Trade Studies and a Conceptual Design of a Turbofan Inlet Lip Skin for Boeing New Midsize Aircraft (NMA)

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Introduction

Problem Statement

Aerospace primes are evaluating a replacement for the current midsize commercial aircraft to meet the market needs further. Engine design is essential, and it is currently under early stages of research and development. The new engine demands a redesign of the current lipskin product to accommodate the updated technology and materials. Standards of the new lip skin design will meet all customer specifications and characteristics of the new engine. Our design based on the results from the jet engine, lip skin material, anti-icing technology, impact simulation, and aerodynamic performance trade-off studies.

Background and Motivation

The *Commercial Airline Market* gap combined with emerging engine technologies drive the re-evaluation of the current airliner products. **Figure 1** displays market vacancy at a travel range of around 5000 nautical miles with a passenger load of 180-250 counts.

The new aircraft addressing this gap will include a new high bypass ratio turbofan engine with a larger fan diameter, alternative means of anti-icing, materials, emerging technologies, and manufacturing techniques.

Our motivation is to develop a conceptual lip skin design that is suitable for the Next Generation Airliner Market.

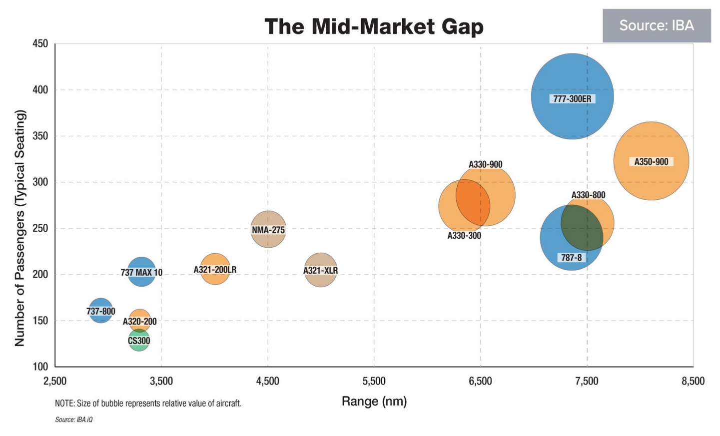


Figure 1: Middle of the Market Gap by Traveling Range and Passenger Load

Customer Specification

Ref: Boeing 755 (Range and Payload)

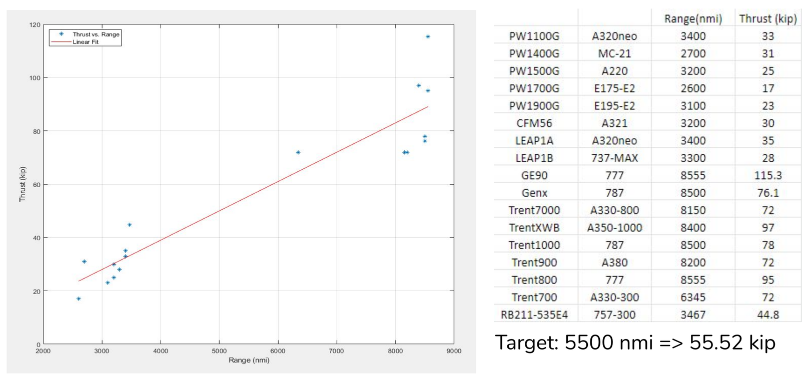
Assumptions for the new lip skin design:

- High bypass ratios with larger fan blade diameters
- Limited under-wing ground clearance
- Alternate anti-icing system
- Incorporating emerging engine technologies
- Limited under-wing ground clearance
- Aerodynamic drag reduction
- Alternative materials

