Extended Abstract with Poster

Fall Semester Mini-Project: Reverse Engineering a WWII Fighter - The North American P-51D Mustang

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In the fall of 2012 the senior design capstone class has been assigned a semester mini-project that challenges the students to reverse engineer a high performance WWII fighter aircraft. The capstone course mini-project experience during this first semester has been initiated to teach students when and how to operate disciplinary design tools that prepare them for design trade-studies they will encounter in the second semester senior design project. The class has been divided into three groups of 14 people and assigned the Messerschmitt Bf 109, Supermarine Spitfire, and the North American P-51 Mustang. This paper is the story of the group that focuses on the North American P-51 Mustang. The engineering team first forms a methodology that parametrically reproduces the documented aircraft performance specifications; the simulation results are validated by direct comparison with historical data found in research; this validation step enables them to calibrate the tools used to achieve an appropriate accuracy. Throughout the course of the project students are able to first-hand understand why certain design choices have been made with the P-51 engineering team from the 1940's; the capstone team is in the position to offer insight on how those legacy decisions could be improved using technology from the 21st century. The first step in the project is to choose and introduce the P-51D variant through a literature review, brief history of the aircraft and also to research the design approach, technologies, mission profile and

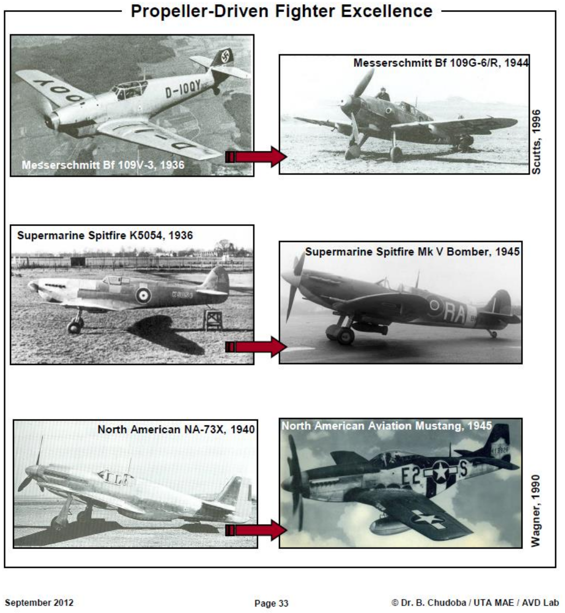


Figure 1 - WWII Fighter Aircraft[1]

various aircraft settings. The student team performs conceptual design tasks by analyzing selected mission operating point for each engineering discipline; the overall conceptual design methodology integrates the individual team efforts. Once the synthesis design tool and disciplinary analysis tools have been established and calibrated, the disciplinary teams agree on quantifying one mission profile point in the WWII B-17 bomber escort mission that highlights the long range cruise condition over a distance of about 1,100 nm. Ultimately the group has been able to reproduce the performance specifications of the 70-year-old P-51 Mustang.

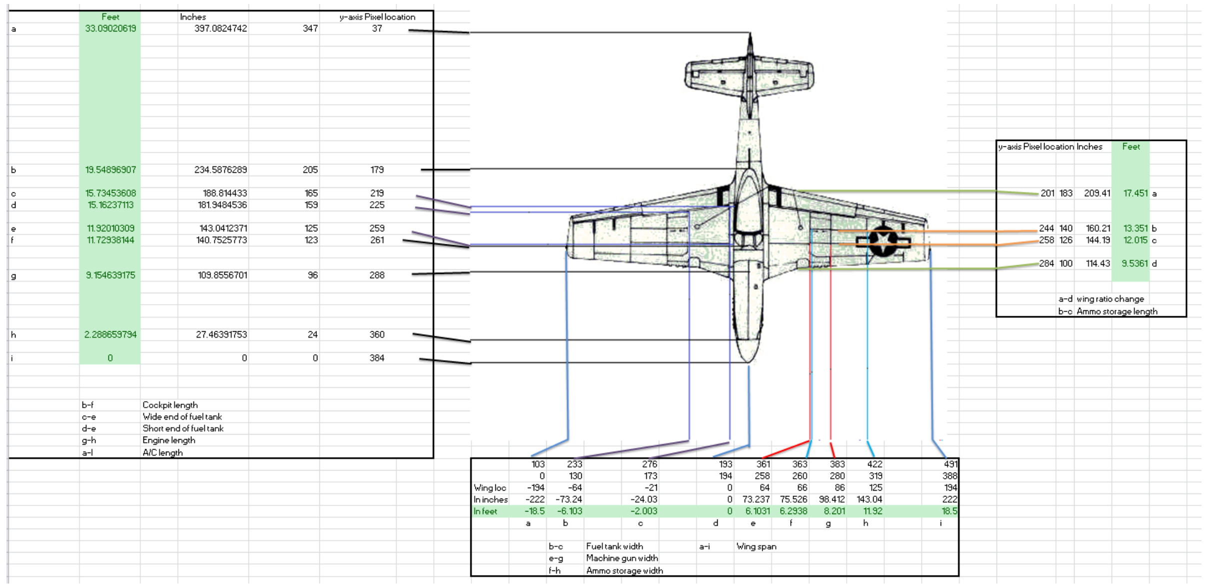
Throughout this project, The UTA MAE students have been able to gain exposure to the incomprehensible knowledge and decisions made by the aeronautical engineering giants of the 1940's, an era that spawned an aircraft capable of exceeding those goals mandated by the circumstances of WWII. But perhaps most importantly, the students learned just how much of their future success rests on knowledge attained from previous generations. In summary, the student group has been experiencing the power of engineering legacy knowledge next to basic engineering understanding and tool proficiency.

