Strip Theory and Some of Its Applications

by Johan Journée

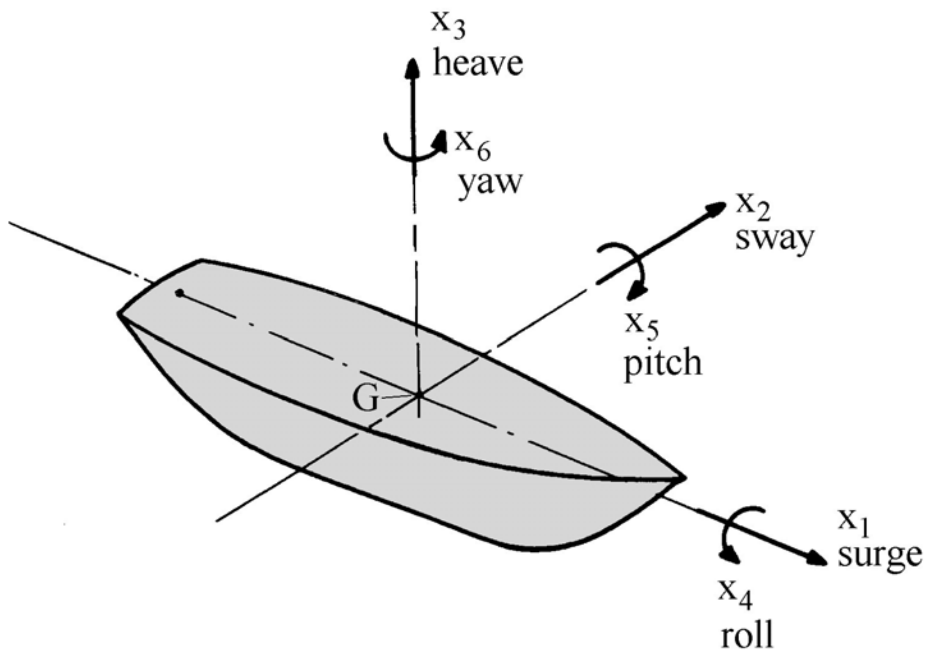
(Presentation for the OCTOPUS User Group Meeting, held at Nijkerk, November 5th, 2009.)

Theory and references can be found at:

Website: www.shipmotions.nl
(see there DUT Section "Papers and Reports")

- **Paper 10:**
  Experimental and Numerical Simulations of Sloshing Behaviour in Liquid Cargo Tanks and Its Effect on Ship Motions
  Paper at NMTCP'84 , Venice, by N.E. Mikelis and J.M.J. Journée, July 1984.
- **Paper 22:**
  Liquid Cargo and Its Effect on Ship Motions
  Paper at STAB'97, Varna, by J.M.J. Journée, September 1997.
- **Paper 34:**
  Fluid Tanks and Ship Motions
  Lecture at Kyushu University, Fukuoka, by J.M.J. Journée, October 2000.
- **Report 40:**
  Theoretical Manual of Strip Theory Program "SEAWAY for Windows"
  DUT Report by J.M.J. Journée and L.J.M. Adegeest, September 2003.

The Strip Theory



Newton's second law:

$$\sum_{j=1}^{6}\{M_{ij}\cdot\ddot{x}_j\} = \text{sum of all forces or moments in direction } i \qquad \text{for: } i = 1,...6$$

RHS:

- **hydromechanic forces and moments**
  caused by harmonic oscillations of the body in the undisturbed surface of a fluid, being previously at rest

- **exciting wave forces and moments on the restrained body**
  caused by the incoming harmonic waves

So:

$$\sum_{j=1}^{6}\{(M_{ij}+a_{ij})\cdot\ddot{x}_j + b_{ij}\cdot\dot{x}_j + c_{ij}\cdot x_j\} = F_i \qquad \text{for: } i = 1,...6$$

History of Strip Theory Developments

1949, Ursell:
2-D potential deep water theory for semi-circular cross sections

1950's, Tasai, Grim, Gerritsma, et.al.:
Ursell's potential theory and conformal mapping techniques
(most popular: Lewis conformal mapping, 1929)

1953, Denis en Pierson:
Superposition principle to describe irregular waves

1957, Korvin-Kroukovski en Jacobs:
Inclusion of forward ship speed effects: OSM and MSM

1957, Haskind:
Relations between diffraction and radiation potentials
1962, Timman and Newman:
General confirmation of these "Haskind" relations

1962, Fukuda:
Internal sheer forces and bending moments in a cross section

1967, Frank:
Deep water pulsating source theory for arbitrary shaped symmetrical cross sections

1970, Boese:
Added resistance by the integrated pressure method
1972, Gerritsma/Beukelman:
Added resistance by the radiated energy method

1974, Keil:
Shallow water theory with Lewis conformal mapping

1978, Ikeda, Himeno and Tanaka:
Viscous roll damping components

Some Remarks on the Strip Theory

- **Slender body theory, so in practice (roughly): L/B > 3.**
  The ship's cross sections don't produce longitudinal waves.

- **Potential flow theory, so viscous effects are neglected.**
  Viscous roll damping will be added by empirical formulas.

- **Substantial disagreements can be found between calculated and experimental data of wave loads at low frequencies of encounter in following waves.**
  In practice, these "near-zero frequency of encounter" problems are solved by forcing the wave loads to go to zero, artificially.

- **For high-speed vessels, unsteady divergent wave systems become important. This effect is neglected. All waves generated by the ship are propagating in directions perpendicular to the centre plane of the ship. Interactions between cross sections are neglected.**
  Again, the ship's cross sections don't produce longitudinal waves.

- **Strip theory is based upon linearity. Shipmotions are supposed to be small, relative to the cross sectional dimensions of the ship. Only hydrodynamic effects of the hull below the still water level are accounted for.**
  Also, the strip theory does not distinguish between various above water hull forms.

- **Added resistance of a ship due to waves is proportional to the vertical relative motions squared; its inaccuracy will be gained strongly by these motions.**

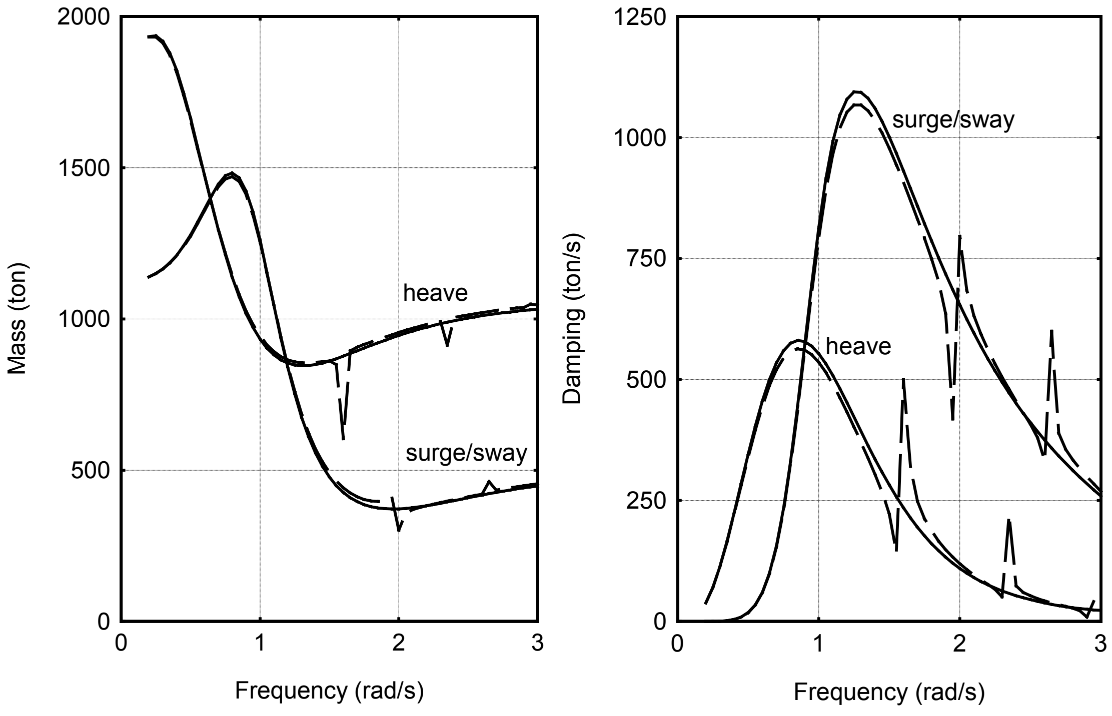
Nevertheless these critical remarks, seakeeping prediction methods based upon the strip theory provide generally fairly-well to good results.

