Aligned with your needs.

2006 ASME Rayleigh Lecture

The Cost of Silence

Donald E. Thompson
Alion Science and Technology
Mystic, Connecticut

ALION
SCIENCE AND TECHNOLOGY

Introduction

- Cost has Always been a Major Driver in the Commercial World
- Cost has Become a Major Driver in Military Applications
  - Advanced Propulsion Systems Symposium – American Society of Naval Engineers
- Acoustic Requirements Can be a Major Cost Driver
- Implementation of Acoustic Mitigation Methods for a System Component Does Affect Other Components in the System
- Acoustic Design and Optimization of a Component Must Occur in Context of a Systems Approach
- Concept and Mitigation Method Innovation Required

Scope of Presentation

- System Design and Optimization
  - Focusing on System Approach
- Innovative Concepts
  - A Select Few
- Innovative Components / Methods
  - A Select Few

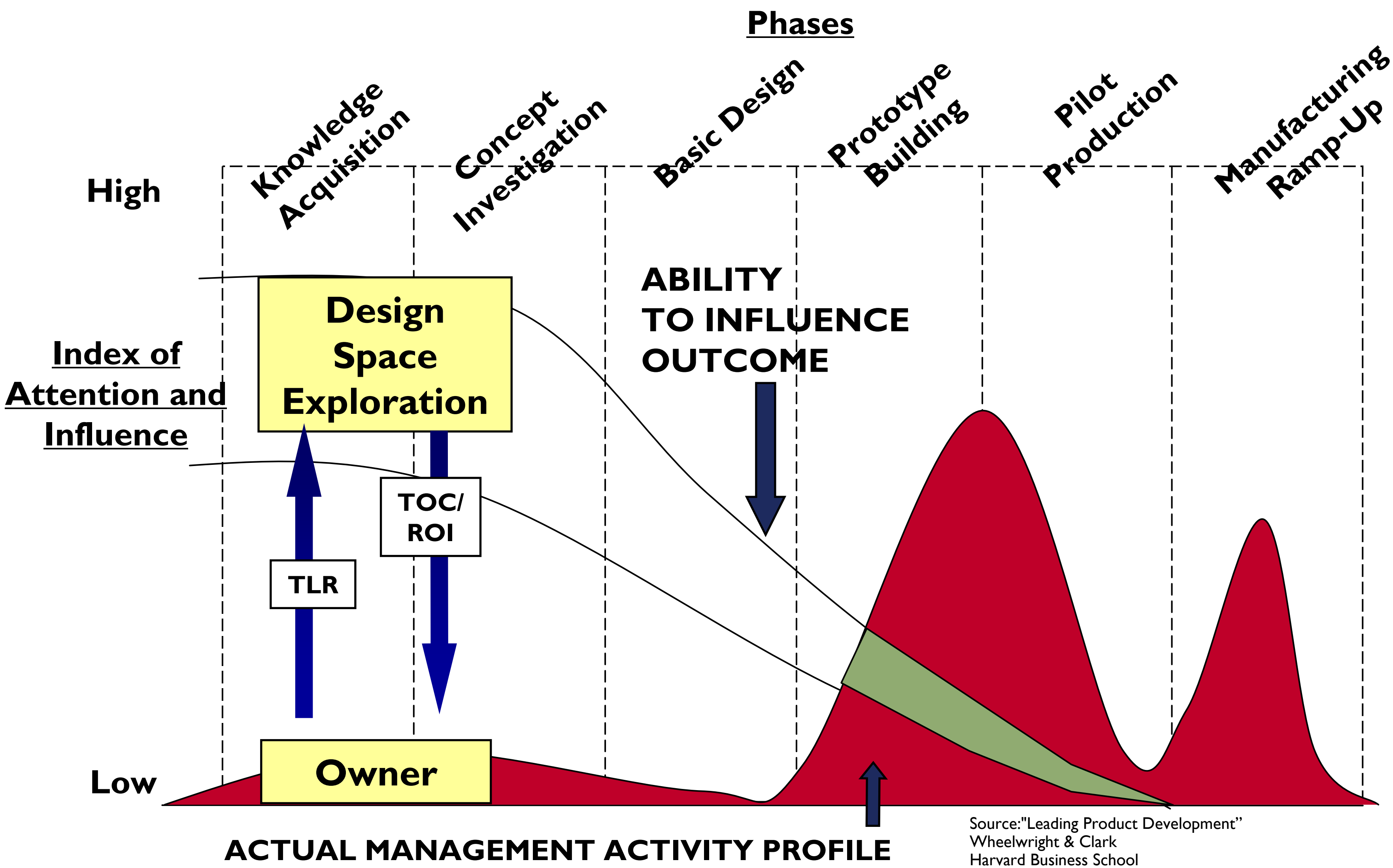
System Design and Optimization

Overall Objective

- Reduce Cost by Improving Design Process
  - Especially at the Early Stages of Assessment of Alternatives (AOA) and Preliminary Design
- Reduce Cost by Rapid Response to Requirements / Mission Changes
- Eliminate Stovepipes in Design Community
- Reduce Cost by Rapid Solution of Design Mods Due to Test Feedback

Vibration and Radiated Noise are a Very Important Consideration for Both Commercial and Military Applications

Design Space Exploration

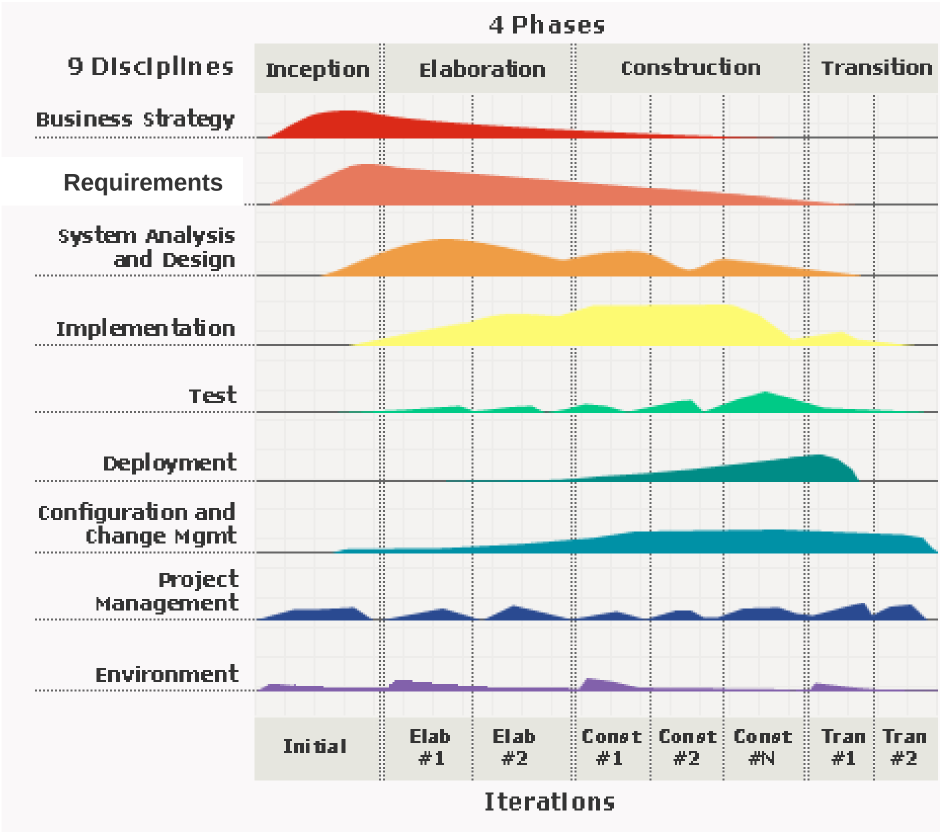


Source:"Leading Product Development"
Wheelwright & Clark
Harvard Business School

Rational Unified Process
Applied to *FlagShip Designer* Development

Development Phases

Workflows



Each phase is broken into multiple iterations

Overall Approach

- Consider All Systems in an Integrated / Interactive Manner
- For Each System, Employ State-of-the-Art Design / Performance Tools
  - AOA
  - Preliminary Design
  - Final Design
- Link the Tools with a Robust Framework
  - Allows Rapid Data Exchange
  - System and Subsystem Toolboxes Easily Exchangeable
  - Expandable
- Employ Optimizer
  - Several Approaches Available

AOA, Preliminary Design, and Final Design

<u>AOA</u>

- Define Best Combination of Systems to Perform Specified Mission(s) with Given Constraints and Goals
  - Simple, Fast, but Accurate
  - Numerous Iterations
  - Tradeoff System Concepts
  - Determine Gross Characteristics (size, arrangements, speed, etc.)
  - Downselect

<u>Preliminary Design</u>

- Tune Subsystem Characteristics
  - Higher-fidelity Tools
  - Limited Iterations

<u>Final Design</u>

- Define Subsystem and System Details
  - Predict Final Performance
  - Precise Tools
  - No Iterations (hopefully)

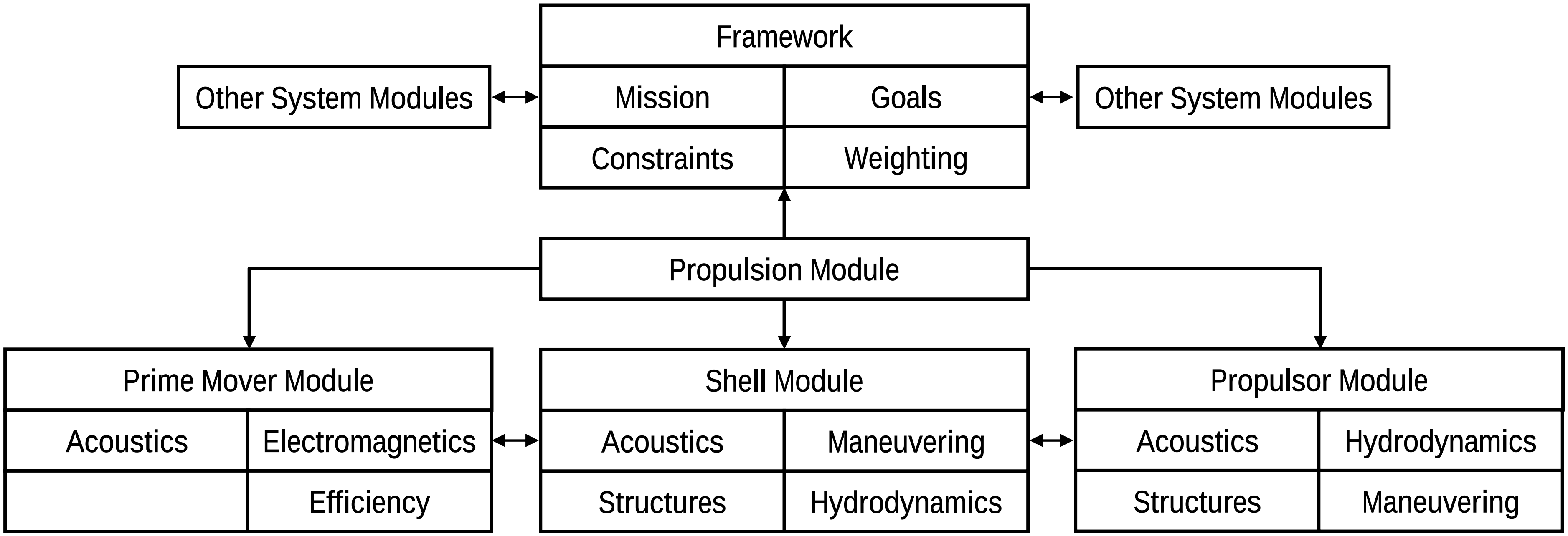
Cost is a Big Driver

Typical Systems (unmanned underwater vehicle)

- Guidance and Control
- Energy
- Payload
- Navigation
- Propulsion
- Communication
- Shell

Propulsion Subsystems

- Prime Mover
- Gears (?)
- Shaft
- Propeller


Framework
Mission
Goals
Constraints
Weighting
Other System Modules
Other System Modules
Propulsion Module
Prime Mover Module
Acoustics
Electromagnetics
Efficiency
Shell Module
Acoustics
Maneuvering
Structures
Hydrodynamics
Propulsor Module
Acoustics
Hydrodynamics
Structures
Maneuvering

Several Approaches are Being Developed

Consider Two of Those Approaches as Examples

- Synthesis of Naval Architecture Concepts (SNARC)
  - Being Developed by NUWCDIVNPT
  - Part of Multidisciplinary Design Optimization (MSDO) Program
  - Sponsored by K. Ng, ONR 332
  - Focused on Weapons and UUVs
- *FlagShip Designer*
  - Developed but Being Expanded by Proteus Division, Alion Science and Technology
  - Legacy Code Developed with Internal Funds (commercial applications)
  - Expansions Sponsored by NAVSEA and ONR (military applications)

MSDO

- Objective
  - Develop Capabilities for Design Analyses, Evaluation, and Optimization
  - Reduce Total Ownership Cost
- Approach
  - Implement and Integrate Computational and Design Tools
  - Develop Distributed Design and Virtual Environment for Prototyping
  - Incorporate Silencing and Propulsion Efforts
- Payoff
  - Design Infrastructure, Analysis Tools, and Concepts That Support Affordable Undersea Weapons

MSDO (Cont’d)

- Major Performers
  - NUWCDIVNPT
  - ARL / PSU
  - NSWC-CD
  - NSWC-IH
  - SAIC
  - Alion Science and Technology
  - CDI
  - Barber-Nichols
  - Fuel Cell Energy
  - University of Maryland
  - Georgia Tech
  - Wright State University
  - MIT
  - University of Vermont

MSDO Impact / Metrics

- Quantify Cost Effectiveness
- Support Affordable Undersea Weapon Acquisition
  - 30% Reduction in Development Time
  - 50% Reduction in Total Ownership Cost
  - 80% Reduction in Paper Process

SNARC
NUWCDIVNPT

Reference
2006 ONR Supercavitating Torpedo and Multidisciplinary Systems Design and Optimization Workshop

20–22 June 2006
Whispering Pines Conference Center
West Greenwich, Rhode Island

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Automating the Analysis of Design Alternatives

- Assemble configurations capable of performing given missions from a list of eligible components.
  - Selectively investigate missions and/or technologies.
  - Identify opportunities for improvement: what-if studies.
- Size selected components.
  - Focus on concept/preliminary design level-of-detail.
  - Define as few parameters as possible yet maintain fidelity sufficient to provide useful comparisons.
- “Exhaustively explore all possibilities.”
  - Actually, study good while weeding out bad configurations.
  - Therefore, find configurations in order from most desirable to least desirable.
- Optimize with respect to user-defined metrics.
  - Allow specification of evaluation criteria and rankings.
  - Assist in design selection.

