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Performance prediction of ships in waves – meeting today's requirements on model tests

Prediktera fartygsprestanda i vågor – att möta dagens krav på modellförsök



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Executive Summary

This report summarises work carried out at SSPA Sweden AB in order to further develop testing and evaluation techniques for seakeeping tests with ship models in waves.

In the context of environmental aspects and the introduction of the Energy Efficiency Design Index (EEDI) the topic of “added resistance in waves”, has recently received a lot of attention. Here “added resistance” refers to a concept describing that a ship, which sails in waves, will experience an additional resistance component.

In order to minimise the extra fuel consumption associated with this increase in resistance a large number of energy-saving ideas are currently being explored across the shipbuilding industry. Common measures include small changes to hull form design, such as bow or bulb modifications.

In order to **experimentally assess** the differences in added resistance created by such small changes to an original/parent hull it is necessary to have modern, high-accuracy testing and evaluation techniques. The aim of the project summarised here was to develop such methods and techniques.

Research and development was carried out in four separate “Work Packages” WP1-WP4.

WP1 looks at creating tightly controlled laboratory conditions for seakeeping tests. More specifically it deals with the question of how to generate harmonic water waves of a very high quality (constant height and length).

WP2 deals with post-processing of experimental results and how to correct for unwanted small variations in test speed that almost always occur in “real life”.

WP3 is about verification & validation of the ideas and methods developed in WP1&2

WP4 finally summarises efforts that were made to document and disseminate results and findings.

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List of Symbols and acronyms

EEDI	Energy Efficiency Design Index
h	Water depth in basin
Lpp	Length between perpendiculars (of a ship)
MDL	Maritime Dynamics Laboratory (research facility at SSPA)
V_s	Ship speed
$\alpha(t)$	Wave maker flap angle as function of time
λ	Wave length of a regular wave
WP	Work Package (of the research project described in this report)
RAW	Added resistance in waves
QTF	Quadratic transfer function
RAO	Response Amplitude Operator (a transfer function)
LNG	Liquified Natural Gas
IMO	International Maritime Organisation
R&D	Research & Development

1 Sammanfattning

Forskning och utveckling inom området fartygs sjöegenskaper och prestanda i vågor har ökat signifikant inom såväl akademi som industri under de senaste åren. Anledningarna är flera men är mestadels relaterade till bränslebesparingar, miljöpåverkan, införandet av Energy Efficiency Design Index (EEDI) med tillhörande lagstiftning, IMO (2011 & 2013). Framförallt har vad som kallas "tilläggsmotstånd i vågor" och hur detta kan predikteras och minimeras fångat intresset hos forskare och skrovdesigners, se Kim et al. (2019), Seo et al. (2014) och Lee et al. (2013).

"Tilläggsmotstånd i vågor" är ett begrepp för att beskriva att ett fartyg i sjögång upplever ett tidsvarierande motstånd vars medelvärde kan vara större än motståndet i stilla vatten. Skillnaden mellan motståndet i sjögång och i stilla vatten kallas "tilläggsmotstånd" (eng. added resistance) och brukar anges med R_{AW} , se Figure 1. Tilläggsmotstånd i vågor undersöks ofta genom tester i "regelbundna" vågor, dvs. harmoniska vågor med olika våglängder. Testresultat visas i form av linjära överföringsfunktioner för respektive rörelse i de sex frihetsgraderna för skrovets rörelse samt kvadratiska överföringsfunktioner för tilläggsmotståndet. Höger sida av Figure 1 illustrerar schematiskt en typisk överföringsfunktion för tilläggsmotstånd. Det visar sig att tilläggsmotståndet är som störst för våglängder i närheten av skrovets längd. I dessa fall uppstår resonans och skrovets rörelser relativt vattenytan är som störst. Framförallt hävnings- och stampningsrörelserna (eng. heave och pitch) resulterar i bildandet av vågsystem som transporterar iväg energi från skrovet. Detta manifesterar sig i form av en motståndsökning i förhållande till stilla vatten.

För handelsfartyg utgörs en signifikant del av det totala motståndet av tilläggsmotstånd, även i moderata sjötillstånd. Tilläggsmotståndet hos fartyg med fylliga linjer kan uppgå till nästan 30% av det totala motståndet, se Figure 2.

Härmed är det inte förvånande att designers och varv alltmer fokuserar på att optimera fartyg för att prestera väl i sjögång genom att försöka förstå hur skrovformen påverkar tilläggsmotståndet i vågor.

Vanliga åtgärder för att reducera tilläggsmotståndet inkluderar små ändringar av skrovformen, t.ex. modifieringar av bulb eller stäv. Ett exempel på en liknande modifiering illustreras i Figure 3, där en modern "energibesparande" stäv jämförs med en mer traditionell variant.

Även om beräkningshydrodynamik (eng. Computational Fluid Dynamics, CFD) och datorsimuleringar blir alltmer pålitliga så är experimentella metoder och fysiska modellförsök fortfarande huvudvalet när det handlar om prediktion av fartygs prestanda.

För att **experimentellt** kunna bedöma de små skillnaderna i tilläggsmotstånd skapade av de två stävformerna i exemplet i Figure 3 är det nödvändigt med en väldigt hårt kontrollerad laboriemiljö under modellförsök i vågor. Mer specifikt kräver sådan precision:

1. Vågor av väldigt hög kvalitet (konstant höjd och längd)
2. Moderna utvärderingsmetoder som tar hänsyn till de små variationerna i fart som är ofrånkomliga vid försök med friseglände modeller.

Denna rapport sammanfattar forsknings- och utvecklingsarbete utfört vid SSPA som syftar till dessa två punkter.

Arbetet har finansierats av Trafikverket, Hugo Hammars fond för sjöfartsteknisk forskning och Fru Martina Lundgrens fond för sjöfartsteknisk forskning vid SSPA. Specifika delar relaterade till våggenerering har finansierats separat av SSPA.

Förbättrade metoder för våggenerering (AP1)

Även om försöks- och utvärderingsmetoder vid SSPA generellt sett är mogna så är ett område där förbättringar är möjliga är generering av regelbundna vågor.

Experiment i SSPAs *Maritime Dynamics Laboratory* (MDL, Figure 3) har visat att de faktiska vågorna avviker från den önskade regelbundna formen, i huvudsak vad gäller amplitud. Även om detta var acceptabelt förr så fokuserar den moderna forskningen alltmer på frågeställningar som kräver vågor av högre kvalitet. Exempel på sådana fall sträcker sig från stävformerna i Figure 3 till validering av CFD-beräkningar för att bestämma 'Minimum Propulsion Power' i enlighet med de senaste EEDI-riktlinjerna (IMO 2013).

Syftet med arbetet i AP1 var att generera vågor av bättre kvalitet. Mer specifikt var målet att generera regelbundna vågor med konstant form, period och framförallt konstant amplitud.

Två olika sätt att förbättra vågkvaliteten undersöktes:

1. Mer avancerad styrning av vågbildarna, dvs. användandet av andra ordningens teori för vågbildare istället för första ordningens teori.
2. Reduktion av vågreflektioner och störningar från bassängens sidor genom att täcka för stränderna och öppningar med plywood-skivor för att åstadkomma en slät vägg.

Följande slutsatser kan dras från arbetet i AP1:

- (1) **Ingen förbättring** kan förväntas från användandet av andra ordningens vågbildarteori för våglängder större än 4 m. Vågor av denna längden eller kortare är dock väldigt viktiga vid försök i MDL.
- (2) Plywoodskivor leder till **signifikant förbättring** av vågkvaliteten. Framförallt:
 - (a) Vågorna är mer stabila och jämna över hela bassängen
 - (b) Störst effekt för korta vågor.
 - (c) Långa vågor fortfarande begränsade av effekten av vattendjupet med, i praktiken, en gräns för våglängd-vattendjupförhållande omkring två.
 - (d) Användandet av täckskivor leder till längre väntetider mellan försök på grund av tvärreflektioner och lägre dämpning.
- (3) Benchmark-försök med en KVLCC2-modell visar god överensstämmelse mellan resultat från MDL och publicerade överföringsfunktioner tilläggsmotstånd och rörelser i vågor. Resultaten finns i kapitel 5 i denna rapport.

Förbättrade metoder för analys av försök i vågor (AP2)

Försök i vågor i MDL för att studera ett fartygs sjöegenskaper kan utföras med antingen en fast inspänd modell eller med en helt friseglände modell. Vid försök med fast inspända modeller så tillåts de vanligtvis att häva och stampa (eng. heave och pitch) men hålls låsta i de andra fyra frihetsgraderna. Vid försök med en friseglände modell, å andra sidan, kan modellen röra sig obehindrat i samtliga frihetsgrader.

Försök i vågor i utförs vanligtvis med friseglände modeller. Denna försöksteknik innebär att modellens beteende noga efterliknar beteendet hos det riktiga fartyget men innebär dessvärre ett antal svårigheter.

Tilläggsmotståndet i vågor beräknas i linje med vad som beskrivs i Figure 1, dvs. genom att subtrahera motståndet i stilla vatten från tidsmedelvärdet av motståndet i vågor. **Motstånd** beräknas baserat på uppmätta tidsserier av **propellertryckkraften** samt en så kallad *sugfaktor* uppmätt i stilla vatten. Denna faktor bestäms typiskt med hjälp av motstånds- och självdriftsförsök med en större modell av samma fartyg i en släpräna.

I början av ett försök i vågor accelereras modellen med hjälp av vagnen som den är kopplad till via hart spända linor. När modellen har uppnått sin nominella fart släckas linorna och modellen

fortsätter att segla fri, framdriven endast med hjälp av sin propeller. Denna procedur är nödvändig för att få upp modellen till full fart så snabbt som möjligt för maximal mätsträcka.

Under själva försöket hålls propellerns varvtal konstant och modellens fart är ett resultat av detta varvtal. Detta tillvägagångssätt med konstant varvtal liknar hur ett riktigt fartyg framförs och har flera praktiska och experimentella fördelar. Dessvärre har det även en signifikant nackdel: För att uppnå en konstant fart måste propellertryckkraft och skrovmotstånd uppnå jämvikt. Antagandet om hydrodynamisk jämvikt erfordrar en perfekt *a priori* gissning av propellervarvtalet så att tryckkraften exakt balanserar motståndet vid den önskade farten. Om varvtalet är felaktigt så kommer modellen att antingen öka eller minska sin fart under försökets gång och den antagna stationariteten uppnås inte.

Följaktligen ”förorenas” kraftmätningarna genom modellens **variation i hastighet** och det är därmed inte möjligt att på ett korrekt sätt dela upp den totala tryckkraften i en stilla vatten-del och tilläggstryckkraft. Detta påverkar så klart kvaliteten på resultaten. I extrema fall måste försöken köras om med justerat varvtal vilket leder till experimentellt svinn i storleksordningen 30-40 %.