In 1940 the British Purchasing Commission expressed interest in contracting North American Aviation (NAA) to convert their established assembly line (in just 120 days time) to manufacture the Curtis P-40 under special license. NAA opposed the idea and proposed to engineer an entirely new fighter plane in less than 120-days. 102 days later the NA-73X was rolled out and waited 20 days for the Allison V-1710 engine to arrive. The Royal Air Force (RAF) was the first to fly the Mustang with primary uses as a tactical-reconnaissance aircraft and fighter-bomber. The airframe was praised for its superb aerodynamic characteristics and industry first laminar flow wing, however the aircraft was not suited to long-range escort missions because of engine power limitations. By 1944 the P-51D was the defining variant powered by the more powerful V-1650-7 Rolls Royce/ Packard Merlin V-12 Engine, also featuring a new bubble style canopy and dorsal fin vertical tail. There were two production plants in the U.S. (one in Inglewood, California and one in Dallas, Texas) and during the height of WWII they were producing a new P-51 every 21 minutes. Over 15,000 Mustangs were produced at an estimated cost of just over \$50,000 (in 1945 USD). Adjusted for inflation that number is just over \$600,000 (in 2011 USD). The P-51 had an unprecedented service length from 1942 until its retirement in 1984. The retired fighters fly under the Limited Type Certification (LTC-11 Revision 5) and many of them are converted to civilian air race planes. Today incomplete project P-51's and fully restored models sell from anywhere between 400 thousand and 2.2 million dollars. The North American P-51 Mustang is considered by many to represent the highest level of refinement ever achieved by any propeller driven fighter aircraft.

In the beginning of the project, the student engineering team determined the single most important factor for success was to establish and maintain a high level of communication for information sharing. Lines of communication between group members consisted of cell phone, text message, e-mail, drop box, YouTube playlists and a private Facebook group. The next logical step was to appoint a Chief Engineer and assign the remaining group members to the various aircraft categories or teams (Modeling & Sizing, Weights & Structures, Aerodynamics, Stability & Control, Propulsion, Performance and Loftin Sanity Check). Early on the team established a mentality of parallel disciplinary methods as opposed to the more conventional trickle down or series method. This helped reduce the waiting period between team output to input exchange and induced an overall sense of urgency, obligation and team dependency. Great emphasis was placed on group communication; each team was dependant upon one another from the start. The entire process was more a melting pot of information sharing rather than a one-way flow from inputs to deliverables.

A few weeks into the project, after speaking with Amit and Dr. Chudoba, it became apparent that the team's plans were excessively ambitious. Initially the plan was to reverse engineer the P-51, produce results for 3-5 mission profile points, perform flight simulations in MATLAB for verification and create a model to fly in the X-Plane simulator. The group was advised to consolidate their efforts, make assumptions when necessary, identify and completely answer the important questions regarding the project objective. Even if the end result was to analyze just one base line cruise condition point in an oversimplified mission profile and present a closed loop result, it would hold greater value than an incomplete evaluation of multiple points. From that point on, the team's mission was to keep it simple and not get lost in the detail despite the overwhelming amount of information provided in the P-51 D Mustang literature to review. Furthermore it was brought to the team's attention that an appropriate measure of merit for their speculative results would be somewhere within 40% accuracy compared to the aircrafts historical performance deliverables. When discussing the formation of the group and team methodologies, the Chief Engineer proposed that everyone aspire to calculate results to within 25% accuracy of historical values (with the maximum acceptable error of 40% as the group's personal measure of merit).

Responsibilities of the Chief Engineer were as follows; Define the project scope and primary plan of action, guide teams in establishing individual project objectives, make group governing decisions, promote communication amongst sub-groups (teams), produce desired deliverables to team individuals, create project presentations, poster and video. Initial decisions made by the Chief Engineer that established group direction were choosing the variant & mission profile. The P-51D Mustang Variant was chosen because over 8,000 of the more than 16,000 Mustangs produced were "D" variants; it was also thought that this choice would lead to the greatest abundance of historical aircraft information and the least hassle during the group literature search. The Packard V-1650-7 (developed by Rolls-Royce Merlin) became the engine variant of choice for the same reasons as 6,325 of these engines were produced primarily for the P-51D. Students then chose to focus on the WWII B-17 bomber escort mission profile because it represented simplicity that highlighted a single point at the max-range cruise condition. It was both important and helpful to define the aircraft variant and specify one mission profile before getting too in depth with the literature search. After the variant and mission profile had been selected, it was time to apply the standard to design to this unique reverse engineering research project. The student engineering team followed these seven steps. Analyze one Mustang variant (P-51D V-1650-7) in one mission profile (B-17 bomber escort). Integrate available historical data from any point in the profile to achieve an equation to return the performance specifications of the aircraft. Iterate established method until resulting error is reduced to within appropriate accuracy. Converge on one cruise point in the mission profile for all teams to produce specifications. Screen solution space for aircraft specs at specified mission point and compare to theoretical calculations. Visualize the aircraft specifications in the solution space using the Loftin Sizing Method. Assess Risk and estimate error between specifications defined by group theoretical calculations, Loftin Sizing Method, and given Historical Values. Measure of Merit achieved if results were below or within 25%-40% of physical aircraft performance specifications.