Statistical Approach

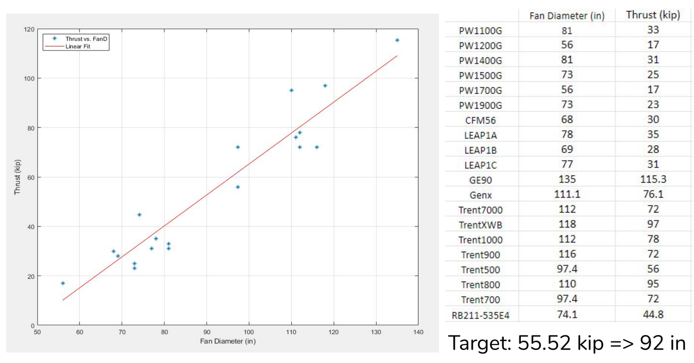
Two main characteristics of the engine, thrust and fan diameter, are estimated by statistical approach. Data from several Boeing and Airbus airplanes are gathered to predict the relation between thrust Vs. range and thrust Vs. fan diameter. Linear trends are favored in both plots. Based on the range requirement of 5500 nmi, the airplane requires a set of engines with a total thrust capacity of 55.52 kip and about 92 inch fan diameter.

Thrust Vs. Range



Target: 5500 nmi => 55.52 kip

Thrust Vs. Fan Diameter



Target: 55.52 kip => 92 in

Analysis-Based Design Process

Weights and Determining Criteria

Zero (0) weight indicates not considered or no influence on engine nacelle selection while the aircraft are rated on a scale of 3-optimal, 2-criteria meet and acceptable, and 1-inadequate

Airplane Trade Study

Boeing 737-MAX, 757, 787, Airbus 320NEO, 330, 220, and the New Midsize Aircraft are selected for the aircraft trade-off study based on their service in major airline companies as seen in **Figure 2**. Essential requirements for the air transportation market include an appropriate range of 4500~5000 nautical miles, total passenger load of 180~220, appropriate pilot training time, price, and maintenance requirements. Impact on airport infrastructure, takeoff height, and maximum cruising speed are also listed as major criteria due to air traffic planning and marketing considerations. Results from the rankings indicate criteria cannot be fully met by selected serving aircraft and the NMA dominant by optimal performance in range, passenger, maintenance requirement, wing shape, and ground clearance.

Key Characterisitcs and Requirements	Weight	737MAX	A320 NEO	757	787	A330	A220	NMA	Comments
		RANK							
		0	16	17	16	19	0	23	
Range (4500-5000 mi)	1	1	1	2	1	2	1	3	
Passengers (180-220)	1	3	2	3	1	1	1	3	
Max Take-off Weight	1	2	2	1	1	1	1	2	
Wing span	0								Does not effect nacelle
Max landing weight	0								Does not effect nacelle
Max zero fuel weight	0								Does not effect nacelle
Max fuel capacity	0								already implied with range
Overall Length	0								We know that gear length will factor into overall length of plane
Maximum Cruising Speed (MPH)	1	1	2	1	2	3	3	2	
Part Commonality	0								Complex and out of project scope
Airport Infrastructure	1	1	3	3	2	3	3	3	No impact = 3, GSE impact = 2, Gate impact = 1
Pilot Training	1	1	2	3	3	3	3	2	737 MAX accident related to new MCASystem, pilot need more training
Price	1	2	2	2	1	1	3	2	
Maintenance Requirment	1	2	2	1	1	2	2	3	
Life Span	0								Does not effect nacelle
Durability	0								Does not effect nacelle
Readiness	0								Does not effect nacelle
Wing shape	1	2	2	2	3	3	2	3	Winglet and wingspan are driving the rating
SFC	1	2	3	2	2	1	3	2	
Underwing Clearance	1	0	1	2	3	3	0	3	

Figure 2: Trade Study of Popular Aircrafts Currently Serving in Major Aerospace Primes

Engine Trade Study

Engine selection is determined based on the criteria of thrust, fan diameter, thrust to weight ratio, length, specific fuel consumption, noise production, cost, life-span, safety, delivery date, price, and new material, fan, and reverse thrust technologies. In **Figure 3**, five jet engines from prime manufacturers are compared to four new engine from Pratt & Whitney, General Electric, CFM, and Rolls-Royce. Zero weight on PW1100G, GE9X, and GEnx indicate engine unacceptable due to a significant deviation from customer specifications. Out of our selections, CFM New Engine dominant by optimal takeoff thrust (55,000 lbs), thrust to weight ratio, specific fuel consumptions, life-span, and reliability factors. Based on the result of this trade study, we assume the CFM New Engine is the ideal for the next midsize airliner.

