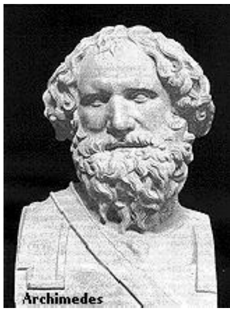
Chapters 1 Preliminary Concepts & 2 Fundamental Equations of Compressible Viscous Flow

Historical Outline

Faces of Fluid Mechanics



Archimedes
(287-212 BC)

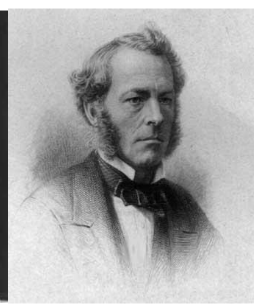
Newton
(1642-1727)

Leibniz
(1646-1716)

Bernoulli
(1667-1748)

Euler
(1707-1783)

Navier
(1785-1836)



Stokes
(1819-1903)

Reynolds
(1842-1912)

Prandtl
(1875-1953)

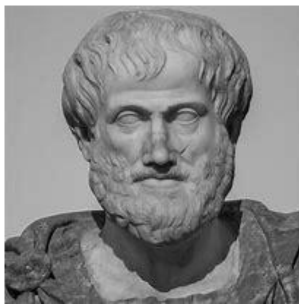
Taylor
(1886-1975)

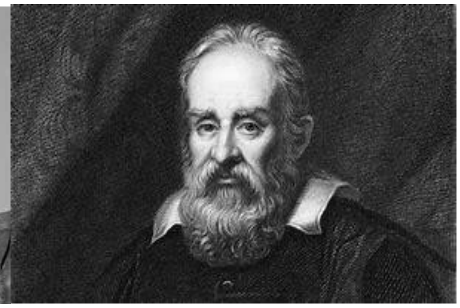
Kolmogorov
(1903-1987)

Pope
(1949-)

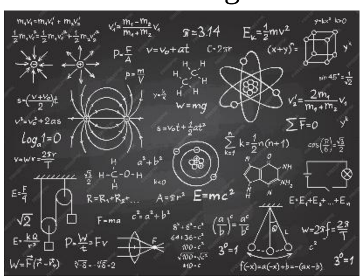
Moin
(1952-)

21st Century Scientific Method Paradigm

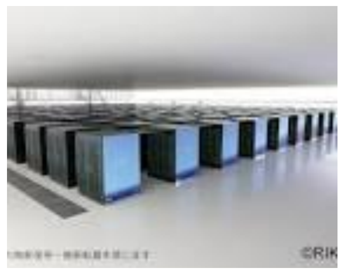




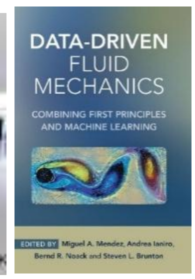
Logic Observation/Experimentation



Mathematical Physics

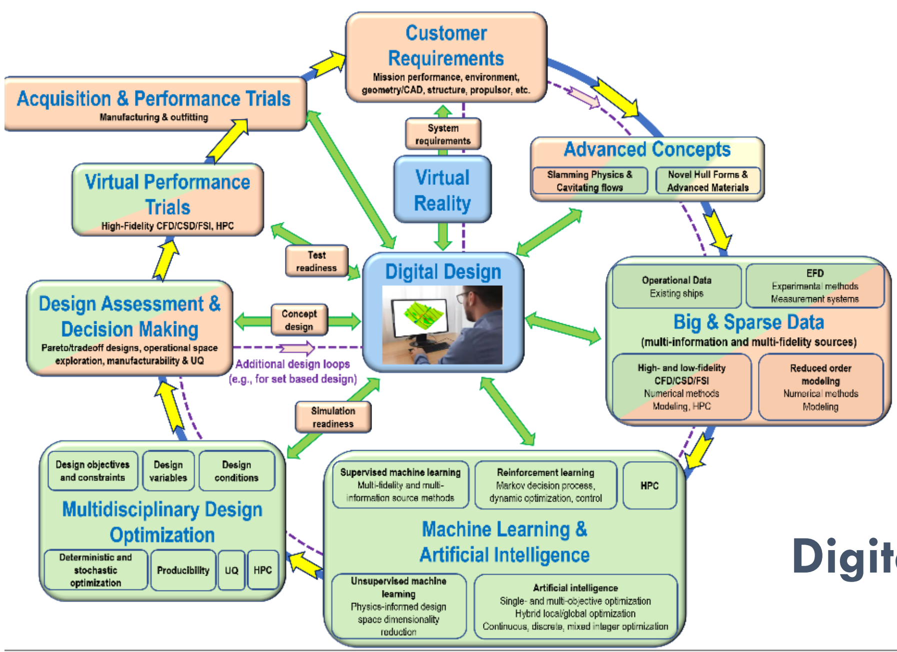


El Capitan: fastest in world
Speed: **1.809 exaFLOPs** (quintillion calculations per second)
11 million CPU and GPU cores
Hewlett Packard Enterprise (HPE)
Lawrence Livermore National Laboratory