	Feet	Inches		y-axis Pixel location
a	33.09020619	397.0824742	347	37
b	19.54896907	234.5876289	205	179
c	15.73453608	188.814433	165	219
d	15.16237113	181.9484536	159	225
e	11.92010309	143.0412371	125	259
f	11.72938144	140.7525773	123	261
g	9.154639175	109.8556701	96	288
h	2.288659794	27.46391753	24	360
i	0	0	0	384

b-f Cockpit length
c-e Wide end of fuel tank
d-e Short end of fuel tank
g-h Engine length
a-l A/C length

y-axis Pixel location		Inches	Feet	
201	183	209.41	17.451	a
244	140	160.21	13.351	b
258	126	144.19	12.015	c
284	100	114.43	9.5361	d

a-d wing ratio change
b-c Ammo storage length

	103	233	276	193	361	363	383	422	491
	0	130	173	194	258	260	280	319	388
Wing loc	-194	-64	-21	0	64	66	86	125	194
In inches	-222	-73.24	-24.03	0	73.237	75.526	98.412	143.04	222
In feet	-18.5	-6.103	-2.003	0	6.1031	6.2938	8.201	11.92	18.5
	a	b	c	d	e	f	g	h	i

b-c Fuel tank width
e-g Machine gun width
f-h Ammo storage width
a-i Wing span

Figure 2 - Initial Aircraft pixel Sizing (Top View)[2]

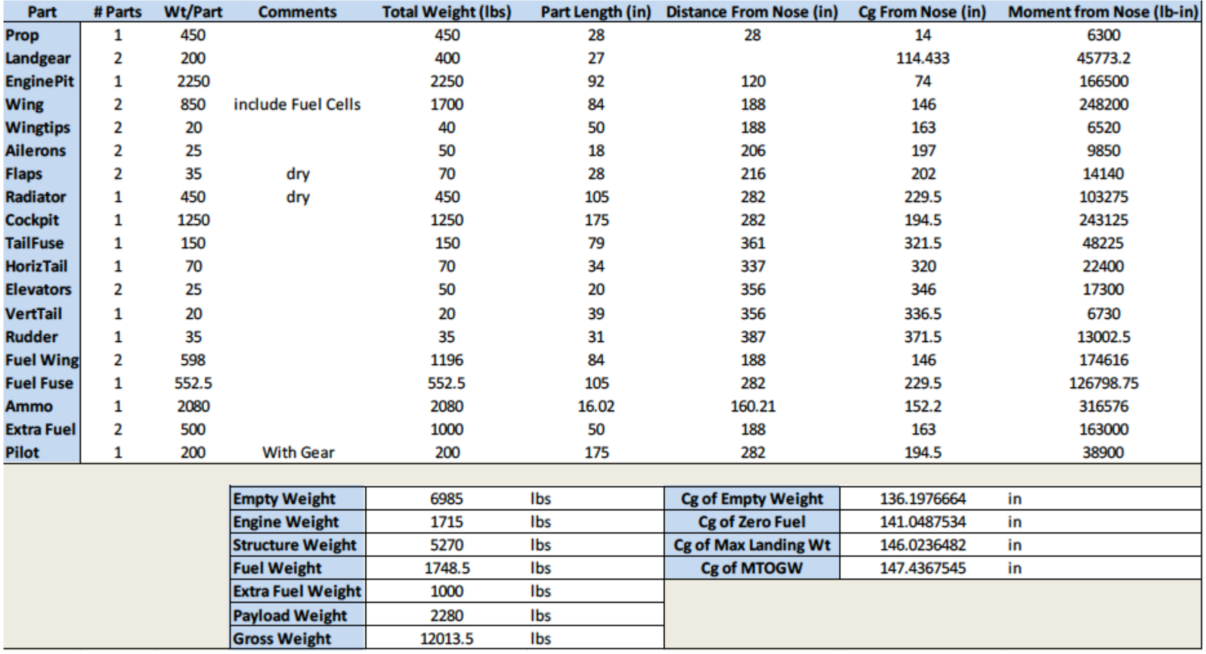
Once the project mission had been established and the literature review conducted to determine the aircraft variant & mission profile, one profile point was then used for analysis (starting with given Historical Data/Inputs), which ultimately culminated in the Loftin Sanity Check where analytical results were compared to the original historical aircraft performance specifications. If the results were favorable, the methodology concluded with desired mission deliverables. If the results were not within an acceptable range of accuracy, the process re-iterated, starting all over with the aircraft sizing.

