PASI 2010 in Dynamics and Control of Manned and Unmanned Marine Vehicles

Dynamics and Hydrodynamics of High Speed Craft

1400-1545, June 29, 2010
Barranquilla, Colombia

Armin Troesch
Naval Architecture and Marine Engineering
University of Michigan

OUTLINE

- Planing Hull Hydrodynamics and Dynamics

  Selected experiments and theories
  with practical applications

- Nonlinear Dynamics Analysis Applied to Planing Hulls

- Stochastic Vibro-Impact Model for Extreme Planing Craft Acceleration Estimation

With a little help from friends:

Recently Active UM Graduates:
Dr. Lixin Xu
Dr. Carolyn Frank Judge
Wayne Arguin (USCG)
Timothy Conners (USCG)
Dr. Richard Royce
Tony Daniels
Dr. Kevin Maki
Dr. Brant Savander
Oscar Tuscan (Dr. to-be)
Fredy Zarate

And many more…….

Planing and Impact Research at UM

Kang, K.G. (1988) Non-linear Impact Hydrodynamics. Ph.D. Thesis.

Talmor, A. (1991) Non-linear Slender-Body Approach for Predicting Planing Performance, Ph.D. Thesis.

Hicks, J.D. (1993) Analysis Method for Planing Hull Vertical Motions. Professional Degree Thesis.

Lai, C. (1994) Hydrodynamic and Dynamic Analysis of High Speed Planing, Ph.D. Thesis.

Akers, R.H. (1995) Planing Hull Design Environment. Professional Degree Thesis.

Wang, M. (1995) A Study on Non-linear Free Surface Flows. Ph.D. Thesis.

Savander, B.R. (1997) Planing Hull Steady Hydrodynamics. Ph.D. Thesis.

Xu, L. (1998) A Theory for Asymmetric Vessel Impact and Steady Planing. Ph.D. Thesis.

Judge, C.F. (2000) Impact of Wedges with Horizontal and Vertical Velocities. Ph.D. Thesis.

Arguin, W. (2001) Simulation of Planing Hull Dynamics in the Transverse Plane. MSE Thesis.

Conners, T. (2001) Coupled Surge, Sway, Roll, and Yaw Hydrodynamic Coefficients for High Speed Planing Craft. MSE Thesis.

Royce, R.A. (2001) Impact Theory Extended to Planing Craft with Experimental Comparisons. Ph.D. Thesis.

Daniels, A.S. (2002) Design and Construction of the Stepped Planing Hull Dynamometer. Professional Degree Thesis.

Maki, K. (2005) Transom Stern Hydrodynamics, Ph.D. Thesis.

Tascon, O. (2010) Numerical Computation of the Hydrodynamic Forces Acting on a Maneuvering Planing Hull via Slender Body Theory - SBT and 2-D CFD Impact Theory. Ph.D. Thesis

Rose, C. J. (2010) Marine Systems Application of Extreme Value Prediction of a Vibro-Impact System Subject to Stochastic Excitation, MSE Thesis

Zarate, F. (2010) CFD Modeling of Yawed and Heeled High Speed Planing Hulls, MSE Thesis

Selected University of Michigan References

Troesch, A.W. and Kang, C.-G. (1986) "Hydrodynamic Impact Loads on Three Dimensional Bodies," Proceedings of the 16th Symposium on Naval Hydrodynamics, Berkeley, July.

Troesch, A. and Falzarano, J. (1993) "Modern Nonlinear Dynamical Analysis of Vertical Plane Motion of Planing Hulls," Journal of Ship Research, September, pp. 189-199.

Troesch, A. and Hicks, J.D. (1994) "The Efficient Use of Simulation in Planing Hull Motion Analysis," Naval Engineers Journal, January, pp. 75-85.

Lai, Canhai and Troesch, A.W. (1995) "Modelling Issues Related to the Hydrodynamics of Three Dimensional Steady Planing," Journal of Ship Research, Vol. 39, No. 1 March.

Hicks, J.D., Troesch, A.W. and Jiang, C. (1995) "Simulation and Nonlinear Dynamics of Planing Hulls," Journal of Offshore Mechanics and Arctic Engineering, Vol. 117, No. 1, February.

Vorus, W.S. (1996) A flat cylinder impact theory for analysis of vessel impact loading and steady planing resistance. Journal of Ship Research, Vol. 40, No. 2, pp. 89-106.

Kim, D. J., Vorus, W. S., Troesch, A.W., and Gollwitzer, R. M. (1996) "Coupled Hydrodynamic Impact and Elastic Response," Proceedings of the 21th Symposium on Naval Hydrodynamics, Norway, June.

Lai, Canhai and Troesch, A.W. (1996) "A Vortex Lattice Method for High Speed Planing," International Journal for Numerical Methods in Fluids, Vol. 22,, pp. 495-513.

Xu, L., Troesch, A. W., and Vorus, W. S. (1998) "Asymmetric Vessel Impact and Planing Hydrodynamics," Journal of Ship Research, Vol.42, 5. September.

Akers, R.H., Hoeckley, S. A. Peterson, R. S., and Troesch, A. W. (1999) "Predicted vs Measured Vertical-Plane Dynamics of a Planing Boat, " Proceedings of FAST'99, Seattle, WA. Sept..

Savander, B.R., Scorpio, S.M., and Taylor, R.K. (2002) "Steady Hydrodynamic Analysis of Planing Surfaces. " Journal of Ship Research, Vol. 46, No. 4.

Judge, C., Troesch, A. W., and Perlin, M. (2003) "Initial Water Impact of a Wedge at Vertical and Oblique Angles." Invited contribution for a Special Issue on Water Impact in the Journal of Engineering Mathematics.

Maki, K. J., Troesch, A. W. and Beck, R. F. "Experiments of Two-Dimensional Transom Stern Flow," Journal of Ship Research, Vol. 52, No.4, Dec. 2008, pp. 291-300.

Hamza, Karim, Troesch A.W., Saitou, K., "Design of an Instrument Shock Isolator for a High Speed Marine Vehicle via a Multi-Objective Genetic Algorithm, " IEEE World Congress on Computational Intelligence (Special Session on Evolutionary Computation for Expensive Optimization Problems), July 16-21, 2006, Vancouver, BC, Canada

Savander, B. and Troesch, A., "Mission Configurable Modular Craft Concept Study", Proceedings of 1st International Conference on Ship Design and Naval Engineering, March 2009, Cartagena de Indias, Colombia.

Tascon, O., Troesch, A., Maki, K., "Numerical Computation of the Hydrodynamics Forces Acting on a Maneuvering Planing Hull via Slender Body Theory – SBT and 2-D Impact Theory," 10th International Conference on Fast Sea Transportation, FAST 2009, Athens, Greece, October, 2009

Planing Craft Resistance and Dynamics

Armin Troesch
University of Michigan
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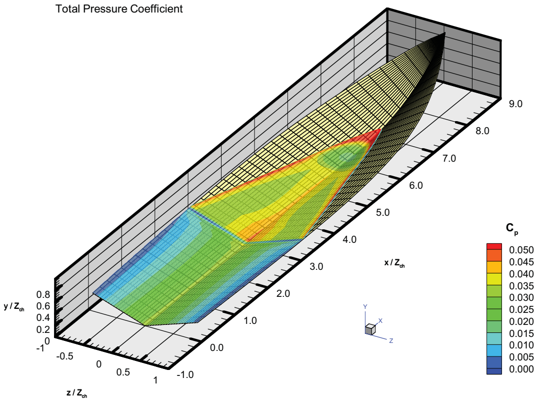
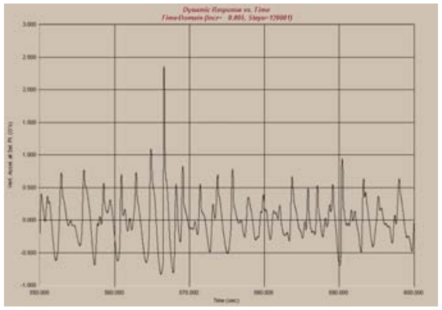
Design & Analysis Process Overview

- Steady (?) Hydrodynamic Analysis
  - Defines global geometry
  - Defines weight distribution
  - Defines operating parameters



- Seakeeping/ Maneuvering Analysis
  - Defines structural loading
  - Defines operability boundaries



- Structures
  - Quasi-Static & Transient
  - Primary, Secondary, Tertiary
  - Fatigue Life (Endurance Limit)
  - Fracture Mechanics (Module Dis-assembly)

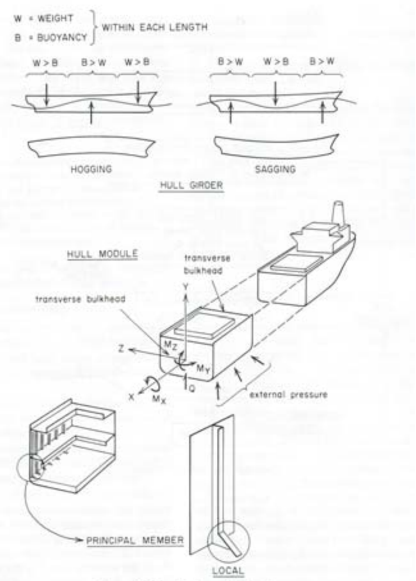
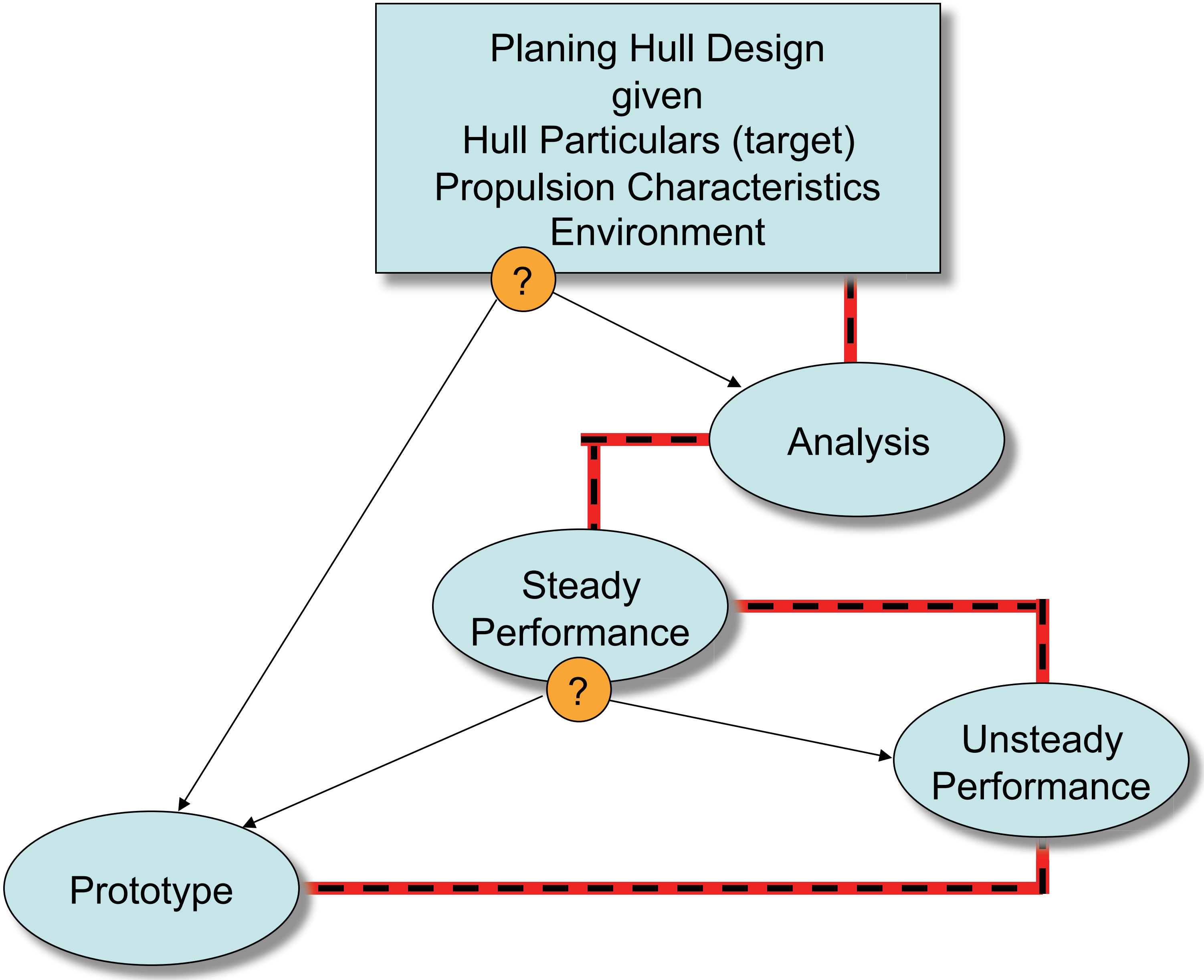
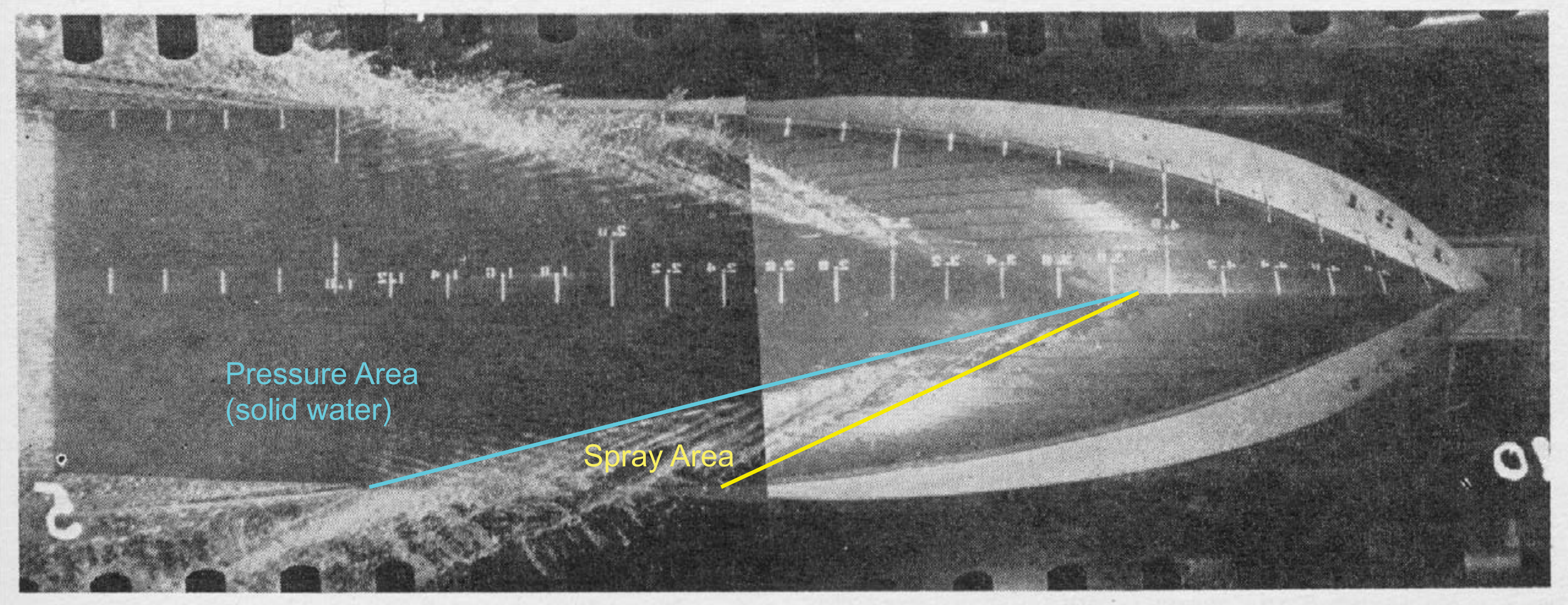


Figure 1.2 Levels of structural analysis.


Planing Hull Design
given
Hull Particulars (target)
Propulsion Characteristics
Environment

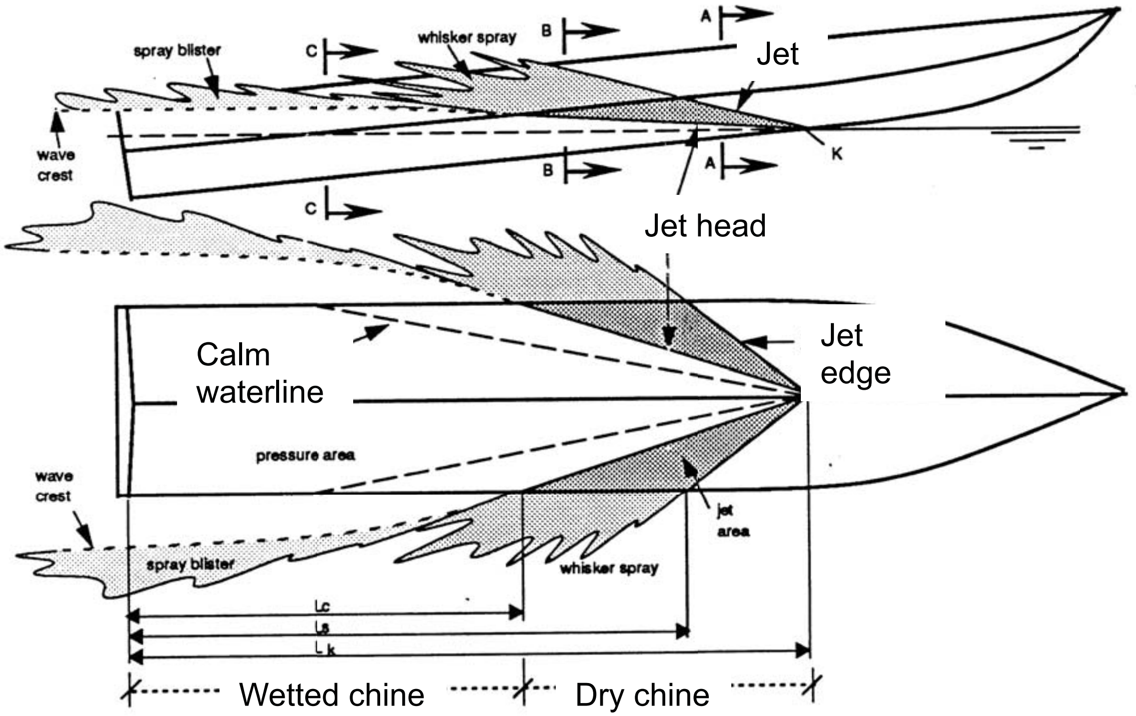
Underwater Photograph of a Planing Hull

David Taylor Model Basin: Model 4434



Saunders, H.E.   Hydrodynamics in Ship Design. Vol. 1. The Society of Naval
Architects and Marine Engineers, New York, 1957.

