ADDED RESISTANCE FROM A LINEAR THEORY

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• Introduction
• Numerical method
  • Rankine source code
  • Inherent limits
  • Practicalities
• A word on the nature of added resistance
• A word on experiments
  • Ways to measure added resistance
  • Practical issues
• Correlation between predicted and measured results
  • ‘Wall-Sided” ships
  • Container ships and LNG carriers
  • Cruise ships
• Trends in the predicted added resistance
  • Governing factors
  • Non-linear character of added resistance
• Conclusions
INTRODUCTION

• Objective of the investigation
  • Identify & resolve the practical issues in the use of the adopted Rankine source code
  • Understand the limitations of this linear theory
  • Use the mismatch with measured data to speculate on the nature of the “missing” physics
  • Use the calculated results to obtain an understanding of the effect of hull form on added resistance in waves

• Limitation
  • “Sharp-bow” ships in head waves in the Fn150-Fn250 speed range
NUMERICAL METHOD: RANKINE SOURCE CODE

• Rankine source code “FATIMA”, facilitating:
  • Linearisation w.r.t. the “actual” free surface
    • Obtained with the non-linear potential flow code “RAPID”
  • Adequate description of the dispersion of reflected and radiated waves
  • Detailed description of interaction of steady and oscillating flow field

• Consequences
  • Improved account for fwd speed
  • Improved description of relative wave elevation (fwd and aft)
  • Account for effects fwd speed on wave making roll damping component
NUMERICAL METHOD: INHERENT LIMITATIONS

- Change in hull viscous drag
  - Due to dynamic flow components
  - Downstream effects from appendages
  - Effects of a drift angle
- Change in hull wave making drag
  - Loss of “bulb performance”
- Change in appendage drag
  - Bilge keels
  - Bow thruster tunnels
- Flow separation
  - At bulbous bow
  - At bilges and bilge keels
  - “Kutta” condition at aft end of skeg and transom stern
- Wave breaking
  - Reduction in relative wave elevation
- Non-linear changes in hull immersion
- Dynamics of steering and course keeping
- Changes in propulsive efficiency
  - Decrease of wake fraction
NUMERICAL METHOD: PRACTICALITIES

• Particularly suitable for “smooth” steady flows
  • Off-design drafts and speeds are not always straightforward

• Numerical problems - Evaluation of:
  • The vertical steady flow pressure gradient on the hull
  • The higher-order longitudinal derivatives of the steady flow
  • The dispersion of very short reflected and radiated waves
    • Normal free-surface grid comprises 1%L_{pp} square cells

• Efficient computation procedure
  • Strip theory: 40 panels (for 20 sections each)
  • Conventional panel methods: 2000-4000 panels
  • Rankine source code: 20,000-30,000 panels
  • RANSE: 5M-25M cells
The added resistance is the delicate sum of opposing components.

The relative wave elevation along the water line is the largest added resistance component:
- This relative wave elevation is governed by:
  - The heave and pitch motions
  - Motion induced radiated waves
  - Reflected waves

The opposing forward forces originate in:
- Suction over the submerged part of the hull (largest around the bow)
- A forward force related to the phasing of the heave excitation and the pitch response
EXPERIMENTS: ISSUES & METHODS

• Issues
  • Frictional resistance is relatively high on model scale (+20-40% ?)
  • The accuracy of a towing test is ~1%
  • RAW is difference between test in waves and test in calm water (increasing the error to ~2%)
  • Added resistance of the model is 5-20% of the total model resistance
    • 5% error around the peak
    • 40% error in the HF tail

• Methods
  • Towing
    • Captive, at constant speed
      • Tow force = output
    • At constant tow force
      • Velocity = output
  • Self propelled, free-running
    • Thrust measurement, requires estimate thrust deduction
    • Thrust & speed = output
  • Captive, partly self-propelled
    • Thrust and tow-force = output
EXPERIMENTS: ISSUES & METHODS

