X-57 Whirl Flutter & Propeller Stability Assessments

Josiah Waite
NASA Langley

Andrew Kreshock
Army Research Lab

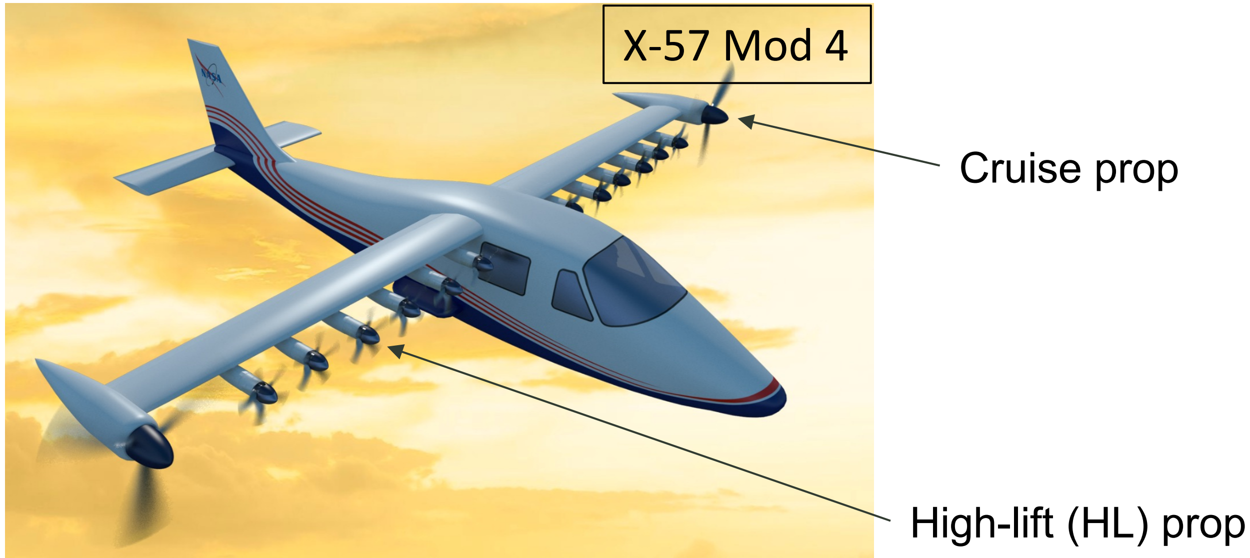
Jinwei Shen & Kyle Nelson
University of Alabama

BACKGROUND

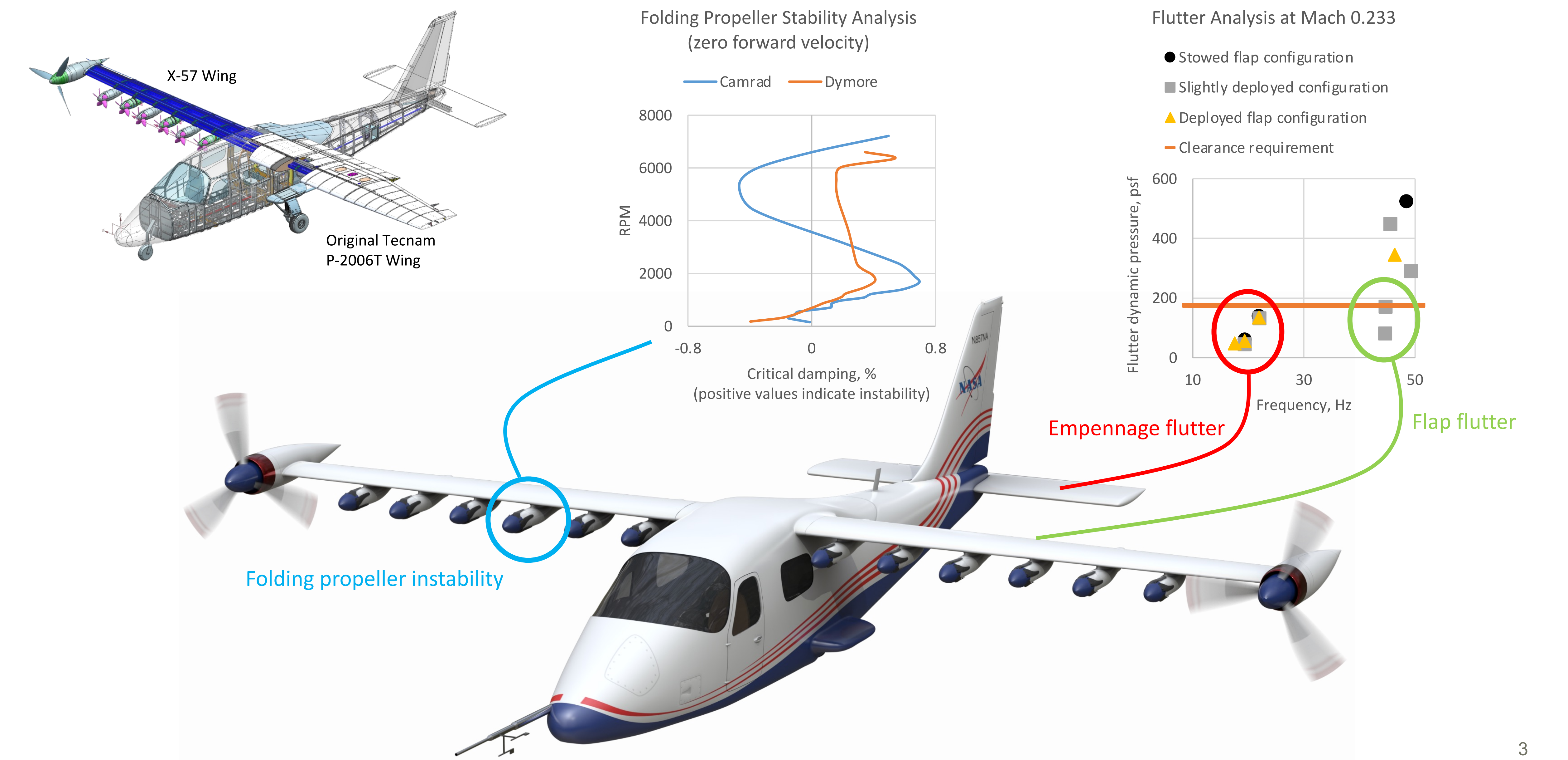

Tecnam P2006T
N780TT


X-57 Mod 2


X-57 Mod 3


X-57 Mod 4
Cruise prop
High-lift (HL) prop

WHERE WE WERE 3 YEARS AGO…



Whirl Flutter Analysis Overview

LIMITATION, ASSUMPTION, CHALLENGES

Wing Structure

- Reduced order model is only as good as the FEM
  - The rotational component of the mode shape at the hub nodes is critical
  - No structural damping is assumed
  - Mod IV NASTRAN cruise nacelle FEM has not been experimentally validated
  - Because the FEM is not validated a flutter speed margin of 50% is used
- CAMRAD II currently limited to 100 modes (software variable limitation)
- DYMORE 5 analysis used all 183 modes from NASTRAN output

Aerodynamics

- No wing aerodynamics
- Rotor Aerodynamics
  - 2D airfoil tables generated from CFD, only limited validation against FUN3D
  - Not valid around stall
- No aerodynamic interaction between rotors
- Blade Aerodynamics based on BET (Blade Element Theory)

LIMITATION, ASSUMPTION, CHALLENGES

Rotor Structure

- Blade Modeling of Cruise Prop
  - Beam properties not available and estimated based on NASTRAN frequencies
  - Geometry is based on VSP model and not validated against as built
- Blade Modeling of High Lift Prop
  - Beam properties not available. Assumed rigid based on cantilevered testing.
  - The folding hinge of the high-lift propellers assumes a single torsional spring constraint without a friction model

Trim Simulation

- Trim: HL props tend to produce excess thrust and so the vehicle thrust was trimmed with the cruise props only. Also trimmed to 0 thrust versus 0 torque.
- Simulations including the high-lift propeller will use a constant 5400 RPM for flight speeds above 120 KTAS

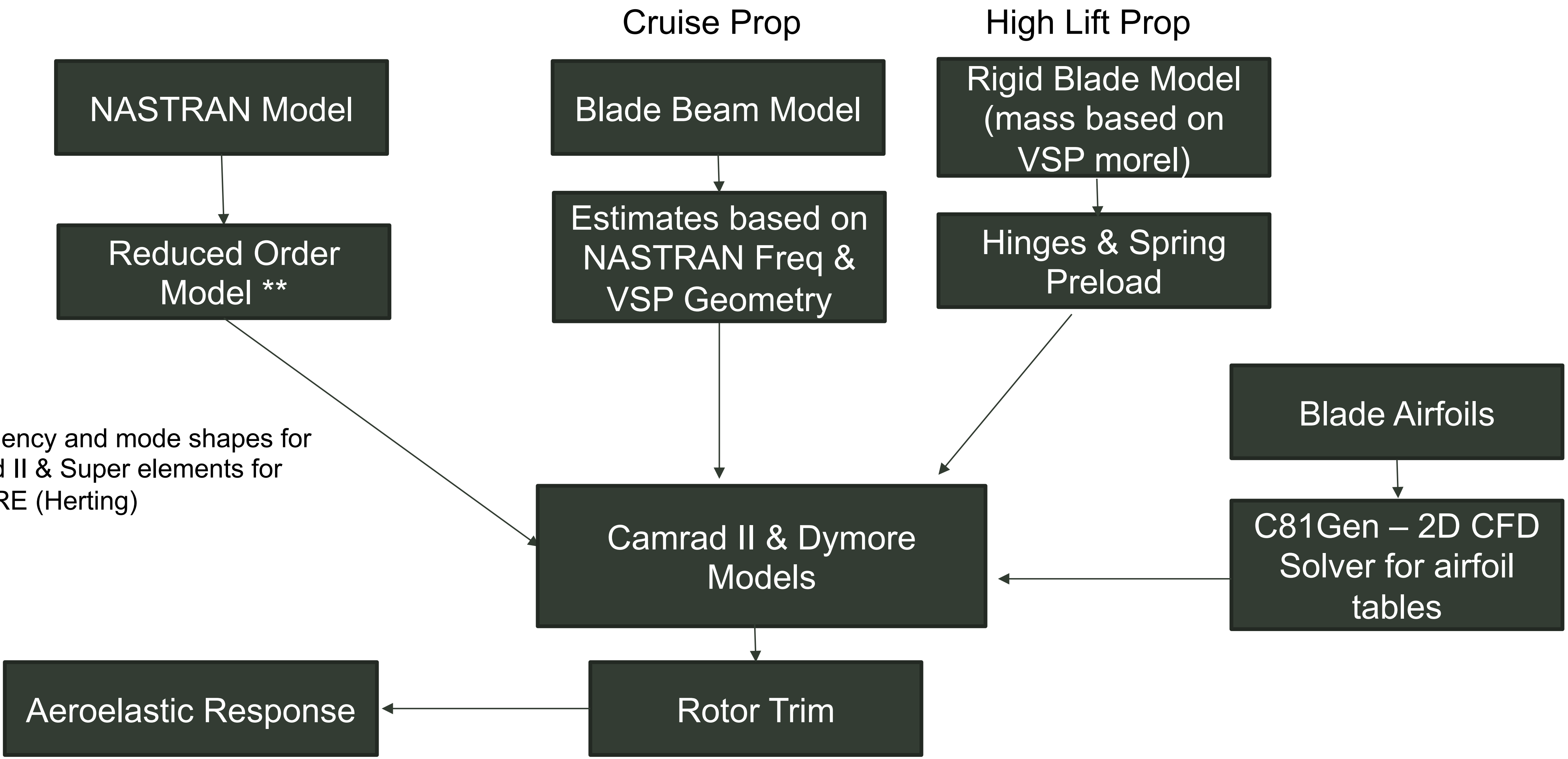
Cruise and HL Prop Shaft Boundary Condition (BC)

- Free Shaft DOF is representative of unpowered shaft (equivalent to Pinned BC beam)
- A free shaft is a conservative whirl flutter BC assumption, because shaft is allowed to flex at motor connection point
  - The unpowered shaft BC decouples the roll motion from the pitch and yaw motion
  - Including the roll motion always has a stabilizing effect for whirl flutter

Validation

- No experimental validation for whirl flutter
- Aeroelastic analysis results are compared between two (2) codes

WHIRL FLUTTER ANALYSIS WORKFLOW



**Frequency and mode shapes for Camrad II & Super elements for DYMORE (Herting)

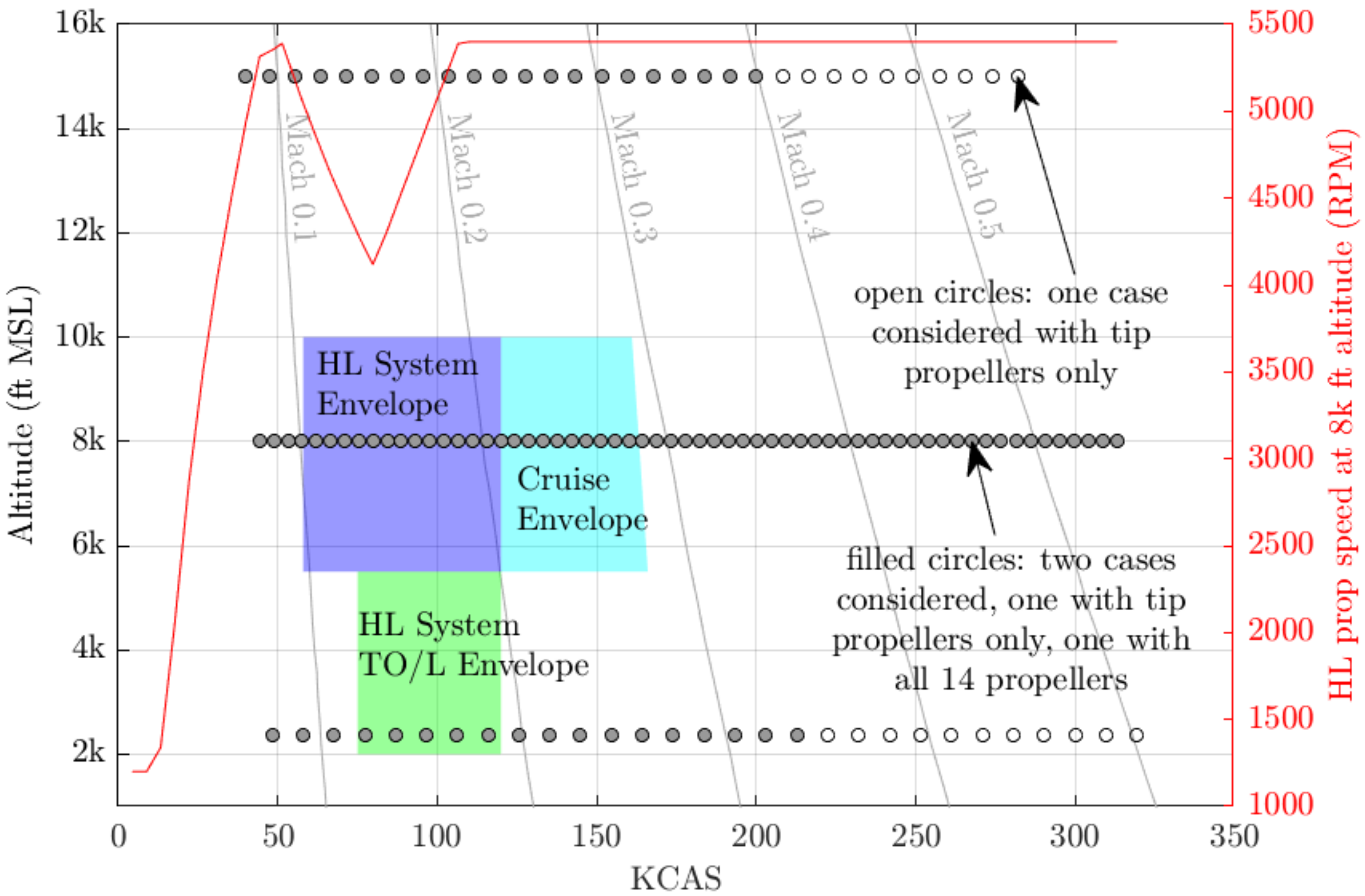
CAMRAD II – Eigenvalues
Dymore – Time domain perturbations

WHIRL FLUTTER ANALYSIS PARAMETER VARIATION

		Cruise props		
		Cruise, 2250 RPM	Takeoff, 2700 RPM	Overspeed, 3080 RPM
HL props	0 RPM	8,000	8,000	2,372 8,000 15,000
	Scheduled RPM	8,000	8,000	8,000
	Overspeed, 5940 RPM	8,000	8,000	2,372 8,000 15,000

RPM combinations for high-lift (HL) propellers and cruise propellers for analyses conducted at various altitudes.

WHIRL FLUTTER ANALYSIS PARAMETER VARIATION



X-57 Mod IV flight envelopes with open/closed circles indicating where whirl flutter analyses were conducted. Green axis and line indicate the scheduled RPM values for the HL props at 8k ft altitude.

FLIGHT & TRIM CONDITIONS

		Cruise Prop		
High Lift Prop		Cruise RPM	Take off RPM	Overspeed
		2250	2700	3080
	0 RPM	Wind Milling	Wind Milling	Wind Milling
	Scheduled HL Prop	Wind Milling	Wind Milling	Wind Milling
	Overspeed 5940 RPM	Wind Milling	Wind Milling	Wind Milling

		Cruise Prop		
High Lift Prop		Cruise RPM	Take off RPM	Overspeed
		2250	2700	3080
	0 RPM	Net Thrust = Aircraft Drag	Net Thrust = Aircraft Drag	Net Thrust = Aircraft Drag
	Scheduled HL Prop	Net Thrust = Aircraft Drag	Net Thrust = Aircraft Drag	Net Thrust = Aircraft Drag
	Overspeed 5940 RPM	Net Thrust = Aircraft Drag	Net Thrust = Aircraft Drag	Net Thrust = Aircraft Drag

Velocity is in true airspeed (KTAS)
Altitude is at 8k
All Rigid Blades (High Lift Props have hinges)

Wind Milling Trim
- Cruise prop are trimmed to Thrust = 0
- Free Shaft DOF for all rotors

Drag Trim
- Thrust = X*q = (2 rotors)*1.92 ft^2*q
- Cruise Props take up the vehicle drag and thrust from HL props are in excess
- Free Shaft DOF for all rotors

Whirl Flutter Cases, Wind Milling

		Cruise Prop		
High Lift Prop		Cruise RPM	Take off RPM	Overspeed
		2250	2700	3080
	0 RPM	Wind Milling	Wind Milling	Wind Milling
	Scheduled HL Prop	Wind Milling	Wind Milling	Wind Milling
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WIND MILLING WHIRL FLUTTER CASES

		Cruise Prop		
High Lift Prop		Cruise RPM	Take off RPM	Overspeed
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	0 RPM	Wind Milling	Wind Milling	Wind Milling
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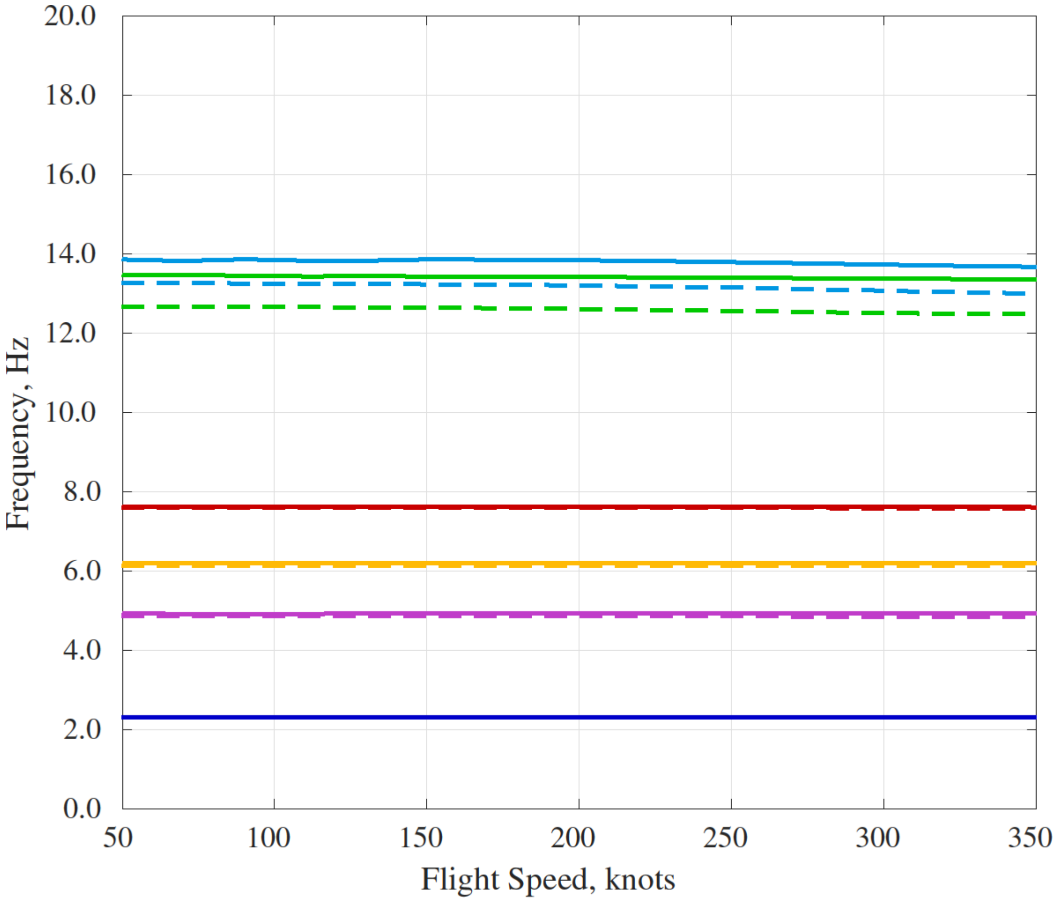

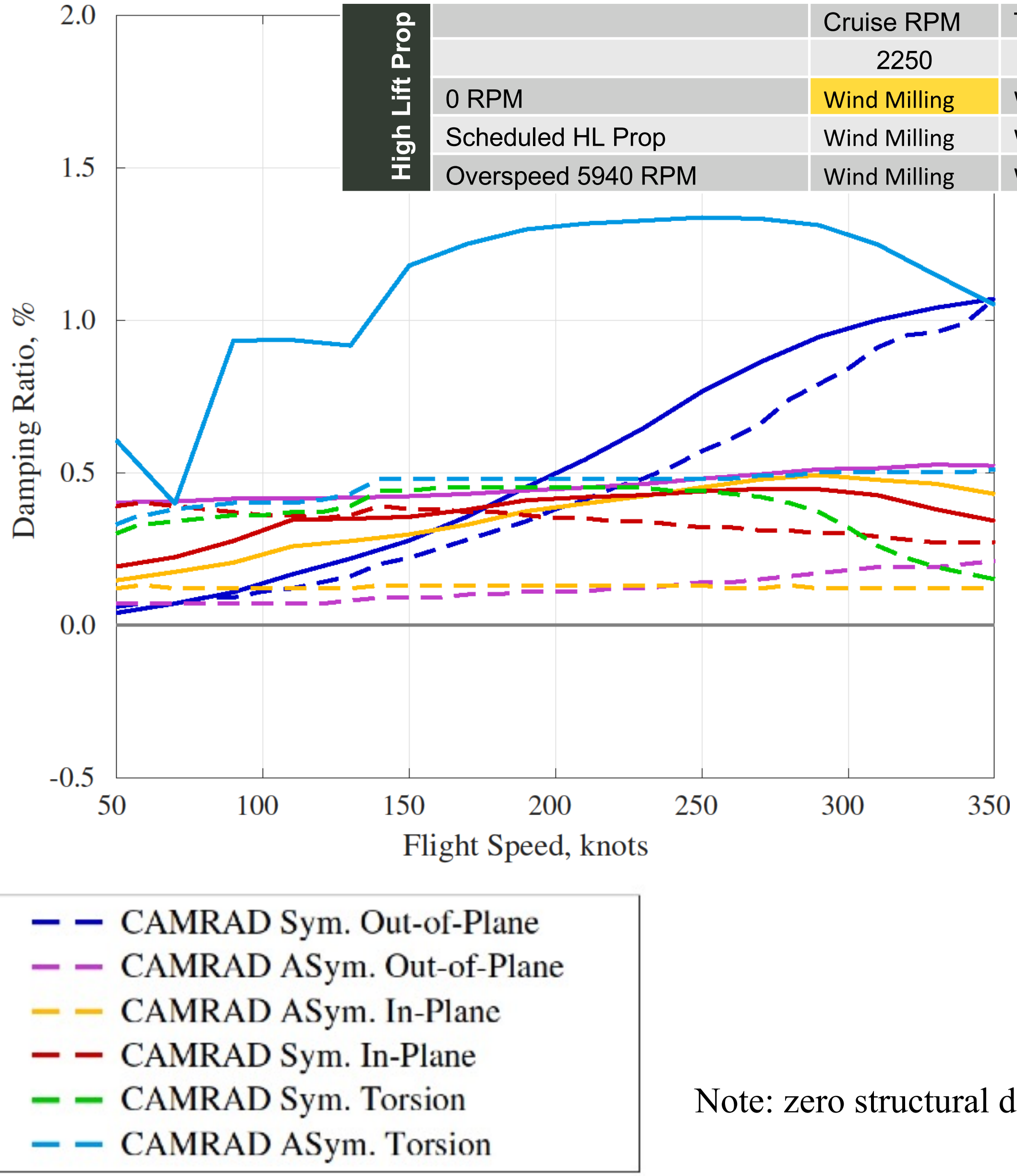

Note: zero structural damping assumed

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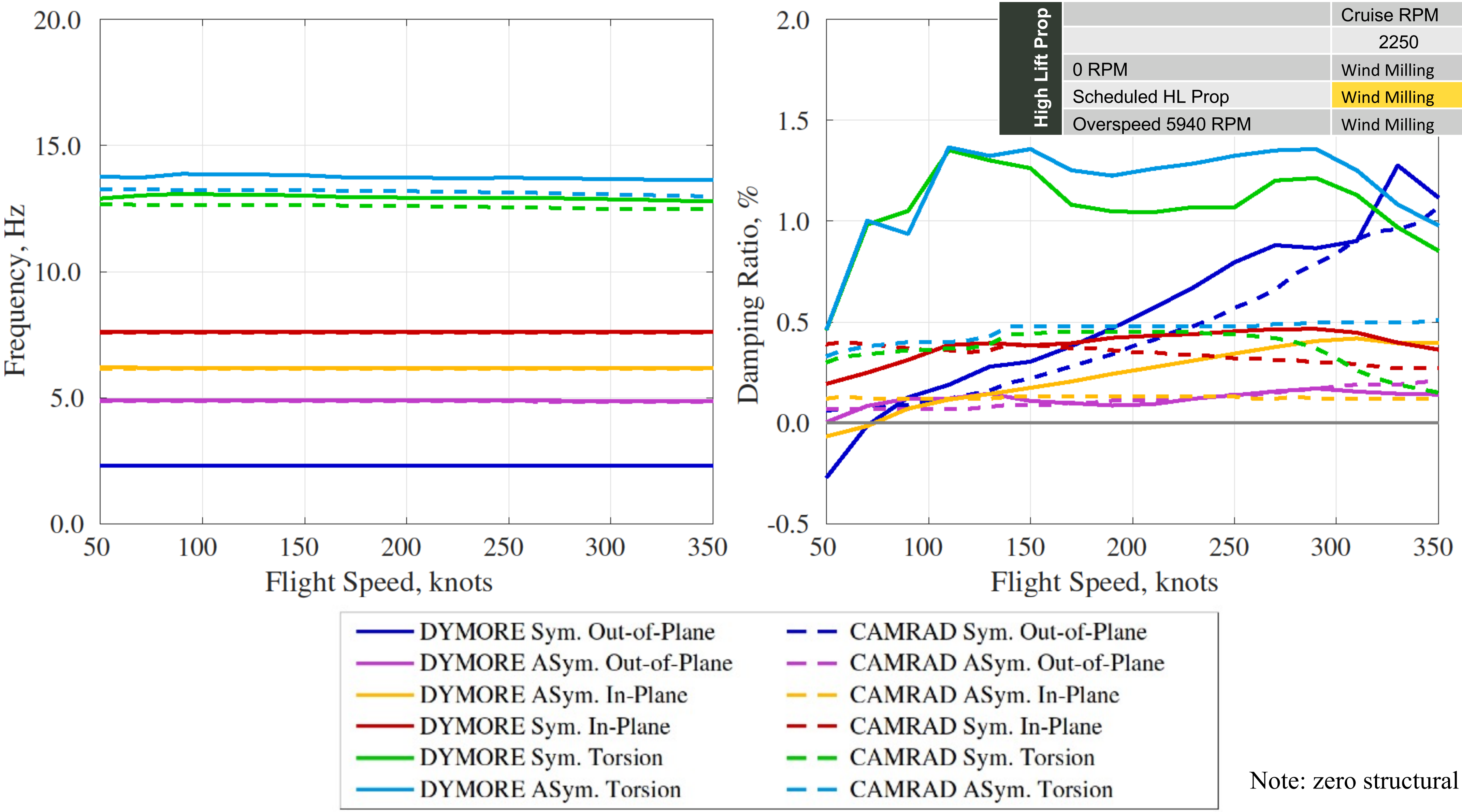