Physics of Planing - Some Definitions



Jet

Jet head

Calm waterline

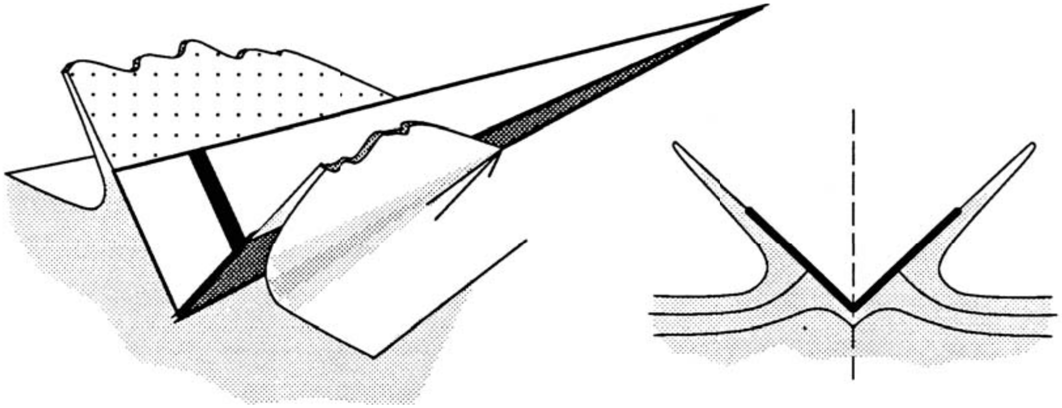
Jet edge

Wetted chine

Dry chine

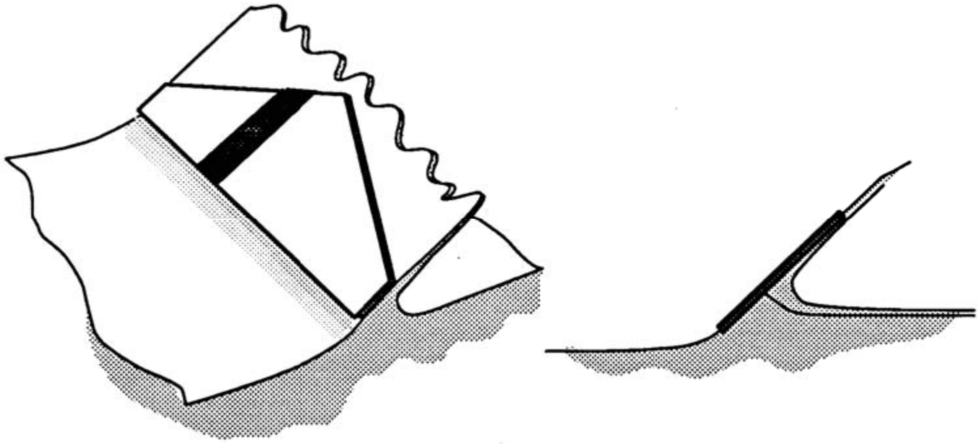
Physics of Planing - Some definitions and idealizations

Slender, low aspect ratio, prismatic hulls:
Wagner (1931, 1932), von Karman (1929)



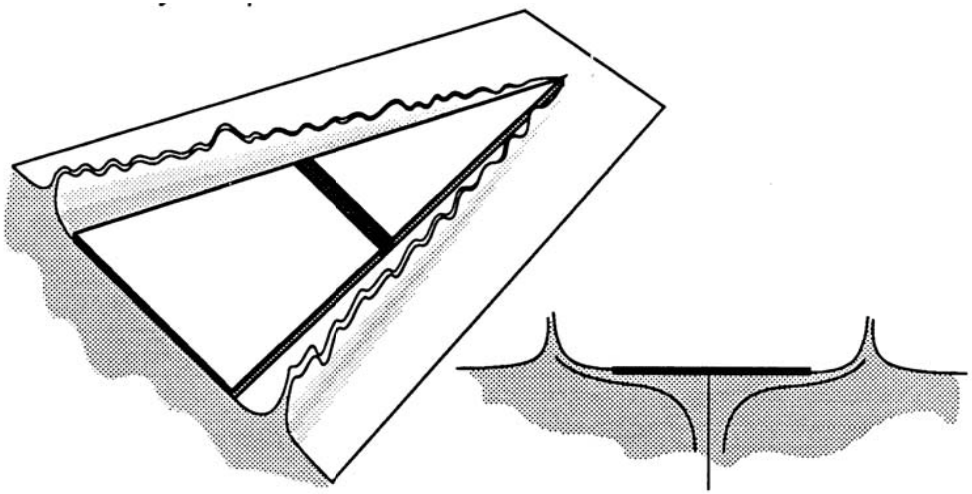
Physics of Planing - Some definitions and idealizations

High aspect ratio, flat hulls:
Green (1936)



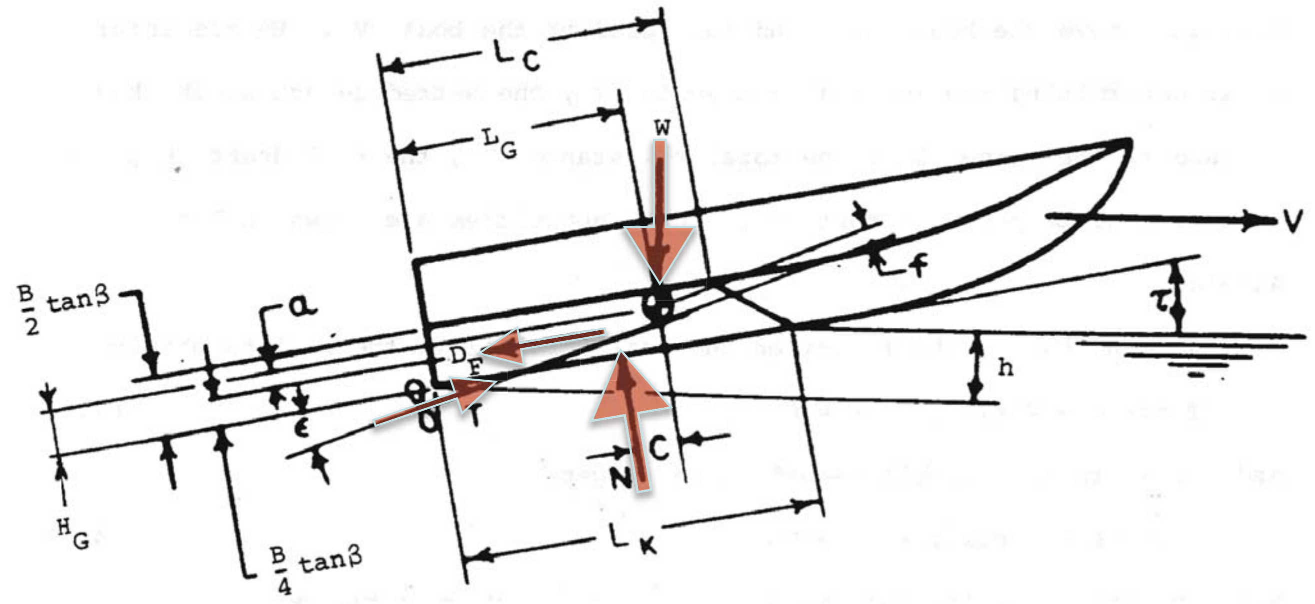
Physics of Planing - Some definitions and idealizations

Slender, low aspect ratio, flat hulls:
Tulin (1957)



Physics of Planing - Force and moment balance

Ref: Experiments of prismatic planing hulls, Savitsky (1964)



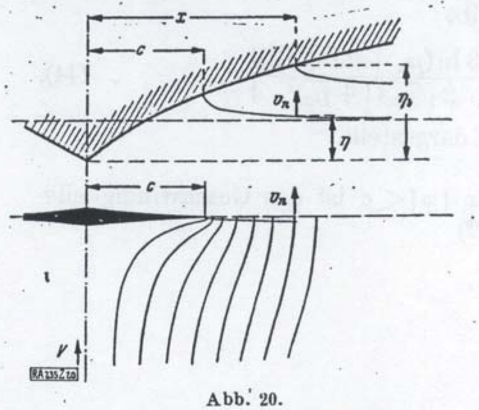
Relationship between planing and impact hydrodynamics

- Low order approximation
- Coordinate transformation between time and longitudinal coordinate

$X = U\,t$

- Transverse plane is equivalent to 2-D impact or strip theory approximation of planing

Seminal Work in Impact Hydrodynamics, Wagner (1932) Model:



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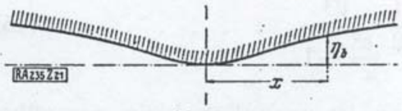

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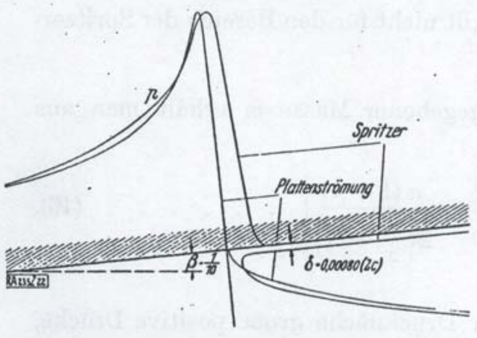

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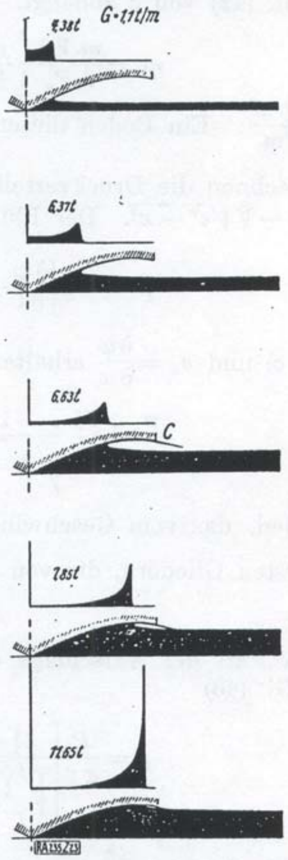

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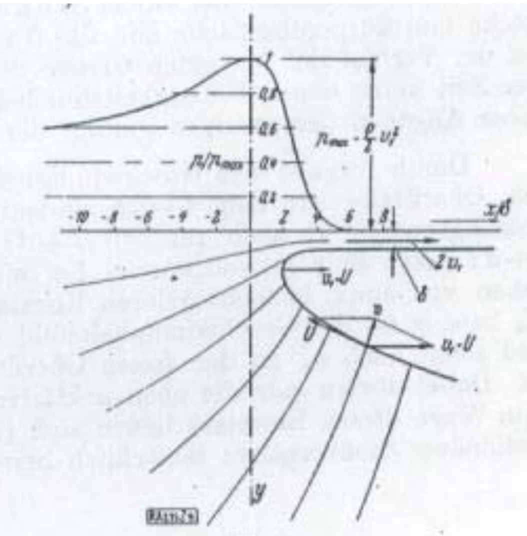
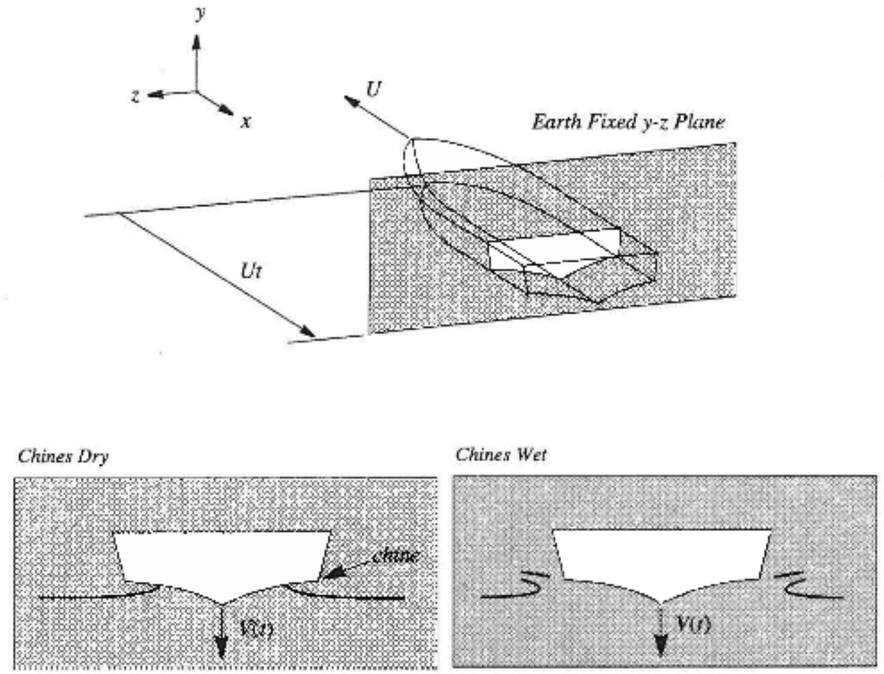
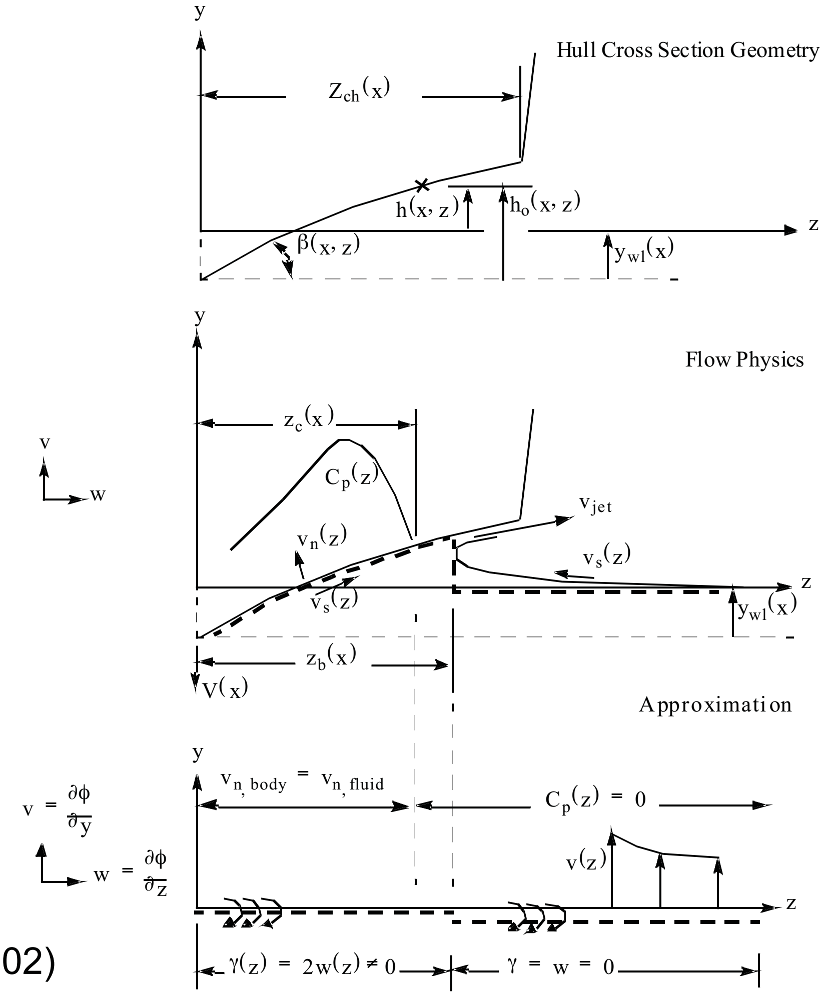


Abb. 9.

Reduction of physical model to 2-D impact solution space



Planing surface passing through earth-fixed plane



Slender Body Theory Planing Model, Savander, et al. (2002)

The Boundary Value Problem

- *Nonlinear dynamic free surface boundary condition*

$$\left(V_S - z_{c\tau}\zeta\right)\frac{\partial V_S}{\partial \zeta} + z_c \frac{dV_S}{d\tau} = 0 \qquad 1 \le \zeta \le b(\tau)$$

- *Body kinematic boundary condition*

$$\gamma_c(\zeta,\tau) = -\frac{2\cos\overline{\beta}(\zeta,\tau)\zeta\kappa(\zeta,\tau)}{\sqrt{1-\zeta^2}}\left[V(\tau) + \frac{1}{\pi}\int_{s=1}^{b(\tau)} \frac{\gamma_S(s,\tau)ds}{\kappa(s,\tau)\sqrt{\left(s^2-1\right)}} + \right.$$

$$\left. + \frac{\zeta^2-1}{\pi}\int_{s=1}^{b(\tau)} \frac{\gamma_S(s,\tau)ds}{\kappa(s,\tau)\sqrt{\left(s^2-1\right)\left(s^2-\zeta^2\right)}}\right] \qquad 0 \le z \le z_c(\tau)$$

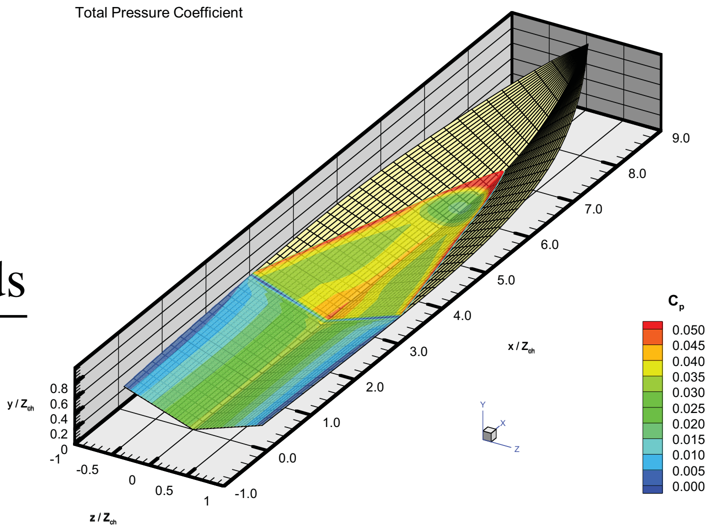
The Boundary Value Problem, con't.

- *Velocity continuity condition (i.e. Kutta condition)*

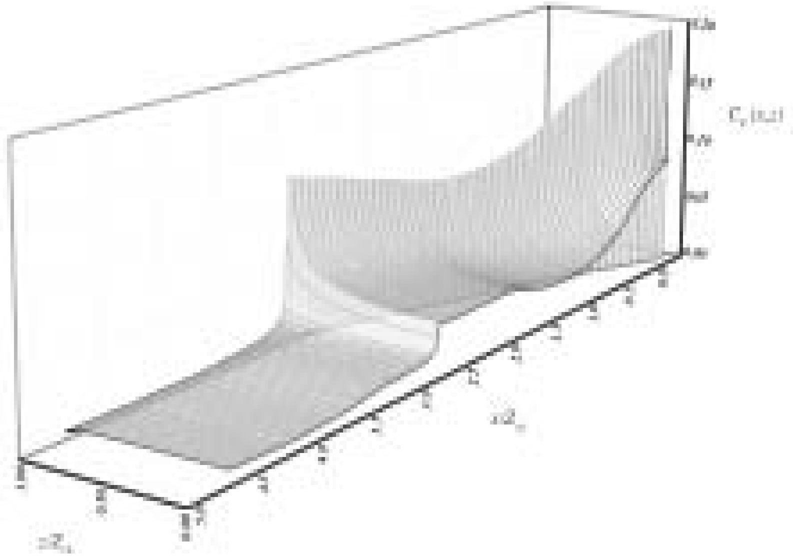
$$V(\tau) + \frac{1}{\pi} \int_{s=1}^{b} \frac{\gamma_s(s,\tau)ds}{\kappa(s,\tau)\sqrt{\left(s^2 - 1\right)}} = 0 \text{at} \quad z = zc(z = 1)$$

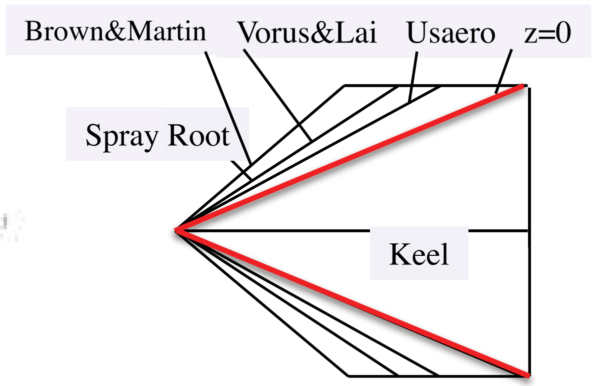
- *Displacement continuity condition*

$$Y_{wl}(\tau) = \frac{2}{\pi} \int_{s=0}^{1} \frac{\cos \overline{\beta}(s,\tau) h_c(s,\tau) ds}{\kappa(s,\tau)\sqrt{1 - s^2}}$$



3-D Pressure Distribution and Spray Sheet

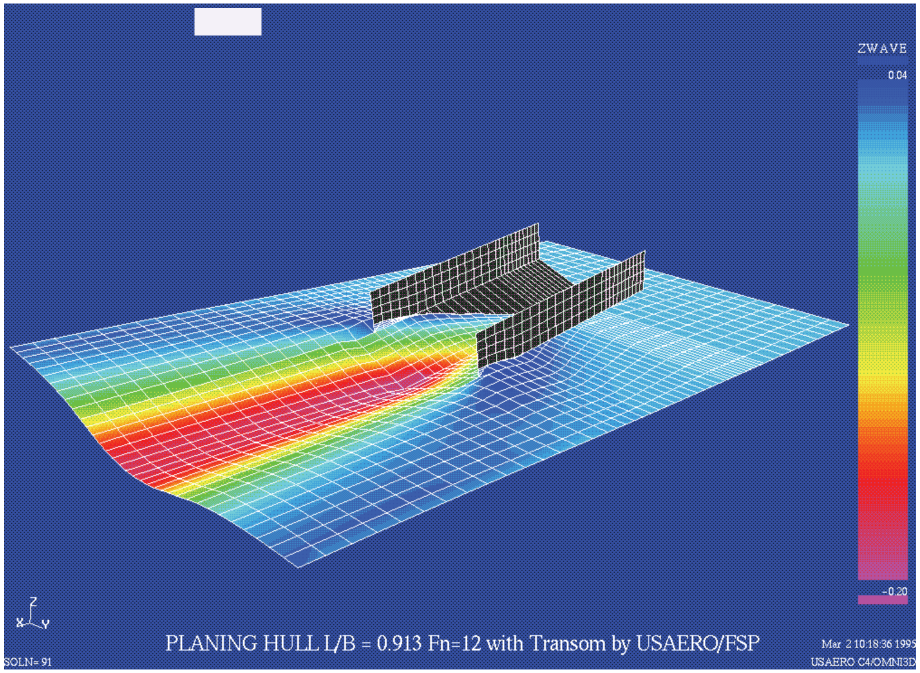



Brown&Martin
Vorus&Lai
Usaero
z=0
Spray Root
Keel

C_L (Savitsky)	0.091
C_L (USAERO)	0.053
θ_0 (z=0)	23.29°
θ (USAERO)	29.17°
θ (Vorus&Lai)	32.88°
θ (Brown&Martin)	39.47°
$\lambda = 0.913$, $\tau = 9°$, $\beta = 20°$	

Variable deadrise 40 mph ski boat

Calculations based on 3-D boundary integral method (Savander, 1997)