- Sources of error
  - Calibration errors
  - Zero-reference (electronic)
  - Non-stationary character of resistance and/or thrust signals
    - Random components induced by the turbulent boundary layer
    - Noise in the towing carriage speed
    - Low frequency variations in amplitude incident wave

- Calm water reference resistance
  - Wave maker induced flow in the basin

- Reference wave
  - Measurement procedure

- Other issues
  - Indeterminate transition of laminar-turbulent boundary layer (1m/s limit ?)
  - Changes in flow separation
    - Full block ships
    - Towed/propelled models
  - Effect of ship motions
WALL-SIDED SHIPS

- Wigley (DUT, 1992)
  - L/B=5
  - Towed set-up
  - Low damping in pitch (9%)
  - RAO Rel. wave ampl. at bow = 6
  - $\zeta_a \sim 2$ and $3\%L_{pp}$

- Results
  - Fair agreement of linear prediction with data measured in lowest wave
  - Clear (30%) non-linearity in PV QTF

- It’s tempting to assume that the motion amplitude is the source of the non-linearity. However..
  - This does not explain the discrepancies at low frequencies
  - Why the linear prediction is not above the values recorded in the lowest wave
WALL SIDED SHIPS

- **Kuroda (2010)**
  - 1:48 model of 300m container ship
  - Towed model
  - $\zeta_a \sim 0.5%L_{pp}$
  - Bow flare replaced by vertical wall

- **Results**
  - Good reproduction of motions and added resistance
WALL SIDED SHIPS

- NSMB 1980’s CRS-RAW
  - Focus on short waves
  - Schematic wall sided hull
  - Towed model
  - $\zeta_a \sim 1\%L_{pp}$

- Results
  - Good agreement at “lower” frequencies
  - Results at $F_n=0.210$ show some effect of free-surface refinement
• Tentative conclusion
  • On average linear theory is doing well for “linear” (wall-sided) cases
  • Relative errors are largest in short waves
• Nakamura (1971) Hull No. 1
  • Towed set-up
  • $\zeta_a \sim 2\%L_{pp}$
  • Low damping in pitch
  • Flare in upper part of bow

• Prediction
  • too low at Fn250
  • OK at Fn200
  • too high at Fn150
SHIPS FROM THE 1970’S

- Nakamura (1971) Hull No. 3
  - Towed set-up
  - $\zeta_a \sim 2\% L_{pp}$
  - Low damping in pitch
  - Flare in upper part of bow

- Results
  - Excellent agreement
CONTAINER SHIPS

• Nakamura Hull No. 2
  • Towing tests
  • $\zeta_a \sim 2%L_{pp}$
  • Looks more like contemporary container ship
    • more flare
    • higher $GM_L$

• Results
  • Excellent agreement
SLENDER HULLS

- Nakamura
  - Hull No. 1 (SL175)
  - Hull No. 2
  - Hull No. 3
- Kuroda
  - Wall-Sided Hull

- Observations
  - Good agreement, perhaps a slight increase for higher values (around the peak of the QTF)
  - Apparently this is what a “good” correlation with linear theory looks like
LNG CARRIER

- Adding ships with high deadrise in the bow
  - Blunter than previous ships

- NSMB, Blok-Bunnik, 1983
  - 1:70 Towed model
  - $\zeta_a \sim 0.8%L_{pp}$

- Results
  - Over-estimate of PV
  - Under-estimate of HF Tail
Observations

- LNG carriers feature higher ND RAW
- Despite increased “bluntness” still good agreement between linear prediction and measured values
CONTAINER SHIPS

- NSMB 1971
  - 4th Gen. Container Ship
  - Free-running model
  - $\zeta_a \approx 1.7\% L_{pp}$

- Results
  - Over-prediction at lower speed
  - Under-prediction at higher speed
CONTAINER SHIPS

- Flokstra Panamax
  - Free running model
  - $\zeta_0 \sim 0.8 L_{pp}$

- Results
  - high error in HF tail
  - PV ok at higher speeds
CONTAINER SHIPS

- Kuroda with flare
  - Towed set-up, Fn246
  - $\zeta_a \sim 0.5\%L_{pp}$

- Results
  - Increase at the peak and along the HF tail
  - Effect increases with speed
  - Results suggest a relatively strong effect of flare