Key Characterisitcs and Requirements	Weight	PW1100G	PW1400G	GE 9X	GEnx	LEAP 1A	LEAP 1B	LEAP 1C	Trent 1000	PW New Engine	GE New Engine	CFM New Engine	RR New Engine (UltraFan)	Comments
		RANK												
		0	25	0	0	27	26	25	18	30	33	34	29	
Take Off Thrust (***55,000 lbf***)	1	1	1	0	0	2	1	2	2	3	3	3	3	
Bypass Ratio (**12:1**)	0	2	2	1	1	1	1	1	1	2	2	2	2	Implied by SFC
Fan Diameter (~92in)	1	2	2	0	0	2	1	2	1	2	2	2	2	
Pressure Ratio (50:1)	0	2	2	3	1	2	2	3	2	2	2	2	2	
T/W	1	2	2	1	1	2	3	1	1	2	1	3	1	
Length (max 120 in)	1	2	2	2	1	2	3	1	1	2	2	2	1	
SFC	1	2	2	3	3	2	2	2	1	2	3	3	1	
Noise	1	2	2	1	1	2	2	2	2	2	2	2	2	
New material Technology	1	2	2	3	3	2	2	2	1	2	3	3	2	GE composite fan blades: RANK: 3
New Fan Technology	1	2	2	3	2	2	2	2	1	2	2	2	3	Rolls royce new CTi fan system, RANK: 3
New reverse thrust Technology	1	2	2	2	2	2	2	2	1	2	2	2	3	Rolls royce new reverse thrust technology by pitching the fan blades, RANK: 3
Maintanance Cost	1	1	1	3	3	2	2	2	1	1	3	2	1	New engines reflect the last engine maintenance cost for each manufacturer
Life Span	1	1	2	2	2	2	2	2	1	3	3	3	3	
Safety/Reliability	1	0	2	2	2	2	1	2	2	3	3	3	3	
New Engine Delivery	1	1	1	1	1	1	1	1	1	2	2	2	2	
Price	1	2	2	1	1	2	2	2	2	2	2	2	2	

Figure 3: Trade study of Current Commercial Engines and Future Engines

Material Trade Study

Specific materials and their characteristics are the key when choosing the material that the lip skin would be composed of. From this section of the trade study, a variety of materials ranging from different titanium and aluminum metal alloys to graphene-epoxy carbon fiber are considered due to their material and economic advantages. Traditionally, engine inlet lip skins are manufactured with aluminum alloys through a spin-forming technique, however, many industries are starting the transition from using aluminum alloys to Grade 4 commercially pure titanium (Cp-Ti). The advantages of using Cp-Ti relative to the aluminum alloys can be demonstrated through its higher fatigue and specific strength, formability, high and low service temperature capabilities, and ability to resist corrosion. Two notable trade offs to using Cp-Ti compared to the top aluminum alloy contender (aluminum 2219-T62) would be its expensive material cost and weight. On one side of the token, titanium can be undesirable for being heavier and costly. On the other side of the token, the formability of Cp-Ti allows it to be manufactured more easily and precisely. In the aerospace industry, safety is the priority. Thus, any defect in production is unacceptable. Therefore, the higher quality of Cp-Ti in terms of its material properties and formability are vastly superior compared to the traditional aluminum alloy.