PLANING HULL L/B = 0.913 Fn=12 with Transom by USAERO/FSP

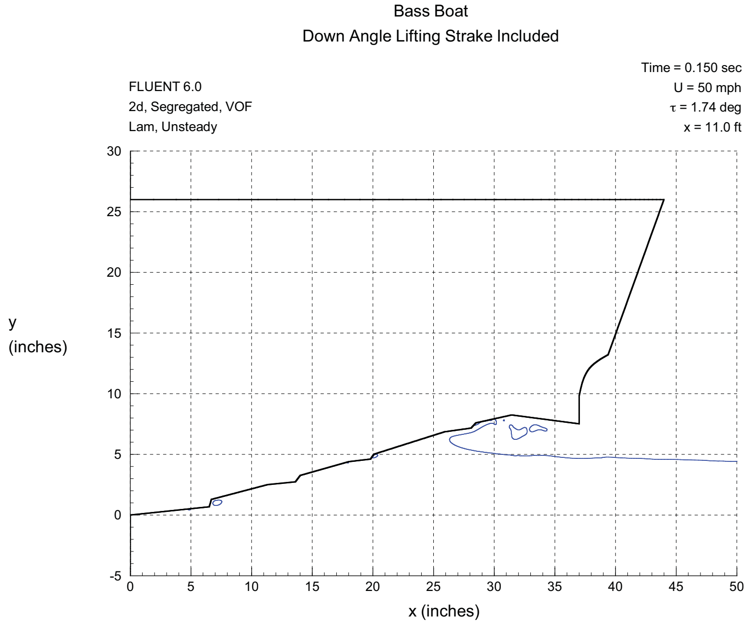
FLUENT 6.1 (CFD) Analysis: Straight Line Running

Transverse Flow @ Transom:

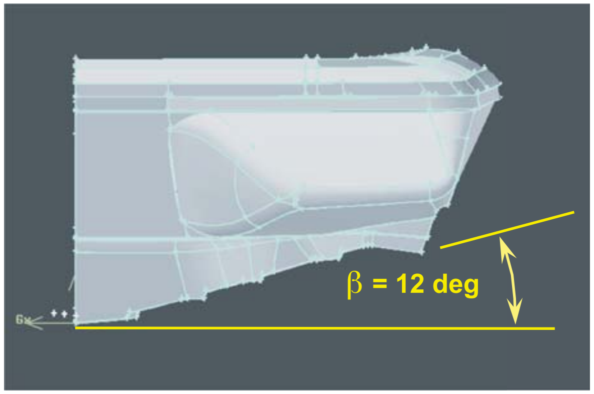
50 mph

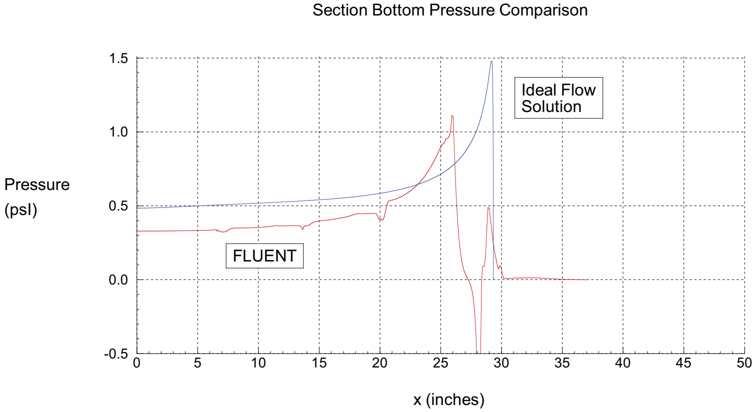
Engine Trim ¼ Out

Straight Line



Starboard Transom of Bass Boat



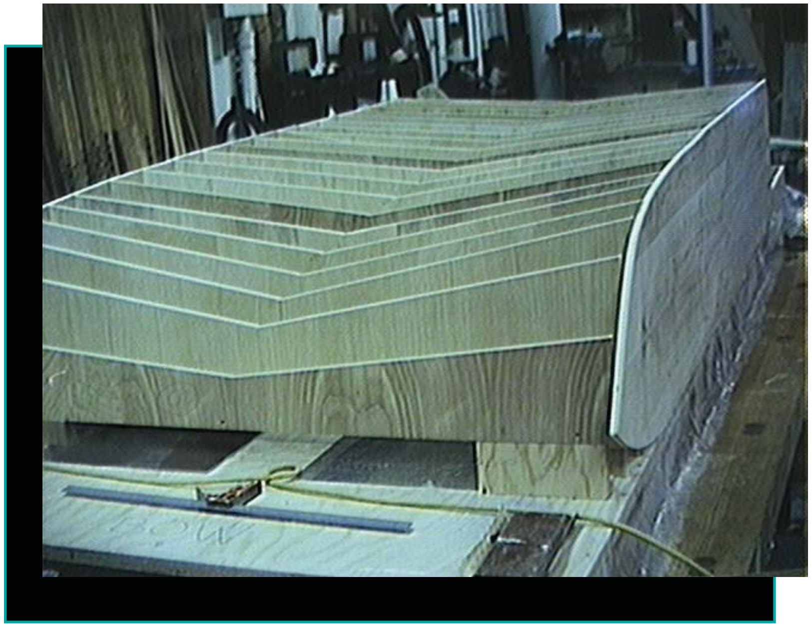


Conclusions of planing modeling analysis

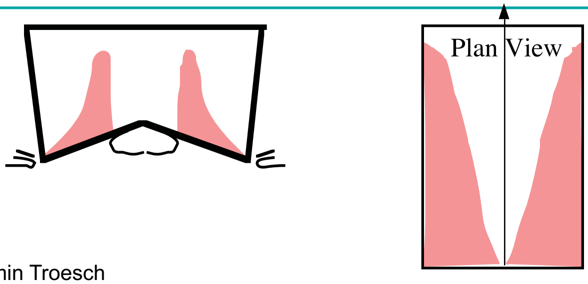
(the more significant ones?)

- Modeling the jet separation point (line) is critical to accurate planing predictions.
- Prediction of the correct wetted surface is critical to accurate planing predictions.
- There may be significant non-slender effects for large θ.
- The reduction to the z=0 plane works well in the chines dry regime but less so in the chines wet regime.
- Both slender body theory and 3-D Models have the potential to predict steady lift and drag accurately enough for design purposes.

Validation and Application of Technology



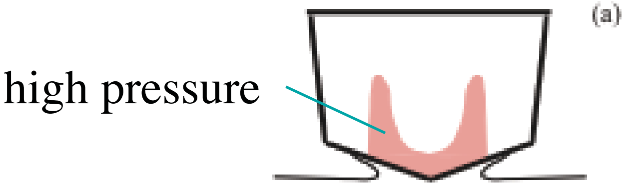
Calculated variation of deadrise to achieve maximum lift to drag ratio

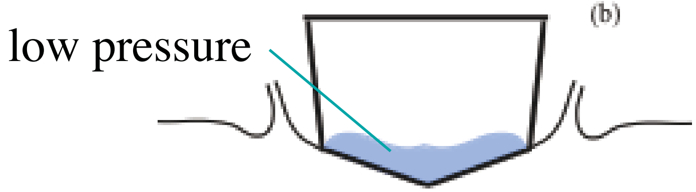


Extension of 2-D Planing Theory to Innovative Hull Form Design

(a) High pressure region in chines dry impact

(b) Low pressure region in chines wet impact





Validation and Application of Technology

SOLAR SPLASH: Intercollegiate Solar/Electric Boat Regatta

featuring

The University of Michigan's Inverted "V" Planing Hull

OUTLINE

- Planing Hull Hydrodynamics and Dynamics

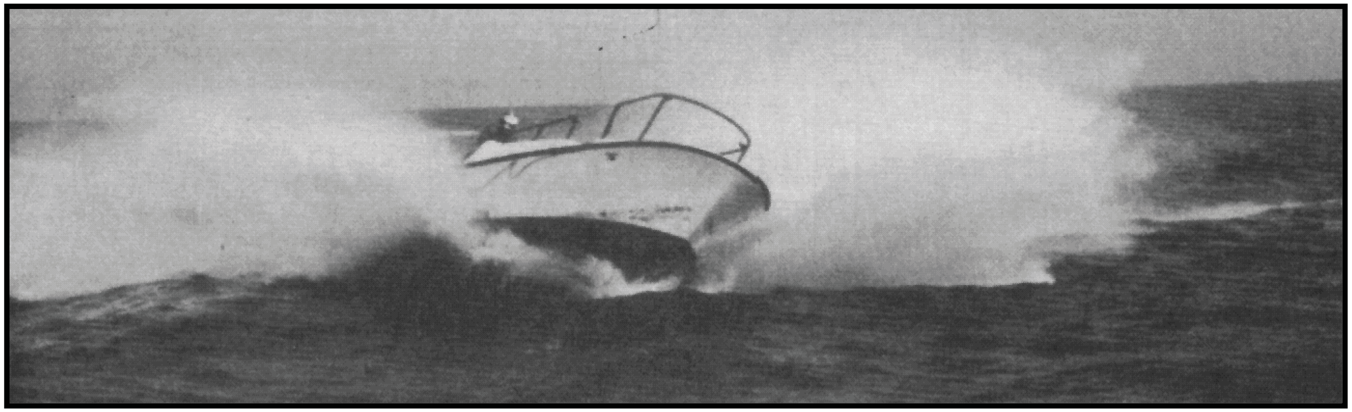
  Selected experiments and theories
  with practical applications

- Nonlinear Dynamics Analysis Applied to Planing Hulls

- Stochastic Vibro-Impact Model for Extreme Planing Craft Acceleration Estimation

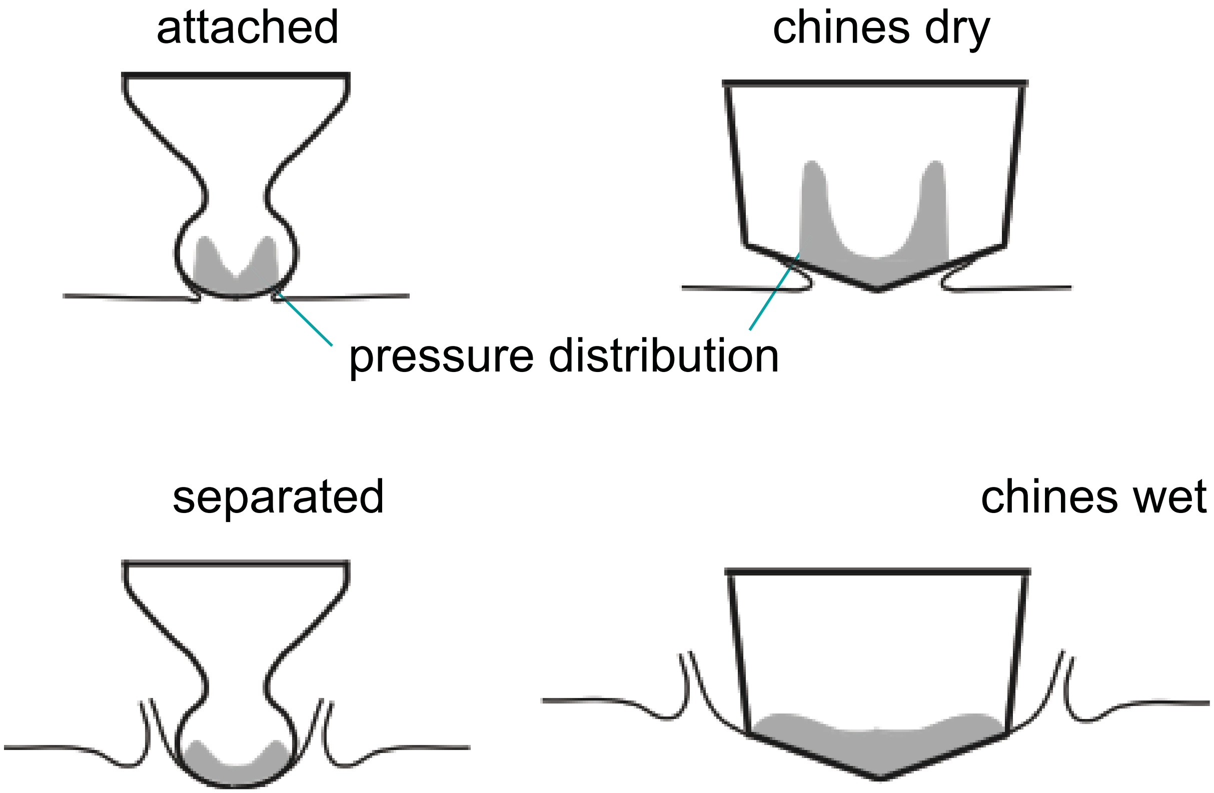
RATIONALE FOR DYNAMIC ANALYSIS:

Identification of design parameters that are critical to performance.



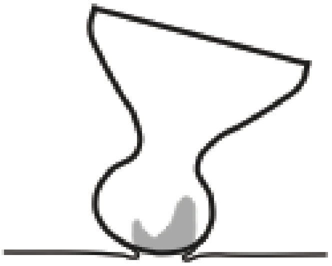
Example: “A Case Study of Dynamic Instability in a Planing Hull”, Codega and Lewis. *Marine Tech.,* April, 1987

Problem Definition : Steady Symmetric Planing

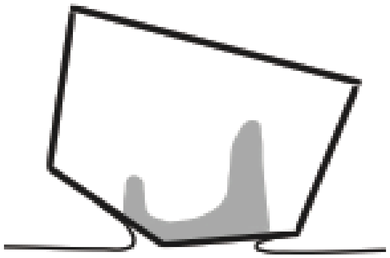


Problem Definition : Steady Asymmetric Planing - Type “A”

attached

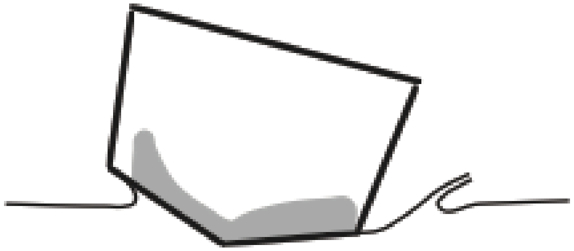


chines dry



separated

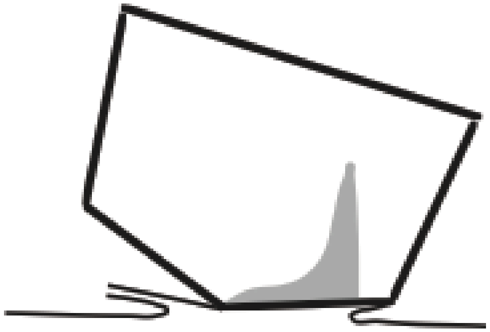
chines dry/wet



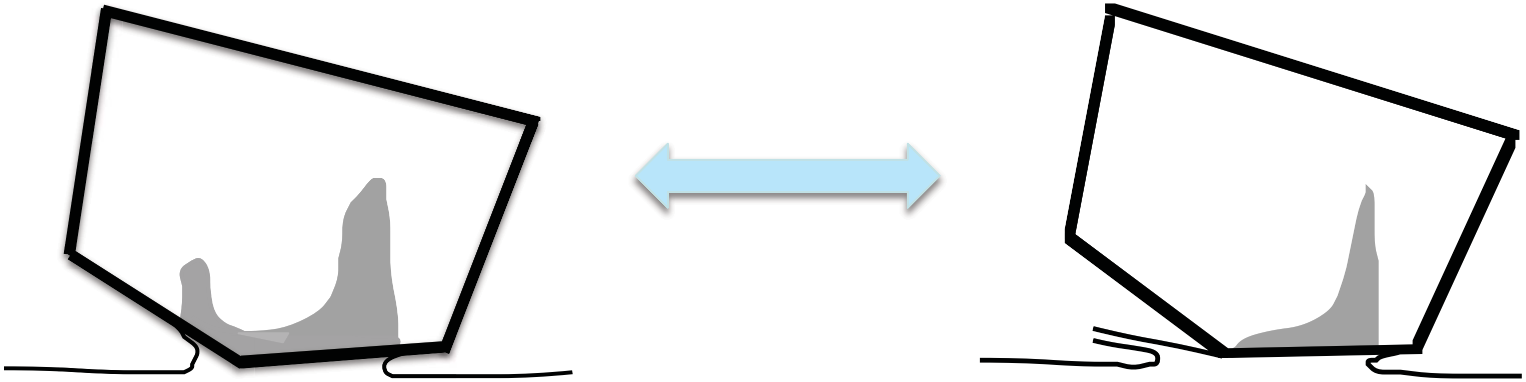
Problem Definition : Steady Asymmetric Planing - Type “B”

keel separation/attached

keel separation/chines dry

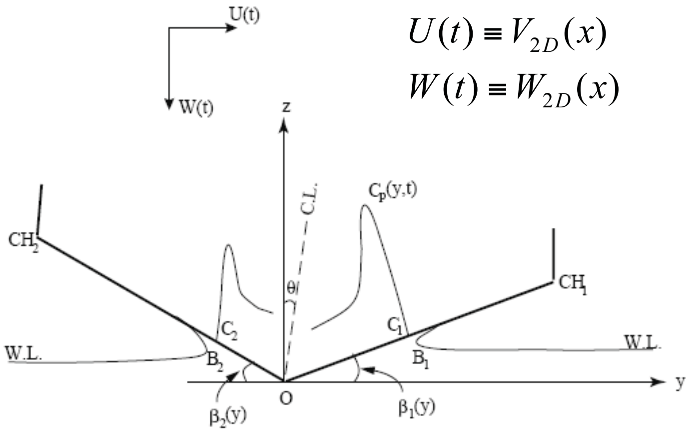


Transition to Steady Asymmetric Planing - Type “B”

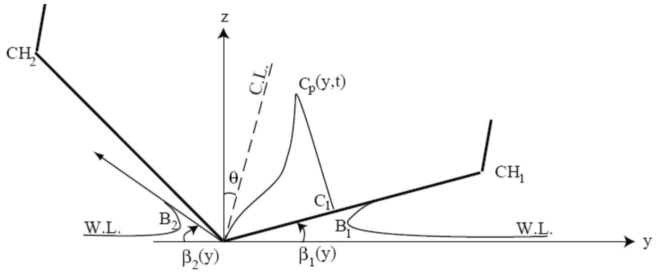


Steady Transverse Planing Modeling: Asymmetric Impact Theory

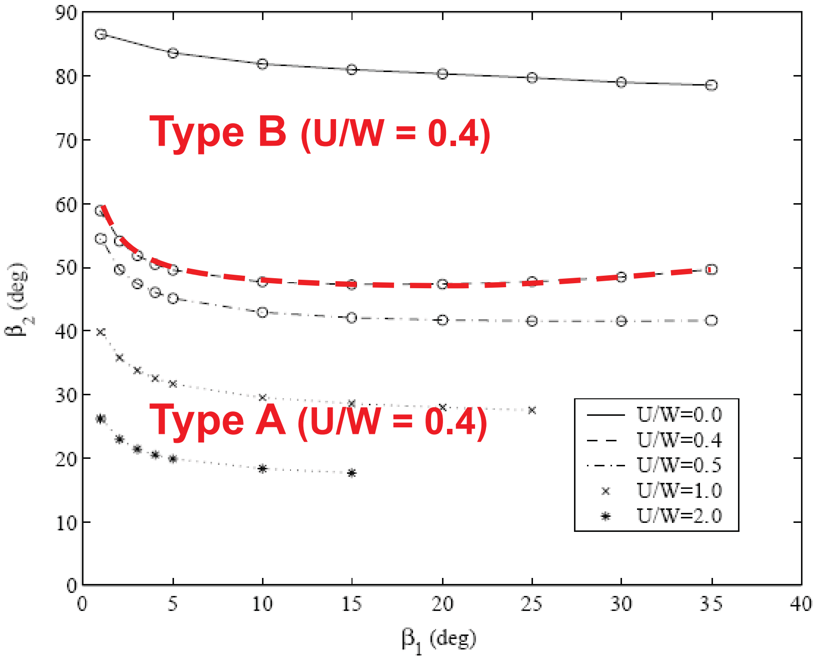
$$U(t) \equiv V_{2D}(x)$$
$$W(t) \equiv W_{2D}(x)$$



Type A model of cylinder asymmetric impact (small asymmetry) and horizontal impact velocity



Type B model of cylinder asymmetric impact (large asymmetry) and horizontal impact velocity



Type B (U/W = 0.4)

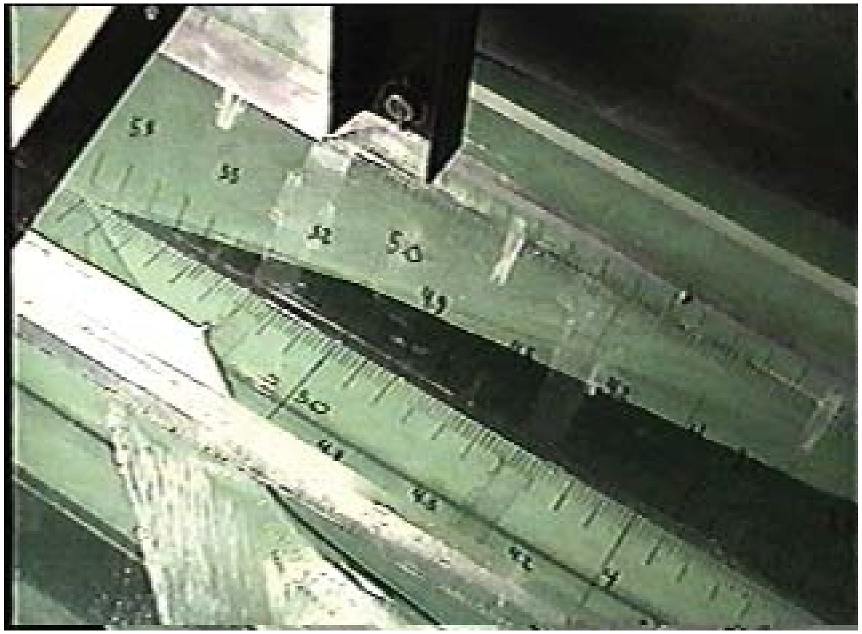
Type A (U/W = 0.4)

