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ANALYSIS OF THE INFLUENCE OF THE CHANNEL PROFILE VALIDATING THE POWER REQUIREMENT IN THE FINNISH-SWEDISH ICE CLASS RULES

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FOREWORD

In its report no 66, the Winter Navigation Research Board presents the results from a project: Analysis of the influence of the channel profile. Validating the power requirement in the Finnish-Swedish Ice Class Rules.

Finnish-Swedish ice class rules include requirements for the strength and performance of a ship proceeding in ice. The performance is defined by the maximum speed in a channel of certain thickness. As this requirement is hard to verify, the ice resistance and the power requirement are defined by formulas that use the channel thickness and ship structure as a starting point. The average channel thickness cannot be used in the ice class rules as the profile of the channel also affects the resistance. Instead the brash ice thickness at the centerline of the channel H_M is used. The channel profile in the nature is very uneven and the problem is how to define the centerline channel thickness so that it describes the natural channel thickness as well as possible. The purpose of this study is to compare different ways to define the channel thickness and the resistance and power requirement given by the formulae. These values were compared with the measured resistance and power obtained by full scale and model scale tests.

The Winter Navigation Research Board warmly thanks Ms. Hanna Ritvanen for this report.

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ANALYSIS OF THE INFLUENCE OF THE CHANNEL PROFILE

VALIDATING THE POWER REQUIREMENT IN THE FINNISH-SWEDISH ICE CLASS RULES

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ABSTRACT

In the Swedish-Finnish ice class rules the formulae for approximation of the power and ice resistance are defined by the speed requirement in a channel of certain thickness. As a parameter the formulae use the thickness at the centerline of the ice channel. This thickness is defined by fitting the actual uneven channel profile into a simplified profile based on soil mechanics. Theoretically the channel profile should be measured and taken into account over the whole width where the ice is plowed by the ship. On the other hand, it would be simpler to only measure it up to the beam of the ship or for instance to 1.6B. In this study the different ways of defining the thickness of a channel were studied and the resistance and power requirements derived from the different definitions were compared to the measured values in both model and full scale tests.

According to this study there does not seem to be any distinctive difference between the different ways of calculating the channel thickness. Instead, it was found that the rule formulas gave remarkably larger values of resistance and power especially in high speeds and in thick ice compared to what was measured in the full scale and model tests. However, when the speed and the channel thickness did not exceed the values stated in the rule requirements, the difference between the measured and calculated results was not significant.

Key words: Channel profile, effective beam, rule profile, rule resistance, rule power

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LIST OF SYMBOLS

A_{wf}	water plane area of the fore ship
B	beam of the ship
B_E	effective ship beam
B_I	width of the sloped part in the new channel profile
C	empirical coefficient
D_p	propeller diameter
H	channel thickness
H_{AV}	average channel thickness (measured over the whole width of the channel)
H_F	thickness of the ice layer displaced and moved onto the side of the ship
H_M	channel thickness in the middle
K_T	thrust coefficient
L_{bow}	length of the fore ship
L_{par}	length of the parallel mid body
L_{WL}	length of the ship at the waterline
P	power
P_S	shaft power
R	resistance
R_{CH}	channel resistance
R_{ow}	open water resistance
R_T	total resistance
T	draught
t	thrust deduction factor
T	thrust
T_{net}	net thrust
T_{pull}	bollard pull
v	speed
Δ	displacement
α	water plane entrance angle
φ_1	stem angle
φ_2	stem angle at B/4
ψ	flare angle

1. INTRODUCTION

Finnish-Swedish ice class rules include requirements for the strength and performance of a ship proceeding in ice. The performance is defined by the maximum speed in a channel of certain thickness. As this requirement is hard to verify, the ice resistance and the power requirement are defined by formulas that use the channel thickness and ship structure as a starting point.

The average channel thickness can not be used in the ice class rules as the profile of the channel also affects the resistance. Instead the brash ice thickness at the centerline of the channel H_M is used. The channel profile in the nature is very uneven and the problem is how to define the centerline channel thickness so that it describes the natural channel thickness as well as possible.

The purpose of this study is to compare different ways to define the channel thickness and the resistance and power requirement given by the formulae. These values were compared with the measured resistance and power obtained by full scale and model scale tests.

The concepts used in the study include:

Average thickness of a channel H_{AV} is the geometric mean channel thickness, measured over a certain width of the channel. The widths used are the ship beam B, 1.6B and an equivalent channel width B_E.

Mid thickness H_M refers to the ice thickness on the centerline of the channel or ship

Channel thickness H refers to the ice thickness used in the resistance calculations. Normally same as H_M.

Channel profile is the cross-section of an ice channel, which in the model tests is defined as the average of several measured cross sections.

Theoretical channel profile refers to the simplified channel profile derived from soil mechanics. I use two different profiles which I refer to as the **rule profile** or **new profile**. I shall describe these in chapter 2.1.

All the values are given in full scale units.

2. STARTING POINT AND METHODS OF THE STUDY

2.1 The channel profile

The channel profile used in the Finnish-Swedish ice class rules is a simplified model of a natural ice channel that gets thicker towards the sides. This shape is based on soil mechanics as the brash ice pile slopes depend on the brash ice properties. The rule profile is in theory infinitely wide (Figure 1), and I used as a comparison a more natural profile, where the width of the sloped part of the profile B_I is limited to 30 meters after which the thickness is uniform. This version of the channel profile I refer to as the *new profile*.