Remarks on Irregular Frequencies

So-called "irregular frequencies" can appear when calculating added mass and damping with the 2-D Frank-method or the 3-D approach for free surface piercing bodies; fully submerged bodies do not display these characteristics.

An effective method to reduce the effects of irregular frequencies is "closing" the body by means of a discretisation of the free surface inside the body, i.e. putting a "lid" on the free surface inside the body.
Paul Kaplan (author of SCORES of LRS, London) suggested me this method already in the late seventies.

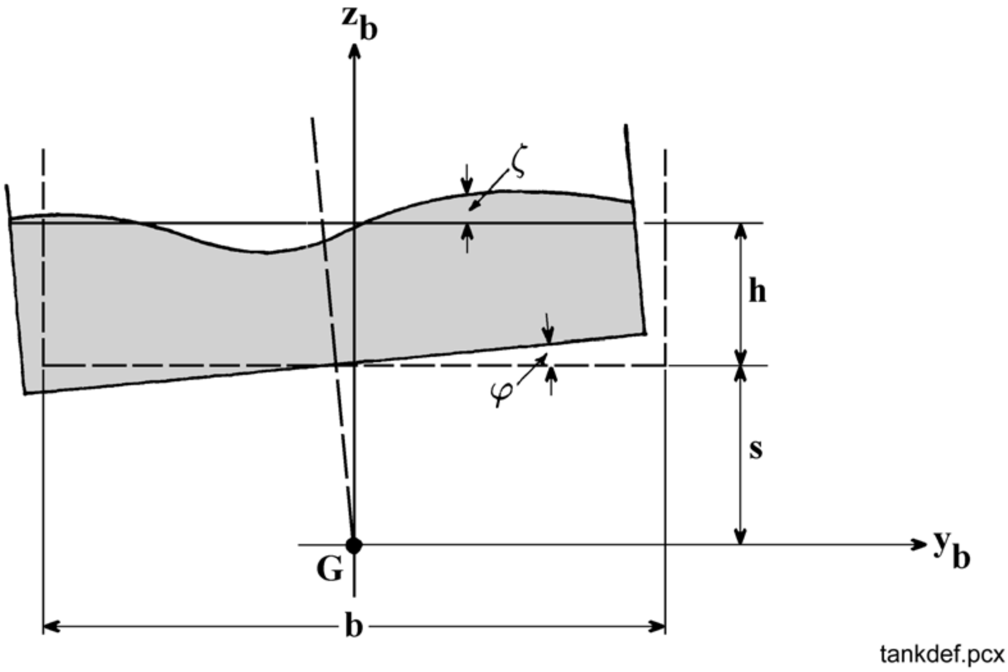
See the computed added mass and damping data of a hemisphere by Frank's method in SEAWAY in the figure below. The solid line results from including the "lid".



Effect of Use of "Lid-Method" for Irregular Frequencies

This phenomenon brought me on an idea for calculating potential fluid tank moments simply by Frank's method (see further on).

Fluid Tanks

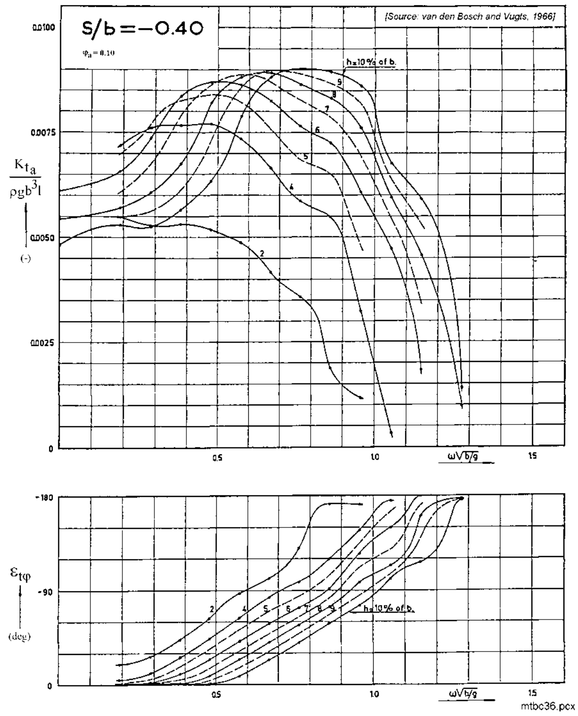


Rolling Fluid-Tank

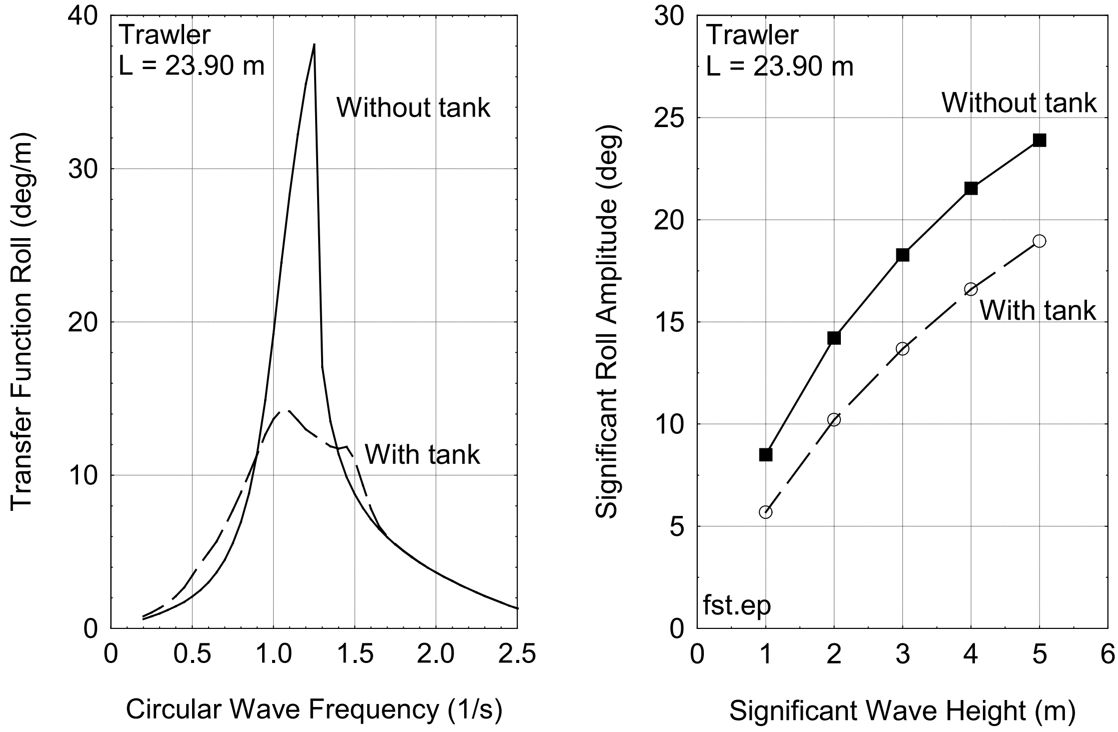
Topics:

- **Experiments with free-surface tanks by Van den Bosch and Vugts (1966)**
- **Shallow water theory of Verhagen and Van Wijngaarden (1965)**
- **Results of space vehicle studies, carried out by NASA (1966)**
- **2-D potential theory of Frank (1967)**
- **3-D potential theory by DELFRAC of Pinkster (±1995)**

Experiments with Free-Surface Tanks by Van den Bosch and Vugts (1966)



Experimental Data on Anti-Roll Free-Surface Tanks



Effect of a Free-Surface Anti-Roll-Tank on Roll

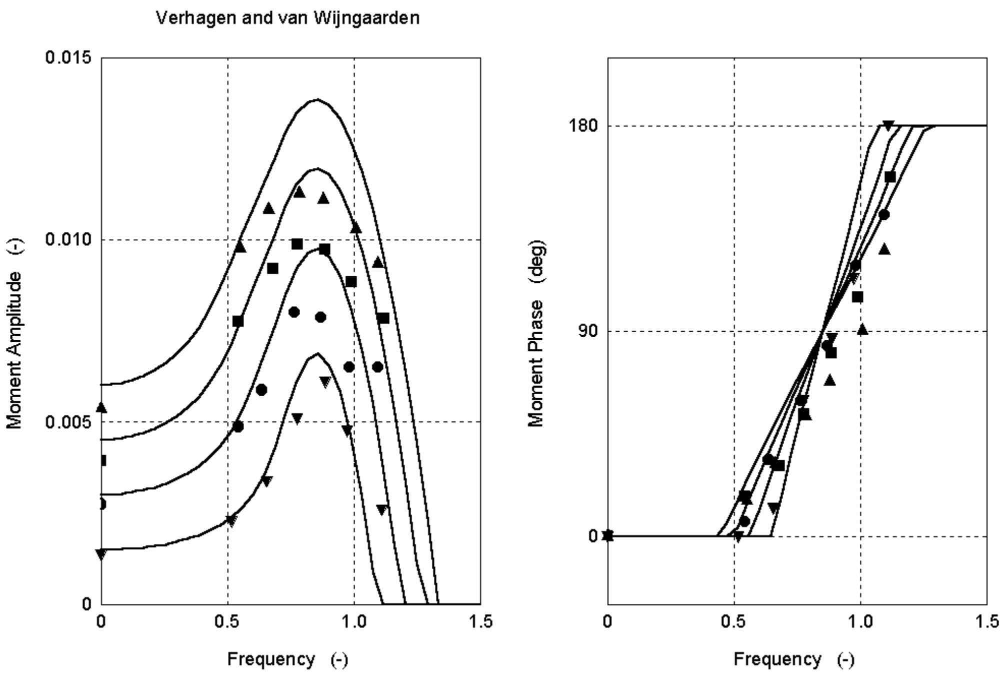
Theory of Verhagen and Van Wijngaarden (1965)

Theory based on gas-dynamics for a shock wave (by a piston) in a gas flow (under similar resonance circumstances).

Different formulas for:

- **Low-frequency region**
- **Natural-frequency region**
- **High-frequency region**

Artificial connection of these three regions.

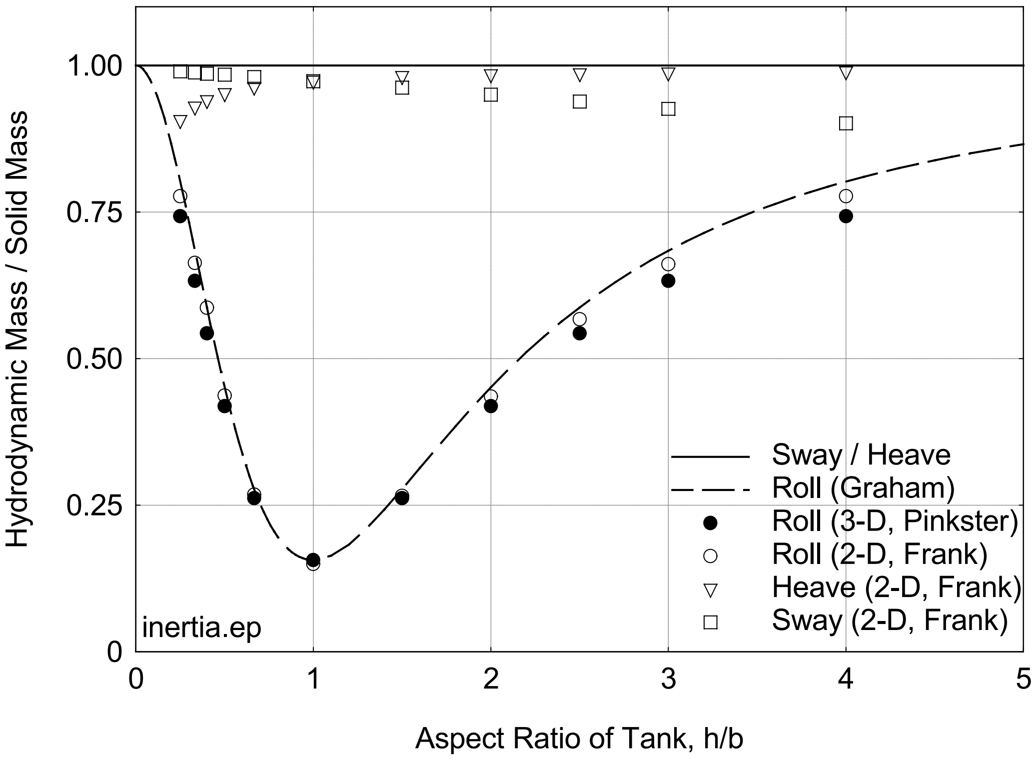


Comparison between Theoretical and Experimental Data of Verhagen and Van Wijngaarden for various shallow water depths (center of rotation at the bottom)

Fully-Filled Rectangular Tanks

Calculations by:

- **Formulas obtained from space vehicle studies of NASA**
- **SEAWAY, 2-D (Frank/Journée)**
- **DELFRAC, 3-D (Pinkster/Journée)**

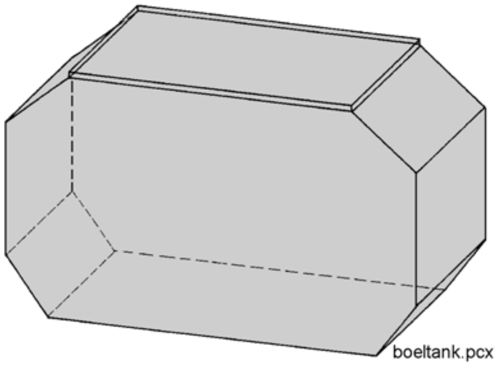


Mass and Moment of Inertia of a Fully Filled Rectangular Tank

For small and large aspect ratios deviations can be expected, caused by the limited number of 16 line elements in SEAWAY or 30 panels in DELFRAC on the contour of half the cross section of the tank.