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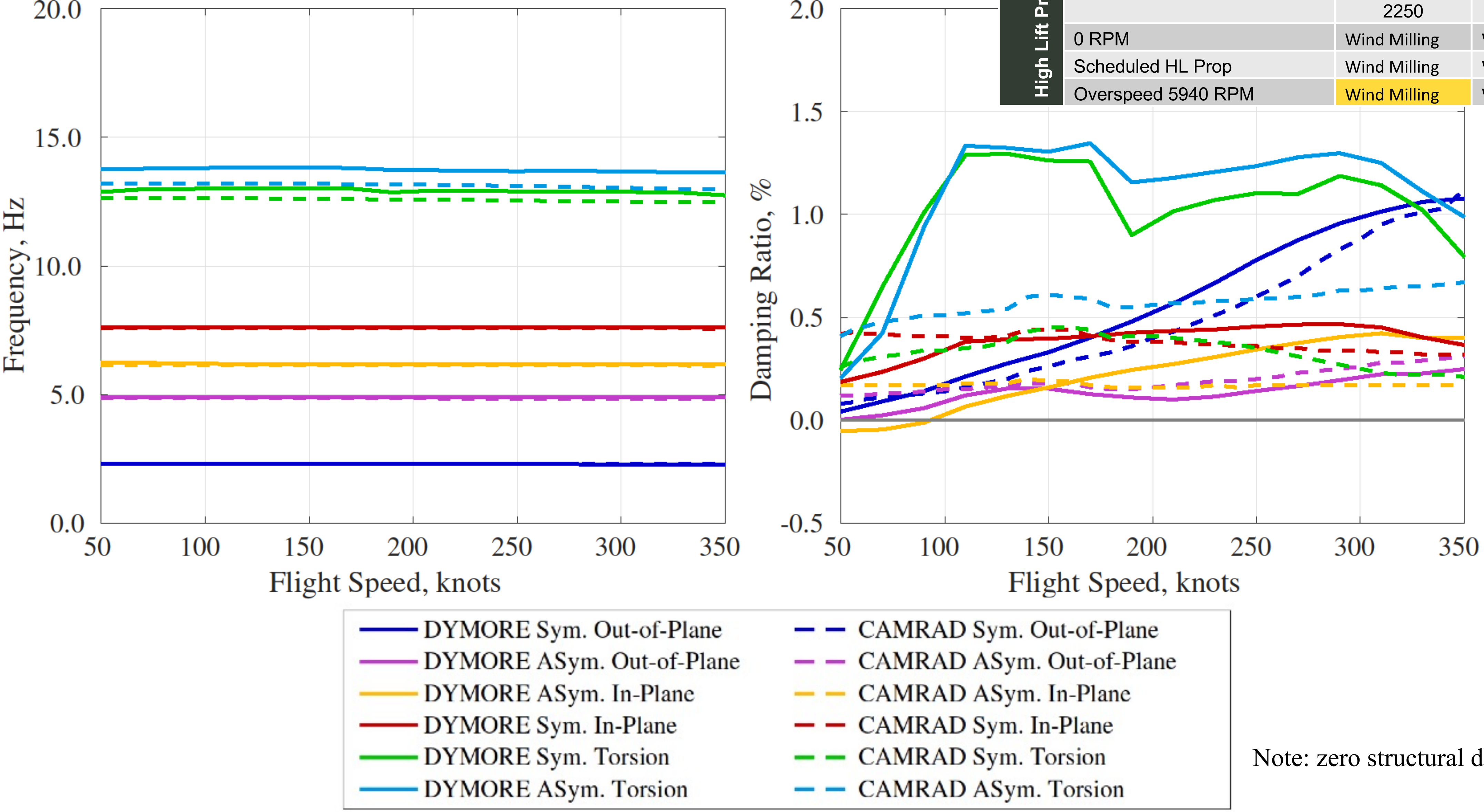

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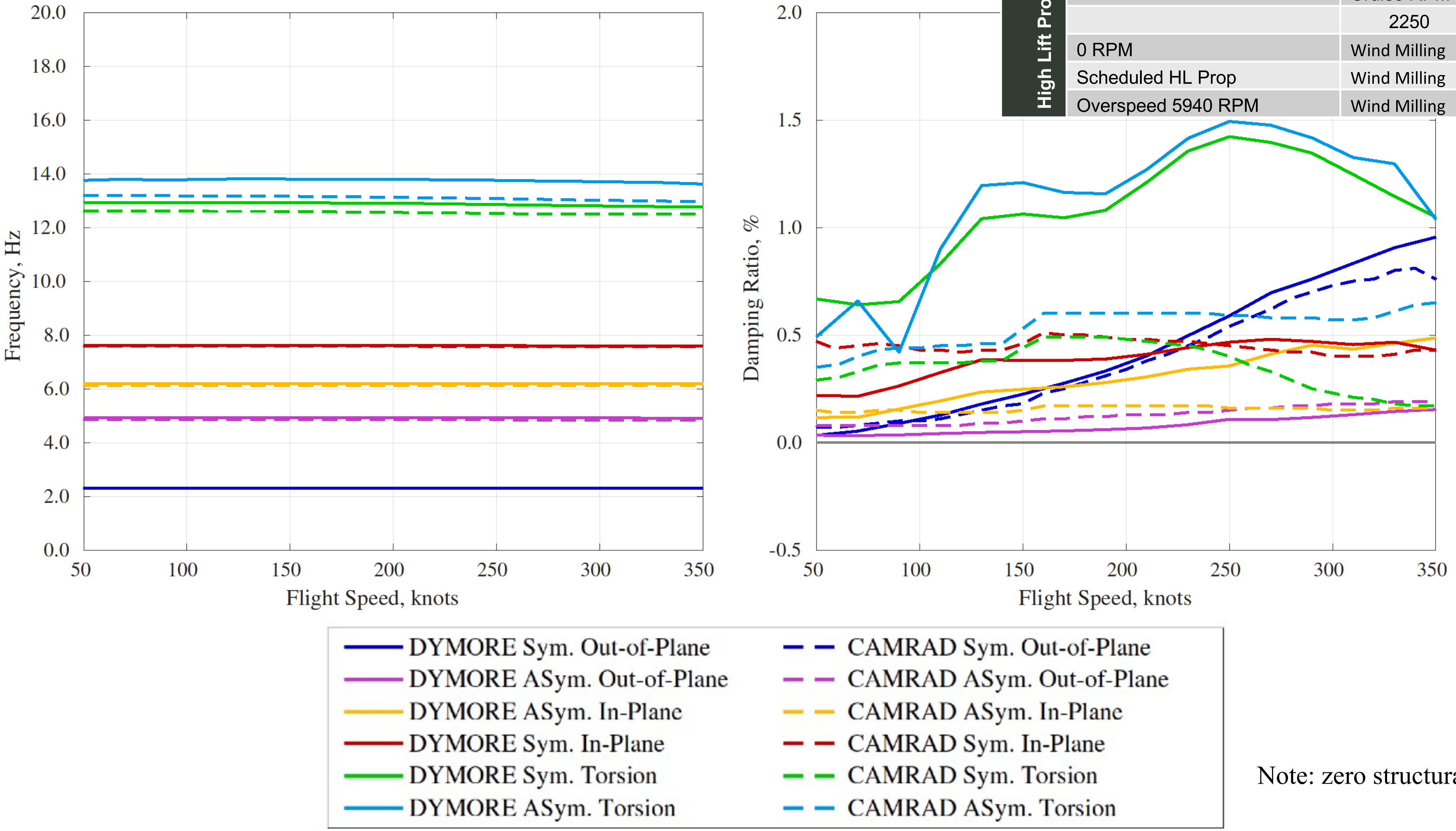

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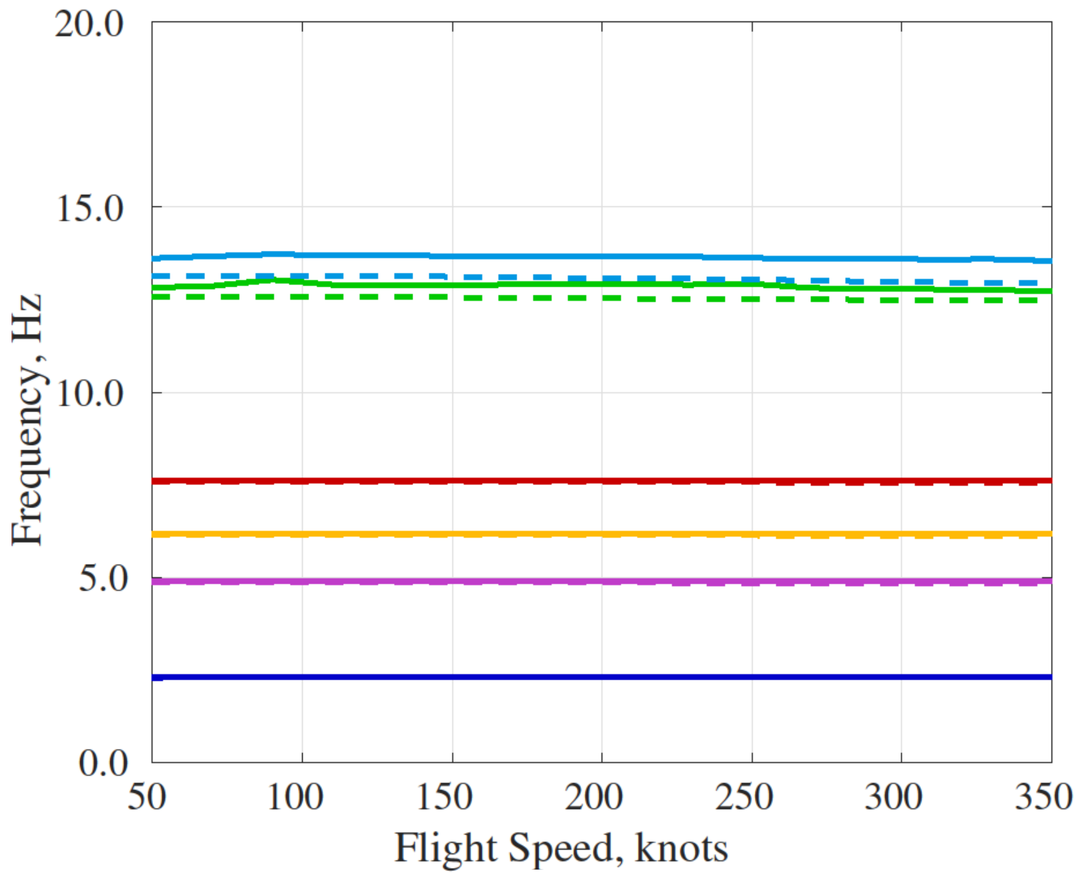

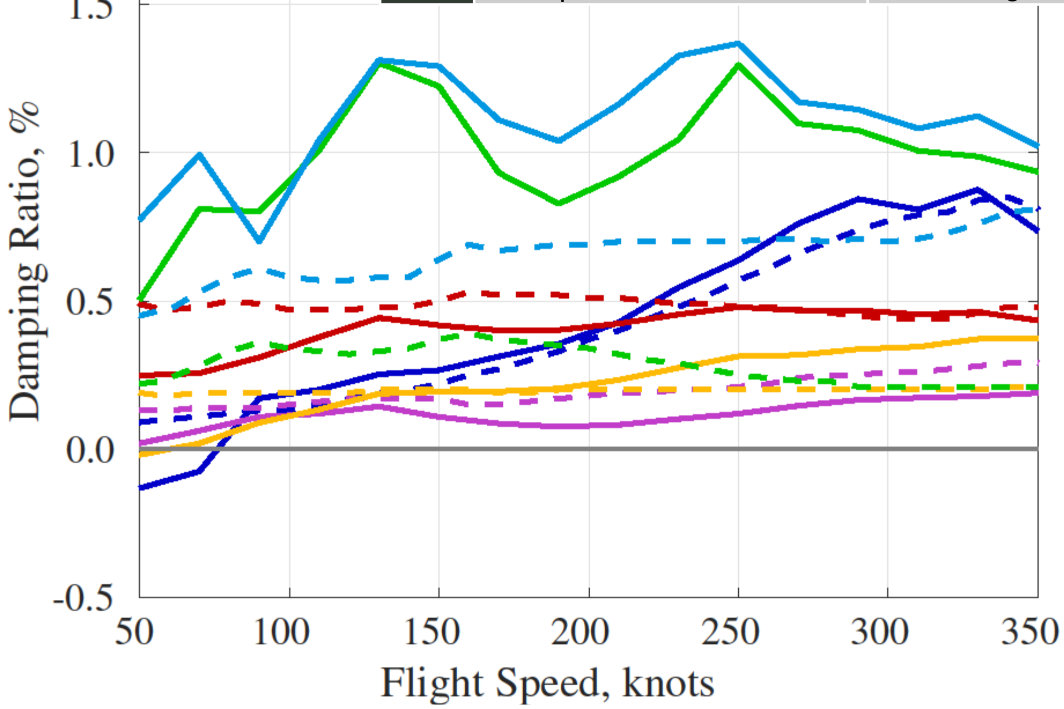

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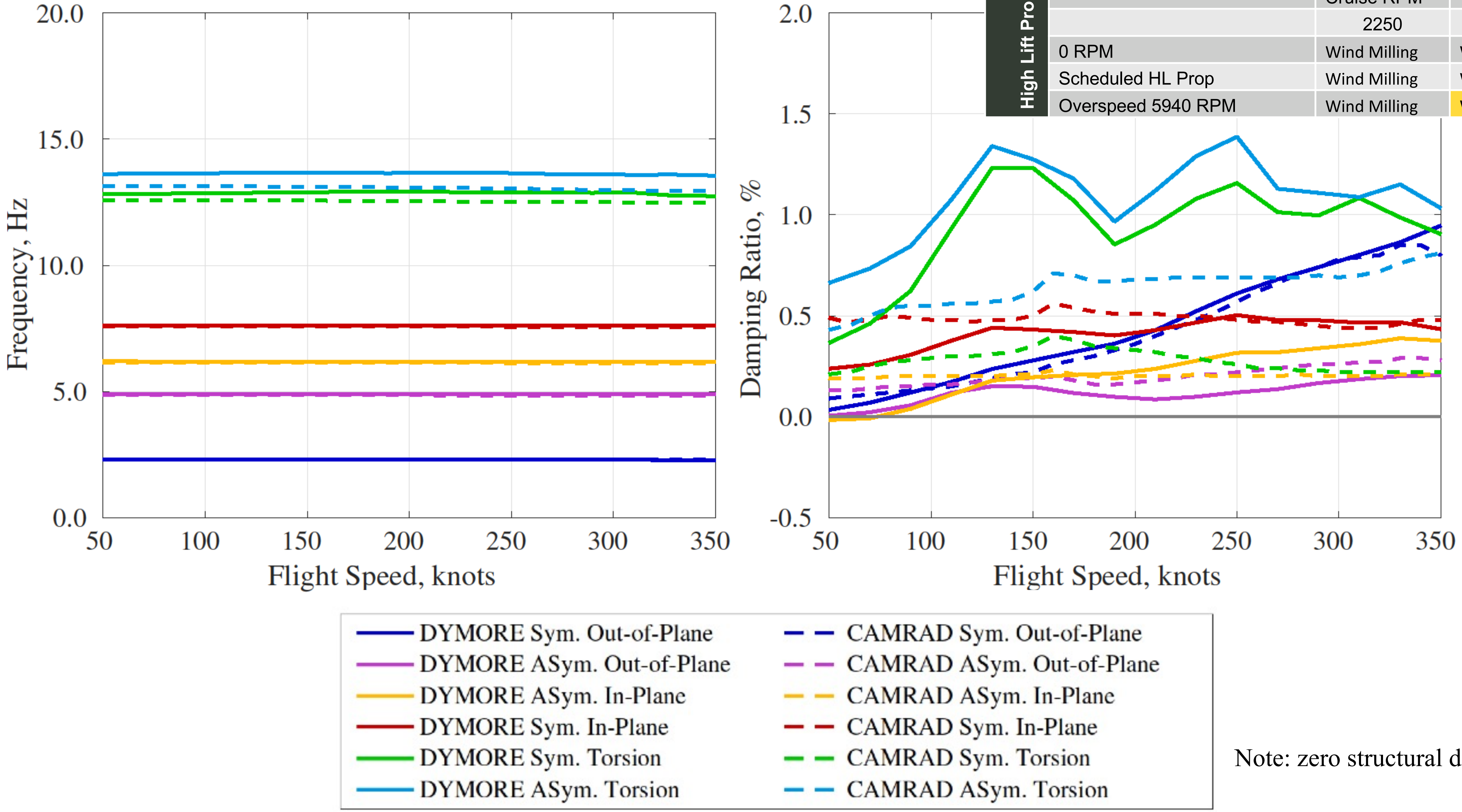

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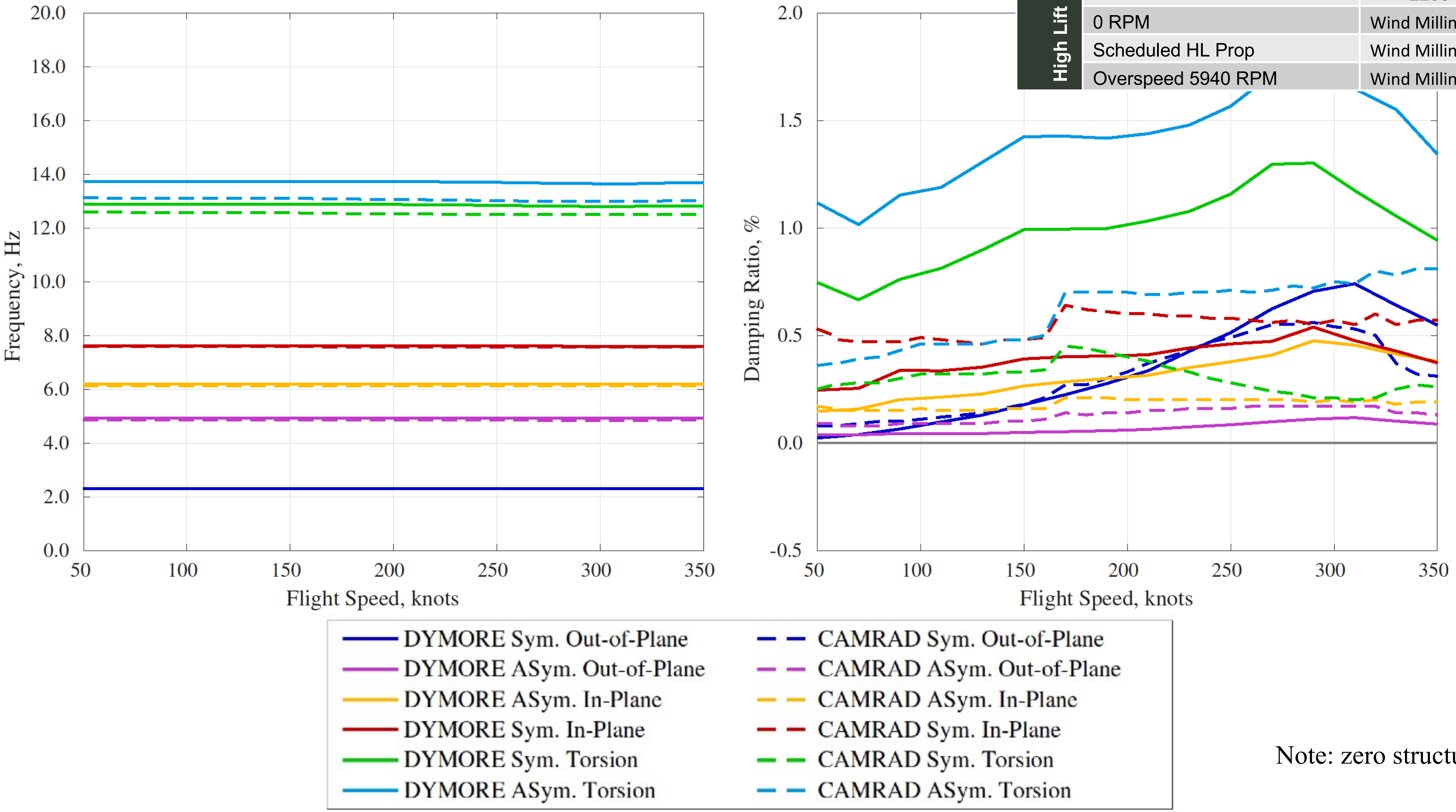

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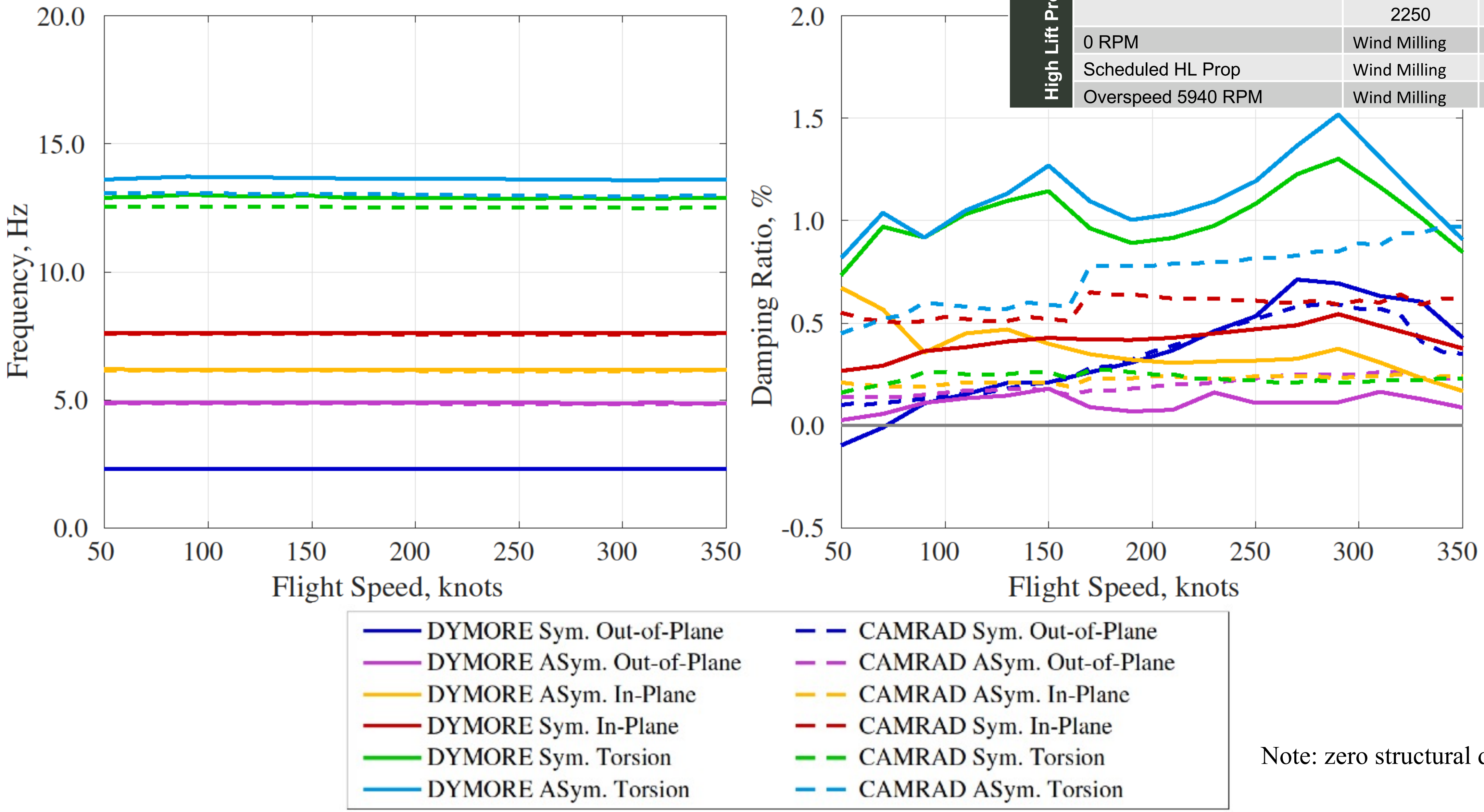

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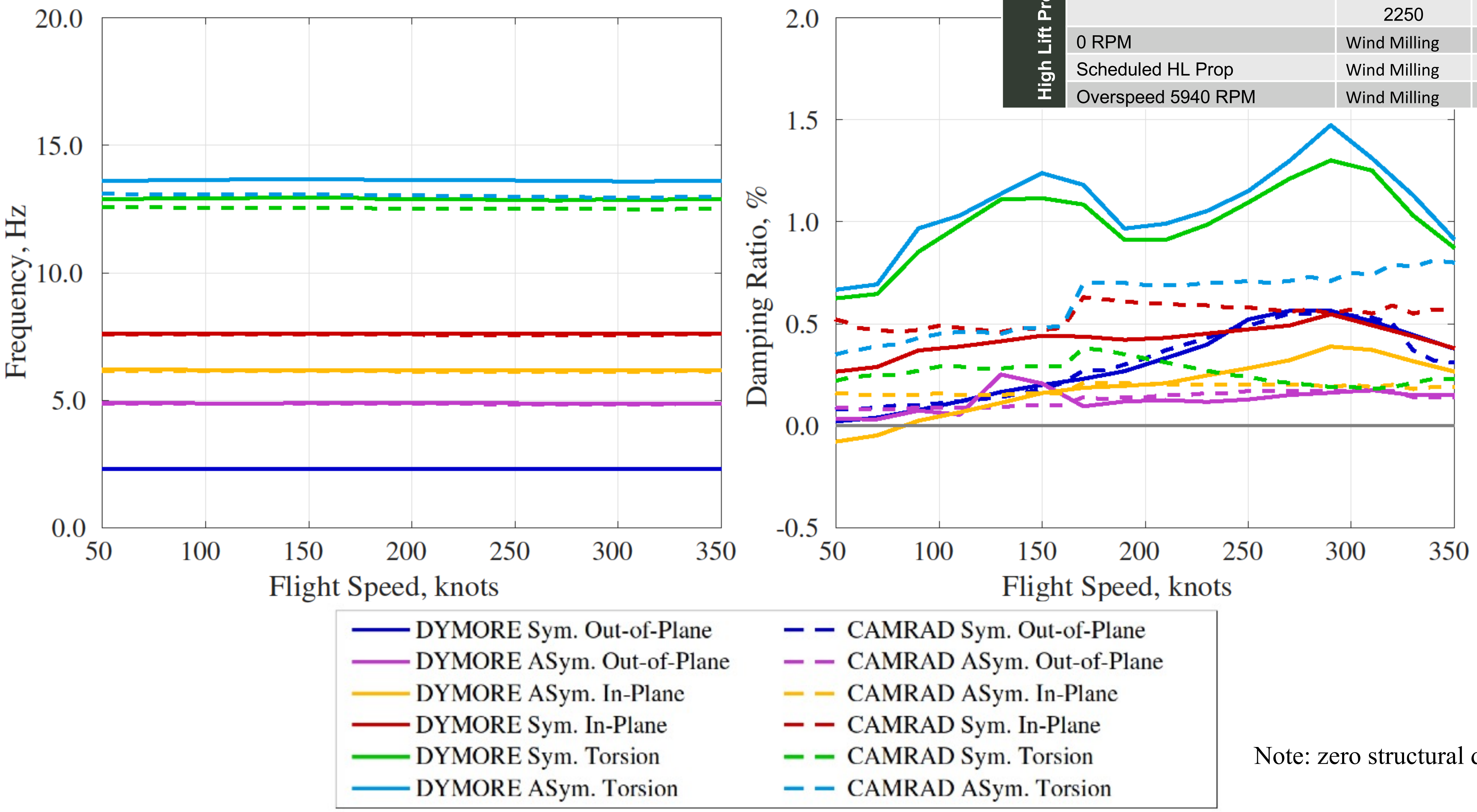