Data Driven/ML&AI

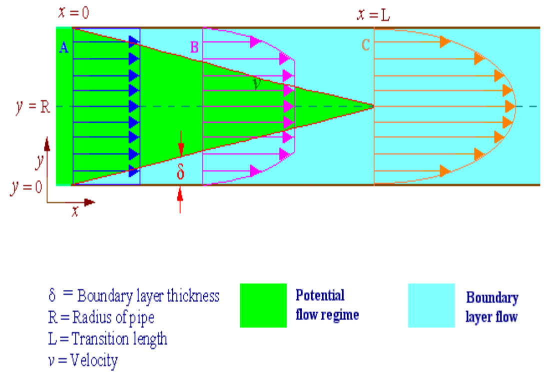
Future: Digital design, which combines logic/mathematical physics/computers, experiments/validation and data driven ML&AI along with productivity, manufacturability and virtual shipyard methods for scientific engineering



Digital Design

Some Examples of Viscous Flow Phenomena

Analytical Fluid Mechanics (AFD)



Development of boundary-layer flow in pipe

$$\nabla \bullet \mathbf{U} = 0$$

$$\frac{D\mathbf{U}}{Dt} = -\nabla p + \frac{1}{\mathrm{Re}} \nabla^2 \mathbf{U} + \nabla \bullet \overline{u_i u_j}$$

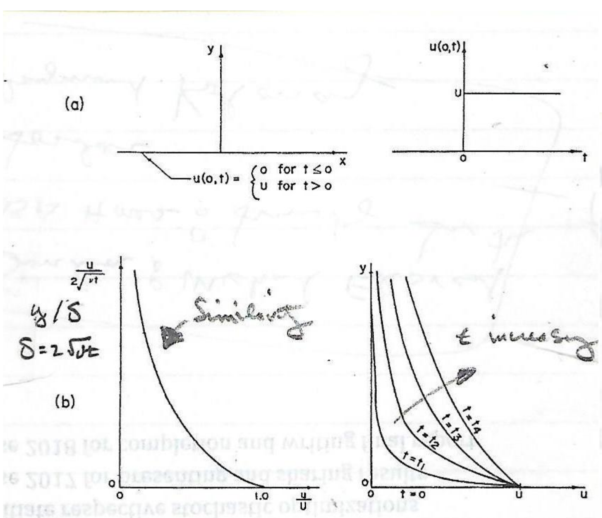


FIGURE 7.4
(*a*) Definition sketch for Stokes' first problem and (*b*) the solution curves in terms of the similarity variable and in terms of the dimensional variables.