The Modeling & Sizing Team obtained initial general aircraft dimensions and airfoil dimensions from historical documentation. Then arbitrary geometry (control surfaces and trim surfaces) was calculated using pixel ratio method, scale model method, and ultimately verified by physical measurements method. A simplified beam model was created for the Structures Team, simplified wing and tail plane models were created for the Aerodynamics Team. Finally a full wing body detailed 3D model was produced with accurate aerodynamic and control surface sizes.

The Weights & Structures Team obtained weight components from historical data then combines them with component locations from the Modeling & Sizing Team to find the C.G. location for the P-51. Variation in component weights such as fuel and ammunition lead to the formation of the C.G. travel diagram. Lift distribution and drag data obtained from the Aerodynamics Team was used in conjunction with propeller torque values obtained from the Propulsion Team to calculate the stress analysis (wing loading) and safety factor of the simplified structural 3D model provided by the Modeling and Sizing Team (featuring one single I-beam as the wing spar). The Weights and Structures Team also produced a weight buildup diagram showcasing the different aircraft weights at different points throughout the mission profile (primarily used by the Performance Team and Loftin Sanity Check).

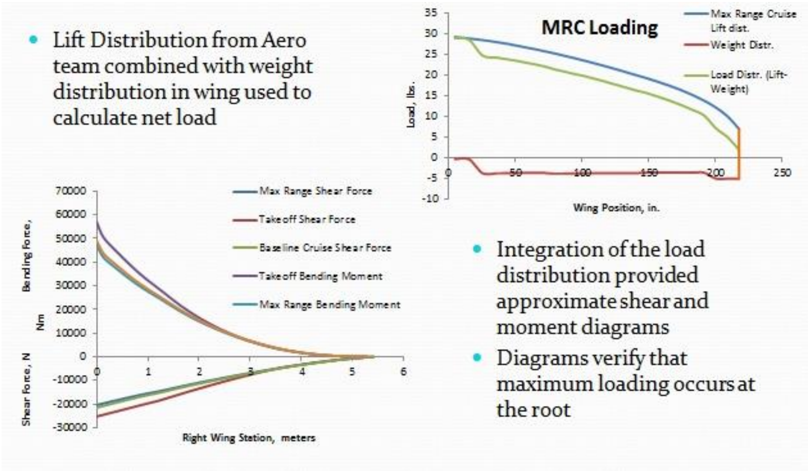
Figure 3 - Final 3D Model[3]

Table 1 – Weight Componenets & Cg Locations for Historical Aircraft Geometry[4]



Part	# Parts	Wt/Part	Comments	Total Weight (lbs)	Part Length (in)	Distance From Nose (in)	Cg From Nose (in)	Moment from Nose (lb-in)
Prop	1	450		450	28	28	14	6300
Landgear	2	200		400	27		114.433	45773.2
EnginePit	1	2250		2250	92	120	74	166500
Wing	2	850	include Fuel Cells	1700	84	188	146	248200
Wingtips	2	20		40	50	188	163	6520
Ailerons	2	25		50	18	206	197	9850
Flaps	2	35	dry	70	28	216	202	14140
Radiator	1	450	dry	450	105	282	229.5	103275
Cockpit	1	1250		1250	175	282	194.5	243125
TailFuse	1	150		150	79	361	321.5	48225
HorizTail	1	70		70	34	337	320	22400
Elevators	2	25		50	20	356	346	17300
VertTail	1	20		20	39	356	336.5	6730
Rudder	1	35		35	31	387	371.5	13002.5
Fuel Wing	2	598		1196	84	188	146	174616
Fuel Fuse	1	552.5		552.5	105	282	229.5	126798.75
Ammo	1	2080		2080	16.02	160.21	152.2	316576
Extra Fuel	2	500		1000	50	188	163	163000
Pilot	1	200	With Gear	200	175	282	194.5	38900

Empty Weight	6985	lbs	Cg of Empty Weight	136.1976664	in
Engine Weight	1715	lbs	Cg of Zero Fuel	141.0487534	in
Structure Weight	5270	lbs	Cg of Max Landing Wt	146.0236482	in
Fuel Weight	1748.5	lbs	Cg of MTOGW	147.4367545	in
Extra Fuel Weight	1000	lbs			
Payload Weight	2280	lbs			
Gross Weight	12013.5	lbs			



- Lift Distribution from Aero team combined with weight distribution in wing used to calculate net load
- Integration of the load distribution provided approximate shear and moment diagrams
- Diagrams verify that maximum loading occurs at the root

Figure 4 - Shear Moment Diagrams[3]

The Aerodynamics Team obtained major dimensions; coordinate locations of major aircraft features and airfoil section models from the Modeling & Sizing Team. C.G. location at various flight conditions was obtained from the Weights & Structures Team. And aerodynamically meaningful geometry such as chord length, taper ratio, wing sweep, aspect ratio, mean aerodynamic chord, etc. was all obtained from within the Aerodynamics Team. These inputs were then plugged into thin air foil theory, flat plate skin friction analysis, finite wing theory and wing body aerodynamics to yield the lift curve, polar, and zero lift drag. Vortex Lattice Method Tornado was used to find the aircraft stability and control derivatives and wing lift distribution.

