# FROUDE'S LAW OF SIMILITUDE – CONTEMPORARY AND FUTURE SEAKEEPING TESTING

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## SUMMARY

Historically "scale effects" in the interpretation of tests with scale models in waves using Froude's Law of Similitude are mostly associated with viscous effects. Nowadays, with a much more complete modelling of reality and a focus on higher order non-linear phenomena, scaling of model test results implies a wider range of assumptions than the validity of Froude's Law. Our contribution to the conference is a visionary review of contemporary and future problems in the interpretation of these tests. In this context we will discuss the developments in test techniques, including the development of a new Two-Phase Laboratory facilitating seakeeping and sloshing tests at reduced air pressure.

## 1. INTRODUCTION

Starting point for the present review is the notion that seakeeping tests are often performed to assess the expected operational performance of a given ship design.

Photograph 1: Seakeeping model of a ferry

The performance is largely determined by the operational limits in terms of sustained speed, the risk of damage to ship and cargo and crew performance and safety. Besides normal ship motions and added resistance these limits are determined in particular by non-linear features of the behaviour and the incident waves. The magnitude of slamming induced vibrations, impact loads due to green water and the heel angles due to loss of stability, broaching or parametric roll as well as the loads due to steep breaking waves increases disproportionally above a certain wave height. The fact that the conservatism of the captain, which seems a natural reaction on the chaotic unpredictable character of the non-linear aspects of the behaviour, magnifies their impact on ship performance turns them into an important aspect of a seakeeping assessment.

## 2. SEAKEEPING AND PERFORMANCE – WHAT NEEDS TO BE MODELLED

### 2.1 ASPECTS OF SHIP BEHAVIOUR GOVERNING PERFORMANCE

Aspects of seakeeping of conventional ships that determine the operational limits and performance relate to the magnitude and the on-board predictability of:

- Rigid-body motions
  - Related local accelerations
  - Related relative wave elevation
  - Course keeping in combination with a risk of broaching and excessive heeling
  - Excessive heeling due to weakly non-linear parametric excitation or temporary loss of stability
- Flexural vibrations in the global bending and torsion modes
  - Transient, decaying "whipping" vibrations driven by "strongly non-linear ship-wave interaction" (impulsive slamming pressures below the fore foot, in the bow flare and below the stern and direct impacts from steep, breaking waves)
  - Continuous "springing" vibrations due to low level first and second order excitation around the waterline in the bow area
- The involuntary speed loss related to:
  - The wind drag
  - The added resistance from waves (with components related to the reflection and radiating of waves, the excessive damping of flared sections and the piling up of water in front of a blunt bow at deep immersion)
  - Reduced propulsive performance due to the increased propeller loading and ventilation
  - Reduced engine output due to large or rapid propeller torque variations.

For contemporary conventional ships the impact of propeller cavitation and ventilation in a seaway, through excessive vibrations, power-train issues and under-water noise seems, as far as we are aware, quite limited. Off course the traces on the water surface are an issue for naval ships; the calm water "cavitation bucket" may be of little value in realistic operational conditions [19].

Similarly, although spray is a nuisance in terms of the forward view of the crew, corrosion and cargo wetting, it is generally not an explicit issue in the design of the bow of conventional ships. Because of icing problems this may change with increasing arctic endeavours. For naval and research ships the noise aspect of the spray impacting on the water surface adds to these issues.

2.1 (a) Mild Weather Conditions

In mild conditions below the operational limits ship motions are generally small. An exception is the roll, which shows, in particular combinations of speed, heading and wave period, a first-order resonant response. At lower speeds, where the non-linear damping components dominate, this roll shows a non-linear character. When not acceptable, the roll is typically mitigated with a change in course.

Also in mild conditions, large ships may develop springing at higher wave encounter frequencies in waves from forward directions if the structural stiffness and damping are relatively low.

2.1 (b) Operational Limits

In near limiting conditions from forward directions the added resistance from wind and waves leads to notable involuntary speed loss.

In addition to the involuntary speed loss, the rigid-body motions become an issue in terms of passenger comfort, sea fastening of cargo, habitability and crew performance and safety. The relative wave elevation leads to shipping of green water and bow, stern and propeller emergence.

Because the slamming induced vibrations that occur in these conditions correlate positively with the rigid-body motions and because of their particular (negative exponential) statistics [10] they contribute significantly to "incidents" like sea fastening failures, passenger discomfort and structural fatigue damage [1]. The slamming vibrations experienced by the crew and the observation of green water on the foredeck seem the main clues for a "voluntary" speed reduction.

The most common reaction of the master is a reduction in speed, which reduces the accelerations, the risk of water on deck and the slamming induced vibrations. A deviation from head seas breaks the symmetry of the green water flow on the foredeck, strongly reducing breakwater impacts.

Photograph 2: Breakwater impact in head seas

Parametric roll develops in conditions where three conditions are met simultaneously: sufficiently large stability variations with a dominant period of about half the natural period of roll and a low roll damping. Typically these are met by larger ships at reduced speed in head or following seas.

