

Multi-Fidelity Structural Modeling for Set Based Design (SBD) of Advanced Marine Vehicles

by Oliver Raj
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Presentation Outline

- Acknowledgements
- Thesis Focus
- Set Based Design
- HY2-SWATH Requirements
- Machinery, Equipment, Stores Loads
- AMVS Substructures and Plots
- AMVS Design Space Exploration
- AMVS Results
- MAESTRO Model Setup
- MAESTRO Model Results
- Conclusions
- Future Work
- References





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- Parents
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Thesis Fundamental Focus

- Development of a parametrically modifiable Advanced Marine Vehicle Structural (AMVS) module
 - Low-fidelity numerical 2D FEA applied to the concept ultra-high-speed Unmanned Surface Vehicle (USV) Hybrid Hydrofoil SWATH (HY2-SWATH)
 - Conduct preliminary design space exploration
 - Varying material, structural member dimensions, and structural member count
 - Demonstrate capability for module incorporation in global software manager for use in Set Based Design (SBD) method
 - Evaluate the structural feasibility of the HY2-SWATH structural design
- High-fidelity MAESTRO 3D FEA comparison of baseline reference HY2-SWATH to that calculated in AMVS module





Set Based Design (SBD)

- SBD is summarized in three steps or phases as follows:
 - 1. Explore the design space
 - A. Design space contains all possible solutions to design problem bounded by current and future-potential capabilities
 - 2. Identify overlapping solution set regions
 - 3. Refine feasible design regions

Set-Based Design Process [15]





AOE

AEROSPACE & OCEAN EN HIS Y2-SWATH SBD Specialty Groups









HY2-SWATH Requirements

- Displacement Mode:
 - 8-25 knots
- Flying Mode:
 - 120+ knots
- Operate in sea state 3
 - wave heights of 1.67 4.08 ft.
 (0.5 1.25 m)
- Transport 3-5 MT payload
- Accomplish 5 day mission

Displacement and Foilborne Operating Conditions







Structural Analysis Models

- Advance Marine Vehicle Structural (AMVS) low-fidelity model
 - FEA Euler-Bernoulli beam theory code written using 2D frame elements
- MAESTRO Marine highfidelity model
- Analyzes the HY2-SWATH:
 - Buoyancy Mode
 - Flying Mode
 - Hogging Wave Condition (with slamming)
 - Sagging Wave Condition (with slamming)



Hogging and Sagging [14]





Reference HY2-SWATH Loads

Table contains the list of machinery loads, equipment loads, stores loads, and structural loads. "Loads" means forces and moments

Loads Applied Mass (Each, MT) Reference Vessel Weight (Each, N) Load Quantity 0.255 + 5% allowance Electric Motor 2 2,316.67 Payload 1 5 49.030 76,262.8 (AMVS); Wing-Superstructure 1 Calc. + 5% allowance 85,866.5 (MAESTRO) Cables and Pipes 0.65+ 5% allowance 1 6,692.6 43,672.6 (AMVS); Struts Calc. + 5% allowance 1 62,406.6 (MAESTRO) 15,799.75 (AMVS); Hull 2 Calc. + 5% allowance 18,752.1 (MAESTRO) Fore foil 2 1.535 + 5% allowance 15,804.8 Aft foil 2 1.57 + 5% allowance 16,165.2 Rotating Mech. Fore 2 0.125 +5% allowance 1.287.04 0.125 + 5% allowance Rotating Mech. Aft 2 1,287.04 Elec. Nav. Equip. 1 0.5 + 5% allowance 5,148.15 Liquids 1 0.3 + 5% allowance 2,941.8 Fuel 1 Calculated 157,502.0 Gas Turbines 2 1.5 + 5% allowance 15,444.5 2 0.75 + 5% allowance 7,722.23 Genset





AMVS Substructure Frames

- Divided HY2-SWATH into three interdependent substructures.
- Together provide an accurate representation of whole vessel





AEROSPACE & OCEAN ENGINE ERING AMVS Substructure Frames (1)

Divided into 3 substructure frames:

- 1. Forward two struts connected via the wing-shaped superstructure
- 2. Aft two struts connected via the wing-shaped superstructure
- 3. Torpedo-shaped demi-hull



forward two struts connected via the wing-shaped superstructure (red)

aft two struts connected via the wing-shaped superstructure (blue)









Substructure 2: Loads







Substructure 3: Loads







Substructure 3: Loads (1)





ARROSPACE & OCEAN ENGINE AMONS Module Element Cross-Sections

- Element cross-section parametric inputs:
 - Shell plating thickness
 - Number of longitudinal stiffeners and their dimensions
 - Ring stiffeners and their dimensions



Forward Struts Frame Element Cross-Sections





AMVS Module Reference Vessel Flying Mode Plots





AMVS Module

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Reference Vessel Flying Mode Plots (1)







Design Space Exploration

- Shell thickness varied from 4 7 mm
 - Flying mode hull elements 9-13 required an additional 6 mm to input shell thickness
 - Flying mode hull elements 8 & 14 required an additional 3 mm
- Material properties

Material Prope	erty Parametric In	puts		
	ho (kg*m ⁻³)	σ_{yield} (MPa)	$ au_{yield}$ (MPa)	E (GPA)
Aluminum 7075 - T6; 7075 - T651	2810	503	331	71.9
316L Steel	8000	205	370	193
Aluminum 6061 - T6; 6061 - T651	2700	276	207	68.9
AISI Type S20910 Stainless Steel, high strength	7890	725	570	200
Titanium Ti - 6 Al - 4 V (Grade 5), Annealed	4430	880	550	113.8

• Longitudinal stiffener count

	Stiffener Count	Parametric Input	
	Forward Strut Frame Stiffeners	Aft Strut Frame Stiffeners	Hull Frame Stiffeners
Run 1	(8, 12, 12, 6, 6, 6, 6, 6, 6, 12, 12, 8)	(8, 12, 12, 6, 6, 6, 6, 12, 12, 8)	6/element (20 elements)
Run 2	(16, 24, 24, 12, 12, 12, 12, 12, 12, 24, 24, 16)	(16, 24, 24, 12, 12, 12, 12, 24, 24, 16)	12/element (20 elements)
Run 3	(32, 48, 48, 24, 24, 24, 24, 24, 24, 48, 48, 32)	(32, 48, 48, 24, 24, 24, 24, 48, 48, 32)	24/element (20 elements)





Design Space Exploration (1)

• Data Results (Example)

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Design Space Exploration (2)

• Constraints (Example)

	Buoyancy Mode Oper	ating Condition Constraints
1	Buoyancy (initial waterline) > 1.1*weight	Initial waterline provides excess buoyancy. Constraint ensures vessel does
		not sink.
2	Abs(Trim angle) < 0.5°	Reduced drag, increased fuel efficiency and range
	Hu	II Frame
3	Max vertical deflection of hull < total hull length *x%	Ensure hull vertical deflection does not cause failure
	Forward	Struts Frame
4	Max horizontal deflection < forward starboard strut length *x%	Ensure horizontal deflection of starboard strut does not cause failure
5	Max horizontal deflection < forward port strut length *x%	Ensure horizontal deflection of port strut does not cause failure
6	Max vertical deflection < forward wing span *x%	Ensure forward portion of the wing superstructure vertical deflection does not cause failure
	Aft St	ruts Frame
7	Max horizontal deflection < aft starboard strut length *x%	Ensure horizontal deflection of starboard strut does not cause failure
8	Max horizontal deflection < aft port strut length *x%	Ensure horizontal deflection of port strut does not cause failure
9	Max vertical deflection < aft wing span *x%	Ensure aft portion of the wing superstructure vertical deflection does not cause failure
	Where x = (0.25% and 0.20%





Design Space Exploration (2) Histograms to help analyze data







Design Space Exploration (3)





Occurrences





< 0.5°



Ref. Mass = 49.0335t > Vessel Mass + 5%







Design Space Exploration (4)