Critical angle β2 versus the corresponding β1 at which ventilation occurs off the keel for different ratios of impact velocities

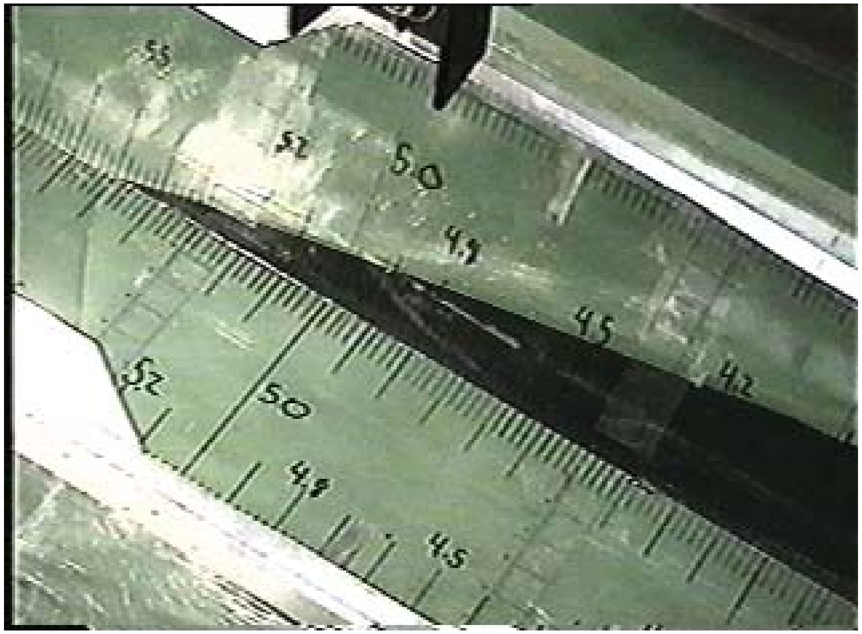
(Judge et al, 1999
Xu et al, 1998, 1999)

Steady Transition to asymmetric planing - Type “B”

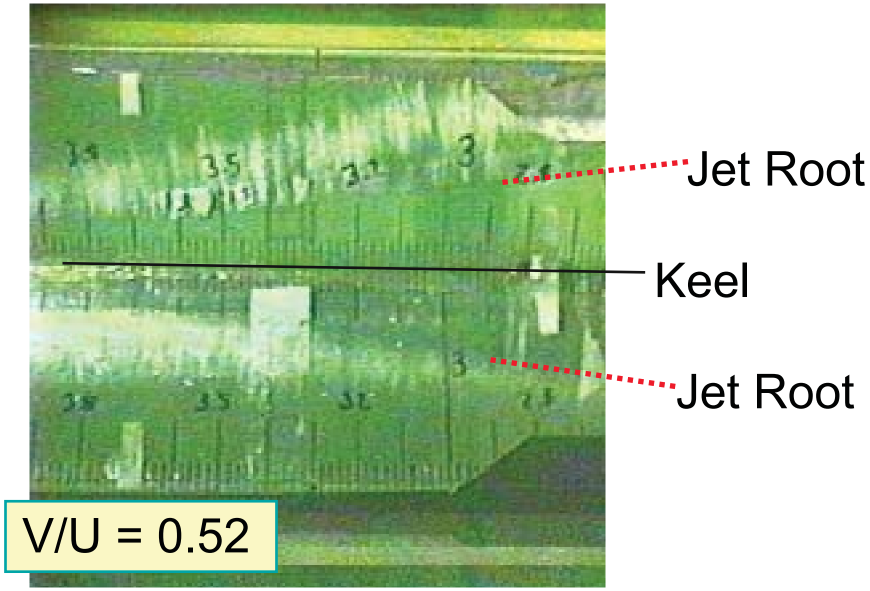
35 deg deadrise heeled 20 deg



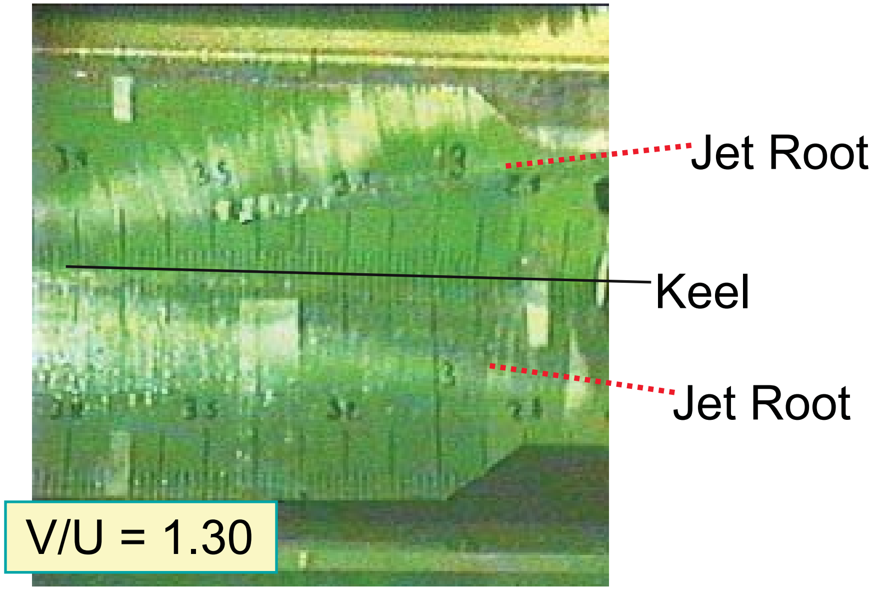
35 deg deadrise heeled 29 deg



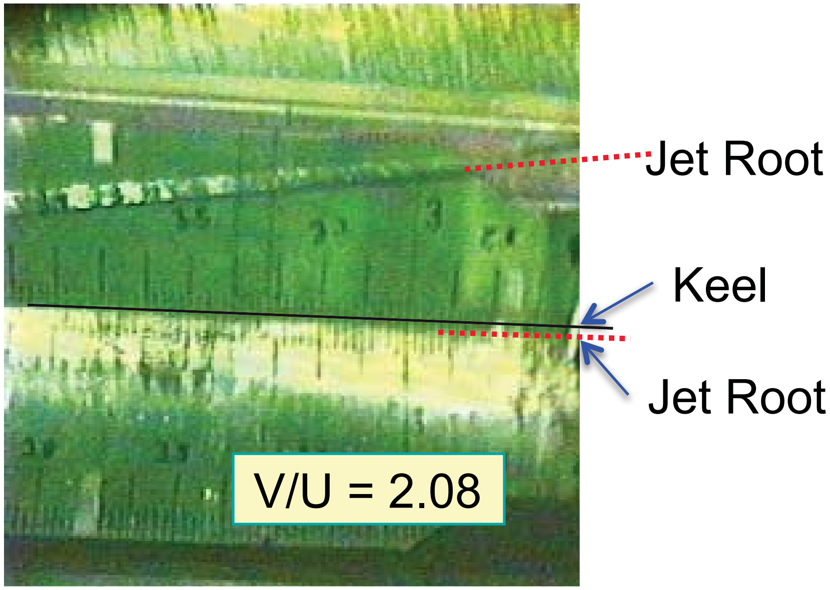
Onset of Separation Due to Transverse Velocity



V/U = 0.52



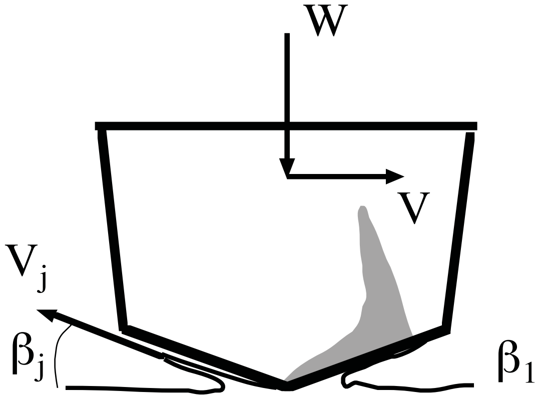
V/U = 1.30



V/U = 2.08

Direction of V

Steady Asymmetric planing due to horizontal velocity



Estimate of the horizontal velocity required for separation:

$$\frac{V}{W} \cong \frac{V_j/W \sin\beta_j - \tan\beta_1 \cos\beta_j}{\tan\beta_1}$$

β_1	V/W
20°	4.2-4.5
35°	2.0-2.5

Ref: Xu, Troesch, 1999 and Judge, et al. 2002

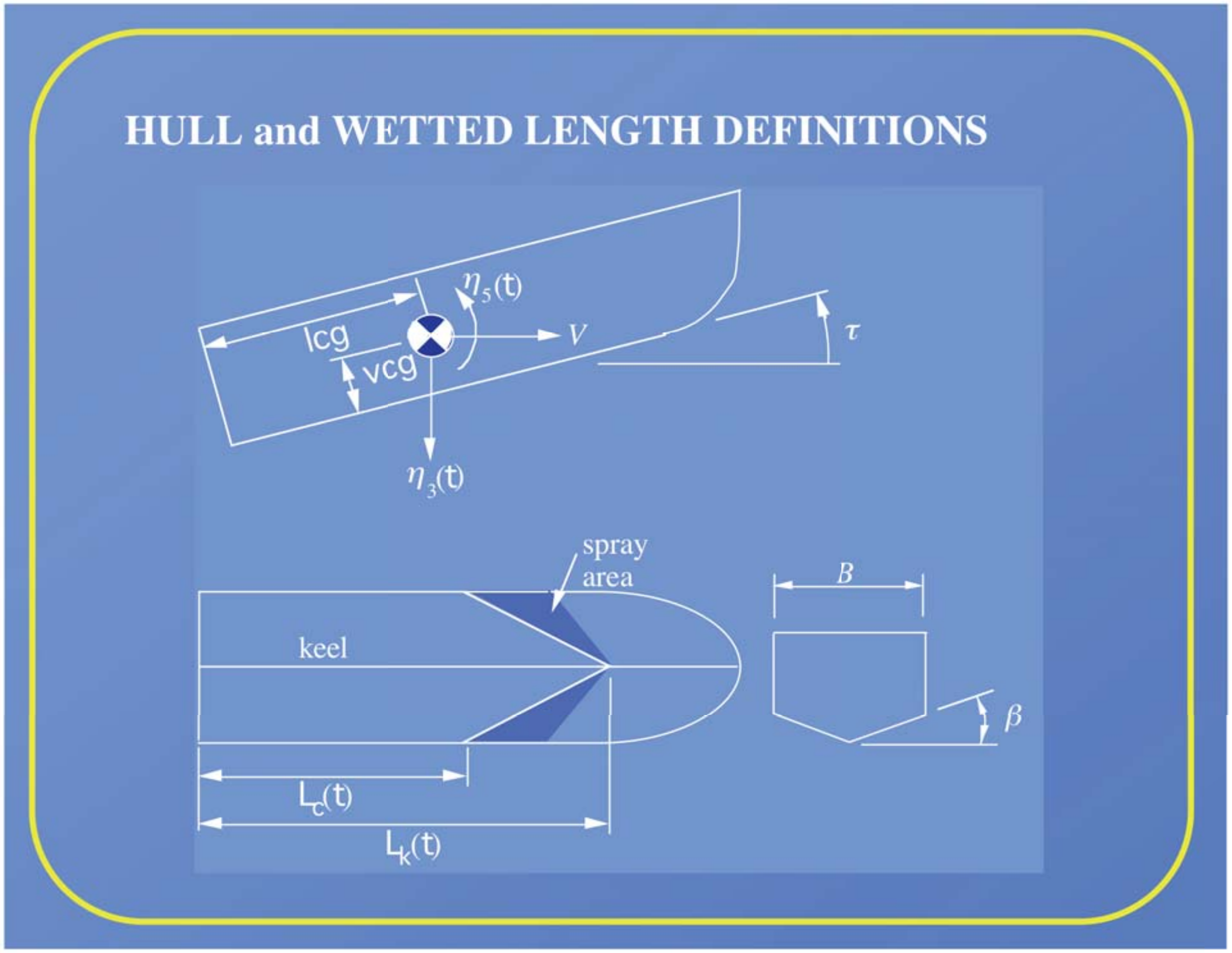
The Synergy of Experiments and Theory

Experiments with prismatic hull forms

- Steady planing
- Unsteady planing - vertical plane motions

For example: Savitsky (1964), Altman (1968), Fridsma (1969, 1971), De Zwaan (1976), Savitsky & Brown (1976), Troesch (1992), and others…….

On the Hydrodynamics of Vertically Oscillating Planing Hulls



HULL and WETTED LENGTH DEFINITIONS

Equations of Motion

$$Z = m\,\ddot{\eta}_3(t)$$

$$M = I_{55}\,\ddot{\eta}_5(t)$$

May be ***Modeled*** as

$$\left[m + \mathbf{A}(\eta;\omega)\right]\left\{\ddot{\eta}(t)\right\} + \left[\mathbf{B}(\eta;\omega)\right]\left\{\dot{\eta}(t)\right\} + \left[\mathbf{C}(\eta)\right]\left\{\eta(t)\right\} = \left\{F(t)\right\}$$

Geometry: Dynamic wetted length

$$L(t) = lcg + \frac{vcg}{\tan\left(\tau - \eta_5(t)\right)} - \frac{\left(z_{wl} + \eta_3(t)\right)}{\sin\left(\tau - \eta_5(t)\right)}$$

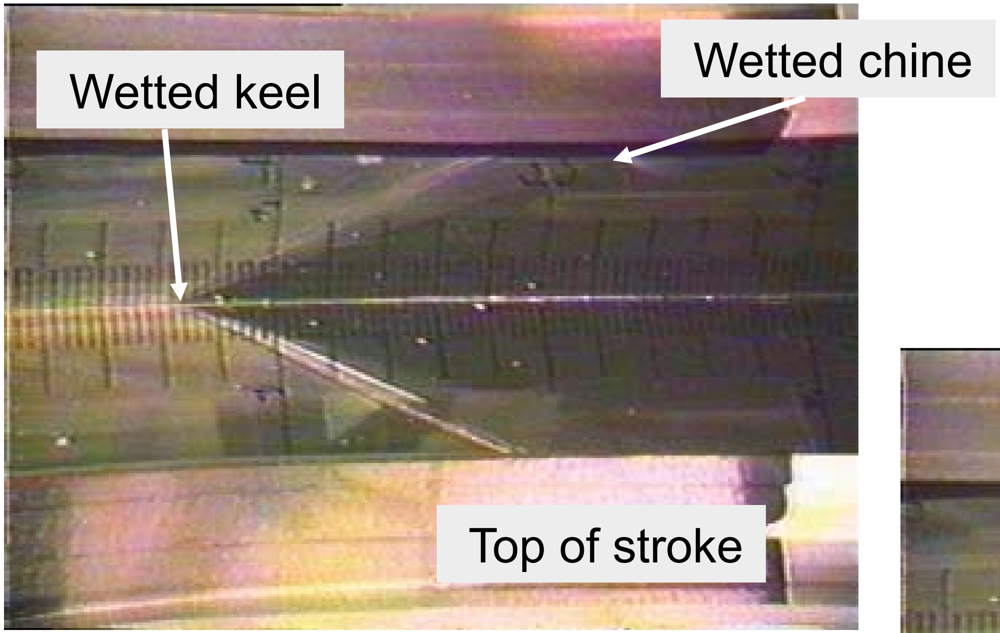
$$\lambda_{ave} = \left(\lambda_k + \lambda_c\right)/2 + 0.03$$

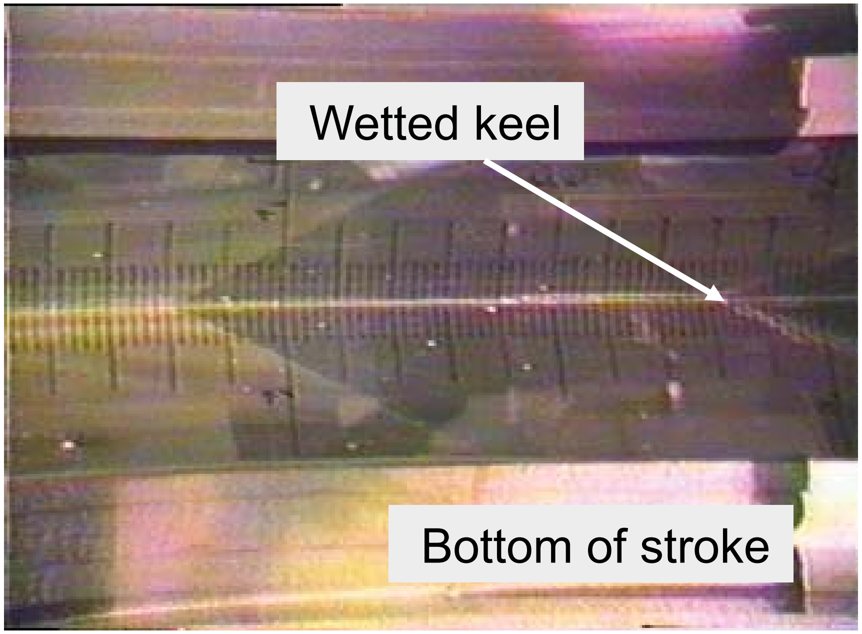
$$\hat{\lambda}_k = \hat{\lambda}_{ave} + 0.5\left(0.57 + 0.001\beta\right)\left(\tan\beta/(2\tan(\tau - \eta_5)) - 0.006\beta\right) - 0.03$$

$$\hat{\lambda}_{\mathrm{c}} = \hat{\lambda}_{\mathrm{k}} - \left(0.57 + 0.001\beta\right)\left(\tan\beta/(2\tan(\tau - \eta_5)) - 0.006\beta\right) \quad for \quad \hat{\lambda}_{\mathrm{c}} \geq 1$$

Steady mean wetted length from Savitsky (1964)and Savitsky & Brown (1976) modified for motions (Troesch 1992)

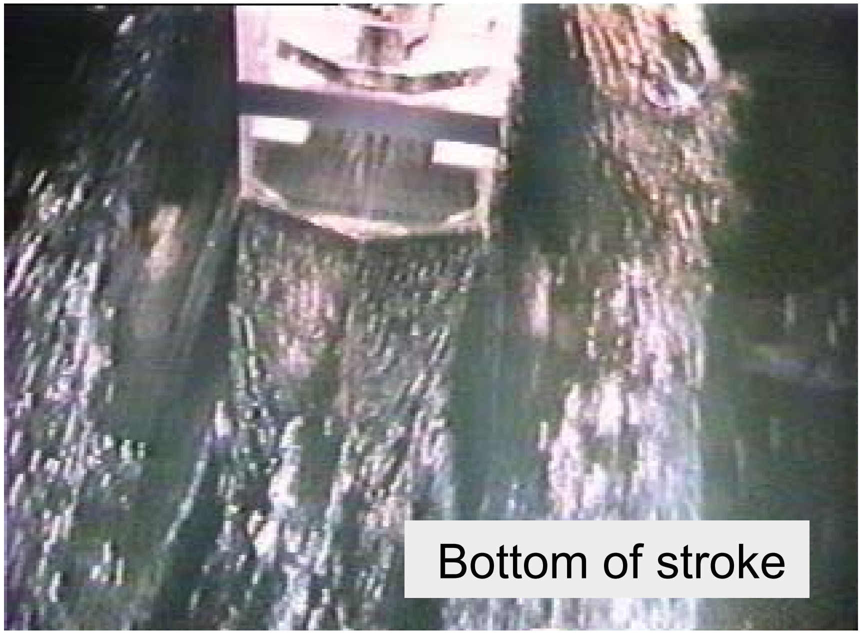
Geometry: Dynamic wetted length in heave