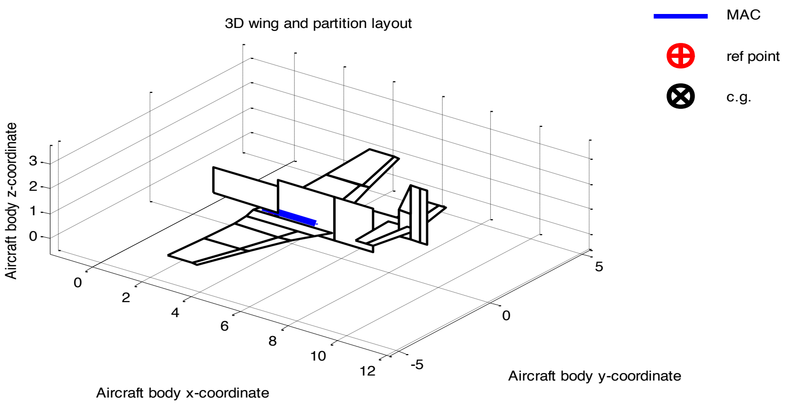


Figure 5 - Vortex Lattice Method Geometry[3]

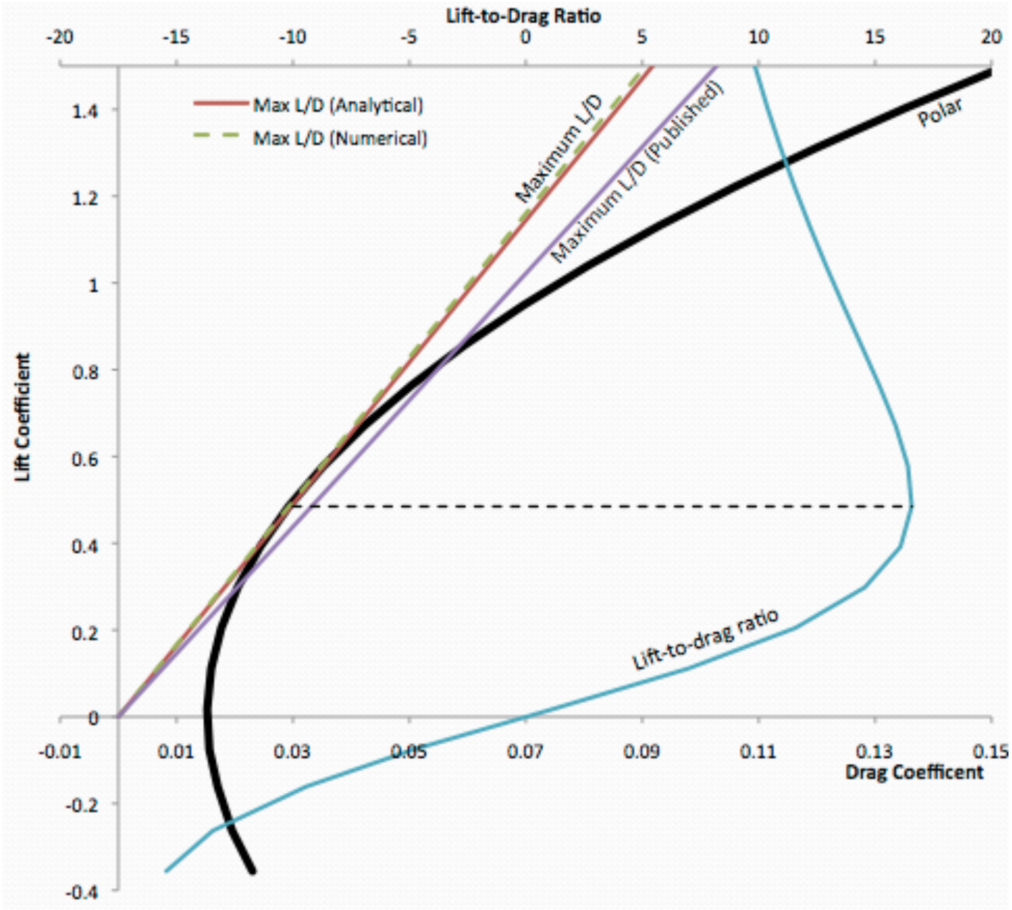


Figure 6 - Polar and L/D Ratio[3]

The Stability & Control Team needed stability derivatives, control surface sizing, propeller torque and aerodynamic coefficients from the Aerodynamics Team, Propulsion Team and Modeling & Sizing Team to calculate the static stability derivatives. If the derivatives predicted static stability then they were used to find the control surface deflections required to trim the aircraft and determine if the aircraft could be trimmed in all phases of flight. This information was used to find the total drag produced in flight at the baseline cruise condition. Minimum control airspeed was also found and

