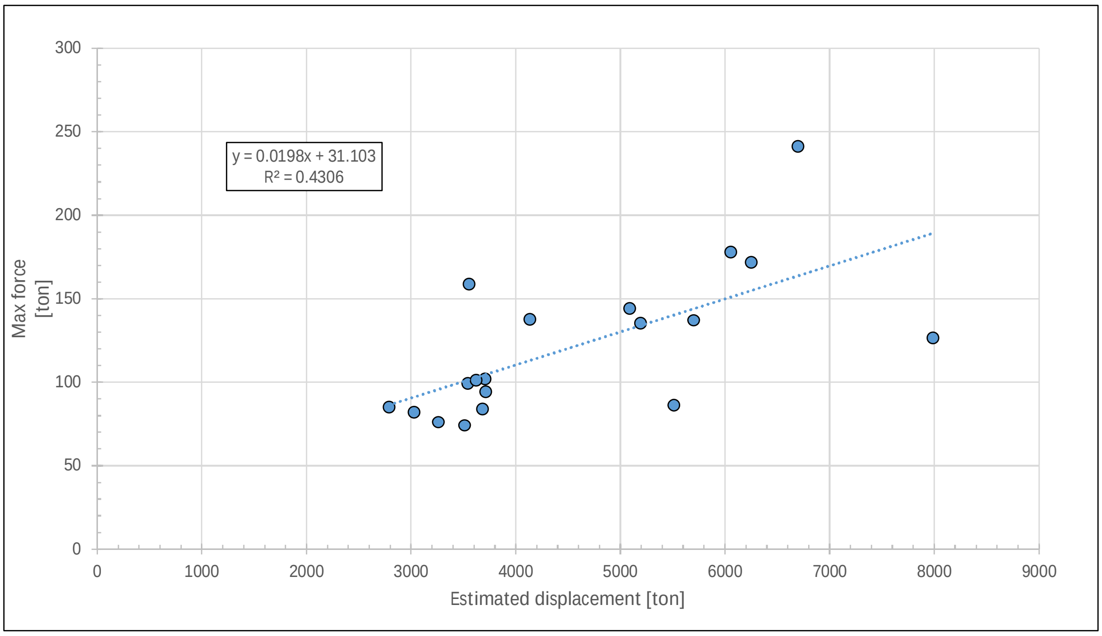

Figure 7-3: Maximum towing force versus estimated displacement of the towed vessel.

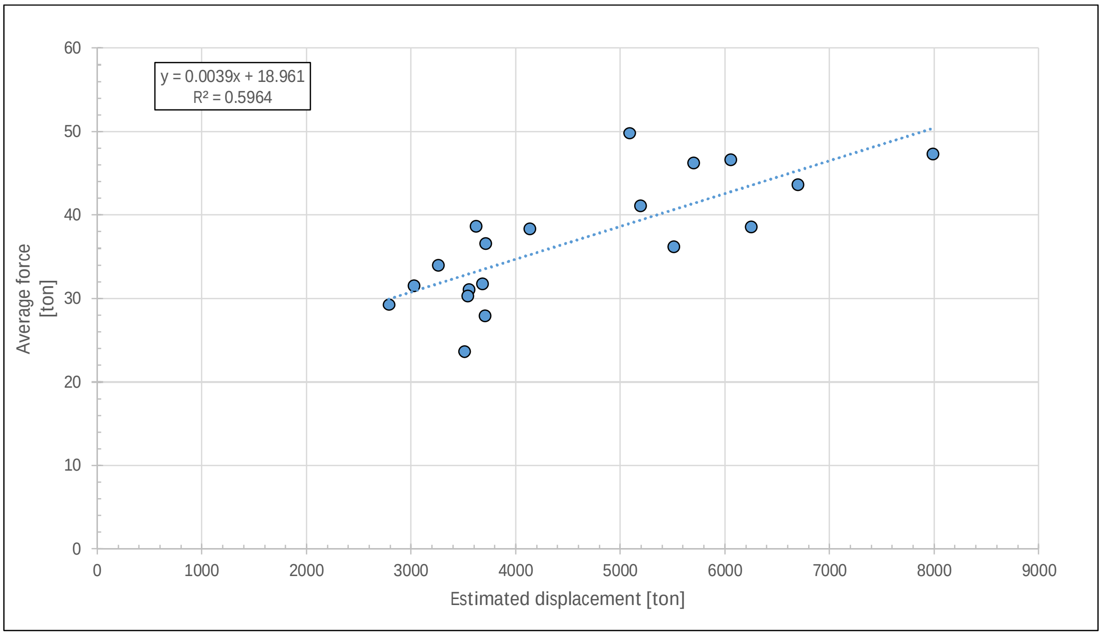

Figure 7-4: Average towing force versus estimated displacement of the towed vessel.

Also the power of the of the towed vessel influences the forces. Instead of comparing the towing force directly to the power, it is better to compare the force to the power/displacement ratio which represents how powerful the vessel is, as the engine power is related to the vessel size. The comparison is presented in Figure 7-5 and Figure 7-6. There is clear correlation visible, especially with the maximum forces, as higher forces occur with the least powerful vessels. However, the limitations between the actual and reported engine power should be noted when investigating power.

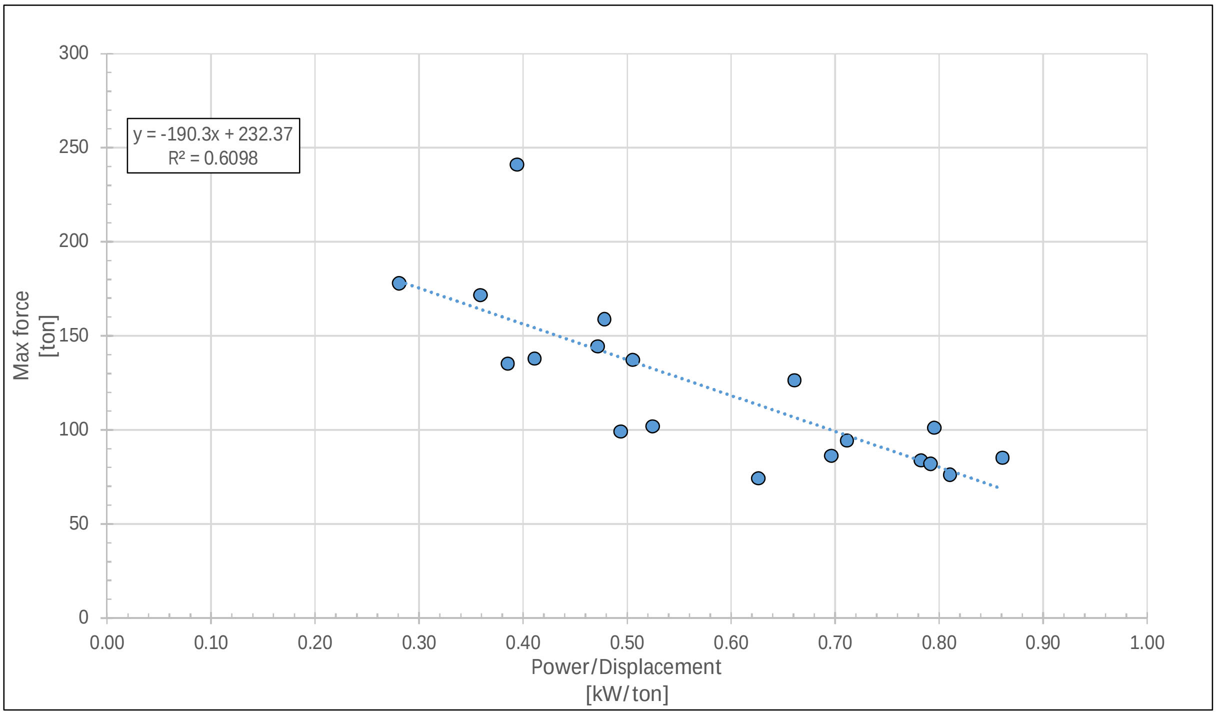

Figure 7-5: Maximum towing force versus power/displacement ratio of the towed vessel.

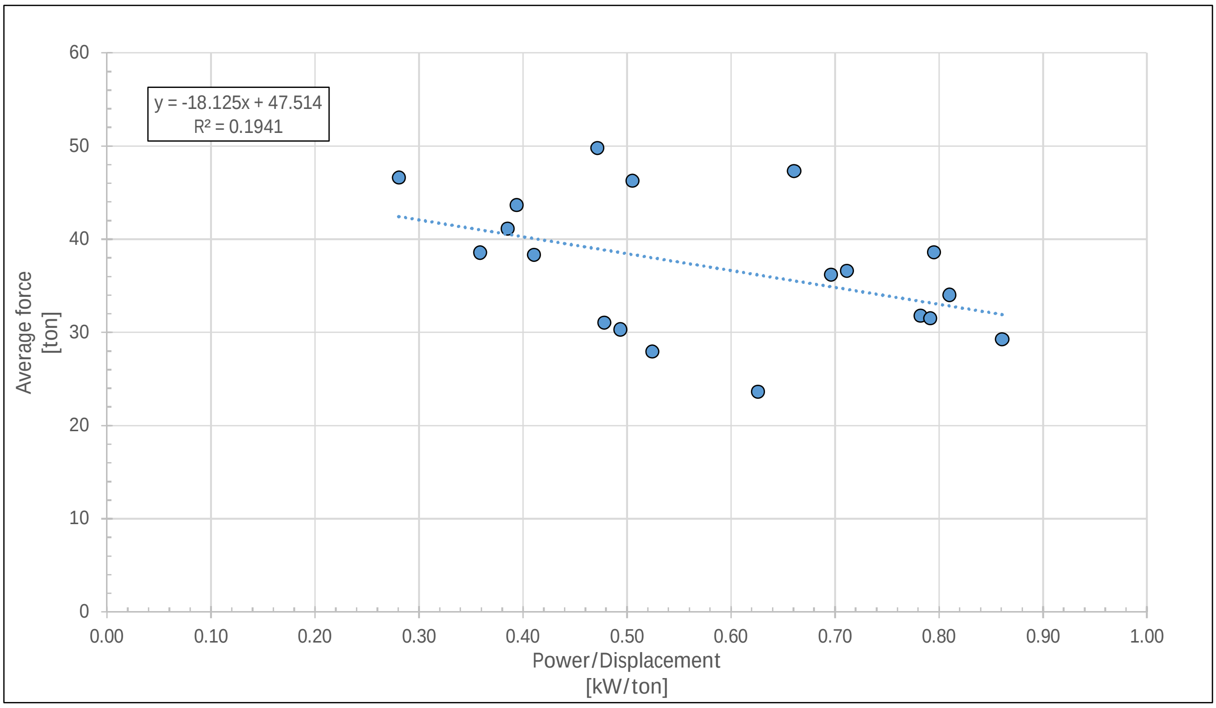

Figure 7-6: Average towing force versus power/displacement ratio of the towed vessel.

The bow form of the towed vessel affects how well it fits into the towing fork. The bow forms were divided into three categories: no bulb, bulbous bow and bulbous bow with ice knife. Comparison between the towing forces and bow types are presented in Figure 7-7 and Figure 7-8.
There is no clear trend between the forces and bow types. The effect of bow type is not so straightforward because the mass, fore draft and shape of the bulb of the towed vessel also affects how well the vessel can be fitted into the towing fork. In addition, the data set is relatively small. There is very few points (3) especially with bows without bulb.