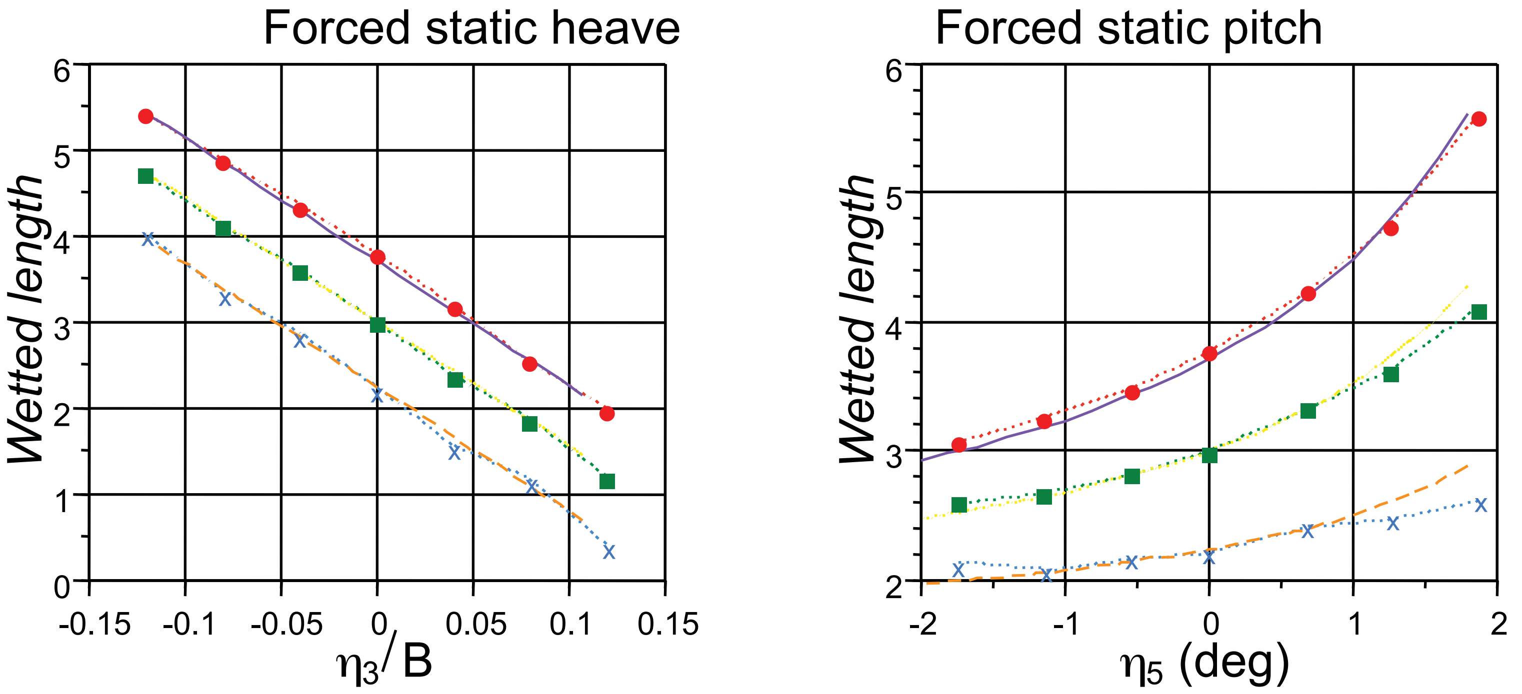


Geometry: Dynamic wetted length in heave


Top of stroke


Bottom of stroke

Geometry: Dynamic wetted length

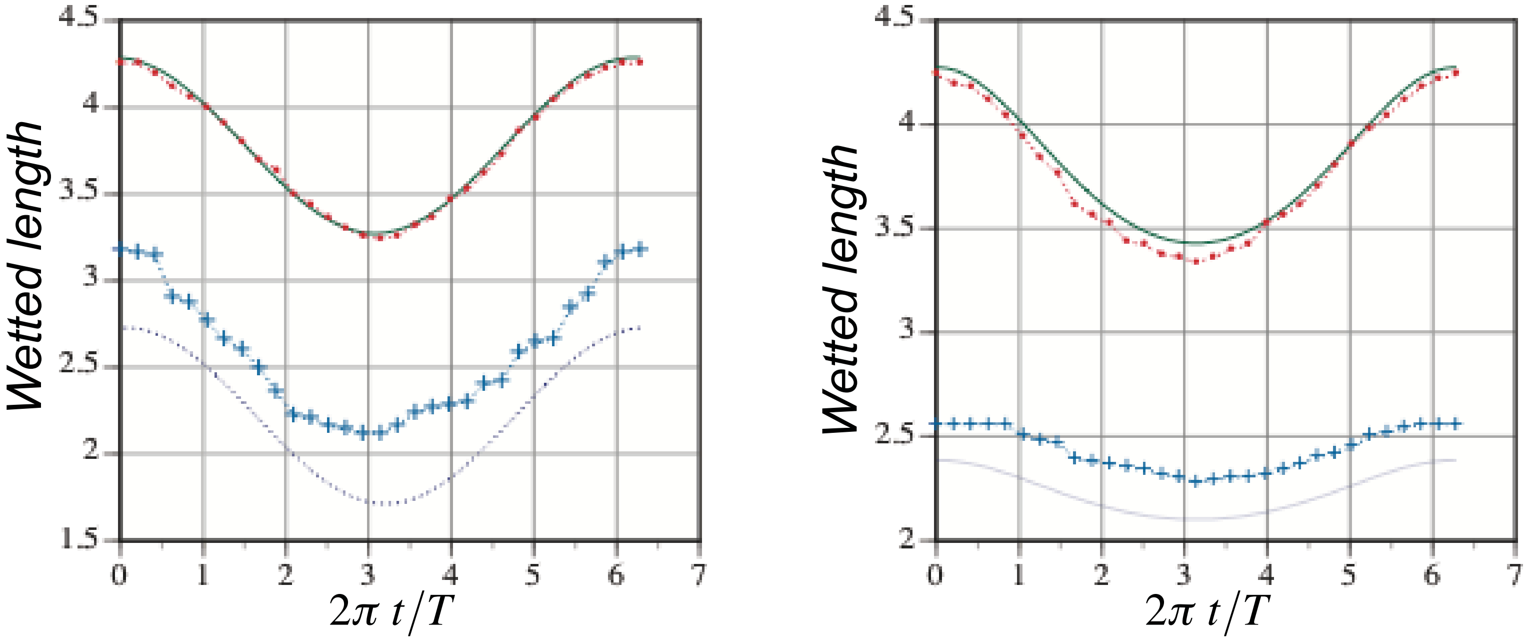


Wetted length versus constant heave and pitch displacement. -■-, λ_{ave}; - - - , Eq. (5); -●-, λ_k; —, Eq. (6); -×-, λ_c ; - - -, Eq. (7).

Geometry Dynamic wetted length

Forced heave

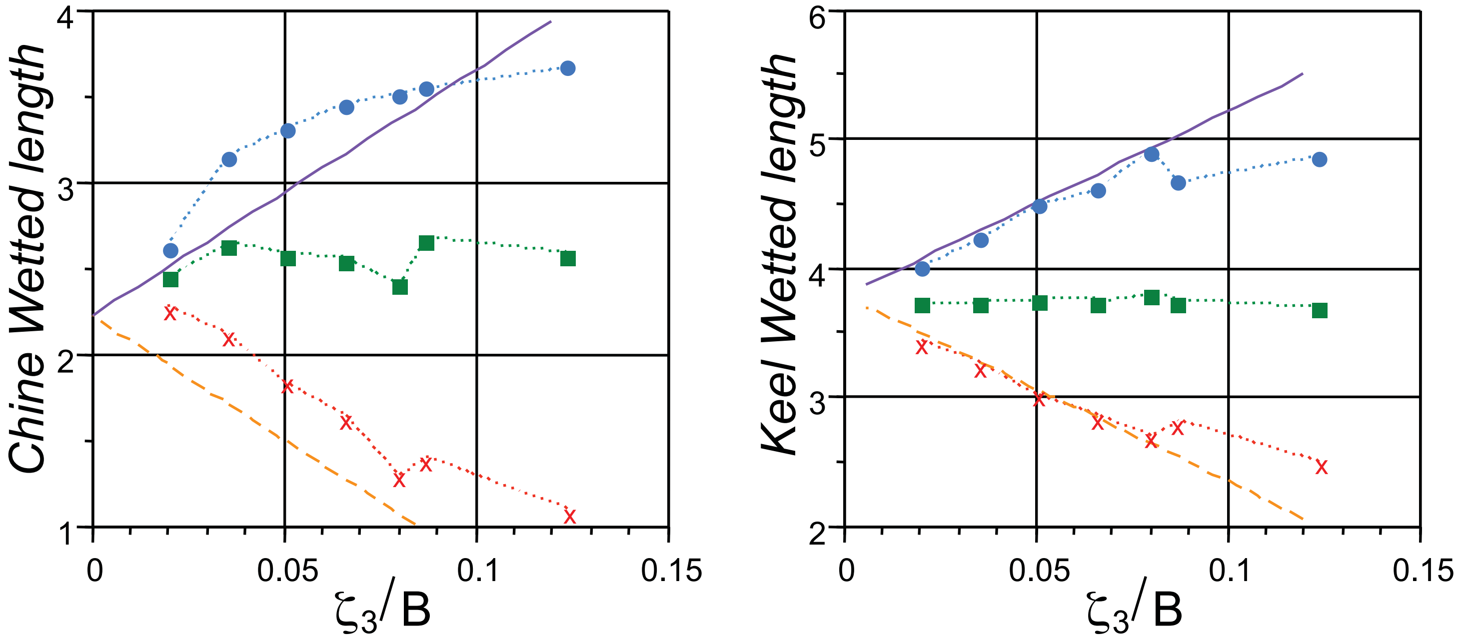
Forced pitch



Wetted length during one cycle of heave and pitch oscillation.
$\xi_3/B = 0.036$, $\omega\sqrt{B/g} = 1.13$. + , λ_c; - - -, Eq. (4); ● , λ_k; —, Eq. (4).

Geometry: Dynamic wetted length

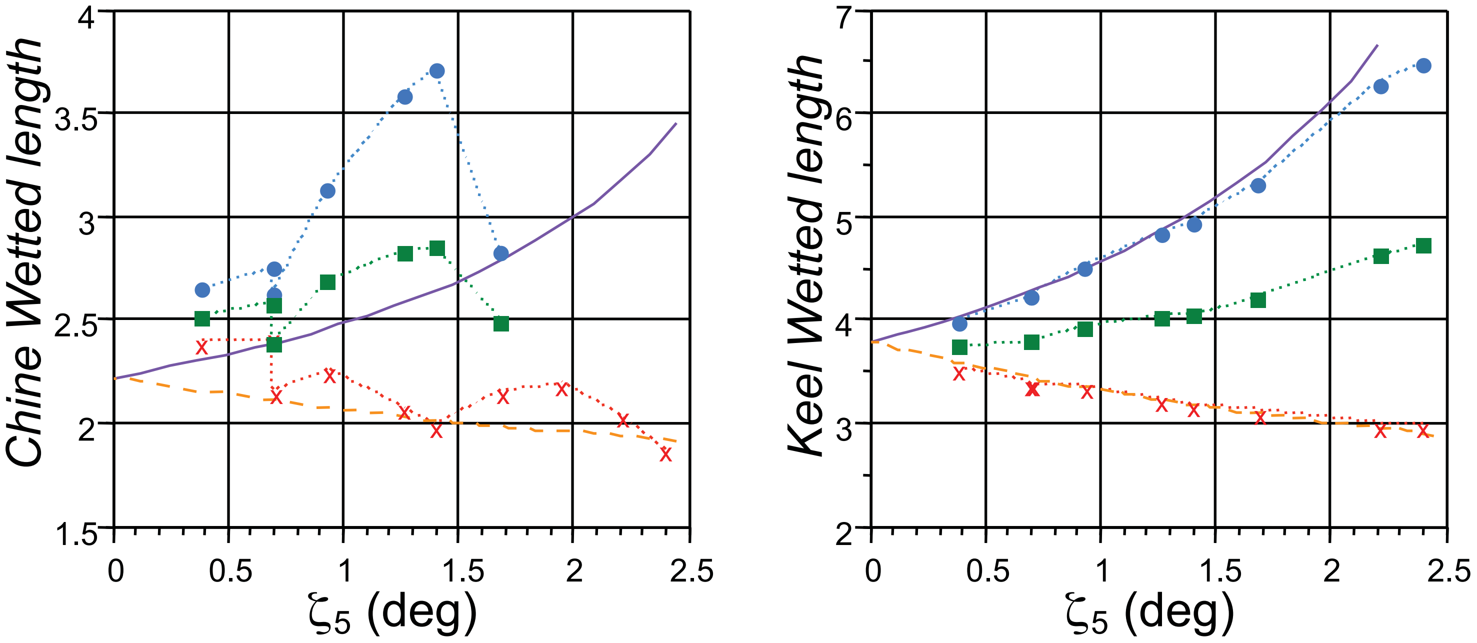
Forced heave



Wetted maximum and minimum chine and keel lengths as a function of heave amplitude. -●- , λ_{max}; —, Eq. (4); -×-, λ_{min}; - - -, Eq. (4); -■-, λ_{ave}

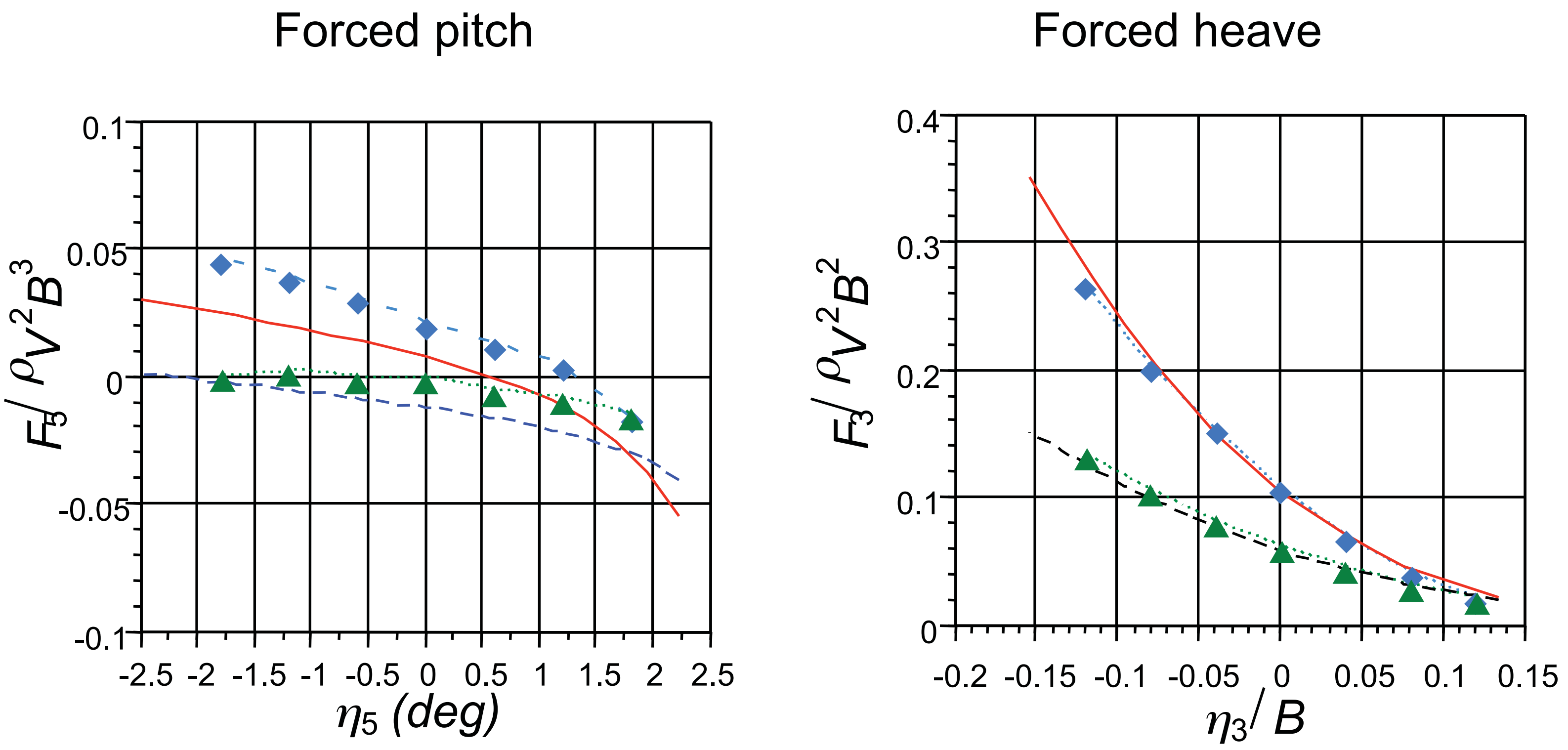
Geometry: Dynamic wetted length

Forced pitch



Wetted maximum and minimum chine and keel lengths as a function of pitch amplitude. -●- , λ_{max}; —, Eq. (4); -×-, λ_{min}; - - -, Eq. (4); -■-, λ_{ave} .

Hydrodynamic stiffness, C_{55} and C_{33}


Forced pitch

Forced heave

: Total vertical force and moment versus constant linear heave and pitch displacement. L/B = 3.0 , τ = 4.0 deg. $C_V = 1.5$; -◆-, exp; —; Savitsky [14]. $C_V = 2.5$; -▲-, exp; - - -, Savitsky [14].

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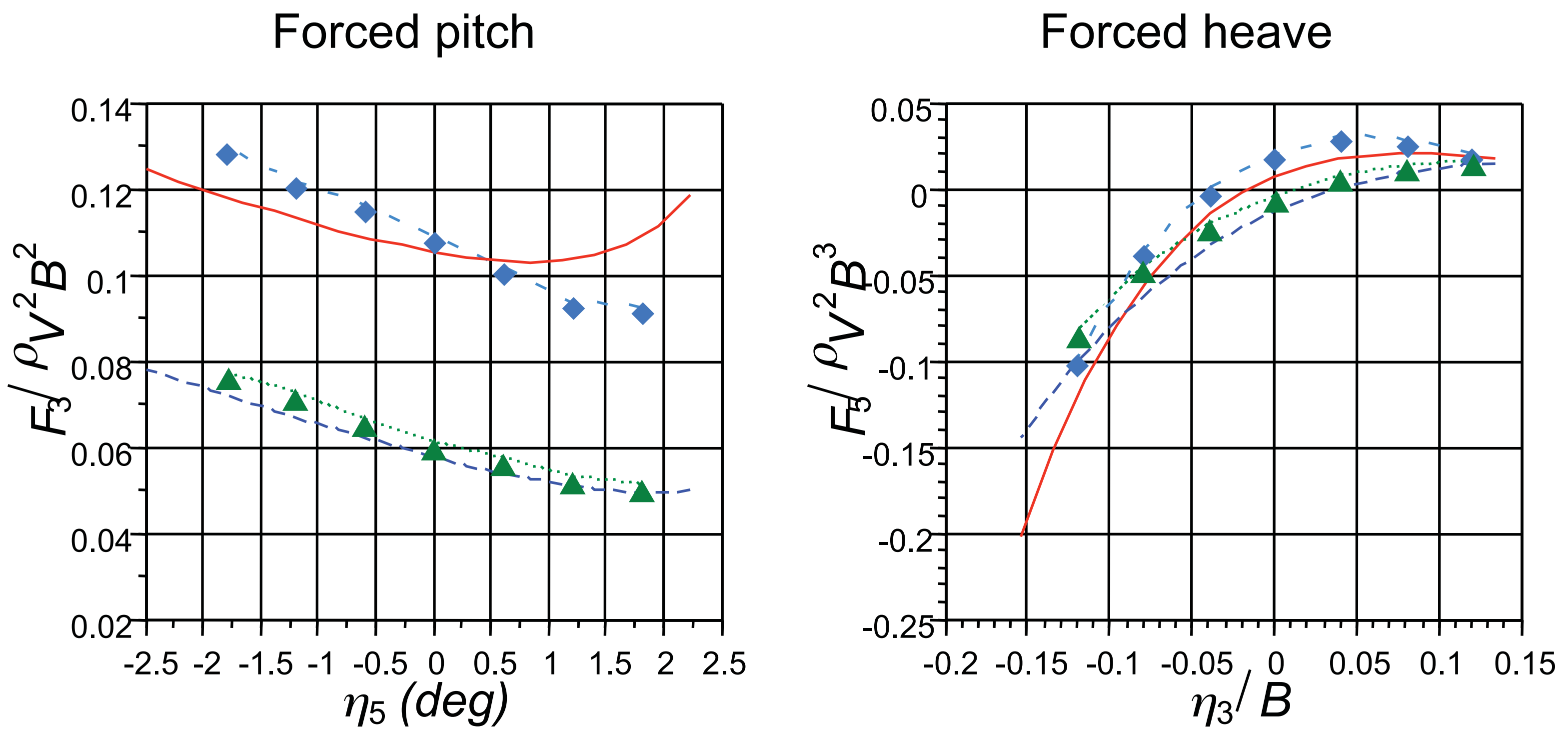
Hydrodynamic stiffness, C_{35} and C_{53}


Forced pitch

Forced heave

: Total vertical force and moment versus constant linear heave and pitch displacement. L/B = 3.0 , τ = 4.0 deg. $C_V = 1.5$; -◆-, exp; —; Savitsky [14]. $C_V = 2.5$; -▲-, exp; - - -, Savitsky [14].