2.2 The methods to define the channel thickness

Leiviskä (2004) compared the different methods of calculating the channel thickness in a series of full scale tests that served specially to verify the power requirement of the Finnish-Swedish ice class rules for wide ships. He introduces is his study the concept of *effective beam* B_E, which stands for the channel width which the ship moving through the ice affects. Hence the effective beam is determined by the profile of the channel up to B_E, and the beam of the ship. Figure 1 illustrates the rule profile. The effective beam can be calculated by setting the areas A_1 and A_3 equal. This gives us the effective width for each rule channel where the H_M is given (Leiviskä 2004, p. 6)

$$B_E = B\left(1+\sqrt{\frac{\frac{4H_M}{B}+\tan\delta}{\tan\delta+\tan\gamma}}\right), \qquad (1)$$

where the angle δ is the channel slope (assumed to be equal to 2^o) and the angle γ is the angle of repose of the brash ice i.e. the slope angle of the pile plowed under the channel (assumed to be 22.6^o). For rule channel thicknesses and normal ship beams, the value of effective channel width is about 1.6B. Similar, but a bit more complicated formula can be derived for the new channel profile shown in Fig. 2.

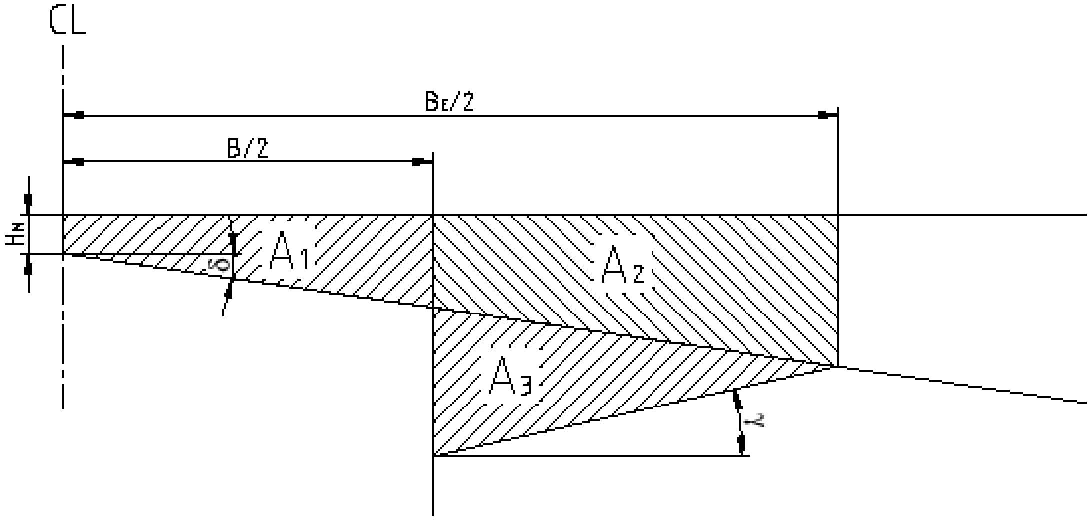

Figure 1: The idealized channel profile before the passing of the ship (areas A_1 and A_2) and after the ship has passed (A_2 and A_3) (Leiviskä 2004, p. 5).

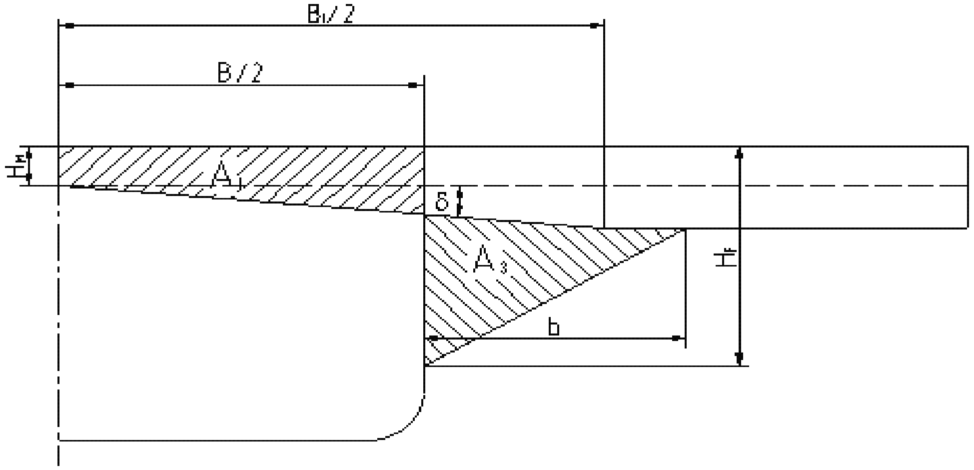

Figure 2: The new channel profile.

In reality the channel thickness is non-uniform and thus the rule value H_M must be determined by fitting the rule profile shape on the shape of the actual channel profile. This is done by first determining the channel profile cross sectional area versus the (half)width as

$$A_{CH} = f(B_E). \tag{2}$$

The measured actual area must be

$$A_{CH} = A_1 + A_2 + A_3$$

$$= \left[\frac{H_M\left(B_E - B\right)}{2}\right] + \left[\frac{B_E^2 \tan 2^\circ}{8} - \frac{B^2 \tan 2^\circ}{8}\right] + \left[\frac{\left(B_E - B\right)^2}{8}\left(\tan 2^\circ + \tan 22{,}6^\circ\right)\right]$$

$$= \frac{1}{8}\left(B_E - B\right)\left[4H_M + \left(B_E + B\right)\tan 2^\circ + \left(B_E - B\right)\left(\tan 2^\circ + \tan 22{,}6^\circ\right)\right] \qquad (3)$$

These areas are depicted in Fig. 3.