Model tests showed that the natural speed variations in irregular waves play an important role in occurrence of parametric roll. Although counter-intuitive from the point of view of rigid-body and slamming induced accelerations as well as shipping green water, an increase in speed is often effective in reducing the risk of parametric roll.

In storm conditions from aftward directions smaller ships can develop problems with maintaining a steady course, surf riding and a related risk broaching, in particular if the stability is moderate. At these low encounter frequencies ships with a low stability are vulnerable to severe heeling due to loss of stability.

Photograph 3: Capsizing model

The speed variations and the occasional large course deviations seem the most important clues for a speed reduction.

## 2.2 ASPECTS OF THE ENVIRONMENT GOVERNING SHIP PERFORMANCE

In order to obtain a correct impression of the behaviour of a ship it is also important to model the most important aspects of the environment.

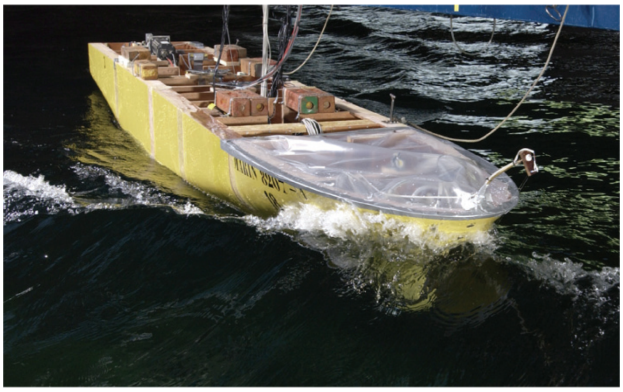
2.2 (a) Waves

The growth of waves is a fairly well defined process in which waves first become steeper before they grow. In these steep waves non-linear wave-wave interaction transfers energy from the short waves (where the energy input takes place) to longer wave components, which in the end contain most of the energy.

After the passage of the wind field the waves decay, partly through spatial dispersion of the frequency and direction components and partly because of energy loss due to bottom friction and (occasional) white capping.

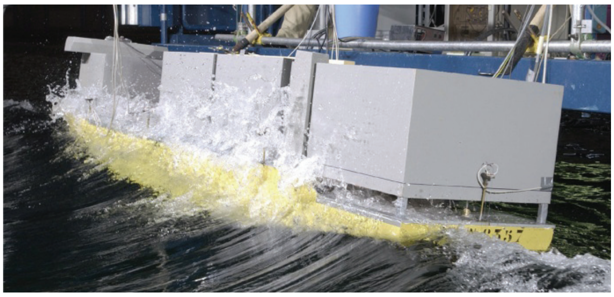
In many practical cases the remnants of older and/or distant storms mix with local wind waves into bi-modal spectra with wind and swell components from different directions.

**Confused seas**
Steep oblique waves lead to quite high relative wave elevations along the sides of a ship and to excessive resonant roll. Combinations of these waves with higher, longer waves over the bow (for instance in rapidly turning winds or complex frontal systems) can lead to situations in which the master does not have the opportunity to seek “shelter” behind the breakwater. If these conditions occur frequently or if the ship is particularly vulnerable in this respect (exposure of containers or out-board located life boats) it seems important to account for the actual a-symmetric directional characteristics in quite some detail.



Photograph 4: Bow flare impact from a steep wave from the bow quarter

**Wave steepness**
Obviously, the typical wave period largely determines the wave steepness. But, in addition to the wave period, the steepness is also determined by the choice of the spectral bandwidth and directional spread. The wave trains in the narrow banded (JONSWAP) wave spectra show individual waves with a wave steepness that is higher than predicted by linear superposition of the wave frequency components. These waves have a considerable effect on certain aspects of ship behaviour, like slamming in the bow flare or the ingress of green water.



Photograph 5: Impact from a breaking wave from abeam

As firstly observed by Forristall [12] and confirmed later by many others the wave crest distribution as described by second order theory is an important improvement on linear superposition. However there are interaction phenomena which cause even higher waves. Expert evidence from full scale measurement is given by e.g. Haver [14]. These sudden “freak” or “rogue” waves are now commonly recognized as a normal risk at sea [15].

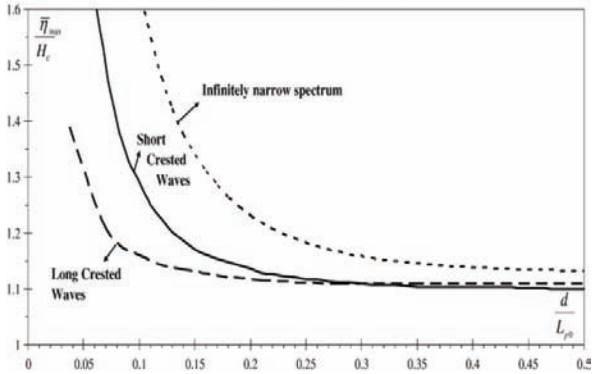



Figure 1: The ratio $\eta_{max}/H_C$ of the nonlinear and the linear height of the largest wave crest as a function of water depth d. With $H_C$=8*R.M.S of wave [3]

As shown in the above figure, the effect of nonlinearity for the highest crest increases by decreasing the water depth, whichever the spectrum is. Surprisingly one sees that the enhancement of the non-linear effect in shallow water for short crested seas becomes larger than for long crested waves [3,6].