Syftet med arbetet utfört i AP2 var att utveckla en ny utvärderingsmetod som kan ta hänsyn till ovanstående variationer i hastighet som är en naturlig del av försök med friseglände modeller. Detta förväntas höja kvaliteten på resultaten och samtidigt effektivisera försöksprocessen.

En ny utvärderingsmetod har således utvecklats, implementerats som ett tillägg till den befintliga utvärderingsmjukvaran samt använts till att analysera försöksresultat från experiment med en modell av ett tankfartyg byggd för ändamålet.

Den nya metoden är baserad på Newtons andra lag och är kvasi-stationär i sin natur. Den tar hänsyn till modellens lilla oönskade acceleration som i praktiken nästan alltid uppstår vid modellförsök.

Verifikation och validering av förbättrade metoder för försök i vågor (AP3)

Syftet med arbetet i AP3 var att **verifiera och validera** de tekniker och metoder som utvecklades i AP1 och AP2.

För detta ändamål konstruerades och tillverkades en speciell fartygsmodell som användes för försök i de förbättrade vågorna från AP1. Resultat från försöken utvärderades sedan med den nya metoden från AP2 för att korrigera för tröghetskrafter på grund av oönskad acceleration av modellen vid friseglände försök. Slutligen jämfördes resultat från försöken med benchmark data från litteraturen.

Resultaten från undersökningen visar att den föreslagna nya metoden ser lovande ut då den minskar experimentell spridning och resulterar i värden på tilläggsmotstånd som ligger närmare resultat från CFD. De flesta försök i regelbundna vågor på SSPA utvärderas numera med denna metod.

Dokumentation och dissemination (AP4)

Vissa delar sammanfattade i denna rapport var delfinansierade av SSPA, *Hugo Hammars fond för sjöfartsteknisk forskning (HHS)* och *Fru Martina Lundgrens fond för sjöfartsteknisk forskning vid SSPA (FL)*.

För dessa delar har ett antal interna rapporter och dokument författats:

Rapporttitel	Rapportnummer	Datum
KVLCC2 model design	TF107102-B	Nov. 2017
Partial covering of L-side beaches in MDL: Results and conclusions	RI40178363-01-00-A	Feb. 2018
Laboratory generation of regular waves	RF40178363-01-00-A	May 2018
Numerical experiments	Projektrapport_HHI 121_ML106	Oct. 2019

Rön från projektet publicerades även nyligen vid *6th International Conference on Advanced Model Measurement Technology for The Maritime Industry (AMT)*: Kjellberg, M., Gerhardt, F. C. "Improved methods for the experimental determination of added resistance in waves.". **6th AMT**. 2019. Rome.

Ytterligare en publikation från arbetet planeras för en specialutgåva av *Journal of Ocean Engineering* inriktad på "the state-of-the-art in model and full-scale measurement technology for the maritime industry".

2 Introduction

Research and development within the field of ship performance in waves has significantly increased in both academia and industry during the last years. The reasons for these efforts are many but are mostly related to fuel savings, environmental aspects, the introduction of the Energy Efficiency Design Index (EEDI) and associated legislation, IMO (2011 & 2013). Especially the topic of “added resistance in waves”, and how to predict and minimise it, has received attention by researchers, designers and shipyards, see e.g. Kim et al. (2019), Seo et al. (2014) and Lee et al. (2013).

2.1 Background

“Added” resistance in waves is a concept to describe that a ship, which sails in a seaway, will experience a time-varying resistance that, on average, can be greater than the calm water resistance. The difference between “average resistance in waves” and “calm water resistance” is called “added” resistance R_{AW} , see Figure 1. Added resistance is often investigated by testing in “regular” i.e. harmonic waves of different length. Test results are shown in the form of linear transfer functions called *Response Amplitude Operators* (RAOs) for motions (surge, sway, heave, roll, pitch, yaw) and a *Quadratic Transfer Function* (QTF) for added resistance. The right-hand part of Figure 1 schematically illustrates a typical added resistance QTF. As can be seen, added resistance is largest for wave lengths approaching the ship length. Under this condition resonance occurs and the relative motions between ship and water are largest. In particular heave and pitch motion generate wave-systems that carry energy away from the hull. This transfer of energy manifests itself as a resistance increase compared to calm water.

For very long waves relative motions are small and R_{AW} becomes negligible. For short waves, on the other hand, R_{AW} approaches a small but finite value that is associated with wave diffraction and reflection, see Lloyd (1989).

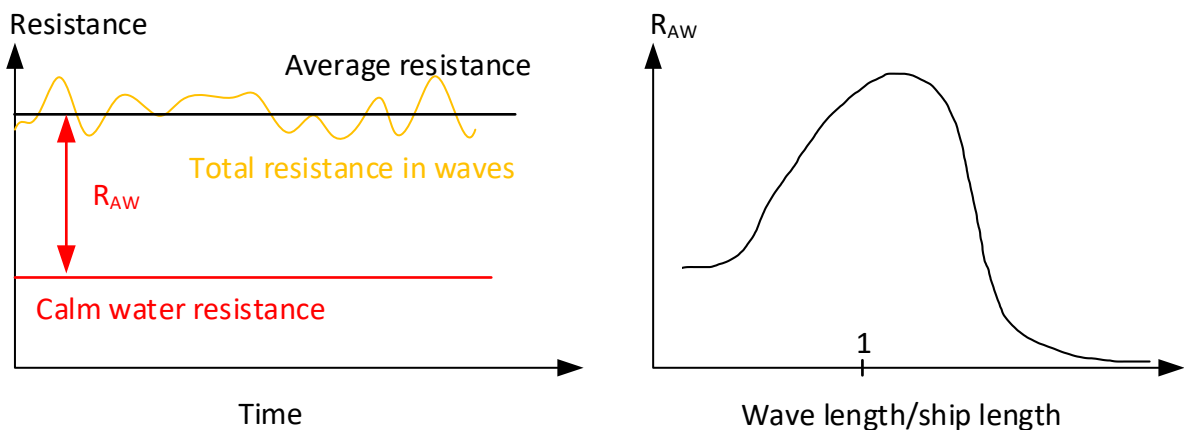


Figure 1: The concept of “added resistance” (left) and a schematic of a RAW QTF (right)

For merchant ships “added resistance” constitutes a significant part of the total resistance, even in moderate sea states.

As Figure 2 illustrates R_{AW} of vessels with full lines, such as bulk carriers or oil tankers, can account for almost 30% of the total resistance.

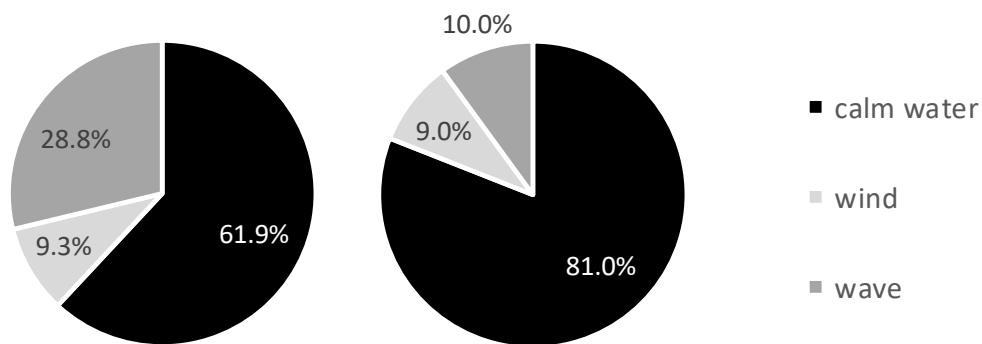


Figure 2: Resistance components in irregular short-crested head seas of 3 metres significant height. Wind speed 12.6m/s. Large bulker (left) and LNG-carrier (right)

It is therefore understandable that designers and shipyards increasingly focus on optimising vessels to perform well in waves by trying to understand the effect of hull form on added resistance.

Common measures to reduce added resistance include small changes to hull from design, such as bow or bulb modifications. A typical example is shown in Figure 3 which compares a modern “energy saving” bow to a more traditional design.

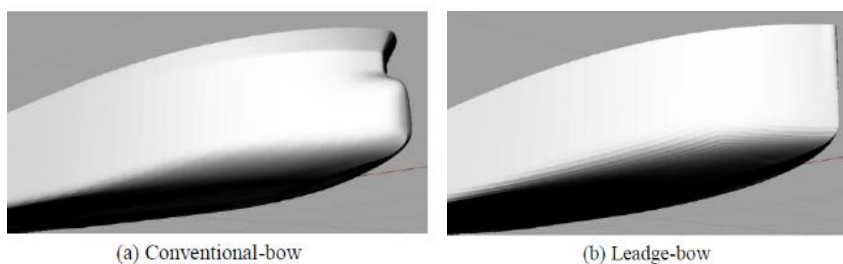


Figure 3: Bow shapes designed to reduce added resistance in waves, from Lee et. al (2016)

Although Computational Fluid Dynamics (CFD) and computer simulations are getting more and more reliable, experimental methods and model testing are still the main method of choice when it comes to performance prediction of ships.

In order to **experimentally** assess the tiny differences in added resistance created by the above two bow-shapes it is necessary to have very tightly controlled laboratory conditions during seakeeping model tests. More specifically such precision tests require:

1. Waves of a very high quality (constant height and length)
2. Modern evaluation methods that can account for the small variations in test speed that are inherent to free-sailing seakeeping tests

The current report summarises Research & Development (R&D) work carried out at SSPA in order to address these two issues.

Work was generously funded by the *Swedish Transport Administration (Trafikverket)*, the *Hugo Hammars fond för sjöfartsteknisk forskning (HHS)* and the *Fru Martina Lundgrens fond för sjöfartsteknisk forskning vid SSPA (FL)*. Specific parts related to wave generation were separately financed by SSPA.

2.2 Structure of this report

Work was organised in several work packages (WP) and the structure of this report reflects this subdivision:

- Chapter 3 (WP1) summarises investigations into generation of high-quality harmonic water waves
- Chapter 4 (WP2) looks into improved evaluation methods for the analysis of free-sailing seakeeping model tests.
- Chapter 5 (WP3) applies the methods and tools developed in WP1&2 to typical seakeeping tests, presents a benchmark-study and compares results to data from the literature.
- Chapter 6 (WP4) gives an overview of research output and publications that resulted from the work described here.

3 Improved methods for generation of harmonic waves (WP1)

This chapter looks into the first of the two research questions that were introduced above, i.e. it deals with the issue of how to generate harmonic water waves of a very high quality (constant height and length).

3.1 Introduction

While testing and evaluation techniques in SSPA's Maritime Dynamics Laboratory (MDL) are generally mature, one area in which improvements are possible is the generation of regular (i.e. harmonic) waves.