• Sensitivity plots to help analyze input variables impact on stresses





AMVS Reference HY2-SWATH Displacement/Stress Results

Innovative

		AMVS	Max D	isplacement	Result	s Summary			
	Forward Frame	Forward Fram	e	Aft Fram	ne	Aft Frame	Hull Frame		Hull Frame
Load Case	Location	Displacement (r	nm)	Location	n	Displacement (mn	n) Location	D	isplacement (mm)
Buoyancy Mode	Node 7	-5.33		Node 6	5	-4.50	Node 10		0.752
Flying Mode	Node 7	-5.33		Node 6	5	-4.50	Node 11		-65.1
Hogging	Node 7	-21.0		Node 6	5	-17.78	Node 21		-43.0
Sagging	Node 7	-21.0		Node 6	;	-17.78	Node 11		-14.9
		AMVS M	ax Vo	n Mises Stres	s Resu	lts Summary			
	Forward Frame	Forward Frame	5	Aft Frame	5	Aft Frame		tion	Hull Frame
Load Case	Location	Stress, σ _{vm} (Pa)	Location		Stress, σ _{vm} (Pa)	Hull Frame Loca	tion	Stress, σ _{vm} (Pa)
Buoyancy Mode	Element 6	3.931*10 ⁶		Element !	5	2.653*10 ⁶	Element 10		1.037*10 ⁶
Flying Mode	Element 6	3.931*10 ⁶		Element !	5	2.653*10 ⁶	Element 11		7.614*10 ⁷
Hogging	Element 6	1.553*10 ⁷		Element !	5	1.047*10 ⁷	Element 7		6.933*10 ⁷
Sagging	Element 6	1.553*10 ⁷		Element	5	1.047*10 ⁷	Element 6		4.02*10 ⁷
		A	MVS V	on Mises Stre	ess Sta	tistics			
Load Case	Stress Range, N	/lax-Min (Pa)	Aver	age, μ (Pa)	Stan	dard Deviation, σ (Pa	a) Max Stress S	td. De	ev. From Avg. ($\mu \pm \sigma$)
Buoyancy Mode	3.903*	*10 ⁶	1.	332*10 ⁶		1.149*10 ⁶		2.	.27
Flying Mode	7.615*	*10 ⁷	1.	622*10 ⁷		2.445*10 ⁷		2.	.45
Hogging	6.933*	*10 ⁷	1.	236*10 ⁷		1.562*10 ⁷		3.	.65
Sagging	4.020*	*10 ⁷	1.	371*10 ⁷		1.199*10 ⁷		2.	.21





MAESTRO High-Fidelity Model

- Rhino model was converted to a mesh (quad and tri-elements) and imported into MAESTRO
- Material properties and structural element thicknesses applied
- Same machinery/equipment/stores loads applied to the AMVS module were applied to the HF model.
- Structural loads calculated by MAESTRO





MAESTRO Shell Plating Mesh

- Rhino model discretized into finite element mesh (mostly by hand)
- Imported into MAESTRO as .ply file



AEROSPACE & DECAMPANY AESTRO Internal Structure Mesh

>12,000 quads and tri-elements to define the stbd side of the vessel



AEROSPACE & OCEAN ENGINE AND Discontinuities



AOE







AEROSPACE & OCEAN ENGINEERING

Thickness

Aluminum 7075 Material Properties

Material

Name AI 7075-T6 ID 2	Type Isotropic 💌
Name	Value
Young's Modulus Ex(N/m^2)	7.19e+10
Poisson Ratio	0.33
Density(kg/m^3)	2950.5
Yield Stress(N/m^2)	5.03e+08
Ultimate Tensile Strength(N/m^2)	5.72e+08

ID	Name 🛆	Material	#Layers	Thickness(mm)
1	Null Plate Prop	ST24	1	0
2	6mm Al 7075 (default)	AI 7075-T6	1	6
5	6.35mm AI 7075 (girders/rings)	AI 7075-T6	1	6.35
3	9mm Al 7075 (hull shell)	AI 7075-T6	1	9
4	12mm Al 7075 (hull shell)	AI 7075-T6	1	12





Concentrated Loads

- The reference vessel loads applied in the AMVS module were applied to the MAESTRO model. (Best for comparison purposes)
 - Concentrated loads remained concentrated and distributed loads remained distributed (which also made logical sense going $2D \rightarrow 3D$)