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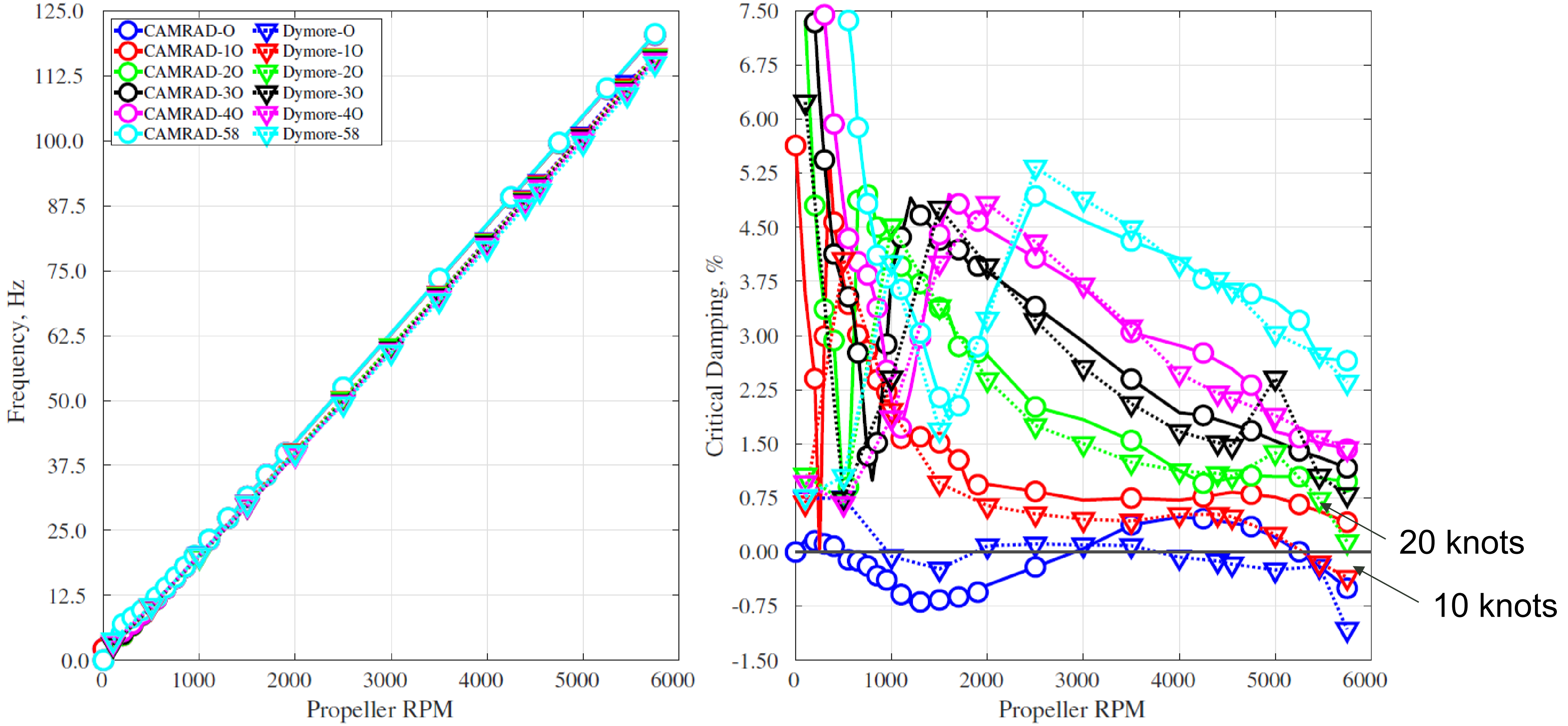
CONCLUSIONS

- Whirl flutter analyses conducted with 50% margin on airspeed and altitude, and with 10% margin on rotor speed
- No whirl flutter concerns at high speeds
- Small instability (negative damping) predicted at low speeds—within assumed margin of at least 1% structural damping
- Whirl flutter stability boundary lies beyond the margins imposed in these analyses

High Lift Propeller Rotor Stability

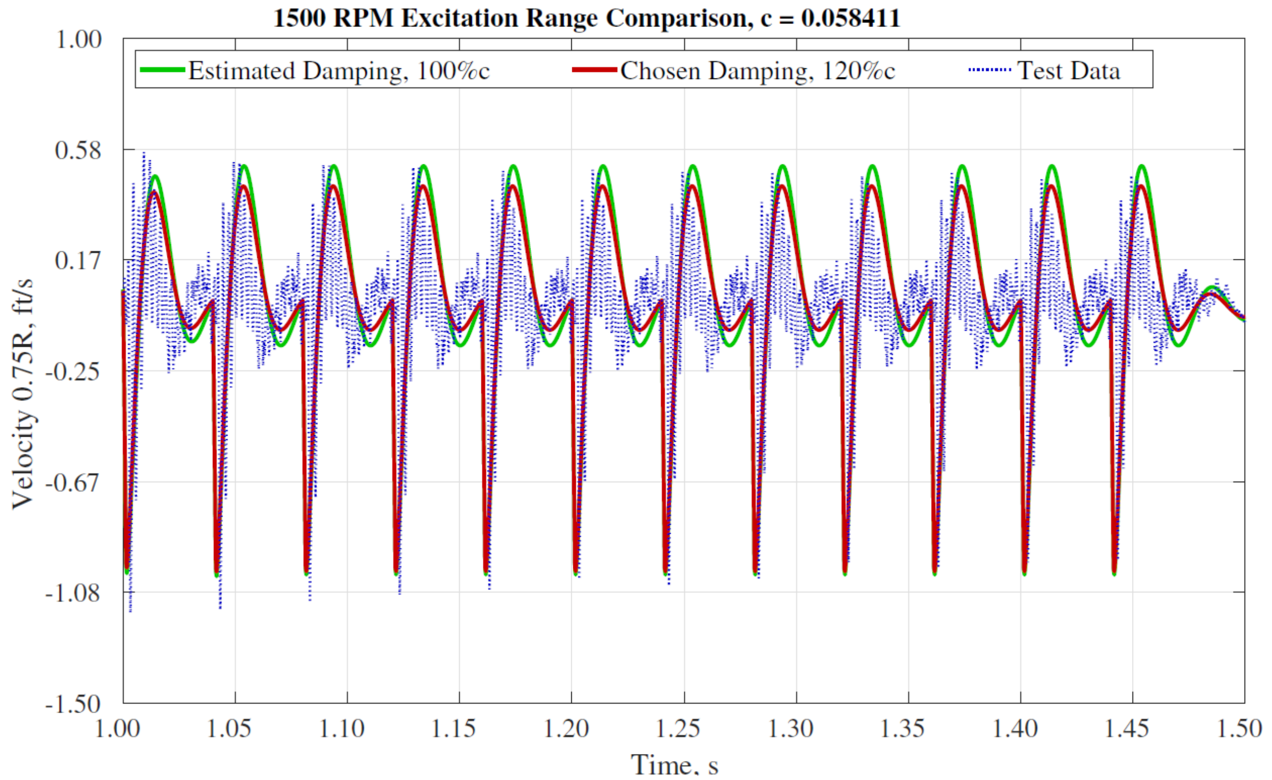
PREDICTED HIGH LIFT PROPELLER STABILITY



Instability was found in the Isolated High Lift Propeller at 0 knots.
This is primarily due to the hinge geometry and built-in pitch/twist

TEST IN LOW SPEED AEROACOUSTICS WIND TUNNEL

- Isolated high-lift propeller on a fixed test stand.
- Rotor Speed varied from 1500 – 5000 RPM
- Test Setup / Procedure
  - 0.5s ‘Air-On’ of compressed air to excite the blade folding mode at a specific azimuthal location
  - 1.5s ‘Air-Off’

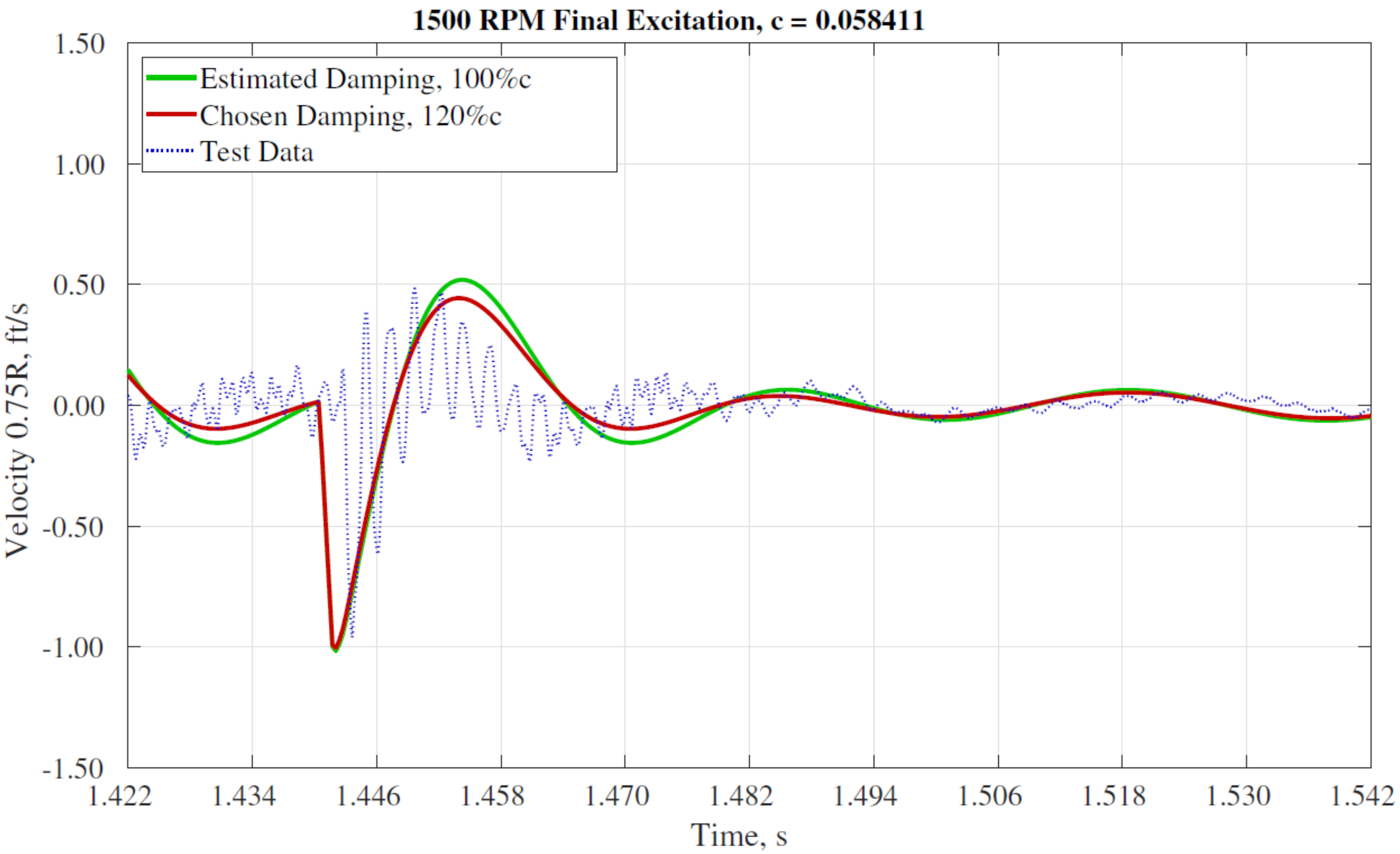


DAMPING ESTIMATION

Experimental Damping was between 8-14%

In order to tune the viscous damper (c) a value of c = 0.058411 ft-lb/rad was used @1500 RPM and varies with RPM.

Ultimately the viscous damper (based on a friction model) stabilizes the isolated rotor both experimentally and analytically.



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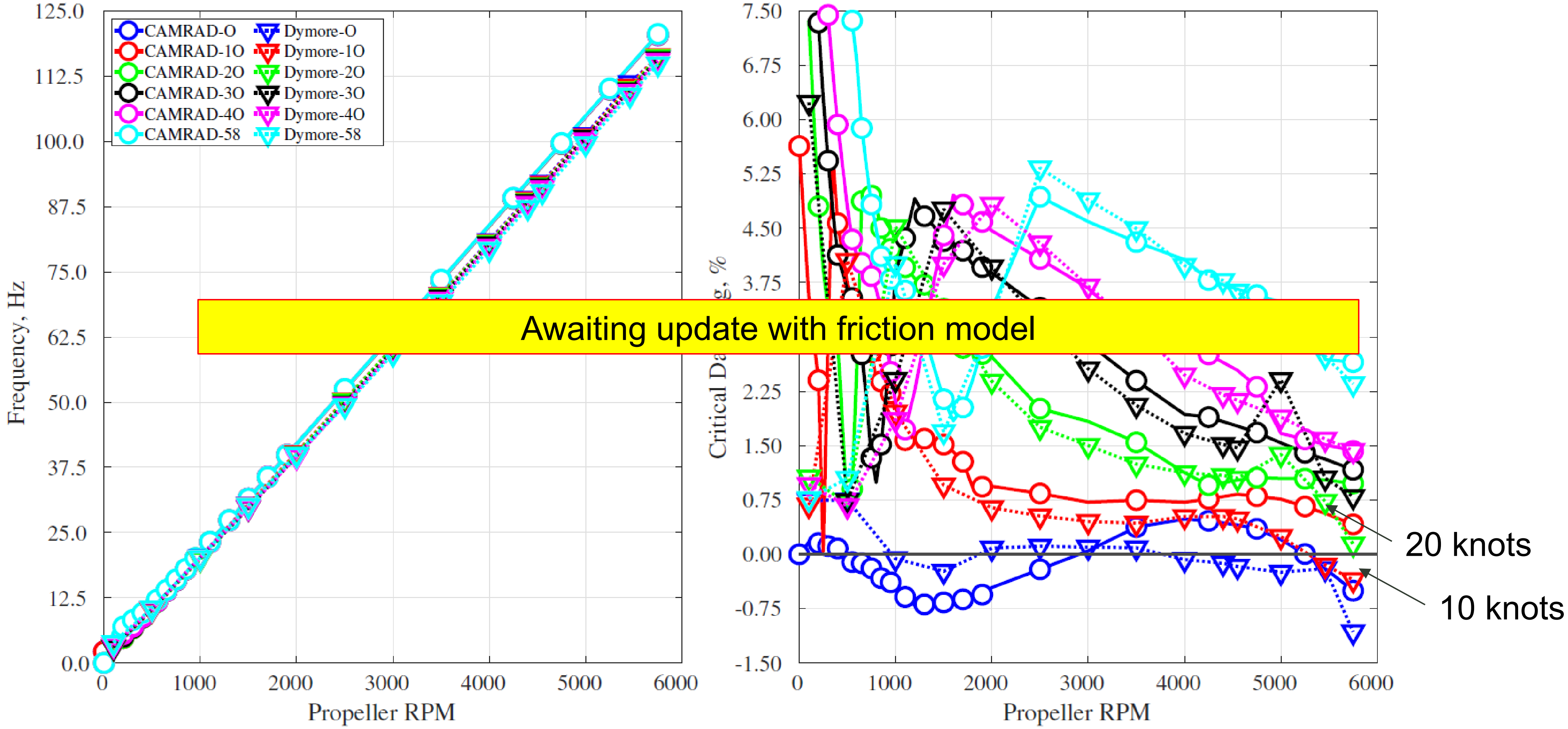

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CONCLUSIONS

Whirl Flutter Conclusions

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- **No whirl flutter concerns at high speeds**
- **Small instability (negative damping) predicted at low speeds—within assumed margin of at least 1% structural damping**
- **Whirl flutter stability boundary lies beyond the margins imposed in these analyses**

Rotor Stability Conclusions

- **Rotor stability tests indicated that there is very little risk of rotor instability at zero forward velocity**

ACKNOWLEDGEMENTS

NASTRAN Modeling
- Carol Wieseman
- Keerti Bhamidipati
- X-57 Structural Dynamics Team

DYMORE Support
- Olivier Bauchau

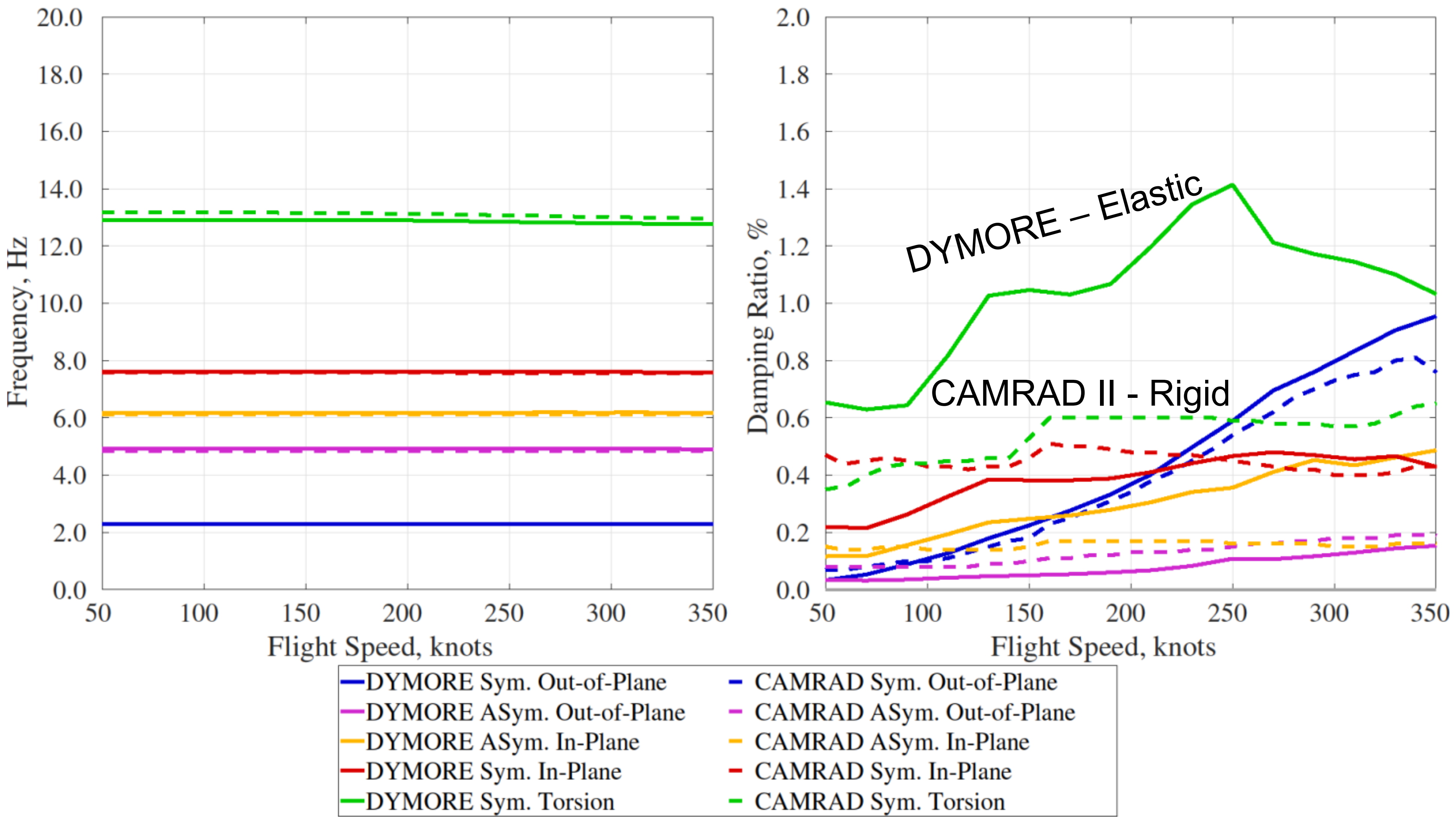
Testing Support
- John Swartzbaugh
- Low Speed Aeroacoustics Wind Tunnel personnel