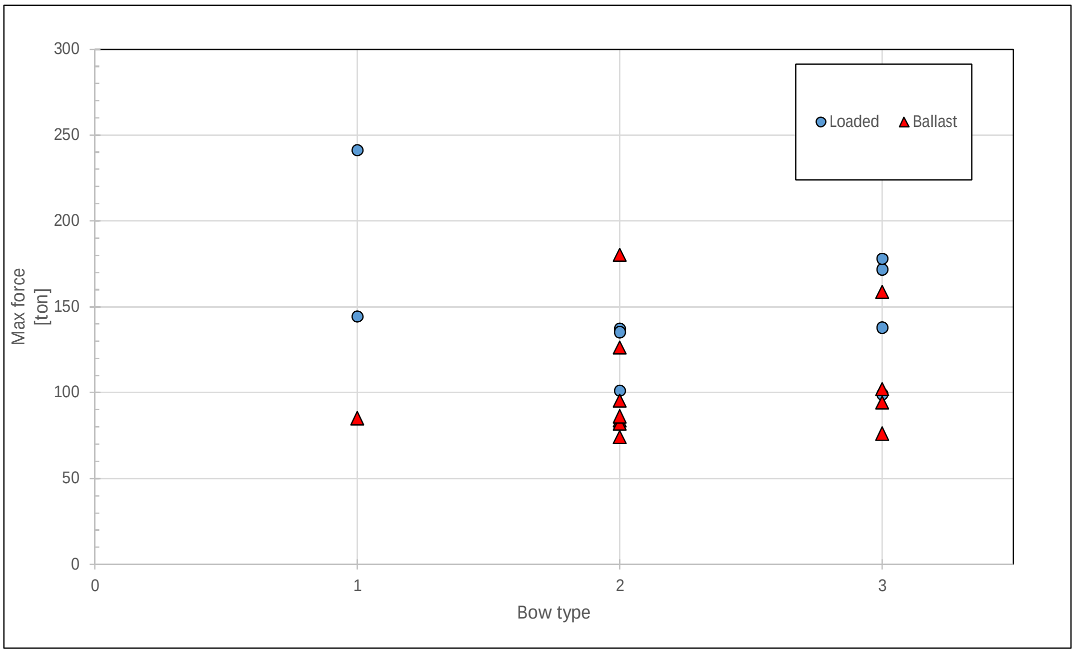

Figure 7-7: Maximum towing force versus bow type of the towed vessel. 1 = no bulb, 2 = bulb, 3 = bulb with ice knife.

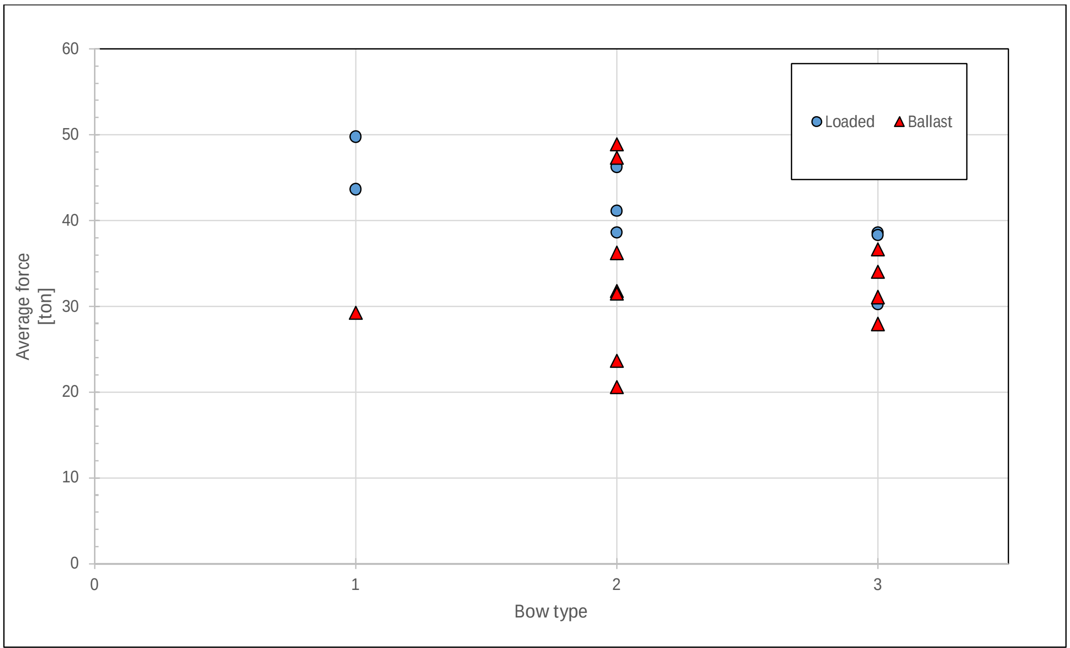

Figure 7-8: Average towing force versus bow type of the towed vessel. 1 = no bulb, 2 = bulb, 3 = bulb with ice knife.

7.3 Towing force compared to speed and power & torque

In Figure 7-9 the measured average towing forces are compared to the average towing speed. A clear downward correlation is visible. Similar trend is also visible if the average towing force is compared to the V_{ow}/average towing speed ratio (Figure 7-10) which represents how fast the vessel has been towed compared to the maximum open-water speed of the towed vessel (data available on some vessels).

From Figure 7-9 and Figure 7-10 it could be possible to make an assumption that the towing force reduces at higher speeds. However, this correlation is most likely due to the fact that in general the towing speed is higher in with lighter/smaller vessels and easier conditions. This is clearly seen in Figure 7-11. When investigating a single towing event, the situation is somewhat different. In appendix C the towing force is compared against the speed during individual towing operations. In many towing operations (not all) there is more or less clear correlation between the force and the speed as the force increases with speed (Figure 7-12). This is reasonable as at lower speed the towed vessel has more power to overcome the ice resistance.

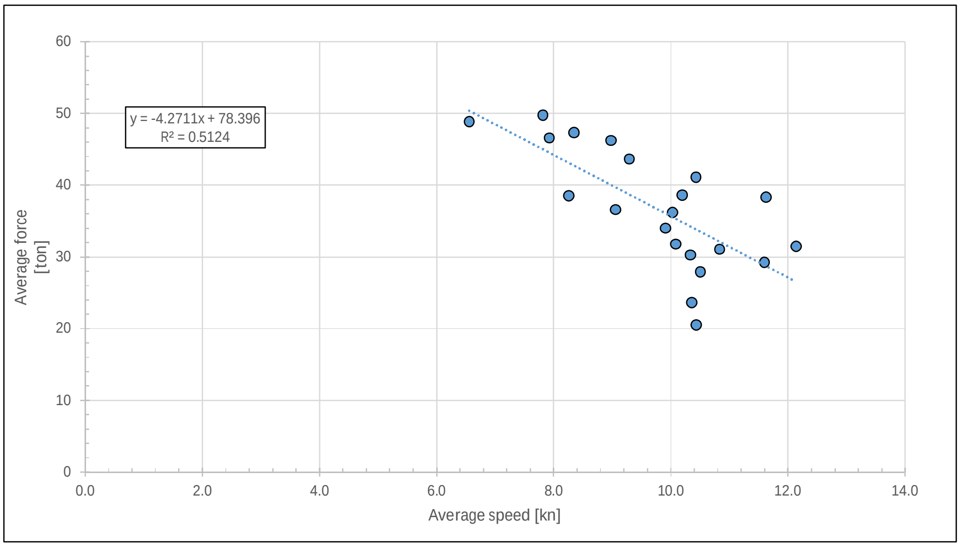

Figure 7-9: Average towing force versus the average towing speed.

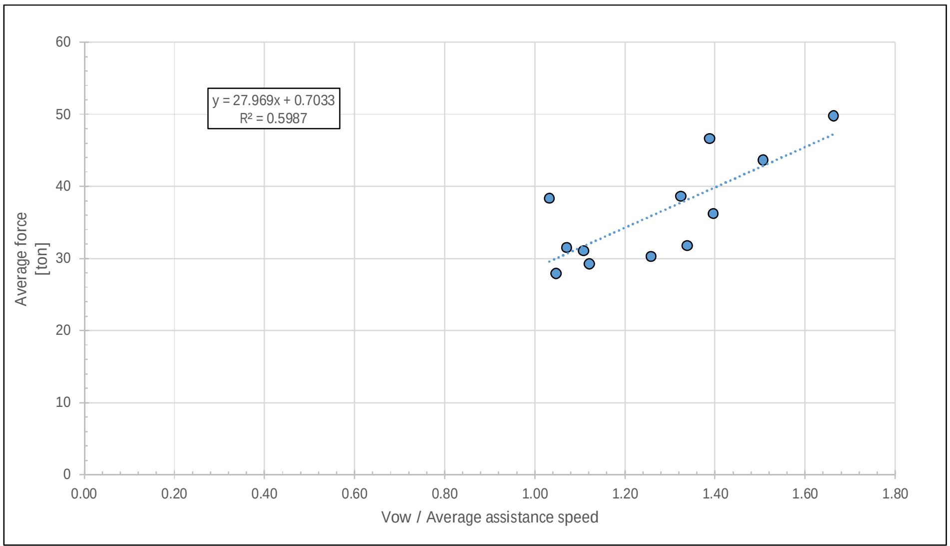

Figure 7-10: Average towing force compared to the V_{ow}/towing speed ratio.

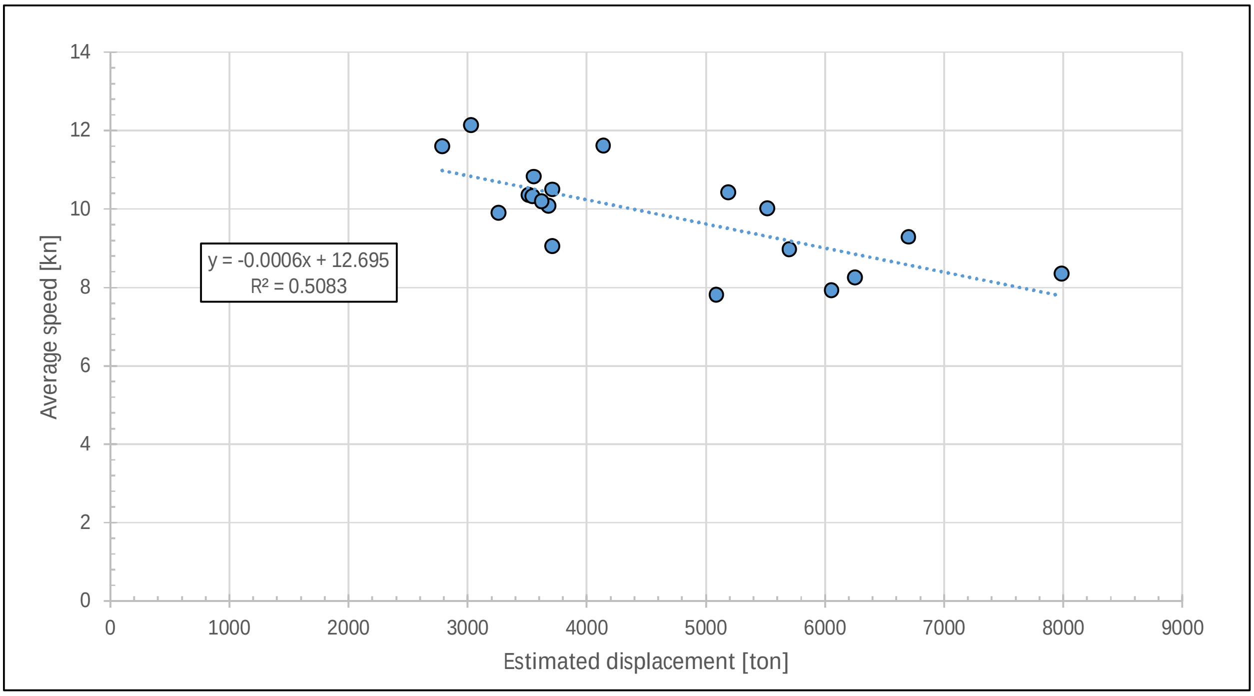

Figure 7-11: The average towing speed compared to the estimated displacement of the towed vessel.