Key Characterisitcs and Requirements	Weight	Ti-6Al-4V Grade 5	Cp-Ti Grade 4	Aluminum-6061 T6	Aluminum-7075 T6	Aluminum 5052-H32	Aluminum 2024-T3	Aluminum 3003-H14	Aluminum 2219-T62	Graphite-epoxy
		Rank								
		47	48	34	38	32	34	36	40	43
Density	0	1	1	2	2	2	2	2	2	3
Impact Resistance	1	3	3	1	2	1	1	1	1	1
Material Maintenance	1	3	3	2	2	2	2	2	2	3
Reliability	1	3	3	2	2	2	2	2	2	3
Material Cost	1	1	1	2	2	1	1	3	3	1
Young Modulus	1	3	3	2	2	2	2	2	2	3
Fatigue Strength	2	2	3	1	2	1	2	1	3	3
Specific Strength	1	3	2	2	3	1	2	1	2	3
Formability	1	3	3	2	1	2	1	3	2	1
Fleet Cost	1	1	1	2	2	1	1	3	3	1
Defect Detectability in Service	1	3	3	3	3	3	3	3	3	3
Defect Tolerable	1	3	3	2	2	2	2	2	2	3
High Temperature Service Capability at 316ºC	1	3	3	1	1	1	1	1	1	3
Low Temperature Service Capability at -80ºC	1	3	3	1	2	1	2	1	1	3
Manufacturing Cost	1	1	1	2	2	2	2	2	2	3
Profile Implementation	1	3	3	3	3	3	3	3	3	1
Corrosion	1	3	3	2	2	3	2	2	2	3
Anti-icing Implementation	1	3	3	2	2	2	2	2	2	1

Figure 4: Trade Study of Common Materials Used in Aerospace Applications

Anti-icing System Trade Study

Starting with multiple anti-icing and de-icing systems, and key characteristics chosen based on energy efficiency, maintainability and cost-benefit analysis, the outcome shows that the electro-thermal heating system is the ideal option. It is essentially composed of thermal mats installed in within the leading edge slats and powered by the electric power produced by a generator fitted in the engines. This system offered multiple advantages such as the reduction of mechanical system complexities, an improved fuel efficiency, the reduction of drag and noise due to the absence of exhaust holes, and more importantly it is a versatile of the system i.e anti-icing (preventive) and de-icing (reactive).

Key Characterisitcs and Requirements	Weight	Bleeding Air Swirl	Evaporative/Running Wet Systems	Bias Acoustics Linear	Superhydrophobic Coating	Bleed air Piccolo Tube	De icing Electrothermal Heating System	Electro-Impulse	TKS deicing sys	Pnuematic Boots
		Rank								
		32	32	31	27	32	34	29	0	0
Certification	1	2	2	2	2	2	2	2	2	2
Cost	1	2	2	2	1	2	1	1	2	2
Installation Max Weight	1	1	1	1	1	1	3	3	1	2
Warm-up Time	1	2	2	2	3	2	3	2	1	3
Manufacturing Schedule	1	2	2	2	2	2	2	2	2	2
Erosion	1	2	2	2	1	2	2	2	2	2
Maintainability	1	2	2	1	1	2	2	1	1	1
Risk/reliability	1	2	2	2	2	2	2	2	1	2
FAA Certification	1	2	2	2	1	2	2	2	2	2
Safety/Environmental limitations	1	2	2	2	2	2	2	2	1	0
In-flight diagnosis	1	2	2	2	1	2	3	3	2	2
Electromagnetic interference	1	2	2	2	3	2	2	1	2	2
Aerodynamics	1	3	3	3	2	3	2	2	2	1
Maturity	1	2	2	2	1	2	2	2	2	2
Repairability	1	2	2	2	2	2	1	1	2	2
Duty Cycle	1	2	2	2	2	2	3	1	0	0

Figure 5: Trade Study of Common Anti-Icing and De-Icing Systems in the Aerospace Industry

Lip Skin Profile Trade Study

Six key characteristics are compared between ten different profiles. Data to determine the rank of the first three rows of the requirements are gathered from the CFD simulation, and data to determine the rank of the last three rows are gathered from the solidworks drawing. Specific domains of each key characteristic are explained briefly in the comment section. The result of this trade study shows that Profile#6 has the highest ranking. Detail dimension of Profile #6 can be seen in the SolidWorks drawing section.