**Wave grouping**
Correct modelling of wave grouping is of particular interest for ship responses that will be sensitive to low frequency excitation: ,i.e. ships that have to maintain a certain position or follow a certain track in waves. Extreme events and their probability of occurrence can be investigated by studying the nonlinear evolution of a wave group [3], Fedele [11] studied the space time evolution of two consecutive extreme wave crests.

2.2 (b) Current

Wind and Coriolis forces govern the wind driven current at sea [18]. Uncorrelated decaying “inertial” currents but in particular tidal currents running against growing waves are well known to lead to very steep wave conditions with freak wave events.

## 3. SEAKEEPING TESTS AS A WAY TO QUANTIFY SHIP BEHAVIOUR

### 3.1 COMMON TEST PROCEDURES

Because a towing arrangement inevitable affects rolling and the behaviour at low encounter frequencies, most seakeeping tests are performed nowadays with free running, self steering models. These tests are normally performed in fresh water. The geometry scaling and the reproduction of the ships weight distribution assure that several (but obviously not all) of the mentioned types of behaviour and design choices are represented in the tests.

Common, because of the large effect on the performance of a ship, is the modelling of elements of ride control, like bilge keels, active fin stabilizers, trim tabs and interceptors, T-foils, rudder-roll stabilisation, passive anti-roll tanks, controlled anti-roll tanks and moving weight systems. Modelling of the dynamic positioning functionality has become common for ships with a high demand in this respect.

If the supplier of the steering, stabilising or positioning system agrees on a schematic representation (which is often the case), the rudders and fins are digitally controlled with a PD controller, reacting on the measured motion response. In other cases the control system of the supplier is hooked into the model control loop.

During self propelled tests it is common to run the model electric motors at constant rpm. If tests at zero speed are required, a 4-line mooring system with linear springs is mostly used.

**Environment**
Seakeeping tests are performed in fresh water at normal atmospheric pressure. The effects of wind are mostly neglected.

To obtain a realistic impression of the ship behaviour which includes non-linear aspects, seakeeping tests are generally performed in irregular waves. The use of regular waves is limited the estimation of the quadratic transfer functions of the added resistance and the linear transfer functions of the behaviour in transit in waves from the stern quarter (where these cannot be obtained from irregular waves).

**Duration**
The target duration of general purpose seakeeping tests is generally in the order of 150-200 wave encounters. This number originates in considerations from linear theory; repeating one test many times with different realisations of the same wave the rms of the rms of 180 independent Rayleigh distributed amplitudes is about 5%.

### 3.2 CHOICES IN AND LIMITATIONS OF MODELLING THE ENVIRONMENT

#### 3.2 (a) Viscosity and Flow Separation

Viscosity materializes in drag through two different mechanisms. The first is the force exerted through the shear forces in the fluid. The second is the pressure drag caused by flow separation.

Fresh water mostly used as a fluid medium in seakeeping tests, it has a viscosity that is similar to that of sea water. This and the stimulation of a turbulent boundary layer on the model and control surfaces, leads to relatively high frictional forces and a relatively thick boundary layer on a scale model.

The effect on the pressure drag due to flow separation depends on “fixation” of the flow separation point. If, like on bluff bodies, it is not well defined the effect can be large. If it is fixed (like on a transom stern or at bilge keels during rolling and manoeuvring) the effects of viscosity could be limited.

**Forces on appendages, fins and rudders**
The effect of the thickness of the hull boundary layer on the wave and motion induced forces acting on appendages like bilge keels is not very clear; in a cross flow the reduced exposure may be partly compensated by a higher angle of attack.

Regarding stabilizer fins around amidships we are aware through dedicated tests that the effect of the hull boundary layer on the lift is small, both on model and on full scale.

Further aft, the boundary layer of the hull reduces the inflow of the propeller. In judging the combined effect of increased wake and increased propeller thrust because of the higher frictional resistance on the reaction forces from a rudder behind the propeller it should be kept in mind that both effects oppose each other [17]. Outside the propeller wake appendages like trim tabs and interceptors may be less efficient on model scale.

The substantial fin-to-hull interaction originating in the pressure field from T-foils below the keel acting on the hull behind [20] it is modelled correctly in a seakeeping test.