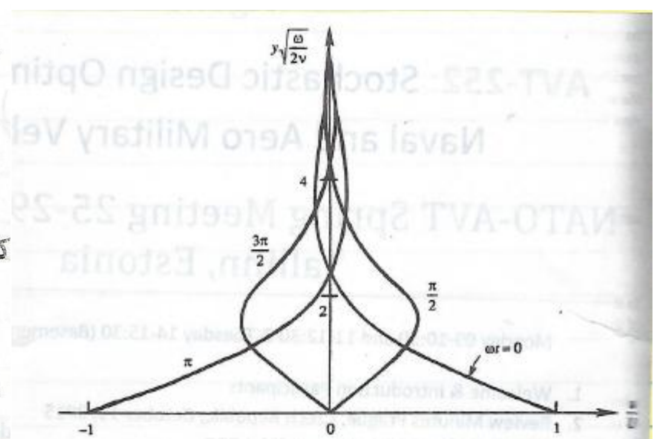
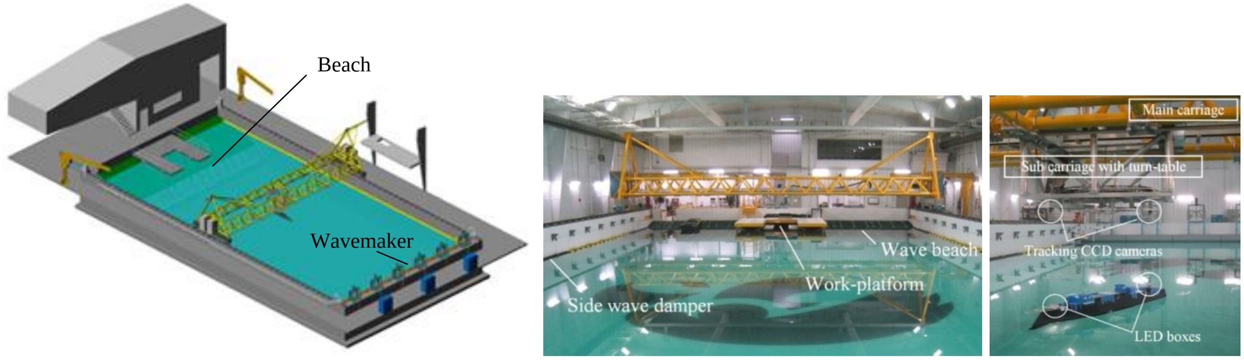
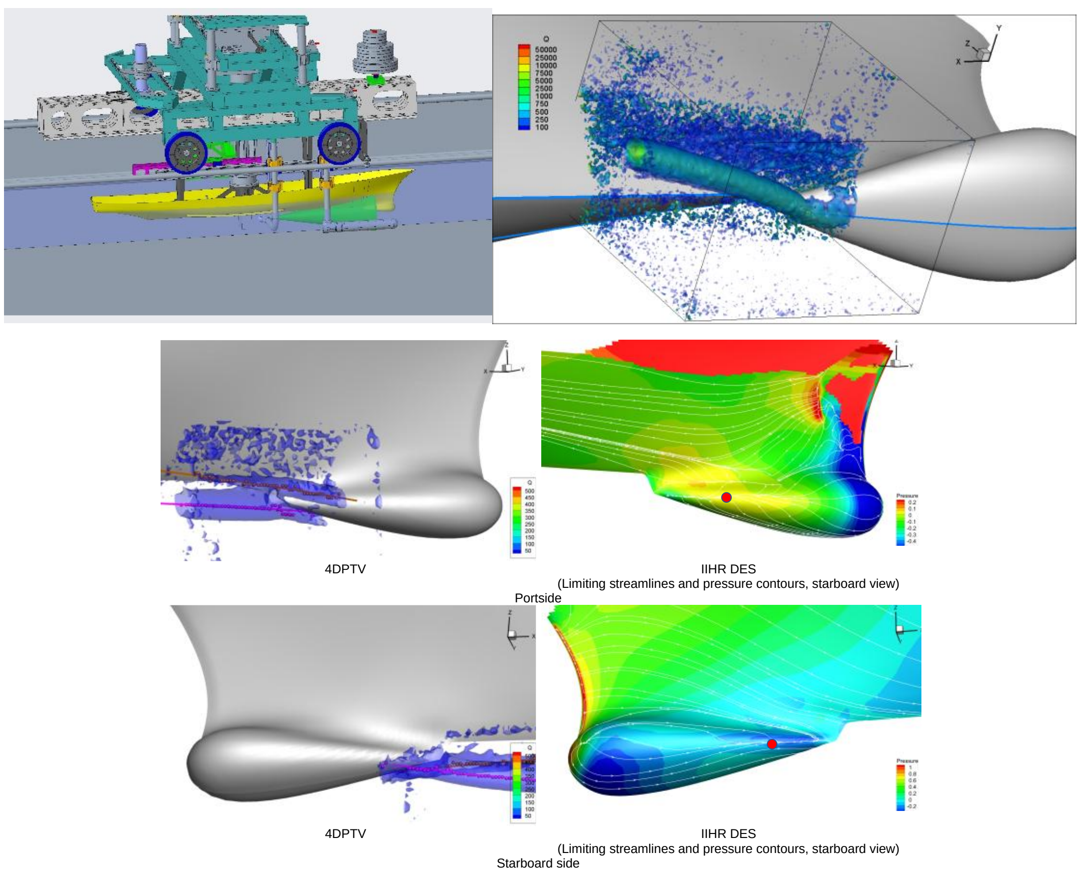


Figure 9.13 Velocity distribution in laminar flow near an oscillating plate. The distributions at $\omega t = 0$, $\pi/2$, π, and $3\pi/2$ are shown. The diffusive distance is of order $\delta = 4\sqrt{\nu/\omega}$.

Experimental Fluid Mechanics (EFD)