Project Support
- Jeff Viken

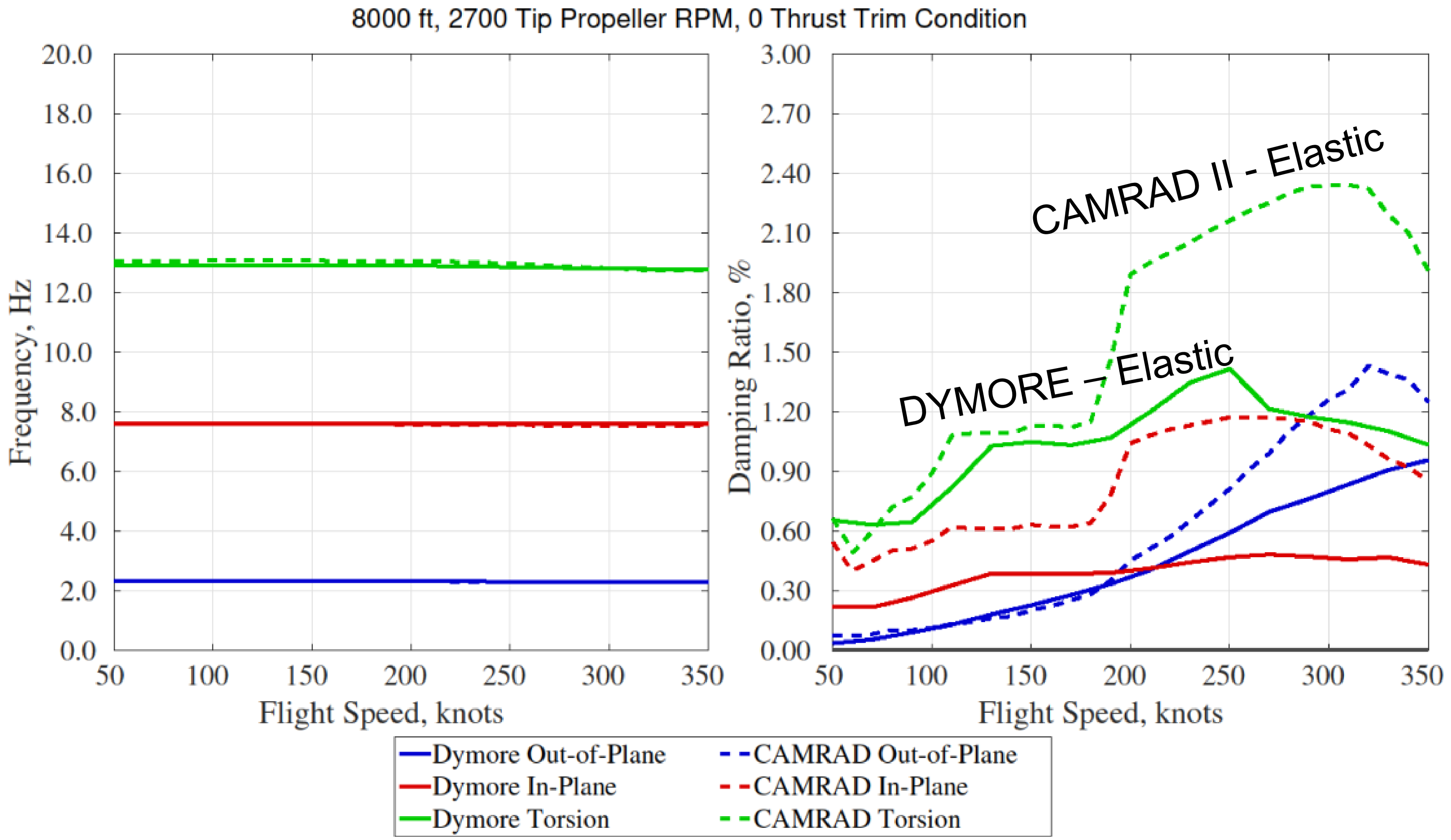
BACKUP SLIDES

Elastic vs Rigid Blades

RIGID BLADES VS ELASTIC BLADES

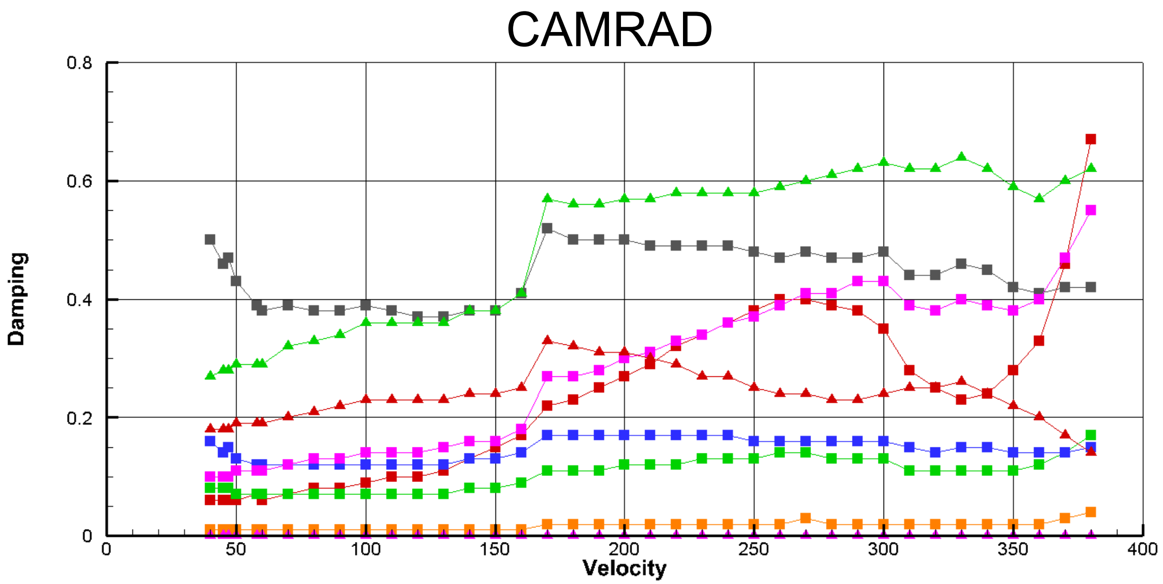


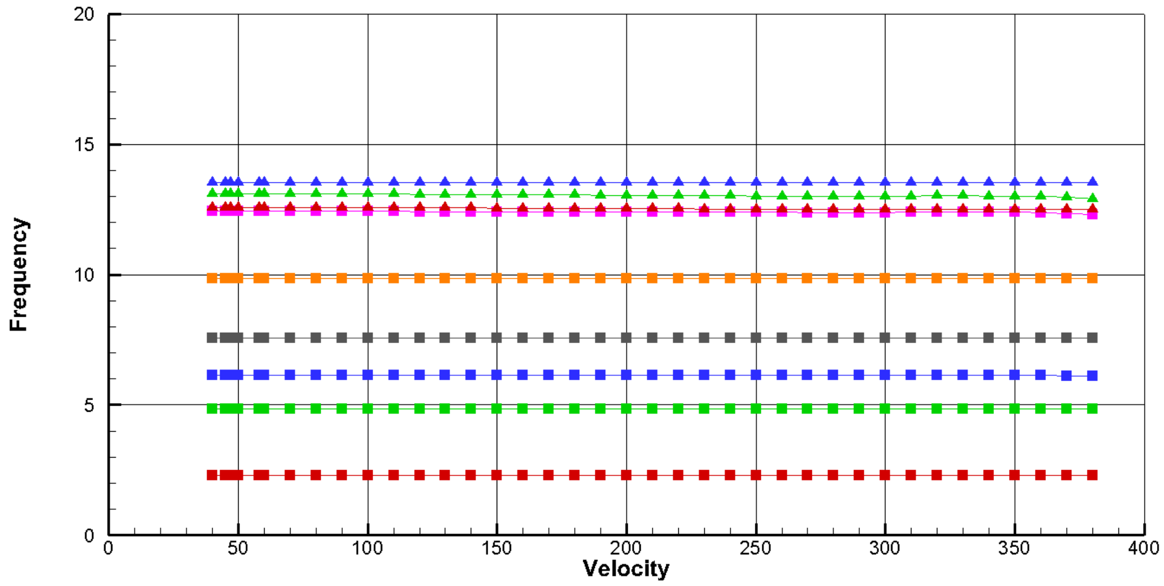
ELASTIC BLADES



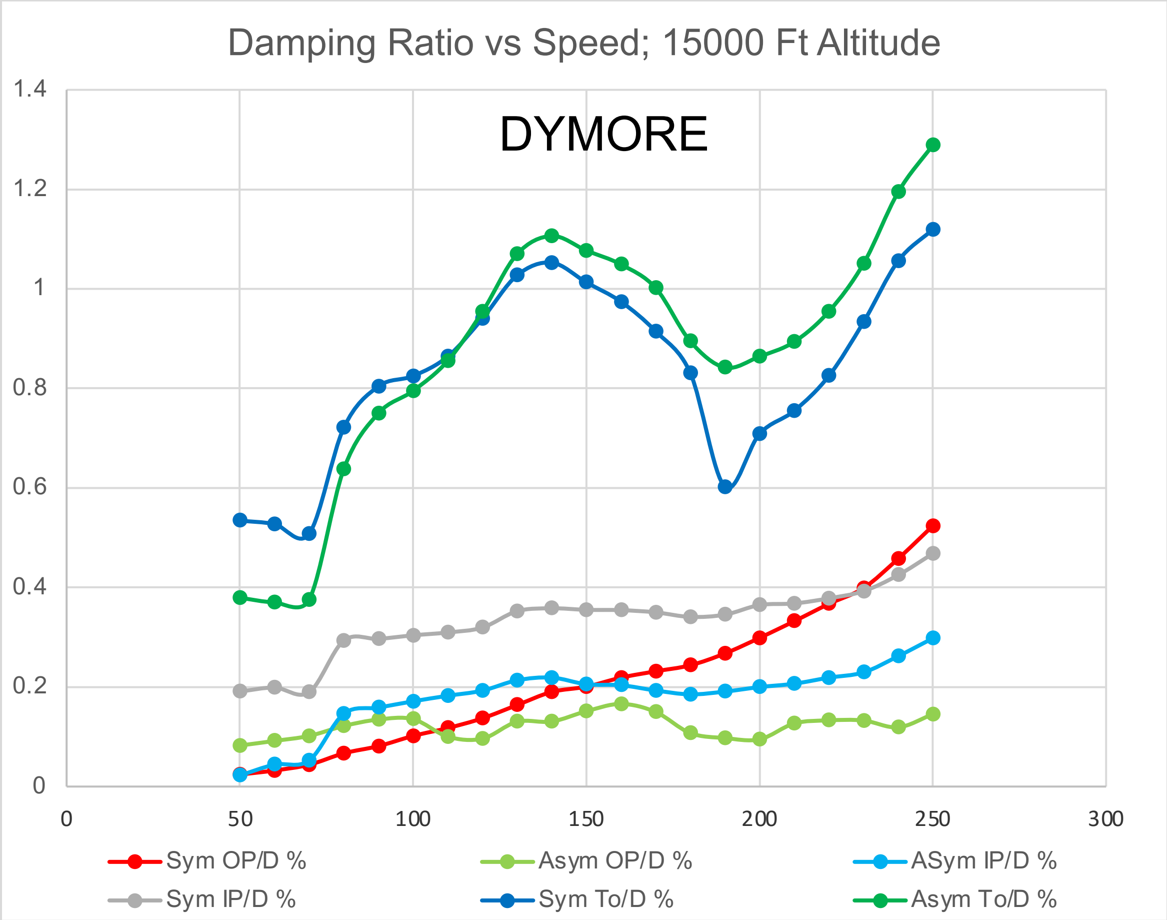
Additional Cases – Altitude Variation

WING MILLING & 15K ALTITUDE





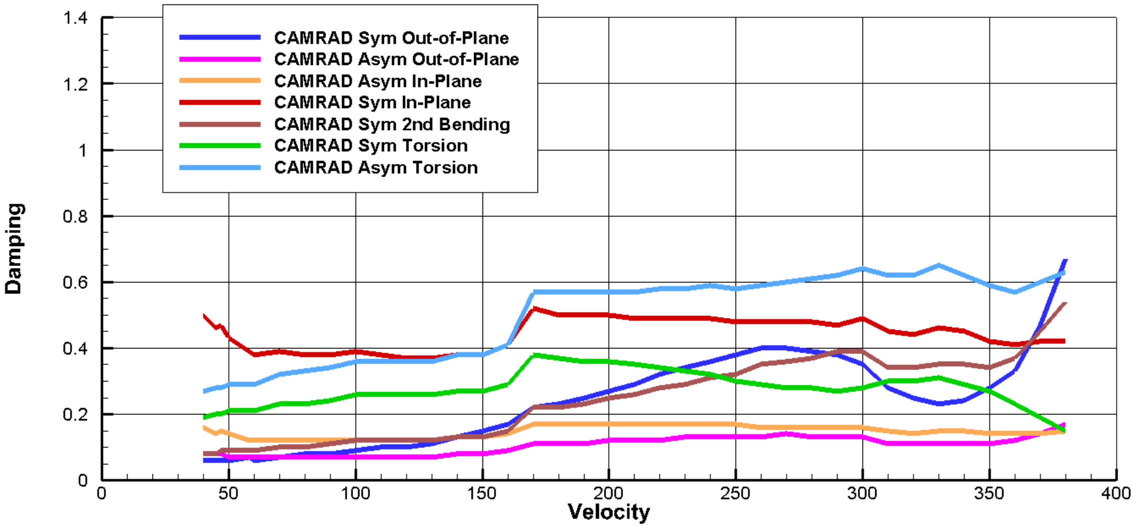
		Cruise Prop		
High Lift Prop		Cruise RPM	Take off RPM	Overspeed
		2250	2700	3080
	0 RPM			
	Scheduled HL Prop			
	Overspeed 5940 RPM			WM

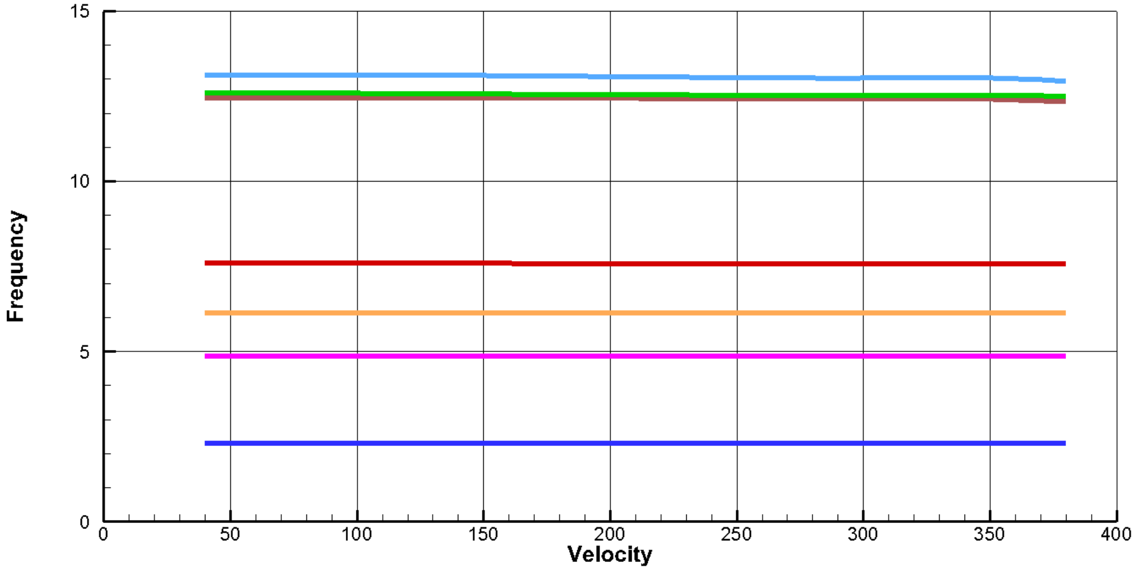


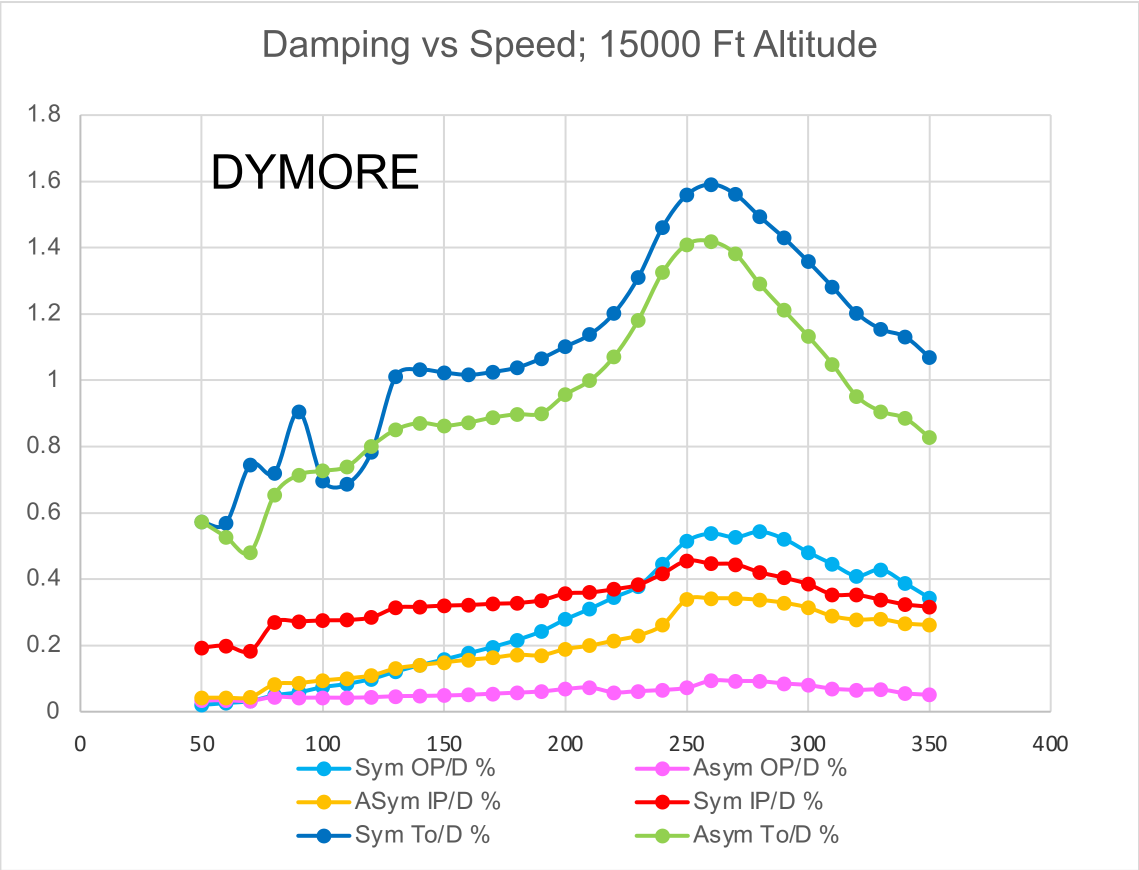
WING MILLING & 15K ALTITUDE

High Lift Prop		Cruise Prop		
		Cruise RPM	Take off RPM	Overspeed
		2250	2700	3080
	0 RPM			WM
	Scheduled HL Prop			
	Overspeed 5940 RPM			

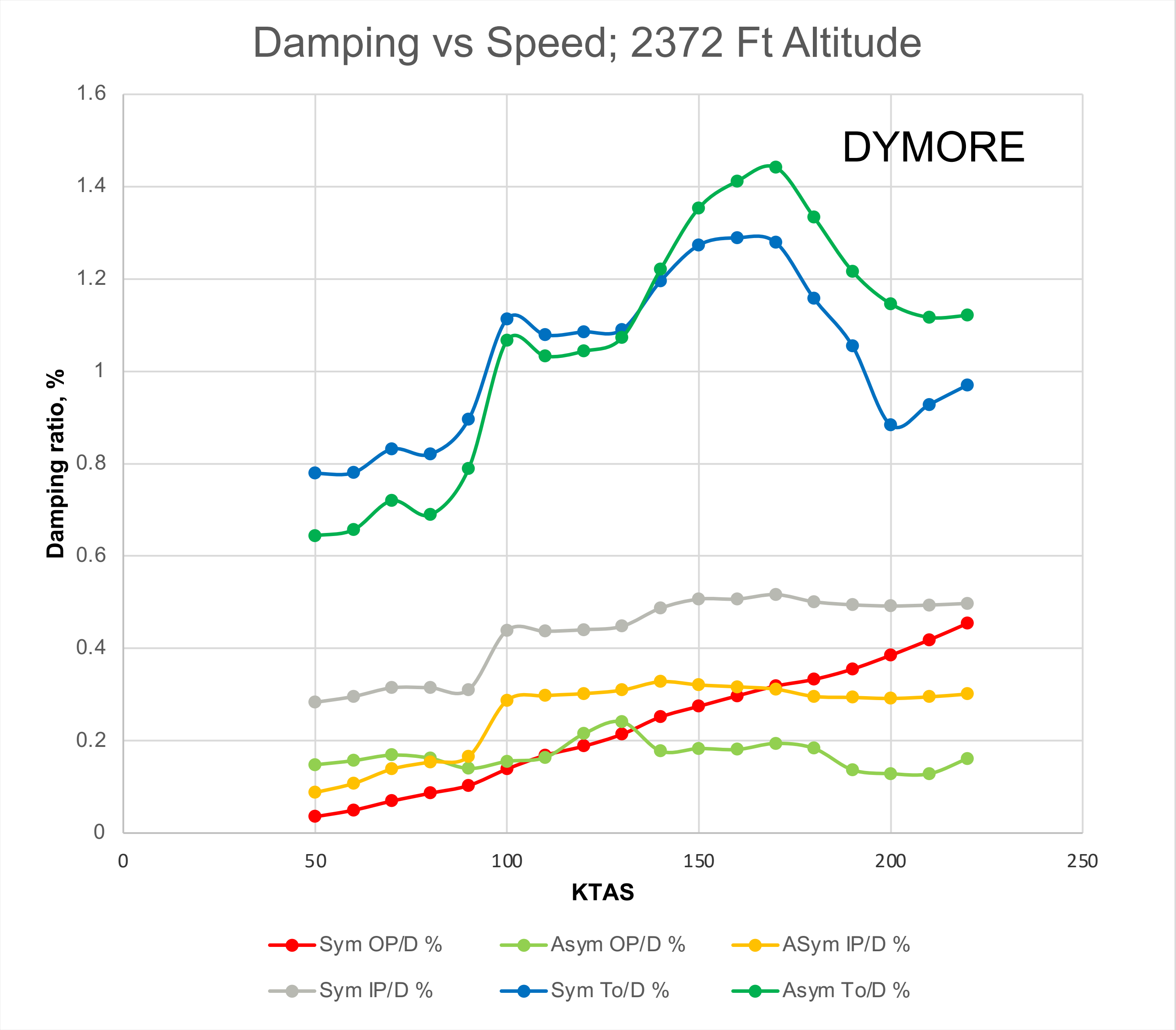
CAMRAD







WING MILLING & 2K ALTITUDE



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	Scheduled HL Prop			
	Overspeed 5940 RPM			WM

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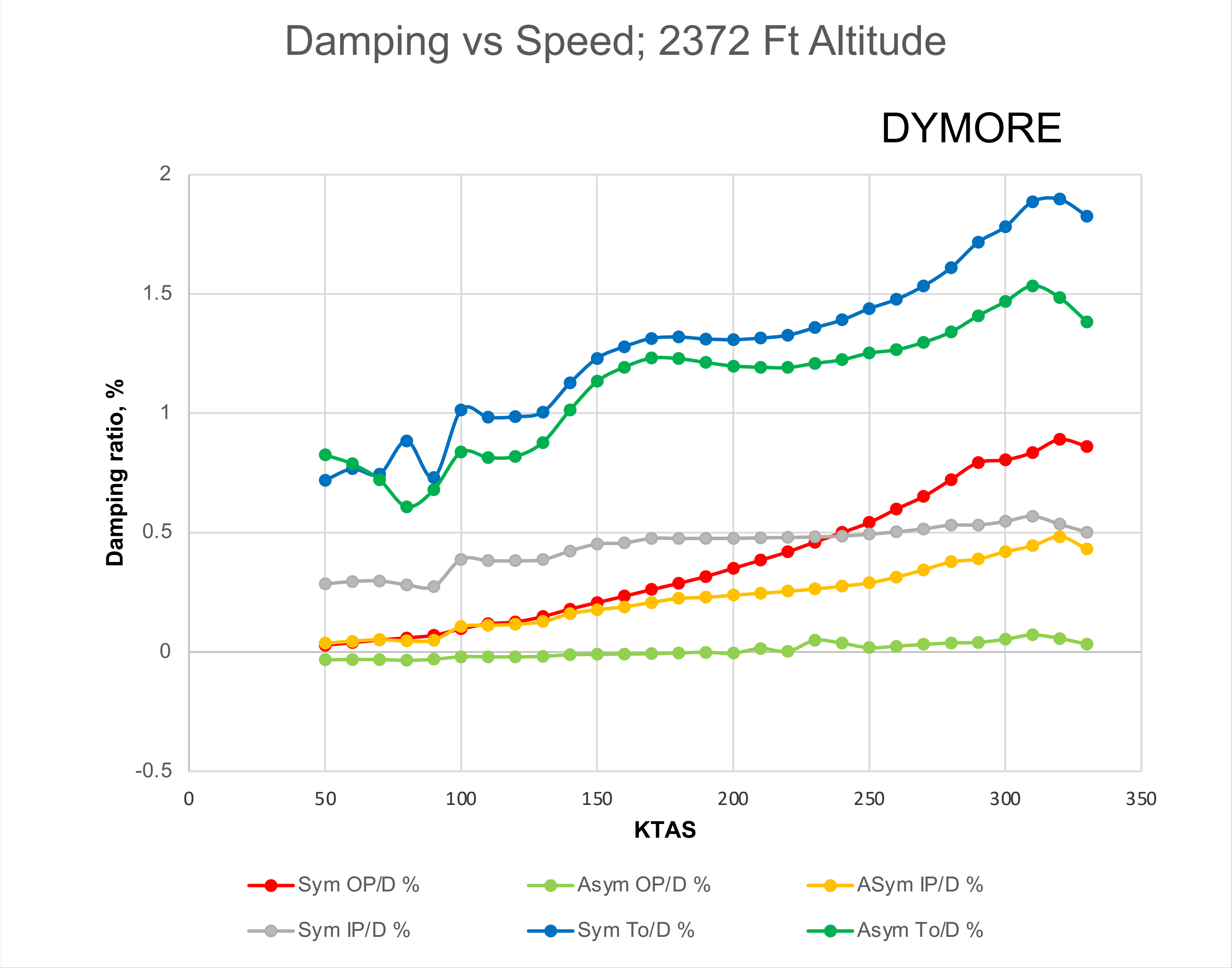

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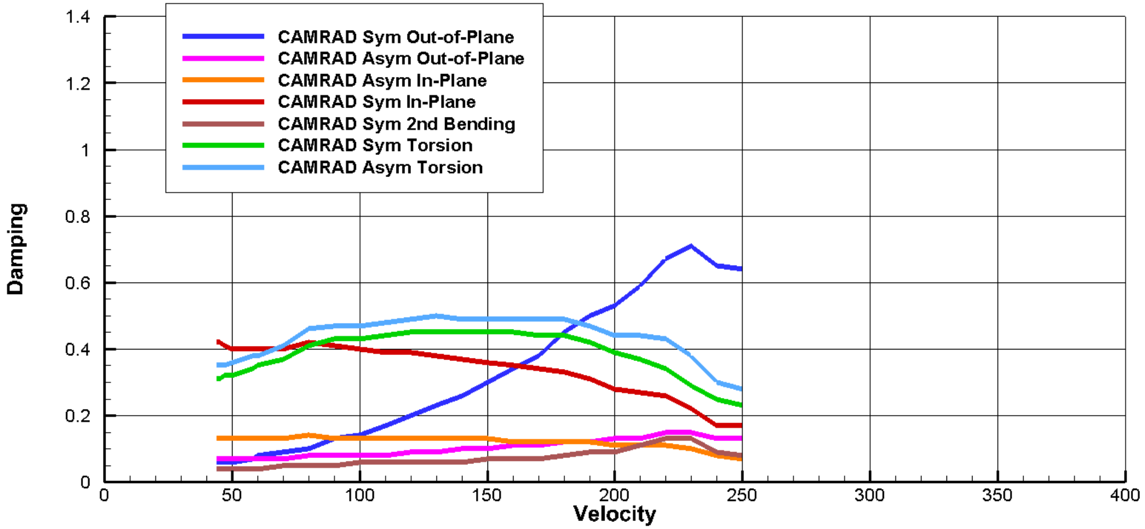
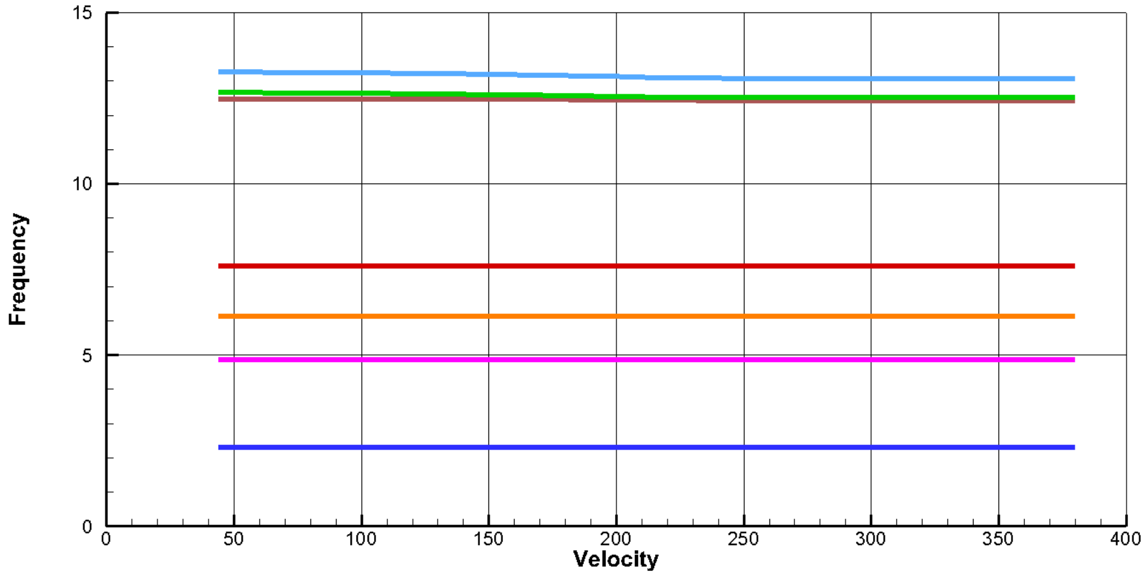
	0 RPM			WM
	Scheduled HL Prop			
	Overspeed 5940 RPM			

Additional Cases - Drag Trim

THRUSTING CASES @ 8K ALT





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		2250	2700	3080
	0 RPM	Drag	Drag	Drag
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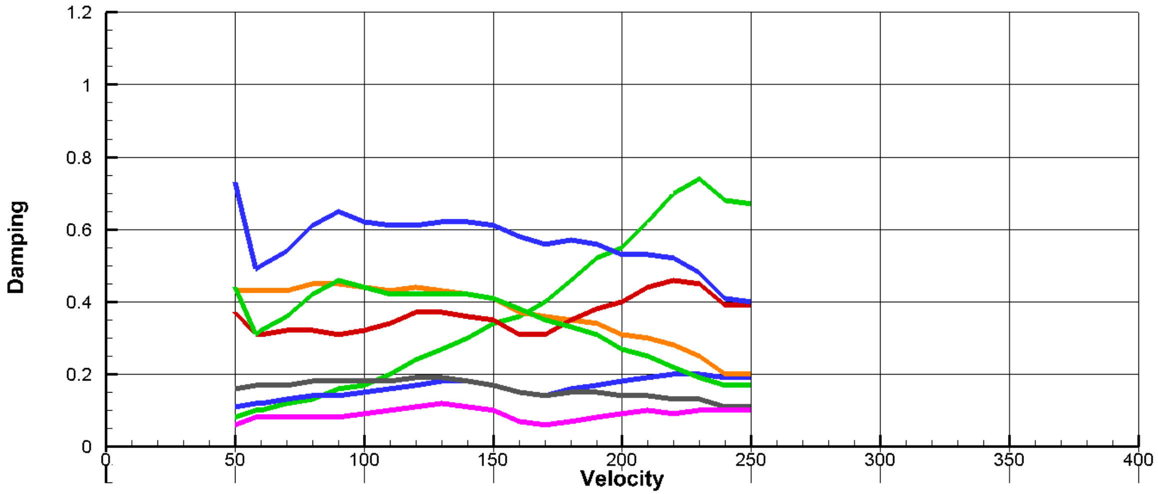