Key Characterisitcs and Requirements	Weight	Profile #1	Profile #2	Profile #3	Profile #4	Profile #5	Profile #6	Profile #7	Profile #8	Profile #9	Profile #10	Comments
		14	26	24	21	22	32	36	27	27	23	
Max local Mach #	1	3	2	2	1	2	3	3	1	2	2	1 : >1.3, 2 :1.2-1.3 , 3 : <1.2
Max adverse pressure gradient	1	3	2	2	1	2	3	3	2	2	1	1 : >2.5, 2 :1-2.5 , 3 : <1 all e5
Cd at cruise	1	3	2	2	2	3	2	2	2	1	1	1 : >0.05, 2 : 0.04-0.05, 3 : <0.04
Highlight Diameter	1	2	2	2	2	2	2	2	2	2	2	
Surface area	1	2	1	2	3	2	2	2	2	3	3	1 : >66800, 2 : 66400-66800, 3 : <66400 all in in^2
Weight	1	1	2	3	1	2	3	2	3	3	1	1 : >160, 2 :150-160 , 3 : <150 all in lbs

Figure 6: Trade Study of Lip skin Profiles for Subsonic Turbo Fan Engine

Product and Detail Design

Super-Ellipse Geometry

$$\left(\frac{x}{a}\right)^n + \left(\frac{y}{b}\right)^n = 1 \rightarrow \text{Internal curve}$$

$$\left(\frac{x}{L}\right)^m + \left(\frac{y}{Y}\right)^m = 1 \rightarrow \text{External curve}$$

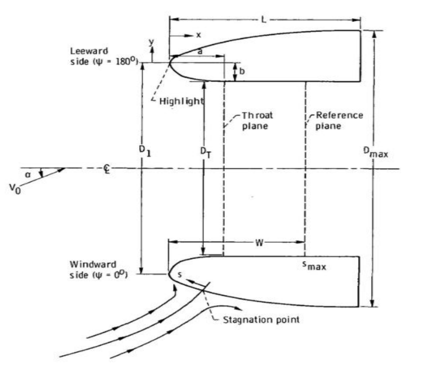


Figure 7: Design Parameters [1]

According to an early study by James A., the geometry known as the super-ellipse geometry is the ideal geometry for a subsonic turbo fan engine [1] as seen in **Figure 7**. The major and minor axis of the internal curve are represented by a and b. Similarly, the major and minor axis of the external curve are represented by L and Y.

The exponent n and m determines the shape of the lip skin, where a higher exponent will result in a blunter shape. For simplicity, the exponents on all profiles are kept as a constant two.

The internal diameter downstream of the throat is constant and should be replaced by the diffuser in the next design process.

Profile #	Dt	A1/At	a/b	a	b	L	Y
1	92	1.3	2	12.9	6.45	47.2	10.5
2	92	1.2	2	8.8	4.39	47.2	12.6
3	92	1.15	2	6.7	3.33	47.2	13.5
4	92	1.1	2	4.5	2.25	47.2	14.5
5	92	1.2	1.5	6.6	4.39	47.2	12.6
6	92	1.2	2.5	11.0	4.39	47.2	12.6
7	92	1.2	3	13.2	4.39	47.2	12.6
8	92	1.15	1.5	5.0	3.33	47.2	13.5
9	92	1.15	3	10.0	3.33	47.2	13.5
10	92	1.1	2.5	5.6	2.25	47.2	14.5