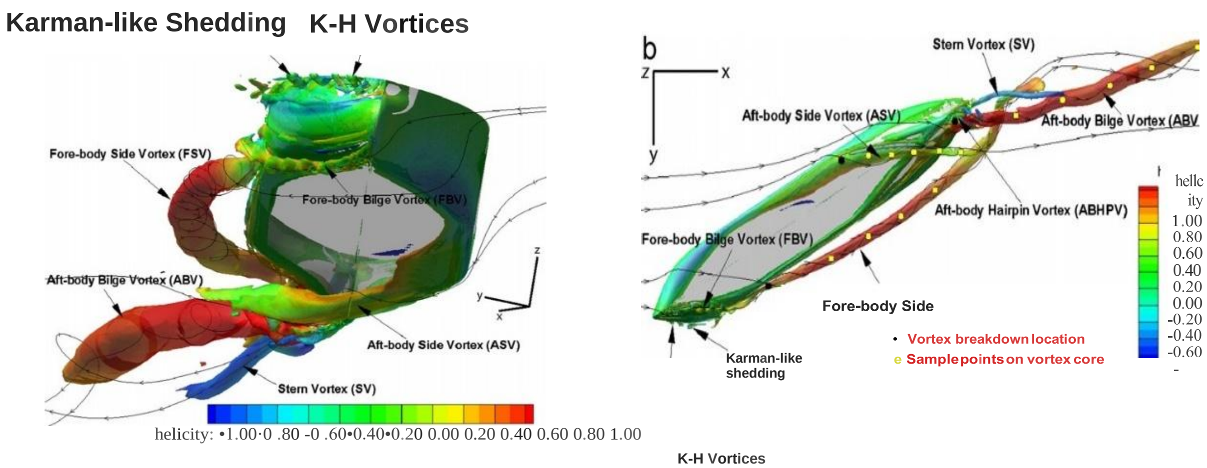


IIHR wave basin

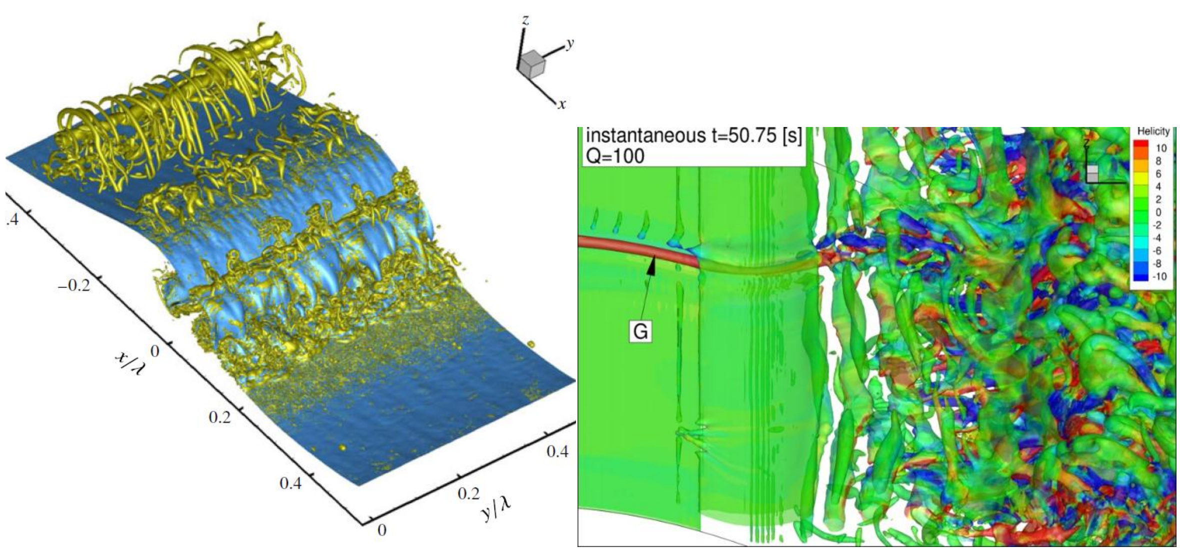


Local Flow 4DPTV Measurement System in IIHR Towing Tank

Computational Fluids Mechanics (CFD)

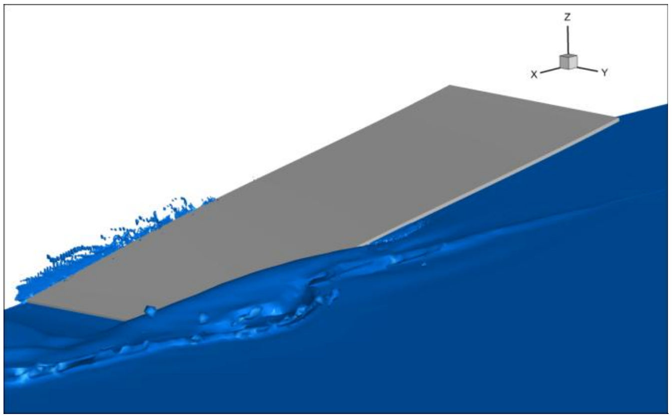


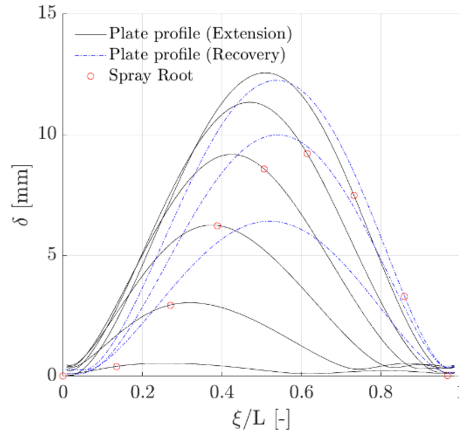
Vortex systemofKVLCC2(iso surface of Q=200 colored by helicity) at β=30º: (a)bow view and (b)bottom view.