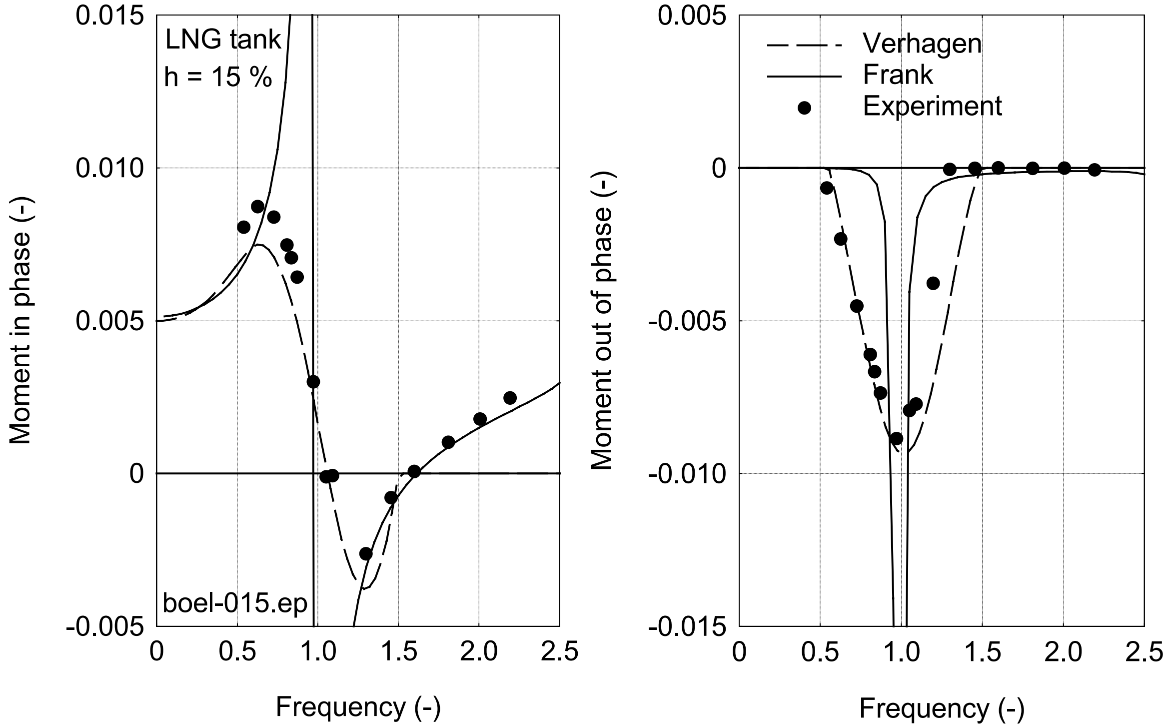
<u>Note:</u> "SEAWAY for Windows" doesn't have this limitation anymore!