**Spray**
In case the rate of change of fluid momentum becomes too high, a non linear flow mechanism yields a prominent spray. The fact that the thickness of and velocities inside the spray root are not governed by viscosity suggests that the launched volume of water and its impulse scales according Froude’s Law. The dispersion into smaller droplets obviously does not.

Photograph 6: Spray on model scale

3.2 (b) Ambient Pressure and Related Air Density

**Slamming induced excitation**
Flat-surface shallow-angle impacts like wedge entries are characterized by a local high-pressure area that travels at high velocity along the surface. In front of the high pressure area a characteristic high velocity spray dissipates a considerable amount of energy.

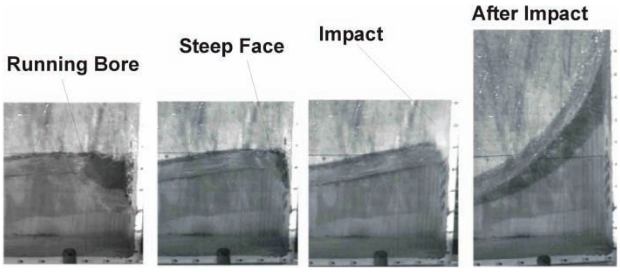
The above character is recognized when the fore-foot slams into a wave trough, when the steep face of an oblique incident wave hits a low-deadrise bow flare at a shallow angle or when a flat stern re-enters the water after emergence. Generally the pressures and the velocities of the pressure front increase rapidly with decreasing relative contact angle.

The fact that the pressures can be reproduced with simulation of an inviscid incompressible flow [22] suggests that the results scale with Froude's Law of Similitude.

In the theoretical case without air above the water the case where the relative angles become very small the compressibility effects cannot be neglected and a shock wave is generated. The resulting acoustic pressure depends on the speed of sound, which is extremely sensitive to the back-ground air contents of the water [16]

In practice escaping air, which reaches extremely high velocities, deforms the water surface. This deformation is affected by the density of the air flow. The compressibility of any entrained air also depends on the density of the air and thus on ambient air pressure.

It seems that the highest impacts are obtained in those cases where the geometry of the contact is such that the escaping air largely escapes. Although other effects play a role as well, it is clear that the representation of the highest pressures with a scale model will improve with a proper modelling of the ambient pressure.




Photograph 7: Tank wall impact

In case of sloshing impact events the applicability of Froude scaling law is not evident. Using a model proposed by Bagnold [4], Bogaert [7 & 8] identified in sloshing experiments impacts with a high and a low impact "number". This simplified 1D model of liquid piston pushing on an entrapped gas pocket balances the kinetic energy of the pushing liquid against the resisting gas pocket. When the pushing liquid dominates, the impact is "hard". When the air compressibility dominates the impact is "soft". The impact number is defined as the ratio between the kinetic energy of the liquid and the ambient pressure. Therefore correct modelling of the ambient pressure is necessary. Bogaert shows that the soft impacts scale with the square root of the scale, high impacts follow Froude's Law.

**Propeller ventilation**
In case the propeller tip reaches too close to the free surface propeller ventilation occurs by means of a local vortex touching down on the propeller tip. This phenomenon, as well as ventilation due to propeller emergence, yields for some propeller types an almost shock like decrease in the thrust and torque. The thrust recovery after immersion seems to depend on the propeller characteristics. In some cases recovery is slow because the air is draining through the tip vortex.


Photograph 8: Propeller ventilation

The creation of the vortex that leads to ventilation depends on the difference between the suction pressures in the propeller tip area and the atmospheric pressure and the local submergence pressure. The ambient pressure does not seem to play a role in this stage. The magnitude of the suction pressure depends on the propeller loading, which is affected by the wake scaling, the increased resistance of a free running model and the modelling of wind.

If the drag of the air influx does not play a role the magnitude of the cavity that develops behind a ventilating propeller seems to be governed mainly by the pressure differences across the propeller blades, which assumes a correct propeller loading. This is a reason to believe that the geometry of the ventity scales properly.

The shock type reduction of thrust and torque that is observed for some propeller types suggests that the dynamic properties of the closed ventity may play a role. Because this ventity contains a too large mass of air the model scale plays a role in this aspect of the response.

Regarding the physics of the shedding of the trapped air, sometimes through the tip vortex, we have insufficient insight to speculate on the effects of ambient air pressure and density and the propeller thrust on the recovery of the thrust after ventilation.

**Cavitation**
Contrary to initiation of ventilation, which is driven by a pressure difference, the occurrence of cavitation is driven by the absolute local pressure. In addition the presence of kernels plays an important role. The absolute pressure is driven again by the propeller thrust and the wake scaling.

It is clear that one (but not sufficient) condition for the modelling of cavitation in seakeeping tests is to reduce the ambient pressure. Considering the areas of propeller ventilation and cavitation [5] it seems clear that more research is required under correct environmental conditions and correct propeller loading.