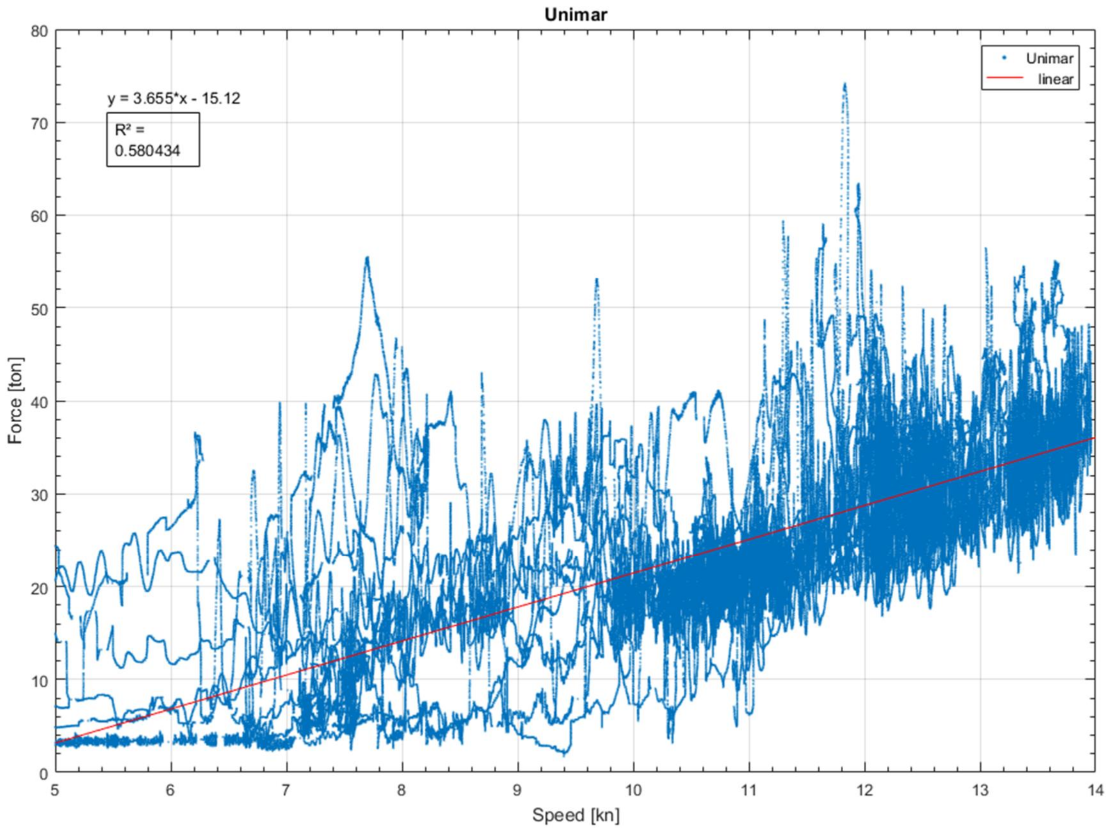

Figure 7-12: Example of the towing force versus the towing speed during one towing operation.

In appendix D the propulsion power of the icebreaker is compared to the towing force. In general, there is an upward trend between the power and towing force as can be seen in Figure 7-13. This is reasonable as the higher power is related to higher towing speed which increases the towing force (Figure 7-12). In addition, the higher power is related to more difficult ice conditions. Similar upward trend is also visible in Figure 7-14 where is an example of the relation between the torque and the towing force (Appendix E).

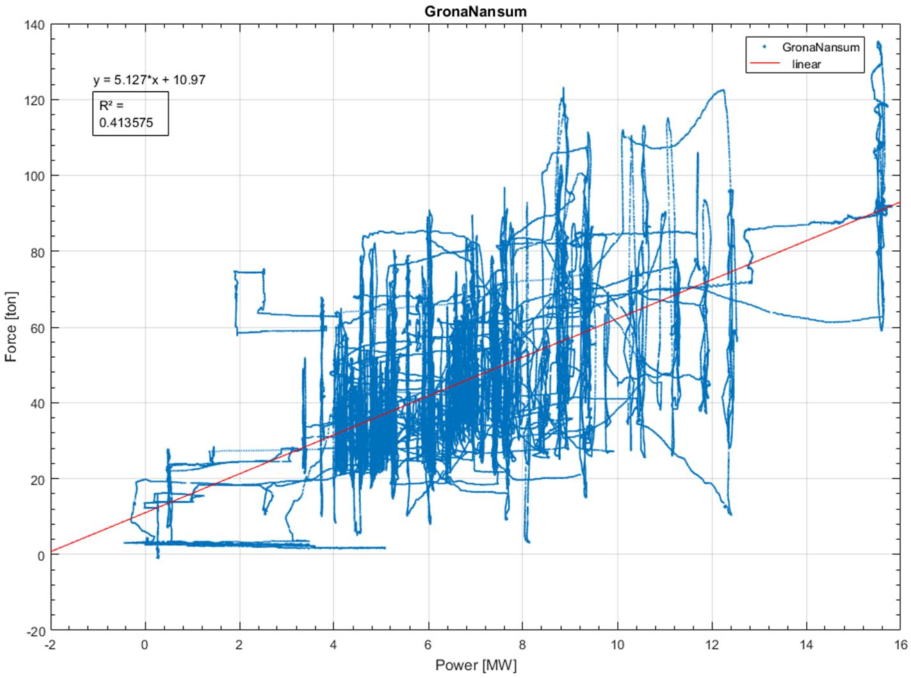

Figure 7-13: Example of the relation between the power and towing force during one towing operation.

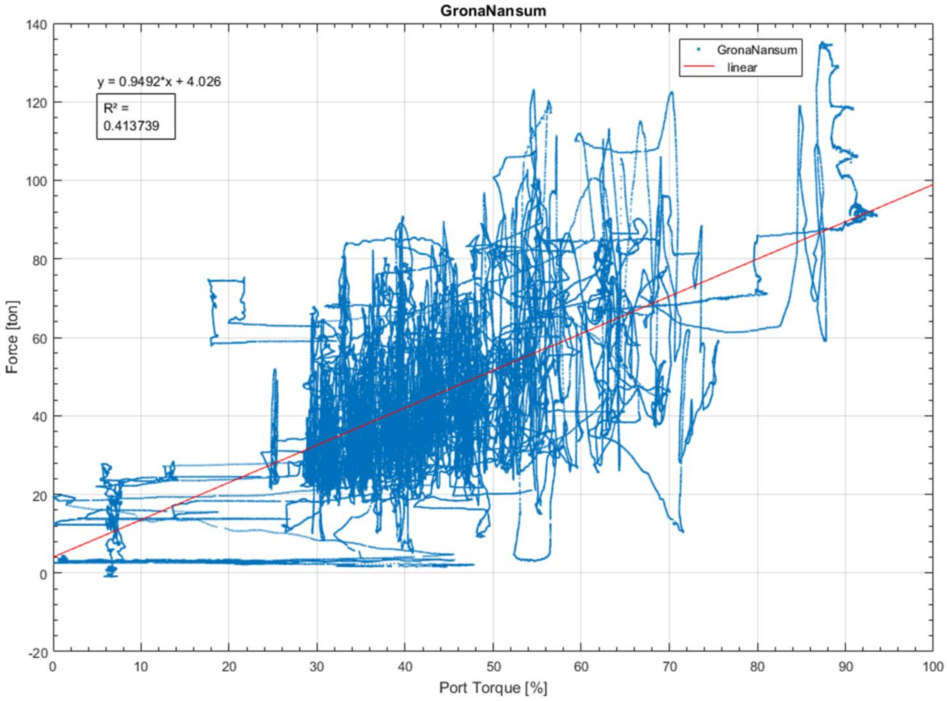

Figure 7-14: Example of the relation between the torque and towing force during one towing operation.

The power and torque are somewhat related to the speed of the vessel. In order to investigate the towing force compared to how difficult the conditions have been the force is compared to power/speed ratio. It is assumed that this represents how difficult the situation is i.e. how many MW is used for each knot. Results for each test are presented in appendix F. In many cases there is an upward trend (Figure 7-15), however the results are not as clear as for the torque or power.
When investigating the whole data set (Figure 7-16), a similar upward trend is visible. This is reasonable: as situation is more difficult, the icebreaker needs to pull more the assisted vessel.

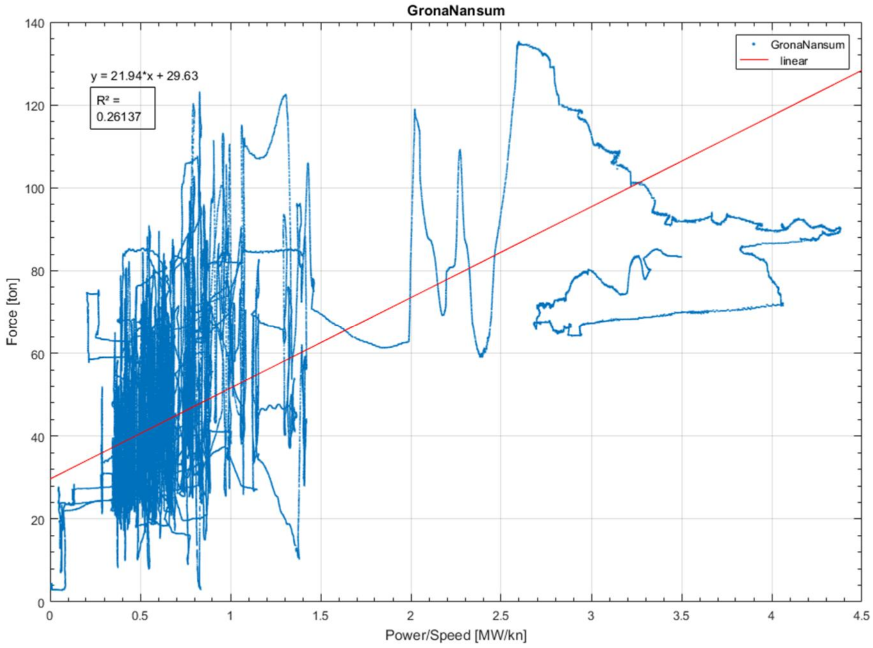

Figure 7-15: Example of the relation between the power/speed ratio and towing force during one towing operation.