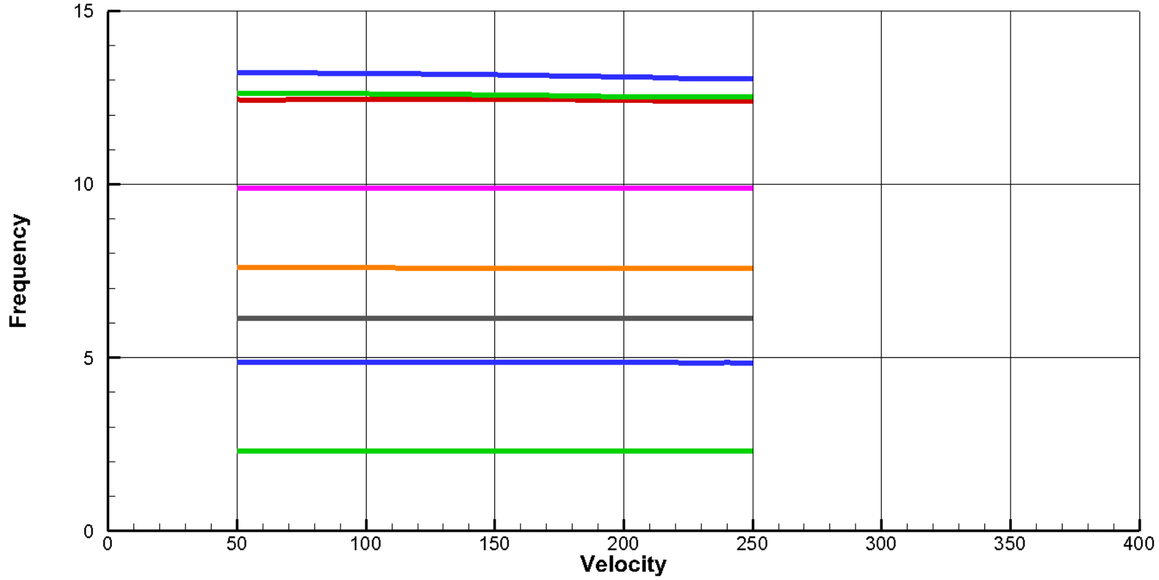

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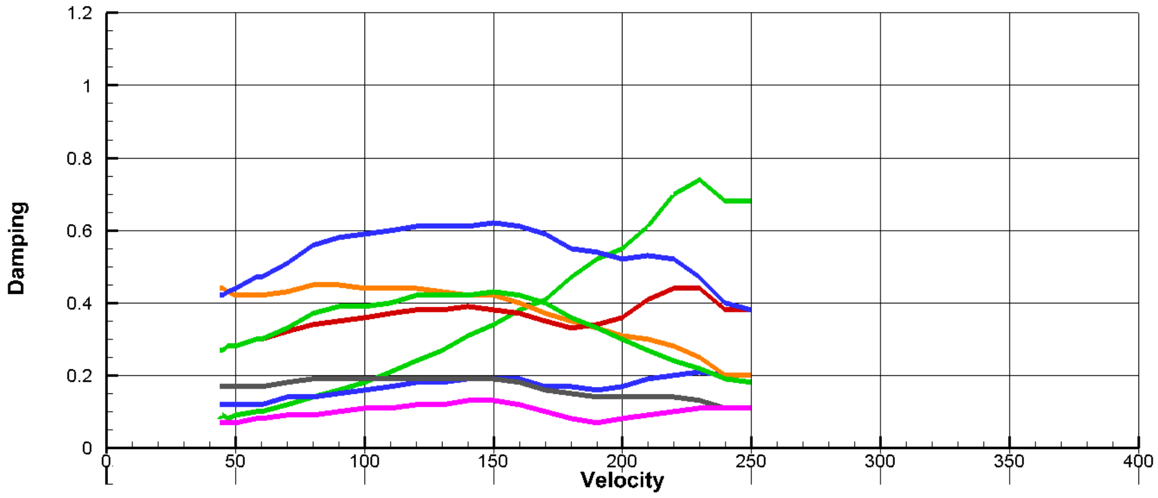

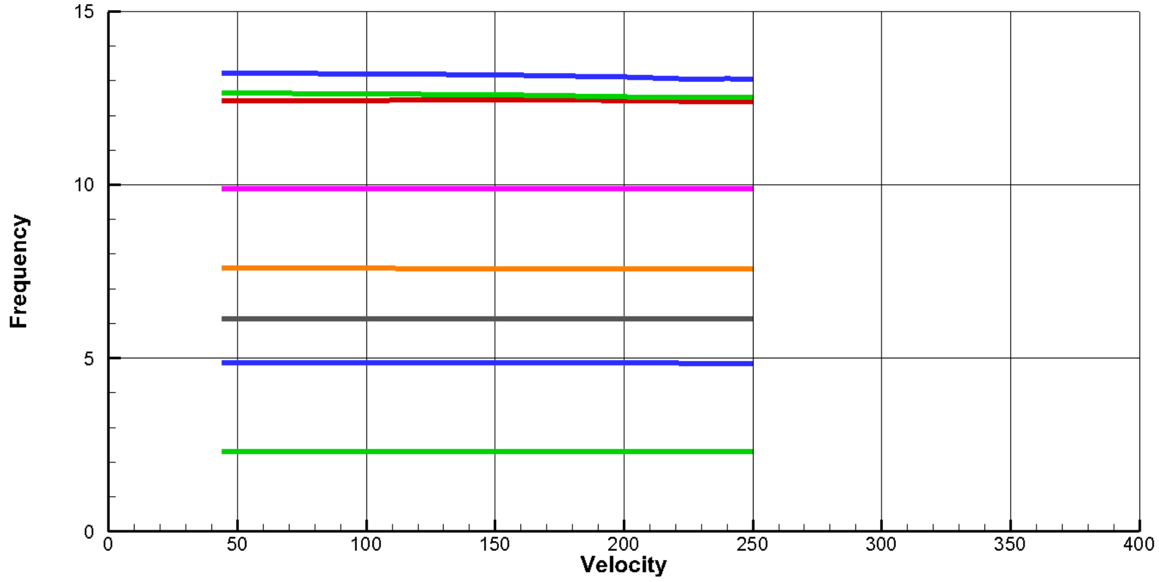

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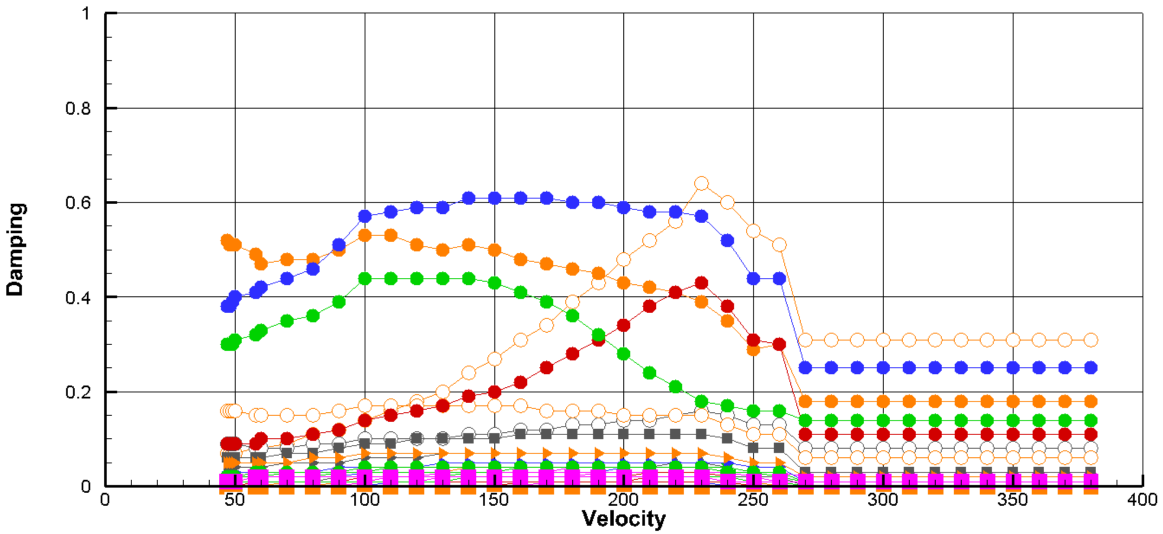

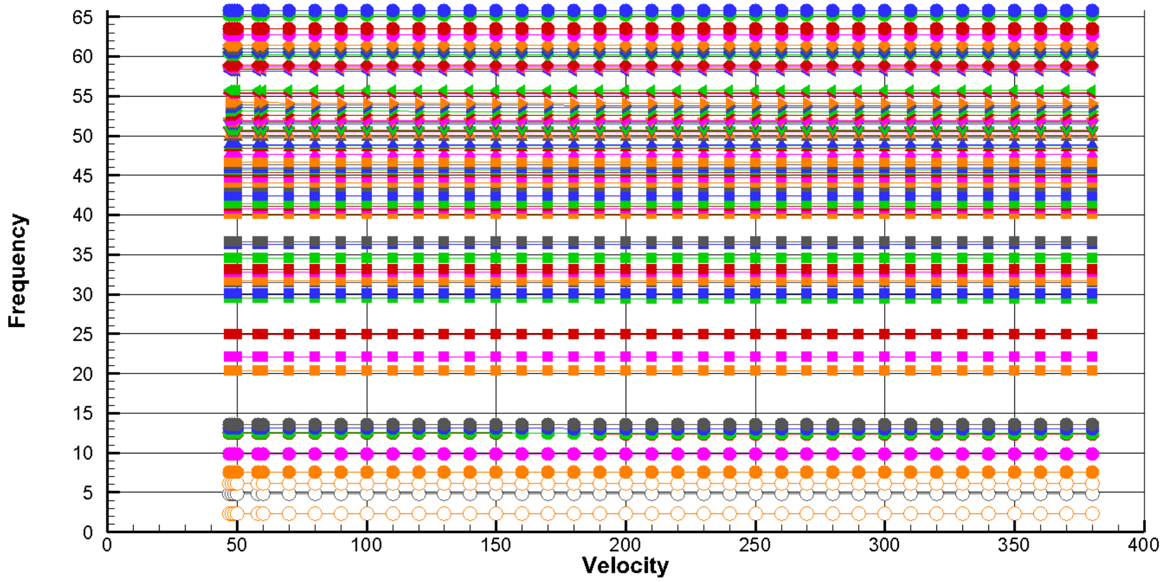

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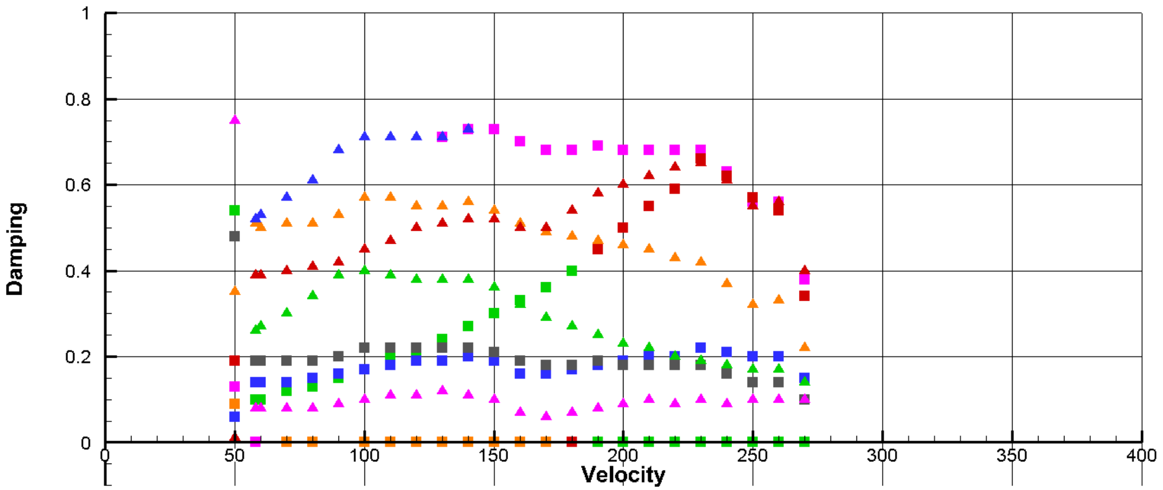

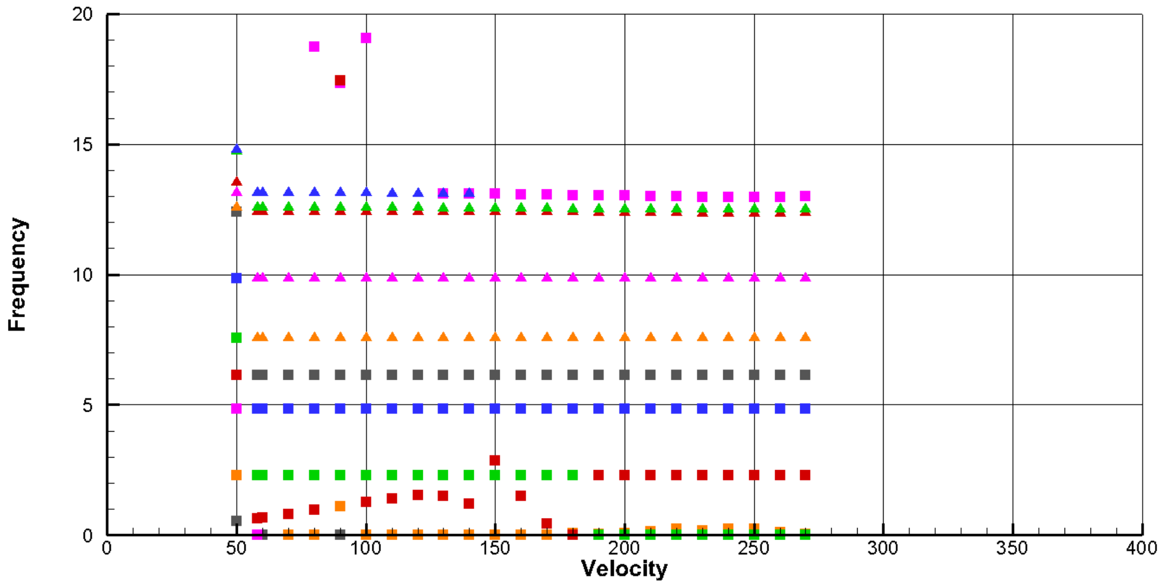

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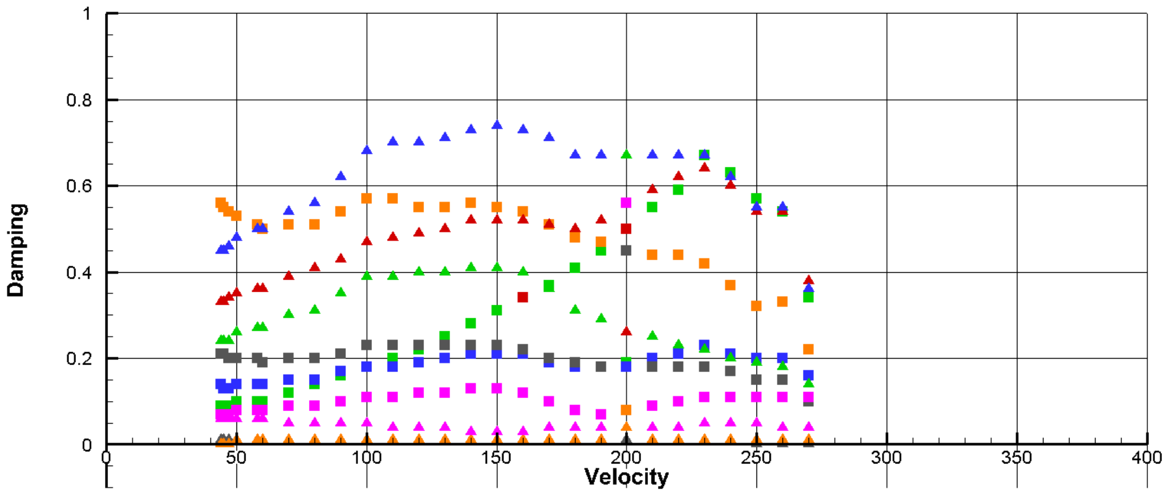
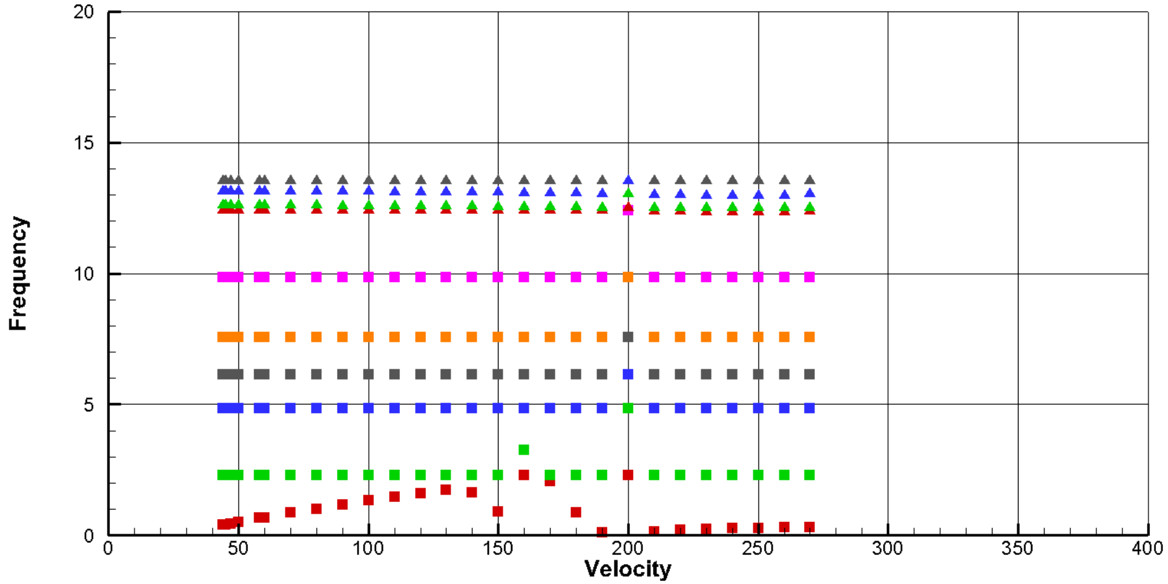
	Overspeed 5940 RPM	Drag	Drag	Drag

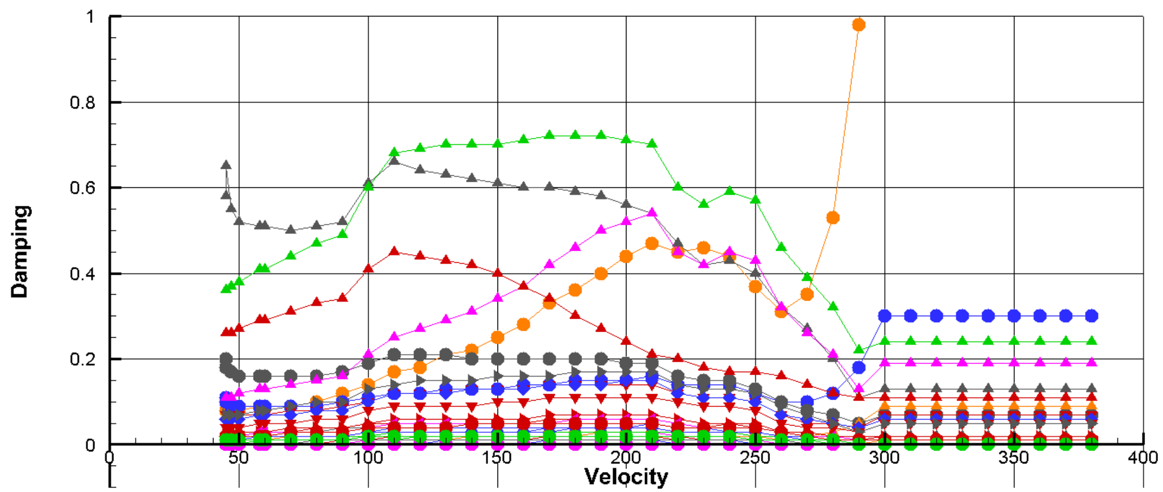
THRUSTING CASES @ 8K ALT

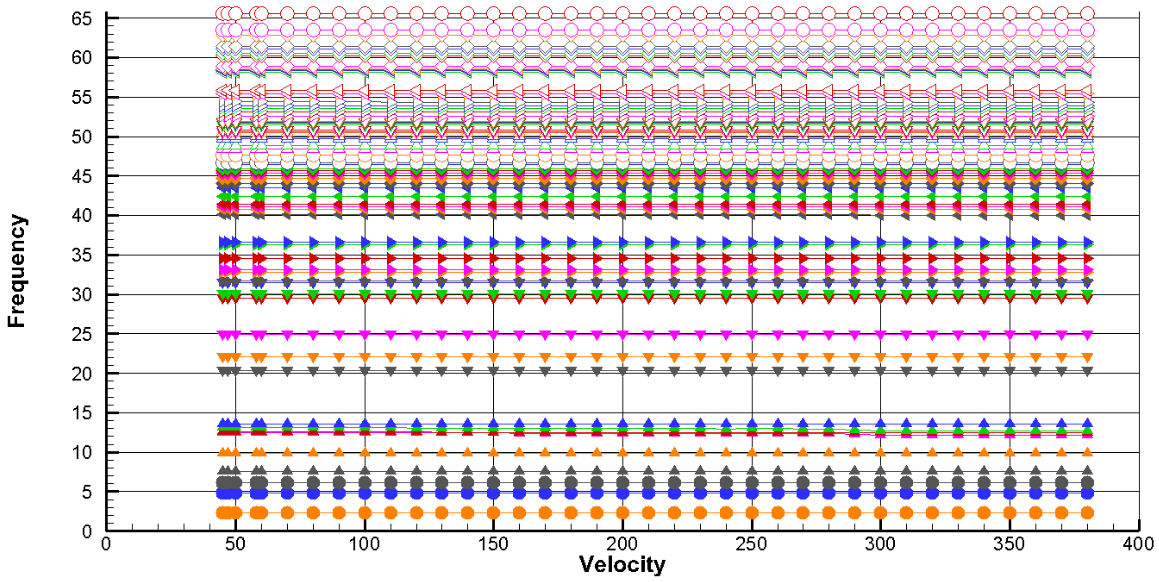




		Cruise Prop		
High Lift Prop		Cruise RPM	Take off RPM	Overspeed
		2250	2700	3080
	0 RPM	Drag	Drag	Drag
	Scheduled HL Prop	Drag	Drag	Drag
	Overspeed 5940 RPM	Drag	Drag	Drag

THRUSTING CASES @ 8K ALT

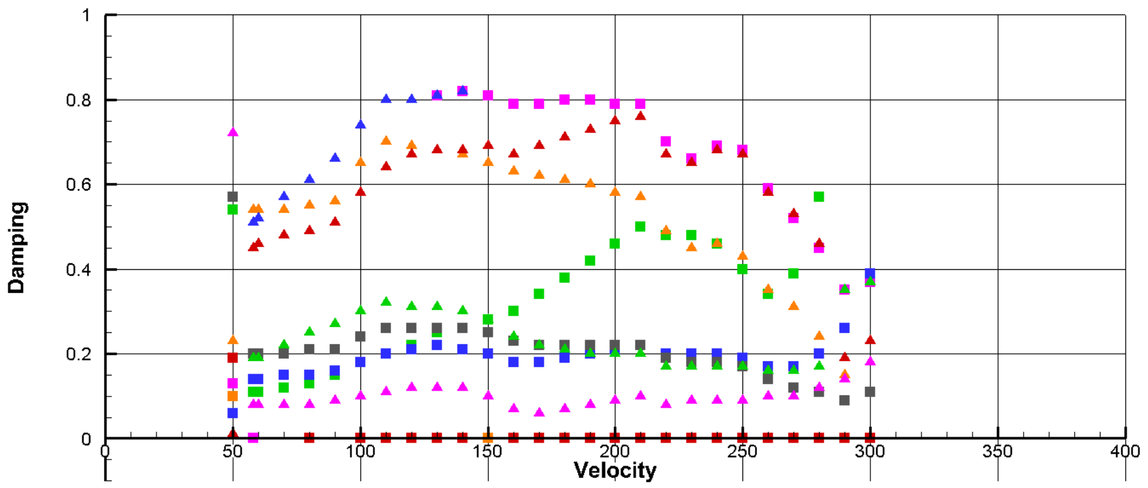


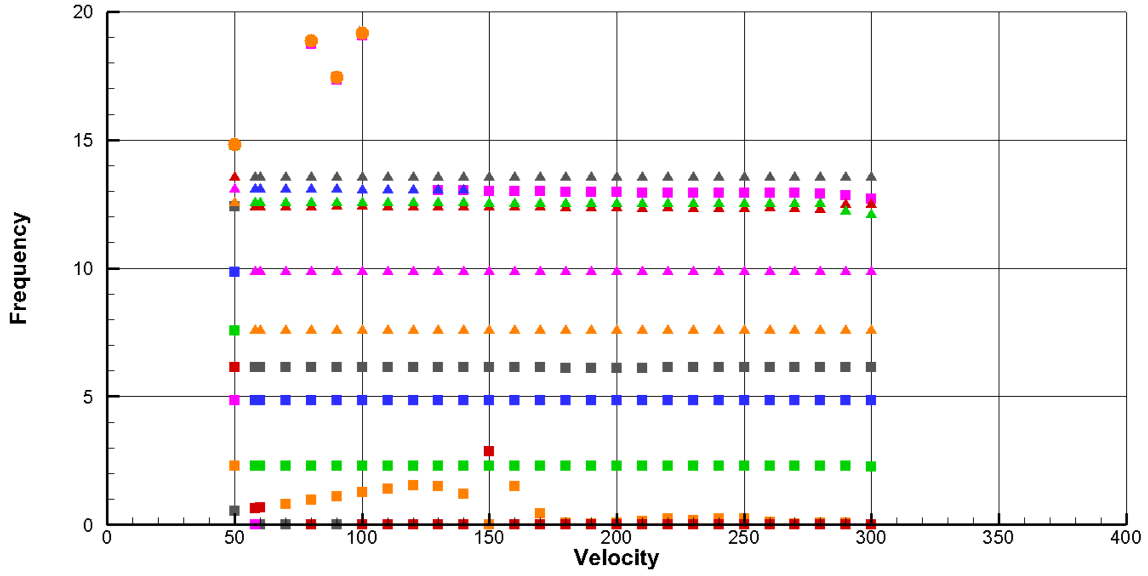


		Cruise Prop		
High Lift Prop		Cruise RPM	Take off RPM	Overspeed
		2250	2700	3080
	0 RPM	Drag	Drag	Drag
	Scheduled HL Prop	Drag	Drag	Drag
	Overspeed 5940 RPM	Drag	Drag	Drag

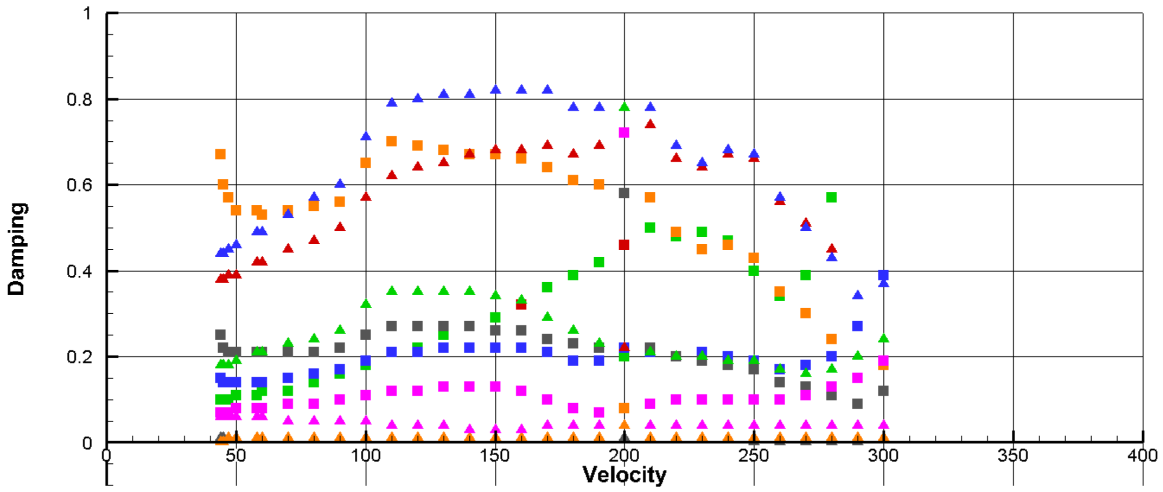
THRUSTING CASES @ 8K ALT

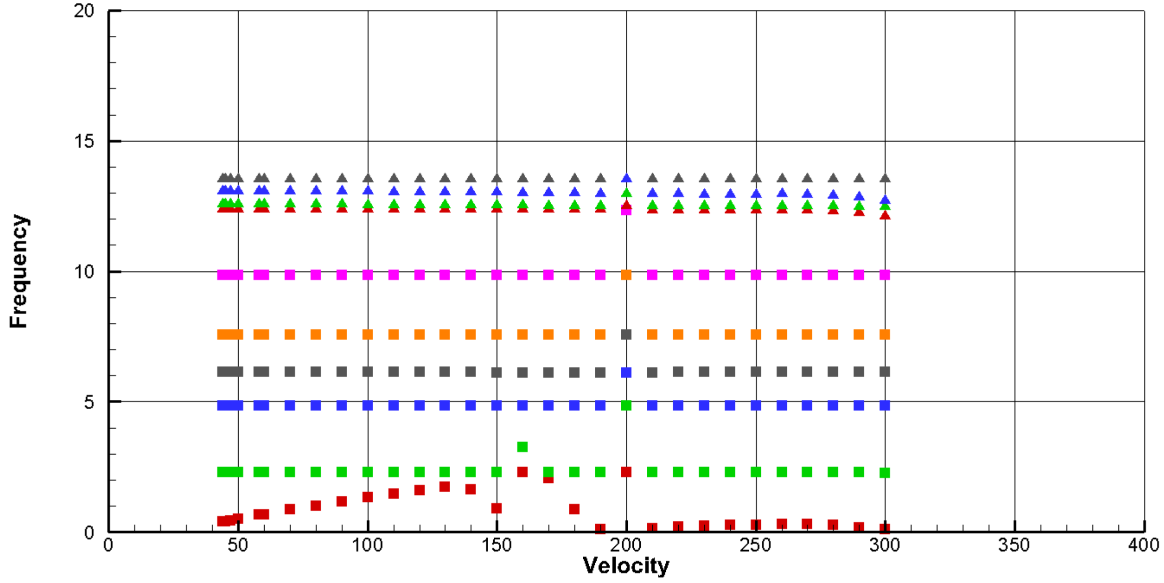
		Cruise Prop		
High Lift Prop		Cruise RPM	Take off RPM	Overspeed
		2250	2700	3080
	0 RPM	Drag	Drag	Drag
	Scheduled HL Prop	Drag	Drag	Drag
	Overspeed 5940 RPM	Drag	Drag	Drag