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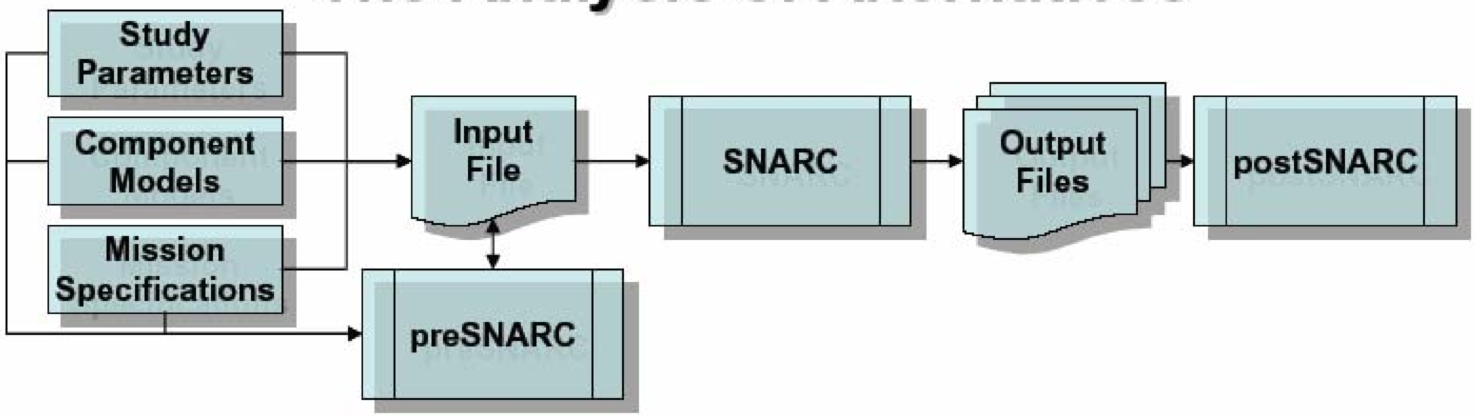
Process to Automate
The Analysis of Alternatives

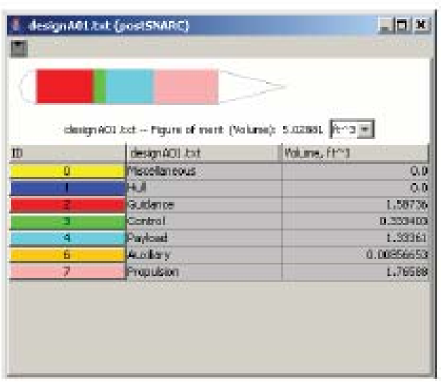


Input

ObjectiveFn1: mxVal1, ranking1
…
ObjectiveFnN: mxValN, rankingN

Battery, Electrical, Engine, Environment, Fuel, Fuel Cell, Gearbox, Hull, Join, Misc. Mach'y, Motor, PowerSink, Section, Sensor, Split, Thruster

Payload: weight, volume, power
Leg1: speed1, range1, depth1
Leg2: area2, depth2
…
LegN: speedN, rangeN, depthN



Output

Goal: develop practical technologies assisting vehicle designers & integrators.

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Usage Samples

- Choose among technology sets.
  - Simultaneously activate various propulsion and energy components (e.g. electric and thermal).
  - Best configuration will depend on mission parameters.
- Play technology "what-if" games.
  - Compare today's technologies with estimates of tomorrow's (e.g. activate battery models with 100%, 110% and 120% of today's energy densities).
  - Provide guidance for research investment.
- Show how tactics influence design.
  - E.g. activate sonar models with varying search speeds.
  - Results will reflect trade-offs between time and energy required to search a given area of uncertainty (AOU).

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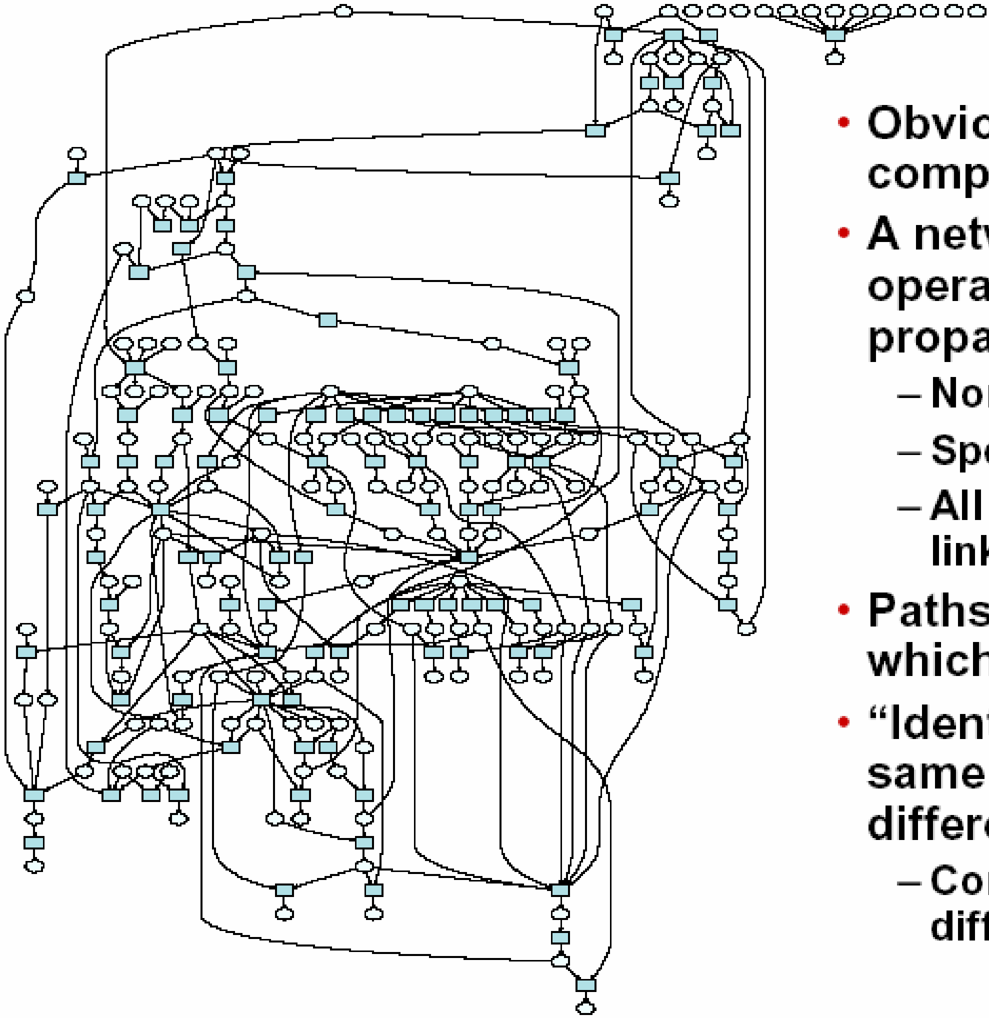
Constraint Network: Complete Design



- Obviously, complete designs are complex.
- A network has values (ovals), operators (boxes) and information propagation paths (arrows).
  - Normal: value→operator→value.
  - Special: operator→operator.
  - All values/operators may not be linked even indirectly.
- Paths are dependent on the order in which values are defined.
- “Identical” designs may have the same values and operators, but different propagation paths.
  - Components may be added in different orders.

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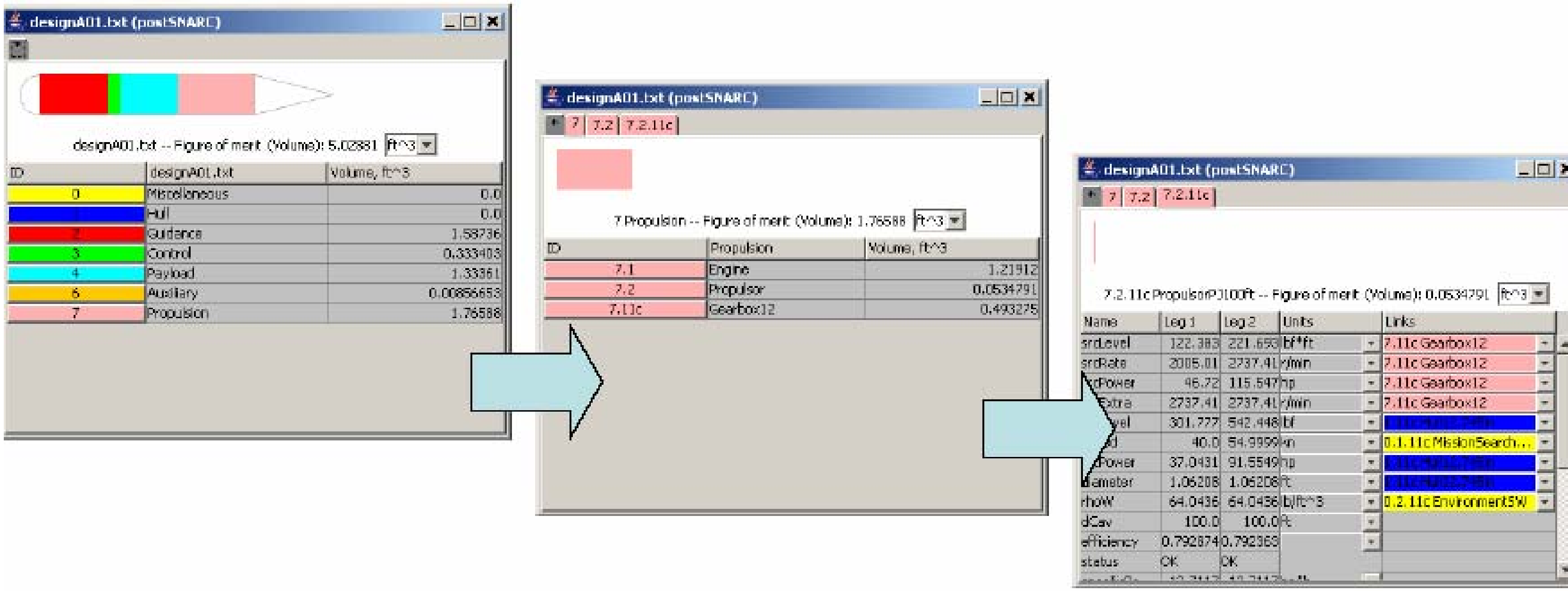
Post-Processing: postSNARC

Department of the Navy ONR Science & Technology



- This tool creates a more understandable representation of the previous constraint network.
  - A schematic of the completed design configuration is presented.
  - Components are placed into categories and subcategories.
  - Each window provides progressively more detailed information on the category and/or component.

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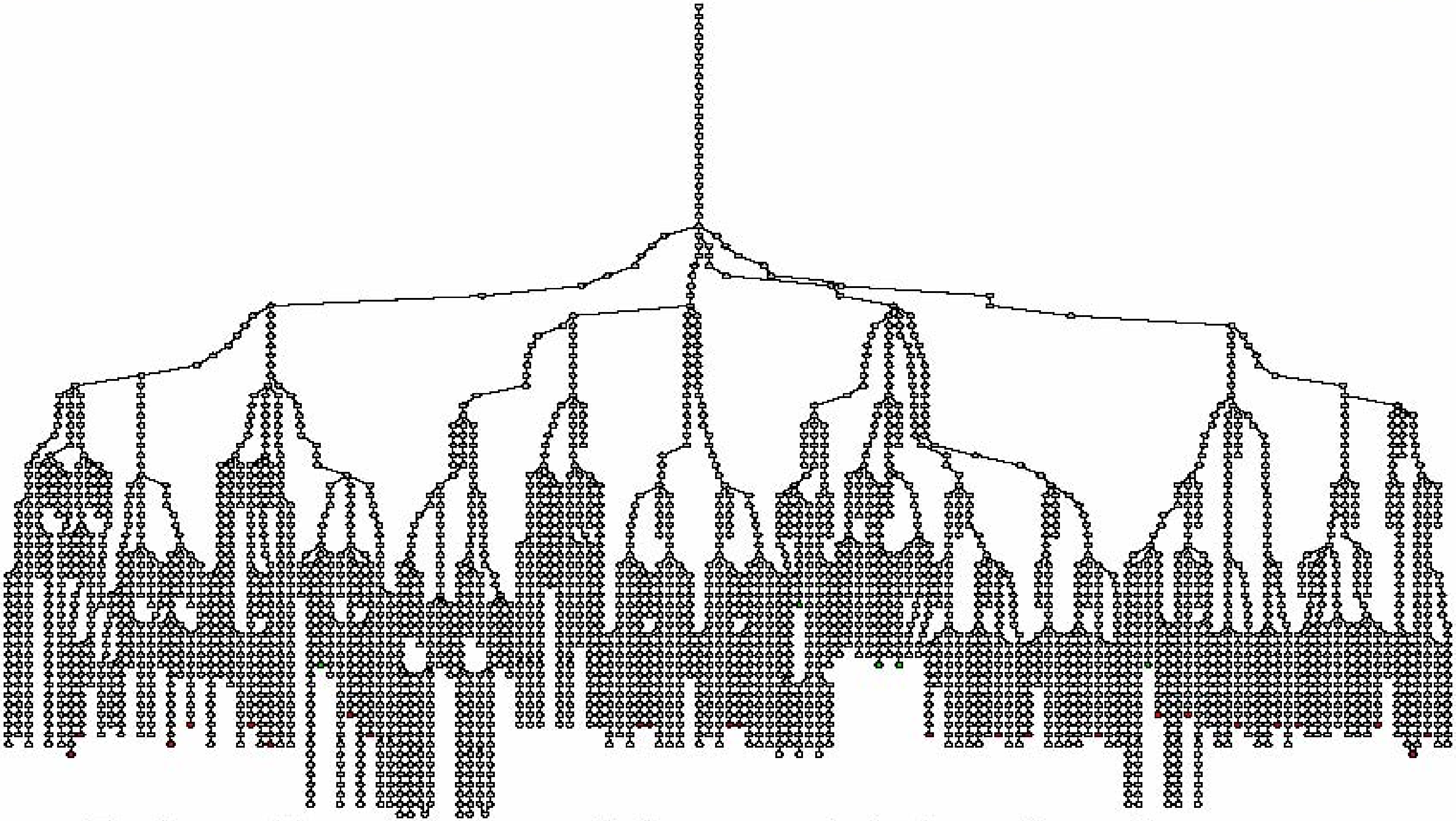
Configuration Decision Tree