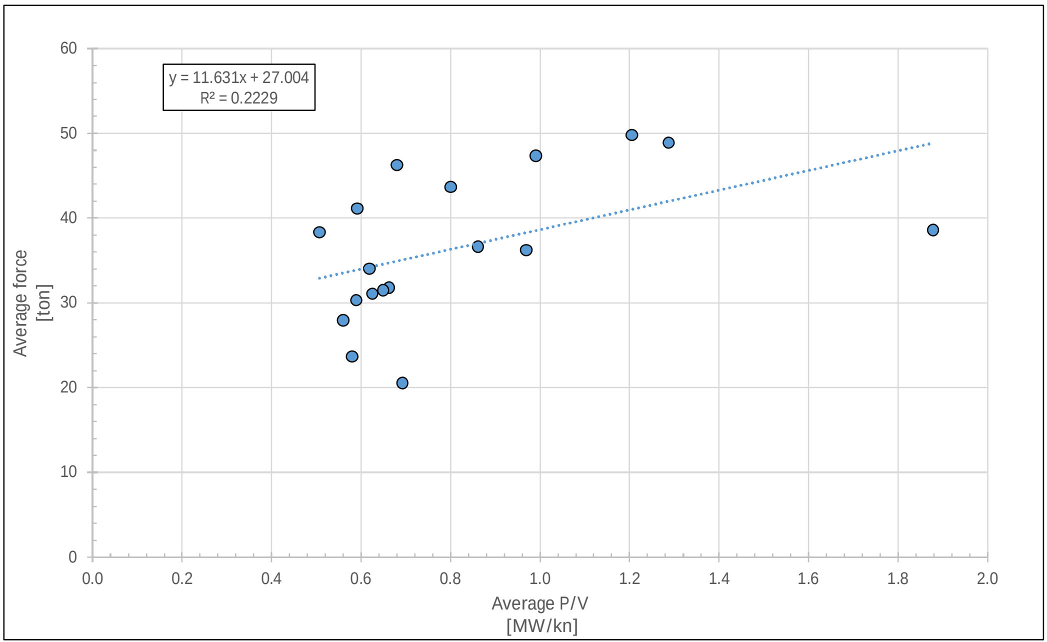

Figure 7-16: Average towing force compared to the average power/speed ratio.

7.4 Towing force compared to relative motions

In appendixes G and H the towing force has been compared to the course and speed differences between the two vessels during the towing operations. In Figure 7-17 through Figure 7-20 the towing forces have been compared to the standard deviation of the speed and course differences. It is visible that higher loads have been occurring when there has been more differences in the motions between the vessels. In addition, from Figure 7-21 it can be seen that the speed and course differences are linked together.

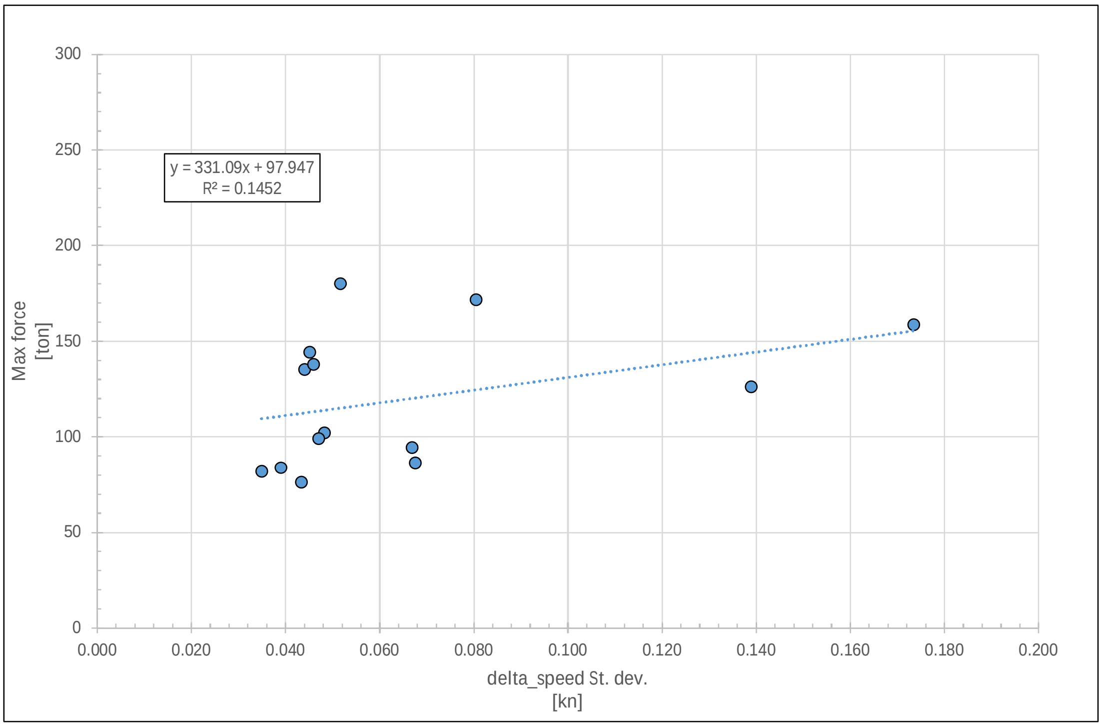

Figure 7-17: Maximum towing force compared to the standard deviation of the speed difference between the vessels.

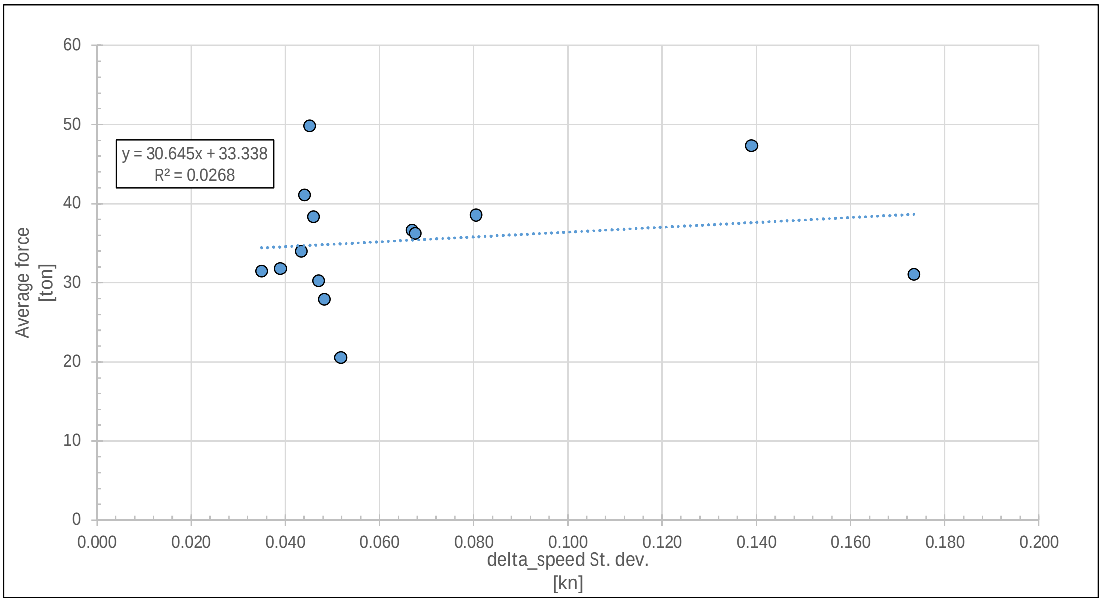

Figure 7-18: Average towing force compared to the standard deviation of the speed difference between the vessels.

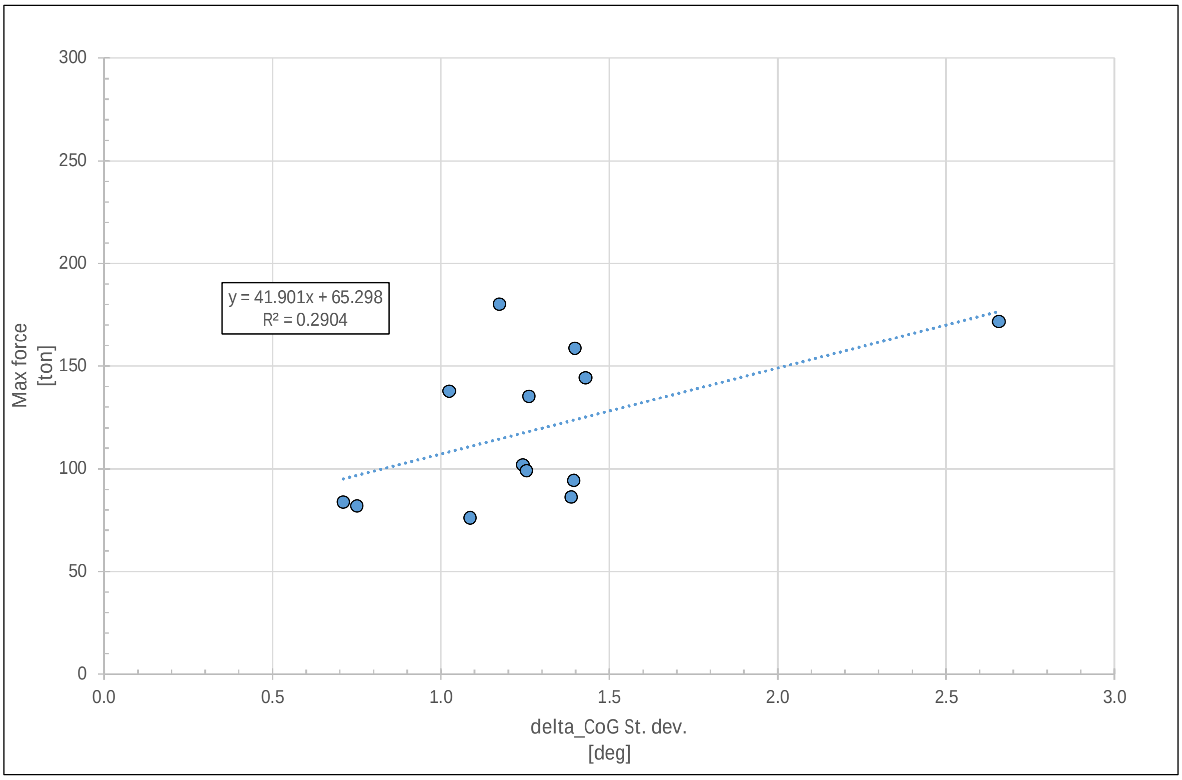

Figure 7-19: Maximum towing force compared to the standard deviation of the course difference between the vessels.

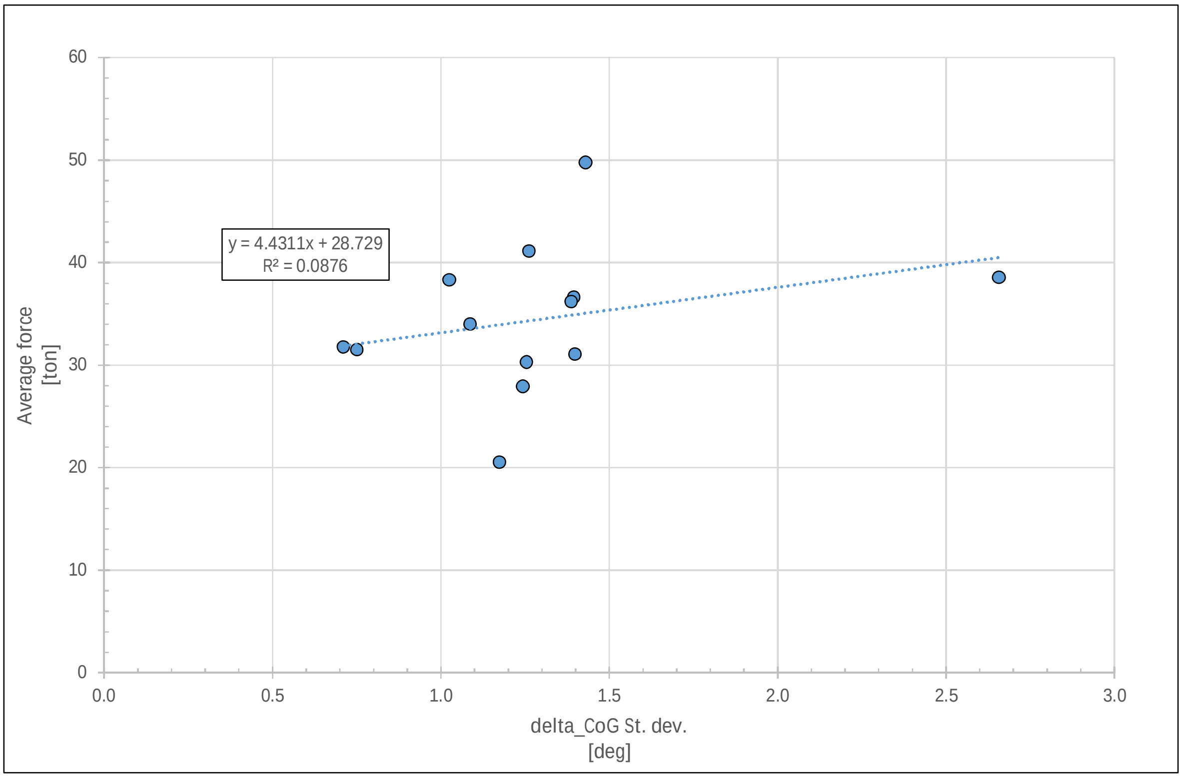

Figure 7-20: Average towing force compared to the standard deviation of the course difference between the vessels.