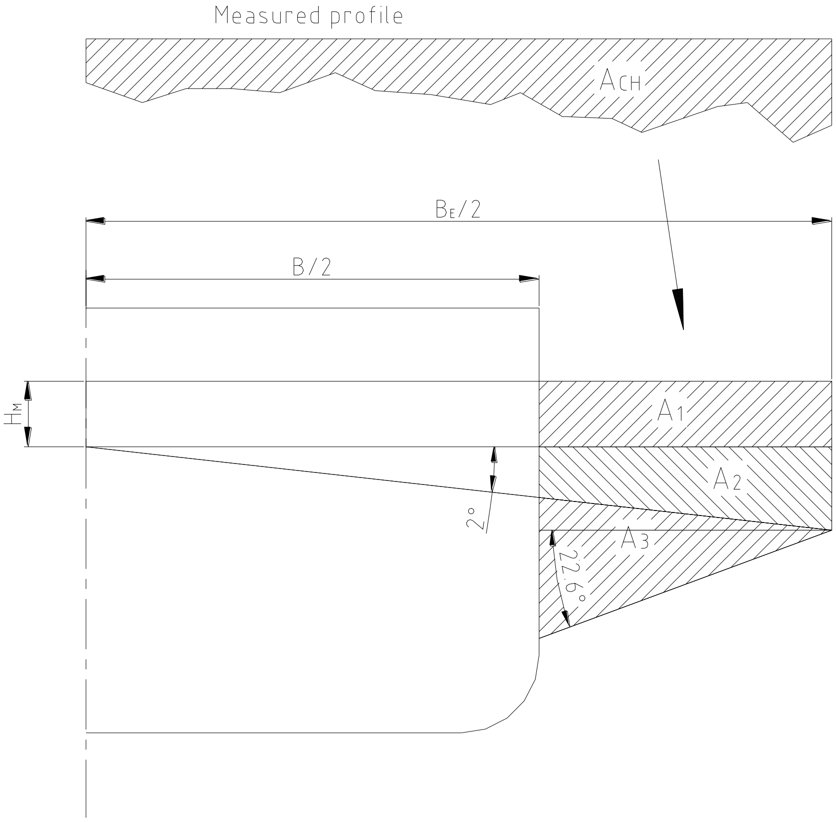

Figure 3: The conversion of the actual channel profile into the rule channel.

As the measured profile must correspond to the rule channel profile we get the last equation as

$$A_{CH} = \frac{H_M B_E}{2} + \frac{B_E^2 \tan 2^\circ}{8}\,. \qquad (4)$$

There is three equations (2), (3) and (4) and three unknown quantities A_{CH}, H_M and B_E. If the two last equations are used to eliminate H_M, then we get finally an equation to determine B_E:

$$A_{CH}(B_E) = \frac{B_E}{8B}(B_E - B)\left[B_E \tan 2^\circ + (B_E - B)\tan 22{,}6^\circ\right] \tag{5}$$

The formula (1) can be simplified by estimating $B_E = 1.6B$, which gives (Leiviskä 2004, p. 7)

$$H_M = \frac{A_{CH} - 0{,}32B^2 \tan\delta}{0{,}8B}\,. \tag{6}$$

As the third estimation for the channel thickness I have used here a method where the channel profile is only taken into account up to the beam of the ship, and the H_M is defined straight from the simplified profile

$$H_M = 2\frac{A_1}{B} - \frac{B\tan\delta}{4}\,. \tag{7}$$

So in all the channels the mid thickness is calculated using six different methods: H_M has been defined as a function of the effective thicknesses $H_M(B_E)$ and $H_M(1{,}6B)$, and the beam $H_M(B)$, both in the infinitely wide rule channel profile and in the new, 30 m wide profile. In the new profile we have three different cases depending on the width of the ship beam in proportion to the width of the sloping part of the profile.

2.3 The model and full scale tests used in calculations

I have used in this study two series of model tests (Leiviskä & Kiili 2004; Wilhelmson 1996) and a series of full scale tests conducted on three different ships; MT Tervi, MT Mastera and MS Birka Express (Leiviskä 2004). Of the Leiviskä and Kiili series I have used the values from the first test in each measurement set to ensure that the channel profile corresponds to the measured profile as well as possible. These tests are all conducted in different channels. The model tests of Wilhelmson are also performed on the same model, Tervi, but varying the length and speed and using only one channel profile. Of this test series I have chosen three results which all have used the full length model on three different values of speed. In Wilhelmson series the draught is 12.5 m whereas in Kiili & Leiviskä series the draught is 7.4 m. The ship particulars are given in Table 1 and the used test results in Table 2.

Table 1: The ship particulars (Leiviskä 2004, 3, 5)

		L_{WL} [m]	B [m]	T [m]	L_{bow} [m]	L_{par} [m]	α [°]	ø1 [°]	ø2 [°]	A_{wf} [m^2]	D_P [m]
MT Tervi	Ballast	180.9	30.2	7.3	34.2	114.5	37	42	39	742	7.1
	Loaded	198.3	30.2	12.5	33.8	132.2	37	42	39	742	7.1
MT Mastera	Ballast	239.3	44	8.9	56.5	108.6	32	90	67	1570	7.6
	Loaded	242.8	44	14.5	49.2	124.2	41	90	66	1370	7.6
MS Birka		154.5	22.7	7	39.2	109	26.5	90	65.5	600	6

2.4 Resistance

The formula given in Finnish-Swedish ice class rules for the resistance of ship going through ice channel is (FMA 2002, 8-9)

$$R_{CH} = C_1 + C_2 + C_3 C_\mu \left[H_F + H_M\right]^2 \left[B + C_\psi H_F\right] + C_4 L_{PAR} H_F{}^2 + C_5 \left[\frac{LT}{B^2}\right]^3 \frac{A_{wf}}{L}, \qquad (8)$$

where the coefficients are

$C_\mu = 0,15\cos\varphi_2 + \sin\psi\sin\alpha$ (to be ≥ 0.45),

$C_\psi = 0,047\psi - 2.115$ (for $\psi \leq 45°$, $C_\psi = 0$),

$$C_1 = f_1 \frac{BL_{PAR}}{2\frac{T}{B}+1} + \left(1+0,021\varphi_1\right)\left(f_2 B + f_3 L_{BOW} + f_4 BL_{BOW}\right),$$