CFDShip-Iowa DNS of breaking wave and bulge-scare air-water interface instability

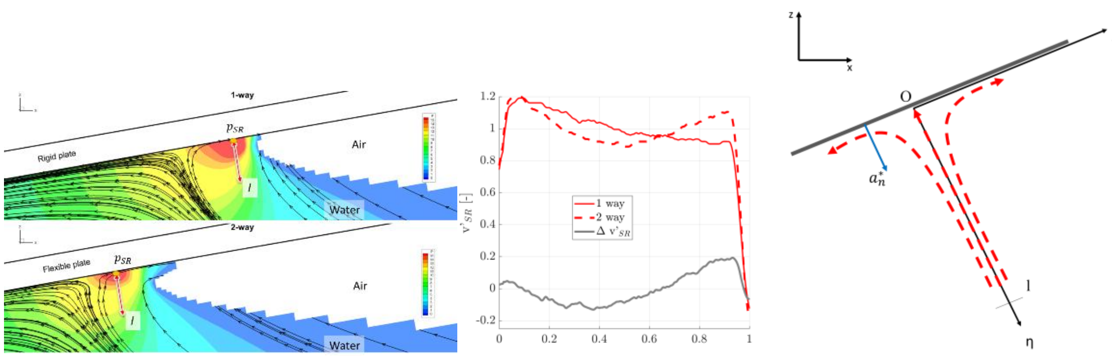
CFDShip-Iowa &ANSYS Fluid Structure Interaction (FSI)





Stagnation Flow Model: Extended Bernoulli Equation Analysis

$$p_{SR} = \rho\left(\frac{\Delta v_n{}^2}{2} - a_n^* l\right) = p_{SR}|_{2\text{way}} - p_{SR}|_{1\text{way}} \propto \rho\left(\frac{\Delta v_n^2}{2} - l a_n^*\right)$$



FSI Conservation of energy analysis

$$-\frac{\delta W}{dt} = \frac{dE}{dt} = \frac{\partial}{\partial t}\iiint_{V(t)} e\rho\, dV + \iint_{S(t)} e\rho(\boldsymbol{u}\cdot\hat{n})dS$$

$$e = k_e + p_{e\varepsilon} + p_{eg}$$

Kinetic energy and elastic and gravitation potential energies

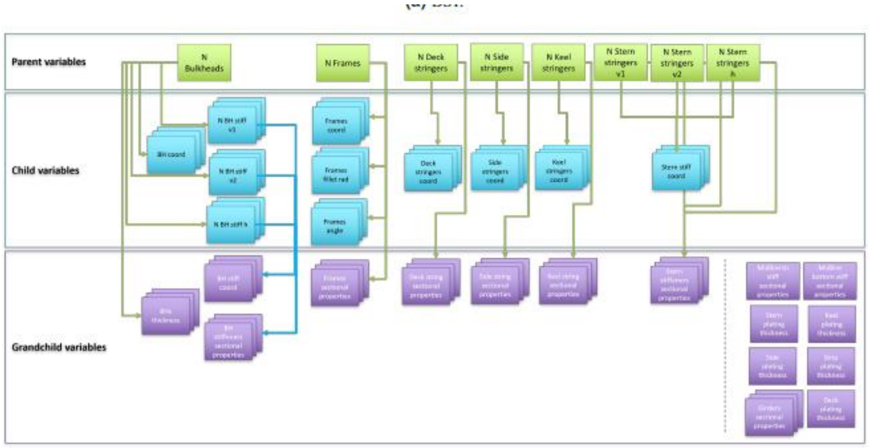
R. Pellegrini, M. Diez, Z. Wang, and F. Stern, 2025, "High-Fidelity Computational Two-Way Fluid-Structure Interaction and Physical Analysis of Flexible Plate Slamming," Physics of Fluids 1 January 2026, Movie 1, 2, 3.

On the Use of Parametric Model Embedding for Structural Optimization with Application to High Speed Small Craft

Riccardo Pellegrini, Matteo Diez
National Research Council
Institute of Marine Engineering
ITALY

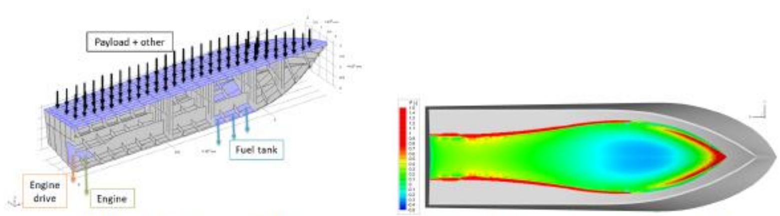
Erik R. Kubina
Naval Surface Warfare Center
Carderock Division, Carderock, Bethesda
USA

Frederick Stern
The University of Iowa, Iowa City, IA
USA



(b) DS2.

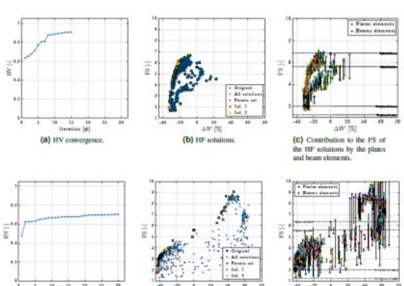
Figure 2: Variables hierarchy.



(a) Design loads for the GPPH hull.