Distributed Loads









AEROSPACE & OCEAN ENG BIAlance the Vessel (Buoyancy Mode)

AOE

Information Only. No effect on FE-Analysis *Displacement= 527529 N, Volume=52.4349 m^3 *The following parameters are in the Ship Coordinate system: *Center of Buoyancy: xCB= 10411.5 mm, yCB=644.096 mm, zCB=0 mm *Center of Gravity: xCG= 10391 mm, vCG=1827.82 mm, zCG=0 mm *Center of Flotation: xCF= 11748.1 mm, vCF=2252.13 mm, zCF=0 mm *Trim Angle(Deg)=-0.375233 *Fore Draft Point (mm)=(19537.011, 2303.141, 3660.728) *Aft Draft Point (mm)=(3764.859, 2199.847, 5299.683) *Fore Draft Point at z=0 (mm)=(19537.011, 2303.141, 0) *Aft Draft Point at z=0 (mm)=(3764.859, 2199.847, 0) *Distance to origin =-2175.143 mm *BMT= 7885.98 mm *BML= 10048 mm *It=4.13501e+14 mm^4 *I1=5.26866e+14 mm^4 *GMT=6702.14 mm *GML=8864.16 mm



MAESTRO Reference Model Displacement **Results (Hogging Condition)** 5.55E+0 5.21E+01





Max Displacement Node Location (Hogging)



MAESTRO Reference Model Stress AOE **Results (Hogging Condition)**

Stress in N/m²

Color code modified to show stresses in red when VM stress was 1/6 of yield stress, i.e. SF of 6

> 1.57E+07 1.05E+07 5.24E+06 Displacement magnified by 42x factor 0.00 E+00 37

8.38E+07

7.86E+07

7.34E+07

6.81E+07

6.29E+07 5.76E+07 5.24E+07 4.72E+07 4.19E+07 3.67E+07 3.14E+07 2.62E+07 2 10 E+07



Stress in N/m²

0.00 E+00



MAESTRO Reference HY2-SWATH Displacement/Stress Results

	MAESTRO Max Disp	placement Res	ults Sur	nmary		
Load Case	Displacement Loo	cation		Di	isplacem	ent (mm)
Buoyancy Mode	FeTag 10693	3			34.	50
Flying Mode	FeTag 3675				-15.	49
Hogging	FeTag 3675				-54.	81
Sagging	FeTag 3675				-54.	34
	MAESTRO Max Von I	Mises Stress Re	esults S	ummary		
Load Case	Stress Location		N	/lax Stress (Pa)		Safety Factor
Buoyancy Mode	Strut Stiffener - Tri 298 - Fe	Tag 12042		5.36*10 ⁷		9.38
Flying Mode	Hull Stiffener - Tri 56 - FeTa	ag 11968		1.20*10 ⁸		4.19
Hogging	Hull Stiffener - Tri 67 - FeTa	ag 11964		2.58*10 ⁸		1.95
Sagging	Hull Stiffener - Tri 56 - FeTa	ag 11968		1.94*10 ⁸		2.59
	MAESTRO Vor	n Mises Stress	Statisti	cs		
Load Case	Stress Range, Max-Min (Pa)	Average, μ (F	Pa)	Standard Deviation,	σ (Pa)	Max Stress Std. Dev. From Avg. ($\mu \pm \sigma$)
Buoyancy Mode	5.361*10 ⁷	2.858*10 ⁶	5	3.528*10 ⁶		14.39
Flying Mode	1.201*10 ⁸	3.106*10 ⁶	5	3.755*10 ⁶		31.13
Hogging	2.577*10 ⁸	1.038*10 ⁷	,	1.359*10 ⁷		18.22
Sagging	1.939*10 ⁸	9.412*10 ⁶	5	1.173*10 ⁷		15.74





Conclusions

- AMVS module design space exploration of 60 different HY2-SWATH variations for four load cases
 - Flying mode hull stress/displacement largest of four load cases
 - Four feasible solutions found!
 - Limited primarily by the buoyancy provided by the hull, material used, and the hydrofoils' designed lift