THRUSTING CASES @ 8K ALT





		Cruise Prop		
High Lift Prop		Cruise RPM	Take off RPM	Overspeed
		2250	2700	3080
	0 RPM	Drag	Drag	Drag
	Scheduled HL Prop	Drag	Drag	Drag
	Overspeed 5940 RPM	Drag	Drag	Drag

Appendix – Additional Info

FULL LIST OF NASTRAN MODES INCLUDED IN CAMRAD

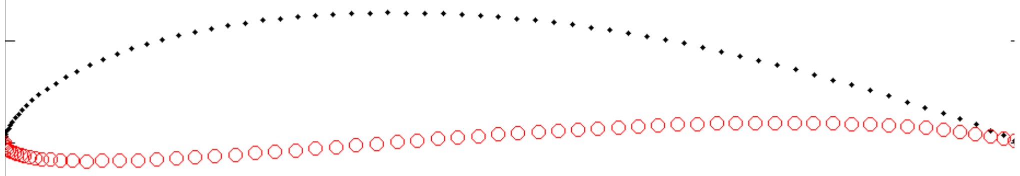
NASTRAN Mode	7	8	9	10	11	13	14	15	16	21	22	25
Freq	2.28751	4.847326	6.126883	7.563687	9.898156	12.563896	12.810463	13.470976	13.545998	20.34602	22.14168	24.93236
NASTRAN Mode	31	32	33	34	35	36	39	41	42	44	45	47
Freq	29.413616	30.376893	31.471862	31.874522	32.761669	33.176606	34.760869	36.58744	36.672267	40.69428	41.00187	41.34609
NASTRAN Mode	48	51	54	55	56	57	58	59	61	62	63	67
Freq	41.449966	42.413348	43.526617	44.01836	44.735875	45.436412	45.650744	45.984773	46.63239	46.80055	47.71474	48.73529
NASTRAN Mode	68	70	72	73	74	75	76	79	81	82	84	85
Freq	48.850597	49.371877	50.114985	50.252796	50.586867	50.640985	50.952279	51.716223	51.891773	51.99303	52.2794	52.91955
NASTRAN Mode	86	88	89	91	92	95	96	103	105	108	111	112
Freq	53.13975	53.767423	53.987421	54.784403	55.447143	55.882392	56.198277	58.1278	58.432189	58.56422	58.92151	59.1678
NASTRAN Mode	120	123	128	133	137	138	149	150	151	163	166	167
Freq	60.859404	61.09643	61.695662	62.238816	63.444205	63.475583	65.778647	66.201089	66.336697	68.77904	69.6895	69.90349
NASTRAN Mode	168	169	170	171	175	176	177	180	183	184	185	186
Freq	70.022069	70.186049	70.319571	70.82668	72.960714	72.974057	73.09487	73.996564	74.765809	75.27459	75.30127	75.3195
NASTRAN Mode	187	188	191	192	193	195	196	198	199	200	203	206
Freq	75.430694	75.629349	76.09066	76.366363	77.151826	77.738601	77.879505	77.972896	78.220315	78.51638	78.78656	79.27521
NASTRAN Mode	207	208	209	210								
Freq	79.336535	79.35709	79.565536	79.665223								

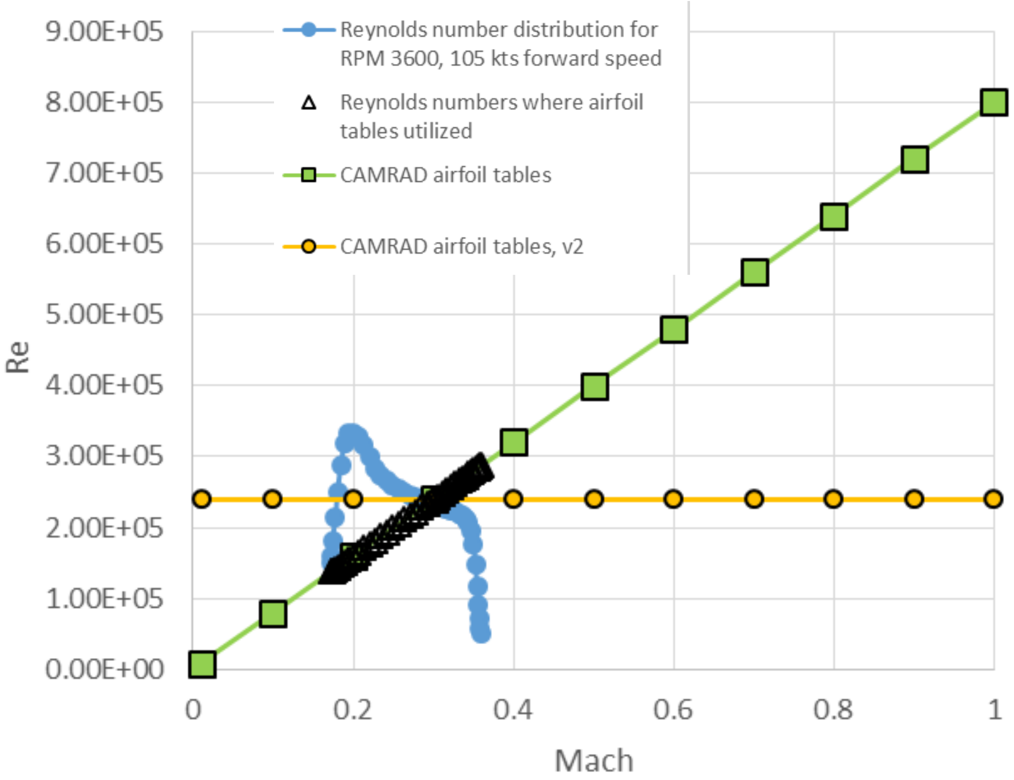
DOWN SELECT ALGORITHM

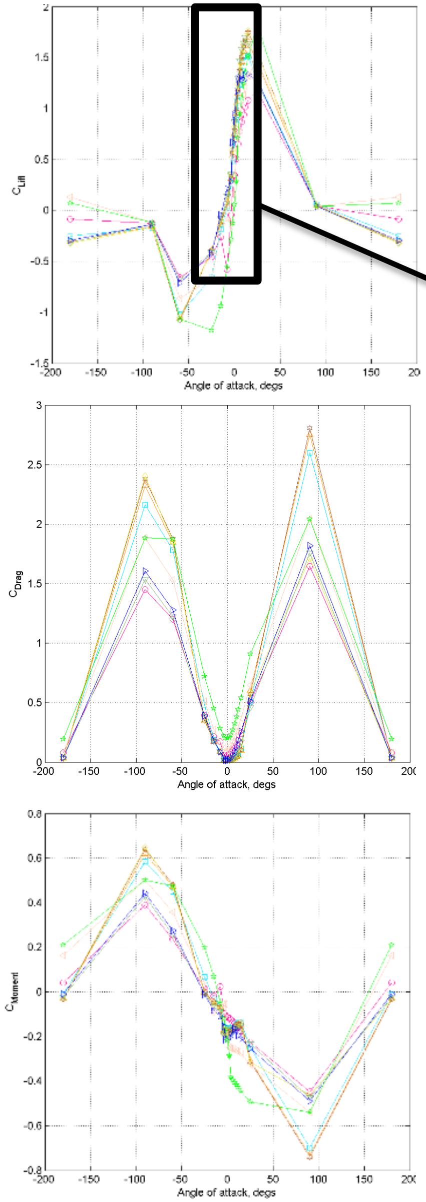
- Step 1. Sum all Translation & Sum all Rotation at hub nodes
- Step 2. Select grid point for sorting (right hand cruise prop)
- Step 3. Keep all modes with sum of Translation > 0.7 (ft/ft)
  Keep all modes with sum of rotation > 0.14 (rad/ft)
- Step 4. Sort all modes based on mode shape amplitude
- Step 5. Keep the highest largest N modes, (N = 100)

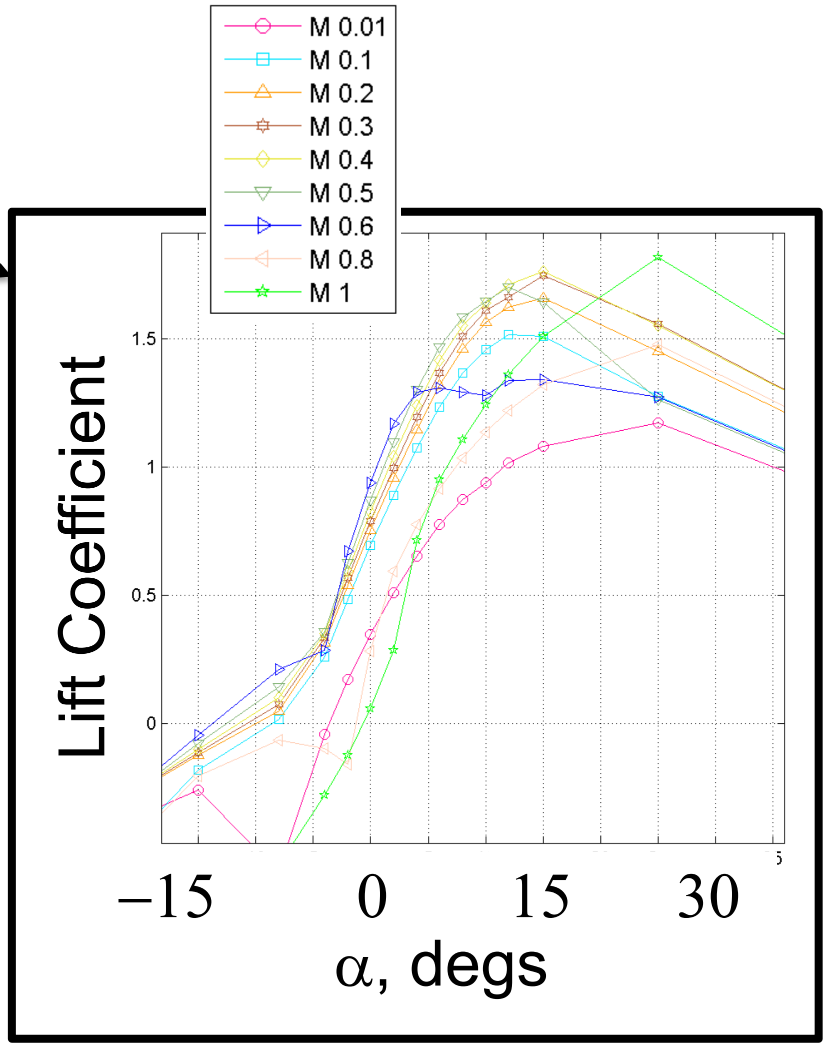
CAMRAD INPUT AERODYNAMIC MODELING

MH114: RANS analyses run with ARC2D Tables of Lift, Drag and Pitching moment

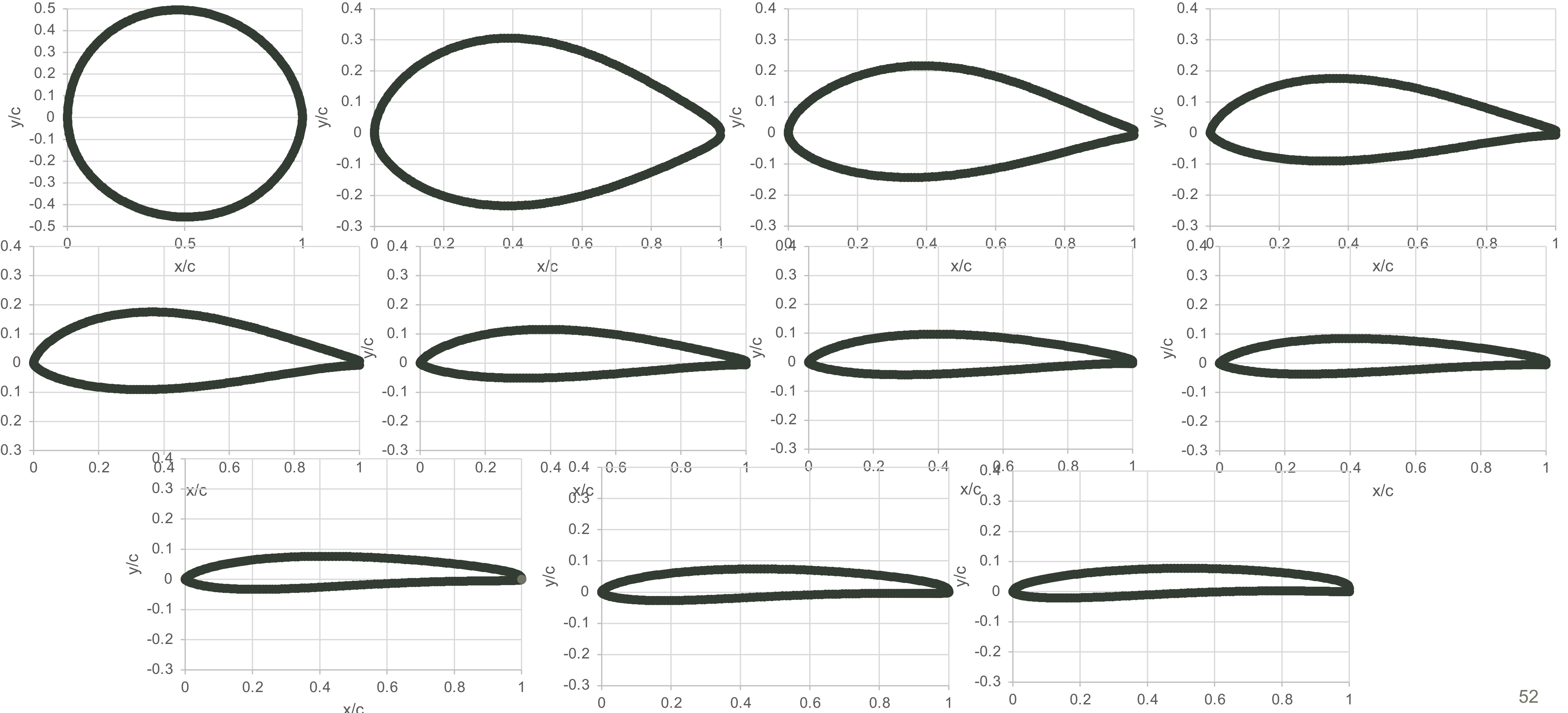




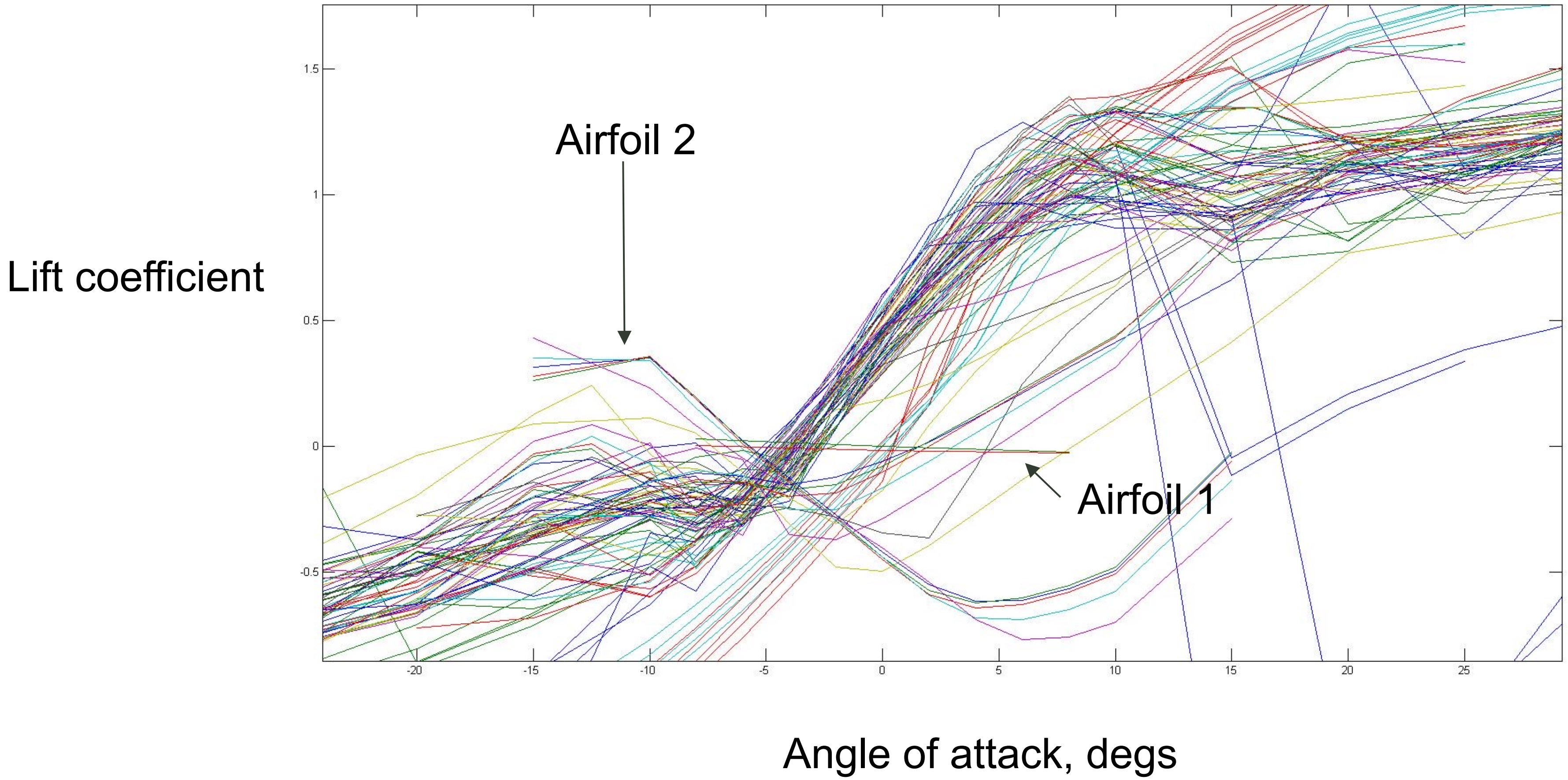




AIRFOIL COORDINATES, X-57 CRUISE PROP BLADES

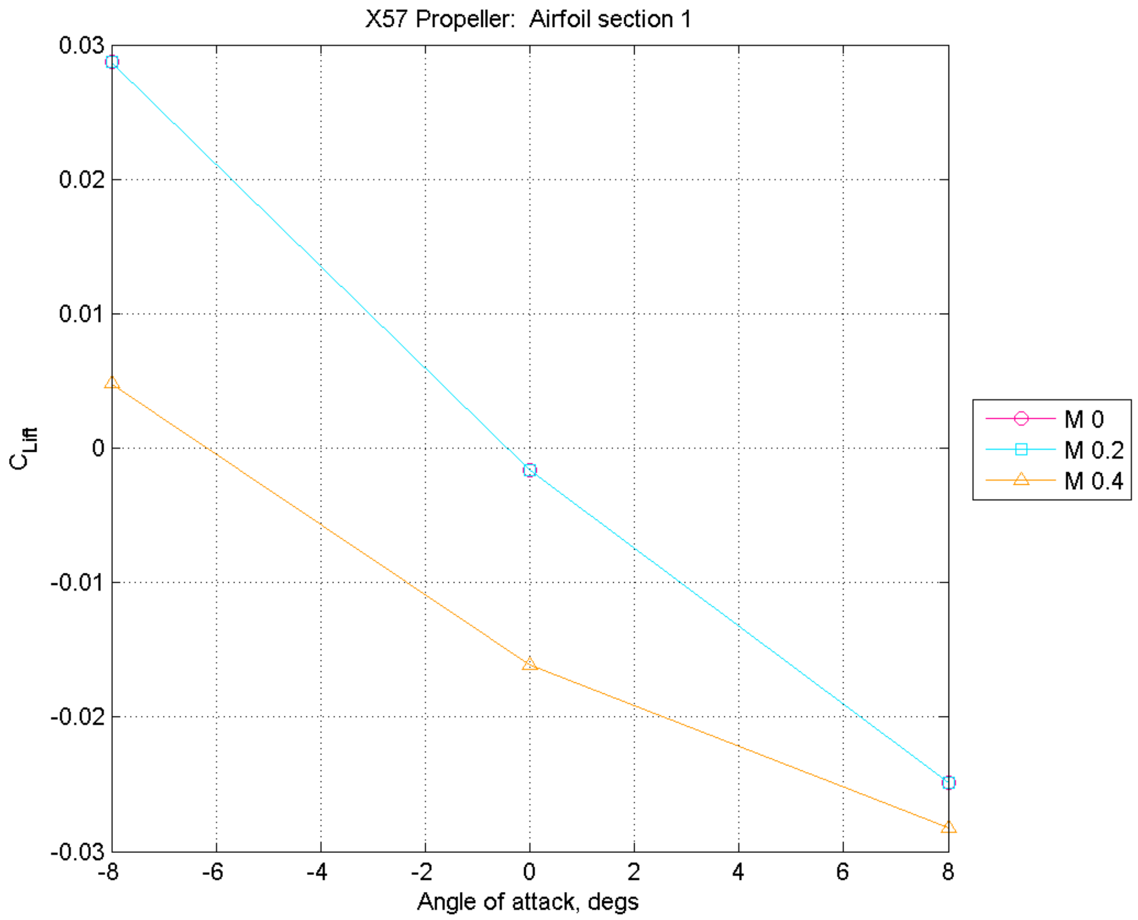


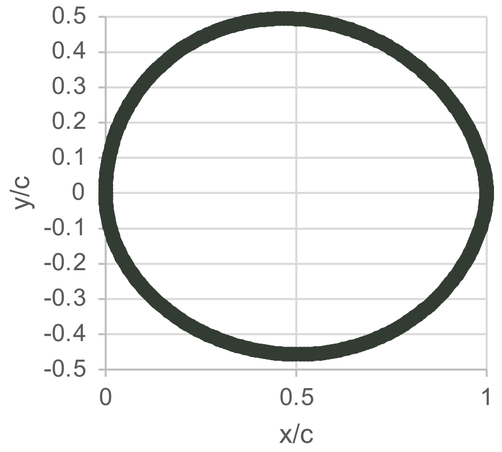
ALL RESULTS OVERPLOTTED, FOR ALL AIRFOILS, FOR ALL MACH NUMBERS, USING ARC2D NAVIER STOKES 2-DIMENSIONAL CODE



CFD results from Andrew Kreshock, November 2017

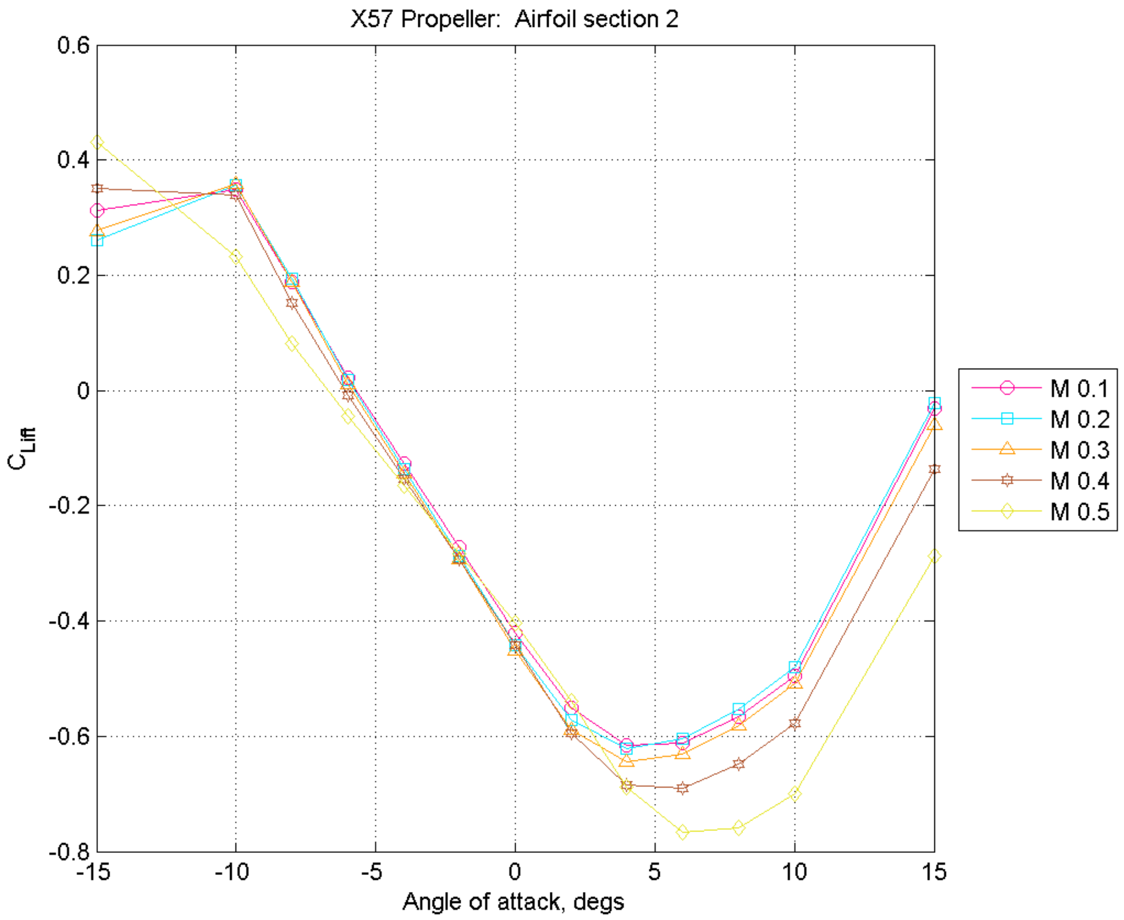
AIRFOIL CFD RESULTS, LIFT VS ANGLE OF ATTACK FOR VARYING MACH NUMBERS, BLADE SECTION 1