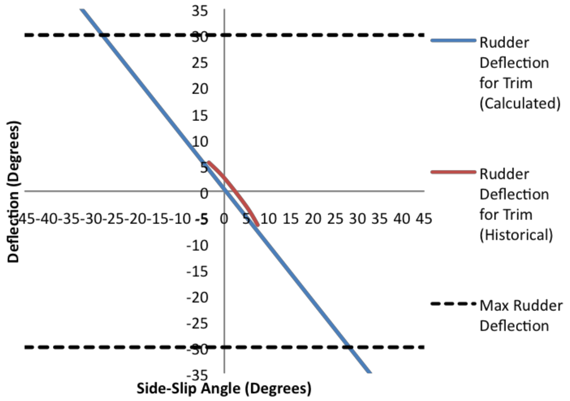


Figure 7 - Rudder Deflection for Trim Historical Comparison (Baseline Cruise Condition - Engine Operative)[3]

used to calculate the minimum power required for flight.

The Propulsion Team input values for given flight conditions, airframe drag and engine specifications into momentum theory and then subsequently output values for power, toque and optimum power/torque rpm. This information was used to calculate things like fuel consumption that were passed on to the Performance Team. Propeller geometry (airfoil section twist distribution and the number of blades) was used to determine the propeller efficiency, thrust, drag due to propeller rotation and net engine moment torque. These variables were passed onto the Performance Team, Structures Team and Stability & Control Team.

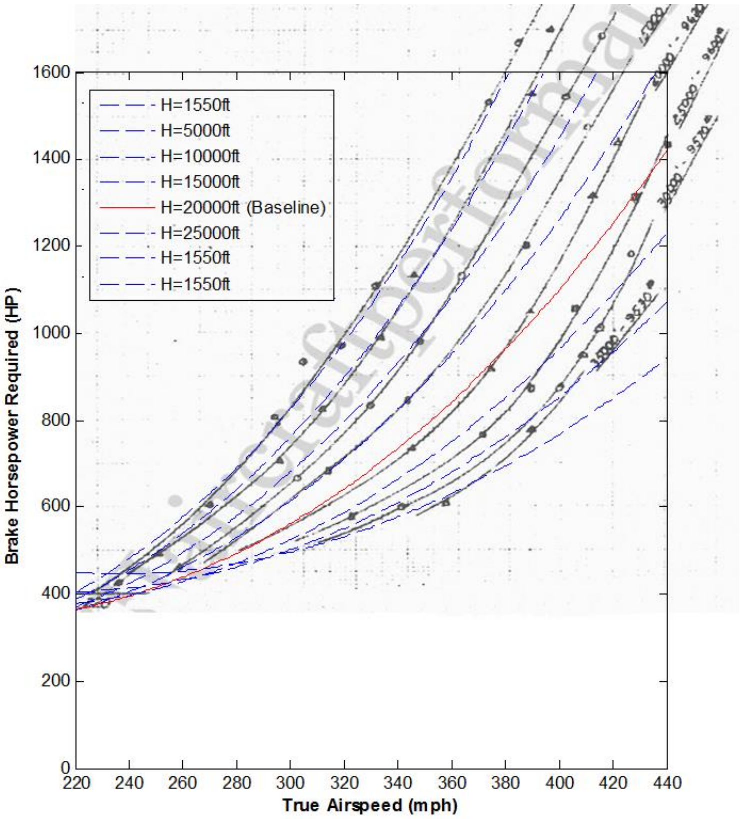


Figure 8 - Required Horsepower Historical Comparison and Validation[3]

The Performance Team was the last step in the analysis; they required input from every other team. Weight, minimum control airspeed, thrust data, wing area & aspect ratio, aerodynamic coefficients were all used to find the aircraft landing distance, runway length, liftoff velocity, climb rate, cruise range, stall velocity, max range cruise velocity, descent ratio, flight path angle (with respect to angle of attack) and vertical force ratio (withrespect to angle of attack) and the L/D maximum.