3.1.1 Background

Experimental investigations in MDL have shown that the actual waves deviate from the perfect harmonic form, mainly in height/amplitude. While this was acceptable in the past, modern research increasingly focuses on questions that require waves of a higher quality. Examples of such cases range from the bow shapes in Figure 3 and the validation of CFD-calculations to tests to determine the 'Minimum Propulsion Power' according to the latest EEDI-guidelines (IMO 2013).

3.1.2 Purpose of study

The purpose of work under WP1 was to produce waves of a better quality. More specifically the target is to produce regular waves of constant form, period and above all constant amplitude.

3.1.3 Scope and limitations

Two different ways to ways to improve wave quality were investigated:

1. Controlling the wave generators in a more advanced way i.e. using control signals that are based on "second order wave maker theory" instead of the current first order approach
2. Reducing wave reflections and disturbances from the sides of the basin by covering beaches and openings with plywood sheets that create a smooth wall

3.1.4 Methodology

In order to investigate the above two ways to improve wave quality the following approach was chosen:

- 1) In-depth literature study of second order wave maker theory, its deviation, application and limitations. Numerical simulations based on potential flow theory
- 2) Design and construction of plywood covers. Experiments to investigate influence on wave quality

Details about the investigations into second order wave maker theory and plywood covers can be found in sections 3.2 and 3.3 respectively.

3.2 Second order wave maker theory - Sine in Sine out?

Today regular waves in the seakeeping basin are produced by moving the flap-type wave makers in a sinusoidal way. The literature is however, full of references indicating that the waves produced by such a harmonic motion of the wave generators do not necessarily have the ideal constant form, that should be expected from the regularity of the flap motion. As the waves propagate down the basin, they can slowly change form and height.

One possible explanation for this was discovered by Biésel & Suquet (1951) and later systematically studied by Hansen & Svendsen (1974). The authors agree that, a sinusoidally varying wave maker motion, as derived for first-order wave maker theory, also produces unwanted free secondary waves, which move at a speed that is slightly slower than the primary wave. The combination of the primary and secondary waves results in a waveform that varies both, spatially and temporally. The solid blue line labelled ‘actual’ in Figure 4 illustrates such ‘distorted’ non-optimal wave profile.

Hansen & Svendsen have shown that this problem can be mitigated by moving the wave maker flap in a clever way.

More specifically this is achieved by sending a bi-chromatic (two frequency) control signal to the wave maker. This signal consists of the principle frequency ω and a superimposed ‘auxiliary’ signal of twice this frequency. The amplitude and the phase shift of this auxiliary signal are chosen in such a way as to suppress the unwanted free secondary wave, compare right hand side of Figure 2B).

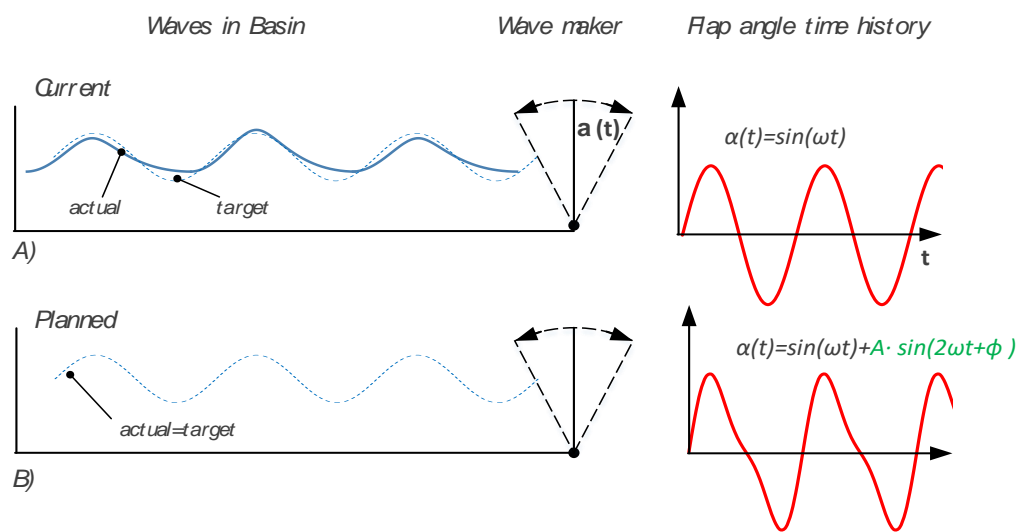


Figure 4: Generation of regular waves of constant form using bi-chromatic wave maker signals

The original aim of this work package (WP1) was to study, understand and implement the ideas of Hansen & Svendsen in SSPA’s Maritime Dynamics Laboratory (MDL).

A detailed study of the theory from Hansen & Svendsen and the underlying calculations of Biésel & Suquet and Fontanet (1961) revealed however, that second order effects in wave making become important only for waves that are long compared to the water depth.

$$h/\lambda < 0.65 \quad (1)$$

or, with the typical laboratory water depth of 2.55 m:

$$\lambda > 4\text{m}$$

Madsen (1971) obtains a similar result based on a somewhat simpler theoretical approach, compare also Hughes (1993).

Practical experience from MDL however shows, that even waves with $\lambda \ll 4\text{m}$ show strong variations in height as they travel down the basin. After some deliberation and supporting calculations based on higher order potential flow theory it was decided that **unwanted free secondary waves could not be the main reason for the poor wave quality in MDL**. Consequently, it was decided to shift the focus of the research and look for alternative explanations.

3.3 Wave reflection from the sides of the basin?

In discussions with long-term employees at SSPA the issue of basin design and the way the “beaches” are constructed was identified as one possible reason for the poor wave quality. There had always been speculation about wave reflection on the concrete pillars of the beaches and it was decided to investigate this further.

3.3.1 Problem: Basin construction and concrete pillars

Figure 5 illustrates the general construction of SSPA’s seakeeping basin MDL. As can be seen there are two wave makers, called Q and L, that can be moved individually or simultaneously. For most commercial testing, only one wave maker is used at a time. Once the waves have travelled down the basin they are absorbed by beaches on the opposite side to avoid reflection. The absorbing beaches (Q and L) are located under the quayside, which is supported by concrete pillars; see also Figure 6 and Figure 7.

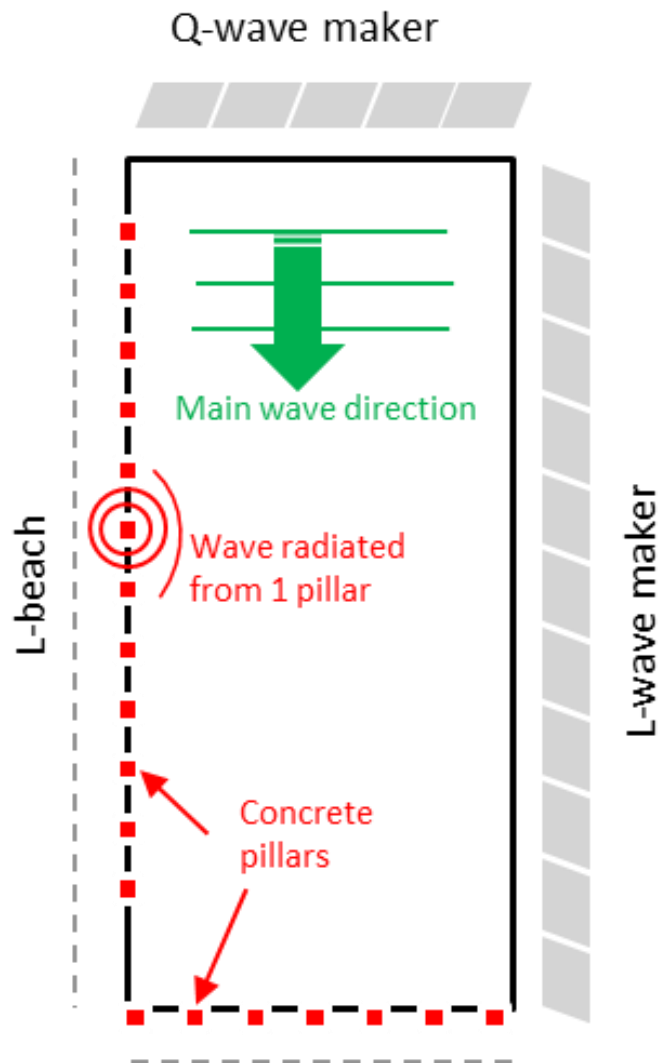


Figure 5: Basin construction. Wavemakers on two sides, absorbing beaches on opposite sides. The beaches are located under the quayside that is supported by pillars. Pillars will create reflection.

Currently the concrete pillars from the “unused” beaches (L-beach in Figure 3) are hit by the incoming waves and this leads to reflected waves being radiated from each of the pillars, see red

circular wave pattern in Figure 3. These reflections are superimposed onto the incoming waves and create a complicated interference pattern thus destroying the regularity of the original wave.

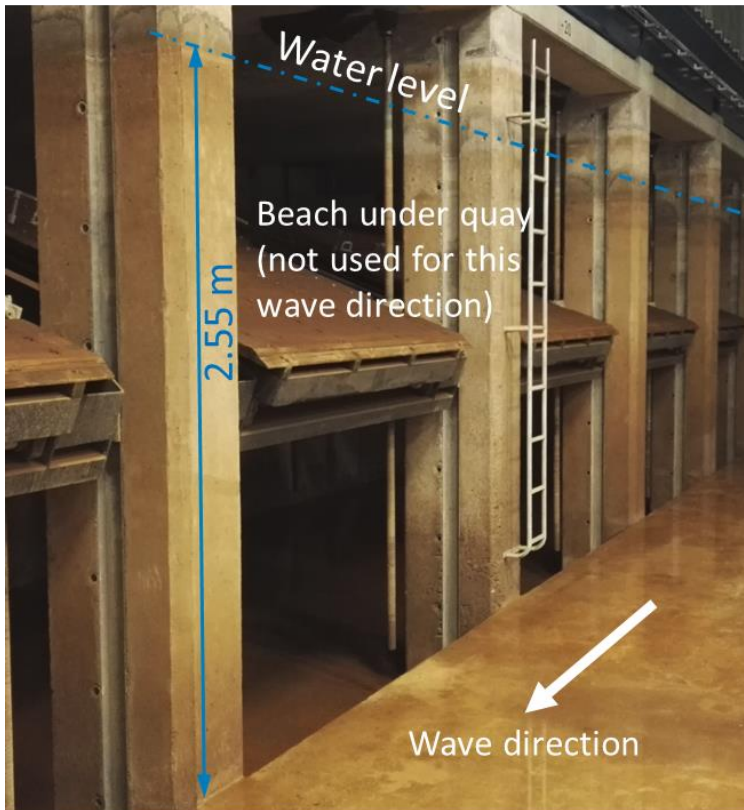


Figure 6: Details of basin construction. Concrete pillars in the foreground, beaches in the centre. Water drained for construction work