- Each oval is a unique partial or completed configuration.
- LWT mission + 14 eligible components (small study), 226 threads (i.e. branchings), 6 complete designs, 14 second total runtime

FlagShip Designer

Proteus
Alion Science and Technology

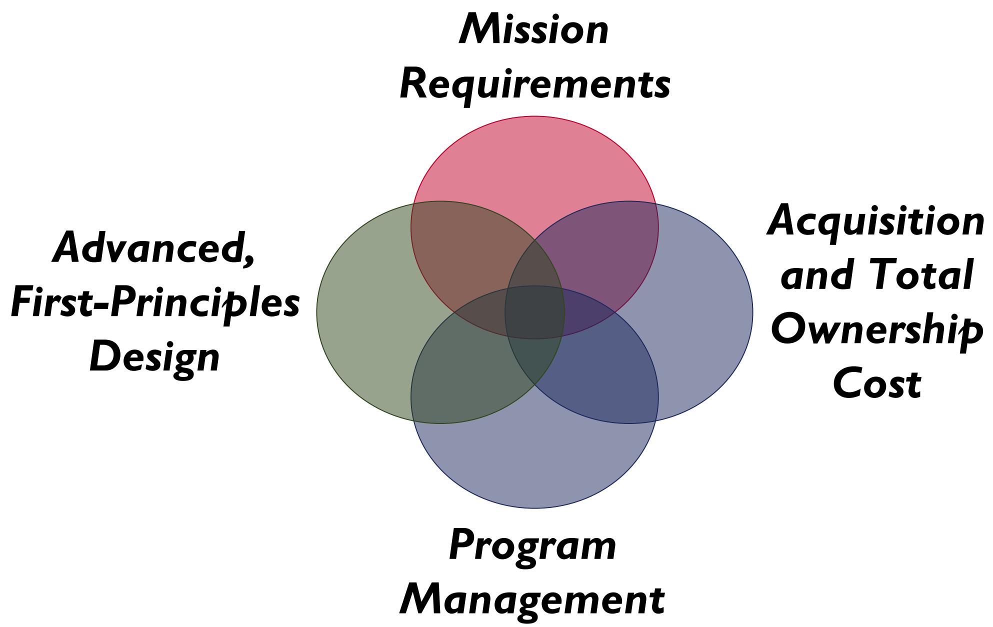
FlagShip Designer Smart Product Model Vision

- A Legacy Commercial Code for Surface Ship Naval Architecture Design
  - Optimization Capabilities Currently Being Included
- An Extensible and Scalable Framework in Which to Integrate Naval Architecture and Related Disciplines
- A Smart Product Model (SPM) Implementation Within the Larger Context of an Integrated Data Environment (IDE)
  - Integration with the U.S. Navy's LEAPS
- Open Architecture to Allow Users to Extend Designer with Their Own Applications and Components
  - Allow and Encourage Third-party Components by Providing a well-defined API
- Focus on Early-stage Design and Analysis
  - Bias Architecture and Implementation Toward Engineering Performance Rather than Toward High Levels of Concurrency
- Cost Component Included

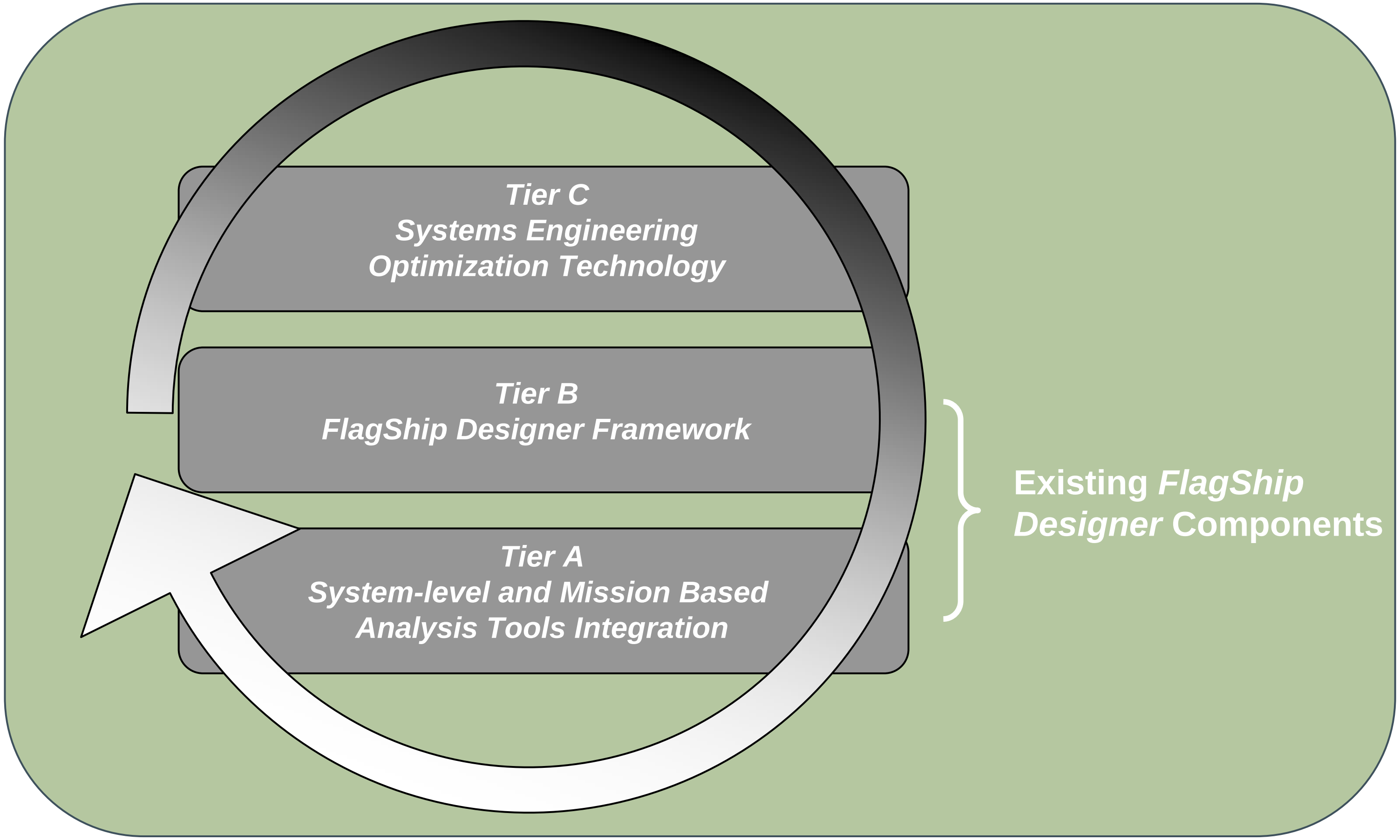
Design Integration Through *FlagShip Designer*

- *FlagShip Designer* Provides a Computer-based "Toolset" to Accurately, Simultaneously, and Efficiently Explore the Full Range of:
  - **Mission Requirements**
  - **Design Options**
  - **Candidate Technologies**

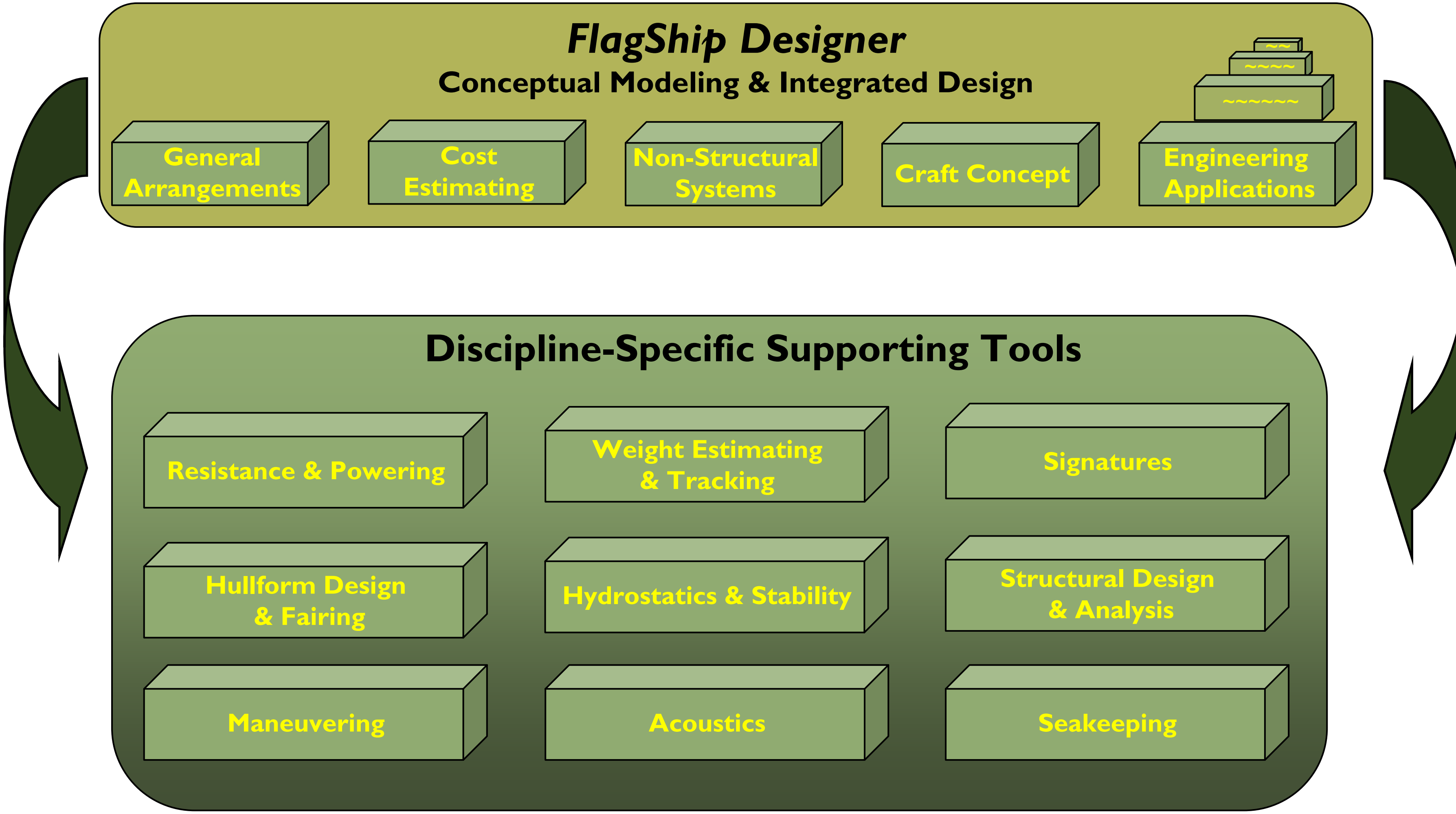
- Enables effective Design Space exploration using first principles
- Generates real-time, accurate cost estimates
- Shortens design/cost iteration cycle time
- Improves design/cost iteration accuracy
- Implements design spiral process evolving from concept through preliminary, contract, and detail design phases



FlagShip Designer's Advanced Engineering Infrastructure Enables Multidisciplinary Optimization



Design Integration Through *FlagShip Designer*



Acoustics in Commercial World

- Cruise Ships – Habitability
  - Machinery Vibration
  - Propulsor-induced Aft Hull Vibration
- General
  - Fatigue Due to Vibration
  - Cavitation Damage – Propellers, Rudders, *et al.*

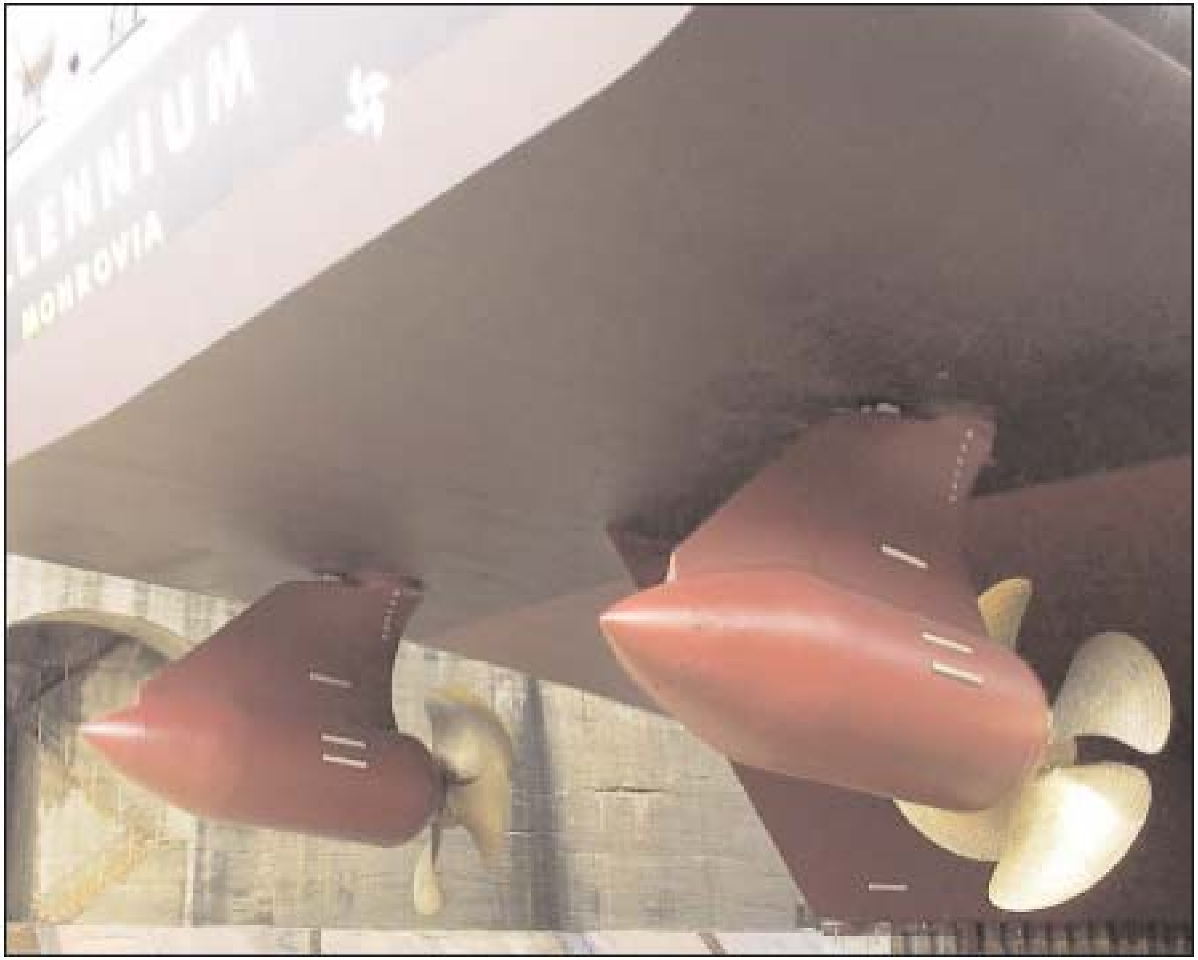
Acoustic Implications of Cost-driven Design and Optimization