$$C_2 = \left(1+0,063\varphi_1\right)\left(g_1 + g_2 B\right) + g_3\left(1+1,2\frac{T}{B}\right)\frac{B^2}{\sqrt{L}},$$

where

f_1 = 23 N/m^2
f_2 = 45.8 N/m
f_3 =14.7 N/m
f_4 = 29 N/m^2

g_1 = 1530 N
g_2 = 170 N/m
g_2 = 400 N/$m^{1,5}$

C_3 = 845 kg/(m^2s^2),
C_4 = 42 kg/(m^2s^2),
C_5 = 825 kg/s^2,

φ_1 = 90° for ships with a bulbous bow (in this case Mastera and Birka) (FMA 2002, 8),

$$\psi = \arctan \frac{\tan \varphi_2}{\sin \alpha},$$

$$H_F = 0{,}26m + \sqrt{H_M B} \text{ and} \tag{9}$$

$$\left(\frac{LT}{B^2}\right)^3 \text{ to be at least 5 and not more than 20.}$$

C_1 and C_2 are taken into account only in partly consolidated channel (or when defining rule resistance for class IA Super). Of the tests analysed here only the Birka Express had this kind of channel.

The definition of H_F, which describes the height of the friction surface, is problematic for several reasons. To start with, the definition of H_F varied depending on the source. In most sources it was described as the full thickness of the ice mass pressing against the side of the ship (e.g. Riska et al. 1997, 41) and this is also the definition given in the rule formula (8). In some sources (e. g. Juva & Riska 2002, 28) it is mentioned as the thickness of only the ice mass displaced by the ship hull, which would make the full thickness of the ice against the hull H_M + H_F. If it is not so, it seems that an extra H_M is added in the third term of the rule formula (8). Any conclusions should not as yet be drawn without further studies.

Another problem with H_F especially in model test series was the thickness of the channels, due to which the H_F in many of the tests was bigger than the draught of the ship. As H_F corresponds to the height of the friction surface, I have used the ship draught as the maximum value for H_F, unless I have mentioned otherwise. This reduced the comparability of the results especially in thicker channels.

The speed is taken into account in the constant C_5, and as the speed used in the rule formula is 5 knots, I have scaled the constant so that it corresponds to the real speed of the ship.

2.5 Propulsion power

The resistance formula only includes the ice resistance; the open water resistance only affects the power formula. In the tests (apart from Wilhelmson series) only the total resistance was measured, and I had to evaluate the part of the open water resistance. In this I used the total and open water resistance values of a ship going through an ice channel measured by Max Wilhelmson in his Master’s thesis (1996, appendices 3 and 4). With these I could estimate roughly the interdependency between the speed and the open water resistance (Figure 4). The ratio between open water resistance and total resistance, which is quite small due to the low speeds, is given in Table 2.

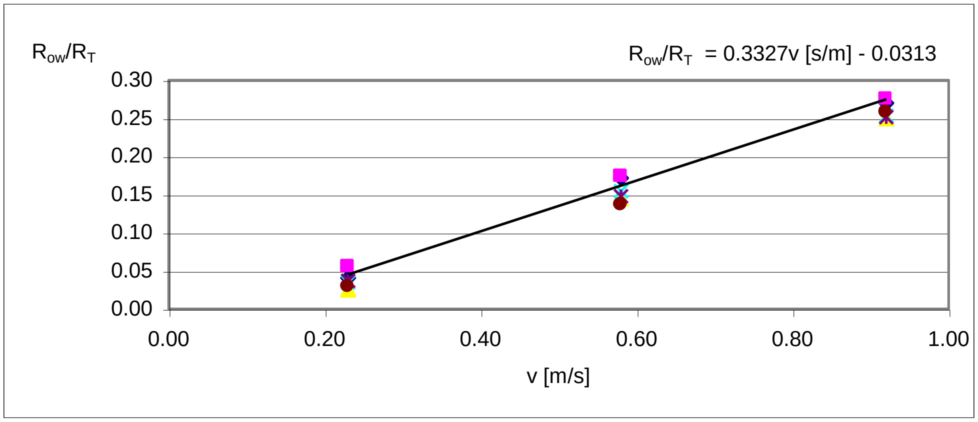

Figure 4: The ratio of open water resistance as a function of ship speed for models of different lengths according to the tests conducted by Wilhelmson with the MT Tervi model. The regression line is fitted to the points of 5.79 m model.

Table 2: The model and full scale tests used, and the corresponding measured values of resistance and power (Leiviskä & Kiili 2004; Leiviskä 2004; Wilhelmson). The open water resistance is approximated using method described in Figure 4. In the Wilhelmson series the open water resistance is measured, and subtracted from the total resistance.

	Test series	Date	R_T [kN]	P [kW]	V [m/s]	R_{ow}/R_T
Kiili & Leiviskä (model of MT Tervi)	1.1	14.5.2003	974	11130	3.31	0.16
	1.2	14.5.2004	1000	10857	3.42	0.17
	2.1	22.5.2003	880	7121	1.52	0.06
	2.2	22.5.2004	733		1.58	0.06
	3.1	28.5.2003	1137	11835	1.89	0.08
	4.1	4.6.2003	1259	12426	0.95	0.02
	4.2	4.6.2004	1500		0.98	0.03
	5.1	12.6.2003	1205	11573	1.16	0.04
	5.2	12.6.2004	1531		1.07	0.03
	6.1	18.6.2003	891	14313	2.72	0.13
	6.2	18.6.2004	1053		2.74	0.13
Wilhelmson (model of MT Tervi)	1	2.8.1996	861 (R_{CH})		1.03	-
	2	2.8.1996	1001 (R_{CH})		2.59	-
	3	2.8.1996	1336 (R_{CH})		4.11	-
Full scale tests with different ships	Birka	1-2.4.2004		6084	2.37	0.12
	Mastera loaded	7.3.2004		1750	3.03	0.11
	Mastera ballast	8.3.2004		2800	2.68	0.13
	Tervi ballast	25.1.2003	596	6346	5.80	0.31
	Tervi loaded	12.3.2004	504	2530	1.59	0.06