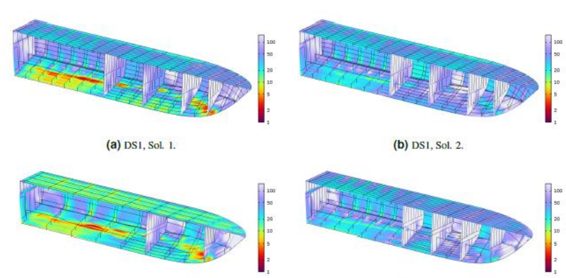
(b) Hydrodynamic pressure, snapshot during slamming in regular wave.

Figure 3: Loads and their distribution on the GPPH hull.



(a) HV convergence.
(b) HF solutions.
(c) Contribution to the FS of the HF solutions by the plates and beam elements.
(d) HV convergence.
(e) HF solutions.
(f) Contribution to the FS of the HF solutions by the plates and beam elements.

Figure 8: HV convergence and HF evaluated solutions, Pareto set, and selected solutions of interest.



(a) DS1, Sol. 1.
(b) DS1, Sol. 2.
(c) DS2, Sol. 1.
(d) DS2, Sol. 2.

Figure 10: Structural response (FS) of Sol. 1 and Sol. 2 designs under regular head wave loads when the slam occurs.

1-2 Some examples of viscous-flow phenomena (continued)

Overview

types of flows:

		continuity eq.
incompressible:	ρ = constant	$\nabla \cdot \underline{V} = 0$
Compressible:	$\rho \neq$ constant	$\rho_t + \nabla \cdot \rho \underline{V} = 0$

inviscid ($\mu = 0$), incompressible flow

ca. 1750 $\rho \frac{D\underline{V}}{Dt} = \rho \underline{g} - \nabla p$ Euler equation $\frac{D}{Dt} = \frac{\partial}{\partial t} + \underline{V} \cdot \nabla$

inertia = (gravitational) body force − (pressure) surface force

ideal flow ($\mu = 0$, ρ = constant, $\underline{\omega} = \nabla \times \underline{V} = 0$)

$$\underline{V} = \nabla \varphi$$
$$\nabla \cdot \nabla \varphi = 0$$
$$\nabla^2 \varphi = 0 \quad \text{Laplace equation}$$

ca. 1750 $\rho \frac{\partial \varphi}{\partial t} + p + \frac{1}{2} \rho \nabla \varphi \cdot \nabla \varphi + \rho g z =$ constant   Bernoulli equation

viscous, compressible flow

ca. 1850 $\rho \frac{D\underline{V}}{Dt} = \rho \underline{g} + \nabla \cdot \tau'_{ij} - \nabla p$ Navier-Stokes equations

$\rho \frac{Dh}{Dt} = \frac{Dp}{Dt} + \nabla \cdot (k \nabla T) + \tau'_{ij} \frac{\partial u_i}{\partial x_j}$ energy equation

$$\tau'_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \delta_{ij} \lambda \nabla \cdot \underline{V} \qquad (\lambda = -\tfrac{2}{3}\mu)$$

Analysis techniques:

Analytical: mathematical solutions
restricted to simplified flows and/or equations (CFD)

Computational Fluid Dynamics: computational solutions
current approach and future approach for SBD (EFD)

Experimental Fluid Dynamics: measured solutions
basis for design and theory and req. for CFD validation

- e
- BL
- NS
- RANS
- LES — DES
- DNS

Uncertainty analysis:

EFD: ASME JFE (1991)

$U_{result} = [B^2 + P^2]^{1/2}$ RSS
bias precision

- load cell
- pitot
- hotwire
- LDV
- PIV
- 4DPIV

CFD: ASME JFE (1993)

$U_{result} = [M^2 + N^2]^{1/2}$ RSS
modeling numerical
eq. + physics num. sol. mathematical equations

determination of modeling errors req.
validation ie comparison with EFD

determination of numerical errors req.
verification ie assessment of iterative
and grid convergence, effects of
artificial viscosity, and order of accuracy

Modern V&V and UQ Methods

Coleman, H.W. and Stern, F., "Uncertainties and CFD Code Validation," ASME J. Fluids Eng., Vol. 119, December 1997, pp. 795 – 803

Stern, F., Wilson, R.V., Coleman, H., and Paterson, E., "Comprehensive Approach to Verification and Validation of CFD Simulations-Part 1: Methodology and procedures," ASME J. Fluids Eng, Vol. 123, Issue 4, December 2001

Xing, T. and Stern, F., "Factors of Safety for Richardson Extrapolation," ASME J. Fluids Eng, Vol. 132, June 2010

Diez M., Broglia R., Durante D., Olivieri A., Campana E.F., Stern F., "Validation of Uncertainty Quantification Methods for High-Fidelity CFD of Ship Response in Irregular Waves," ASME Journal of Verification, Validation and Uncertainty Quantification, JUNE 2018, Vol. 3.