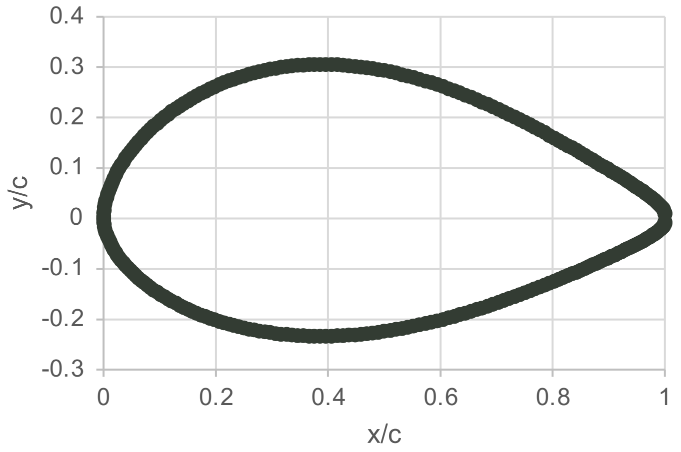




Using ARC2D Navier Stokes 2-dimensional code

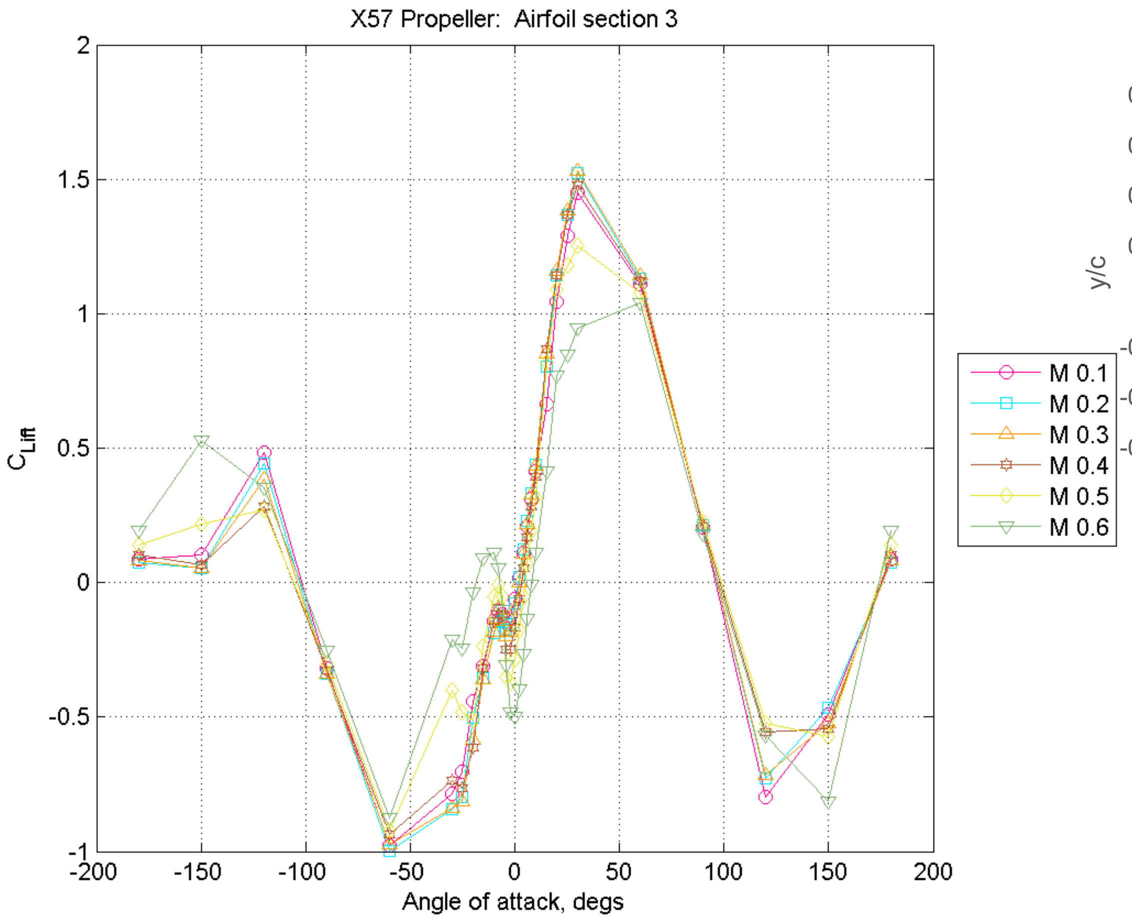
AIRFOIL CFD RESULTS, LIFT VS ANGLE OF ATTACK FOR VARYING MACH NUMBERS, BLADE SECTION 2

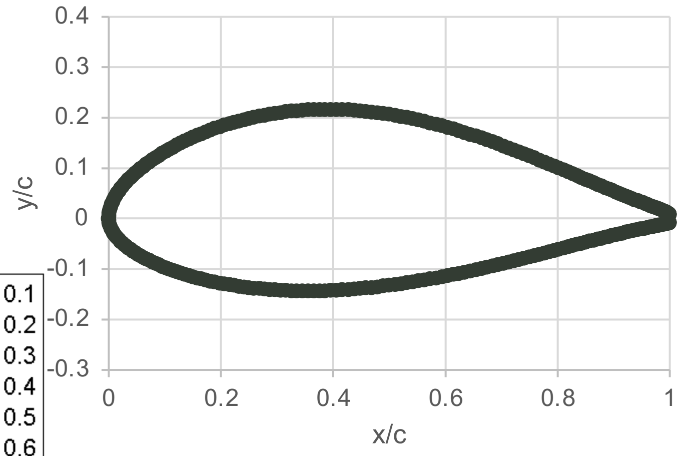




Using ARC2D Navier Stokes 2-dimensional code

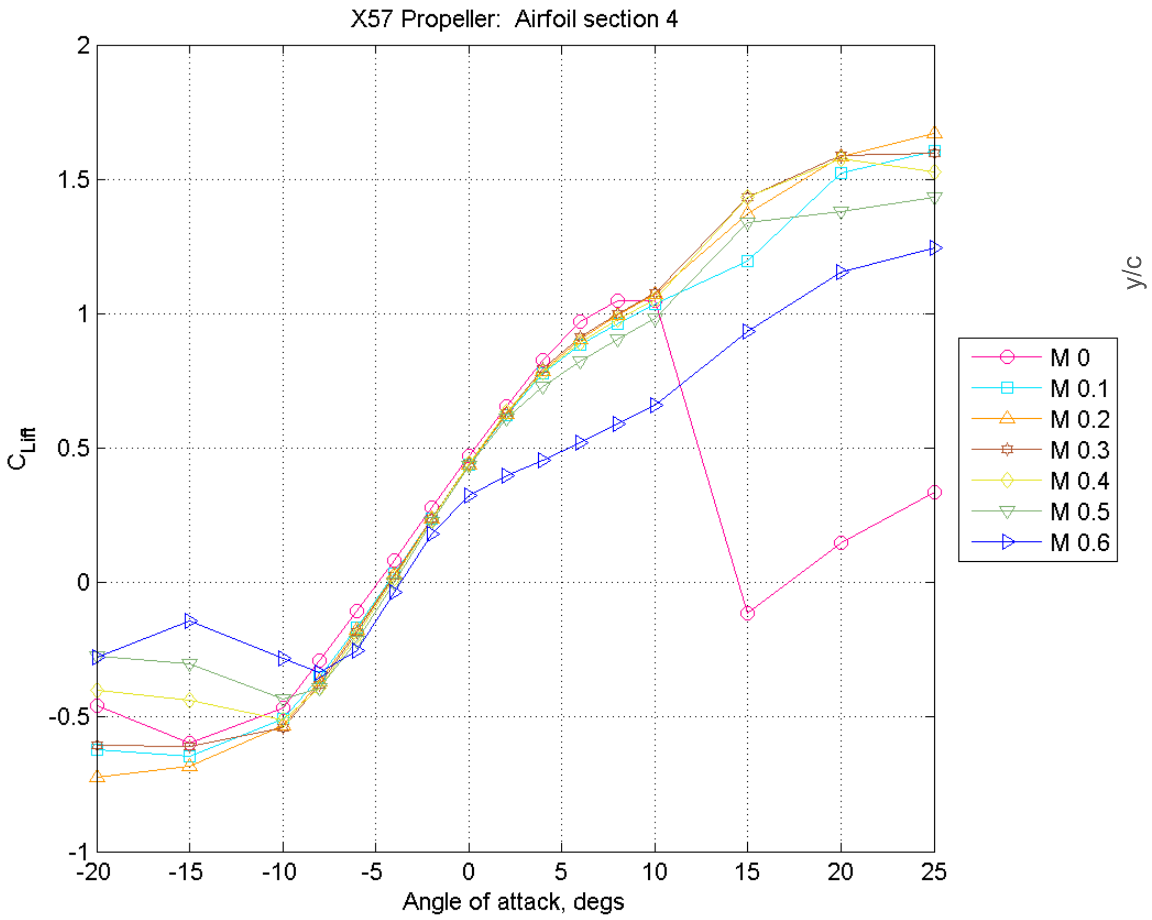
AIRFOIL CFD RESULTS, LIFT VS ANGLE OF ATTACK FOR VARYING MACH NUMBERS, BLADE SECTION 3

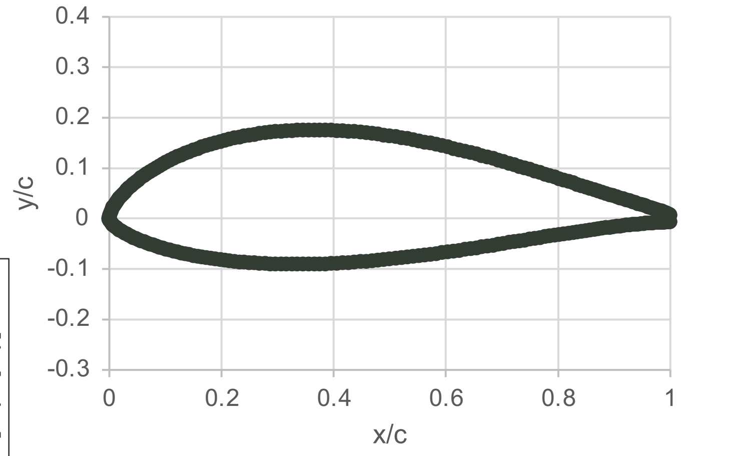




Using ARC2D Navier Stokes 2-dimensional code

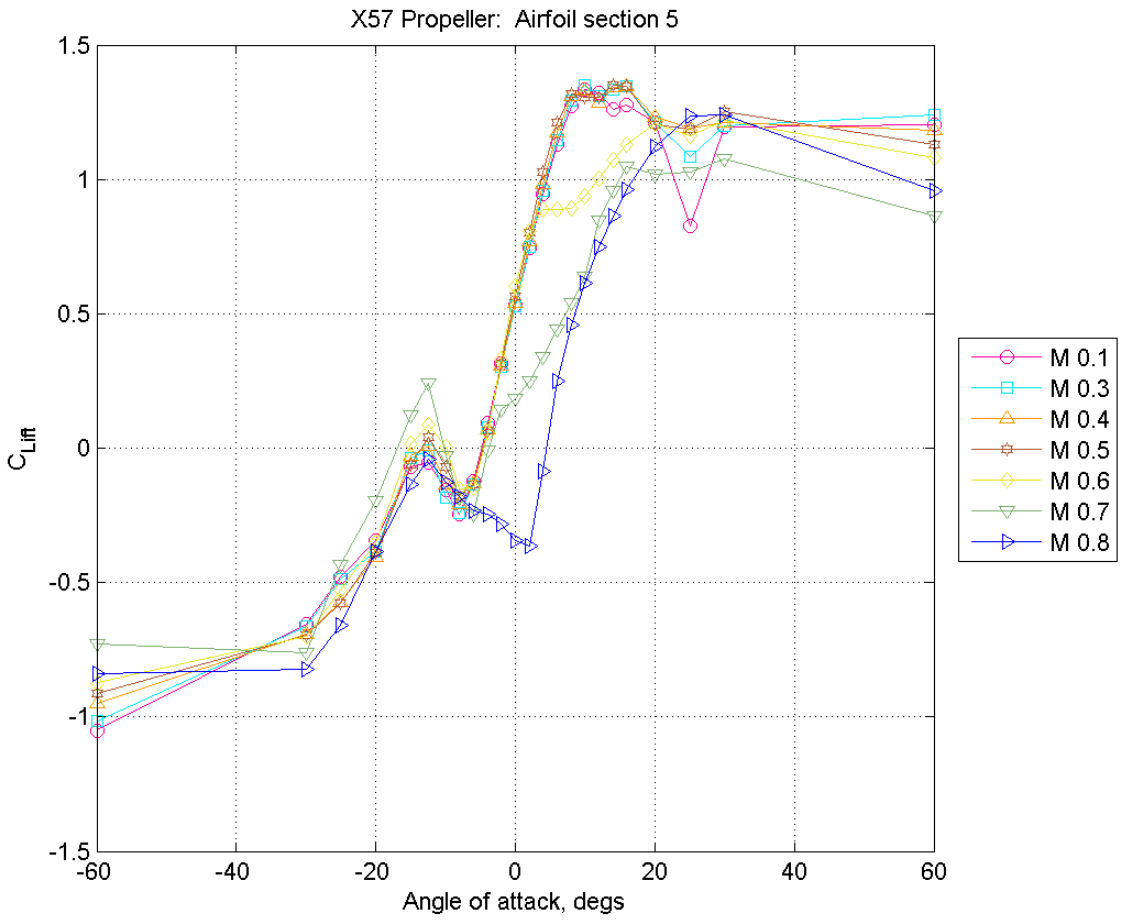
AIRFOIL CFD RESULTS, LIFT VS ANGLE OF ATTACK FOR VARYING MACH NUMBERS, BLADE SECTION 4

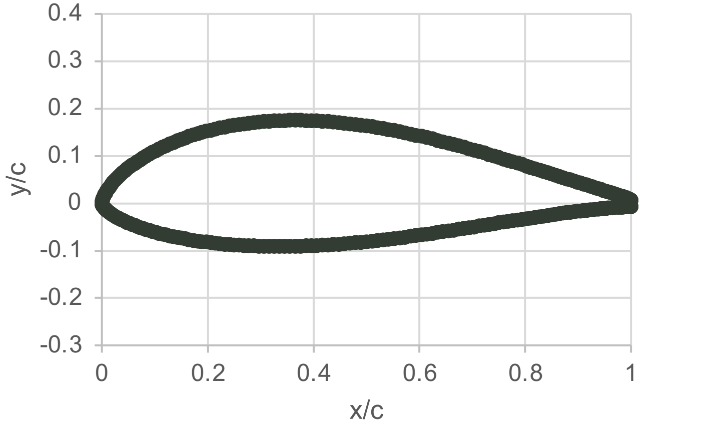




Using ARC2D Navier Stokes 2-dimensional code

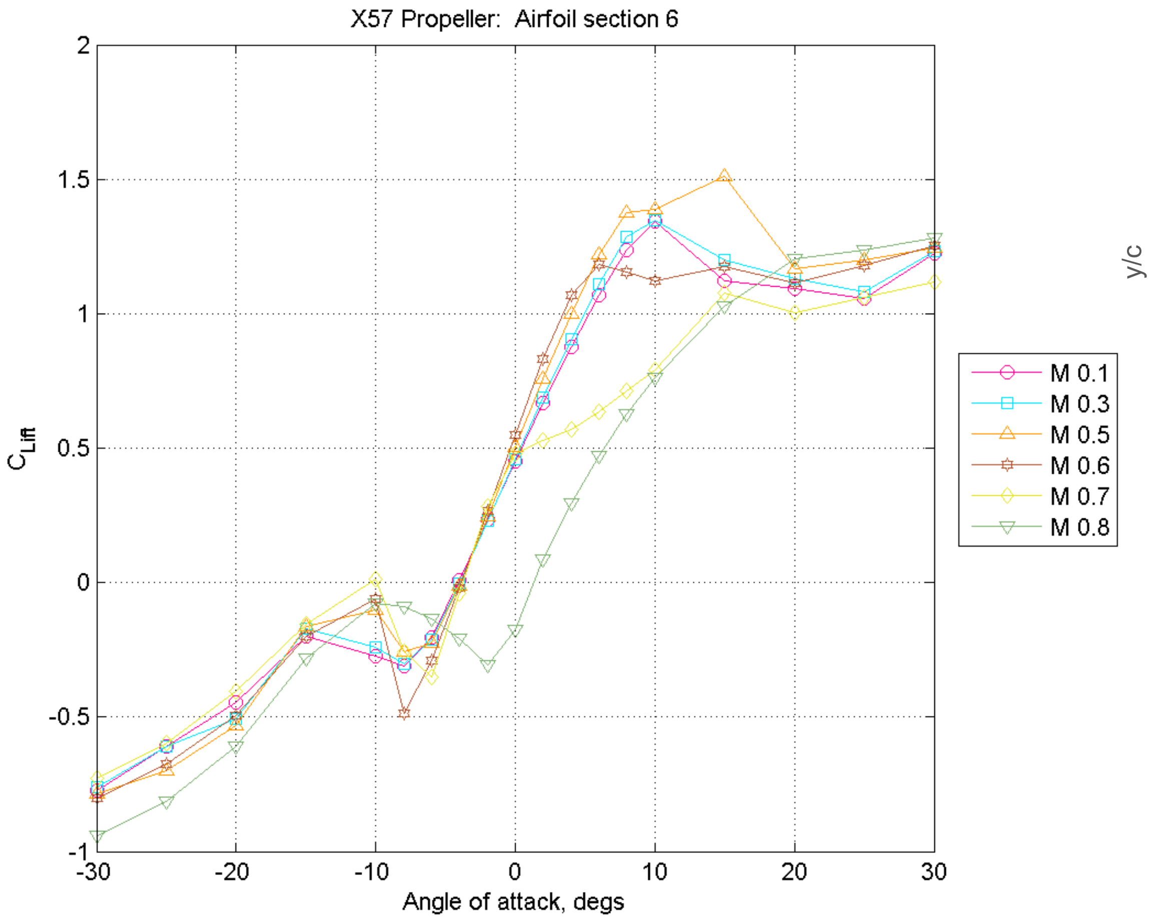
AIRFOIL CFD RESULTS, LIFT VS ANGLE OF ATTACK FOR VARYING MACH NUMBERS, BLADE SECTION 5

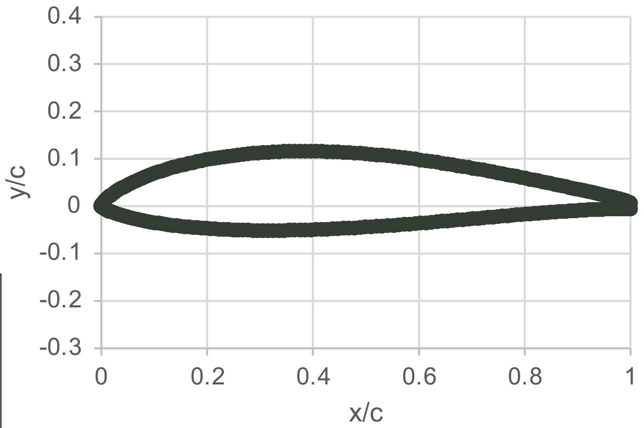




Using ARC2D Navier Stokes 2-dimensional code

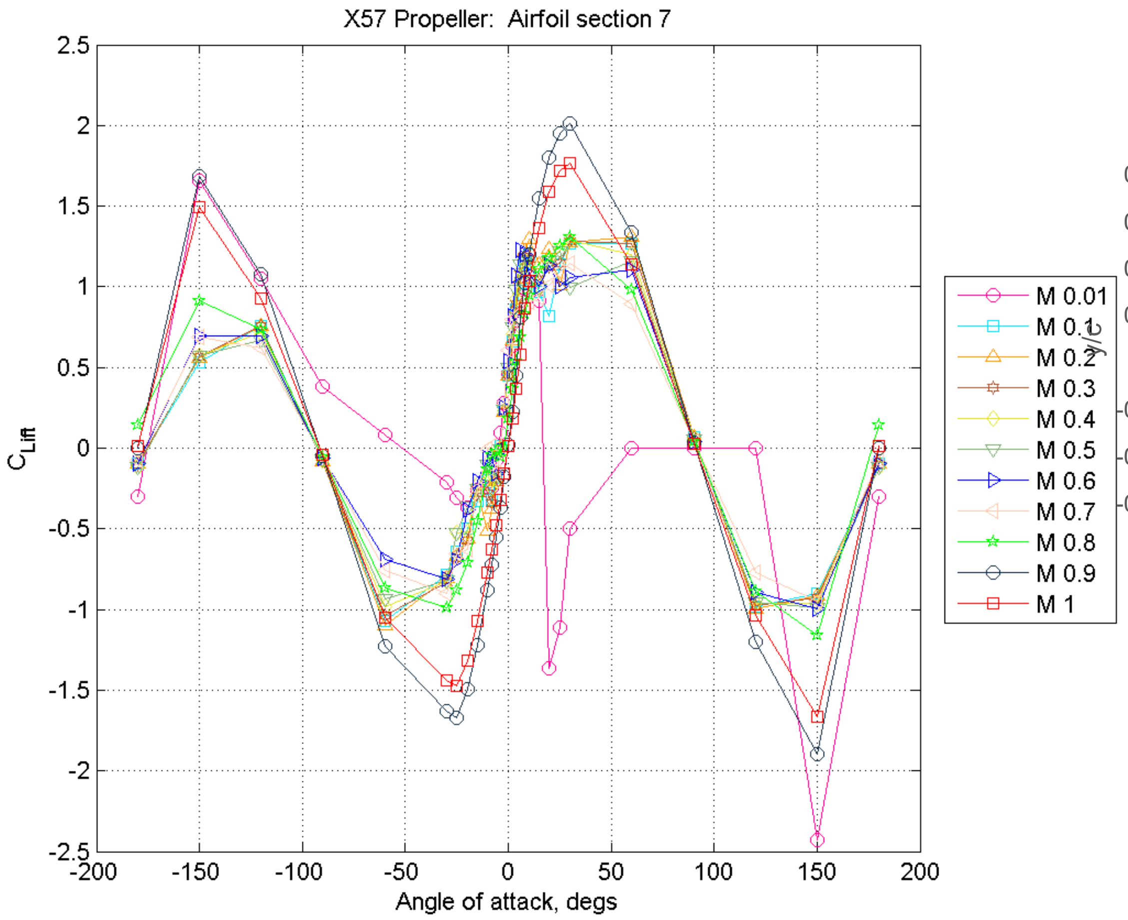
AIRFOIL CFD RESULTS, LIFT VS ANGLE OF ATTACK FOR VARYING MACH NUMBERS, BLADE SECTION 6

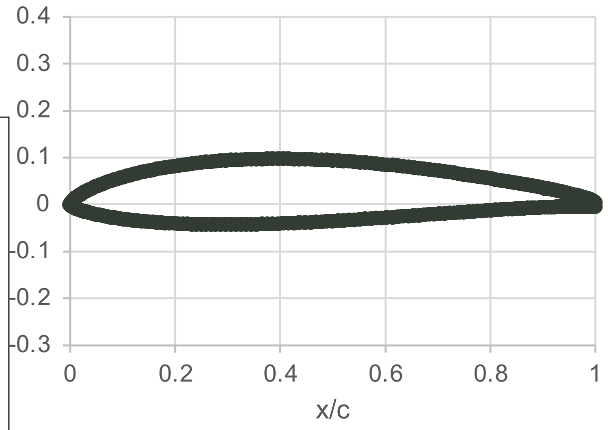




Using ARC2D Navier Stokes 2-dimensional code

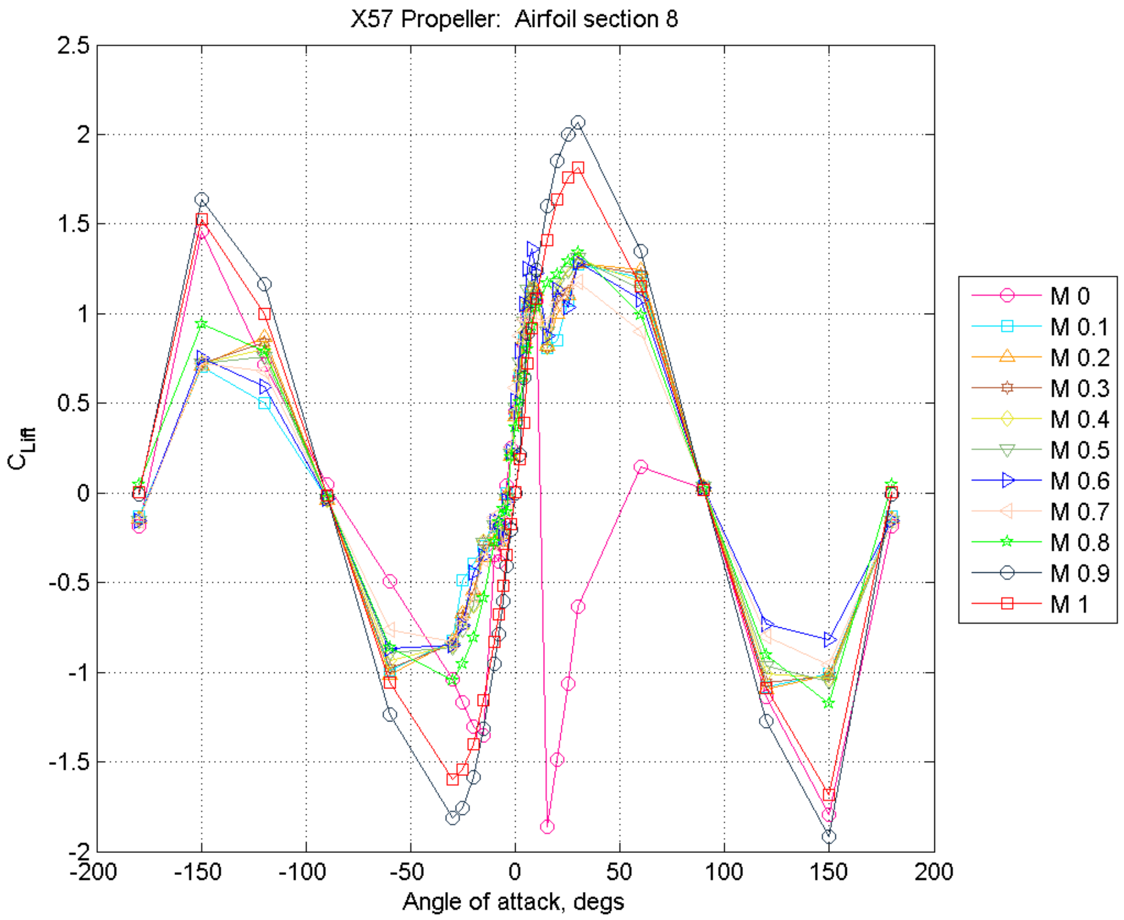
AIRFOIL CFD RESULTS, LIFT VS ANGLE OF ATTACK FOR VARYING MACH NUMBERS, BLADE SECTION 7