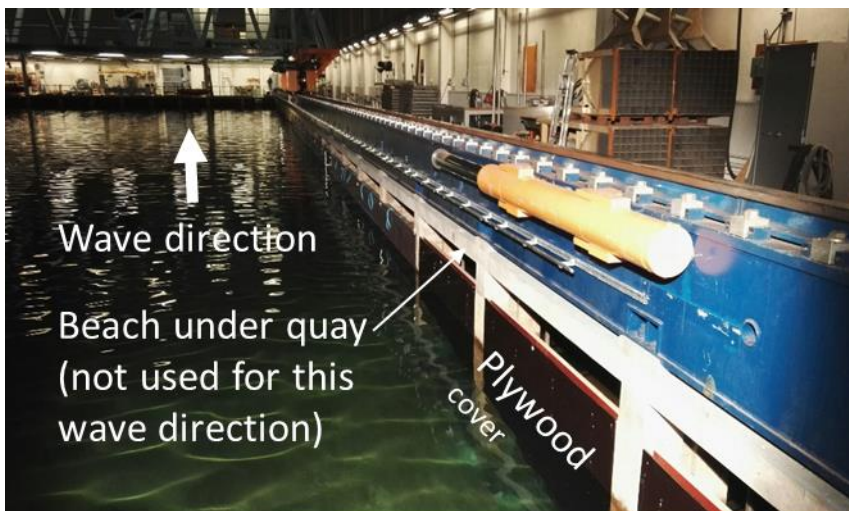


Figure 7: View of MDL basin and concrete pillars (here covered)

The problem of wave reflection from the pillars has been known for a long time. SSPA's "collective memory" in the form of former employees and long-term personnel remembered a project from the 1980'ies where a promising attempt to cover the pillars had been made. A search of the project archive yielded construction drawings and calculations for beach covers that could hydraulically be activated as well as a preliminary setup with temporary wooden covers. Unfortunately, no measured data regarding the influence of the covers on wave quality had survived. It was therefore decided to test temporary wooden covers again. The resulting construction of "plywood cover" was separately financed by SSPA and results are presented below.

3.3.2 Solution idea: Plywood covers

To investigate the effect of covering the pillars a two-step process was adopted:

- 1) Installation of partial covers that could be mounted with the water still in the basin, (orange in Figure 8). Preliminary tests with these partial covers looked promising
- 2) Extend the partial covers to full covers, for this all the water had to be drained from the basin, Figure 9

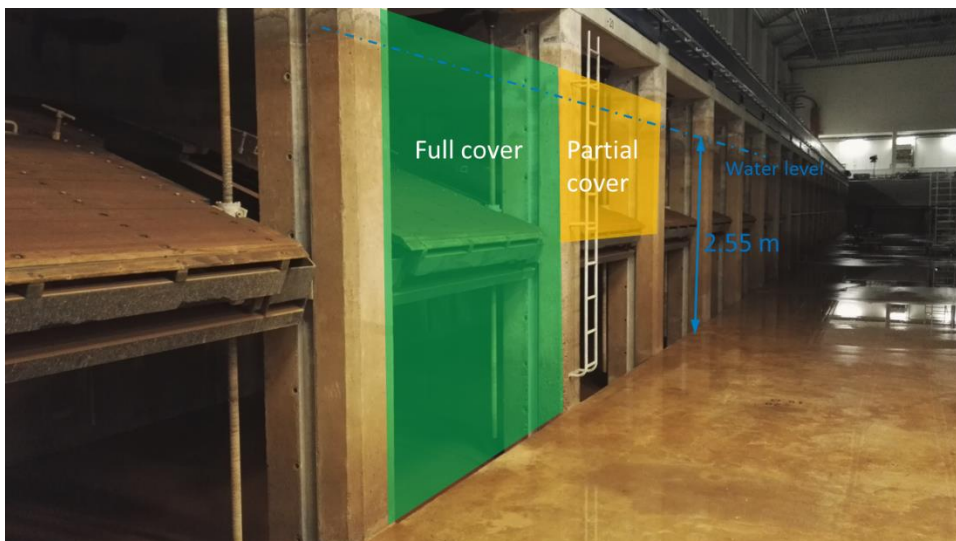


Figure 8: Partial and full covers

As illustrated in Figure 10 the covers had the additional advantage of sealing the end of the wave maker. This end-plate effect reduces three-dimensional effects near the corner of the wave maker and will also improve wave quality.



Figure 9: Two stages of covering the pillars



Figure 10: Added benefit; covers as an end plate sealing the end of the wave maker

Stationary measurements $\lambda/L_{pp} \approx 0.5$

COVERED

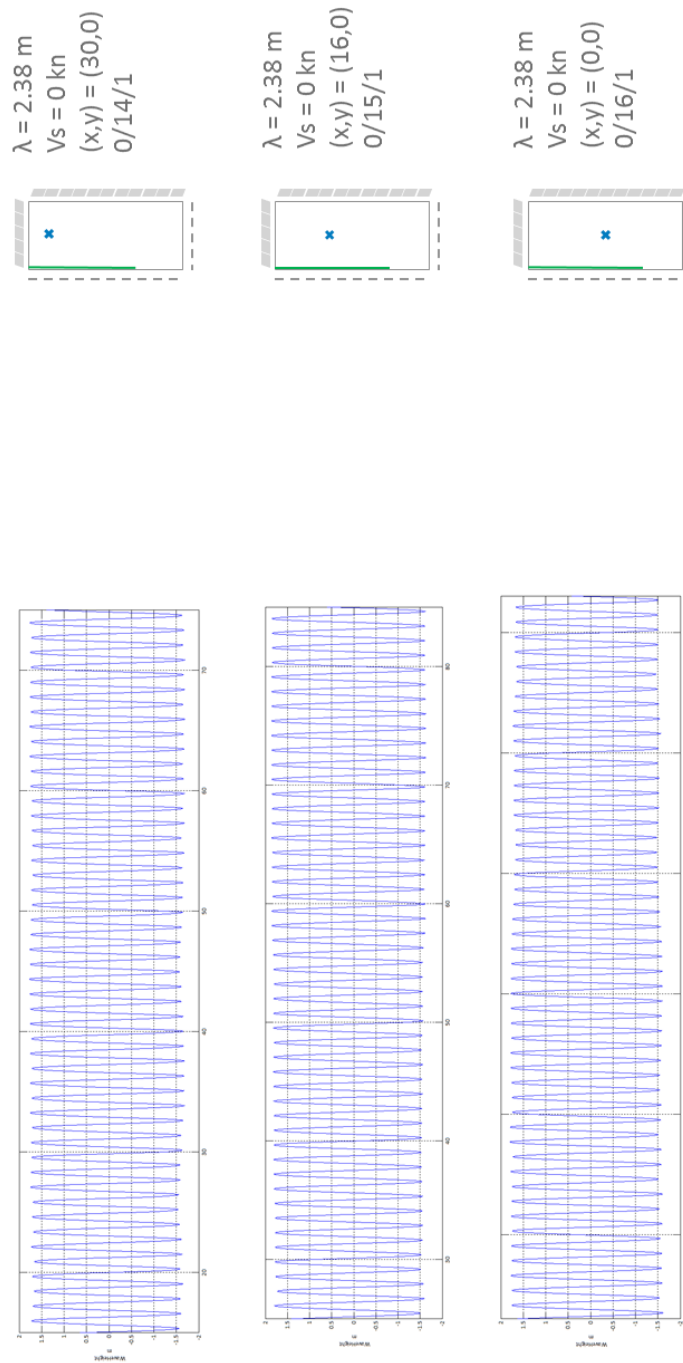


Figure 12: Short wave ($\lambda=2.38m$) at three x positions in basin. Wave height does not change with x , waves have constant form

Stationary measurements $\lambda/L_{pp} \approx 1.1$

COVERED

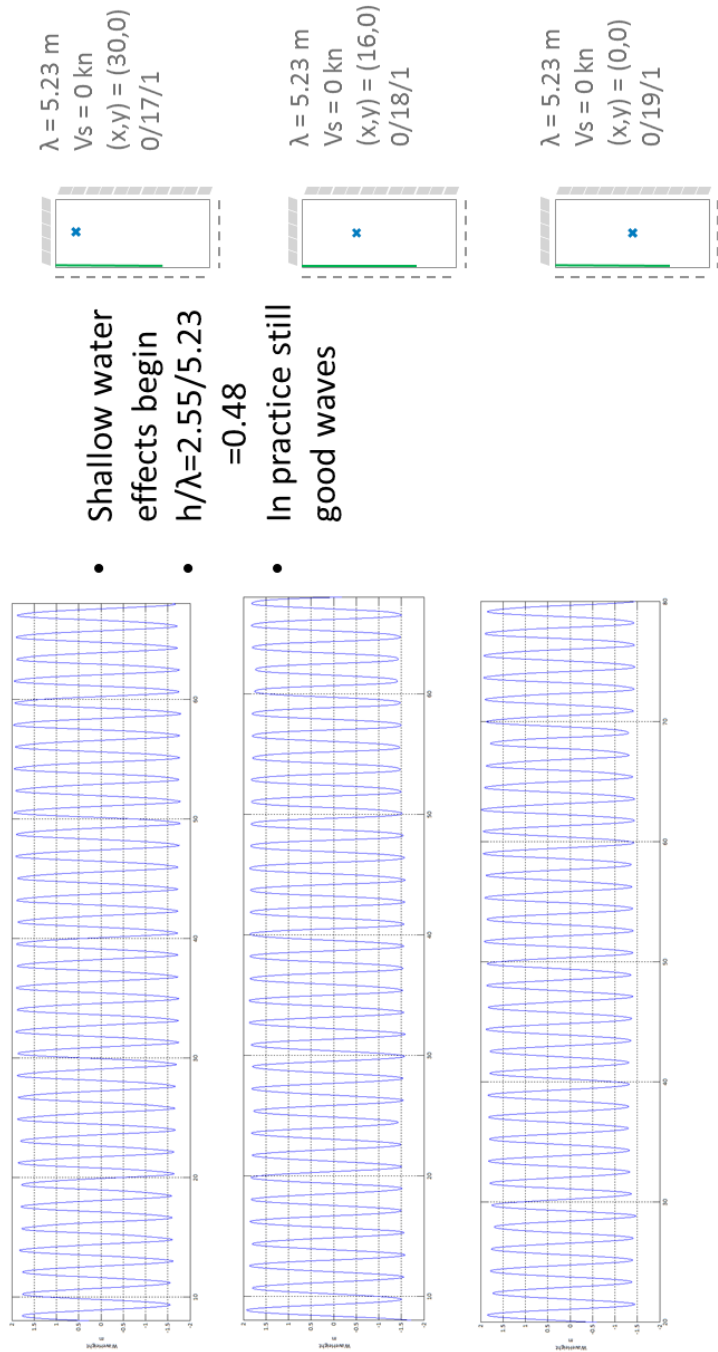


Figure 13: Medium wave ($\lambda=5.23m$) at three x positions in basin. Shallow water effects begin, slight variation of height in time and space, in practice still good wave