Multiple EFD and CFD Methods

Stern, F., Olivieri, A., Shao, J., Longo, J., and Ratcliffe, T., "Statistical Approach for Estimating Intervals of Certification or Biases of Facilities or Measurement Systems Including Uncertainties," ASME J. Fluids Eng, Vol. 127, No. 2, May 2005, pp. 604 – 610

Stern, F., Diez, M., Sadat-Hosseini, H., Yoon, H., Quadvlieg, F., Statistical Approach for CFD State-of-the-Art Assessment: N-Version Verification and Validation, ASME Journal of Verification, Validation and Uncertainty Quantification, 2017, Vol. 2.

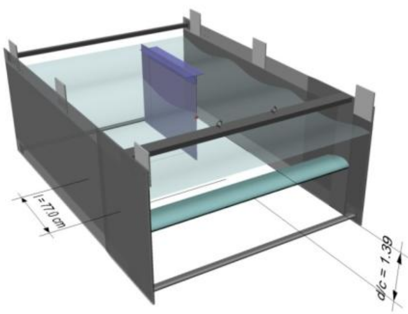
IIHR Ship Hydrodynamics Selected Viscous Flow Examples

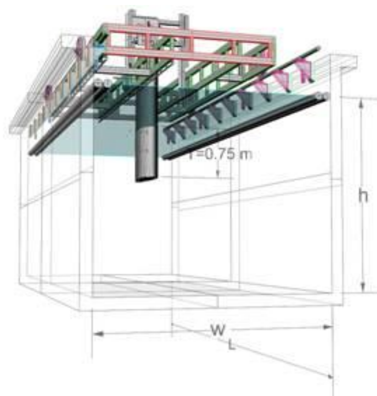
Wave-Induced Separation

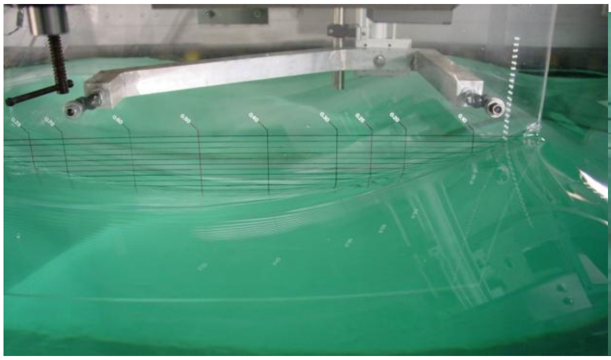
Stern, F., "Effects of Waves on the Boundary Layer of a Surface-Piercing Body," Journal of Ship Research, Vol. 30, No. 4, December 1986, pp. 256 – 274.

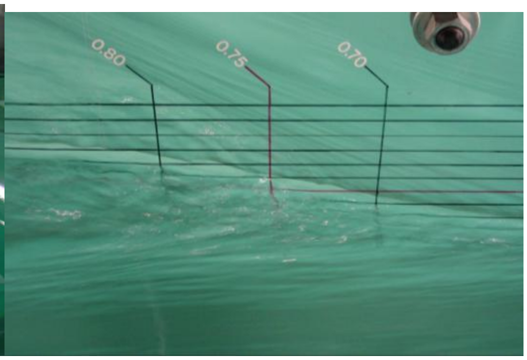
Stern, F., Choi, J.E., and Hwang, W.S., "Effects of Waves on the Wake of a Surface-Piercing Flat Plate: Experiment and Theory," Journal of Ship Research, Vol. 37, No. 2, June 1993, pp. 102 – 118

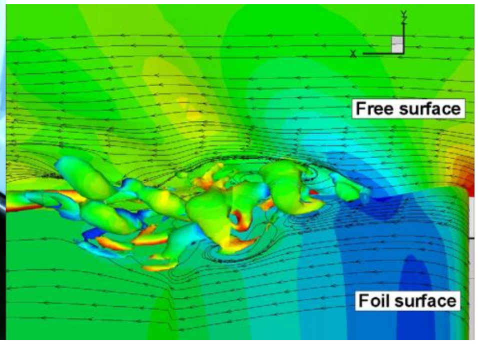
Xing, T., Kandasamy, M., and Stern. F., "Unsteady Free-Surface Wave-Induced Separation: Analysis of Turbulent Structures Using Detached Eddy Simulation and Single-Phase Level Set," Journal of Turbulence, Vol. 8, No. 44, 2007, pp. 1 – 35











Wave Breaking & Air-Water Interface Instabilities

Kang, DH, Ghosh, S., Reins, G., Koo, B., Wang, Z., Stern, F., "Impulsive Plunging Wave Breaking Downstream of a Bump in a Shallow Water Flume – Part I: Experimental Observations," Journal of Fluids and Structures, invited for special issue for FEDSM2010-ICNMM2010, Vol. 32, July 2012, pp. 104 – 120. Movie

Koo, B., Wang, Z., Yang, J., Stern, F., "Impulsive Plunging Wave Breaking Downstream of a Bump in a Shallow Water Flume – Part II: Numerical Simulations, "Journal of Fluids and Structures, invited for special issue for FEDSM2010-ICNMM2010, Vol. 32, July 2012, pp.121 – 134.