3.2 (c) Wind

**Roll excitation and roll damping**
An obvious effect of wind is its contribution in the longitudinal drag forces. Less obvious is the fact that the yaw moment exerted on the ship in oblique wind directions yields a drift angle, which changes the drag of the hull and adds a steering component in this respect.

Also the lower frequency components in the natural turbulence in the wind will excite the roll of ships with a lower stability and a longer natural period of roll.

The changes in the wind forces associated with a roll velocity introduce a roll damping which may not be negligible in many cases. In an indirect way, a wind induced increase in propeller loading increases the roll damping contribution from fixed ducted propellers and rudders. This is known to have an effect on the threshold wave height of parametric roll.

**Course keeping**
In oblique wind (and waves) the transverse wind and wave forces are compensated by the opposing force that is obtained by sailing at a drift angle. For most ships these three forces all apply in the forward half of the ship. This means that the equilibrium in yaw can be obtained with modest helm angles (also because the propeller loading is relatively high).

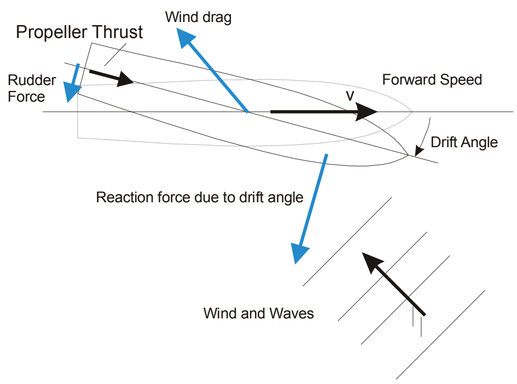



Figure 2: Equilibrium of forces in oblique wind and waves

The above makes it clear that the design of steering arrangement on ships with unusual propulsion configurations (relying less on main propellers aft) or unusual large or atypical wind forces (car carriers, ships with project cargo in the aft part of the ship) requires careful attention for the ability to maintain a given course in storm conditions. Neglecting the wind can give a misleading impression of the ability of a ship to main a course in oblique wind and waves.

**Drifting velocity**
In the assessment of the behaviour of free drifting ships the contribution of the wind in the drifting velocity has a notable effect on the behaviour and relative wave elevation on the weather side of the ship.

**Modelling of wind**
The foregoing makes it clear that in some cases the modelling of wind is inevitable. Because the realisation of wind-tunnel quality wind around a free-running model is hard, the wind loads are mostly generated by means of one or more pulling winches. The challenge is to control them such that they realize the constant part (and, if required, the variable part as well) of the wind force and the change in the wind forces as a function of the ship behaviour.

3.2 (d) Waves

**Target conditions**
Design for service comes with a focus on the particular behaviour with the largest impact on the performance. As far as accessible by numerical means, the relevant combinations of speed, heading, significant wave height and mean period are selected on basis of calculations. Considerations with respect to the effects of wave steepness on performance and other specific issues in the design complete the assessment of the target wave conditions.

The modelling of young, growing waves is relatively straightforward. The relatively narrow mean JONSWAP spectrum is mostly used.

Because longer waves often contain independent wind sea and swell components the selection of a "typical' wave spectrum is less straightforward. A broader banded Pierson Moskowitz is often used.

Several considerations drive the directional spread to be modelled.

One of them is the fact that a directional spread gives a less complete and less clear picture of the particular ship motion characteristics (the transfer functions) that are usually derived to "understand" the motion response.

A second consideration relates to the fact that narrow-banded long crested waves as observed in rapidly growing "young" storm conditions show relatively high non-linear wave-wave interaction. This leads to relatively steep and sometimes breaking waves which can have, depending on the design, a large effect on the performance. In this respect a long crested wave may not be entirely representative for frequency of steep-wave events in real life.

**Wave maker limits**
Wave generation by means of flap-type wave makers along two adjacent sides in a rectangular basin imposes particular limits in the realisation of the target conditions.

Reflections from the beaches opposing the wave makers, which are highest in low, long waves, lead to local variations in wave height and steepness. Because of the spatial averaging the effects of reflection are hardly noticeable in longitudinal and oblique wave directions. At zero speed, and also along the narrow path a model is running in beam seas the effects are largest. Part of effects, the reflection of the reflection from the beach on the wave maker can be reduced with active reflection compensation (ARC) on the wave maker.

The ARC is particularly important in the case of testing long models at zero speed parallel and close to a wave maker to avoid the reflection on the wave maker of the reflection from the model.

In oblique directions the shortest waves that can be generated depends on the width of the wave maker elements. For large ships this is an element in the selection of the model scale.

Obviously the most common wave maker arrangement, along two adjacent sides, limits the range of wave directions that can be generated. The broadest range can be generated with the model travelling in short runs across the width of the basin.

A symmetric short crested wave can be generated by means of the Dalrymple method using the reflections of the (fixed) wave maker along the long side and the wall on the opposite side (removing the beach).