The rule formula for the power requirement is based on net thrust which is derived from a typical K_T-curve equation

$$T_{NET} = T_{PULL}\left(1 - \frac{v}{3v_{ow}} - \frac{2}{3}\left(\frac{v}{v_{ow}}\right)^2\right), \qquad (10)$$

where v_{ow} is the maximum open water speed, T_{NET} is net thrust which is set equal to the ice resistance. The maximum open water speed used in ice class rule formula is 15 knots and required speed 5 knots so this makes the value of the speed dependent coefficient 0.8. In my calculations I have used the same maximum speed but setting the speed to the actual speed of the ship. The power is calculated from the net thrust by the formula

$$T_{PULL} = K_E\left(P_S D_P\right)^{\frac{2}{3}} \qquad (11)$$

where K_E is 0.78 for ships with one propeller (Riska et al. 1997, 16–18).

3. RESULTS AND ANALYSIS

3.1 Comparing the methods to define channel thickness

As it can be anticipated, the real profiles of the channels used are far from the simplified, theoretical channel profile (Figure 1). When comparing the different methods I have in the following arranged the results from the test series according to the mid channel thickness so to make them easier to compare.

The Figures 5 and 6 show that mid channel thicknesses calculated from the actual cross sectional area using different channel widths are for thinner channels very close to each other but for thicker channels variation exists. The differences are not very significant. The more the channel profile resembles the theoretical profile, the less the calculated mid channel thicknesses in the same channel differ from each other. For instance the profiles in tests 6.1 and 5.2 were very steep compared to profiles in tests 3.1 or 4.1.

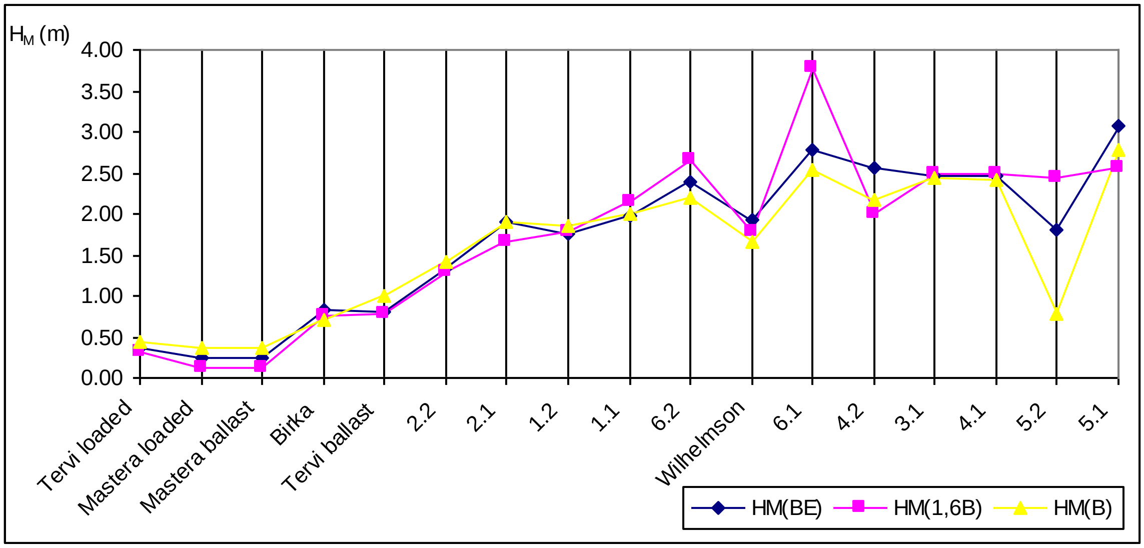

Figure 5: The mid channel thickness calculated from the actual measured profile according to the rule channel profile (see App. 1).

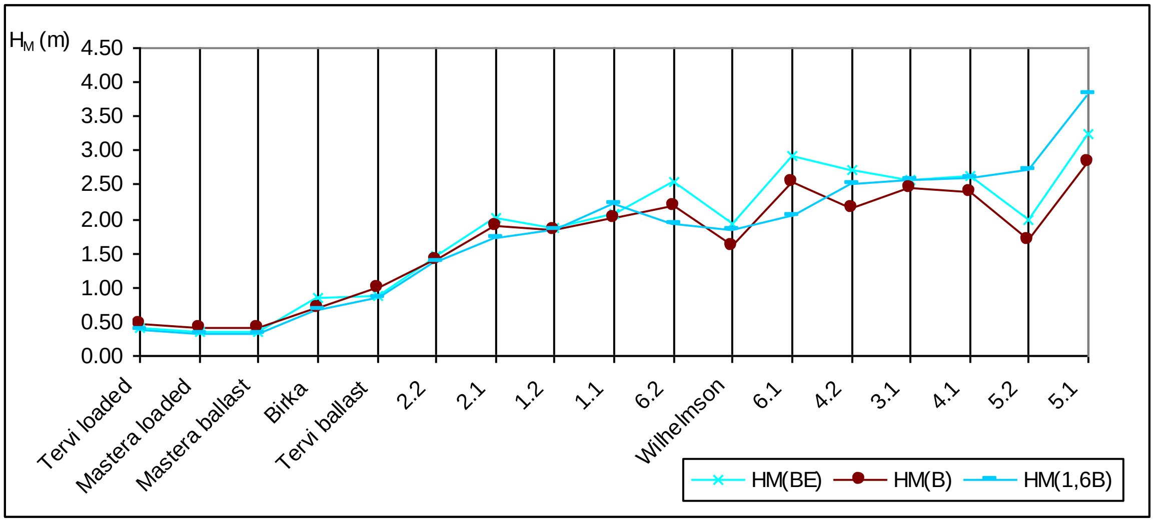

Figure 6: The mid channel thicknesses calculated using different widths of the channel according to the new channel profile (see App. 1).