Added mass and damping, A_{33} and B_{33}

$$-\omega^2\left(m + A_{33}\right) + i\omega B_{33} + C_{33} = \left(f_1 + f_2\right)/\zeta_3 \qquad \text{=>} \qquad \sum F = m\ddot{\zeta}_3$$

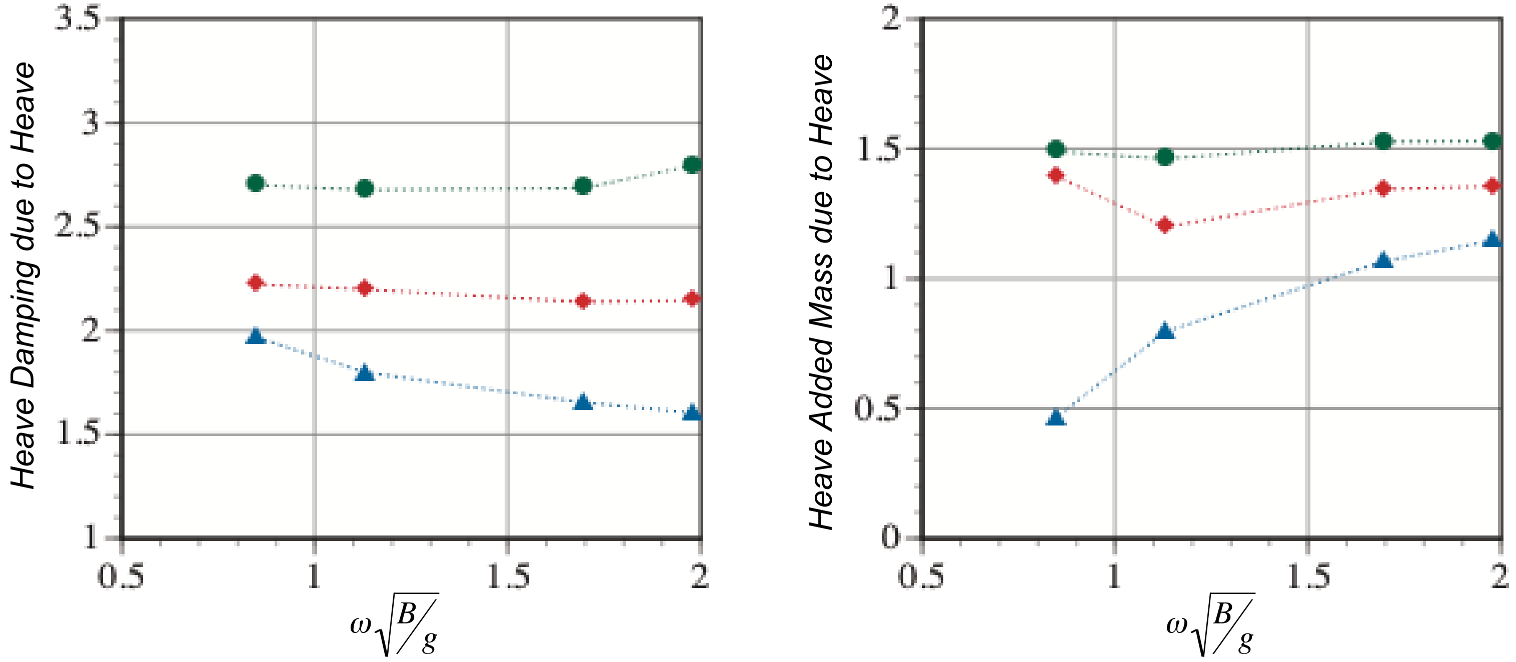
$$-\omega^2\left(-mx_{cg} + A_{53}\right) + i\omega B_{53} + C_{53} = \left(f_1 - f_2\right)L/\zeta_3 \qquad \text{=>} \qquad \sum M = 0$$

Which reduce to

$$A_{33} = \frac{1}{-\omega^2}\left[\frac{mag\left(f_1 + f_2\right)}{mag\left(\zeta_3\right)}\cos\left(\arg\left(f_1 + f_2\right) - \arg\left(\zeta_3\right)\right) - C_{33}\right] - m$$

$$B_{33} = \frac{1}{\omega}\left[\frac{mag\left(f_1 + f_2\right)}{mag\left(\zeta_3\right)}\sin\left(\arg\left(f_1 + f_2\right) - \arg\left(\zeta_3\right)\right)\right]$$

Added mass and damping, A_{33} and B_{33}



Added mass and damping coefficients in heave versus frequency $L/B = 4.0$;
$\tau = 6$ deg. -▲-, $C_V = 1.5$; -◆-, $C_V = 2.0$; -●-, $C_V = 2.5$.

Conclusions of forced motion experiments

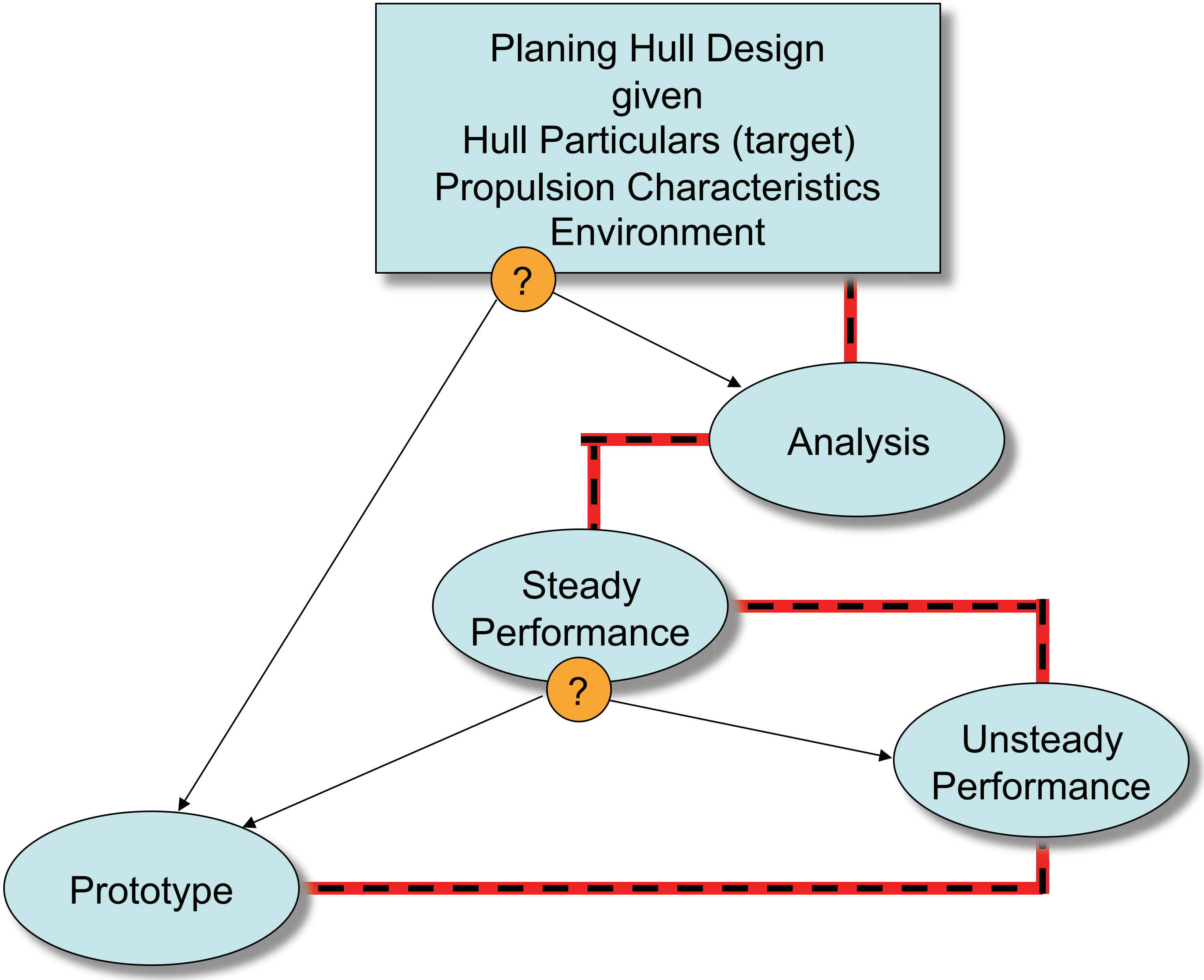
Wetted length: The wetted length and equivalently the wetted surface of an oscillating planing hull is strongly time dependent. For low to moderate amplitudes of motion, the keel wetted length can be treated kinematically as the intersection between the keel and a stationary free surface. The chine wetted length is influenced by spray jet dynamics.

Conclusions of forced motion experiments (con't.)

Restoring force matrix, ***C***. The restoring force matrix is amplitude dependent. A good approximation for prismatic hulls can be found by applying the results of Savitsky [14] with the mean wetted, λ, and effective trim expressed as functions of the heave and pitch motions.

Conclusions of forced motion experiments (con't.)

Added mass and damping matrices, ***A*** *and* ***B****.* For low to moderate planing speeds, C_V=1.5 - 2.5, the added mass coefficient, and to a lesser extent the damping coefficient, can be frequency dependent. When the experimental results were analyzed using a constant restoring force matrix, the added mass and damping in heave, A_{j3} and B_{j3}, j=3,5 showed relatively little amplitude dependency compared to the added mass and damping in pitch, A_{j5} and B_{j5}, j=3,5.



Planing Hull Design
given
Hull Particulars (target)
Propulsion Characteristics
Environment

?

Analysis

Steady
Performance

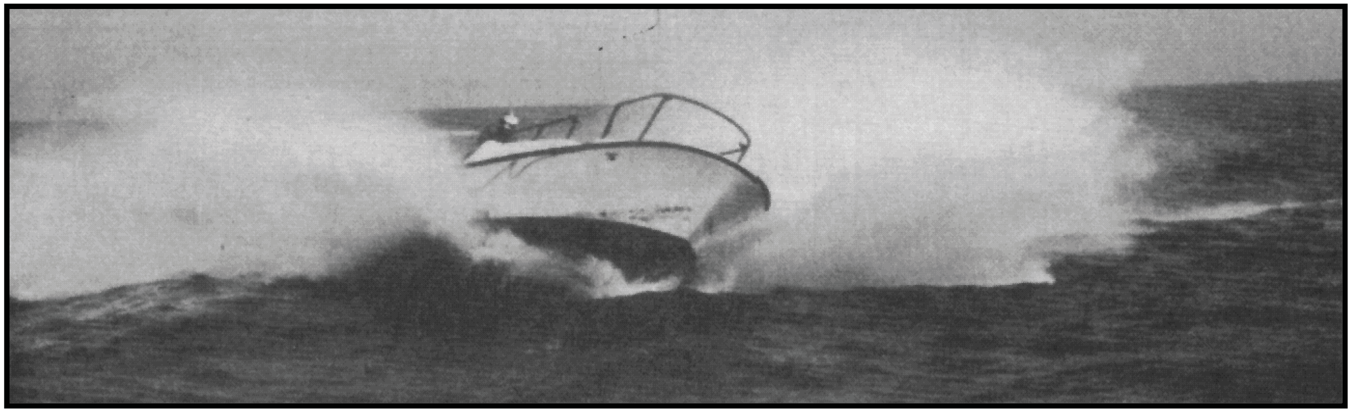
?

Unsteady
Performance

Prototype

RATIONALE FOR DYNAMIC ANALYSIS:

Identification of design parameters that are critical to performance.



Example: "A Case Study of Dynamic Instability in a Planing Hull", Codega and Lewis. *Marine Tech.,* April, 1987

THE ROLE OF SIMULATION IN DESIGN

With regards to the new computer simulators... "If you choose the right parameters, your simulated experiment will normally work just like the corresponding real-world experiment. (However,) there are some edges to this simulated world, and if you step over the simulation breaks down badly..." (Swaine, 1992)

Analysis and Simulation of Nonlinear Planing Hull Dynamics

- **General description** of methods of modern nonlinear systems analysis

- Examples of analysis

  Ref: Troesch and Falzarano (1993),
  Troesch and Hicks (1994)
  Hicks, Troesch and Jiang (1995)

Analysis and Simulation of Nonlinear Planing Hull Dynamics
Simple Model - Complex Dynamics

Ref: Savitsky (1964)
Guckenheimer and Holmes (1983)
Thompson and Stewart (1986)
Seydel (1988)
Troesch (1992)
Troesch and Falzarano (1993)

Analysis and Simulation of Nonlinear Planing Hull Dynamics **Complex Model** - Complex Dynamics

Ref: Zarnick (1978)
Guckenheimer and Holmes (1983)
Seydel (1988)
Akers et al. (1999, etc.)
Hicks et al. (1994, 1995)

VERTICAL PLANE EQUATIONS OF MOTION

Linear (unforced) (Martin, 1978)

$$[\mathbf{A}]\{\ddot{\eta}(t)\}+[\mathbf{B}]\{\dot{\eta}(t)\}+[\mathbf{C}]\{\eta(t)\}=\{0\}$$

Equivalent nonlinear model (unforced) (Hicks et al, 1994)

$$[\mathbf{A}]\{\ddot{\eta}(t)\}+[\mathbf{B}]\{\dot{\eta}(t)\}+\left\lfloor\overline{\mathbf{C}}(\eta(t))\right\rfloor\{\eta(t)\}=\{0\}$$

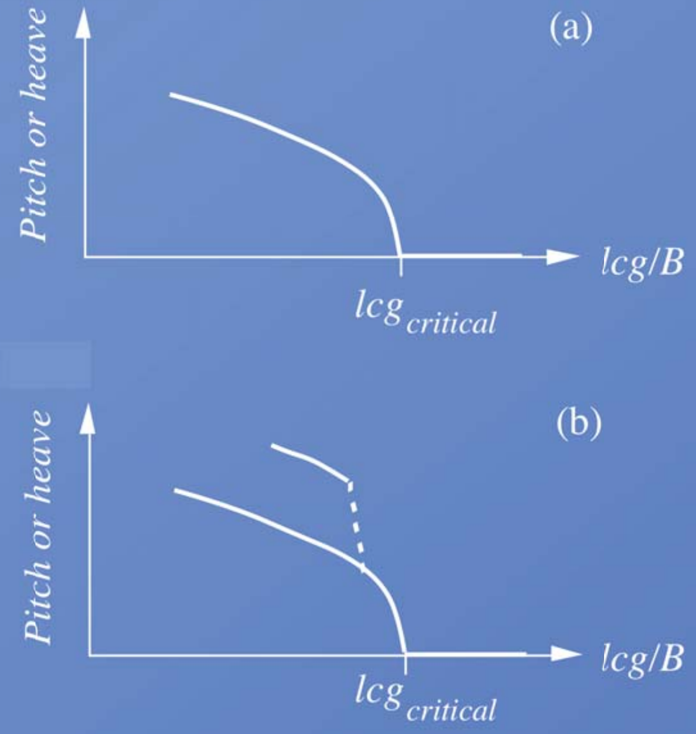
Equivalent nonlinear model (forced) (Hicks et al, 1994)

$$[\mathbf{A}]\{\ddot{\eta}(t)\}+[\mathbf{B}]\{\dot{\eta}(t)\}+\left\lfloor\overline{\mathbf{C}}(\eta(t))\right\rfloor\{\eta(t)\}=\{F(t)\}$$

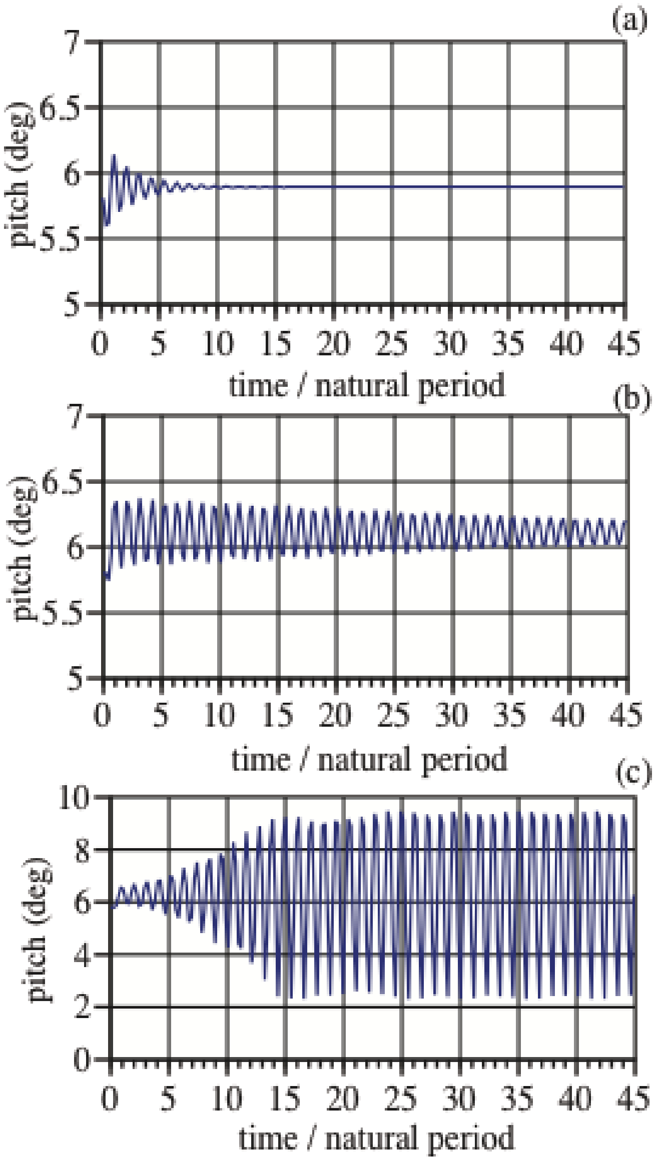
Fully nonlinear simulation (forced) (Zarnick, 1978, Akers, 1994)

$$[\mathbf{M}]\{\ddot{\eta}(t)\}=\{F(t)\}$$

SCHEMATIC OF HOPF BIFURCATIONS
(Unforced motion, i.e. porpoising)



(a) Single branch (b) Multiple branches



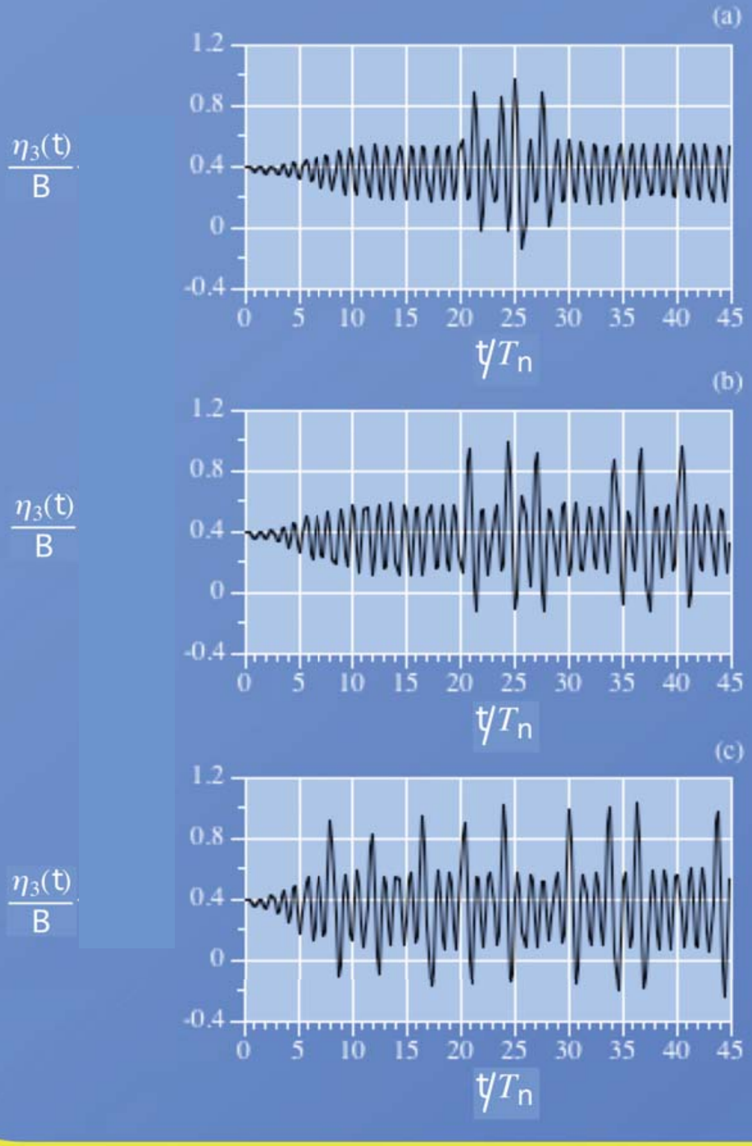
SIMULATION:

TRANSITION TO PORPOISING

lcg/B
(a) 2.09
(b) 2.03
(c) 1.98

$C_v = 4.5$

(Troesch and Hicks, 1994)



SIMULATION:

MULTI-STATE PORPOISING

lcg/B
(a) 2.09
(b) 2.03
(c) 1.98

$C_v = 5.0$

EQUATIONS OF MOTION

Linear (unforced) (Martin, 1978)

$$[\mathbf{A}]\{\ddot{\eta}(t)\}+[\mathbf{B}]\{\dot{\eta}(t)\}+[\mathbf{C}]\{\eta(t)\}=\{0\}$$

Equivalent nonlinear model (unforced) (Hicks et al, 1994)

$$[\mathbf{A}]\{\ddot{\eta}(t)\}+[\mathbf{B}]\{\dot{\eta}(t)\}+\left[\overline{\mathbf{C}}(\eta(t))\right]\{\eta(t)\}=\{0\}$$