3.2 (e) Current

A physical current affects the wave length and thus the steepness of surface waves. If a design is vulnerable in this respect, or if these conditions occur frequently (like on tidal areas) modelling the physical current in a seakeeping test should be considered.

## 3.3 CHOICES IN AND LIMITATIONS OF MODELLING THE SHIP

3.3 (a) Propulsion, Mooring

**Propulsive efficiency**
The Reynolds numbers on the blades of a small scale seakeeping model are usually insufficiently high to use the measured absorbed power directly. The effect of the actual propeller loading on the propeller efficiency (excess frictional drag and the physical modelling of wind forces) and the effect of the increased wake fraction (due to the increased boundary layer thickness) on the overall propulsive efficiency increase this problem.

Because of the above the problem of quantifying the power requirements of a ship in waves is circumvented by using the measured thrust increase as a direct indication for the added resistance in waves. This follows the very common assumption that the interaction of the propeller with the hull (the thrust deduction factor) is not very sensitive to the propeller loading. The related power is derived by assuming that the propulsive efficiency follows calm water characteristics.

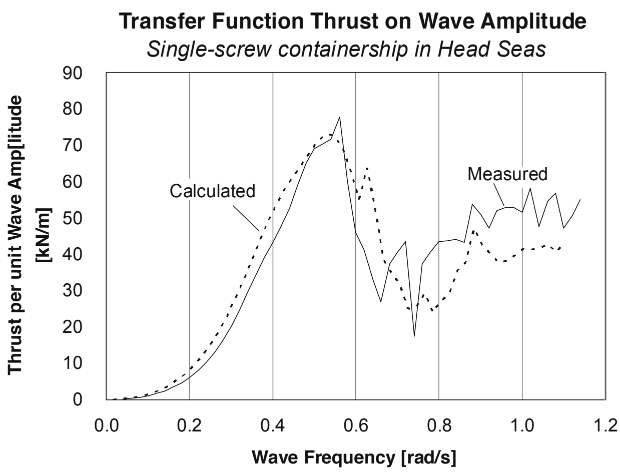


Figure 3: Transfer function of propeller thrust variations

**Wave induced propeller load variations**
The local variations in flow direction and velocity induced by the ship motions, the reflected and radiated waves and the incident wave as well as low frequency speed and course variations and steering yield thrust

variations. In line with the linear relation between the thrust and the entry velocity (at fixed rpm) the first order component of the thrust is generally proportional to the wave height. Following their quadratic nature the low frequency components are large in higher waves. As far as the commonly adopted constant rpm is realistic the natural speed variations seem realistic.

Because the thrust variations scale correctly, the speed variations do so as well.

The natural speed reductions in groups of higher head waves are likely to affect the behaviour in the higher waves. Similarly, it reduces the roll damping, which is known to increase the risk of parametric roll.

In following seas the thrust plays a role in the risk of surf riding.

**Engine reactions**

Considering diesel-direct drives, an added resistance through wind and waves causes a speed reduction in combination with a reduced propeller rpm. If the rpm drops sufficiently the engine does not receive an adequate amount of oxygen to burn the fuel. This may lead to a rapidly decreasing available power with potential dangerous loss of control over the ship. For some ship types, like car carriers, this aspect of the performance may require careful representation in the model.

The dynamic reaction of the propulsive train to the first-order torque variations or the transient loss of torque due to ventilation is an aspect that requires similar attention. In some cases these events are known to lead to loss of propulsive power.

**Mooring**

Tests at zero speed are often performed in a soft mooring arrangement. The effects of this arrangement on the restoring forces in surge, sway and yaw and also in roll, pitch and yaw is determined by the line length, the spring stiffness and the pre-tension.

Attaching the lines at the fore and aft end on the centre line of the model avoids a direct effect of the pre-tension on the stability in roll. The adopted connection height governs the effect through the roll-sway coupling.

Selecting a low stiffness to avoid first-order resonance is not always possible because of problems with the magnitude of the related low-frequency motions of the model. In addition to the above problems, a four-line arrangement has a relatively large stiffness in yaw.

The above problems are avoided by performing the tests in a free-drifting mode. At MARIN this procedure is common for IMO Open-Top Tests and IMO Weather Criterion Tests. In the latter tests the wind loads are modelled as well.

3.3 (b) Motion Control and Steering

**Fin stabilizers**

Mounting fin stabilizers on ship models accounts potentially for the false angles of attack from the ship motions and the incident waves, free-surface effects and the fin-to-hull and hull-to-fin interactions [9].

These important interactions [9,20] between fin stabilizers and the hull are governed by the downstream flow field, which scale according Froude’s Law of Similitude.

Modelling relies, apart from the mechanical control, on the correct representation of lift slope and the stall angle. For lower aspect ratios there are reasons to believe that the first aspect is met quite well on model scale [13]. The fact that the static stall angle shows considerable effects of viscosity may not be representative in the case of oscillating flow conditions which show, also at quite low frequencies, considerable temporary magnification of the lift due to delays in the stalling process. For higher aspect ratios the design of the fin models requires careful consideration to correct for scale effects [21].