3.2 The resistance and power

The open water resistance is subtracted from the measured total resistance in order to make them comparable to the resistances calculated with the rule formula. The family of resistance curves is presented in Figure 7 where measured resistances are compared with calculated resistance using different definitions of the mid channel thickness. The variation in calculated values for each measurement point reflect the unevenness in channel profile, for instance the Birka channel was very smooth which can be seen in the results that settle around the same point independent of the calculation method. The calculated values bracket the measured value in thinner channels but in thicker channels (in excess of H_M=2 m) the measured resistance is clearly lower than the calculated. This conclusion is almost solely based on model test results – only one point (Tervi in ballast) shows the same tendency but here the speed was quite high, about 12 knots, and here the method to superimpose the open water and ice resistance might not be valid.

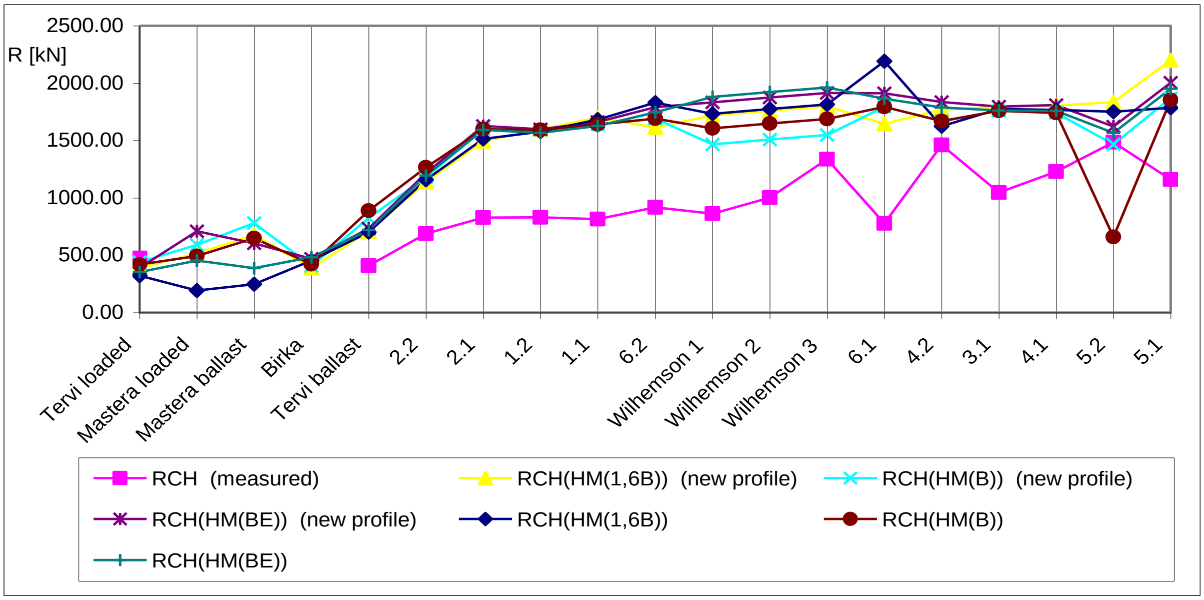

Figure 7: The resistances as functions of mid channel thicknesses calculated with different methods for both rule- and new profiles, and the resistance measured in the tests (see App. 1).

The power required in ice class rules (formula 9) is directly proportional to the 3/2 –power of ice resistance and linearly proportional to the diameter of the propeller. As the power calculated with the rule formula only differs in relation to the resistances given above, in Figure 8 only the rule channel profile is used in representing the power requirements. Tervi’s high rule power requirement in the second measurement point is due to both the high resistance value and the relatively high speed at the time of measurement (see Table 2). The required power of Tervi 04, Mastera 1/04 and Mastera 2/04 is very close to the measured one, for Birka 04 the required is actually lower than the measured one. On the other hand, for thicker channels the measured power is definitely lower than the calculated one.