Stationary measurements $\lambda/L_{pp} \approx 2$

COVERED

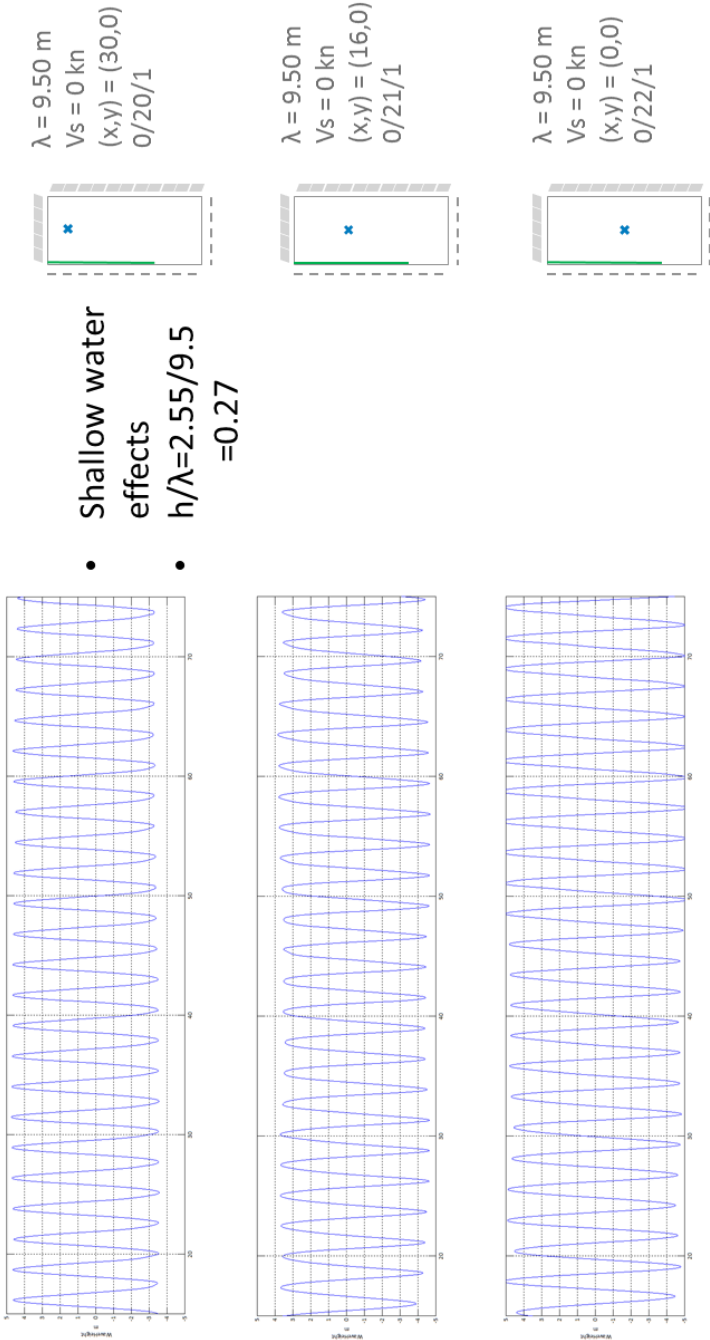


Figure 14: Long wave ($\lambda=9.5\text{m}$) at three x positions in basin. Wave distorted due to shallow water effects

As can be seen:

- Plywood cover lead to significant improvements
- Waves more stable and consistent everywhere
- Long waves are limited by shallow water effects. Height and form of waves varies in time and space above a certain limiting wavelength. Practical limit somewhere around $h/\lambda \approx 0.5$
- Covers lead to longer waiting time between tests due to cross reflections as well as less wave damping

3.3.4 Benchmark tests with KVLCC2 model and plywood covers

In addition to the wave quality investigation described above, tests with a ship model were also conducted. During the tests the “new and improved” waves where successfully used to benchmark experimental results from MDL against published data from the literature. The study was carried out using a model of the well-studied KVLCC2 tanker. More details regarding test setup and experimental results can be found in Chapter 5 of this report.

3.4 Conclusions for WP1

The following conclusions can be drawn from the work carried out in waves in SSPA’s Maritime Dynamics Laboratory (MDL).

- (4) **No improvement** can be expected from second order wave maker theory for wave length of $\lambda < 4\text{m}$. Waves of 4m length and shorter are however crucially important in MDL tests
- (5) Plywood covers lead to a **significant improvement** of wave quality in the basin. In particular:
 - (a) Waves are more stable and consistent everywhere
 - (b) Largest effect for short waves
 - (c) Long waves still limited by shallow water effects, practical limit somewhere around $h/\lambda \approx 0.5$. For the typical depth of $h = 2.55\text{ m}$ this corresponds to $\lambda > 5.1\text{ m}$
 - (d) Covers lead to longer waiting time between tests due to cross reflections as well as less wave damping
- (6) Benchmark tests with a KVLCC2 model show very good agreement between MDL results and published response amplitude operators for added resistance and ship motion in waves. Results can be found in Chapter 5 of this report.

3.5 Future Work regarding wave quality

Future work on improving the quality of the regular waves could address the following issues:

- (1) More permanent solution than the plywood covers. More user-friendly and quicker to install
- (2) Look into second order wave maker theory again and try to improve the long waves. Even with plywood covers these waves are of poorer quality than the short waves. The investigations in this project have shown that it should be possible to improve waves of 4m length and more using higher order theory to control the wave makers, see Hughes (1993)

4 Improved methods for the analysis of wave tests (WP2)

This chapter summarises work package 2 and deals with the second research question formulated on page 11, namely the development of a modern evaluation method that can account for the small deviations in test speeds that are inherent to free-sailing seakeeping tests.

4.1 Introduction

Seakeeping tests can either be conducted with “captive” or “free sailing” ship models. In a captive test the model is normally free to heave and pitch but restricted in all other degrees of freedom. In a “free sailing” tests, on the other hand the motions of ship model are unrestricted i.e. it can move in all six degrees of freedom.

Seakeeping tests in SSPA’s Maritime Dynamics Laboratory (MDL, Figure 3) are normally conducted with “free-sailing” models. While this testing technique closely mimics the behaviour of a real ship it also poses a number of challenges.

4.1.1 Background

In a “free sailing tests” the ship model is equipped with motor, propeller and a shaft dynamometer that measures the propeller thrust. The model steers a constant course relative to the incident waves using an auto-pilot that controls the rudder. Except for some cables and a flexible “measuring-arm”, that determines attitude there is no connection between model and carriage. Using the signal from the measuring-arm the carriage is programmed to “hunt” the model.



Figure 15: Seakeeping test in SSPA’s Maritime Dynamics Laboratory

Flap-type wave generators span two adjoining sides of 88 x 39 meter basin and can be used to generate regular as well as irregular waves.

“Added resistance” in regular waves is obtained along the lines explained in Figure 1 on page 10 i.e. by subtracting the calm water resistance from the time averaged resistance in waves. **Resistance** is calculated from the measured time histories of the **propeller thrust** using the (calm water) thrust deduction factor *tdf*. This factor has normally been determined from resistance and self-propulsion tests with a larger model of the same ship in a towing tank.

At the beginning of a seakeeping test the model is accelerated by the carriage to which it is connected via tautly stretched ropes. Once the target test speed has been reached, the lines are slackened off and the model continues self-propelled in “free-sailing mode”. This is necessary to bring the model up to speed as quickly as possible so that a maximum run-length can be obtained.

During the actual seakeeping test the propeller rate (rpm) is kept constant and the speed of the model is a result of this rpm . This approach of constant rpm mimics the way a real ship is normally operated and has several practical/experimental advantages. However, it has also one significant drawback: To achieve a constant model speed thrust and resistance forces must balance each other at all times. The assumption of hydrodynamic equilibrium requires a perfect *a-priori* guess of the rpm to produce a thrust that exactly balances the resistance. If the rpm was incorrect, the model will either speed up or slow down during the course of the test and the assumed stationarity is not obtained.

Consequently, the force measurements are “polluted” by the variation in model speed and it is no longer possible to cleanly decompose the total thrust into calm water thrust and added thrust. This obviously influences the quality of the results. In extreme cases the “polluted” tests need to be repeated with a new rpm which can lead to experimental “waste” in the order of 30-40%.

4.1.2 Purpose of study

The purpose of the work carried out in WP2 is to develop a new evaluation method that can account for the above-mentioned variations in model speed that are inherent to free-sailing seakeeping tests. It can be expected that this increases the quality of the results, while at the same time making testing more efficient.

4.1.3 Scope and limitations

A new evaluation methodology was developed, implemented as add-on to the existing evaluation software and used to analyse test results from experiments with a purpose-build oil tanker model.

4.1.4 Methodology

The novel method is based on Newton’s second law, quasi-steady in nature and can take the small unwanted model accelerations into account that almost always occur during “real life” testing.

4.2 A novel method to correct for unwanted variations in test speed

This section summarises the ideas and the theory behind the new evaluation method.

Traditionally added thrust in waves T_{AW} is calculated from:

$$T = T_0 + T_{AW} \quad (1)$$

Here T is the total average thrust (as measured during a seakeeping test) and thrust T_0 denotes the calm water thrust at the same speed. Compare Figure 1 and left-hand side of Figure 16.