- Viable Tools for AOA-level Studies – Near Term
  - Robust
  - Fast, Inexpensive to Implement and Execute
  - Verification, Validation
- Integrated with Other Performance Areas at the Component Level, i.e., for a Propulsor
  - Hydrodynamics
  - Shock / Structures
  - Materials
- Integrated at the System Level, i.e., for a Propulsion System
  - Hull
  - Shafting
  - Prime Mover
- Integrated at the System-of-Systems Level, i.e., the Entire Vehicle

Innovative Concepts

Advanced Podded Propulsor Concepts Commercial Cruise Ships

Typical Podded Propulsors Mounted on a Commercial Cruise Ship



Features Compared to Internal Motor with Shaft

- Motor, Shaft, Bearings, etc., in Hub External to Hull
  - Eliminates External Shaft and Strut Drag and Wakes
  - Eliminates Shaft, Bearings in Hull
- Pods Azimuth for Thrust Vectoring
  - Eliminates Rudder and Ancillaries
  - Better Low Speed Control
  - Allows Docking without Tugs
  - Improved Backing Performance
- Location and Type of Propulsor Flexible
  - Tractor (Puller)
  - Pusher
  - Single vs. Co-rotating vs. Counter-rotating Propellers

Why Pods?

- Reduced Construction Time / Cost
  - Pod and Hull Independently / Simultaneously Fabricated
- Hull Internal Arrangement
  - Moving Motor and Shaft to Pod Allows More Cabins Aft
- Improved Efficiency Reduces Operating Costs
- Higher Speeds Possible; Therefore, More Trips Possible
- Easier, Faster Repair
- Improved Cavitation Performance; Therefore, Less Damage
- Reduced Hull Vibration; Therefore, Less Fatigue

Pods are Cost Effective

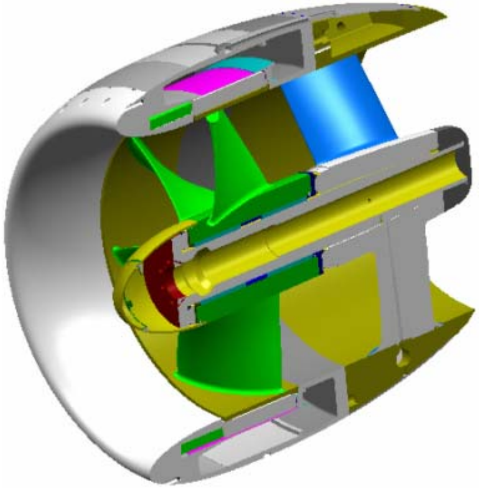
Pod Issues

- Initial Issues with Bearings, Seals, and Stress Cracks Have Apparently Been Solved
- Weight Aft : Ship Balance OK
- Propeller / Support Strut Interaction : Cavitation and Vibration Affected

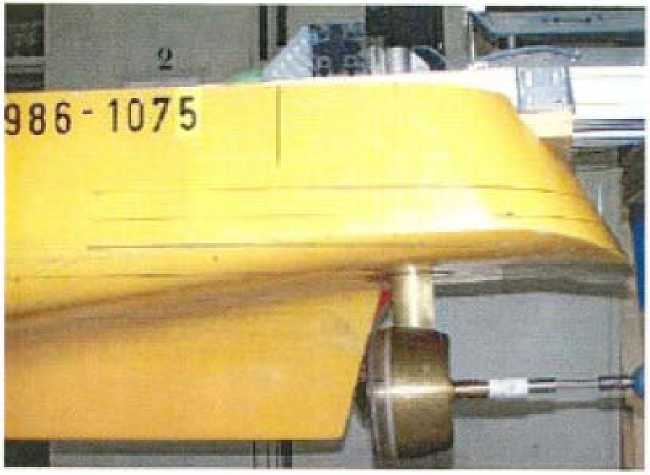
Pods are Cost Effective

Next Generation Pods for Commercial Cruise Ships?

EB Rim Drive Pods for Commercial Cruise Ships



Patents Pending



References

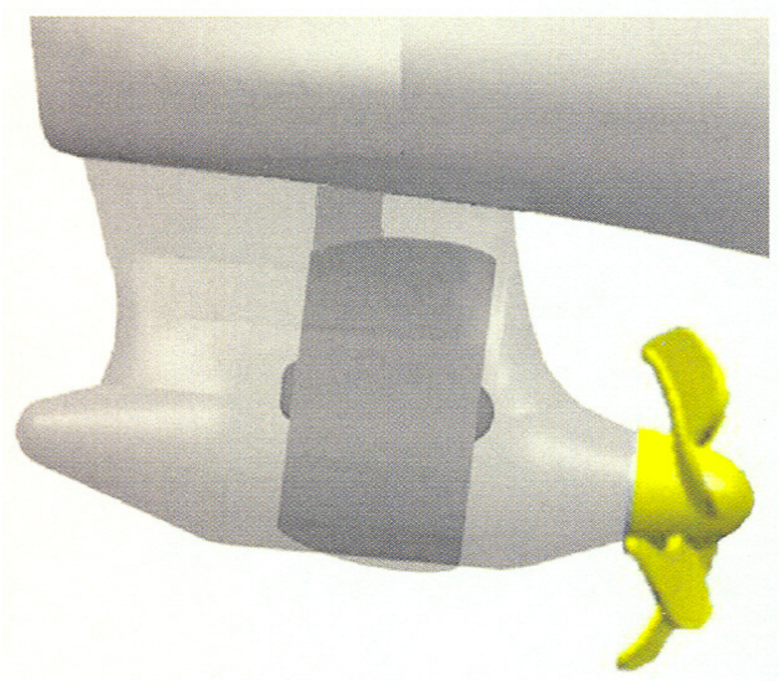
1. **Van Blarcom, Bill, *et al*., "The Commercial Rim-Driven Permanent Magnet Motor Propulsor Pod," *ShipTech 2003 Proceedings*, Biloxi, MS, January 2003.**
2. **Lea, M., *et al*., "Scale Model Testing of a Commercial Rim-Driven Propulsor Pod," SNAME J Ship Production, Vol. 19, No. 2, May 2003.**

Features Compared to Existing Pods

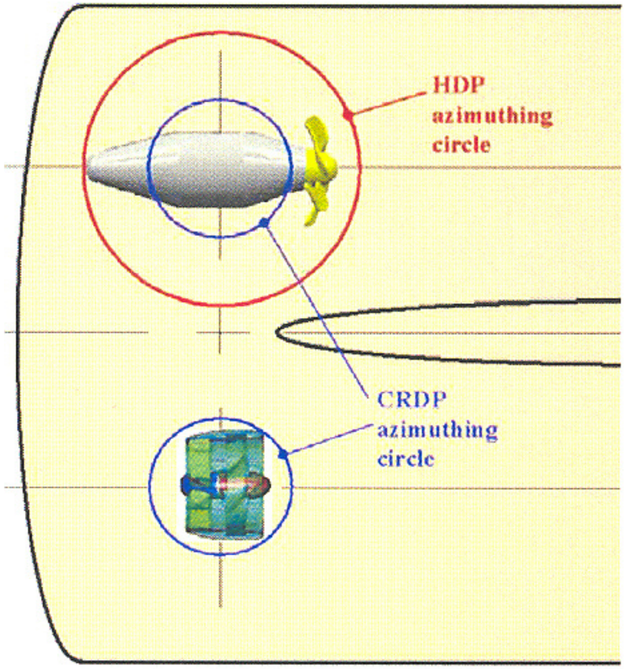
- Integrated Motor and Propulsor
  - Permanent Magnet Motor
  - Ducted Propulsor
  - Motor Stator Integral Part of Duct
  - Motor Rotor on Rim Attached to Rotating Blade Tips
  - Stationary Blades Remove Flow Swirl and Provide Structural Support
- Pods Azimuth

Why Rim Drive Pods?

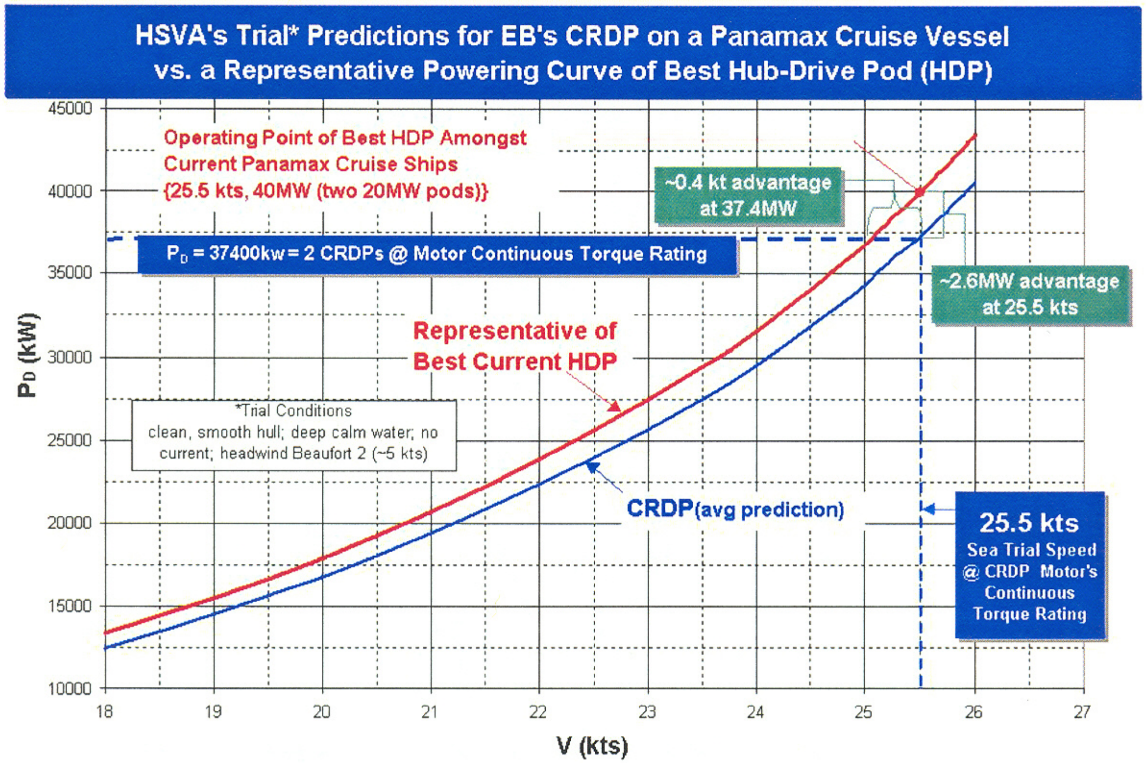
- Gain All Benefits of Existing Pods with Further Improvements in:
  - Efficiency
  - Speed
  - Cavitation (ahead and in turns)
  - Hull Vibration
- Eliminates Motor Cooling Requirements
- Smaller
  - Diameter About the Same as Existing Propeller
  - Much Shorter
- Reduced Weight
- No Propeller / Strut Interaction
- Hydrodynamic Benefits of Duct
- Duct Shielding of Rotor / Hull Unsteady Pressures



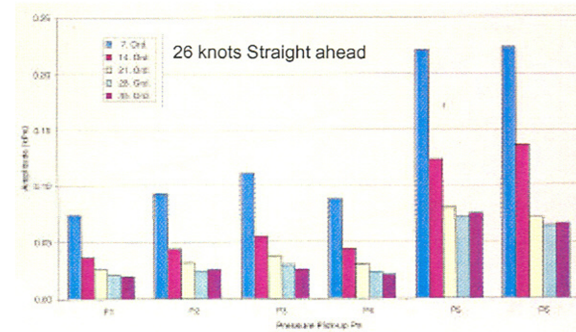
Typical ~20MW Commercial Pod vs. ~18.5MWCRDP
Shown in Relative Size (CRDP ~1/3 length)



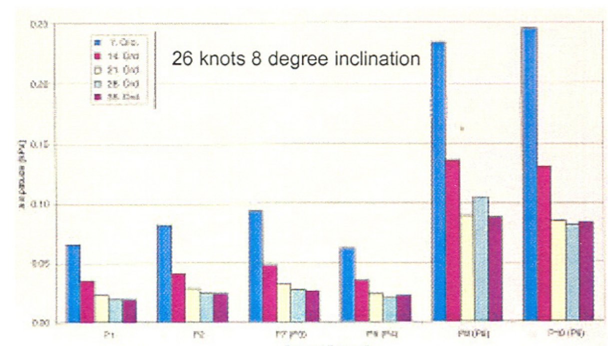
Typical Twin-Screw Panamax Cruise Ship –
Hub-Drive Pod vs. CRDP Arrangement Comparison