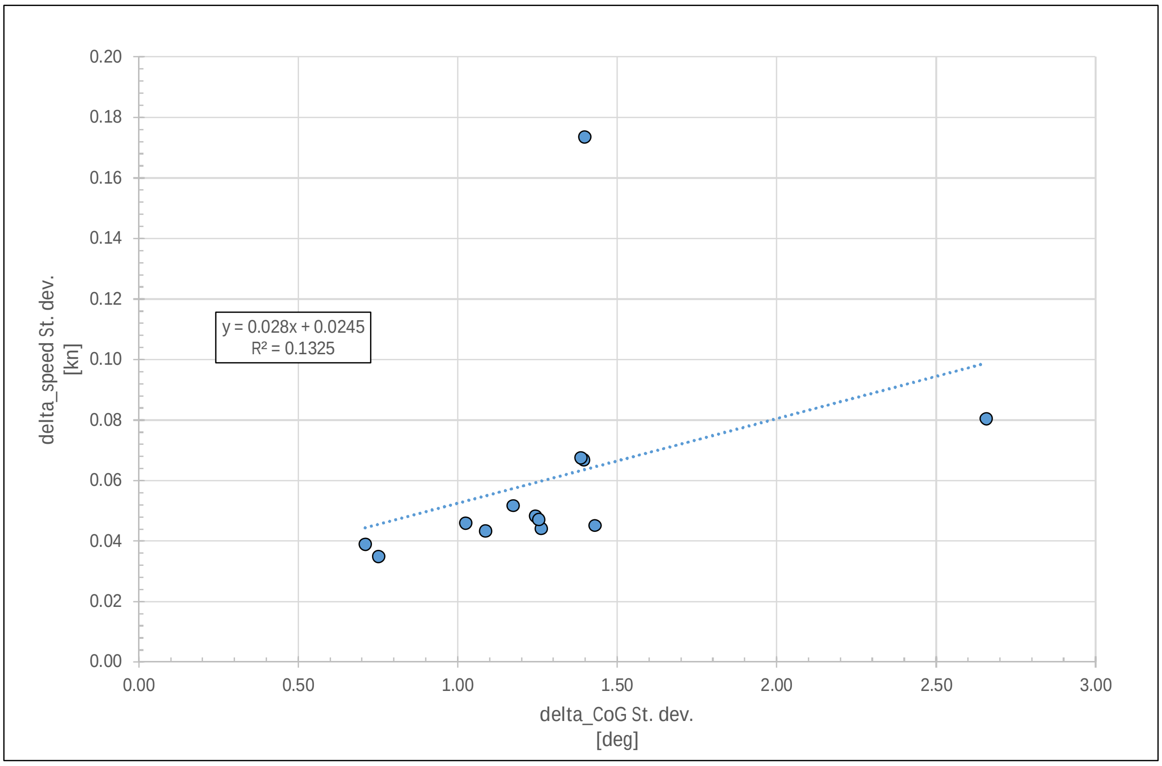

Figure 7-21: The relation between the standard deviations of speed and course differences.

In Figure 7-22 the course differences have been compared to the deviation of the rudder angles of the icebreaker. The standard deviation of the rudder angles is compared to the towing forces in Figure 7-23 and Figure 7-24.

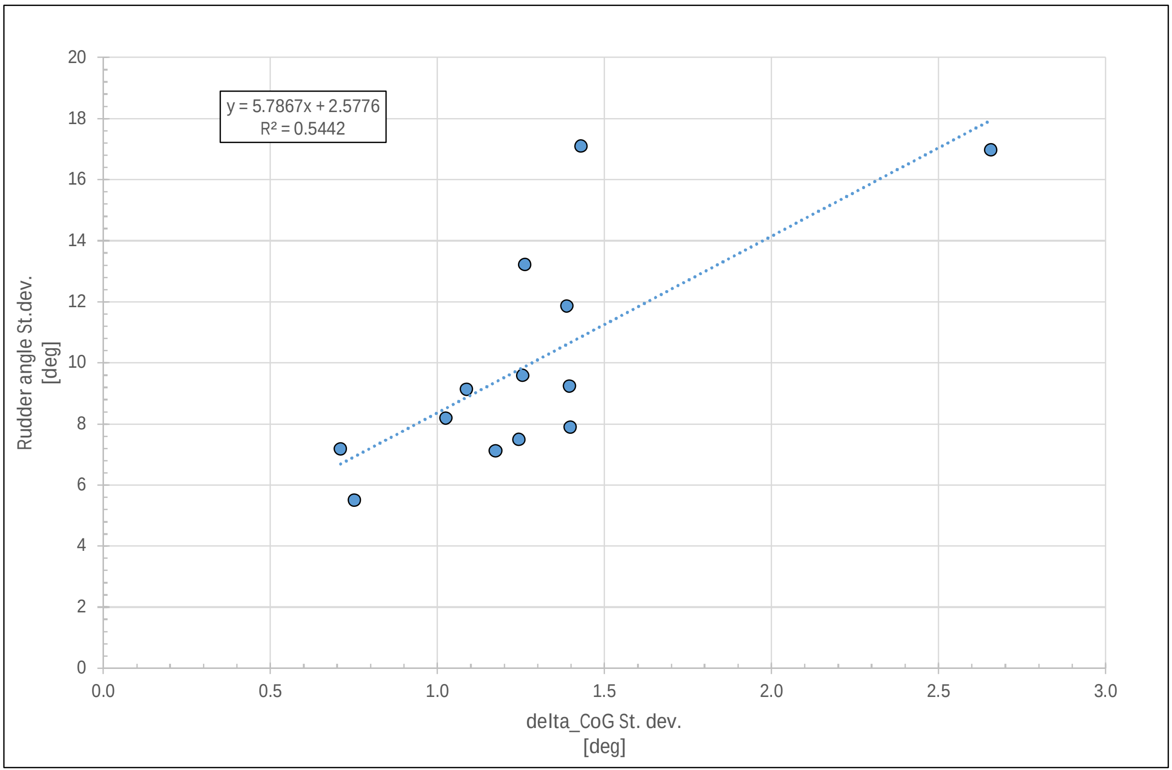

Figure 7-22: The relation between the standard deviations of course difference and rudder angles.

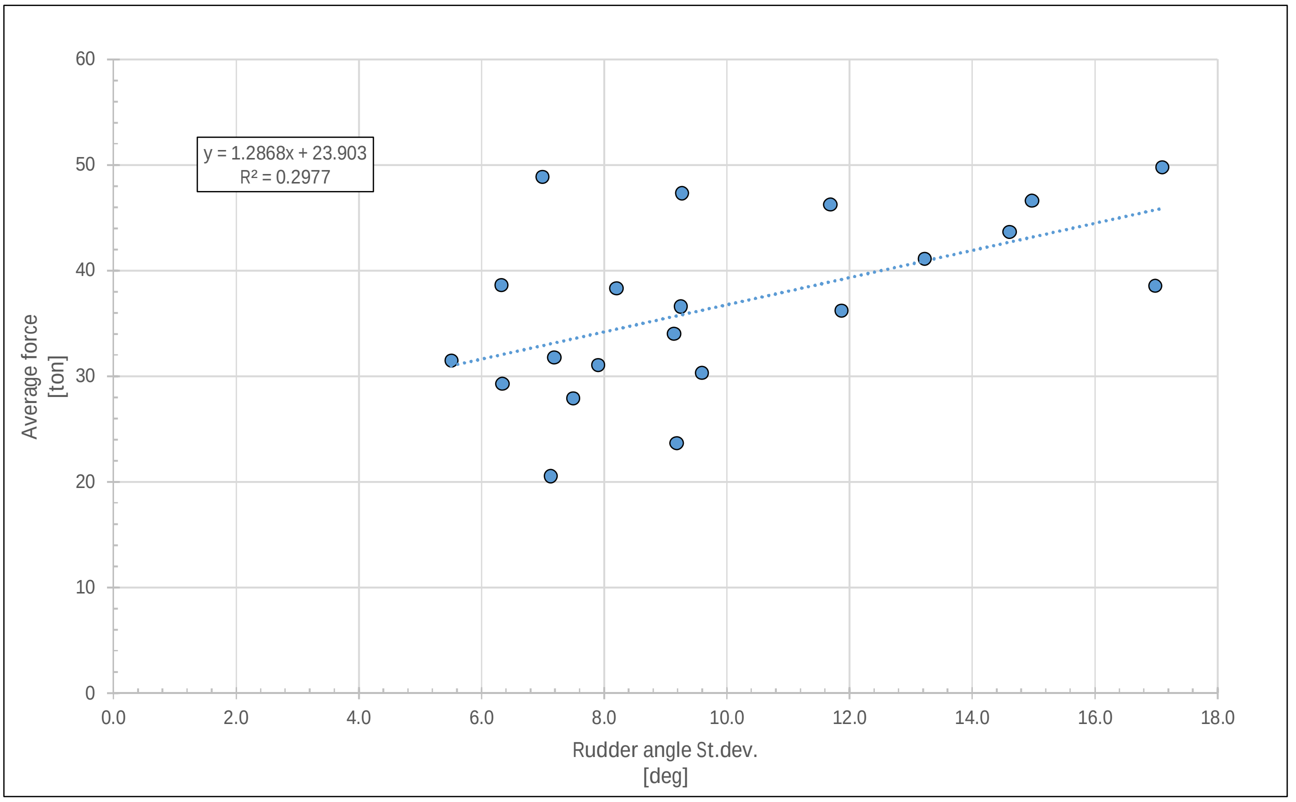

Figure 7-23: Average towing force compared to the standard deviation of the rudder angles of the icebreaker.