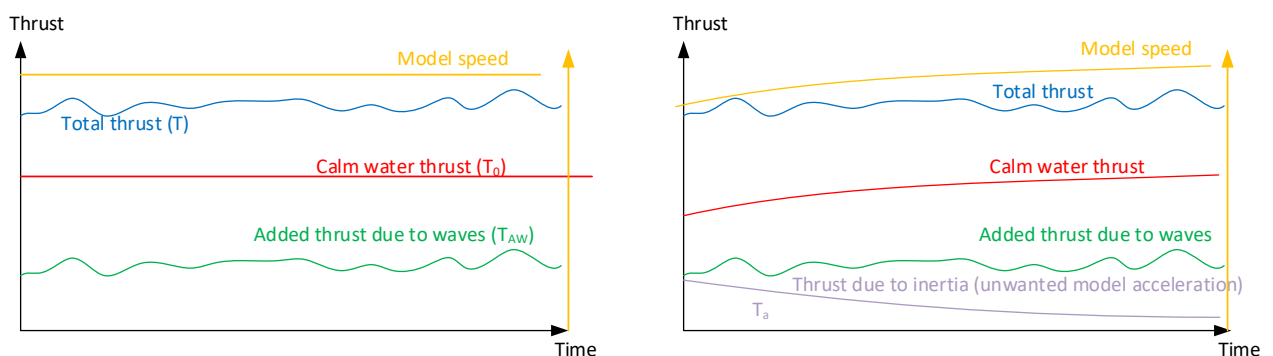


Figure 16: Thrust components during an ideal (left) a typical (right) seakeeping test. Unwanted “polluting” inertial component in purple at the bottom of RHS-plot (exaggerated)

In the case of an accelerating model the above steady state equilibrium is no longer valid. Instead of looking at **time-averaged** force values it is necessary to consider the **entire time history** of the run. The instantaneous total thrust is split into three components: Calm water thrust $T_0(t)$, added thrust due to waves $T_{AW}(t)$ and thrust due to inertia T_a : (ideally this component is zero, in practice it is unavoidable).

$$T(t) = T_0(t) + T_{AW}(t) + T_a \quad (2)$$

The right-hand-side of Figure 16. illustrates this approach for an exaggerated model acceleration. The added thrust now becomes:

$$T_{AW}(t) = T(t) - T_0(t) - T_a \quad (3)$$

The inertial thrust T_a in this equation can be worked out from Newtons second law:

$$T_a = (\nabla + m_{added}) \cdot \dot{V}_m \quad (4)$$

Where \dot{V}_m denotes the model acceleration (calculated from the time history of the measured model speed), ∇ is the mass of the model and m_{added} is the “added mass” in surge. By inserting (4) into (3) it finally becomes possible to subtract the small but nevertheless “polluting” effect of T_a from the added thrust in waves. This correction should increase the quality of the test results.

As part of WP2 the above acceleration correction method was implemented as a computer program (written in Python) and partially integrated with existing SSPA test-evaluation codes. Figure 24 shows a typical screenshot from a summary page created by the new software.

4.3 Using the new method: Results, verification and validation

To demonstrate how the method works, seakeeping tests in head-sea conditions were carried out in SSPA’s model basin. These extensive Verification and Validation (V&V) tests were run as part of work package 3 and are summarised in chapter 5 of this report

4.4 Conclusions for WP2

The results in chapter 5 show that the proposed novel evaluation method looks promising because it reduces experimental spreading and results in added resistance values that are closer to CFD-predictions. Most of the regular wave tests at SSPA are now evaluated using this method.

4.5 Future work

Some work remains to be done regarding:

- Fully integrate the novel method with the existing software packages. Currently some manual work is still required

5 Verification & Validation of improved methods for seakeeping tests (WP3)

This chapter summarises the work carried out in work package 3 (WP3)

5.1 Introduction, background and methodology

The purpose of the work in WP3 was to **verify and validate** the techniques and methods developed in WP1 and WP2.

To this end a special ship model was designed, manufactured and used during seakeeping tests in the improved waves from WP1. Test results were then evaluated using the acceleration correction method from WP2. Finally, results were compared to benchmark data from the literature.

5.2 Ship model

As part of WP3 a reference test setup was developed. Its main component is a purpose build model of a large oil tanker. The hull geometry used here is that of the “KVLCC2-tanker”, a popular reference case for benchmark studies. It is the second variant of the *Korean Research Institute of Ships and Ocean Engineering* (KRISO) Very Large Crude Carrier (VLCC), (Kim et al 2001, Hino 2005). Table 1 provides an overview of the main parameters of ship and model.

Following SSPA standard procedure the model was built in *Divinycell* foam but additionally sheeted with fibreglass/epoxy laminate to ensure long-term stability. When designing the model special care was taken to make ballasting easy and repeatable. Photographs and drawings of the model are shown in Figure 17 and Figure 18.

Table 1: Main particulars of KVLCC2

Parameter	Ship	Model
SSPA model number		M5057-01-A
Scale	68	1
Vol. Displacement	312 653 m ³	0.994 m ³
LPP	320 m	4.706 m
Beam, B	58 m	0.853 m
Draft	20.8 m	0.306 m
Service speed	15.5 knots	0.97 m/s
Roll gyradius		0.4 B
Pitch gyradius		0.25 LPP
Yaw gyradius		0.25 LPP

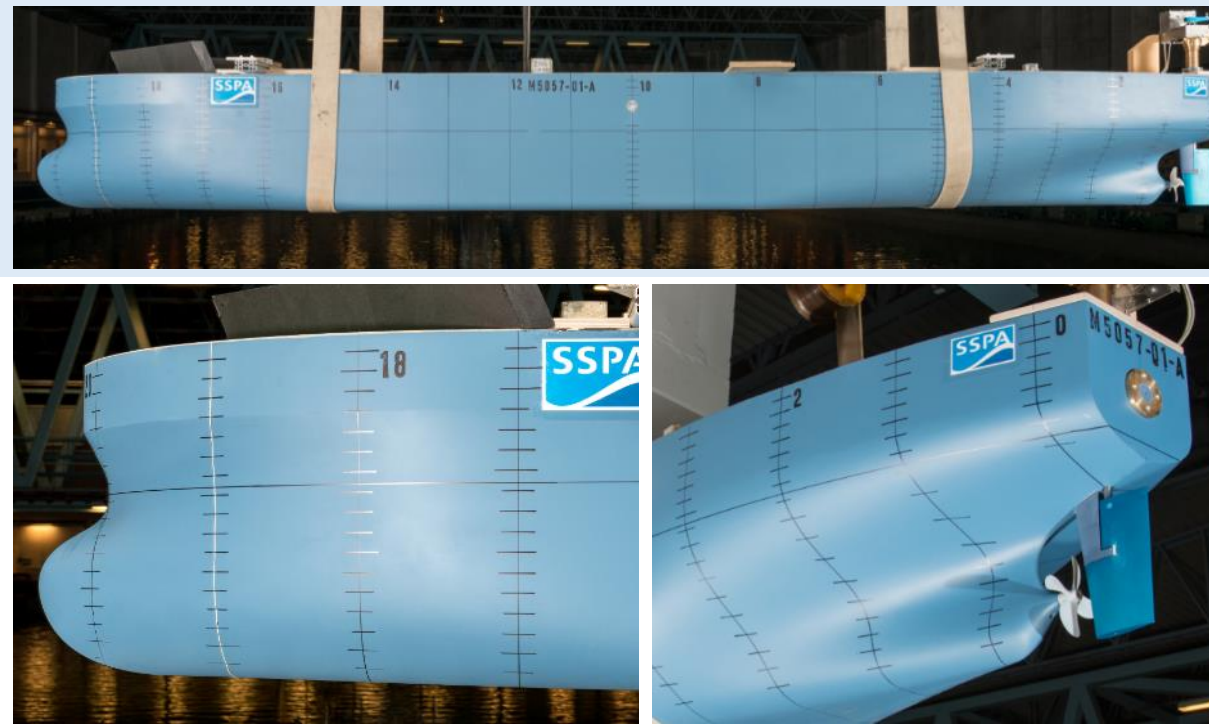


Figure 17: KVLCC2 model (SSPA-M5057-01-A)

A laser scan of M5057-01-A was conducted in order to verify that the shape and dimensions of the finished model are within the allowable tolerances. Figure 19 illustrates the results and shows that, except for two small areas on the port-side bottom and near the skeg the deviation between nominal geometry and actual underwater geometry are within the $\pm 1\text{mm}$ limit suggested by the International Towing Tank Conference, ITTC 2017.

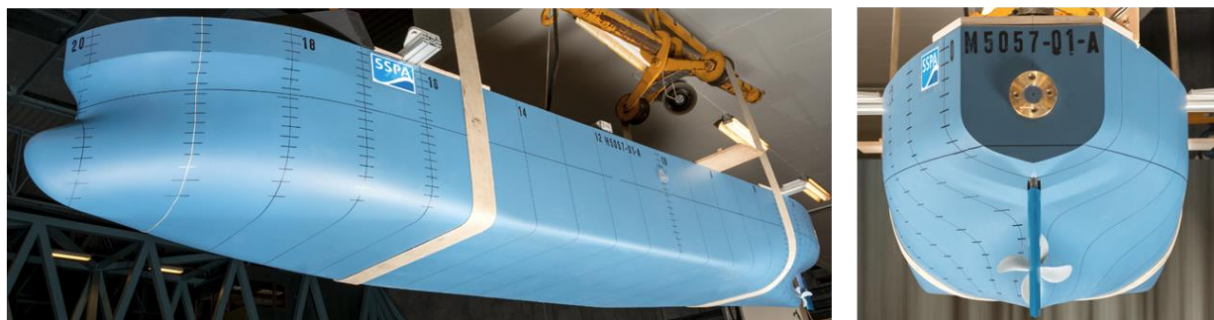
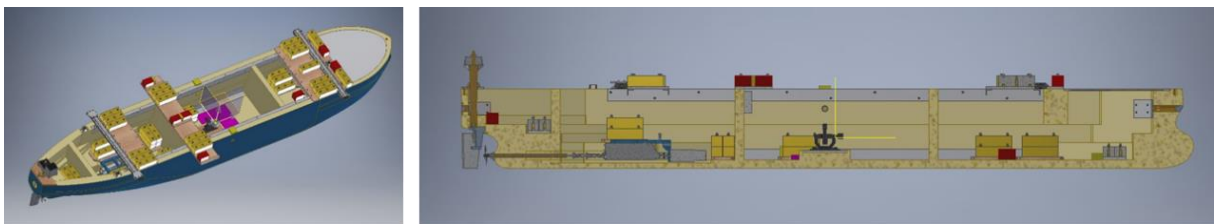