Conclusions (1)

- MAESTRO Reference HY2-SWATH was feasible for all load cases with a minimum stress safety factor of 1.95
 - Hogging wave condition with slamming showed the largest displacement and stress
 - Max displacement in the superstructure at turbojet location
 - Max stress in the hull near aft strut





Conclusions (2)

- The models displacements generally correlated to each other
 - Largest displacements were in the wing-shaped superstructure location of the turbojets
 - High-fidelity model turbojets caused largest displacement overall in flying mode, hogging, and sagging load case scenarios.
 - Low-fidelity model largest displacement overall seen in the hull at midship in flying mode
 - Turbojets caused largest displacement in substructure 2 (aft strut frame) for hogging and sagging load case scenarios.
 - The AMVS module analyzed the hull in a slightly more severe configuration in absence of strut and superstructure, yet loaded as if they (and all internal machinery) were present.
 - Useful to consider a closed longitudinal frame to include the hull, struts and superstructure.





Conclusion (3)

- The models VM stresses generally correlated to each other
 - MAESTRO model calculates a much larger range of stresses and an order of magnitude greater max stress
 - Average and the standard deviation are similar in their OOM

		AMVS Von Mises Stre	ess Statistics							
Load Case	Stress Range, Max-Min (Pa)	Average, μ (Pa)	Standard Deviation, σ (Pa)	Max Stress Std. Dev. From Avg. ($\mu \pm \sigma$)						
Buoyancy Mode	3.903*10 ⁶	1.332*10 ⁶	1.149*10 ⁶	2.27						
Flying Mode	7.615*10 ⁷	1.622*10 ⁷	2.445*10 ⁷	2.45						
Hogging	6.933*10 ⁷	1.236*10 ⁷	1.562*10 ⁷	3.65						
Sagging	4.020*10 ⁷	1.371*10 ⁷	1.199*10 ⁷	2.21						
MAESTRO Von Mises Stress Statistics										
Load Case	Stress Range, Max-Min (Pa)	Average, μ (Pa)	Standard Deviation, σ (Pa)	Max Stress Std. Dev. From Avg. ($\mu \pm \sigma$)						
Buoyancy Mode	5.361*10 ⁷	2.858*10 ⁶	3.528*10 ⁶	14.39						
Flying Mode	1.201*10 ⁸	3.106*10 ⁶	3.755*10 ⁶	31.13						
Hogging	2.577*10 ⁸	1.038*10 ⁷	1.359*10 ⁷	18.22						
Sagging	1.939*10 ⁸	9.412*10 ⁶	1.173*10 ⁷	15.74						





Future Work

- AMVS Module
 - Conduct larger design space exploration
 - Incorporate in global software manager
 - Incorporate additional ship analysis modules
 - Modify more variables (already capable)
 - Consider analysis of additional frames
 - Reinforce structurally weaker areas





Future Work (1)

- MAESTRO HF model
 - Automate the vessel creation and analysis
 - Reinforce structurally weaker areas
 - Refine mesh
 - Create wave load cases with intrinsic wave functions
 - Compare against DNVGL wave load cases





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Backup Slides

Improved HY2-SWATH Structure in MAESTRO:







HY2-SWATH V2.0

- Goal: Reduce large deflections and high stress areas to achieve SF of 6
 - Addition of flanges in the superstructure and some in hull:
 - Weight: 53.76 MT → 55.12 MT





HY2-SWATH V2.0 (1)

- Hogging Wave Condition w/ Slamming:
 - Stresses in superstructure and hull exceeding allowable to
 - provide SF of 6.

• Max Deflection : -54.8mm \rightarrow -31.3mm





HY2-SWATH V2.1

- Goal: Reduce large deflections and high stress areas to achieve SF of 6
 - Removal of most flanges in the superstructure
 - Addition of solid bulkheads in superstructure
 - Weight: 53.76 MT → 54.09 MT







HY2-SWATH V2.1 (1)

- Hogging Wave Condition w/ Slamming:
 - Stresses in the hull exceeding allowable to provide SF of 6.

Max Deflection : -54.8mm \rightarrow -16.8mm