The effects of the fact that the fins are operating inside the exaggerated boundary layer of the model seem to be very small for conventional fin stabilizers.

Modelling the use of stabilisers for stabilisation at zero speed, which builds on the fluid inertia and drag forces and their timing with respect to the roll velocity, obviously requires careful modelling of the actuator characteristics.

**Anti-roll tanks**

An important motivation for mounting anti-roll tanks on board a ship model is that in this way they are subject to the correct combination of linear accelerations and angular motions that determine their performance.

Numerical reproduction of resonant sloshing of the contents of a simple free surface tank by means of a Volume of Fluid Method shows a very limited effect of the representation of viscosity. This implies that their contribution in the roll damping of a model scales correctly.

The resonant response of the contents of a passive or controlled U-tank is generally kept at bay with specially designed damping plates perpendicular to the flow in the cross-duct. The fact that this substantial pressure drag contribution to the internal damping scales more or less correctly gives confidence in the contribution to the roll damping. Off course this is not necessarily true for very smooth U-type tanks, where it affects both the frictional drag and character of the flow separation.

**Rudders**
The prime reason for a rudder on a model is to obtain a more or less straight track of the model in all wave directions. This is typically achieved with a rudder reaction on the course and transverse offset of the model. An additional reaction on the rate of turn yields a very course stable model.

The immediate reaction of the model steering gear and the fact that in most cases no conscious effort is made to model the commands of a human helmsman or an autopilot and the dynamic reaction of the steering engine (typically a delay) has consequences for the test results.

In terms of course keeping there are reasons to believe that this procedure yields a too optimistic impression of the course keeping abilities in waves from the stern quarter.

In terms of roll, the immediate reaction on sway and yaw affects, through the roll-sway-yaw coupling, the roll damping. Similarly the rudder reaction to a transverse offset of the stern by a wave crest from the stern quarter yields a magnification of the wave induced roll moment.

Similar to model stabilizer fins there are reasons to believe that the effects of viscosity on the lift slope are small. The effects on the stall angle are reduced by the turbulence from the propellers.

A point that is modelled correctly is the ventilation of the rudder that occurs at higher speeds.

Because of the above it seems plausible that the control of the rudders is the weakest point in the modelling of the ship response.

3.3.(c) Slamming Induced Flexural Response

**Structural response**
A large part of slamming problems and also the seamanship exerted by the master is not related to the magnitude of the local pressures but to the induced structural vibrations. In some cases the magnitude of the excitation changes with the structural response. This deviation from a linear approach is denoted as a "hydro-elastic" response. If relevant, this phenomenon obviously requires modelling of the flexural modes.

**Whipping**
Depending on the structural design in particular larger ships, show natural frequencies in the lower vertical bending modes that are sufficiently low to be excited by impulsive slamming loads. This yields very characteristic, transient, decaying whipping vibrations.

Assuming that the whipping response does not affect the impulsive load that causes it, one way of quantifying it is by measuring the impulsive excitation and using a finite element analysis to estimate the subsequent vibrations. Considering the local spatial extent of the pressures and the high velocities of the pressure fronts this requires a high density of pressure gauges, sampled at a high frequency. This technique seems applicable for well defined, local areas of excitation (like aft body slamming or green water impacts).

An alternative approach is to represent the deformation mode shapes in the scale model. This technique, which finds increasing application, yields direct information on the response in the flexible modes. It is used to quantify the contribution of slamming in ultimate hull girder loads and fatigue damage, in excessive cargo and container lashing forces and cruise ship passenger discomfort.

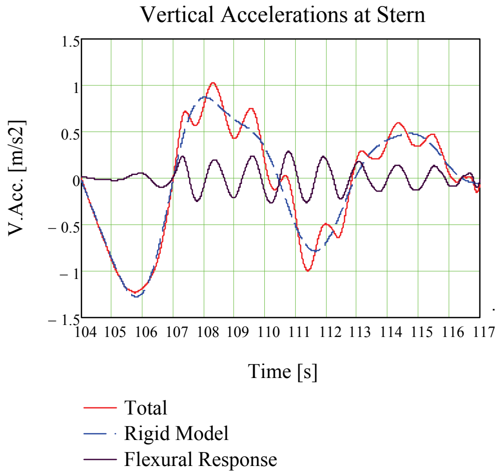



Figure 4: Cruise ship whipping and rigid body accelerations in low waves

Because the rigid body accelerations show substantial correlation with the largest (first) whipping accelerations the effect of structural damping on extreme values seems to be limited. Its contribution to the fatigue damage is larger.

**Springing**
Continuous first and second order wave induced forces yield a resonant response that is referred to as springing. Its magnitude is directly related to the structural damping of the ship. This feature requires adequate representation in the scale model to obtain realistic results.