Wang, Z., Yang, J., and Stern, F., "High-fidelity simulations of bubble, droplet, and spray formation in breaking waves, JFM, 2016, vol. 792, pp. 307-327. Movie

Timur Kent Dogan, Zhaoyuan Wang and Frederick Stern, "Experimental and Numerical Study of Air-Water Interface Instabilities with Machine Learning for Experimental Data Analysis," 33rd Symposium on Naval Hydrodynamics Osaka, Japan, 31 May-5 June 2020. Movies: EFD Instability, SL1 and SL2; DNS 1, 2 & 3

Wei Liu, Wentao Wang, Gengyao Qiu, Decheng Wan, Jianhua Wang, Zhaoyuan Wang and Frederick Stern, "KCS Unsteady Bow Wave Breaking Experiments for Physics and CFD Validation," 34th Symposium on Naval Hydrodynamics Washington, DC, USA, 26 June - 1 July 2022.

Unsteady Separation

Xing, T. Bhushan, S., and Stern, F. "DES for a Tanker at Drift Angles with Analogy to Delta Wings," Ocean Engineering, Volume 55, December 2012, pp. 23 – 43.

Bhushan, S., Yoon, H, Stern, F, Guilmineau, E., Visonneau, M., Toxopeus, S., Simonsen, C., Aram, S., Kim, S.-E. and Grigoropoulos, G., "Assessment of CFD for Surface Combatant 5415 at Straight Ahead and Static Drift $\beta=20^o$," ASME JFE, MAY 2019, Vol. 141.

Shanti Bhushan, Hyunse Yoon and Frederick Stern, "Detached Eddy Simulations and Tomographic PIV Measurements of Flows over Surface Combatant 5415 at Straight-Ahead and Static Drift Conditions," Ocean Engineering Volume 238, 15 October 2021, 109658.

S.M. Yeon, J. Yang, F. Stern, Large-Eddy Simulation of the Flow past a Circular Cylinder at Sub- to Super-Critical Reynolds Numbers, Applied Ocean Research, 59 (2016) 687-708.

Frederick Stern, "Effects of Sway Motion on Smooth-Surface Vortex Separation Onset and Progression: Surface Combatant and Surface-Piercing Truncated Cylinder," AVT-307: Research Symposium on Separated Flow: Prediction, Measurement and Assessment for Air and Sea Vehicles, Trondheim, Norway, 07-09 October 2019.

Yugo Sanada, Sungtek Park, Dong Hwan Kim, Zhaoyuan Wang, Hironori Yasukawa, and Frederick Stern, "Experimental and CFD Study of KCS Hull-Propeller-Rudder Interaction for Self-Propulsion and Port and Starboard Turning Circles," submitted Applied Ocean Research, January 2021. Movie 1 & 2

Yugo Sanada, Zachary Starman, Shanti Bhushan, and Frederick Stern, "4D particle tracking velocimetry measurements of unsteady 3D vortex onset and progress for 5415 straight ahead, static drift and pure sway," Physics of Fluids, special collection Recent Advances Marine Hydrodynamics, editors pick, Vol. 35, Issue 10, 105125 (2023).

Frederick Stern, Yugo Sanada, Zachary Starman, Shanti Bhushan, Christian Milano, "4DPTV Measurements and DES of the Turbulence Structure and Vortex-Vortex Interaction for 5415 Sonar Dome Vortices," 35th Symposium on Naval Hydrodynamics, Nantes, France, 7 July - 12 July 2024.

Christian Milano, Shanti Bhushan, Zachary Starman, Zhaoyuan Wang, Yugo Sanada, and Frederick Stern, "CFDShip-Iowa ARS and IDDES of the Anisotropy and Scale-Resolved Turbulence for the JBC W2025 Test Case1," proceedings Wageningen 2025: a Workshop on CFD in Ship Hydrodynamics https://w2025.nl/. Movie 1, 2

Turbulence Anisotropy

Longo, J., Huang, H.P., and Stern, F., "Solid-Fluid Juncture Boundary Layer and Wake," Experiments in Fluids, Vol. 25, No. 4, September 1998, pp. 283 – 297

Frederick Stern, "Integrated High-Fidelity Validation Experiments and LES for a Surface-Piercing Truncated Cylinder for Sub- and Critical Reynolds and Froude

Numbers," AVT-246: Progress and Challenges in Validation Testing for CFD, Avila, Spain, 26-28 September 2016. Movie (1, 2, 3, 4)

Frederick Stern, "Effects of Sway Motion on Smooth-Surface Vortex Separation Onset and Progression: Surface Combatant and Surface-Piercing Truncated Cylinder," AVT-307: Research Symposium on Separated Flow: Prediction, Measurement and Assessment for Air and Sea Vehicles, Trondheim, Norway, 07-09 October 2019. Movie (1, 2, 3, 4)