Forced Roll Experiments with a 2-D Model of a Cargo Tank of an LNG-Carrier

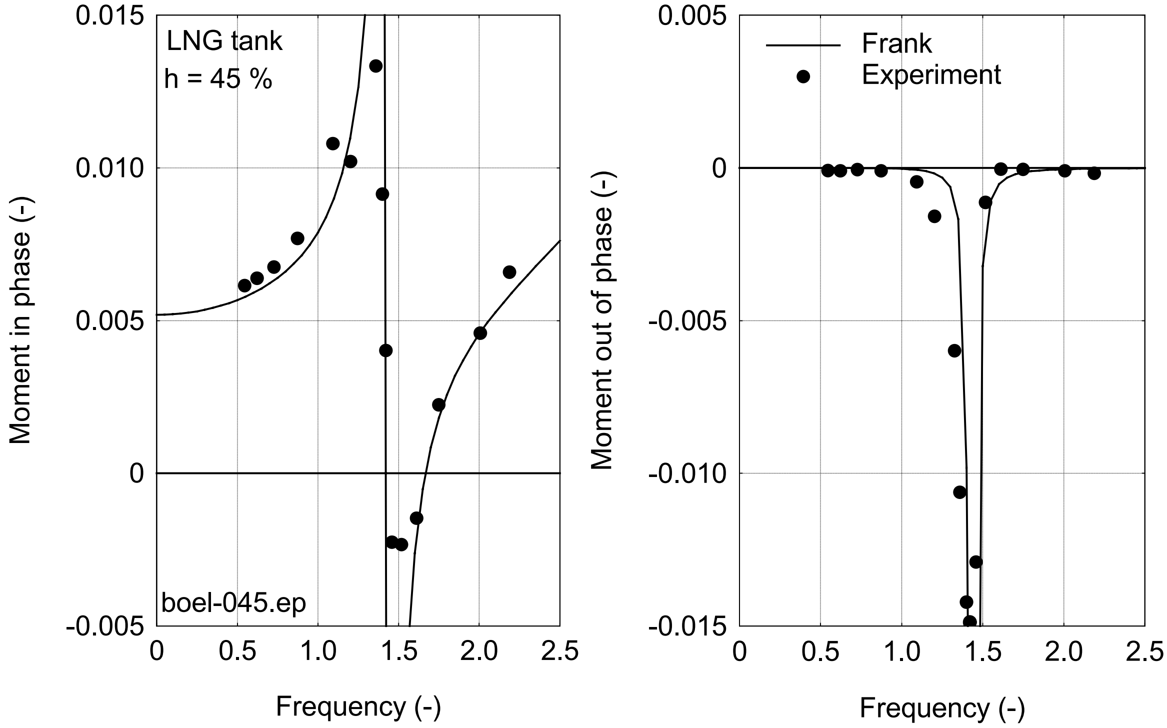


2-D Model of an LNG Tank

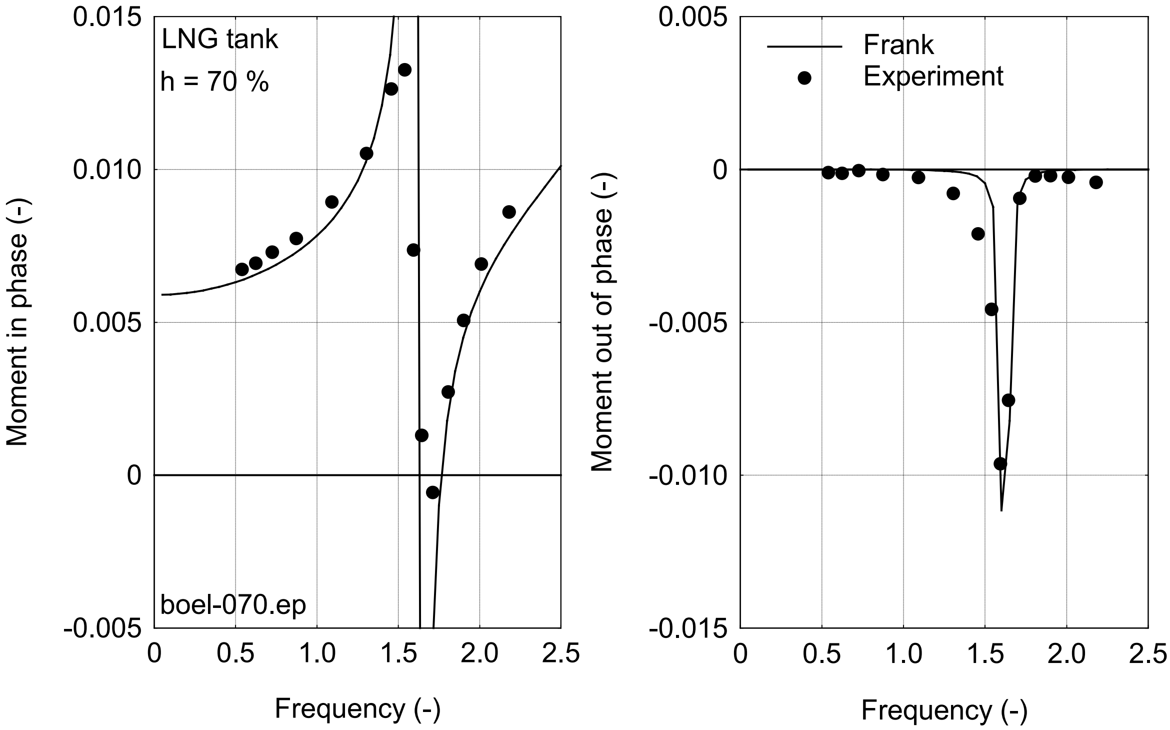
Validation with Frank's theory



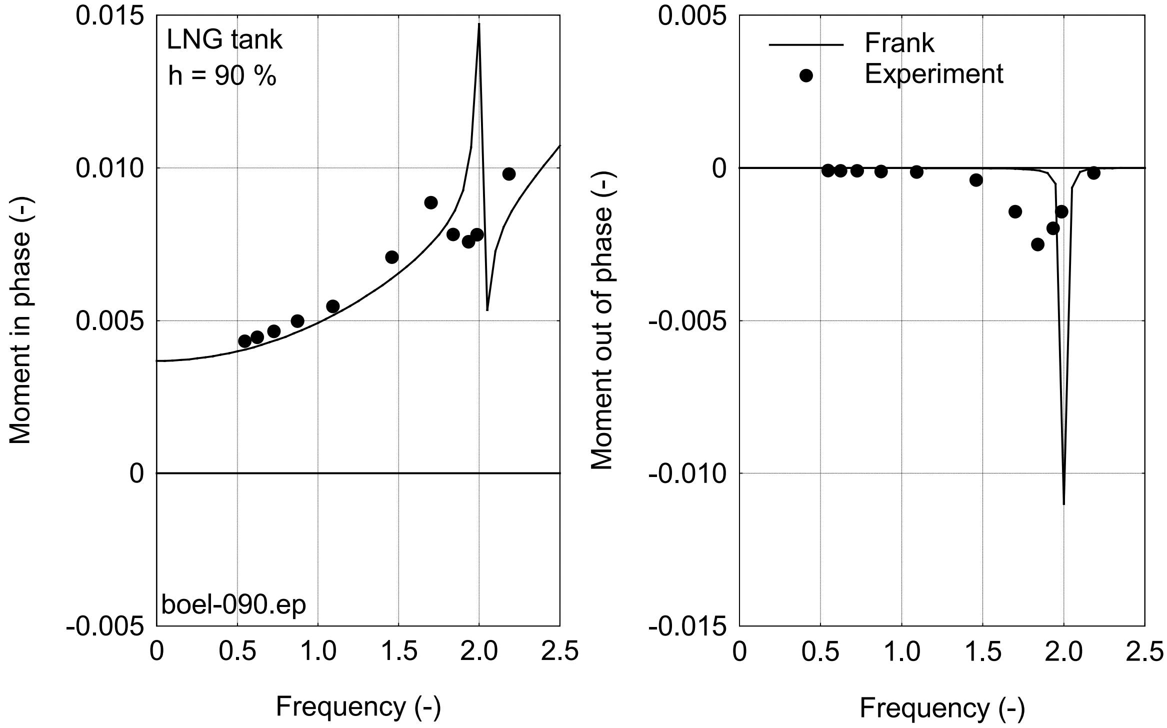
Roll Moments of an LNG Tank with 15 % Filling Level



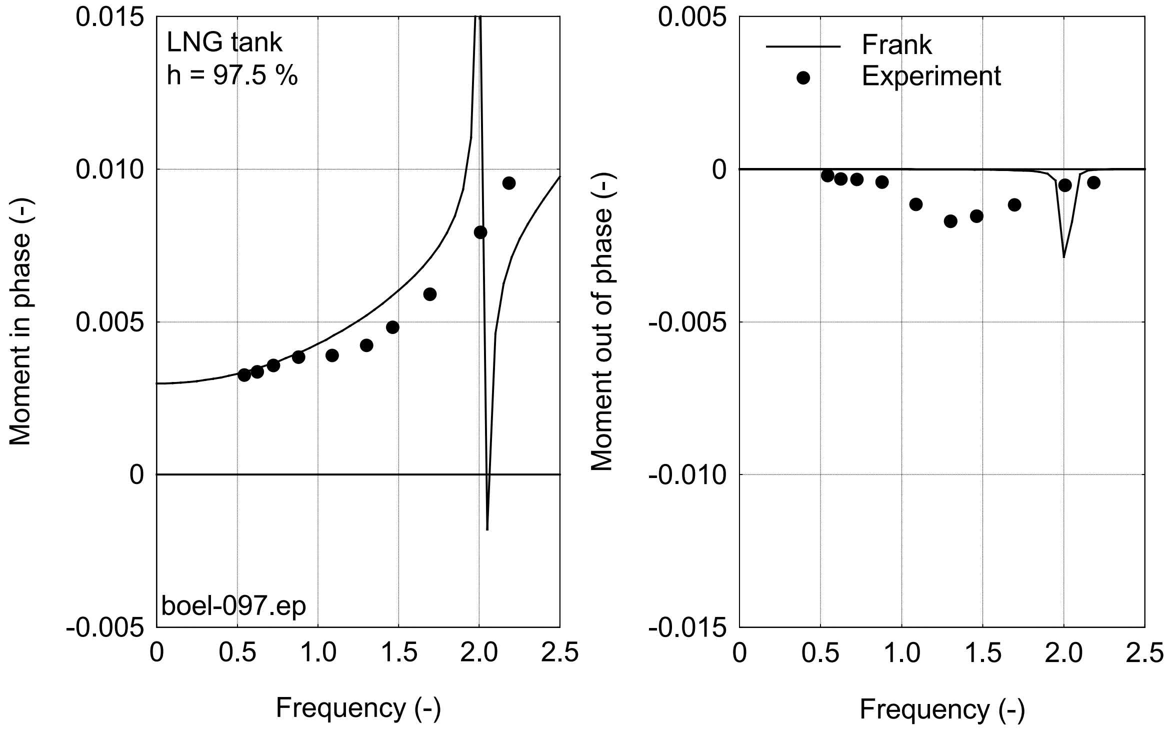
Roll Moments of an LNG Tank with 45 % Filling Level