Figure 18. KVLCC2 model and CAD-drawings

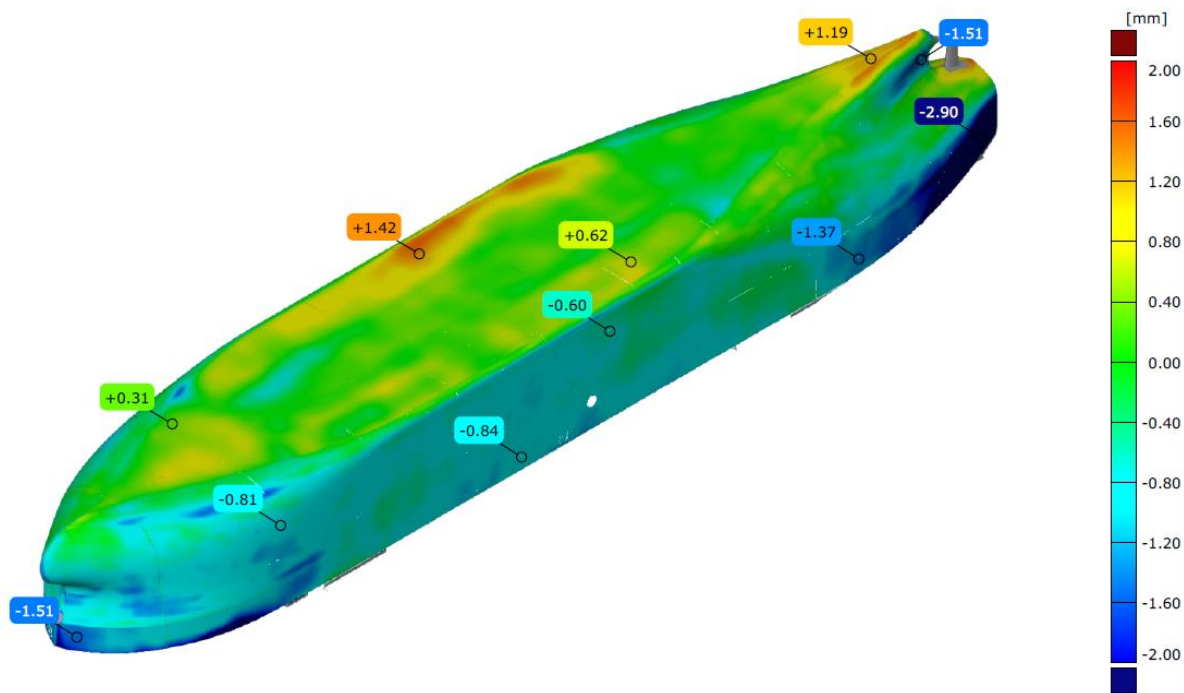


Figure 19: Laser scan of KVLCC2 model and comparison to target geometry

5.3 Seakeeping tests: Technique, experimental program and test evaluation

Tests were conducted in SSPA's Maritime Dynamics Laboratory (MDL). The laboratory consists of a basin with the dimensions 88 m x 39 m and a multi-motion carriage for model control and data acquisition that spans the width of the basin.

During the tests the model was operating in "free sailing mode" i.e. its motions were unrestricted. At the beginning of each test the model was accelerated by the carriage and at the right released from the carriage it then continued self-propelled and autopilot-controlled. The autopilot is a PD-controller that adjusts the rudder angle δ according to:

$$\delta = \Delta\psi P + \Delta\dot{\psi} D; \quad \text{where } P=2 \text{ and } D=0.8 \text{ s.}$$

During the tests the propeller is run at a constant rate of revolution.

Table 2 summarises test program. Regular waves were produced by the Q-side wavemaker and with the new plywood covers from WP1, compare chapter 3.

Figure 20 shows a photograph from a typical seakeeping test. During the duration of each tests the following quantities were recorded at a sampling rate of 100HZ:

- Linear motions: surge, sway, heave
- Angular motions: roll, pitch, yaw
- Propeller thrust, rpm and torque
- Model accelerations in all six degrees of freedom

Table 2: Test program

Wave length λ/LPP [-]	Wave steepness H/λ [-]	Wave direction	Speed [knots]
0.2	2%	180° (heas seas)	15.5
0.3			
0.4			
0.5			
0.6			
0.7			
0.8			
0.9			
1.0			
1.1			
1.2			
1.3			
1.4			
1.5			
1.6			



Figure 20. KVLCC2 model during seakeeping tests in “new” waves

Added resistance due to waves (R_{AW}) was determined by subtracting the mean thrust in calm water from the mean thrust in waves and thus obtaining the “added thrust”.due to waves T_{AW} . The added resistance is then calculated based on the thrust deduction factor (t) as follows:

$$R_{AW} = T_{AW} \cdot (1 - t)$$

Finally, the motion and added resistance amplitudes were determined using Fourier analysis of the measured motion and thrust/ resistance time series.

5.4 Results

5.4.1 Seakeeping tests in “new” high-quality waves

Figure 21 shows non-dimensional vertical plane motion amplitude (heave and pitch) as function of wave-length. The figure also shows a curve from time-domain simulations with the fully non-linear potential flow solver SHIPFLOW-Motions (Flowtech 2019) and it summarises published numerical and experimental data from the literature, Seo et al. (2014) and Lee et al. (2013).

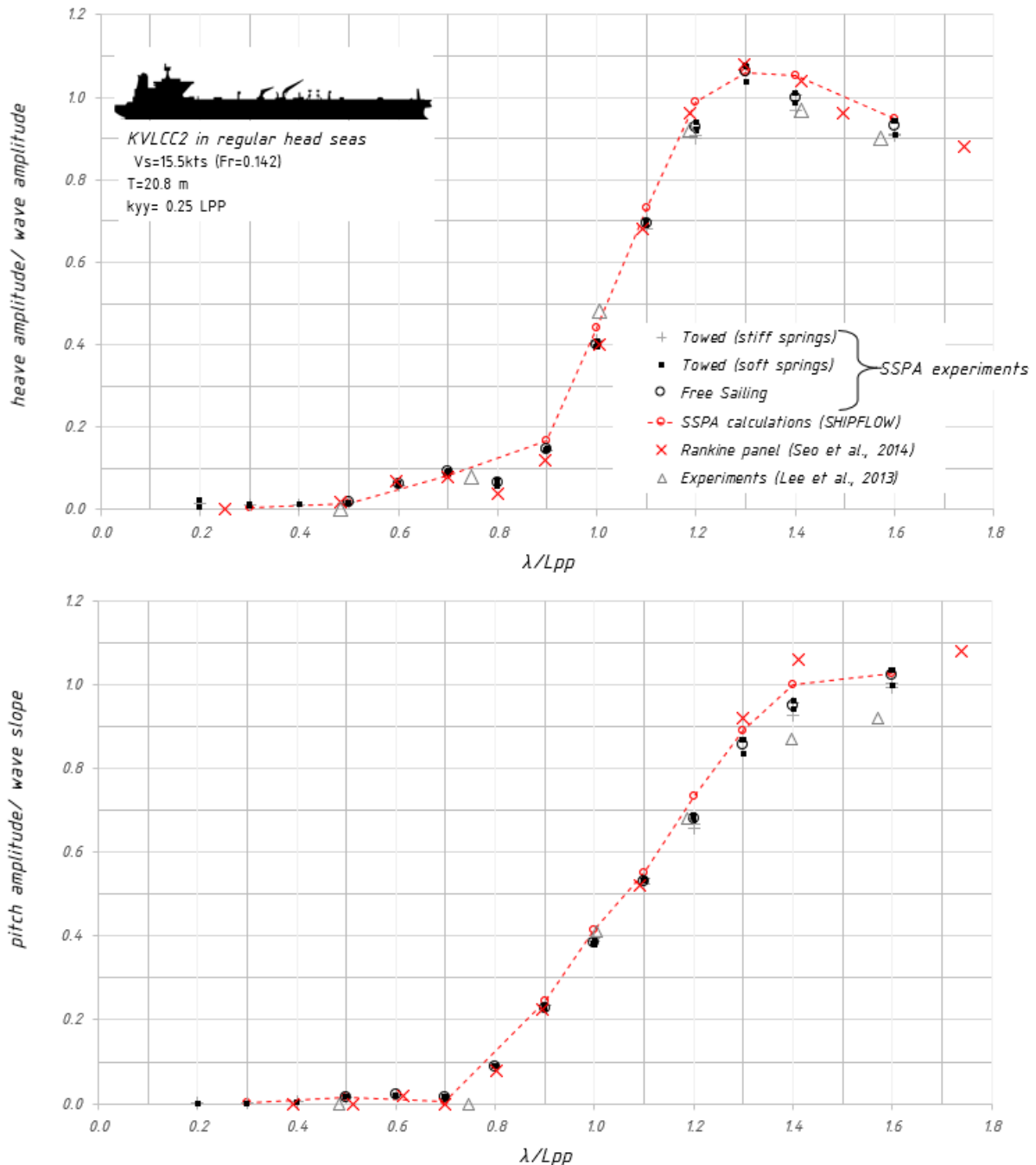


Figure 21: Transfer functions (RAO) for heave and pitch

As can be seen agreement between SSPPA-results, SHIPFLOW-calculations and data from the literature is excellent.

5.4.2 Verification of new evaluation method to correct for unwanted variations in test speed

To verify the novel added resistance correction method from WP2 a number of deliberately accelerated **calm water tests** with the KVLCC2 tanker model were carried out. Figure 22 shows an example where the model was released at a speed of 4 knots with the *rpm* that corresponds to 11 knots. As can be seen in the top part of the figure, the model accelerates and reaches equilibrium sometime after 900 seconds full-scale time. During such a run significant acceleration forces act on the model and this can be used as a test case for the proposed correction method. As illustrated by the purple and green lines the evaluation method works out these acceleration forces, subtracts them and returns a “calm water added resistance” close to zero. This shows that the technique seems to work satisfactorily. Having conducted several such “test-evaluations” for different model speeds it was decided to proceed and apply the method to real seakeeping tests.

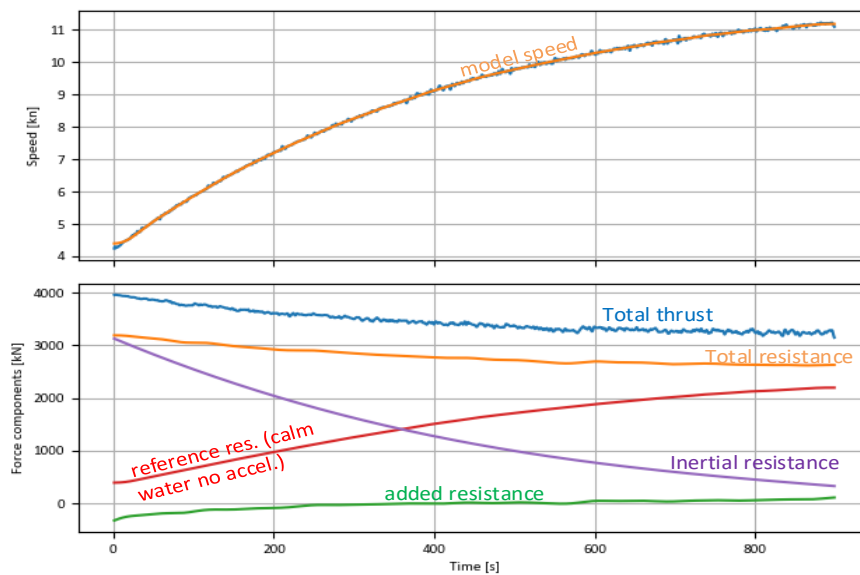


Figure 22: Force components during calm water acceleration from 4 to 11 knots, constant rpm

5.4.3 Validation of new evaluation method: Results of seakeeping tests and comparison to numerical simulations

To validate the ideas and methods from WP2 the propeller thrust measured during the seakeeping tests with the KVLCC2 was evaluated using the acceleration correction technique described in section 4.2.