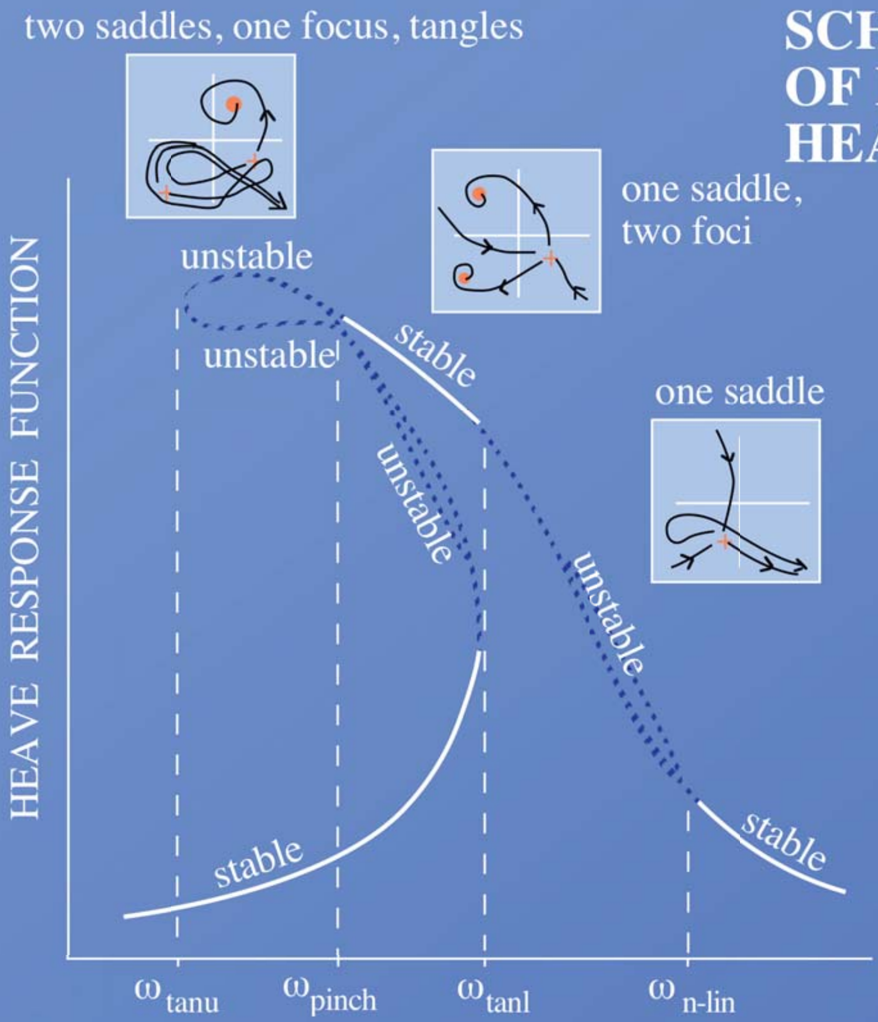
Equivalent nonlinear model (forced) (Hicks et al, 1994)

$$\boxed{[\mathbf{A}]\{\ddot{\eta}(t)\}+[\mathbf{B}]\{\dot{\eta}(t)\}+\left[\overline{\mathbf{C}}(\eta(t))\right]\{\eta(t)\}=\{F(t)\}}$$

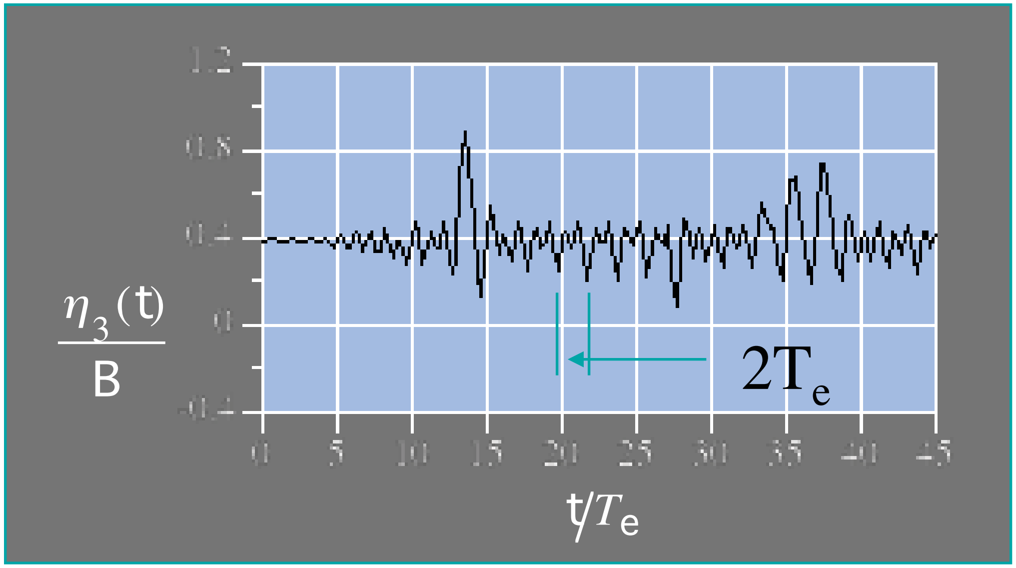
Fully nonlinear simulation (forced) (Zarnick, 1978,
and Akers, 1999, etc.)

$$\boxed{[\mathbf{M}]\{\ddot{\eta}(t)\}=\{F(t)\}}$$

SCHEMATIC OF POSSIBLE HEAVE RAO

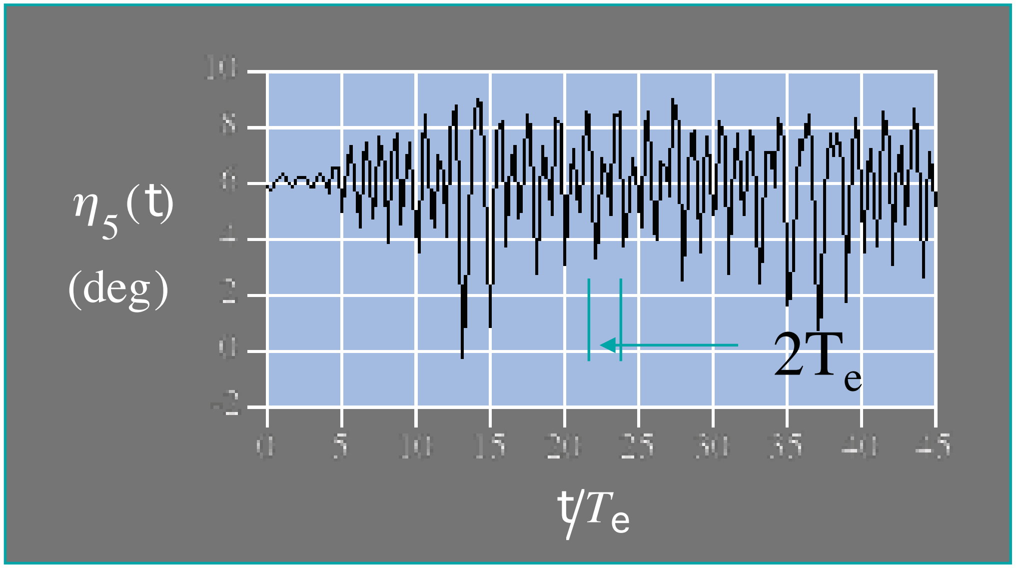


FREQUENCY



SIMULATED FORCED RESPONSE

(Troesch and Hicks, 1994)



$C_v = 4.5$

$\varsigma_o/B = 0.15$

$\lambda/L = 2.40$

$\omega_e\sqrt{B/g} = 2.29$

OUTLINE

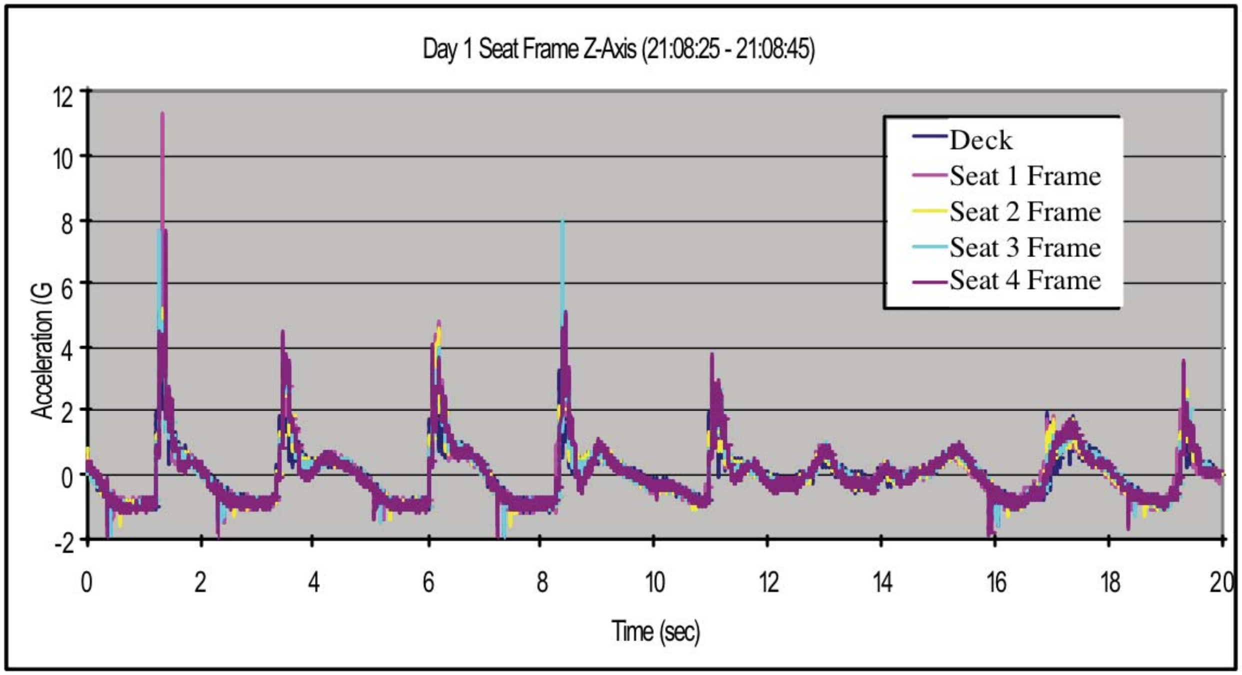
- Planing Hull Hydrodynamics and Dynamics

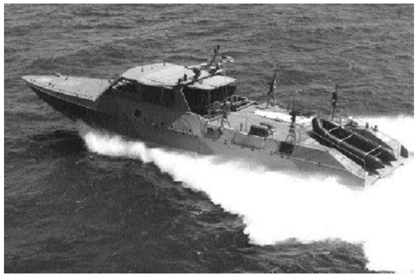
  Selected experiments and theories
  with practical applications

- Nonlinear Dynamics Analysis Applied to Planing Hulls

- Stochastic Vibro-Impact Model for Extreme Planing Craft Acceleration Estimation

Full Scale MARK V Acceleration Time Histories



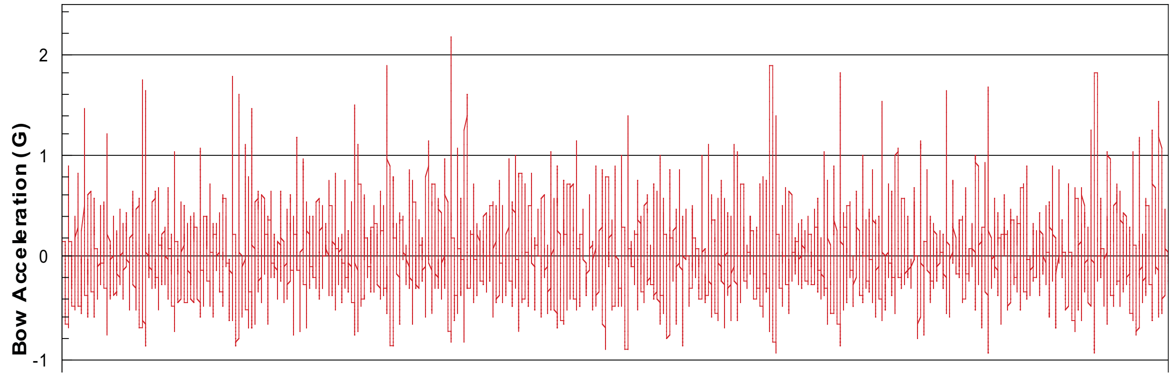


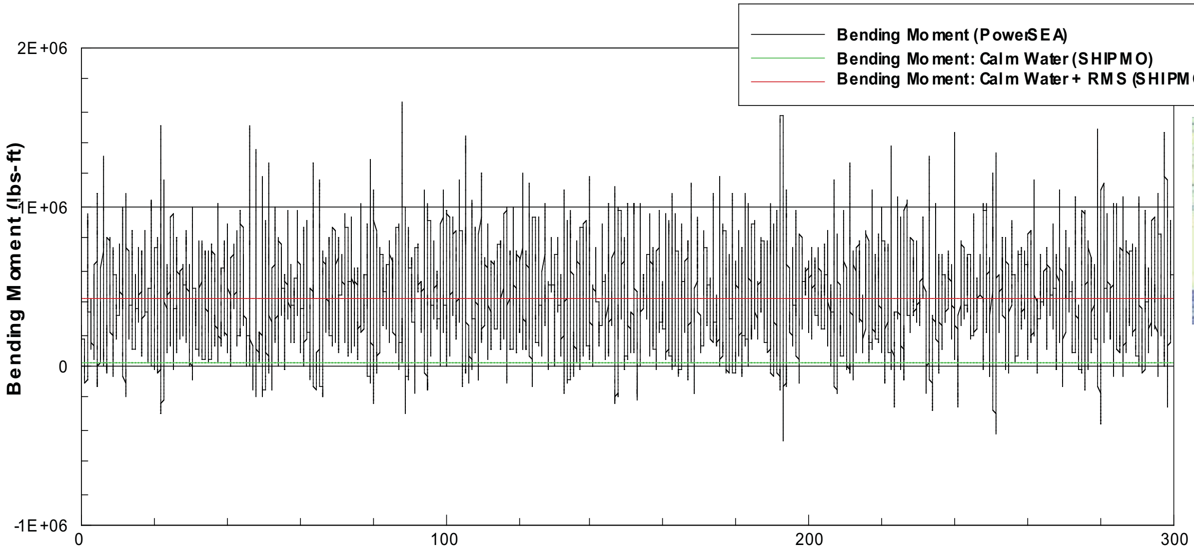
MARK V deck & seat frame acceleration data collected January 10, 2003 by NSWC-PC.

Sea Trial conditions: 3.0 ft significant wave height, 8.3 second wave period

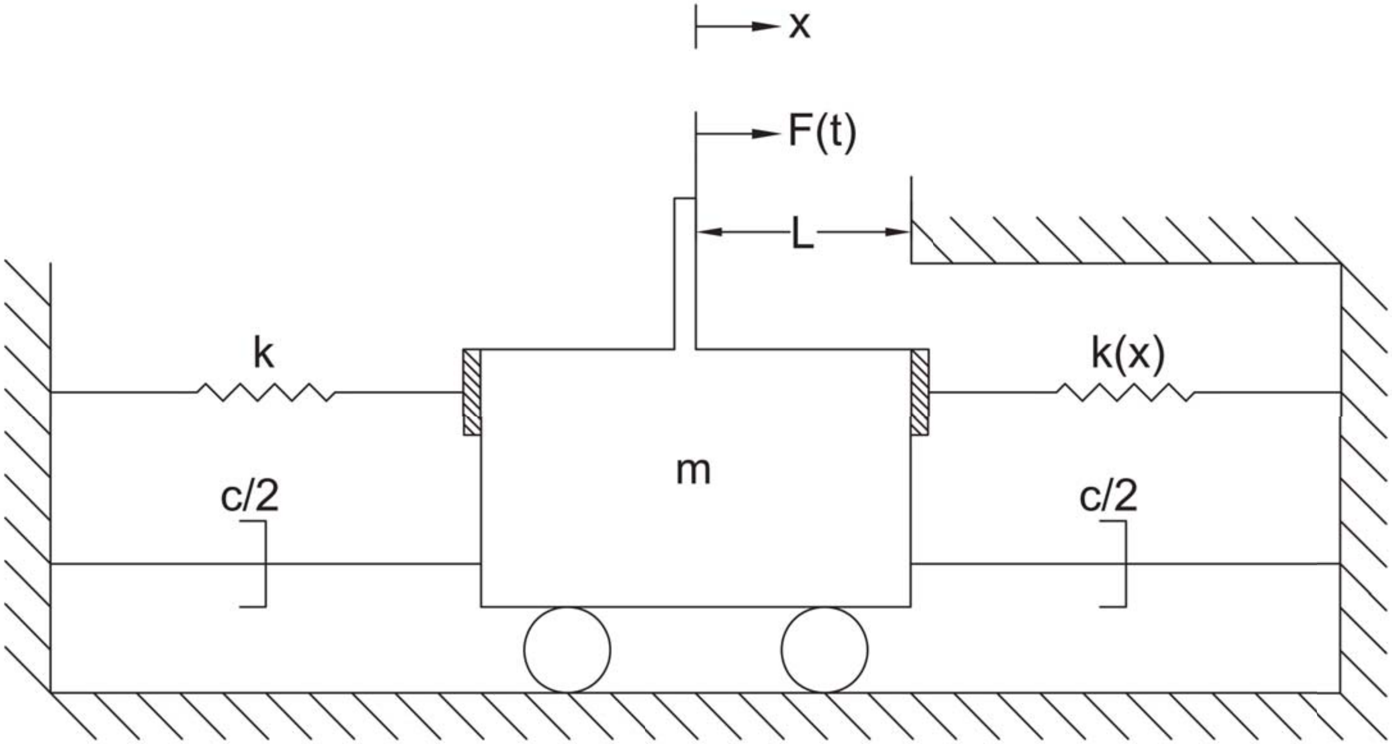
Extreme Responses in Stochastic Design Environments Statistics of Impact

Simulated Mark V Acceleration at Bow and Bending Moment (Sea State 2)





Stochastic Vibro-Impact Model for Extreme Planing Craft Acceleration Estimation



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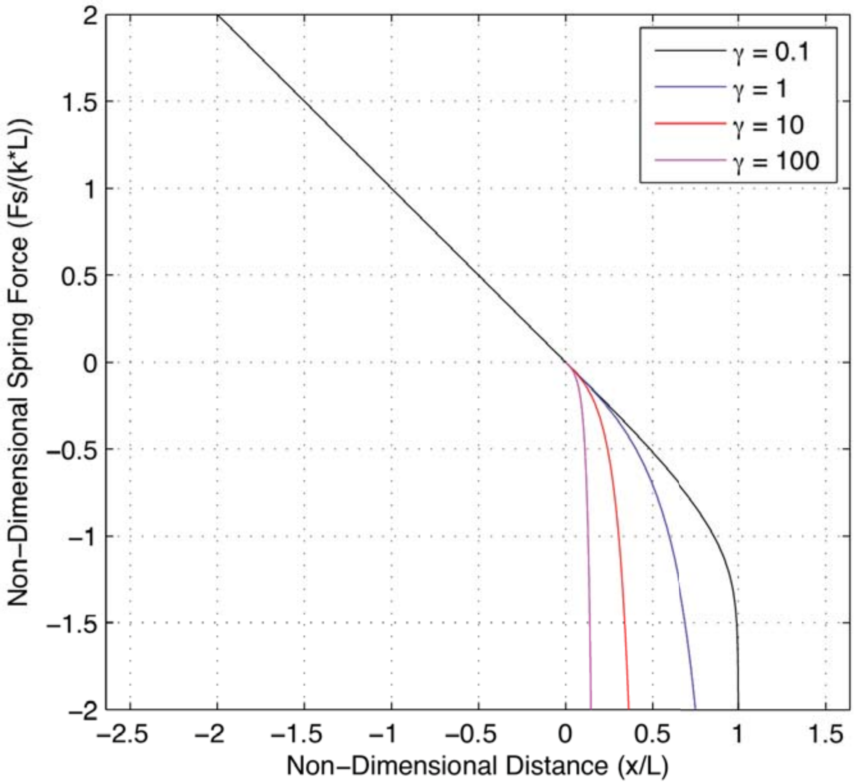
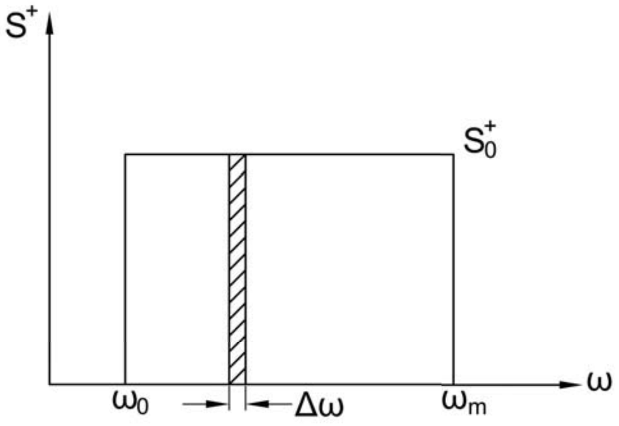
Dynamics and Hydrodynamics of High Speed Craft
June 29, 2010
Barranquilla, Colombia