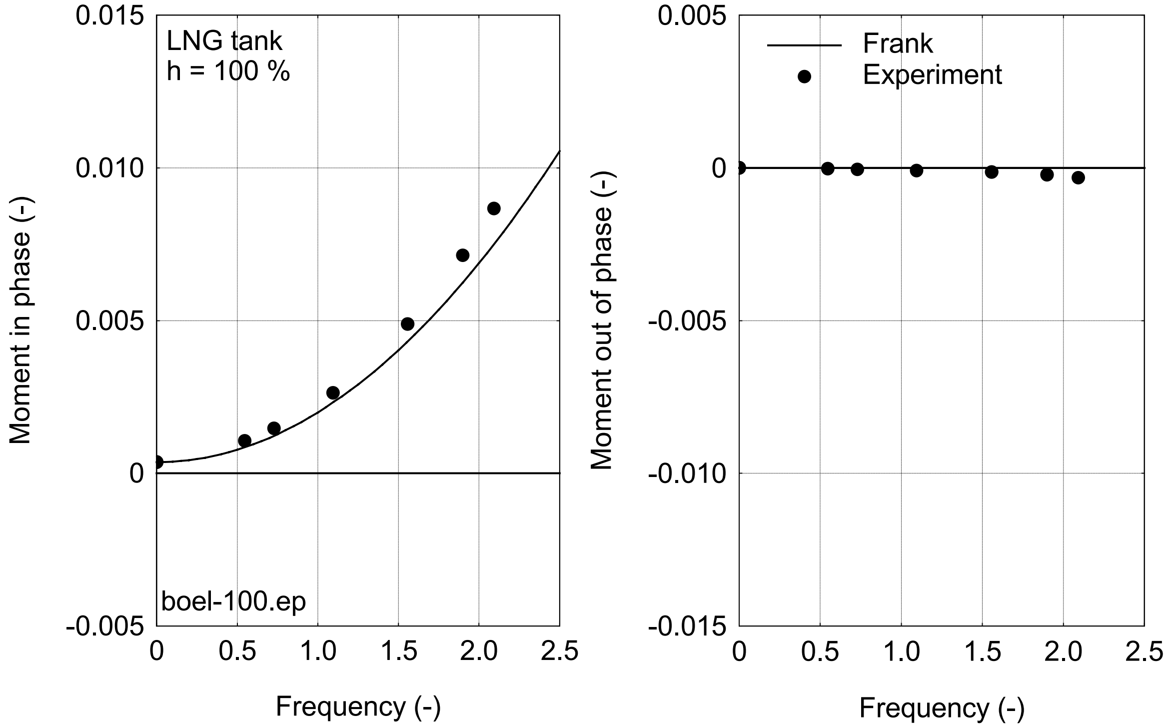
Roll Moments of an LNG Tank with 70 % Filling Level



Roll Moments of an LNG Tank with 90 % Filling Level



Roll Moments of an LNG Tank with 97.5 % Filling Level

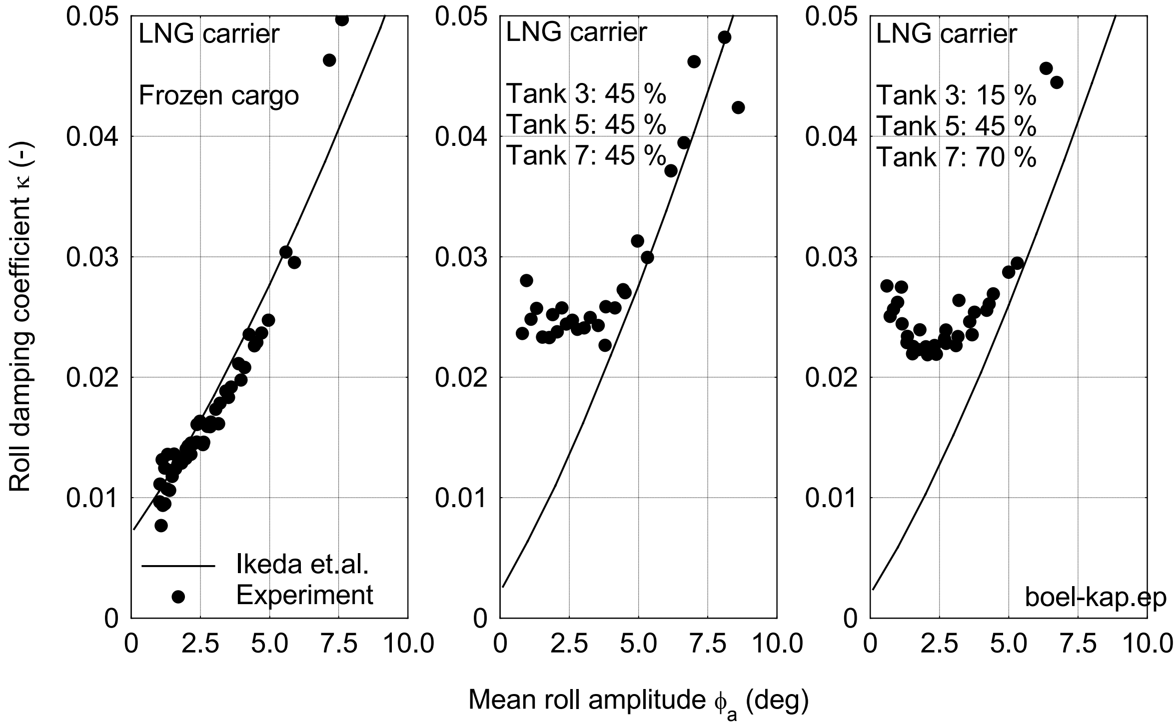


Roll Moments of an LNG Tank with 100 % Filling Level

Experiments with an LNG-Carrier Model (L_{pp} = 164.00 m)

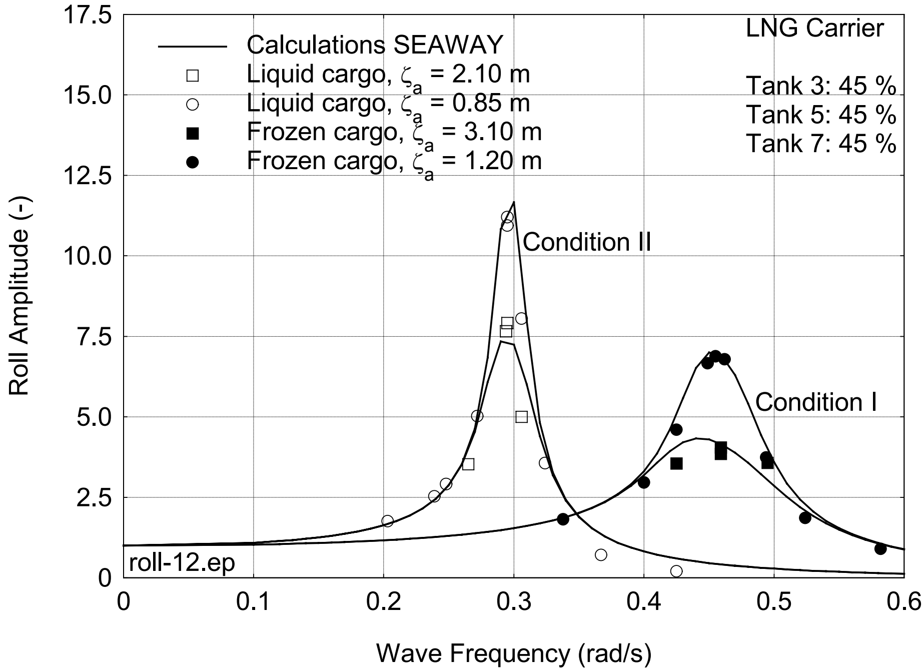
Condition		I	II	III
∇	m^3	51680	51680	51360
KG	m	10.48	10.42	10.60
GM	m	2.75	2.81	2.62
GG'	m	0.00	1.69	1.59
k_{xx}	m	10.14	9.38	9.49
$T_{\phi\text{-measured}}$	s	13.70	21.30	23.00
$T_{\phi\text{-calculated}}$	s		21.18	22.82