SolidWorks Drawing

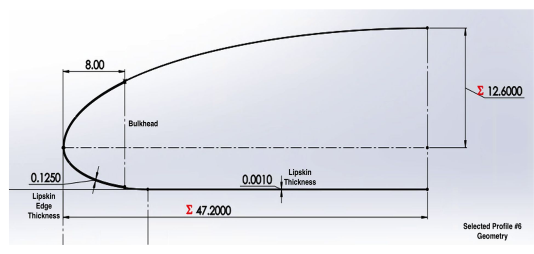


Figure 8: SolidWorks Drawing of Profile #6

Figure 9: Model of Profile #6

Prototype

Figure 8: SolidWorks sketch of Profile #6 display thickness of 0.125 inches at the highlighted area and 0.001 inches after the bulkhead 8 inches from the tip of the lip skin. The prototype will be manufactured by spin forming method (**Figure 9**) as one piece to improve the airflow due to the absence of any intersections, then post-processed to the desired accuracy.

Ansys-fluent CFD Simulation

Two-dimensional CFD simulation was performed since the geometry of all profiles are radially symmetrical. A rectangular test section (two figures on the right side) was designed to be large enough to capture the main behavior of the flow around the lipskin. The dimension of the test sections are 6x8m, and the throat of the lipskin profiles were stretched due to the incomplete nacelle design. A uniform flow of 550 mph was set to depart from the inlet of the test section (left side) in the x-axis direction.

The result shows that the drag coefficient (top left figure) of Profile#6 converged to about 0.04. The maximum velocity and the minimum pressure occurred around the throat, while the minimum velocity and the maximum pressure occurred around the stagnation point.

Details of the pressure on the surface can be seen in the provided graph (bottom left figure).

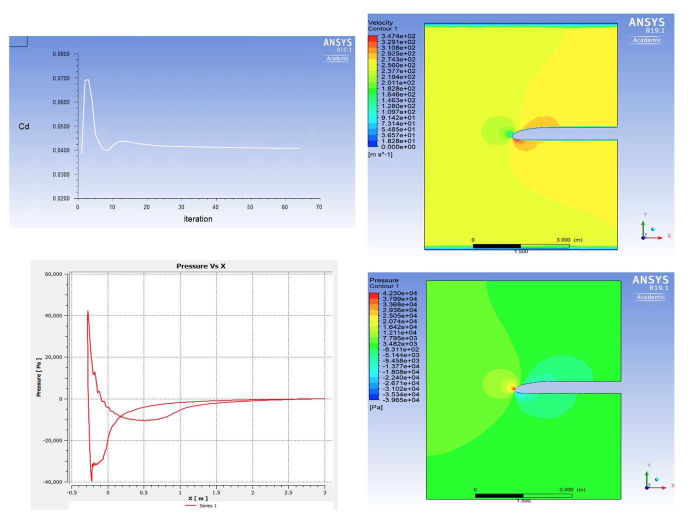


Figure 10: CFD Simulations Result of Drag Coefficient, Velocity and Pressure Around the Lip Skin

Abaqus FEA - Bird Strike Simulation

In addition to choosing the material type and geometry of the lip skin, additional testing was incorporated to account for the possibilities of birds being hit by the lip skin during the take off phase. During the Abaqus simulation, smoothed-particle hydrodynamics is the meshless Lagrangian technique used to simulate an 11 lbs bird striking the leading edge of the lip skin at 180 mph as seen in **Figure 11**. A stress analysis of the simulation for commercially pure titanium yields a von Mises stress of 2.98 MPa while aluminum 2219-T64 experiences 3.06 MPa. These simulation provide computational evidence that the Cp-Ti selection will provide a higher in quality and strength product.