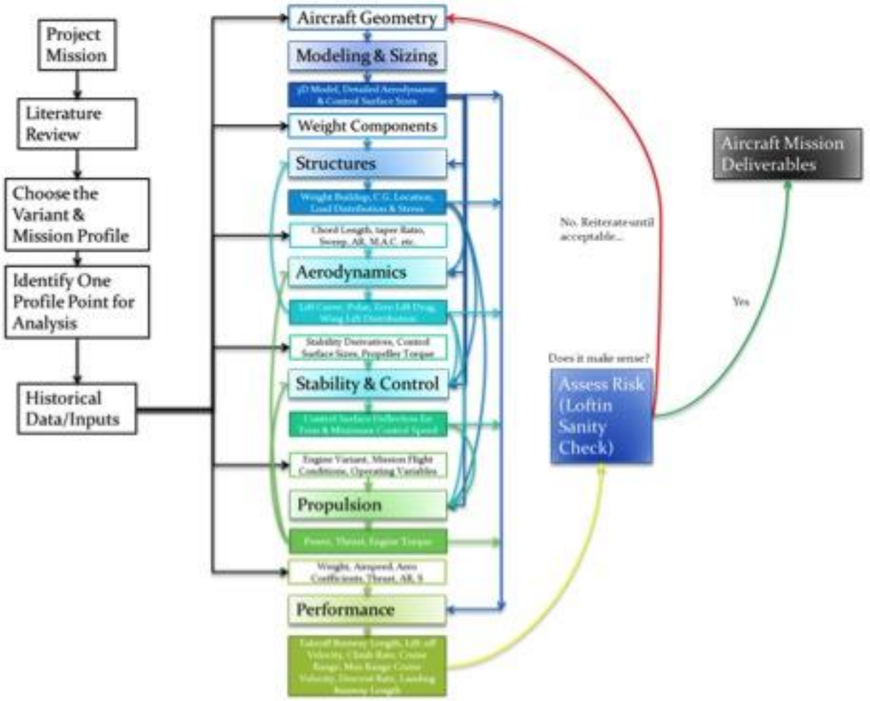
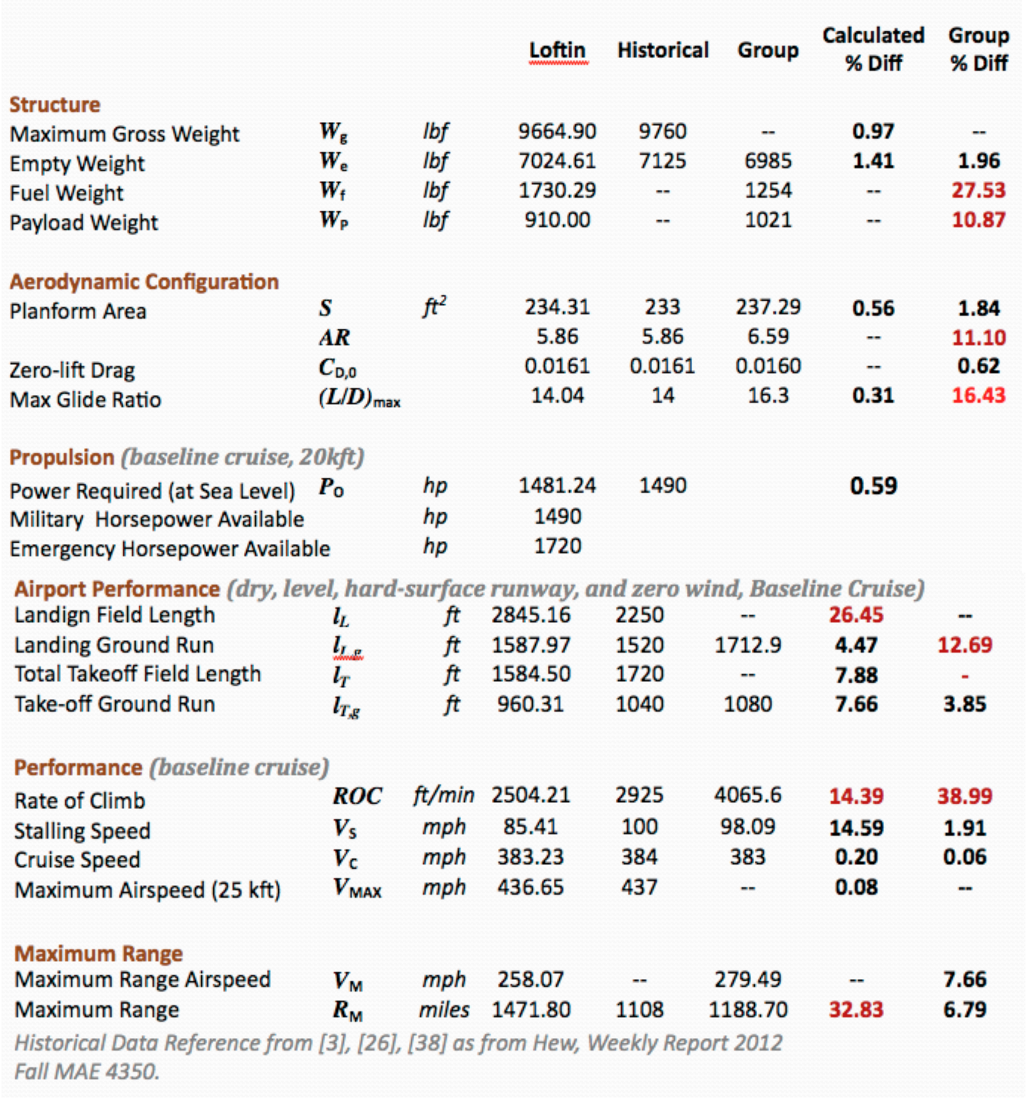


Figure 9 - Horizontally Integrated Group Methodology (Condensed Team Interaction)