Loading Conditions

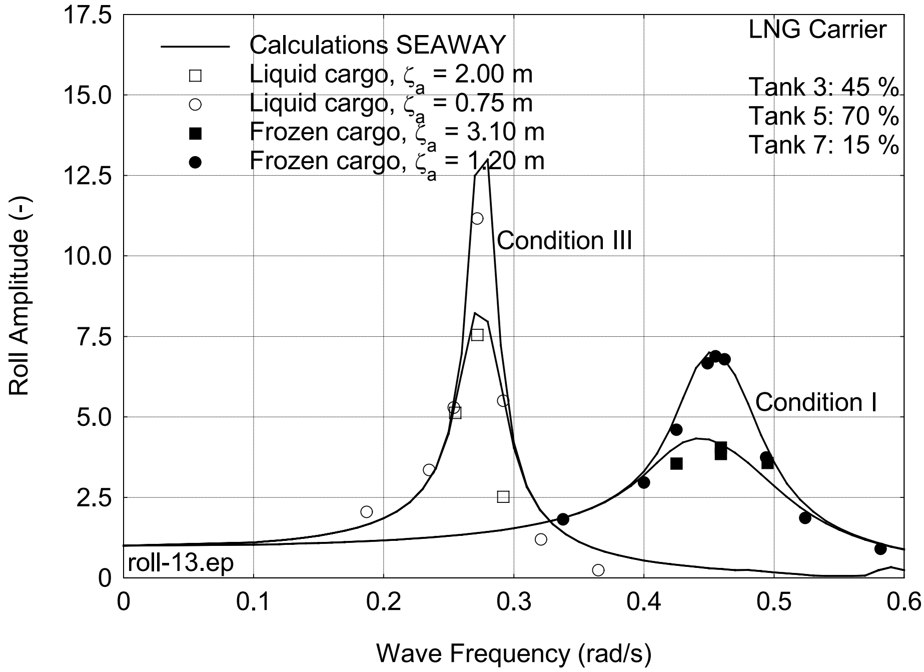


Roll Damping Coefficients

Experiments with an LNG-Carrier Model
(L_{pp} = 164.00 m)

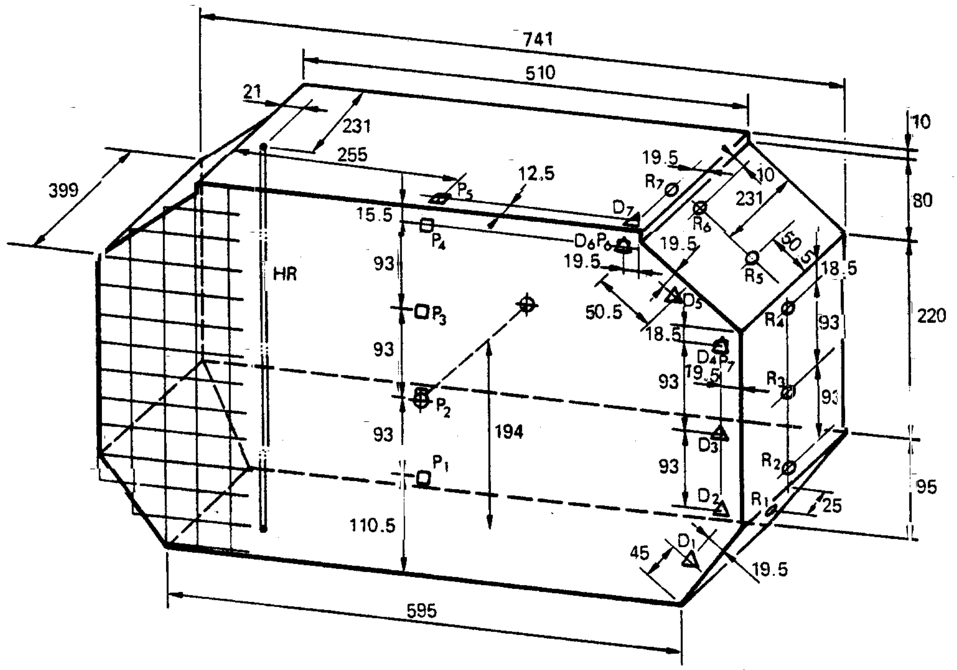


Roll Motions of an LNG Carrier, Conditions I and II

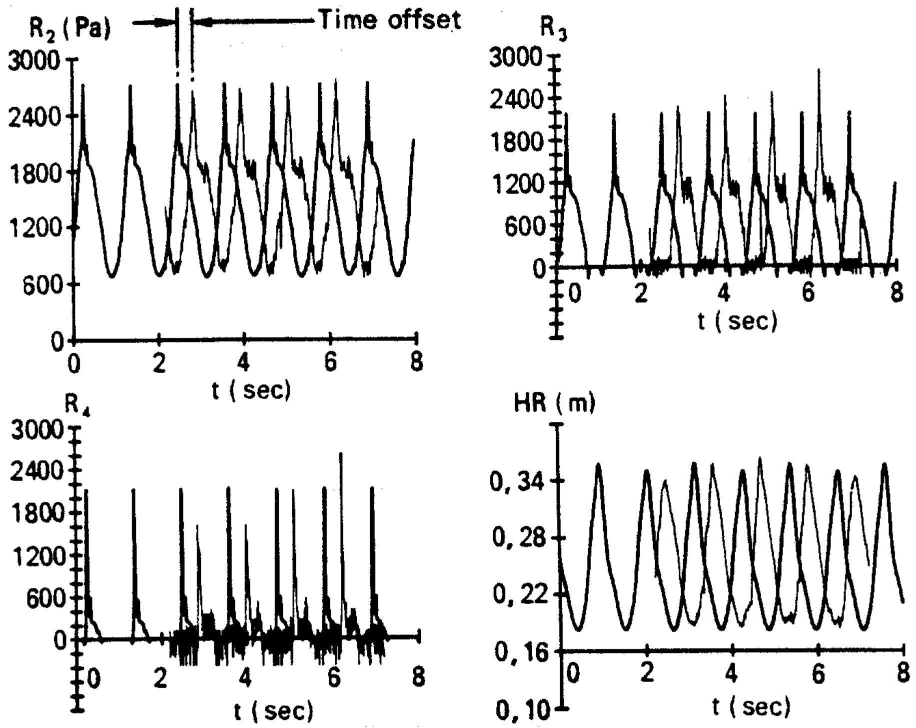


Roll Motions of an LNG Carrier, Conditions I and III

Sloshing



Model Tank, Pressure Transducers, Wave Height Recorder and Grid



Exp. and Comp. Pressures at 3 Transducers (R2, R3, R4) and Wave Surface Height
(Roll, $h/D = 0.61$, $T = 1.112$ sec, $\phi = 0.10$ rad)