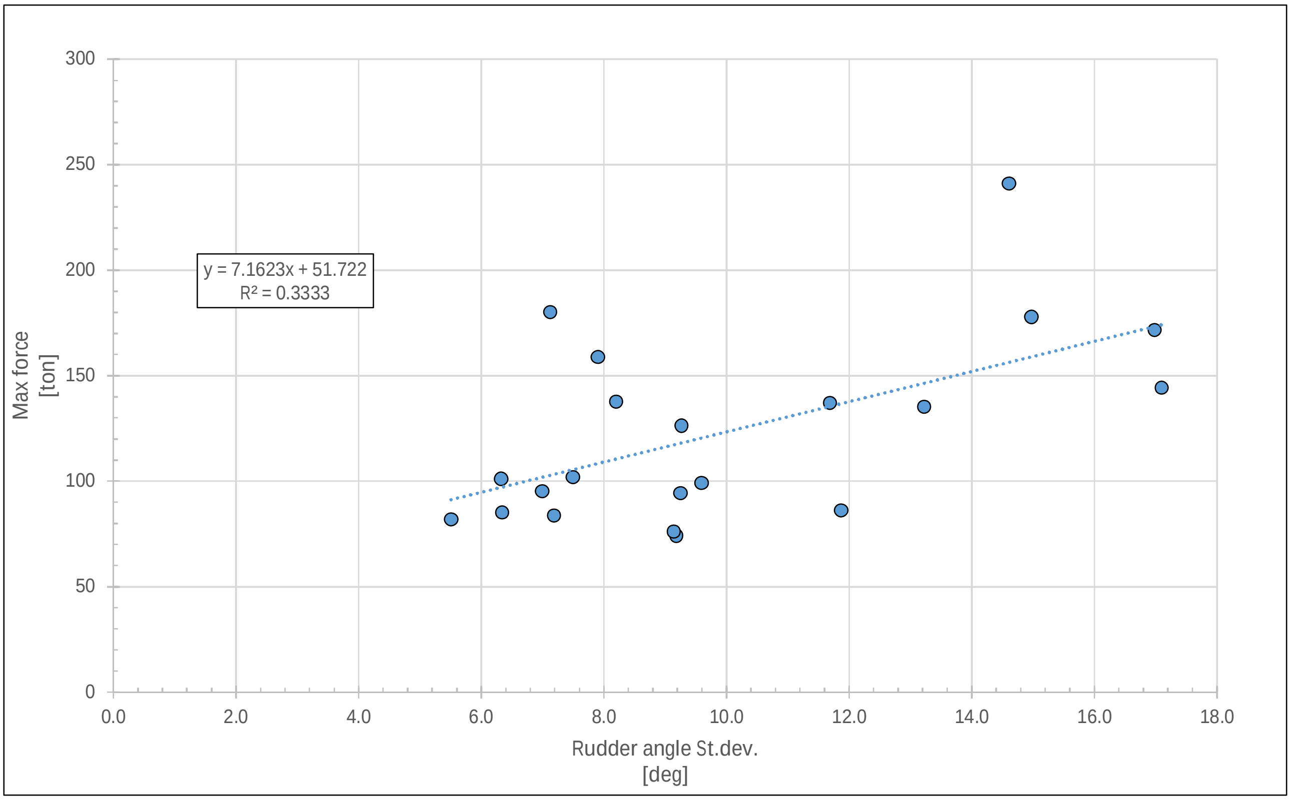

Figure 7-24: Maximum towing force compared to the standard deviation of the rudder angles of the icebreaker.

7.4.1 Contributing factors for speed and course differences

It is visible from the previous figures that both differences in speeds and courses are linked to high loads. In Figure 7-25 and Figure 7-26 the estimated displacement is compared to the standard deviations of the speed and course differences and there is clear correlation. In Figure 7-27 and Figure 7-28 the standard deviation of rudders is compared to the estimated displacement and also to the displacement/power ratio. Again a clear correlation is visible.

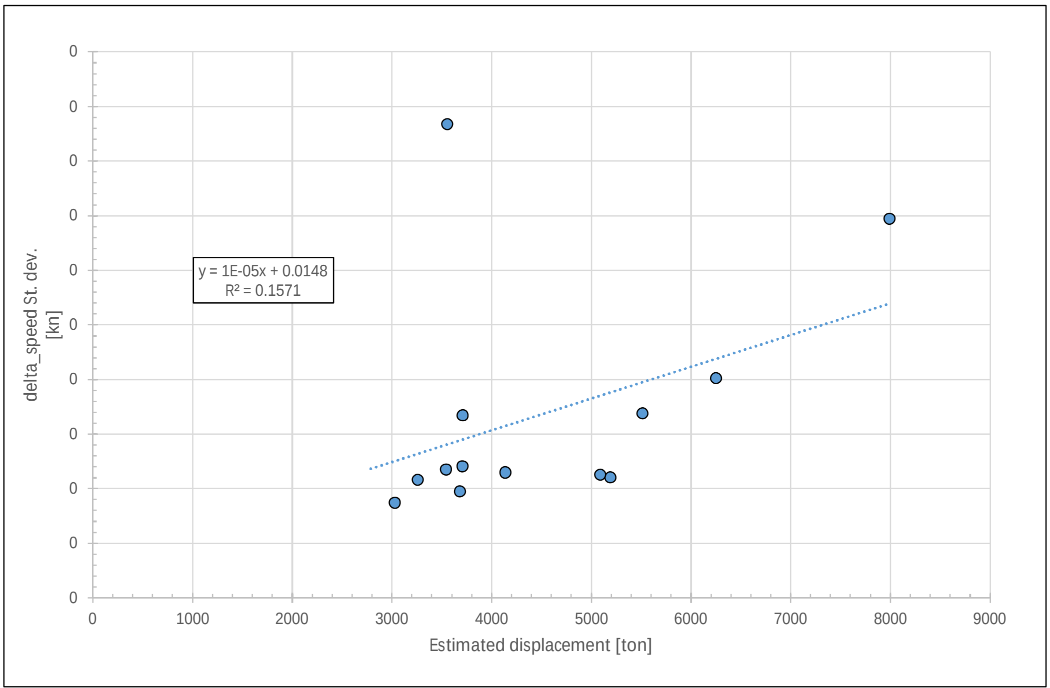

Figure 7-25: Standard deviation of the speed difference versus estimated displacement of the towed vessel.

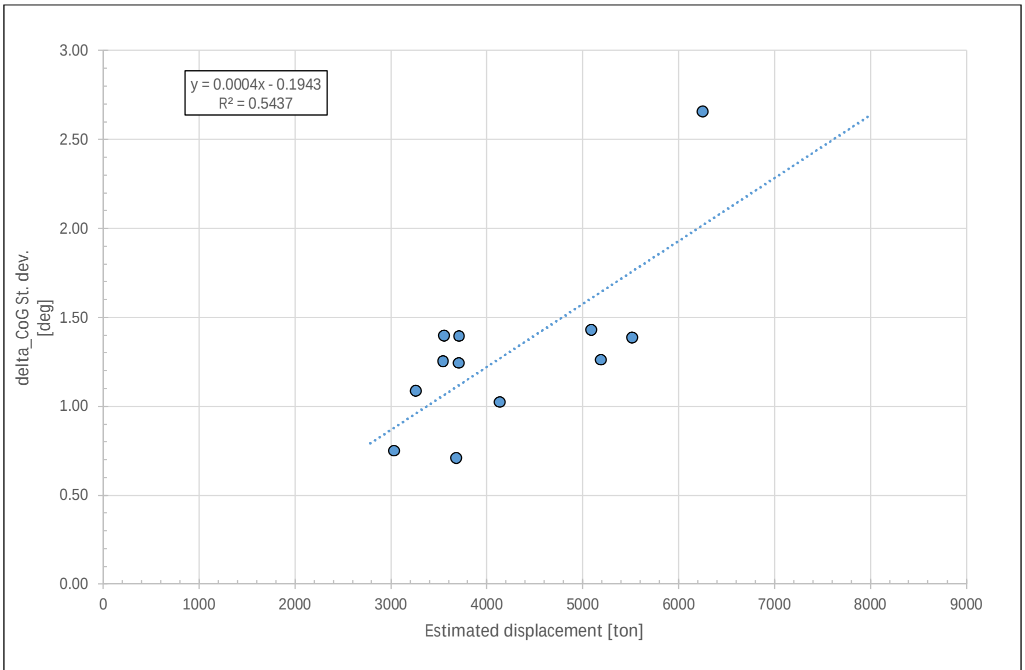

Figure 7-26: Standard deviation of the course difference versus estimated displacement of the towed vessel.

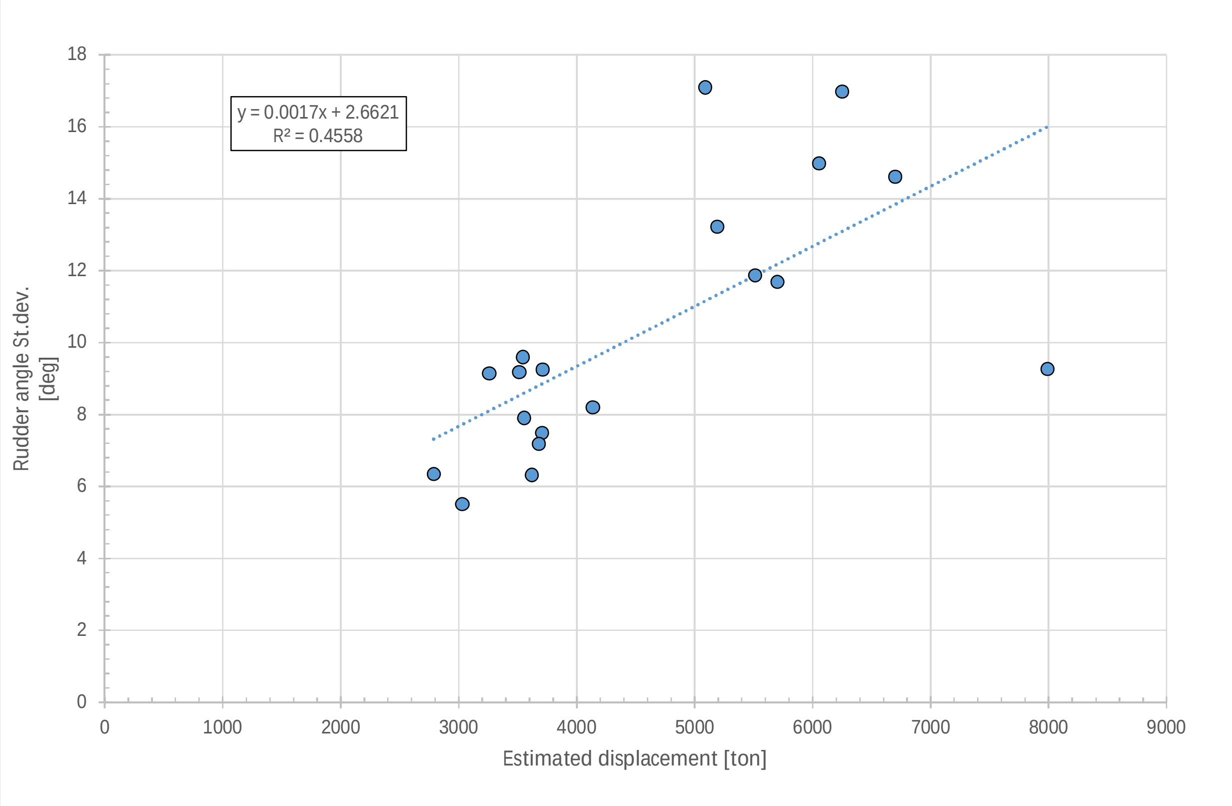

Figure 7-27: Standard deviation of the rudder angles versus estimated displacement of the towed vessel.