Behind Hull Powering Results,
CRDP vs. Good Representative Hub-Drive Pod



CRDP Operating for 26 Knots at 0°



CRDP Operating for 26 Knots at 8°

Hull Unsteady Pressures
(at least 1/5 the levels of existing pods)

Flexible Composite Propeller

AIR Fertigung-Technologie GmbH
Hohen Luckow, Germany

1. **Internet**
2. **Company Brochures**
3. **Personal Communications**

Objective and Approach

Objective

- Provide a Commercial Propeller with Improved Efficiency and Cavitation, Thereby Reducing Operating Cost and Ship Vibrations

Approach

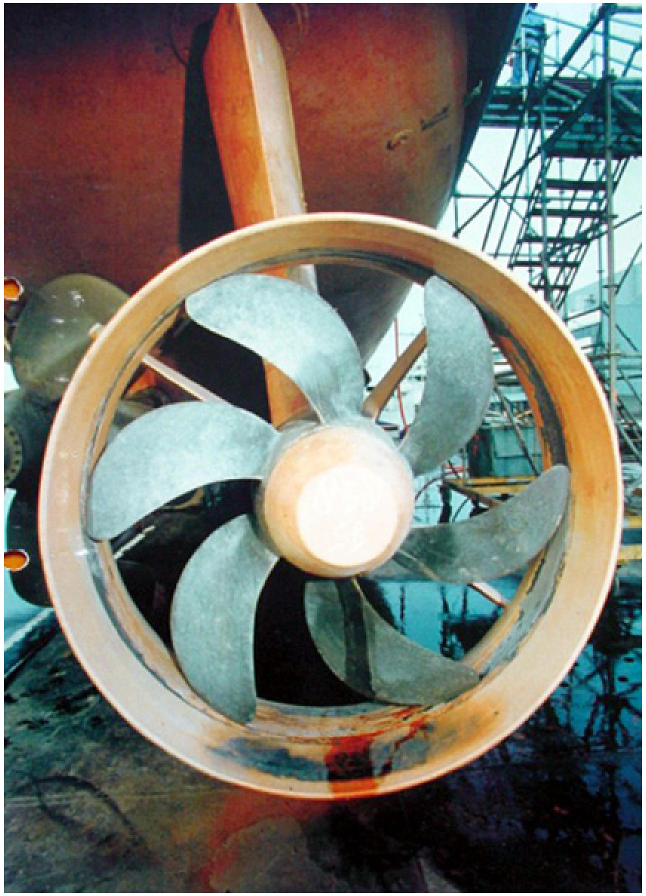
- Employ a Composite Material for the Blades
- Exploit the Tailorability of Composite Materials
- Design the Blades to Flex, so That They Operate on or Closer to Design

Straightforward, Simple Idea

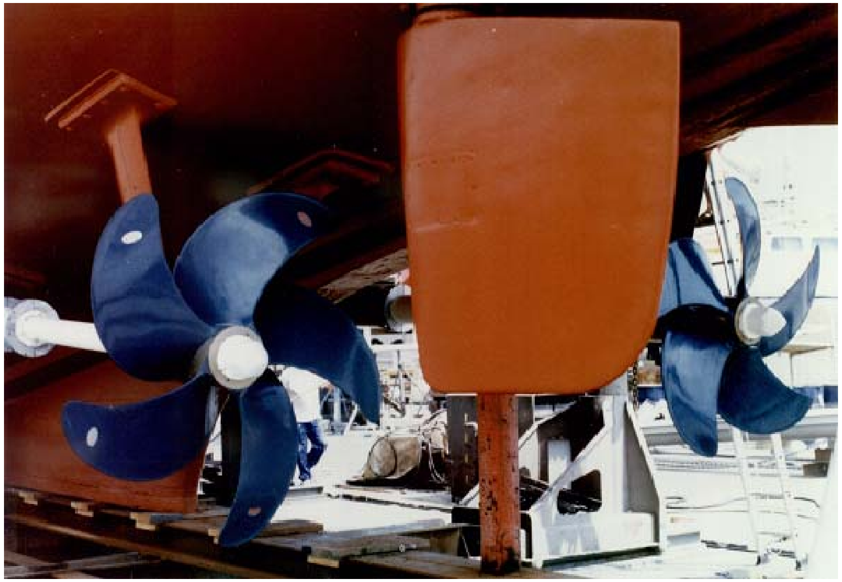
Design Strategy

- A Surface Ship Propeller Typically Operates in a Non-uniform Flow Field due to:
  - Shaft Angle → Circumferential Velocity Non-uniformities
  - Partial Ingestion of Hull Boundary Layer → Axial Velocity Non-uniformities
- Due to Surface Ship Hull vs. Wave Drag, Propeller Operating Point is not Constant
- Standard Metal Propeller Design Approach
  - Design to Spatially Averaged Inflow Field
  - At the Ship Speed Having Most Resident Time
- As Blades Operate in the Non-uniform Flow Fields and at Varying Operating Points, the Blade Angle of Attack Varies, Resulting in Blade Unsteady Pressures (lift)
  - Adverse Impact on Cavitation Performance (aft hull vibration)
  - Adverse Impact on Efficiency (operating cost)
- Flexible Composite Propeller Design Approach
  - Design to Spatially Averaged Inflow Field at Target Ship Speed
  - But Design Blades to Bend and Twist due to Varying Lift so That Varying Lift is Mitigated
  - Average and Varying Lift on Blade is Provided by Hydrodynamic Design
  - Blade Material Tailoring Used to Provide Required Bend and Twist
- Specifics
  - Carbon Fiber Composite Material
  - Blades Fabricated Individually, Then Mounted to Metal Hub

Sample At-sea Installations

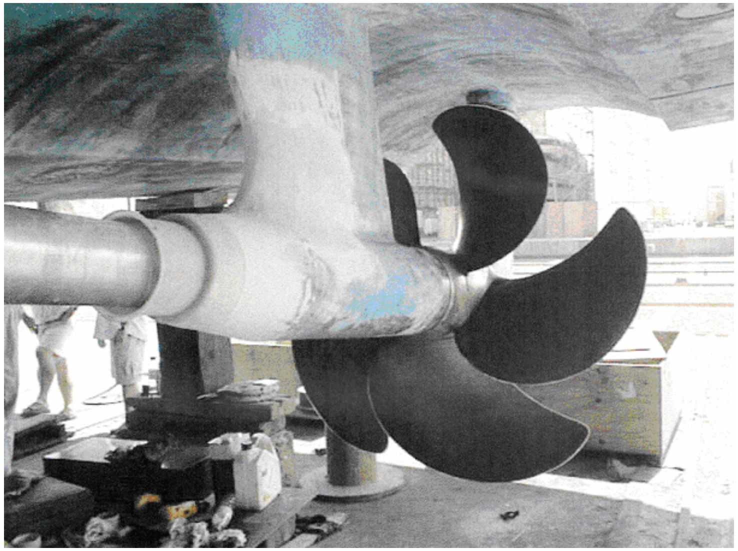


Contur® Carbon Fiber Propellers Fitted on a Mine Hunter of Netherlands Navy



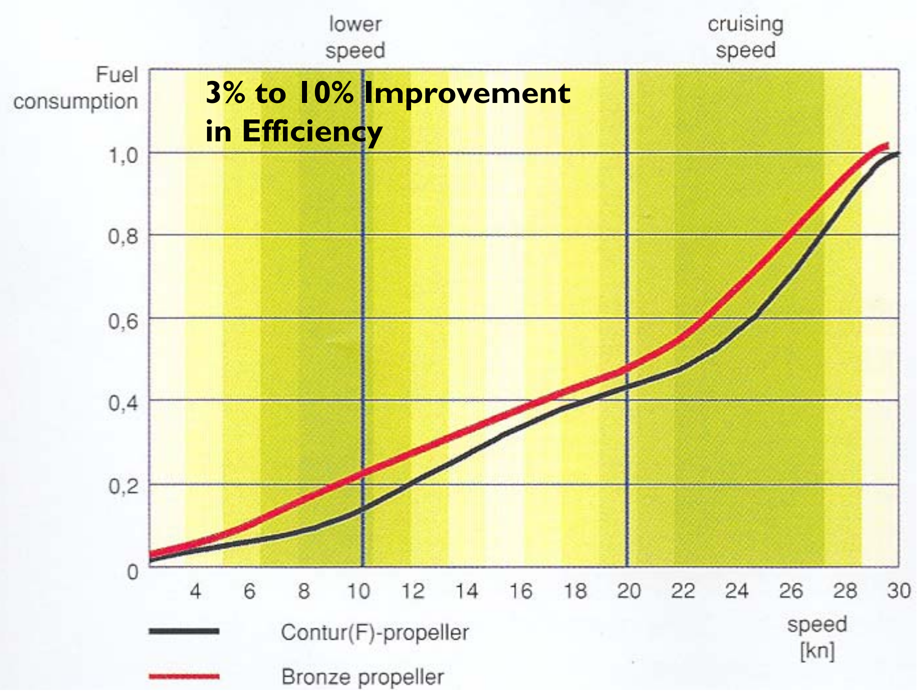
M/Y "Calisto" – The Sister Vessel of Jacques Cousteau's "Calypso" Fitted with Contur® Propellers

M/Y "Red Sapphire" – Dubai During Survey in Dubai Dry Dock



Contur® is the trade name for AIR's composite propeller.

Flexible Composite Propeller Benefits



Benefit of Improved Efficiency (reduced cost)

Per-unit Cost Comparable to Metal but Depends on Total Number Made (mold amortizement)

<u>Other Cost-saving Attributes</u>

- If Damaged, Individual Blades can be Replaced (even underwater)
  - No Drydocking
- Weight Reduction (25% to 35% of metal propeller)
  - Less Stress on Shaft, Bearings, and Stern
- Improved Acceleration (on design operation)
  - Less Fuel
- Reduced Stern Vibration
  - Less Fatigue Damage
- Fabricated Using High-precision Mold ("identical blades")
  - Less Effort in Balancing
- Corrosion Resistant (material characteristic)
  - Less Corrosion Protection
  - No Cleaning, Repair, Replacement
- Anti-fouling Coating
  - No Paint
  - No Cleaning
- Impact Resistant (material tailoring)
  - Less Damage, Repair, Replacement
- Improved Cavitation Performance
  - Less Cavitation Damage, Repair, Replacement

Acoustic Implications of Cost-driven Concepts

- Innovation Required
  - Completely New Concepts
- Modified or New Acoustic Tools for New Concepts
- Acoustic Tools Should be Integrated with Other Design Tools
  - Hydrodynamics
  - Materials
  - Shock
  - etc.
- Systems Approach Should be Taken
- Design and Optimization Codes Should be Used

Innovative Components / Methods

Jonson, M.L.

Sound Power Reduction of Structures with Nearly Degenerate Modes by Material Tailoring

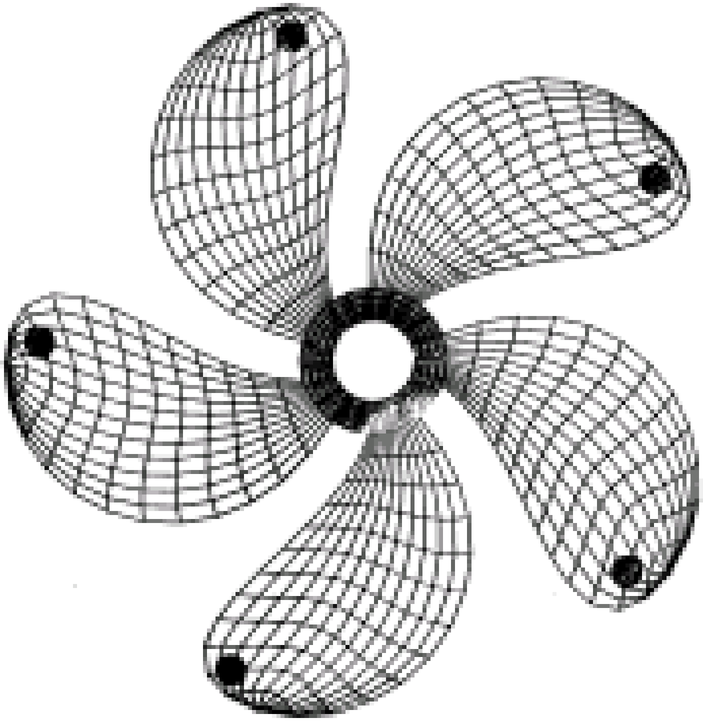
Ph.D. Thesis, Mechanical Engineering
Pennsylvania State University
December, 1998