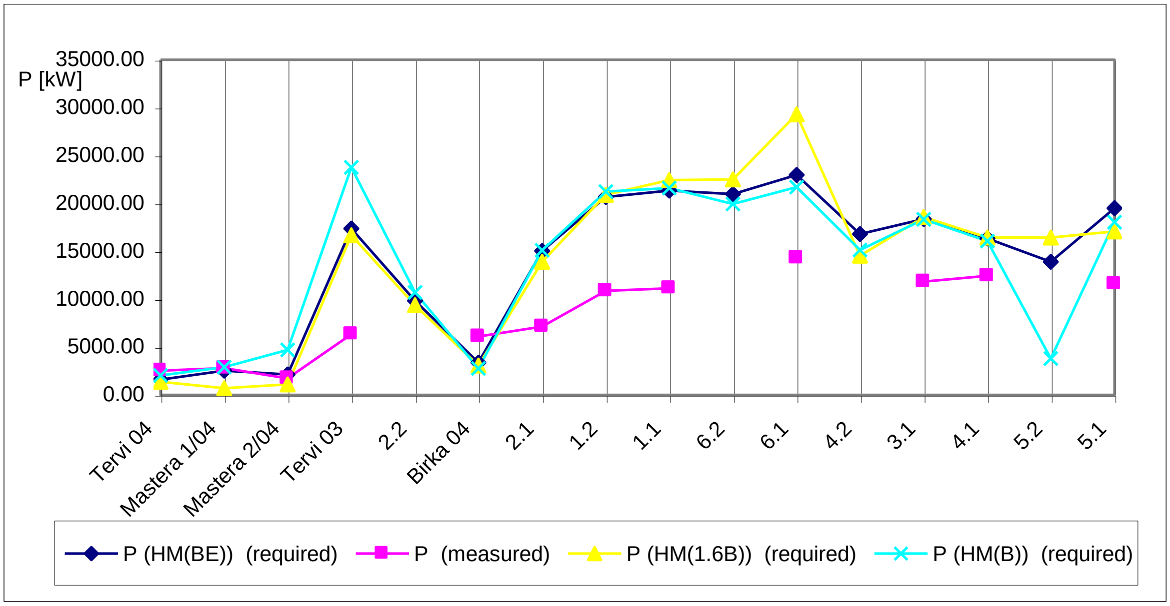

Figure 8: The power requirements in Finnish-Swedish ice class rules compared to the values measured in tests. The rule channel profile is used (see App. 2: Table 2).

3.3 Relative values

The rule formulae give significantly larger values for both resistance and power than what is measured in the tests. In Figures 9 and 10 the deviations of rule values from the measured values are illustrated using the following definition of the relative difference

$$\frac{\Delta R}{R_{CH}} = \frac{R_{CH(rule)} - R_{CH(measured)}}{R_{CH(measured)}} . \qquad (12)$$

It also seems that the thicker the channel the more the rule formula values differ from the measured ones. The rule requirement for ice class IA is speed of 5 knots in a channel of 1 meter, and in this range the differences are not very big. Tervi's high full test value in H_M = 0.81 m is likely due to the speed of over 11 m/s.

When estimating the significance of the deviations, the inaccuracy of the measuring method has to be taken into account. The measurement of ice thickness in model tests is done with accuracy of about one centimeter (Leiviskä & Kiili 2004, 18). Hence the error in full scale can be over 30 cm. The increase of thickness from 1.3 to 1.6 meters can increase the rule resistance up to 25%. Also in the model tests systematic errors due to different measurers can occur.

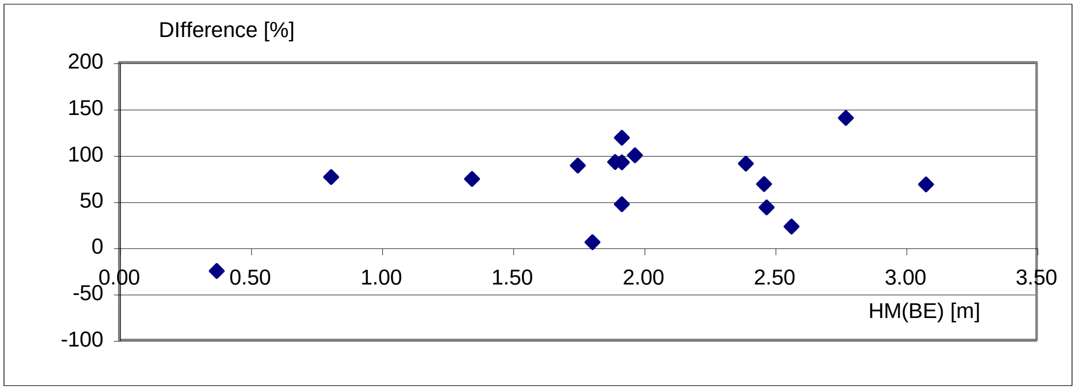

Figure 9: Deviations of rule resistance values from the measured ones on different channel thicknesses calculated with effective beam method in rule profile (see App. 2).

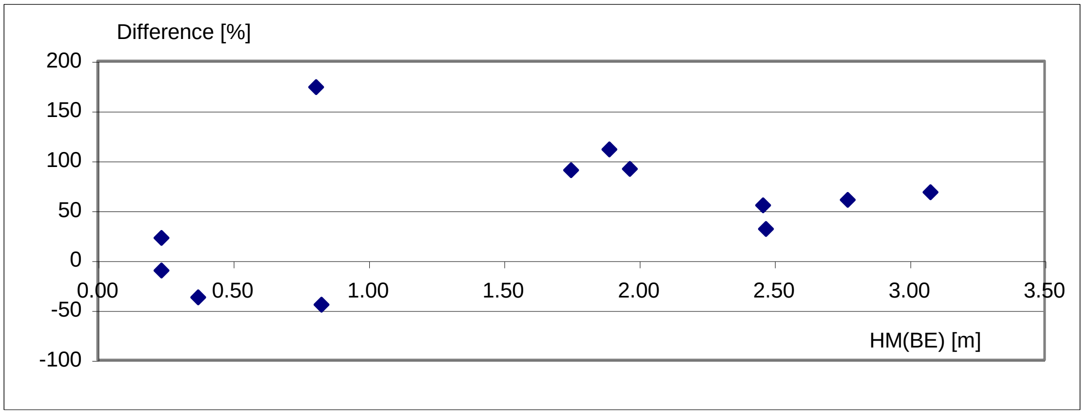

Figure 10: Deviations of rule power values from the measured ones on different channel thicknesses calculated with effective beam method in rule profile (see App. 2).

3.4 H_F poses problems

In chapter 2.4 I described two problems caused by the definition of H_F. In the results I have presented so far I have used the draught T of the ship as a maximum value for H_F. As can be seen from the formula 8, the value or rule resistance grows strongly when the H_F increases. If H_F can not grow over the ship's draught, it creates a deviation from the resistance value given by unchanged formula (Figure 11). This error grows in a linear fashion when the channel thickness grows.