Time Domain

Time Domain Equations of Cummins (1962):

$$\sum_{j=1}^{6} \{ \left[M_{i,j} + A_{i,j} \right] \cdot \ddot{x}_j(t) + \int_0^{\infty} B_{i,j}(\tau) \cdot \dot{x}_j(t-\tau) \cdot d\tau + C_{i,j} \cdot x_j(t) \} = X_i(t) \qquad \text{for } i = 1,6$$

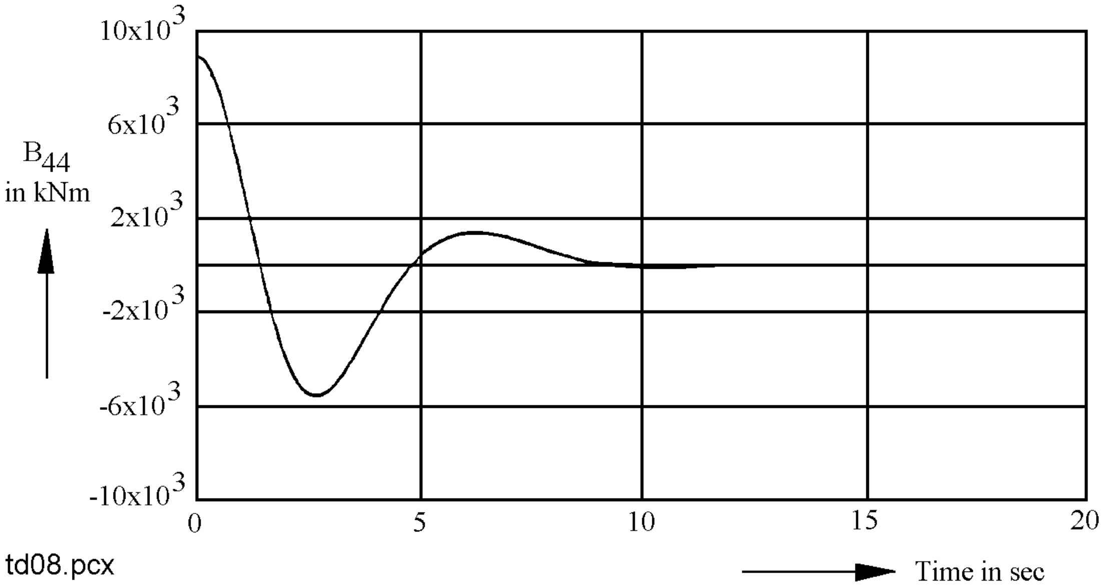
Ogilvie's approach (1964):

$$A_{i,j} = a_{i,j}(\omega = \infty)$$

$$B_{i,j}(\tau) = \int_0^{\infty} b_{i,j}(\omega) \cdot \cos(\omega\tau) \cdot d\tau$$

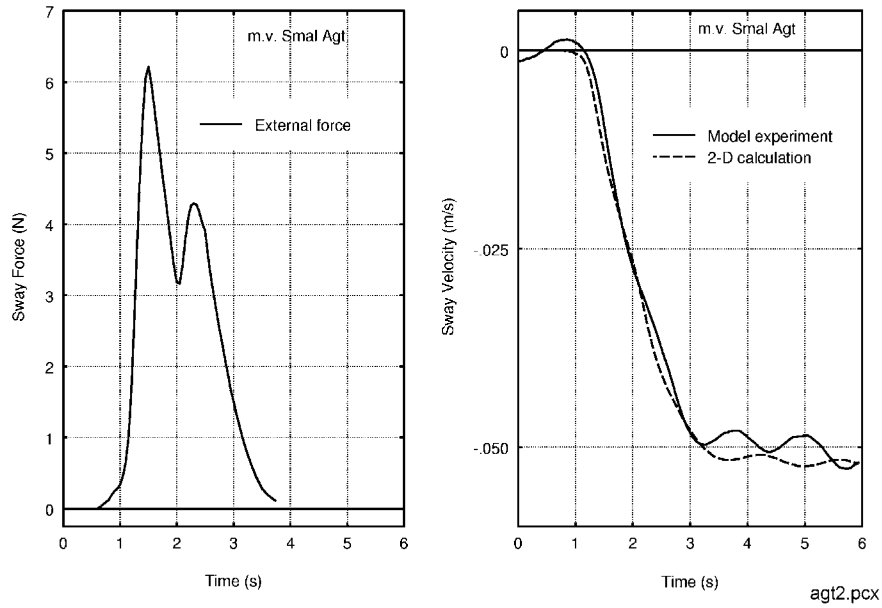
$$C_{i,j} = c_{i,j}$$

Retardation function:

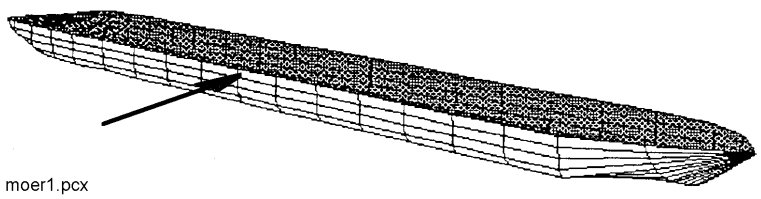


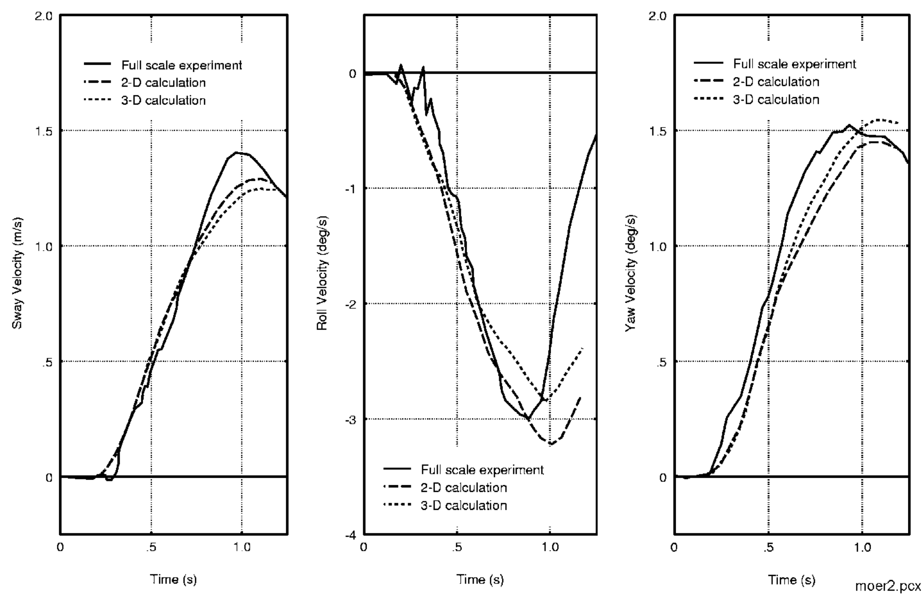
Example of an Retardation Function for Roll

Validations



External Impulse and Resulting Motions
(model experiments on m.v. "Smal Agt")





Ship Velocities, Caused by a Collision