Scope

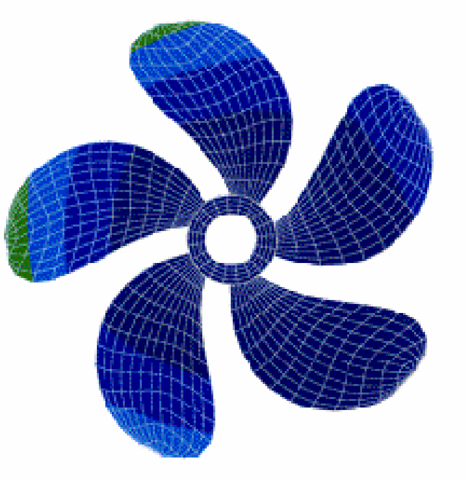
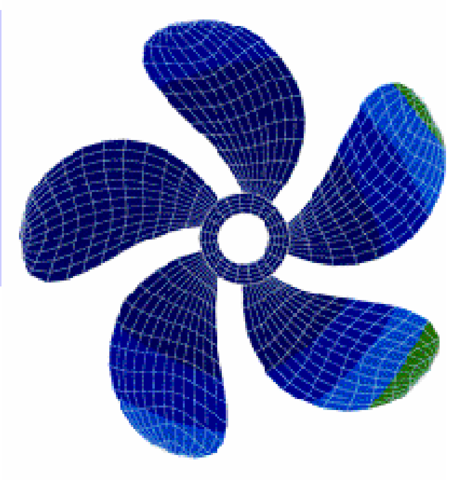
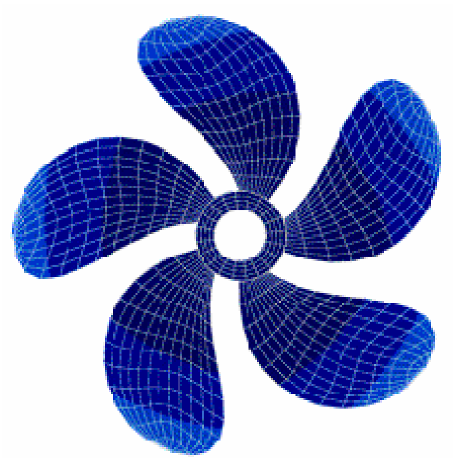
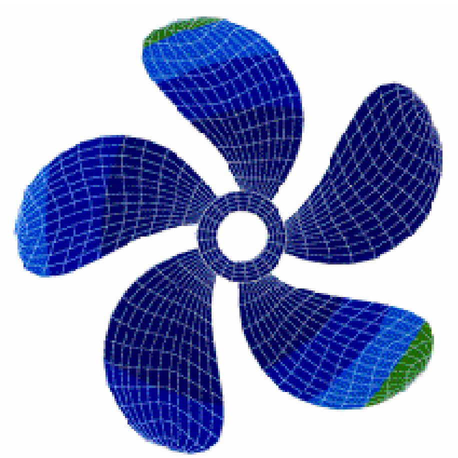
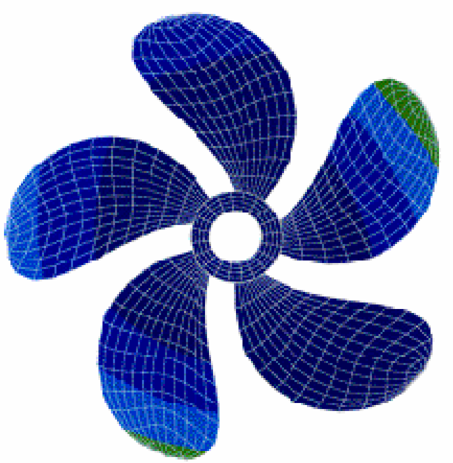
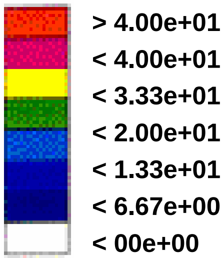
- Objectives
  - Consider the case of a propeller with a central hub surrounded by identical blades
  - Understand natural frequencies and mode shapes
  - Investigate possible radiated noise reduction by material tailoring
- Approach
  - Develop a simple analytical model of propeller for first set of modes.
  - Confirm with computational and experimental studies.

Computational Configurations

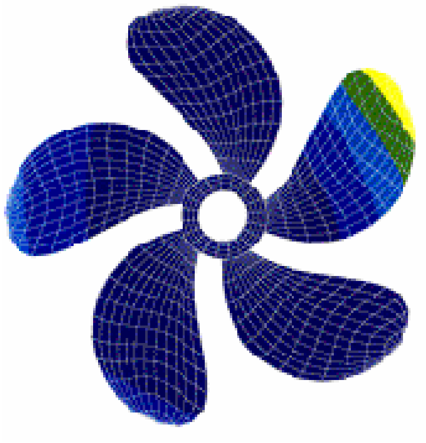
- To verify radiated sound power reduction observed from analytic study, an existing five-bladed propeller will be analyzed
  - In-vacuo with no trim masses (no sound power)
  - In water with no trim masses
  - In water with even trim masses
  - In water with uneven trim masses

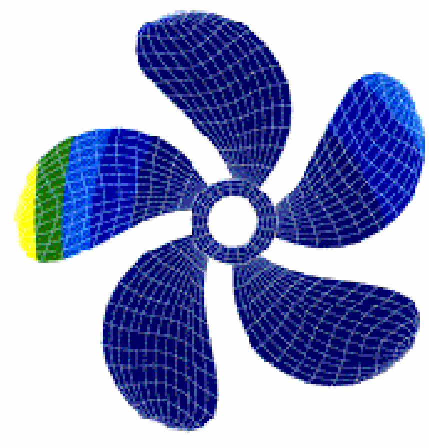


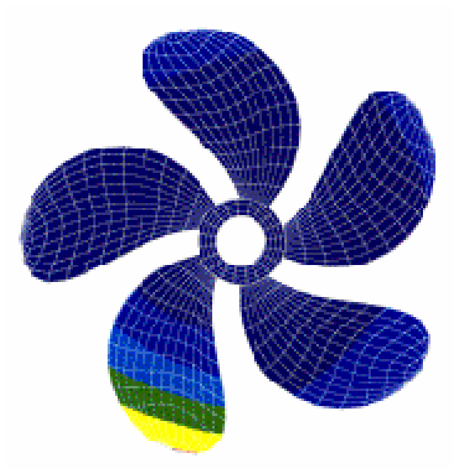
Even Trim Masses

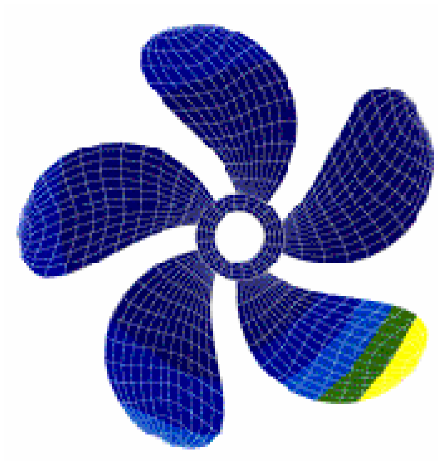







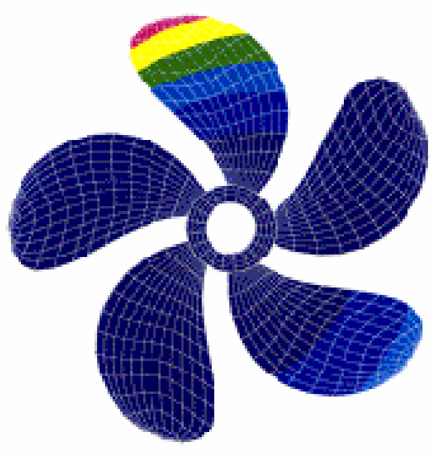
Uneven Trim Masses

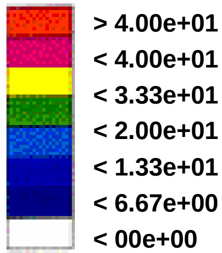






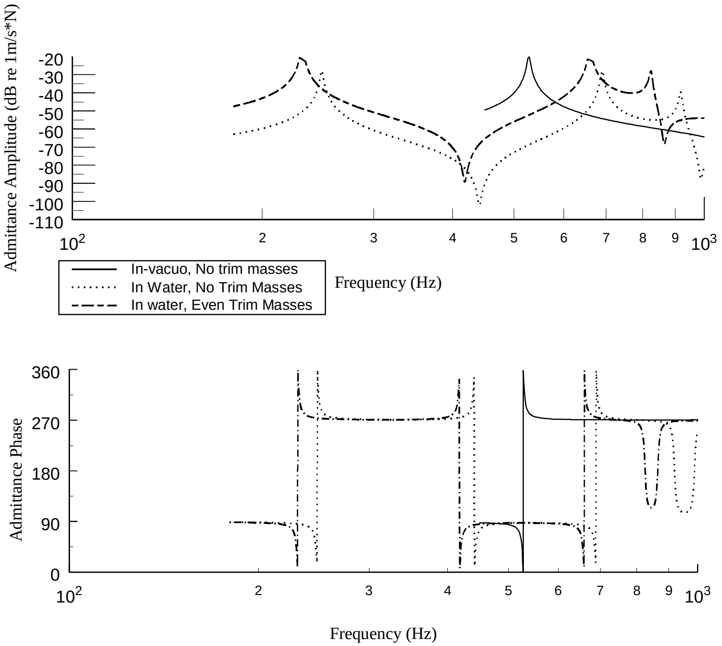






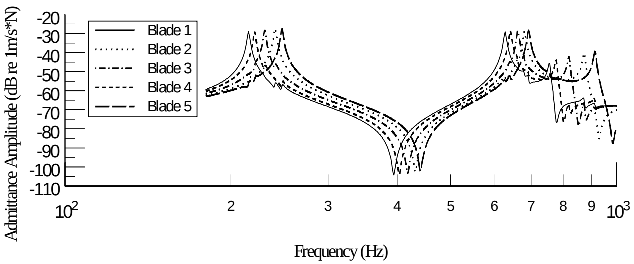
Admittance for Uniform Mass Loading

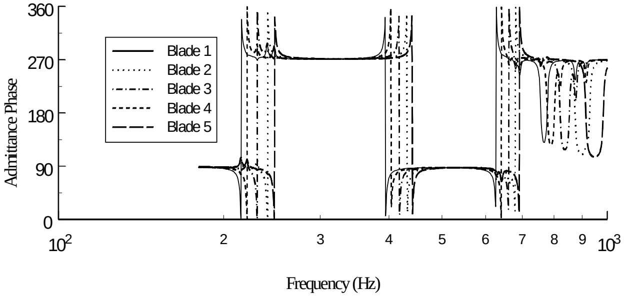
- All blades respond identically.
- Resonance frequencies scale as inversely as mass loading



Admittance for Non-Uniform Trim-Mass Loading

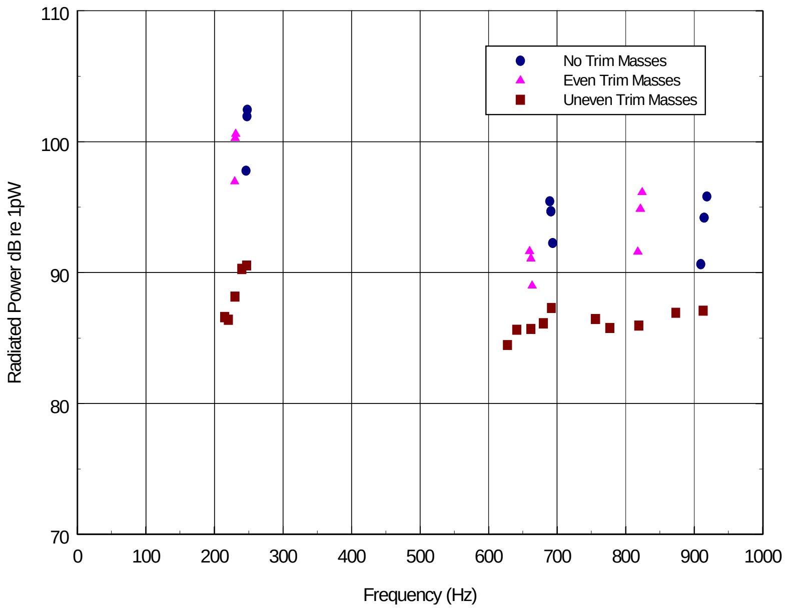
- •Response of every blade is different.
- •Phases of different blades can be 180 degrees out of phase.





Effect of Mass Loading on Radiated Power

Significant Reduction for Uneven Trim-Mass Distribution



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The Pennsylvania State University

Hydrofoil Vibration and Noise Reduction

With Leading Edge Isolation

October 19, 2005

Prepared for:
NOISE-CON 2005

Prepared by:
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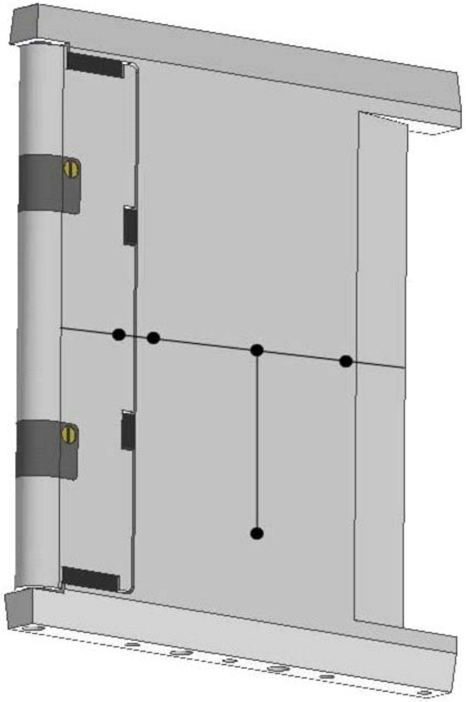

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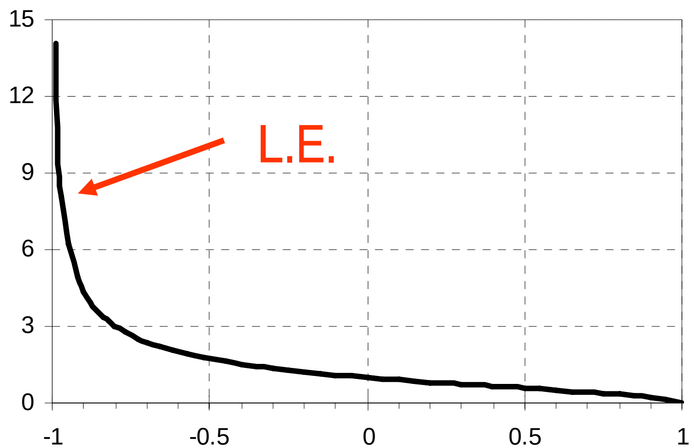
Introduction

Basic Physics – Unsteady Lift

- **Foil unsteady lift dominated by pressure differential in leading edge vicinity**
  - **Expression for pressure jump given by Sears and others**

$$\sqrt{\frac{1-x_1^*}{1+x_1^*}}$$



$$x_1^*$$

$$\Delta p'(x_1^*, k_1^*) = 2\rho_0 U_\infty \sqrt{\frac{1-x_1^*}{1+x_1^*}} v(k_1^*) S(k_1^*)$$