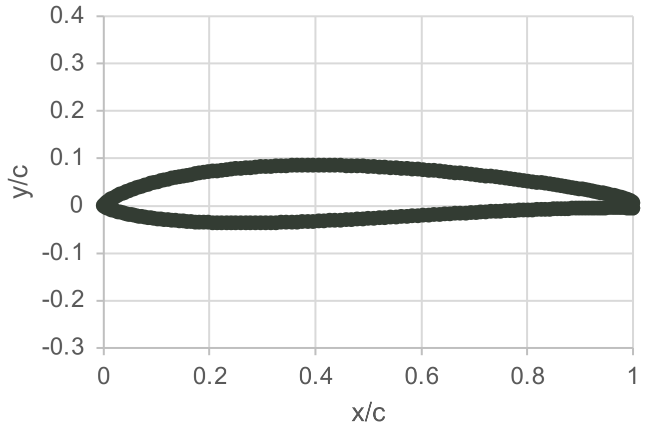




Using ARC2D Navier Stokes 2-dimensional code

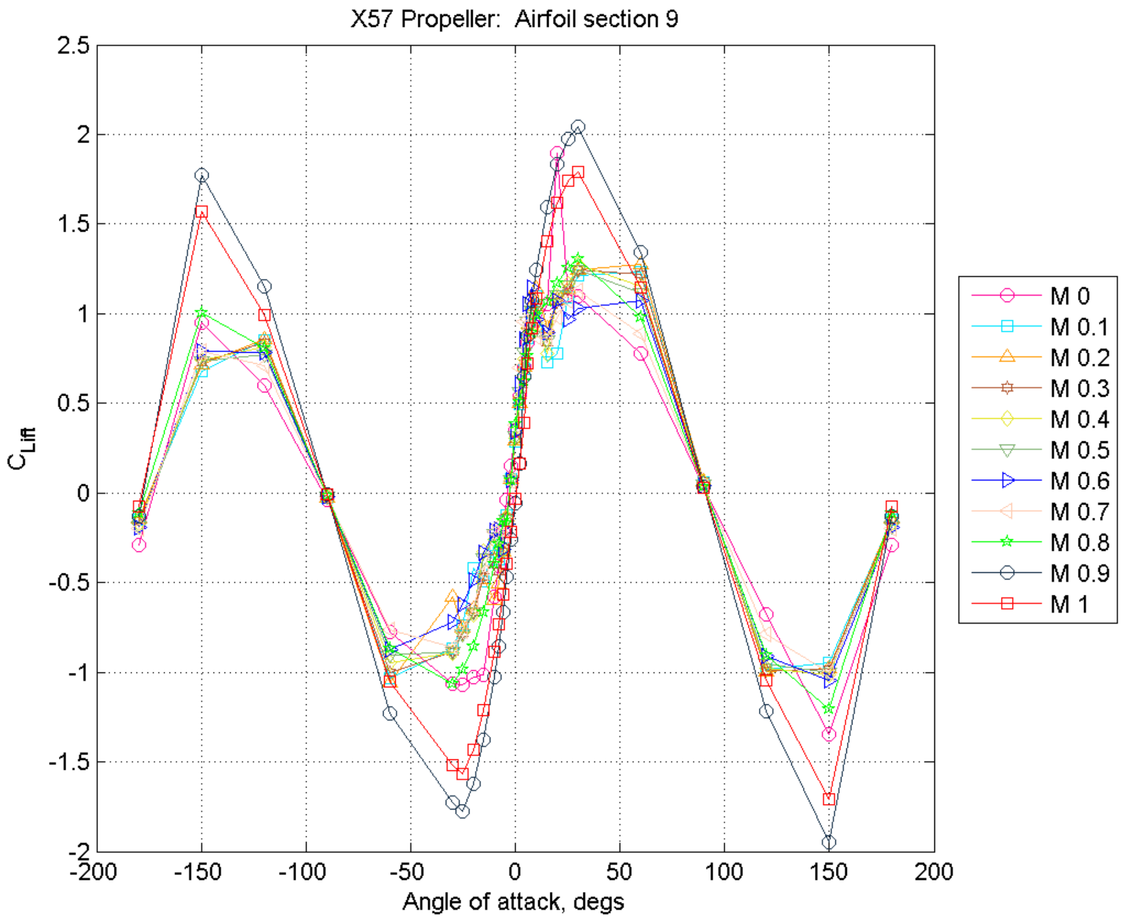
AIRFOIL CFD RESULTS, LIFT VS ANGLE OF ATTACK FOR VARYING MACH NUMBERS, BLADE SECTION 8

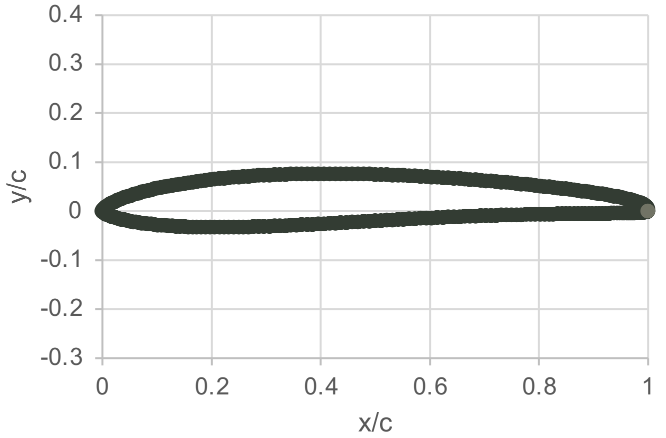




Using ARC2D Navier Stokes 2-dimensional code

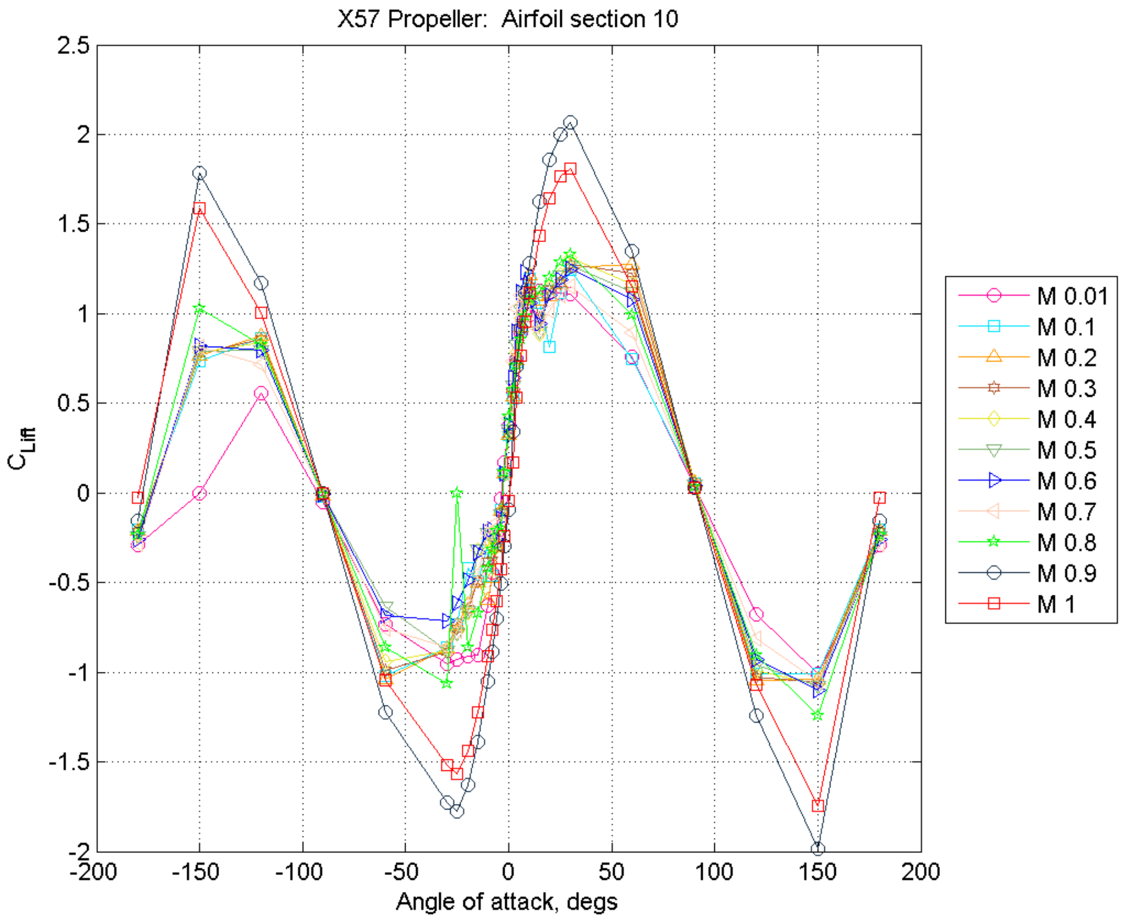
AIRFOIL CFD RESULTS, LIFT VS ANGLE OF ATTACK FOR VARYING MACH NUMBERS, BLADE SECTION 9

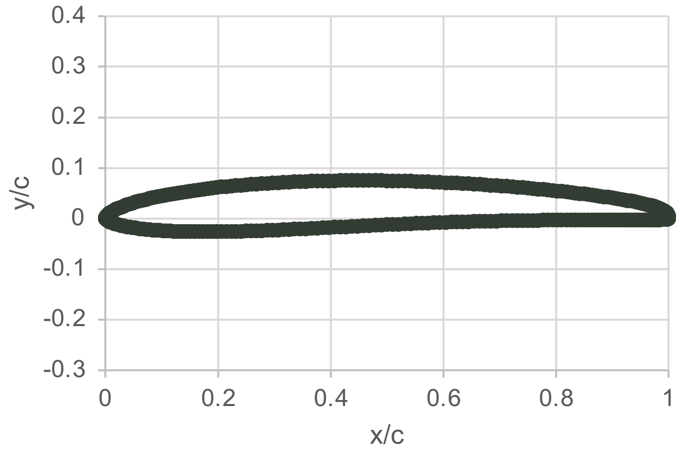




Using ARC2D Navier Stokes 2-dimensional code

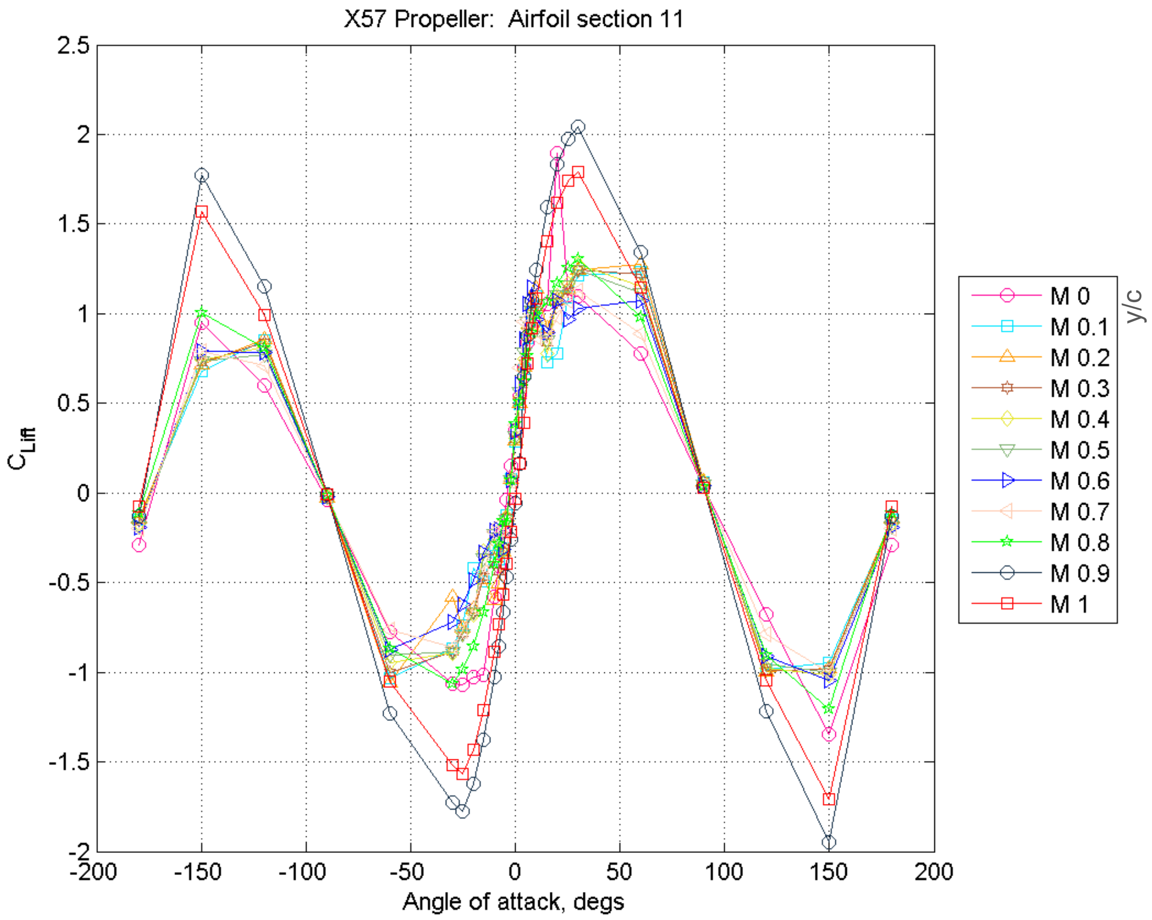
AIRFOIL CFD RESULTS, LIFT VS ANGLE OF ATTACK FOR VARYING MACH NUMBERS, BLADE SECTION 10

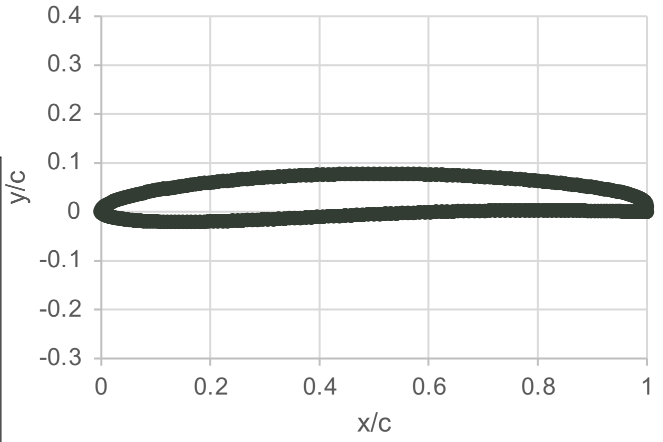




Using ARC2D Navier Stokes 2-dimensional code

AIRFOIL CFD RESULTS, LIFT VS ANGLE OF ATTACK FOR VARYING MACH NUMBERS, BLADE SECTION 11

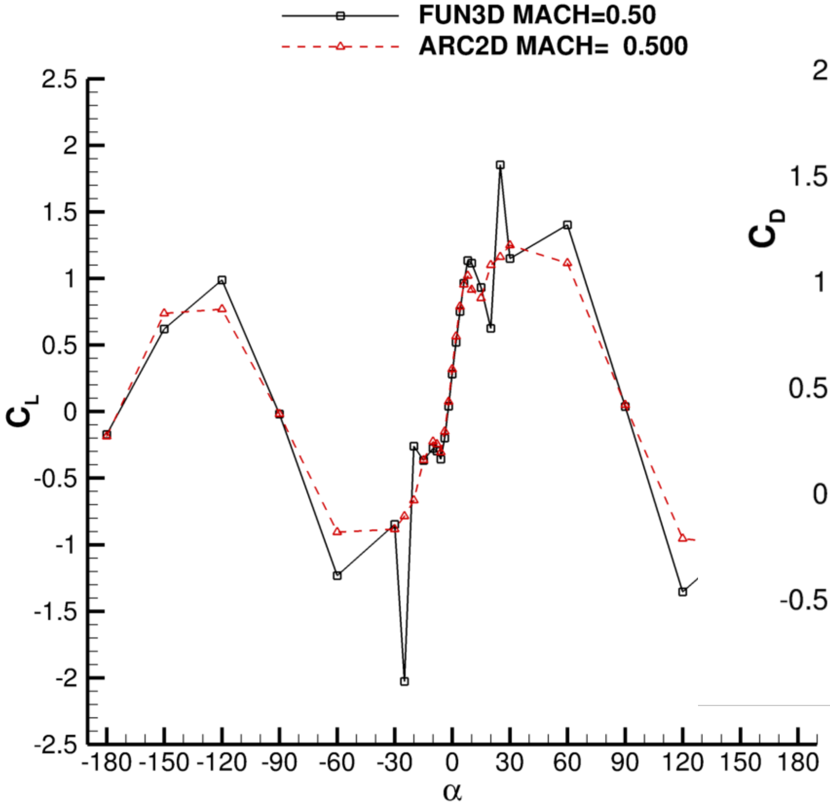


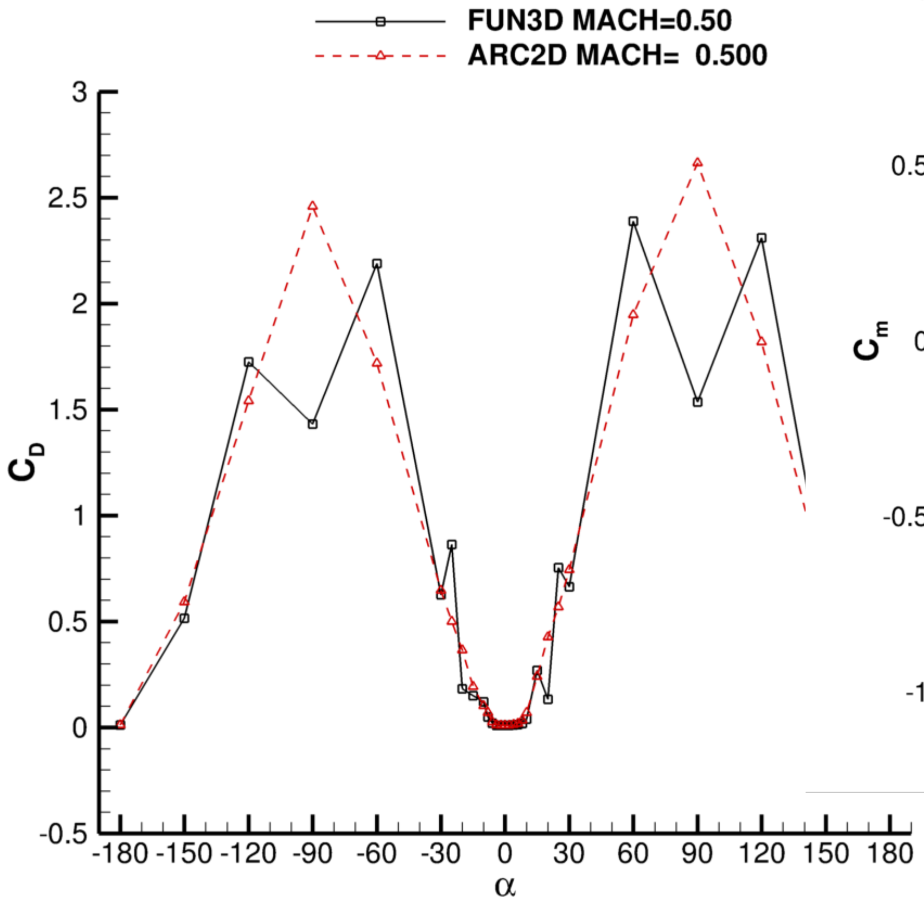


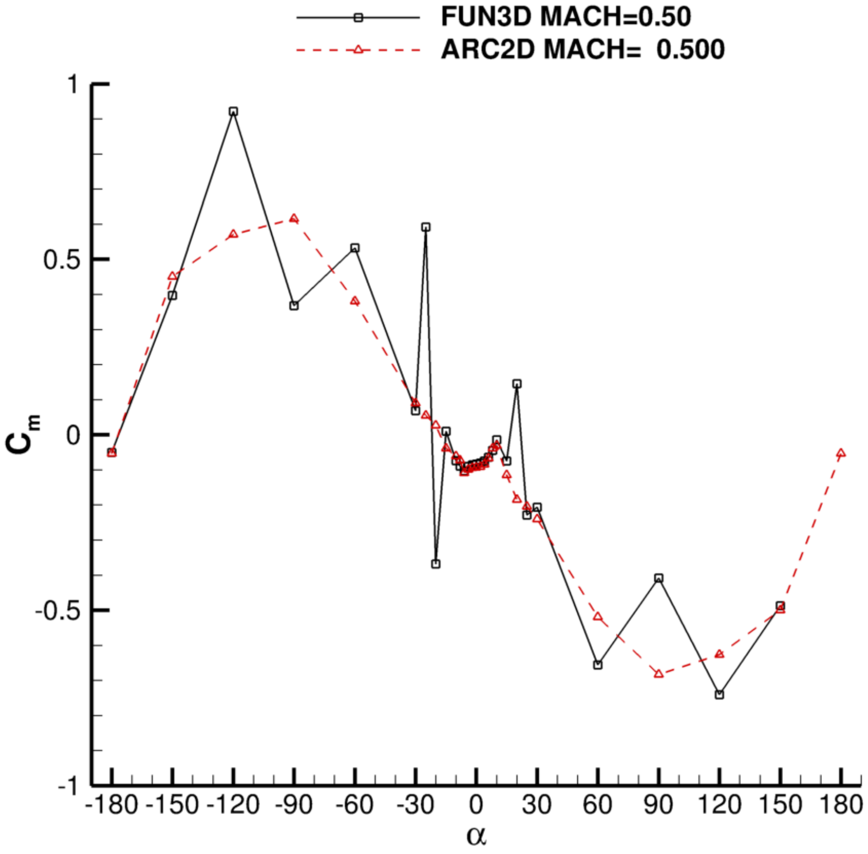
Using ARC2D Navier Stokes 2-dimensional code

AIRFOIL 7 COMPARISON OF C81GEN (ARC2D) VS FUN3D

MACH 0.5



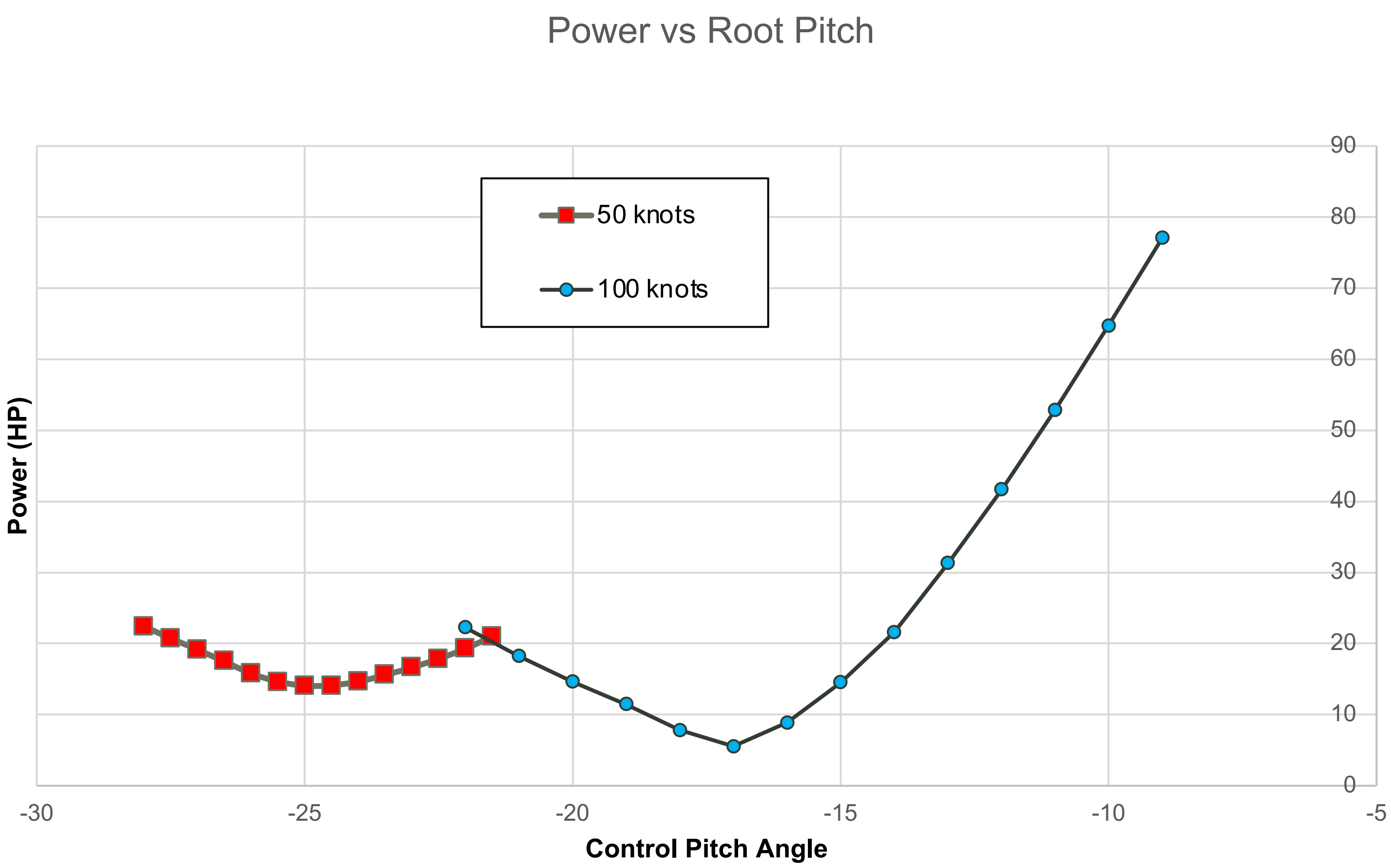


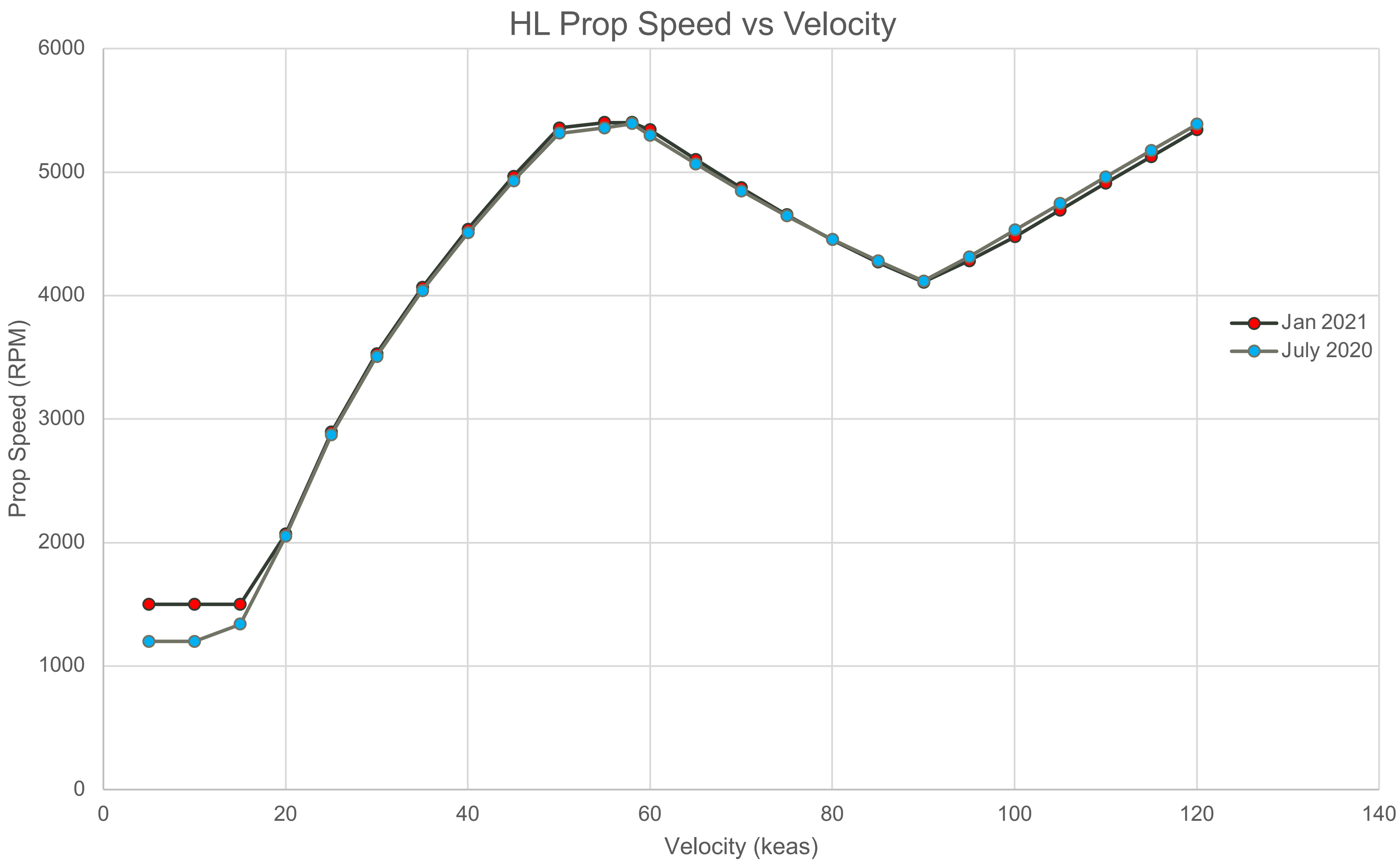


Calculations by Andrew Kreshock (Arc2D) and Steve Massey (FUN3D)

ZERO THRUST TRIM

- **Reason for Zero Thrust Trim was that the zero power condition could not be met until a higher velocity**





All stability runs with the HL prop use the scheduled RPM from July 2020. However there is minimal difference between the two and new rerunning the results were not deemed necessary.