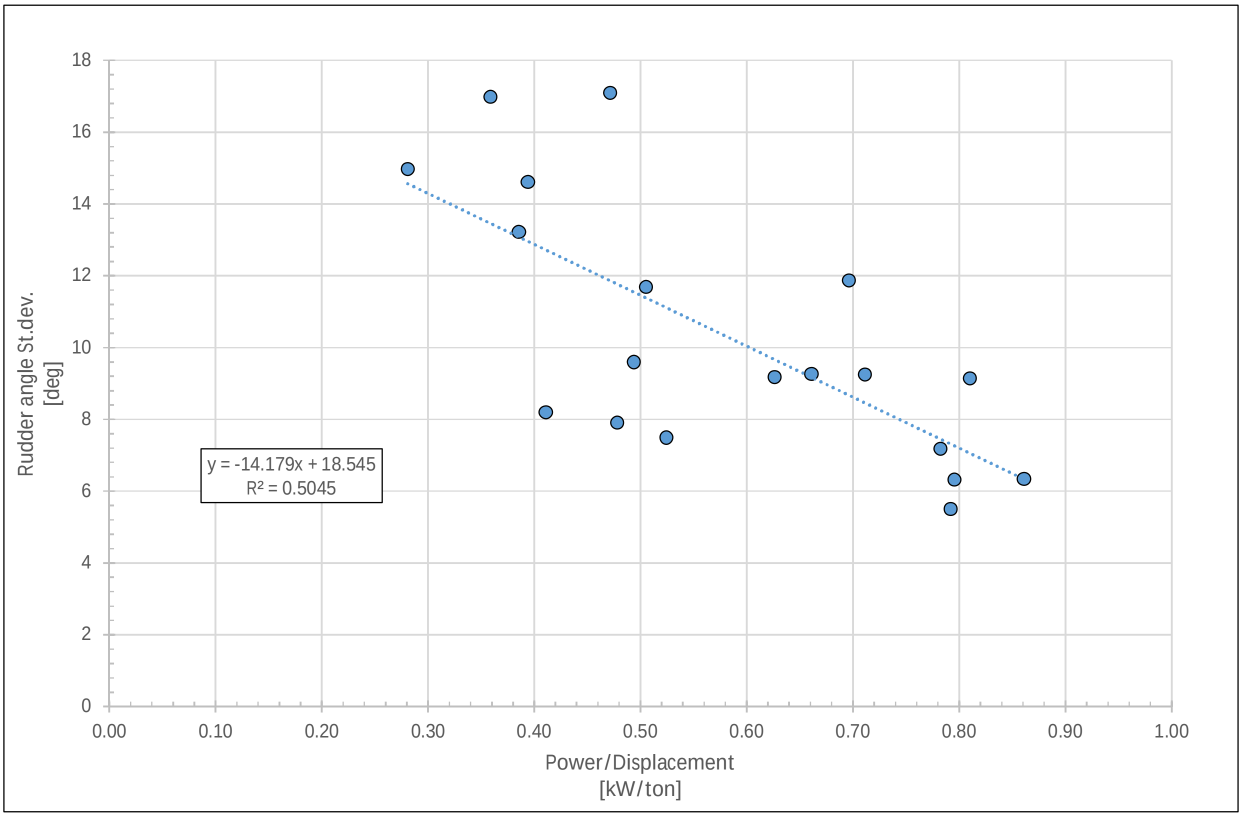

Figure 7-28: Standard deviation of the rudder angles versus power/displacement ratio.

7.5 Maximum force peaks

The events and circumstances resulting high force peaks are discussed in this chapter. The highest four peaks are presented as an examples.

The first example (Figure 7-29 through Figure 7-33) is a presentation of a situation in which the assisted vessel broke loose from the towing fork. The vessel was relatively heavy so it was necessary to have a gap between the two vessels. This resulted difficult steering of the ice breaker which can be seen from the extreme rudder angles.

In the second example (Figure 7-34 & Figure 7-35) is a presentation of a situation in which a small ridge formation has resulted a slack to the towing line and then sudden tightening to the towing line. Again, there was a gap between the two vessels due to the bulbous bow.

The third example (Figure 7-36 and Figure 7-37) displays a situation in which the secondary towing cable failed. The towed vessel had problems following the icebreaker in straight path. Unfortunately no video footage is available from this incident.

The fourth example (Figure 7-38) is the highest measured force during the measurement campaign. Unfortunately no video footage is available. In addition, the GPS was not installed so it is not possible to investigate the relative motions between the two vessels.

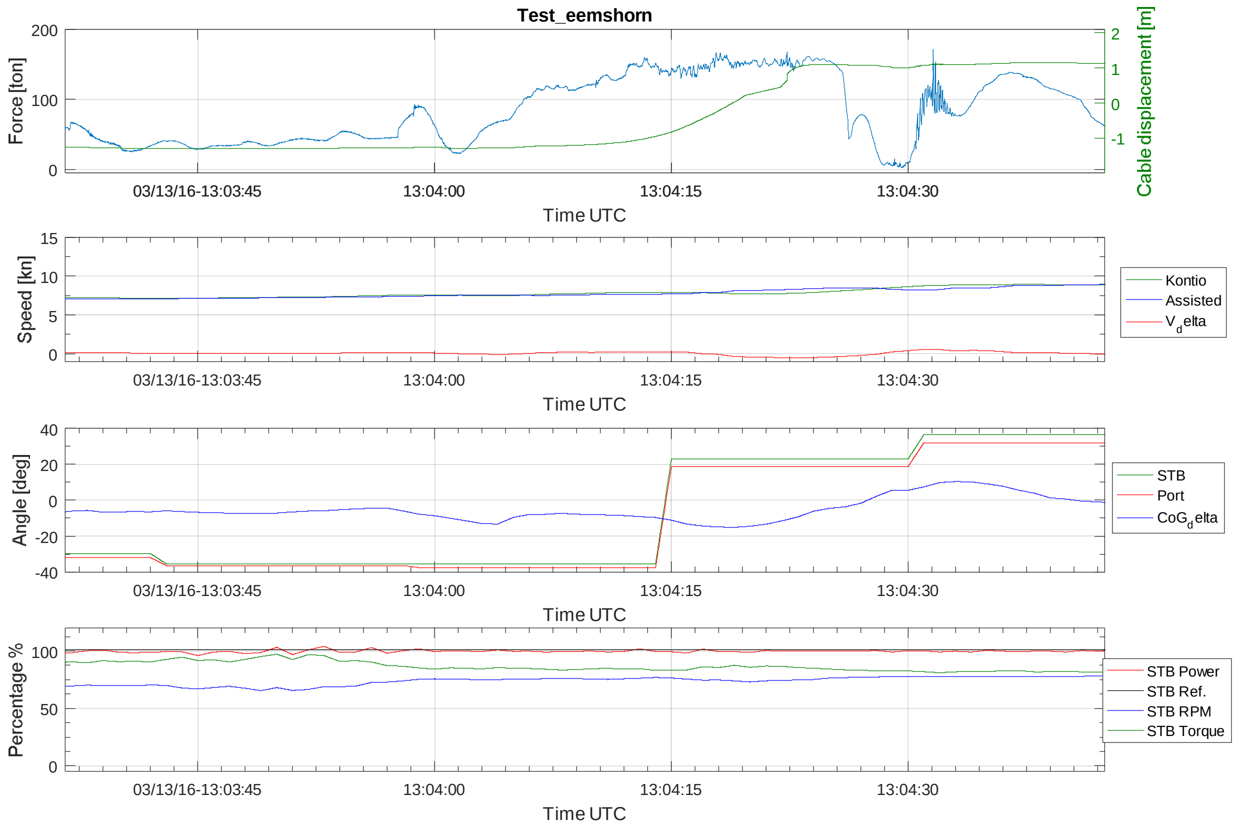

Figure 7-29: Example #1, Time history of test in which the towed vessel broke loose from the towing fork resulting a high force peak at ~13:04:35.

Figure 7-30: The towed vessel pushes the towing fork of the icebreaker causing the icebreaker to turn.

Figure 7-31: The towed vessel breaks loose from the towing fork and moves to the side of the icebreaker. High forces act on the towing line and the towed vessel heels noticeably. The brake of the winch slides and about 2 meters of towing cable slides.

Figure 7-32: Slack is generated to the towing line as the towed vessel moves to the side of the icebreaker and in addition more cable has slid from the winch.

Figure 7-33: As the towed vessel is in contact with the channel edge, it slows down and the cable suddenly tightens again causing a high force peak (172 ton).

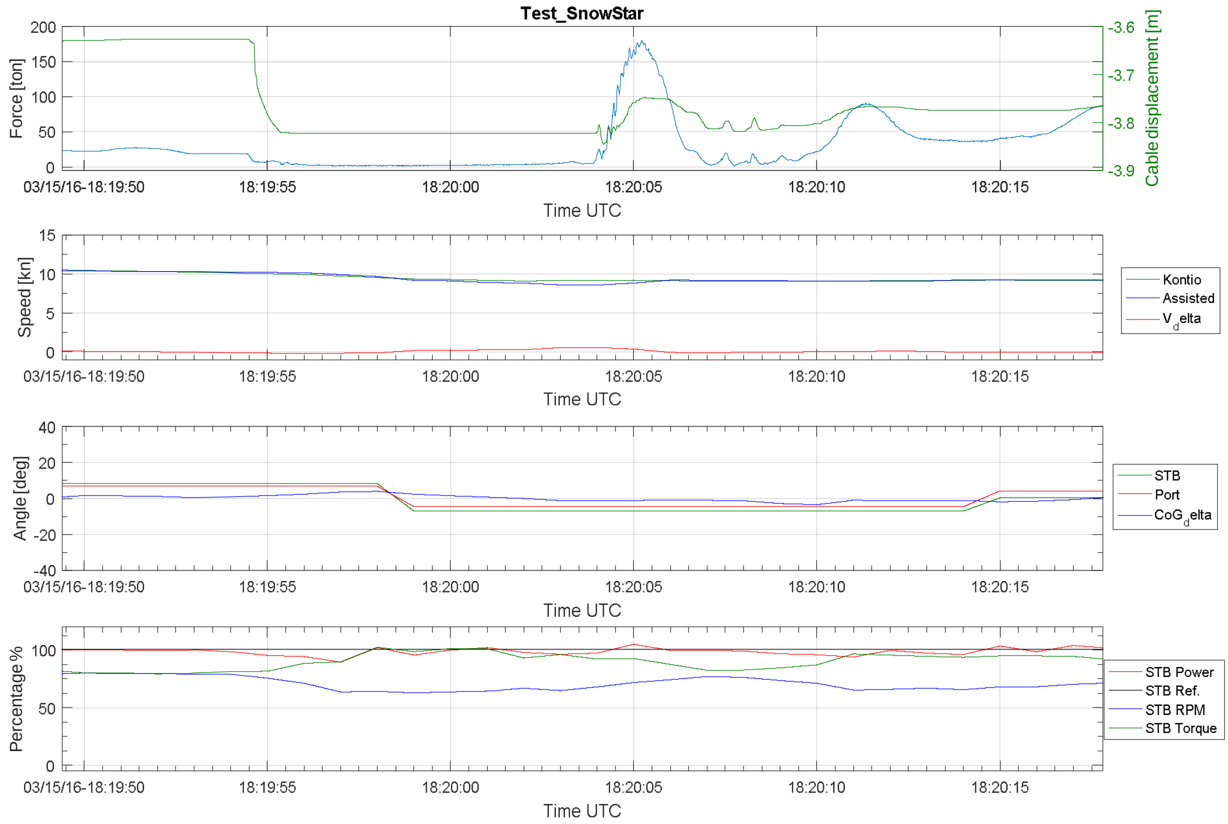

Figure 7-34: Example #2, Time history of a high force peak. It can be seen that the icebreaker has encountered a small ridge (propeller RPM has dropped and torque increased) slowing the icebreaker and allowing the towed vessel to come closer causing slack to the towing wire and dropping the towing line force to nearly zero. As the towed vessel has entered the ridge, its speed has dropped, and on the other hand, the ice breaker is again in easier conditions as the torque is dropping and propeller RPM increasing. As the icebreaker is faster than the assisted vessel, the towing line has suddenly tightened and caused high force peak (180 ton).