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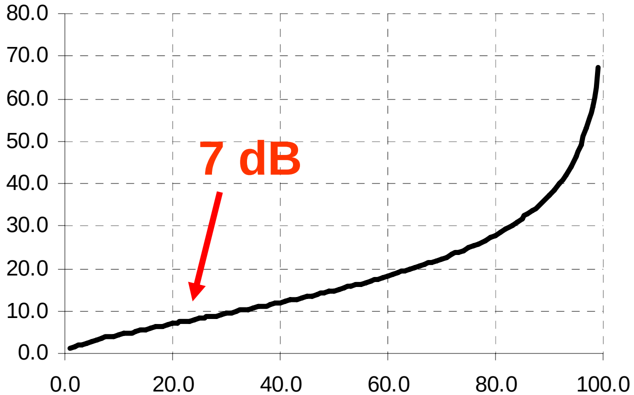
Introduction

Opportunity for Noise Control

- **Reduction of 7 dB by eliminating unsteady lift contribution of initial 20% chord**
- **Noise control can be achieved by inhibiting transmission of L.E. unsteady lift to remainder of foil**
  - **- Incorporate vibration isolation mount into foil**

$$\left|20\log\left[1-\frac{\tilde{L}(\xi)}{\tilde{L}_{Total}}\right]\right|$$



$\frac{1+\xi}{2}x100$ **(Percent Chord)**

$$\tilde{L}(\xi)/\tilde{L}_{Total}=\frac{\int_{-1}^{\xi}\Delta p'(x_1^*,k_1^*)dx_1^*}{\int_{-1}^{1}\Delta p'(x_1^*,k_1^*)dx_1^*}$$

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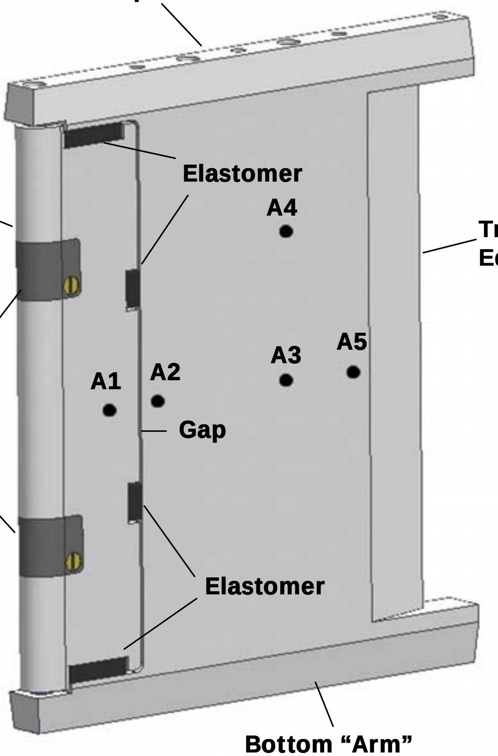
Experimental Set-up

Prototype Quiet Stator Vane

- **Designed, fabricated and tested mock-up stator with isolated L.E.**
  - **Layer of elastomer at 20% chord**
  - **Acts as single stage vibration isolation mount**
- **Instrumented with 5 accels.**
  - **A1 through A5**



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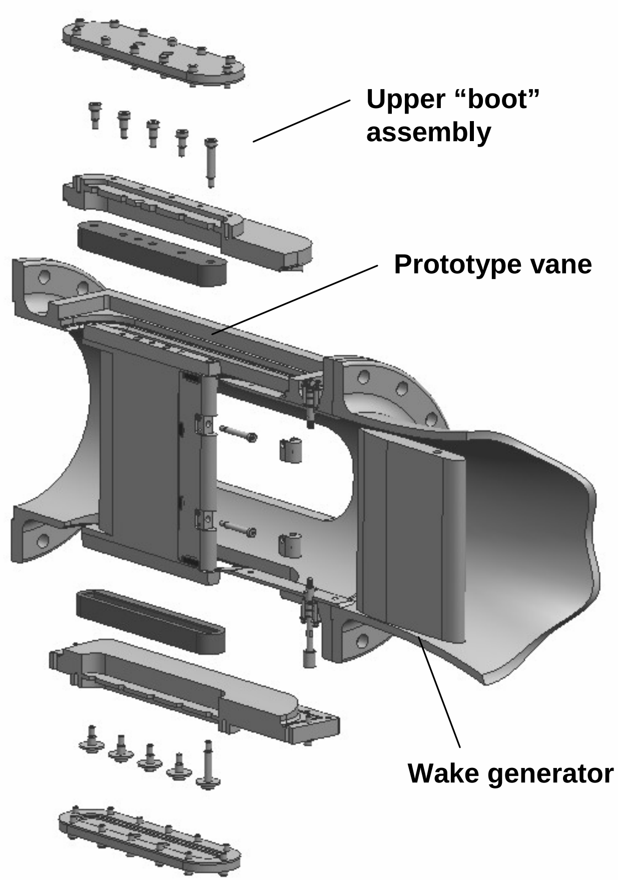
Experimental Set-up

Prototype Quiet Stator Vane in W.T. Facility

- Prototype vane at zero angle of incidence on center-line of 305 mm W.T. test section
- Prototype vane isolated from tunnel with "boot" assemblies
  - Recessed cavities 25 mm deep and lined with soft elastomer
  - Arms fit into cavities and edge of isolated L. E. fits flush with tunnel walls
- Prototype vane 50 mm downstream from wake generator
  - 17% wake generator chord



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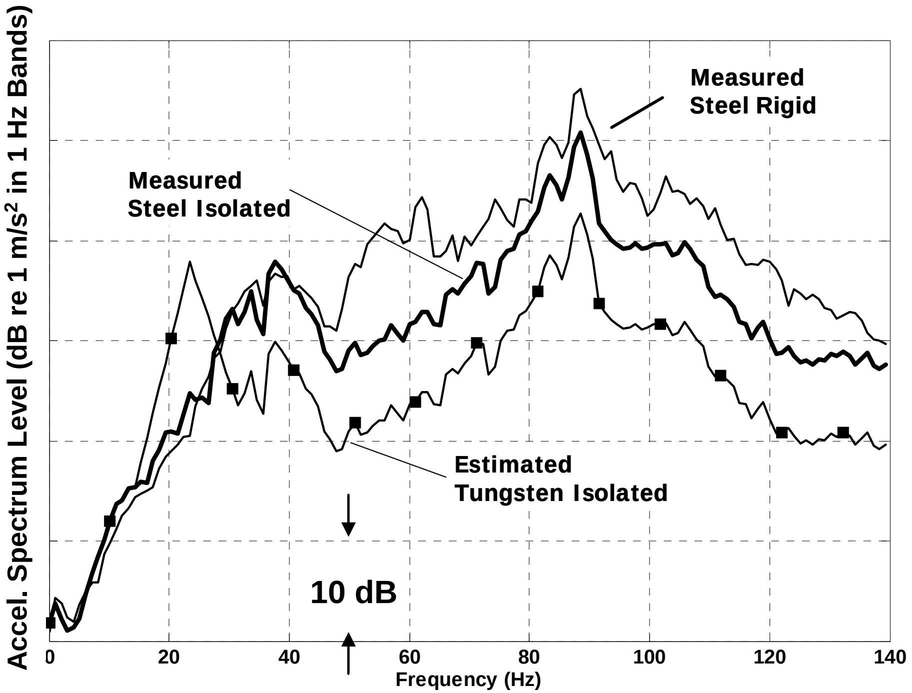
Results

Surface Averaged Vibration Levels – Isolated Portion of Vane

- Isolated steel L.E. reduces vibration levels 5 to 10 dB at frequencies above 45 Hz
- Isolated L.E. with increased density expected to reduce vibration levels approx. 10 to 20 dB at frequencies above 30 Hz
  - Lumped parameter pred.
  - Resonance shifted to 24 Hz



- All comp. attached to isolated portion of vane expected to be excited with up to 20 dB less force using vane with more dense isolated L. E.
  - Reduce vibration of components that cause discomfort and radiate noise

Quackenbush, T.R., B.F. Carpenter, and S. Gowing

Design and Testing of a Variable Geometry Ducted Propulsor Using Shape Memory Alloy Actuation

49th Aerospace Sciences Meeting
Reno, Nevada
January, 2005

Objective, Approach, and Payoff

Objective

- Develop and Demonstrate a Thrust Vectoring Ducted Propulsor

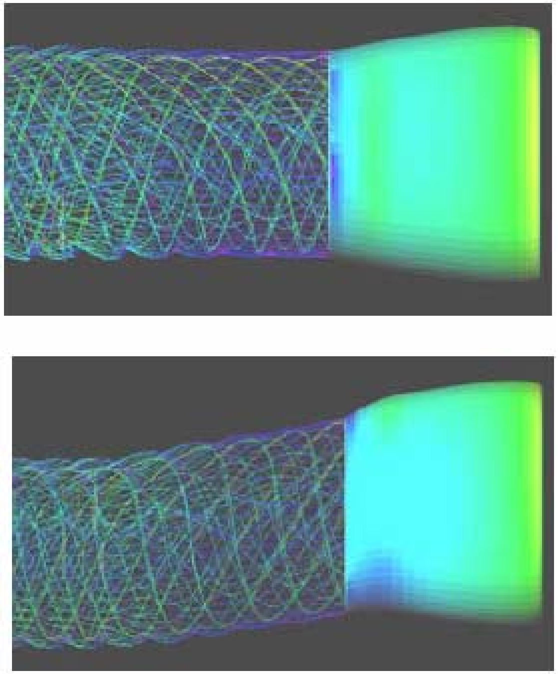
Approach

- Employ Shape Memory Alloy (SMA) Technology on Aft Portion of Duct to Direct Propulsor Exhaust Flow
- Design Model Scale Demonstrator
  - Hydrodynamics of Distorted Duct and Effect on Propulsive Performance
  - Shape Memory Alloy and Actuation Sufficient to Provide Desired Duct Deformation
- Fabricate and Test Model
  - NSWC-CD 36-inch Water Tunnel

Payoff

- Assuming Less Expensive SMAs due to Maturation and Large Orders, Potentially Less Expensive Than Rudders or Azimuthing
- Supports All-electric Approach
- Enhanced Low-speed Control
- Improved Cavitation Performance (no rudder cavitation)
- Eliminates Rudder Actuation Noise
- Reduced Weight

Side View of a Notional Smart Duct Propulsor, Showing the Undeflected (top) and Deflected (bottom) Duct Shape. Propeller Wake is Indicated by the System of Vortex Filaments Trailing from the Ducted Propeller (not shown).

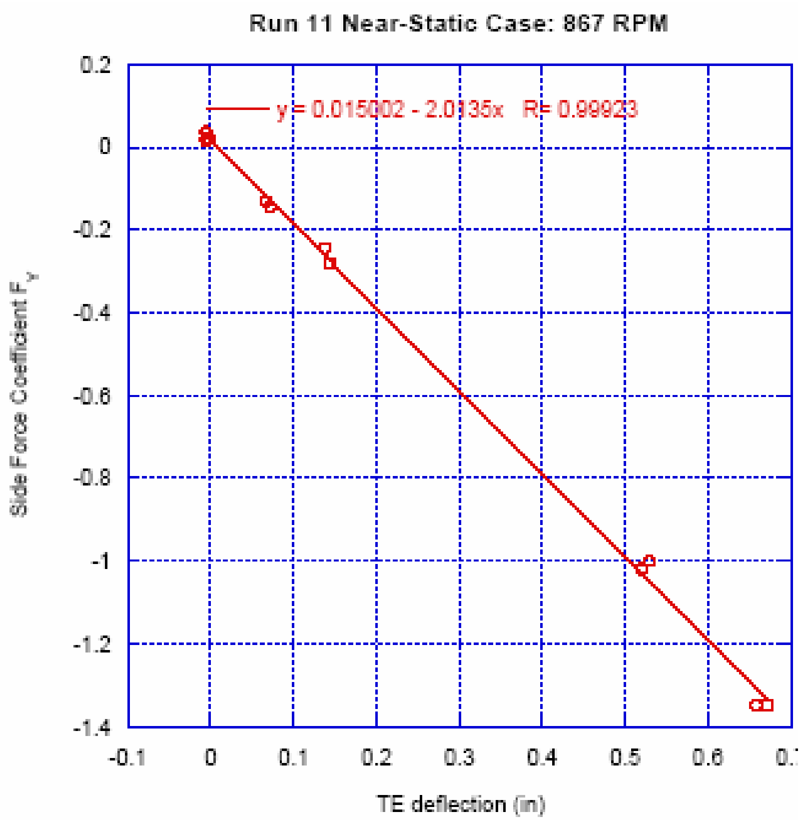


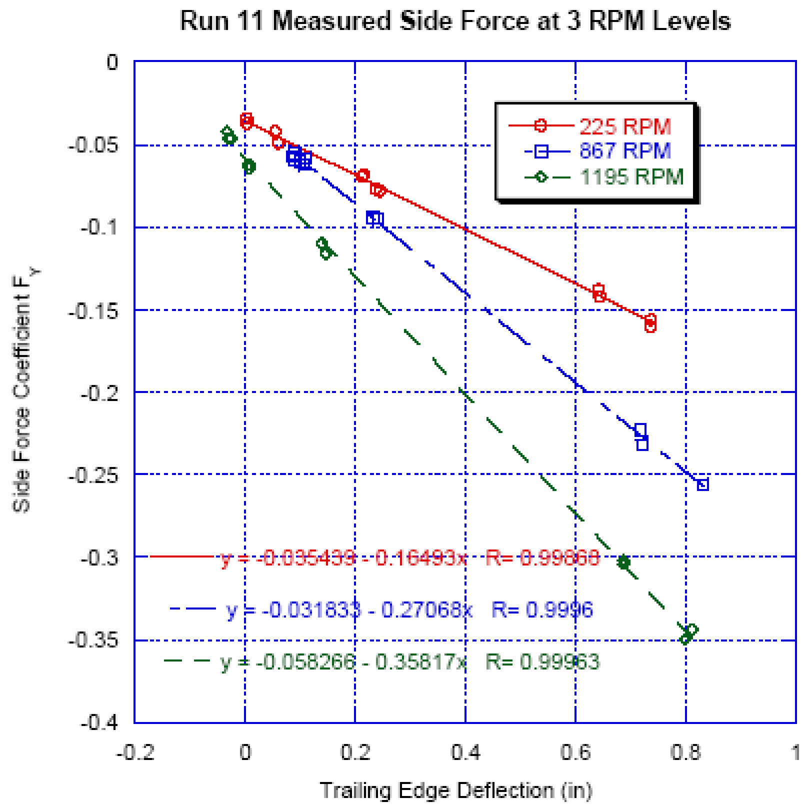
Representative Snapshots of In-water Testing of the 30-cm-diameter Smart Duct Model (without trailing edge fairing and sheathing)

a) neutral position

b) fully deflected

Side View (left) of Installed Propeller + Duct Combination; Top / Oblique View of Propeller in Duct with Deformable Sections at 0.75-inch Deflection (right)