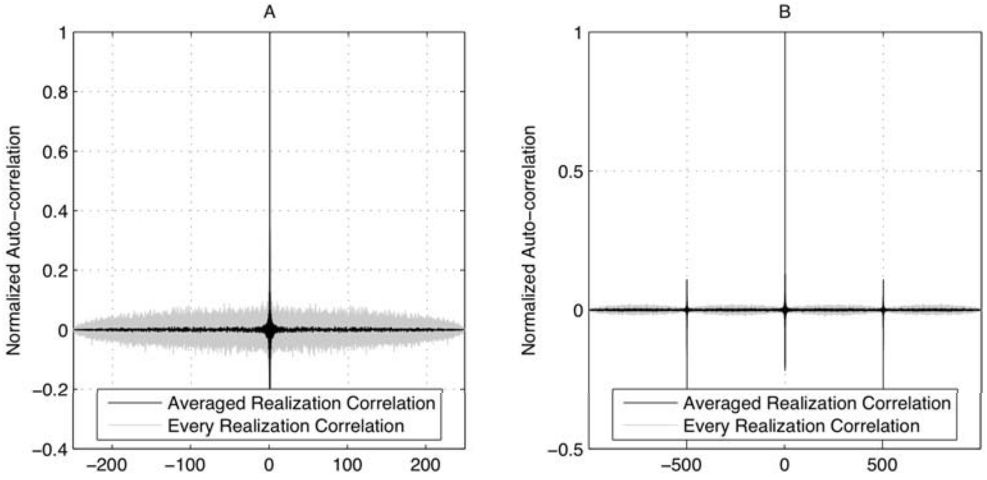
Stochastic Vibro-Impact Model
Parametric Hardening Spring

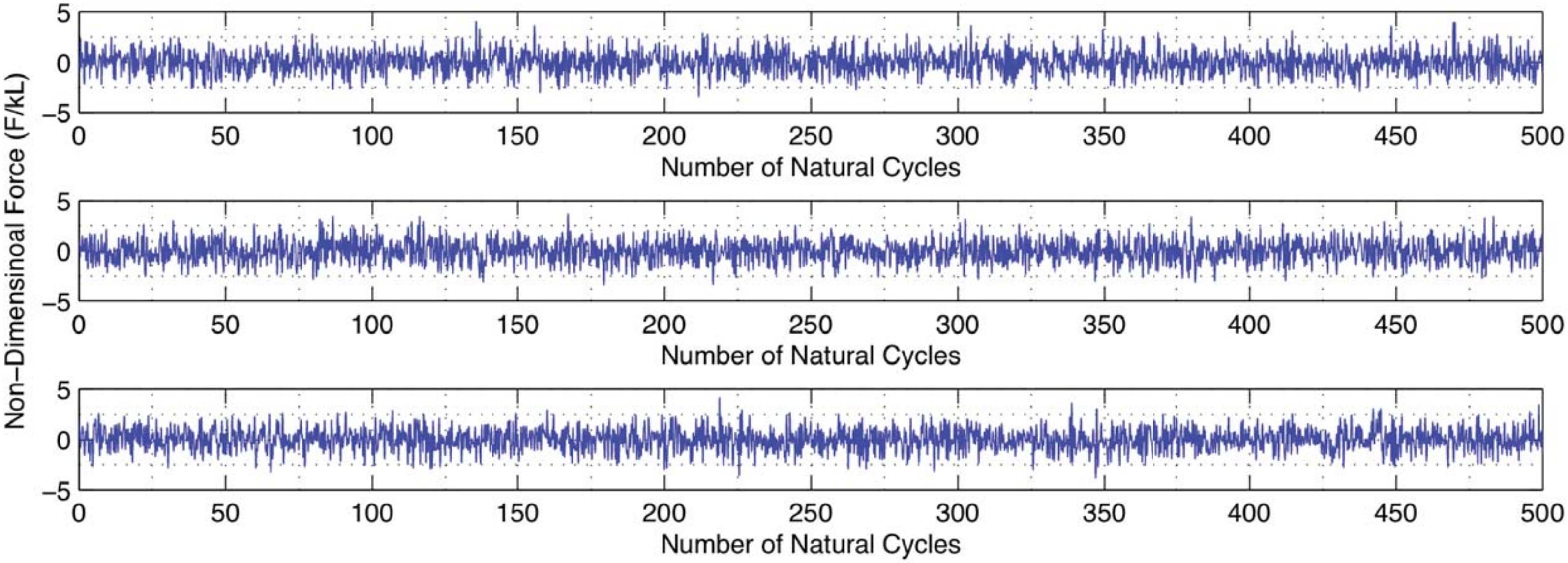
$$\begin{cases} Y>0 & \frac{1}{4\pi^2}\ddot{Y}+\frac{\zeta}{\pi}\dot{Y}+Y\cos^{-\gamma}\left(Y\frac{\pi}{2}\right) \\ Y\le 0 & \frac{1}{4\pi^2}\ddot{Y}+\frac{\zeta}{\pi}\dot{Y}+Y \end{cases} = \sum_{j=1}^{N} F_\sigma\sqrt{\frac{2}{N}}cos(2\pi\eta_j\tau+\alpha_j)$$



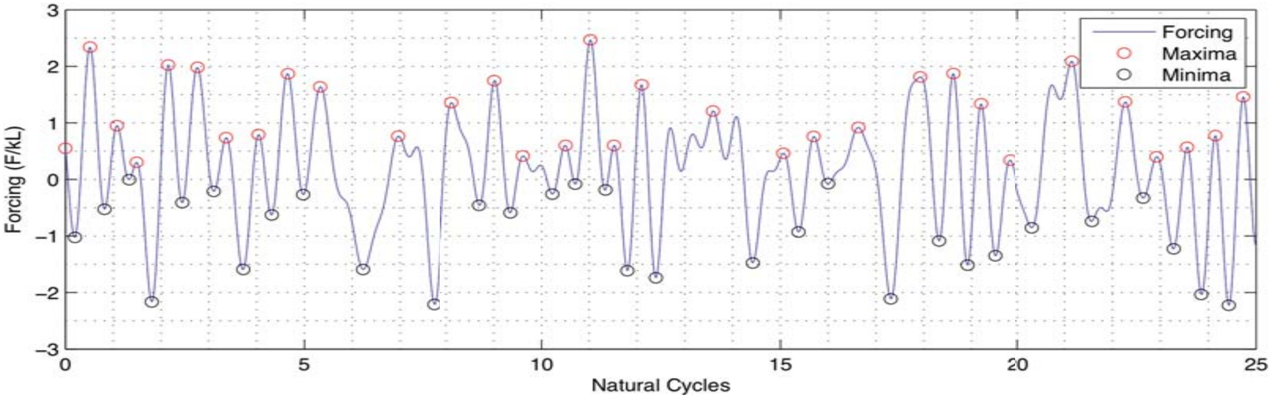
Ensemble of Band-limited Forcing



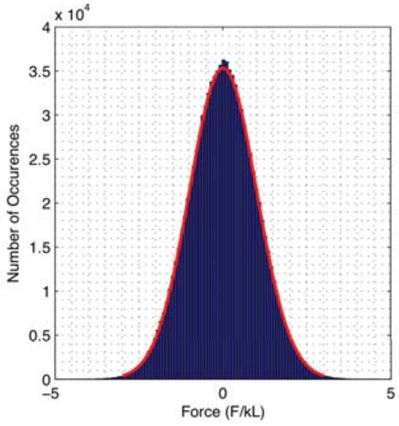




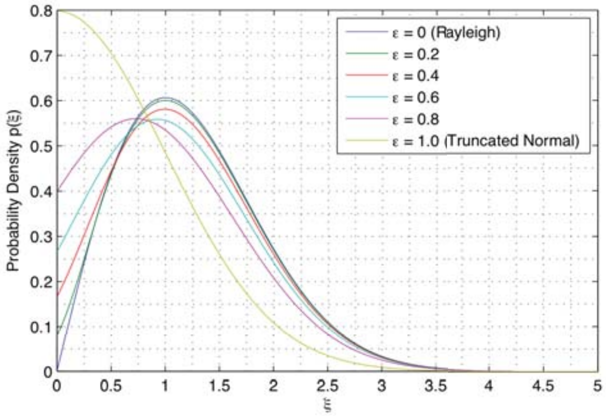
Extreme Value Statistics Background



Elevation PDF



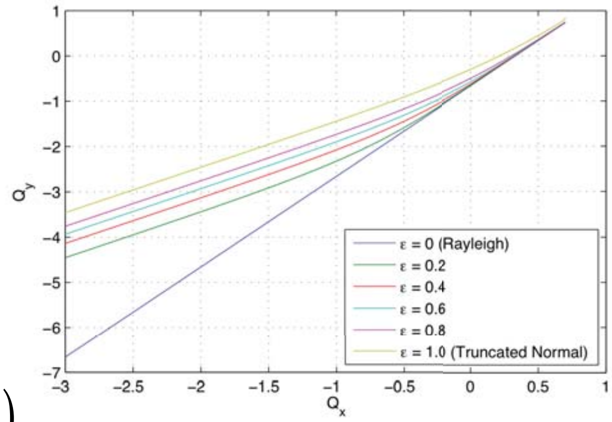
Maxima PDF



$$Q_x = \log_{10}(\xi)$$

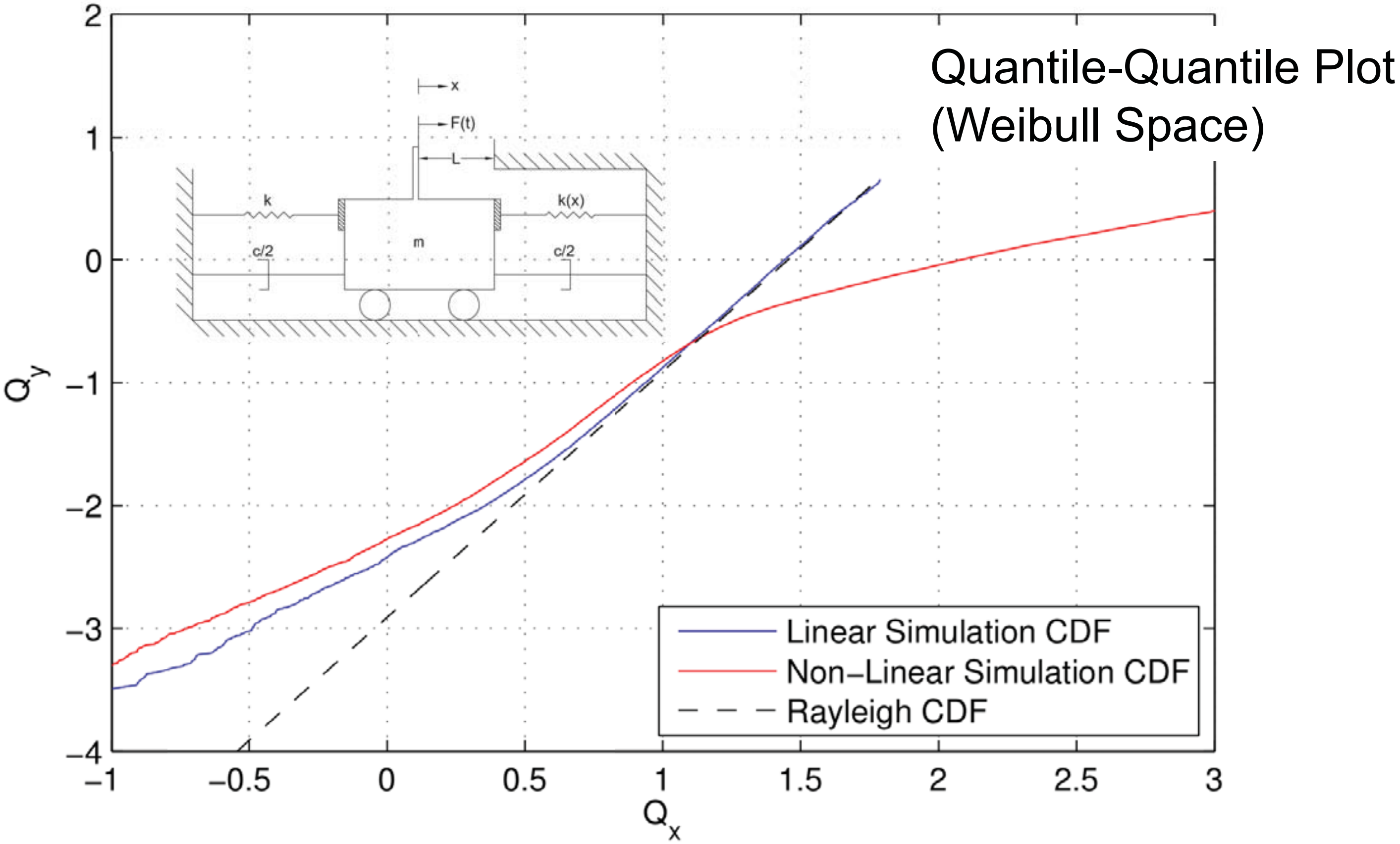
$$Q_y = \log_{10}\left(-\log_{10}\left(1 - P(\xi)\right)\right)$$

Quantile-Quantile Plot
(Weibull Space)



Stochastic Vibro-Impact Model

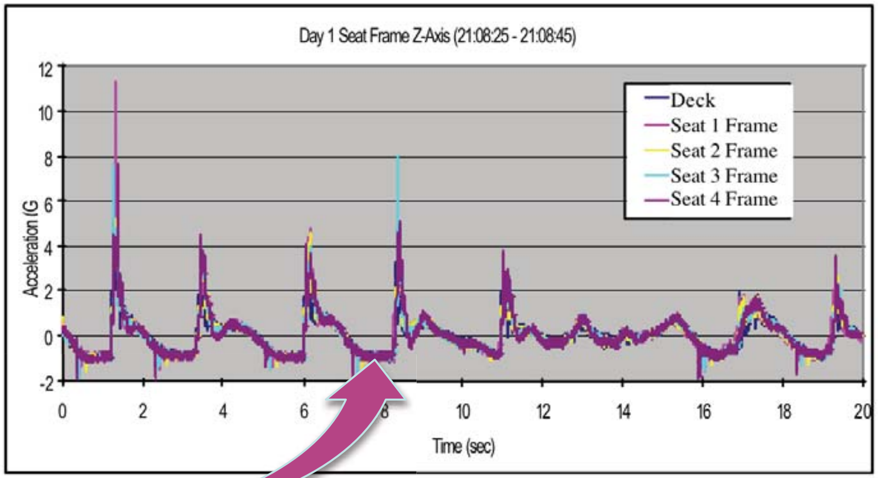
$\zeta=0.5$, $\underline{\eta}=0.5$, $\gamma=1.0$, $\varepsilon=0.5$

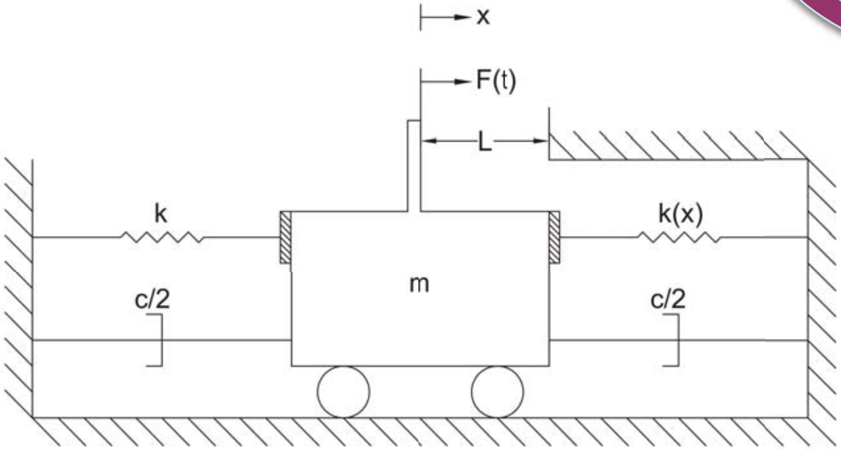


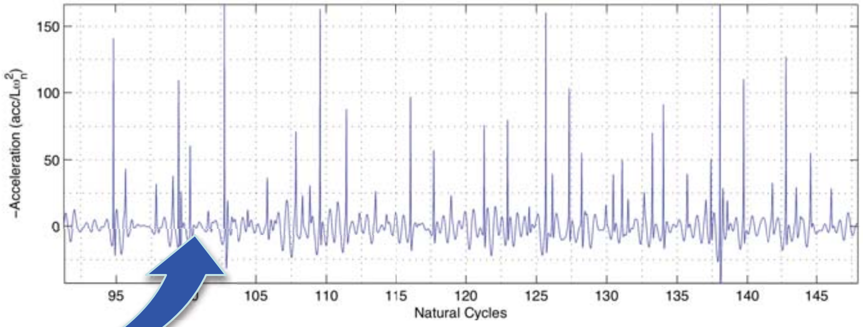
Quantile-Quantile Plot
(Weibull Space)

$\zeta=0.5$ (damping ratio), $\underline{\eta}=0.5$(central forcing freq.), $\gamma=1.0$(wall stiffness)

Stochastic Vibro-Impact Model for Extreme Planing Craft Acceleration Estimation - Application







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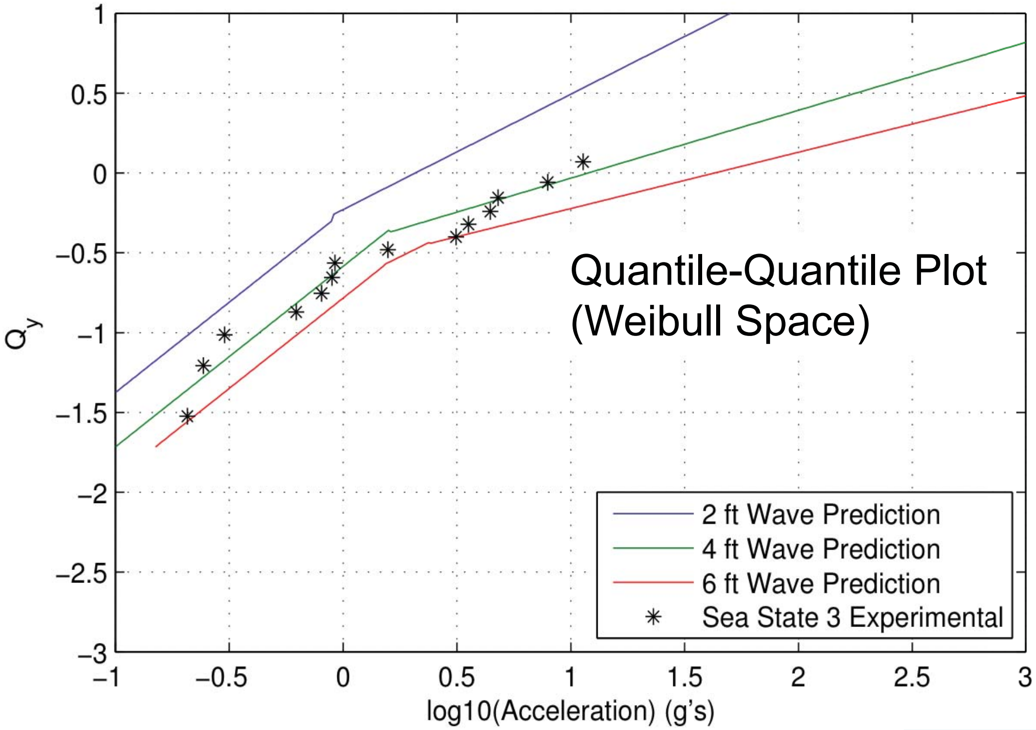
Stochastic Vibro-Impact Model for Extreme Planing Craft Acceleration Estimation



Extreme Acceleration Estimates

$H_{1/3}$	11.5 g	50 g	20”	2’30”
2 ft	95’	600 yr	2.1 g	4.9 g
4 ft	19.3”	2’18”	11.8 g	52 g
6 ft	8.5”	23”	42 g	254 g

Summary

- *Planing Hull Hydrodynamics and Dynamics*

  Selected experiments and theories with practical applications

- Complex coupled hydrodynamics and dynamics
- Appendages play large role in assessing performance
- Steady hydrodynamics relatively mature. Big challenge is resolving jet kinematics and geometry
- Linear theory can be of use in assessing stability boundaries

Summary

- *Nonlinear Dynamics Analysis Applied to Planing Hulls*

- Problem is rich in interesting dynamics and hydrodynamics
- Reduced order nonlinear modeling required to understand global dynamics
- Need to understand underlying physics to support brute force Monte Carlo simulations
- Role that high fidelity simulators play in design and design optimization is not clear

Summary

- *Stochastic Vibro-Impact Model for Extreme Planing Craft Acceleration Estimation*

- Traditional stochastic analysis assumptions for planing dynamics may be invalid
- Extreme values of planing dynamics are the result of highly nonlinear, non-Gaussian processes
- Reduced order models have important place in understanding extreme values

QUESTIONS ???