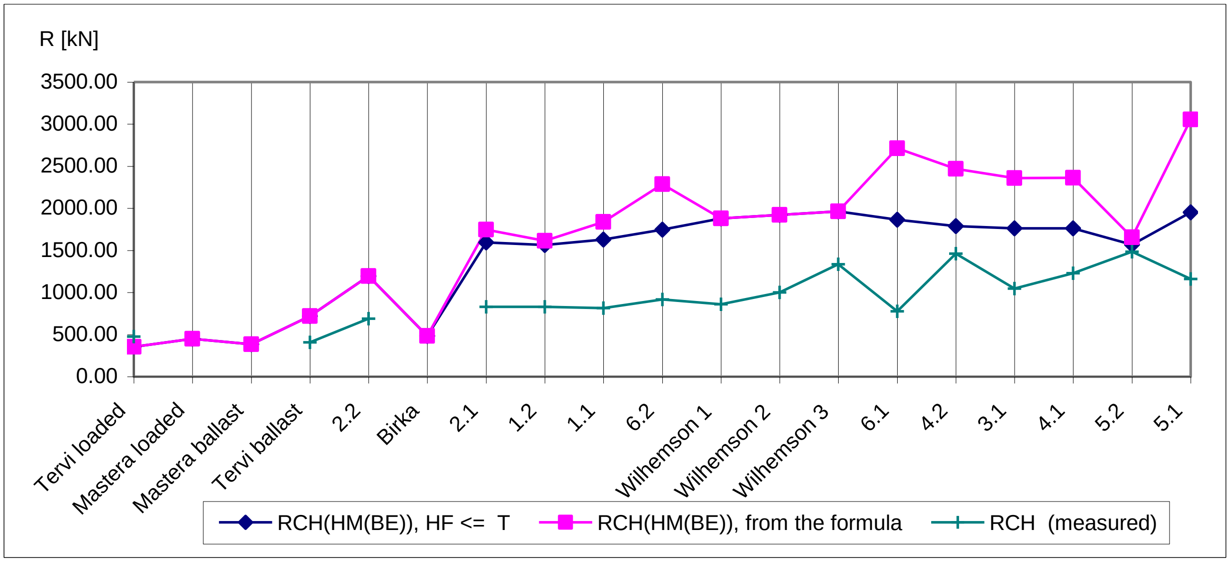

Figure 11: Rule resistance values calculated with effective beam method in rule profile when the maximum value for H_F is T and also when the H_F is taken straight from the formula.

The other question regarding the H_F is its definition in the ice class rule formula (8). If H_F is left out of the third term, the channel thickness is only taken into account through the definition of H_F (9). However, the results seem to correspond better to the measured values (Figure 12).

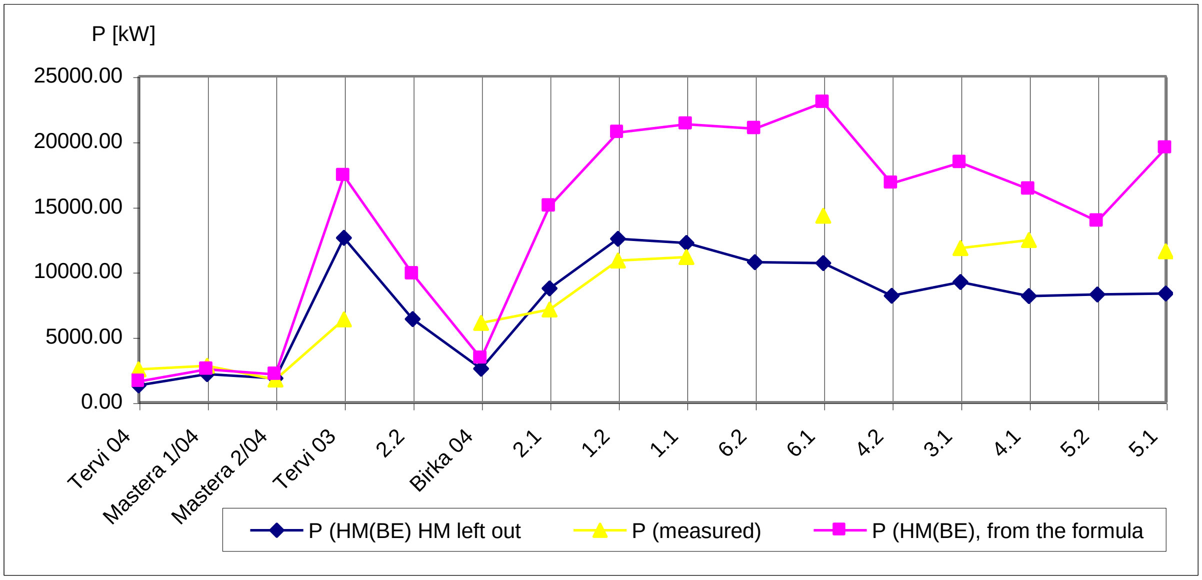

Figure 12: Rule power values calculated with effective beam method in rule profile when the H_M has been left out of the third term of the rule formula, and when the original formula is used, compared to the measured power (see App. 2).

4. SUMMARY

The aim of this study was to compare different ways of defining the channel thickness used in the ice class rule formulas, and the influence of this to the rule resistance and power. There seemed not to be a significant difference between the two different channel profiles used. Also the different methods to calculate the channel thickness did not cause big deviation in the results, at least not in comparison to the large differences between the calculated and measured resistance and power values. The power required in the rules seemed especially in the model tests to be significantly higher than the power measured in the tests. Kvaener Masa-Yards has gotten similar results in full scale tests with MT Mastera, albeit proceeding stern first (Fagerström et al. 2004).

The power requirements and measured values seemed generally correspond better in full scale tests. However, the full scale and model test results were difficult to compare as the channels used in model tests were thick and the speeds low.

The confusion in definition of the friction surface height parameter H_F would be an interesting subject for further studying, as more realistic values for rule power requirement were obtained also on higher channel thicknesses when the H_F-term that caused uncertainty was left out of the rule formula.

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