Non-dimensional Side Force vs. Duct Deflection at 2.5-fps Tunnel Speed and 867 RPM

Side Force Coefficients Measured as a Function of Deflection for Three RPM Levels with a Tunnel Speed of 14 fps

Demonstration of High Authority Control Successful

Rogers, E.O. and J. Abramson

Selected Topics Related to Operational Applications of Circulation Control

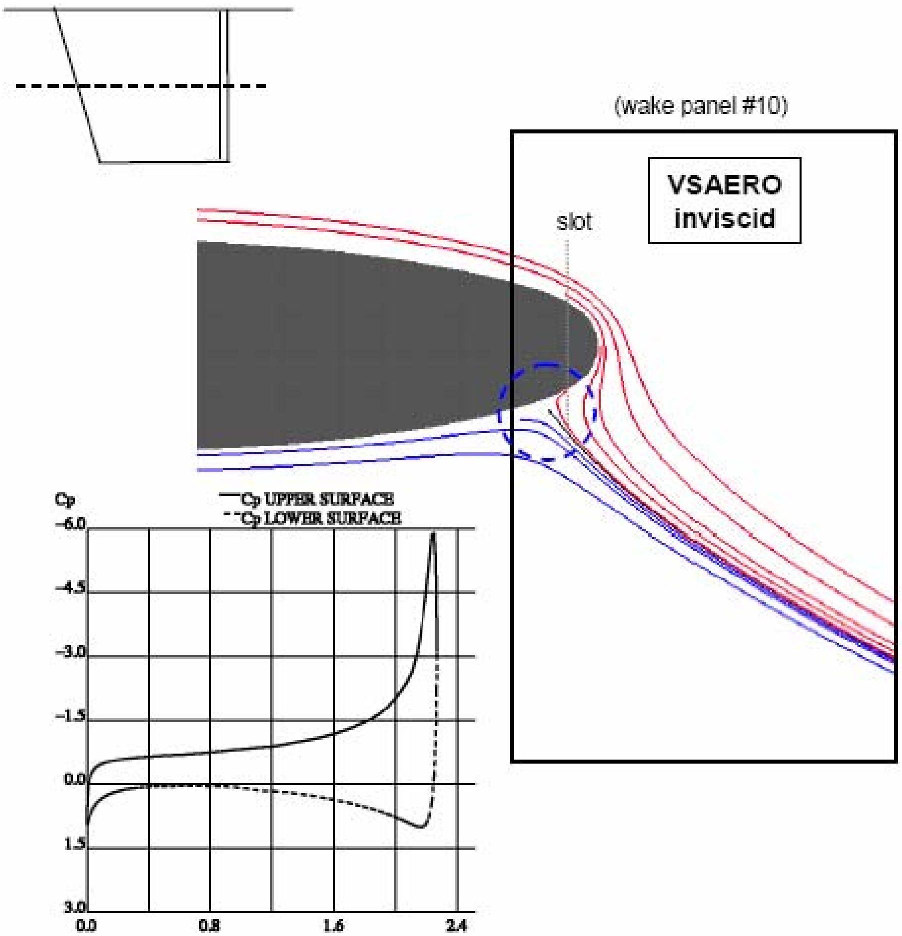
Circulation Control Workshop
NSWC-CD, Bethesda, Maryland
March, 2004

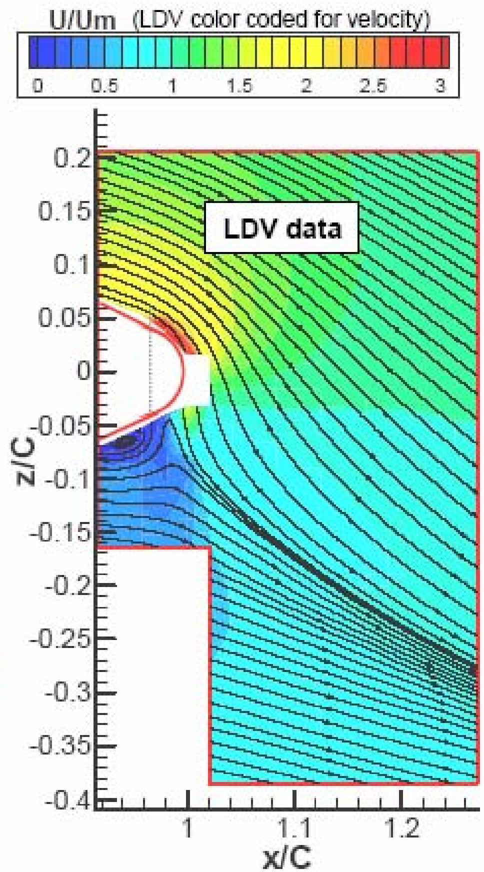
Objectives

- Consider Various Potential Applications of Circulation Control and Prediction Capabilities for Thrust Vectoring
  - Ducted Propulsor Case Considered Here
- Approach
  - Use 3-D Inviscid Panel Methods for Design and Performance Predictions
  - Circulation Control Modeled by Relocating Shed Wake
  - Test at Small Scale
- Payoff
  - Potentially Less Expensive Than Rudders or Azimuthing
  - Supports All-electric Approach
  - Enhanced Low-speed Control
  - Improved Cavitation Performance (no rudder cavitation)
  - Eliminates Rudder Actuation Noise
  - Reduced Weight

Inviscid Solution Streamlines: Comparison to LDV for same CL

C_L = 1.4, AOA =0, $C\mu$ = 0.07 (2D equivalent AOA is approx -13 deg)





CC wing (hydrofoil, 2002)
60% span location,
single slot, $C\mu$ = 0.07

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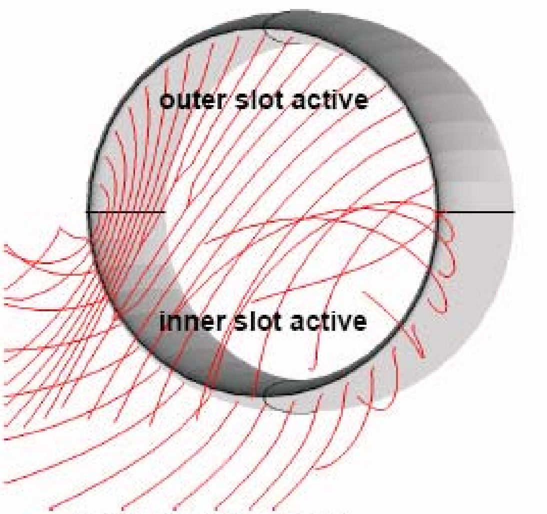
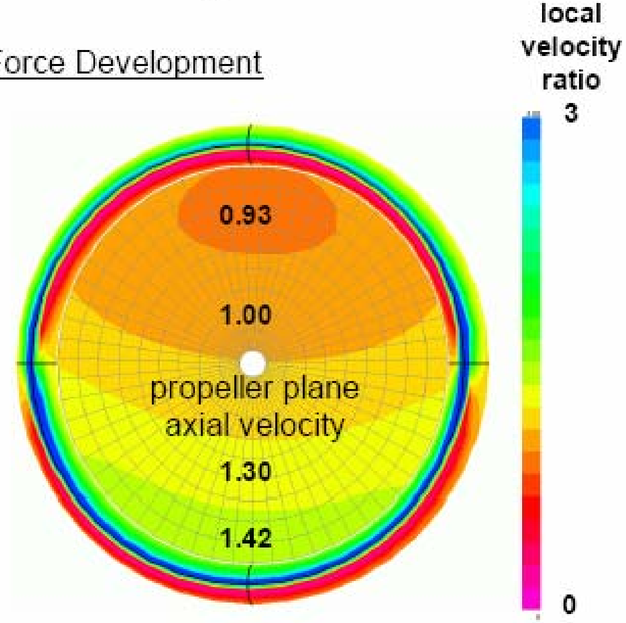
Application of VSAERO to CC Duct Studies

Example of a Dual-Slotted Annular Wing

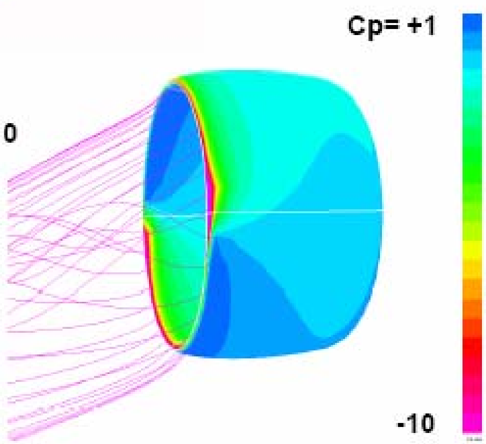
Blowing Configuration 180/180 for Side Force Development



trailing edge views



wake shedding panel location equivalent to airfoil CL of 2.8, AOA = 0



duct interior velocity distortion when in thrust vectoring mode
(LE Cp gradients are OK)

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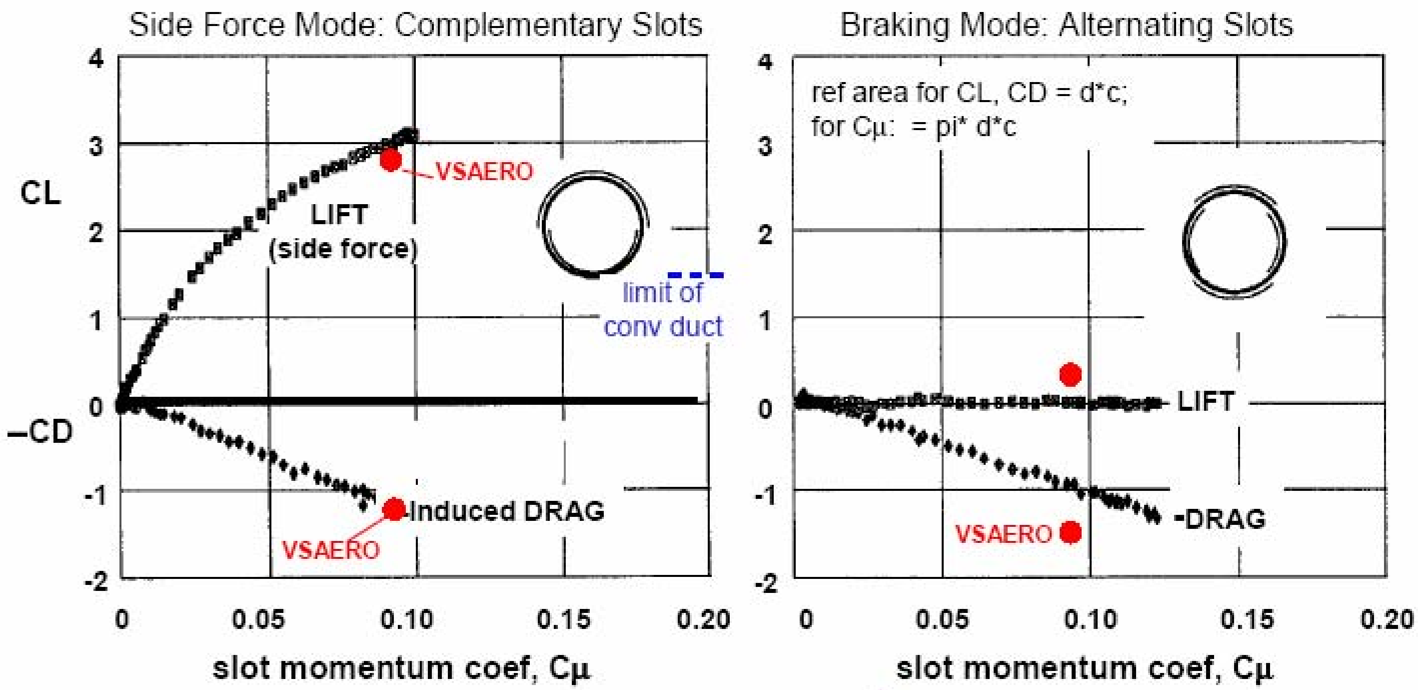
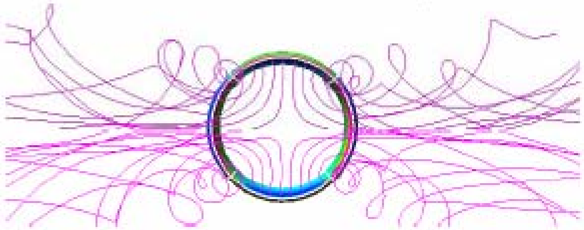
Comparison of VSAERO with CC Duct Data





Data taken in the AARC Acoustic
Wind Tunnel, 1994. Propeller absent.

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Results Summary

- Concept Viability Demonstrated at Fundamental Level
  - Further Model Scale Work Required (with rotor in duct)
- Practical Issues Need to be Addressed
  - Marine Growth
  - Corrosion
- Initial Computational Approach Verified
  - Must Continue with Rotor in Duct

Acoustic Implications of Cost-driven Innovative Components / Methods

- Modified or New Acoustic Tools for New Components / Methods
- Acoustic Tools Should be Integrated with Other Design Tools
- Systems Approach Should be Taken
- Design and Optimization Codes Should be Used

Final Summary

- Cost has Become and Will Continue to be a Major Driver in Acoustic Design
- Acoustic Design Needs to Focus More on Cost Reduction
  - While Maintaining or Improving Performance
- Several Approaches to Help with Cost Reduction have been Discussed
  - System Design and Optimization
  - Innovative Concepts
  - Innovative Components / Methods
- Others Must be Considered
  - Impact of Acoustic Design on Fabrication Costs
  - Reduce Model Scale Testing Using Improved / Verified Preliminary and Final Design Tools