Figure 23 summarises results from such added resistance tests in harmonic/regular head waves of different length. These waves were all created using the plywood covers developed in WP1. The figure shows the non-dimensional added resistance coefficient C_{AW} as function of non-dimensional wave length λ/L_{pp} .

$$C_{AW} = \frac{R_{AW}}{(\rho \cdot g \cdot B^2 \cdot A^2) / L_{pp}} \quad (5)$$

With:

- A Water surface elevation amplitude
- B Beam of ship
- g Acceleration of gravity
- L_{pp} Length between perpendiculars
- λ Wave length of a regular wave
- ρ Density of water

Figure 23 contains two sets of data that have been obtained by evaluating **the same** seakeeping tests in different ways. The solid, square symbols correspond to results obtained in the “traditional” way i.e. without correcting the measured propeller thrust for acceleration components. The open circular symbols come from the same measurements but now the correction method from WP2 has been used. In order to look at experimental spreading a test and a “repeat” have been conducted. This is illustrated by the multiple symbols at the same wave length.

The figure also shows a curve from time-domain simulations with the fully non-linear potential flow solver SHIPFLOW-Motions (cross symbols, Flowtech 2019). Finally, Figure 23 also contains published numerical and experimental data from the literature, Seo et al. (2014) and Lee et al. (2013).

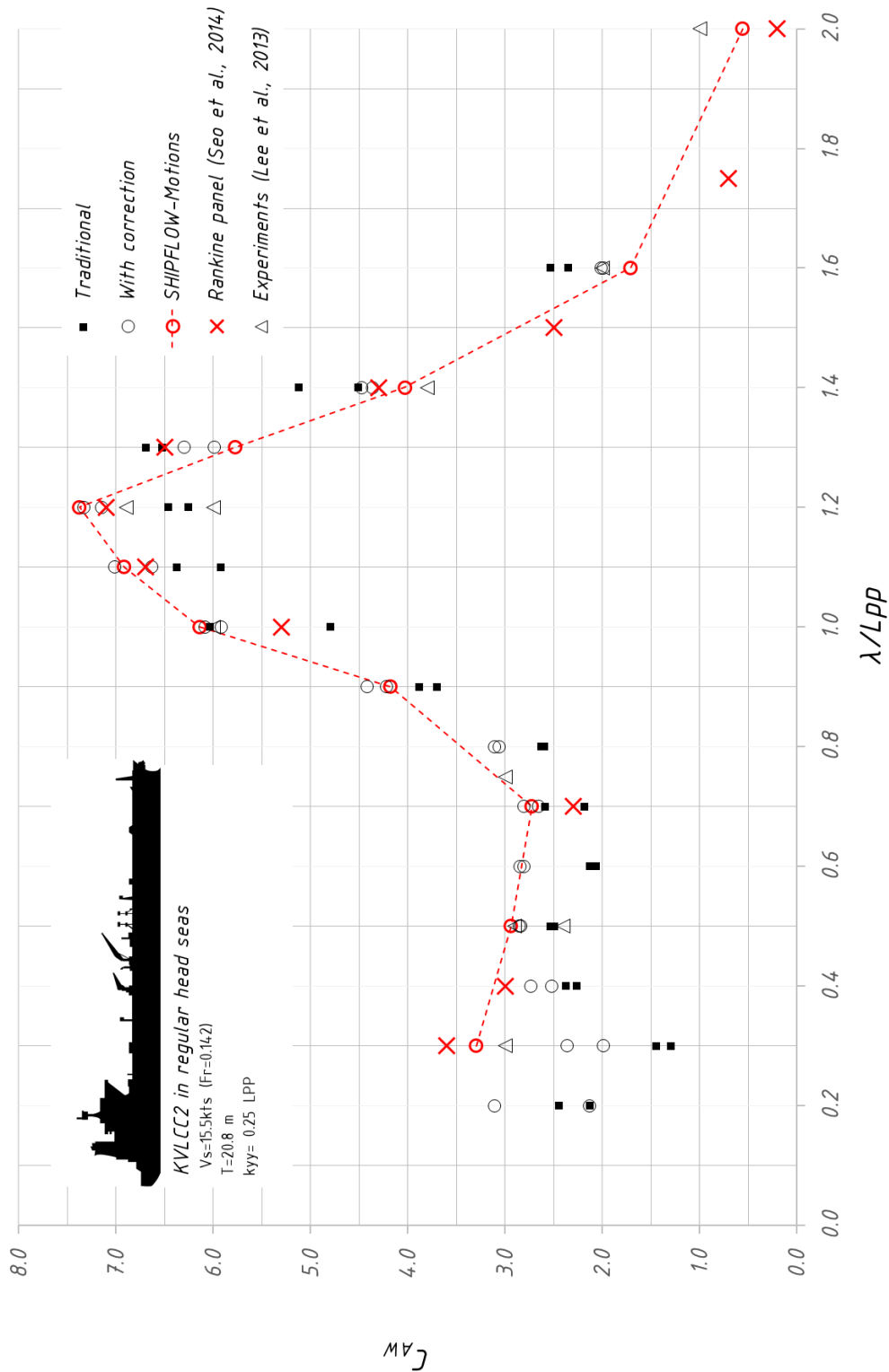


Figure 23: QTF of added resistance coefficient, w and w/o acceleration correction

Several things can be noticed:

1. With acceleration correction the experimental spreading generally goes down. See e.g. $\lambda/Lpp = 1$ for an extreme example. In one case values from test and “repeat” even end up on top of each other ($\lambda/Lpp = 1.6$).
2. The correction seems to shift the peak of the *QTF* to the “left” and upwards. Agreement between SHIPFLOW predictions and experiments are now better.
3. Below $\lambda/Lpp = 0.7$ spreading is generally large. The acceleration correction moves the measured points closer to the experimental results, albeit the spreading in the repeats is not reduced
4. Agreement between SSPA tests and data from the literature is very good

The shift in peak position and value (Observation No. 2) is caused by the fact that the experiments in the “resonance” range of $1 < \lambda/Lpp < 1.4$ are the ones that are most difficult to conduct in free-sailing mode. This is because the large pitch, heave and added resistance values make guessing the initial *rpm* difficult. Figure 24, a screenshot from the evaluation tool developed in WP2, shows an example for $\lambda/Lpp = 1.2$. As can be seen from the top plot the average speed during this run decreases slightly (from 15.7 to 15.2 knots). This deceleration of the model results in a small and negative inertial resistance component (purple line, bottom plot). If this “propulsion” force is neglected, as in the traditional evaluation method, R_{AW} and therefore C_{AW} will be too low. This results in the difference in peak values in Figure 23.

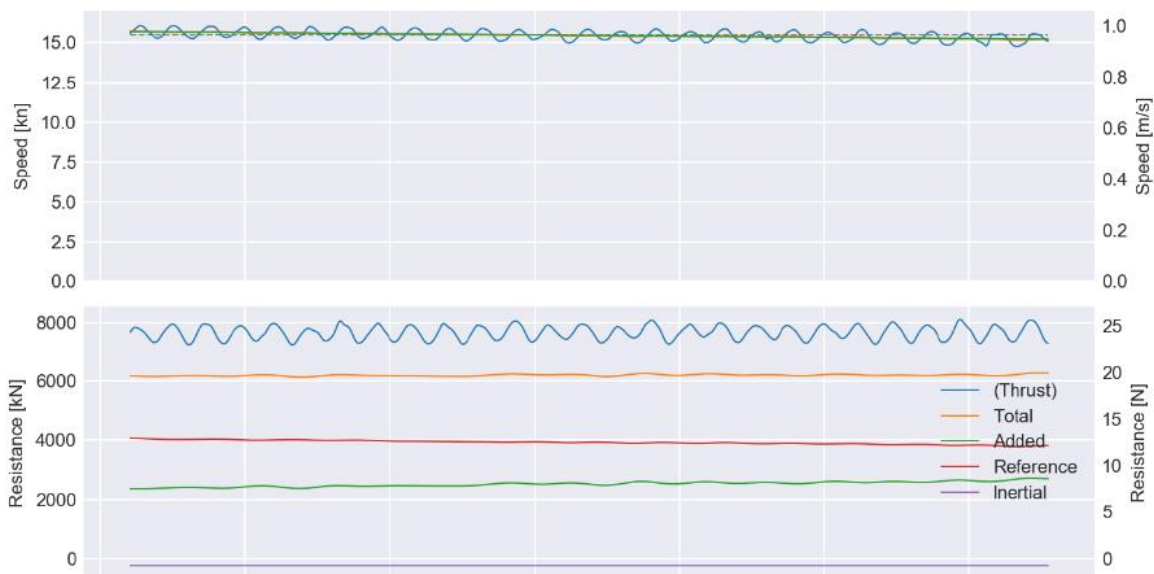


Figure 24: Speed and resistance components during one of the runs at $\lambda/Lpp = 1.2$

Observation No. 3 (large spreading below $\lambda/Lpp = 0.7$) can be explained by the fact that for shorter and lower waves the absolute values of the measured forces become very small. This makes measuring them accurately challenging while, at the same time, taking the difference between calm-water thrust and thrust in waves becomes very sensitive to small errors.

5.5 Conclusions regarding new evaluation method and improved waves

Results from the investigation shown here indicate that the proposed dynamic evaluation method looks promising because it reduces experimental spreading and results in C_{AW} values that are closer to CFD-predictions. Most of regular wave tests at SSPA are now evaluated using this method.

6 Documentation dissemination (WP4)

A summary of the reports and publications resulting from the project can be found below.

6.1 Reports

Certain parts of the work summarised in the current report were co-financed by SSPA, the *Hugo Hammars fond för sjöfartsteknisk forskning (HHS)* and the *Fru Martina Lundgrens fond för sjöfartsteknisk forskning vid SSPA (FL)*. About these parts a number of internal reports and documents have been written:

Table 3: Main particulars of KVLCC2

Report title	Report number	Date
KVLCC2 model design	TF107102-B	Nov. 2017
Partial covering of L-side beaches in MDL: Results and conclusions	RI40178363-01-00-A	Feb. 2018
Laboratory generation of regular waves	RF40178363-01-00-A	May 2018
Numerical experiments	Projektrapport_HHI 121_ML106	Oct. 2019

6.2 Conference and journal papers

Findings were recently also published at the 6th International Conference on Advanced Model Measurement Technology for The Maritime Industry (AMT):

Kjellberg, M., Gerhardt, F. C. "Improved methods for the experimental determination of added resistance in waves." *6th AMT*. 2019. Rome.



Figure 25: AMT 2019, October 2019 in Rome

A publication of the research in the *Journal of Ocean Engineering's* upcoming 2020 *special issue* on "the state-of-the-art in model and full-scale measurement technology for the maritime industry" is currently being prepared.

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