Figure 7-35: The situation just after the force peak. The assisted vessel is inside the small ridge formation.

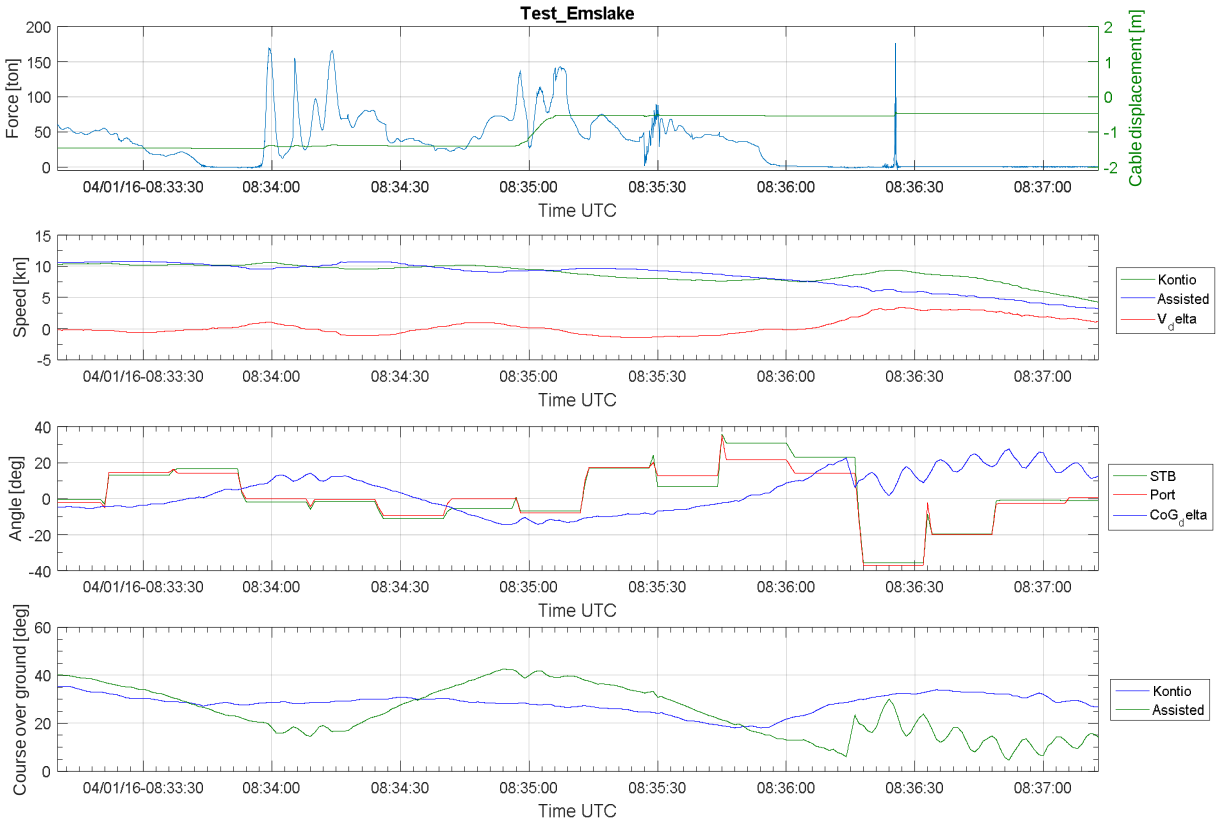

Figure 7-36: Example #3, Time history of the towing operation in which the secondary towing cable failed. The towed vessel had difficulties to follow the icebreaker in a straight path. Instead it was pushing and turning the icebreaker from side to side. Therefore a gap was left between the two vessels in order to help steering. However, the towed vessel still had problems maintaining a straight course which can be seen from the course over ground information, and also from CoG$_{delta}$, In addition to course differences, there has been big speed differences between the vessels. Finally the towed vessel has broken totally loose from the towing fork causing slack to the towing cable. Just before the peak at ~08:36:25 the towed vessel hit the stern of the icebreaker causing a sudden change in the course and rapid force peak in which the secondary towing cable failed. The recorded force peak was ~177 ton which is below the capacity of the main towing cable. However, it is likely that the big difference in courses has caused the secondary towing line to be unevenly loaded and larger load has been acting in the secondary line than at the main cable. In addition, it is possible that the whole peak is not recorded with the 130 Hz sampling rate.

Figure 7-37: The failed towing cable.

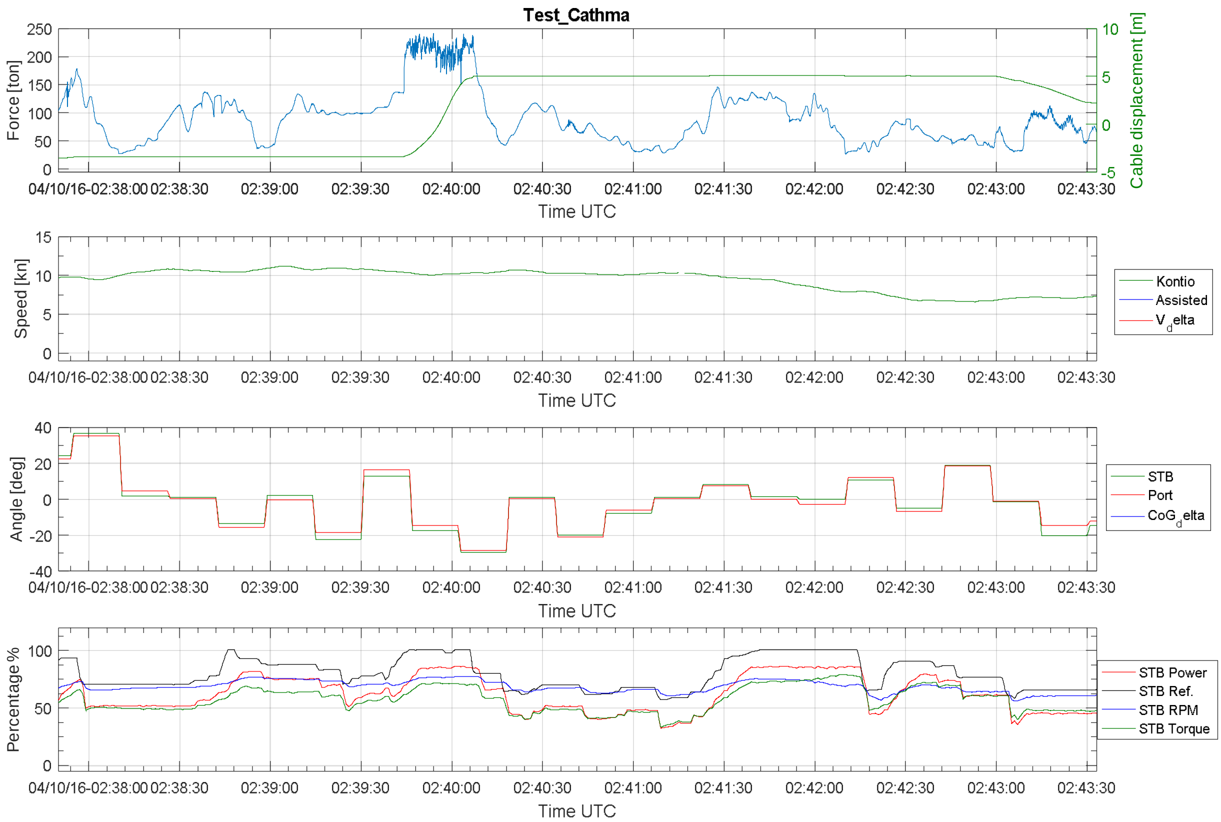

Figure 7-38: Example 4, the highest measured towing force during the measurement campaign. Unfortunately there is no video footage available nor GPS data in order to investigate the relative motions. From the propulsion data it can be seen that the ice conditions have most likely got more difficult as power has been increased and the torque has increased while rpm has stayed relatively the same. As the high load is higher the indicated breaking load of the secondary cable (and also main cable), it is likely that the there was no big relative course difference as the cable did not fail.

8. Conclusions and discussion

Totally 21 towing events were measured during winter 2016 with the Finnish icebreaker Kontio at the Bay of Bothnia. The DWT of the towed vessel ranged from 4106 DWT to 12768 DWT, with the average size of the towed vessel being ~5750 DWT. The average towing speed is relatively high, 9.7 knots.

The towing line force measurements clearly indicate that both the maximum and average forces are linearly dependent on the mass/displacement of the towed vessel. When comparing the forces to a displacement/power ratio of the towed vessel, the maximum forces indicate even better correlation. However, there is more scatter with the average force.
Larger vessel vessels cannot be towed directly in the towing fork in order to improve the manoeuvrability of the icebreaker. The gap between the vessels allow larger differences in course and speed between the vessels which are related to higher forces. The results also indicate that the icebreaker needs larger rudder angles with larger vessels.

The towing force seems to be dependent on the towing speed on many of the measurements. When comparing the whole data set, the average towing force reduces with the average towing speed. This is reasonable as higher towing speeds are possible with smaller vessels and in easier ice conditions.

One common factor for the maximum force peaks is slack in the towing cable. The slack can occur due to variation in ice conditions f.eg. a small ridge which creates speed differences between the two vessels. As the cable is allowed to suddenly tighten, very high forces occur. As explained above, there is larger gap between the vessels when towing larger vessels which in turn allows to have more slack in the cable. Therefore it is more likely to have high force peaks with larger vessels.
During the measurement campaign the secondary towing line failed once and in addition higher forces than the nominal breaking load of the towing lines were measured. In that sense the dimensioning of the cables is insufficient. A broken cable will delay the assistance. However, as the masses are huge, probably no reasonable size cable can withstand sudden speed differences of the vessels. Perhaps some sort of slack compensation for the winch could help to avoid sudden force peaks. In addition, the bow Azipod of the new Polaris-type icebreaker probably improves the situation as the steering can be done with the bow unit and therefore have smaller gap between the vessels.
Another factor for high force peaks is the situation when the towed vessel breaks loose from the towing fork. As the towed vessel is able to move freely behind the icebreaker, the risk of getting slack increases. In addition, the towing line can be in a high angle as the towed vessel can move to the sides of the icebreaker. Again, size of the towed vessels affects this as the larger vessel are further away from the icebreaker which increases the risk of breaking loose from the towing notch. However, the skills of the helmsman of the towed vessel are crucial factor for this as can be seen in the situation in which the towing cable failed. If the towed vessel is not able to follow the icebreaker in straight path, it will push the sides of the towing notch which will turn the icebreaker. In order to improve manoeuvrability, more gap is left between the two vessels which increases the risk of breaking loose from the towing notch. Training of the crew would improve this. In addition, perhaps the design of towing notches could be longer which would reduce the risk of breaking loose from it.

The results did not indicate a clear effect of the bow form to the towing line forces. However, the data set was relatively small.

Measurements were performed during one winter with a limited set of assisted vessels. Longterm measurements would be recommended in order to have better understanding of the towing line forces also during different winters.