When compared to historical data, all the results from the Loftin Sanity Check and Group Analysis represented fell within the desired MoM of 40% accuracy. For analytical performance calculations the students found the outlying value to be rate of climb, which was nearly 40% higher than historical values indicated. Aircraft performance results that seem too good to be true usually are, and it’s not uncommon in aerospace industry to encounter this phenomenon when assumptions are made for calculations. Conceptual design engineers in industry constantly predict aircraft to be of higher performance and lower cost than what they actually end up being. The student engineering team calculated their theoretical P-51D to be larger, lighter and faster with more lift capability than historical data revealed. Common sense lead them to believe that the simplification of most conceptual design calculation methods were to blame for the apparent negligence of some negative performance effects. From a methodological standpoint this mini-project was a great success. The group as a whole was able to complete one entire iteration of their proposed methodology and achieve results within a realistic accuracy.

Table 2 - Loftin Results vs. Historical Data and Group Calculation[3]



			Loftin	Historical	Group	Calculated % Diff	Group % Diff
Structure							
Maximum Gross Weight	W_g	*lbf*	9664.90	9760	--	**0.97**	--
Empty Weight	W_e	*lbf*	7024.61	7125	6985	**1.41**	**1.96**
Fuel Weight	W_f	*lbf*	1730.29	--	1254	--	**27.53**
Payload Weight	W_P	*lbf*	910.00	--	1021	--	**10.87**
Aerodynamic Configuration							
Planform Area	S	ft^2	234.31	233	237.29	**0.56**	**1.84**
	AR		5.86	5.86	6.59	--	**11.10**
Zero-lift Drag	$C_{D,0}$		0.0161	0.0161	0.0160	--	**0.62**
Max Glide Ratio	$(L/D)_{max}$		14.04	14	16.3	**0.31**	**16.43**
Propulsion *(baseline cruise, 20kft)*							
Power Required (at Sea Level)	P_O	*hp*	1481.24	1490		**0.59**	
Military Horsepower Available		*hp*	1490				
Emergency Horsepower Available		*hp*	1720				
Airport Performance *(dry, level, hard-surface runway, and zero wind, Baseline Cruise)*							
Landign Field Length	l_L	*ft*	2845.16	2250	--	**26.45**	--
Landing Ground Run	$l_{L,g}$	*ft*	1587.97	1520	1712.9	**4.47**	**12.69**
Total Takeoff Field Length	l_T	*ft*	1584.50	1720	--	**7.88**	-
Take-off Ground Run	$l_{T,g}$	*ft*	960.31	1040	1080	**7.66**	**3.85**
Performance *(baseline cruise)*							
Rate of Climb	ROC	*ft/min*	2504.21	2925	4065.6	**14.39**	**38.99**
Stalling Speed	V_S	*mph*	85.41	100	98.09	**14.59**	**1.91**
Cruise Speed	V_C	*mph*	383.23	384	383	**0.20**	**0.06**
Maximum Airspeed (25 kft)	V_{MAX}	*mph*	436.65	437	--	**0.08**	--
Maximum Range							
Maximum Range Airspeed	V_M	*mph*	258.07	--	279.49	--	**7.66**
Maximum Range	R_M	*miles*	1471.80	1108	1188.70	**32.83**	**6.79**

Historical Data Reference from [3], [26], [38] as from Hew, Weekly Report 2012 Fall MAE 4350.

The purpose of this mini-project was to immerse students in the conceptual design environment and expose them to multidisciplinary teamwork in preparation for the spring semester capstone project. Both students and professors involved believe that this project exceeded everyone's hopes and expectations in simulating such an environment that will be explored in further detail during the spring semester of 2013. This experience has provided students with an unprecedented learning experience in a fun, competitive, low-risk setting that demanded cooperation, logical thinking and restraint towards over ambition when faced with zero tolerance deadlines. In 60 days the UTA MAE students gained perspective into the conceptual design world and a heightened respect for the engineers that left behind the legacy of a WWII fighter that was built from nothing in less than 120 days, the aerodynamically unprecedented propeller driven perfection that has remained unsurpassed for over 70 years, the North American P-51D Mustang.

References

1. Dr. Bernd Chudoba, "MAE4350 – Lab - Development and Design Features of Propeller Aircraft", 5, Oct. 2012.
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3. Tyler Crosson, "AVD Mustangs Final Presentation.pptx", 30, Nov. 2012.
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As an undergraduate Aerospace Engineering student at the University of Texas at Arlington, Mr. Crosson is leading the current aircraft conceptual design team for the Senior Design Project of engineering a Thrust Vectored - Control Configured B737 equivalent vehicle.

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Dr. Chudoba has developed conceptual design tools for advanced aircraft with the Future Projects Departments of Airbus Industrie (Toulouse, France), British Aerospace (Bristol, England), Aérospatiale Airbus (Toulouse, France), DaimlerChrysler Airbus (Hamburg, Germany). He has also been involved in the development and production of general-aviation aircraft, ultra-light aircraft, solar-powered aircraft and flexible hand gliders.