- However:
  - The more pronounced flare hardly yields a further increase around the peak
• KCS Container Ship
  • Towed set-up, Fn260
  • Tests at constant wave slope
    • Around PV $\zeta_a \sim 1.2%L_{pp}$

• Results
  • Computed added resistance very similar to that of similar container ships
  • Measured added resistance is rather low
    • Confirmed by CFD...
The scatter plot illustrates a comparison between measured and predicted RAW for various slender hulls, LNG carriers, and container ships. Key observations include:

- **Over-all quite good agreement**
- **Most results indicate relative decrease in QTF at higher (peak) values**
Observations
- Most cruise ship results are in line with the container ship results
- Some cases (with higher waves and higher speed) show larger reduction

Hypothesis (for sharp-bow ships)
- The local transition into a non-linear flow regime reduces the relative wave elevation and as such it’s (large) contribution to the added resistance
EXAMPLES OF WAVE BREAKING – FERRY FN277
• Longitudinal radius of inertia

• For Gerritsma’s vd Stel a 4% increase in the $k_{yy}$ introduces a 27% increase in RAW...

• For ships with higher damping the effect is still substantial

• A check on the longitudinal radius of inertia should be part of the routine QA
• Waterline entry angle

• For fine bow ships:
  • Both the peak value and the high frequency tail are proportional to the waterline entry angle
Assume that the RAW is governed completely by:
- Wave amplitude
- Forward speed
- Waterline entry angle

Assume that the RAW is proportional to:
- Radius of inertia $k_{yy}$
- Forward speed
- Waterline entry angle

Correct measured QTF peak values accordingly
Plot the remainder as a function of the wave amplitude
Observation
- Initially strong reduction (50%!!) of the PV QTF with wave amplitude
- In higher waves the effect saturates
- The discontinuity agrees with the physical nature of the relative wave elevation
- After the transition the RAW becomes quadratic again
- Effect is small for hulls with a smaller WL entry angle and less flare (from the 1970’s)

Trend for contemporary ships
- $F_{n200}$
- 15deg WL entry angle
- $K_{yy} = 25\%L_{pp}$
CONCLUSIONS

- Linear theory has been used to calculate the added resistance in head waves.
- Comparing the results with measured data shows:
  - Good agreement for “wall-sided” hulls and older, slender hull forms
  - Substantial scatter in the correlation. Caused by:
    - The above non-linearity
    - Limited accuracy of measurements
    - Peculiar sensitivities of the calculation method
  - Systematic deviation for contemporary hull forms, showing for most ships (not all) a relative decrease in added resistance with increasing:
    - Wave amplitude
    - Waterline entry angle and flare
    - Flare

*It is suggested that the observed transition into a non-linear flow regime reduces the relative wave elevation and thus the added resistance for contemporary hull forms*
Linear theory has been used to estimate trends in the added resistance. Important factors are:

- Speed (roughly proportional)
- Waterline entry angle (again roughly proportional)
- Longitudinal radius of inertia (roughly proportional)

The above trends in the linear results have been used to correct the measured values of the added resistance at the peak of the QTF. The corrected results suggest that:

- RAW is independent of wave amplitude for very slender hulls
- RAW decreases strongly in relatively low waves for contemporary hulls
RECOMMENDATIONS

• Improve the insight in added resistance from experiments with:
  • Development of an adequate quality assurance
  • Checks on the linearity with variations in wave height
    • Identify the transition from a linear to a non-linear flow regime
  • Checks on the relevance of a QTF in predicting the added resistance in irregular waves
    • Perform tests in irregular waves (of sufficient duration)

• Improve the insight in the non-linear and other aspects of added resistance with:
  • Investigations in the nature of the non-linear effects (CFD?)
  • Checks on the validity of linear theory for oblique wave directions
THANK YOU FOR YOUR ATTENTION!