3.4 TEST DURATION

In the analysis of the "first-order" response in irregular waves the number of wave encounters is often useful as a measure for the statistical reliability of results. In case the encounter input spectrum is very narrow banded (as in a Gaussian swell, a JONSWAP spectrum with a high peak enhancement factor or at certain combinations of speed and heading) subsequent wave encounters are insufficiently independent to act in this respect. In this case longer test duration should be considered.

Considering the focus of present day testing on the non-linear aspects of ship behaviour which determine the operational limits it seems that the test duration has not kept pace. The quantification of the probability of occurrence and typical magnitude of relatively rare events like green water loads, ingress of water [2], excessive whipping accelerations or broaching simply requires an adequate number of these events in a seakeeping test.

## 4. FUTURE SEAKEEPING TESTS

Seakeeping tests to verify and improve the operational performance of ships are evolving into a complex and very complete representation of real life performance. Along these lines we see an increased attention for the effects of wind loading, more detail in the control of fins, foils and rudders, active control of anti-roll tanks, more attention for dynamic positioning and first steps in modelling the reaction of the propulsion train on propeller torque variations.

A similar trend is the increased use of flexible models to quantify the impact of slamming induced whipping response on hull girder deformations, fatigue damage, sea fastening issues and passenger discomfort. After a careful design with FE calculations on the mode shapes of the model the flexural accelerations and bending moments recorded during the tests are used to reconstruct the modal response.

One challenge in this area is the simultaneous modelling of the vertical and the coupled transverse and torsion modes. Considering springing, the major challenge is the ability to model a specified mechanical damping level.

### 4.1 (a) Deterministic Testing

Design for service builds on a quantified risk. This means that seakeeping tests should quantify the frequency of occurrence of particular events, for instance by relating them to a number of wave encounters.

If the frequency of events is low, like is inevitably the case with non linear phenomena, like slamming and broaching or capsizing, modelling "key events" by means of tests in deterministic waves may seem attractive. However, although it may give insight in the physics, this type of "event modelling" never gives a clue regarding their probability of occurrence.

### 4.1 (b) Scaling Slamming Pressures, Ventilation and Cavitation

MARIN gratefully acknowledges government funding for extending the functionality of the existing Depressurized Towing Tank into a "Two-Phase Laboratory" (TFLAB). This basin makes it possible to address the issues related to the scaling of the ambient pressure and the density of the air by facilitating seakeeping tests in depressurized conditions. For this purpose it will be equipped with state of the art wave makers along part of the 180m long side and the 18m short side of the basin. In this set up the basin will facilitate tests with large models in irregular waves from a full range of wave directions.

Regarding seakeeping of ships the TFLAB will give insight in the effects of air pressure in:

- The local slamming pressures and global flexural response;
- Green water loads;
- Ventilation induced propeller loads and performance degradation;
- Cavitation of propellers, fins and foils during the operation in waves.

Important other areas of research will be the effect of air compressibility on the progressive flooding of ships and the wave loads on offshore structures.

Because of our increasing awareness of the effects of the directional spread, we anticipate the frequent use of short crested seas.

## 5. CONCLUSIONS

Contemporary seakeeping tests aim at a very complete representation of ship behaviour in waves. Many aspects, like the natural speed variations, the contribution of changes in the steady bow wave system and local non-linear diffraction on the dynamic swell-up, the contributions of stability variations and steering on the ships behaviour are accounted for implicitly. Mimicking the ride control (fins, rudder roll, anti-roll tanks) further adds to the realism.

Modelling the flexural response has become an important and efficient way around the need for defining the highly erratic local slamming pressures to obtain the hull girder vibrations that in the end drive performance.

In the near future the possibility to perform seakeeping tests at reduced air pressure will enhance our insight in the problems in scaling impact loads, ventilation and cavitation which are associated with the pressure and density of the ambient air.

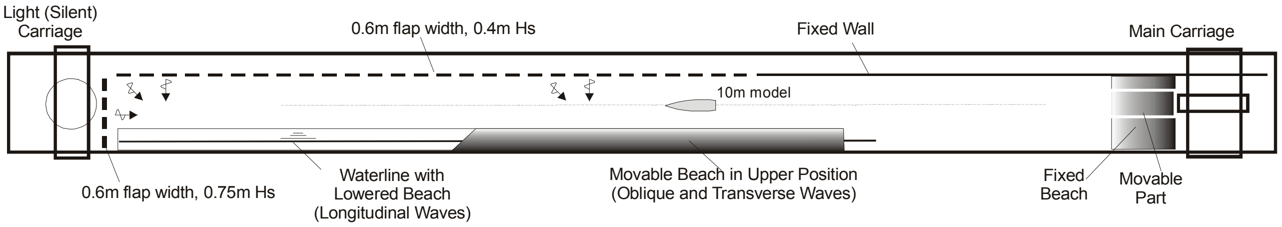



Figure 5: Lay-out of MARIN Two-Phase Laboratory

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