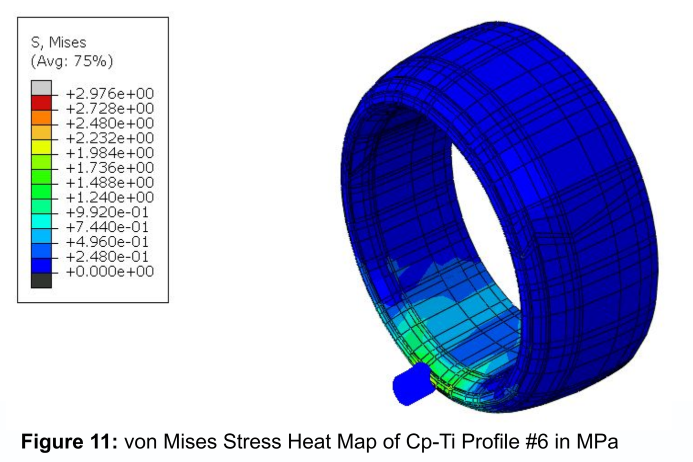
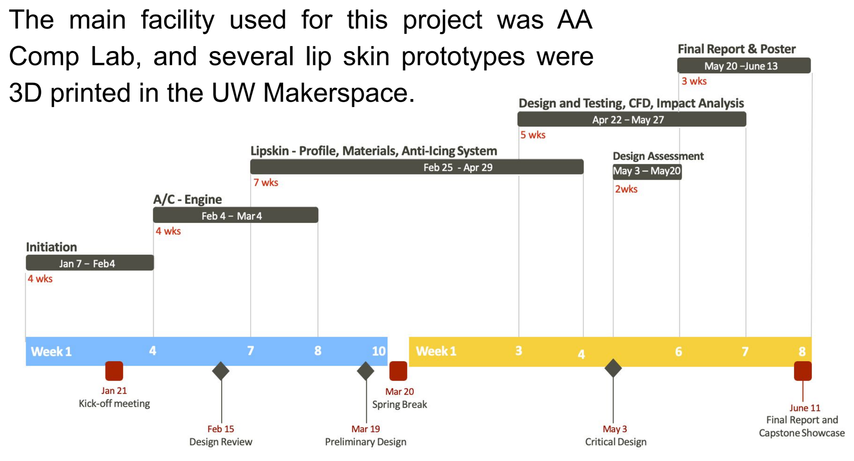


Figure 11: von Mises Stress Heat Map of Cp-Ti Profile #6 in MPa

Final Schedule

The main facility used for this project was AA Comp Lab, and several lip skin prototypes were 3D printed in the UW Makerspace.



Lessons and Conclusion

This project shows the significant value of extensive trade studies in the design process. It is true that the early study can be a useful source for the future design. However, new materials and emerging technologies should also be considered in the design process, and trade studies have been proven to provide the best solutions. Our trade studies show that Grade 4 Cp-Ti and the electro-thermal heating system to be the best choice of the material and the anti-icing system. Based on the lip skin profile trade study, which was supported by the data from CFD and bird strike simulations, Profile #6 was selected to be our best conceptual lipskin design.

References

1. James A, et al, "*Effect of Subsonic Inlet Lip Geometry on Predicted Surface and Flow Mach Number Distributions,*" Lewis Research Center, NASA, Cleveland, Ohio, December 1973
2. Derber, Alex., "*Can Boeing Sell the NMA For Less and Make It Up in Aftermarket?*" MRO-Network.com, July 2018. https://www.mro-network.com/airframes/can-boeing-sell-nma-less-and-make-it-aftermarket

Acknowledgement

Special thanks for our mentors from GKN Aerospace Martin Philo and Dale Edmunds for guiding us through the project.

Final Budget and Cost

No budget was required for this study.

Impact/contribution

Our trade studies yielded results that will produce a durable, easy maintainable lip skin with a good aerodynamic benefits such as lower drag, high fuel efficiency etc.In addition to the determined lipskin profile having a low cost of production which in turn will reduce the overall cost of the aircraft.

These attributes will consequently contribute to a better quality of life of the passenger in term of reduced air fares and safety and thus of the aircrew in term of safety and maneuverability of the aircraft.

Ethical Consideration

Throughout our project, ethical guidelines have been a forefront of our decision making process. The key characteristics used in the trade studies as well as the associated ranking criteria were selected based on two principal engineering ethics: 1) Preventive ethics that focuses on preventing professional misbehavior and engineering disaster. 2) Aspirational ethics that inclined to make a better life via technology.

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