EFFECT OF VORTICITY AROUND WINGLETS

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ABSTRACT

The purpose of this project is when the aircraft moves through the air, it results into the production of wingtip vortices due to its own lifting. These wingtip vortices are higher as the aircraft lift increases. If winglets are fixed to wingtips, then such wingtip vortex goes down and the aircraft performance will turn out to be better. We has hardly emphasized on the analyses of winglets and performance. When winglets are used, drag coefficient decreases since wingtip vortices are reduced by winglets.

Vorticity magnitude of wing will be checked and compared when winglets are used. For that, one wing model without winglet and two wing models with winglets (wingtip fence, racked wingtip) were created and drawn in CATIA V5 and geometry data gathered from the Airfoil Investigation Database and Boeing website. These models import to ICEM CFD and other required operations like meshing in ICEM CFD, flow boundary conditions were applied in CFX-Pre, solving iterations in CFX-Solver for analyzing and the results are visualized in CFX-Post.

The wing and the wing with winglets performance were analyzed in several angles of attack and the lift and drag coefficients were compared when the aircraft is in take off and cruise. Wingtip vortices and pressure from models were checked, studied and compared. All winglet models are reduces the drag coefficient when compared with wing model. The minimum drag coefficient winglet is considered as the best winglet at different angle of attack in cruise and it will be pointed out at the end of this project. From this analysis, Wingtip Fences is best winglet at several angle of attacks in take off and cruise.

Keywords: Winglets, Vortex Development, computational fluid dynamics, induced drag.

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INTRODUCTION

Since the 1970s, when the price of aviation fuel began spiraling upward, airlines and aircraft manufacturers have looked at many ways to improve the operating efficiency of their aircraft. In the 1970's, Richard Whitcomb, a noted aeronautical engineer at the NASA Langley Research Center, refined the winglet concept with wind tunnel tests and computer studies. He then predicted that transport-size aircraft with winglets would realize improved cruising efficiencies of between 6% and 9%. A winglet flight test program at the NASA Dryden Flight Research Center in 1979-80 validated Whitcomb's research when the test aircraft -- a military version of the Boeing 707 jetliner with and without winglets showed that the winglet increased fuel mileage rate of 6.5% and also improved directional stability.

When the aircraft moves through the air, it results into the production of wingtip vortices due to its own lifting. These wingtip vortices are higher as the aircraft lift increases. If winglets are fixed to wingtips, then such wingtip vortex goes down and the aircraft performance will turn out to be better. When winglets are used, drag coefficient decreases since wingtip vortices are reduced by winglets.

WINGTIP VORTEX DEVELOPMENT

Vortices form because of the difference in pressure between the upper and lower surfaces of a wing that is operating at a positive lift. Since pressure is a continuous function, the pressures must become equal at the wing tips. The tendency is for particles of air to move from the lower wing surface around the wing tip to the upper surface (from the region of high pressure to the region of low pressure) so that the pressure becomes equal above and below the wing as shown in fig 1. In addition, there exists the oncoming free-stream flow of air approaching the wing. If these two movements of air are combined, there is an inclined inward flow of air on the upper wing surface and an inclined outward flow of air on the lower wing surface. The flow is strongest at the wing tips and decreases to zero at the mid span point as evidenced by the flow direction there being parallel to the free-stream direction.

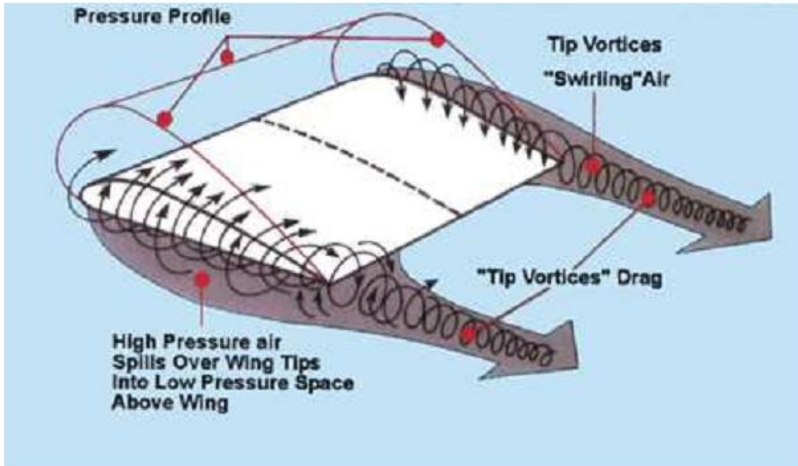


Fig.1: Origin of Wingtip Vortices

When the air leaves the trailing edge of the wing, the air from the upper surface is inclined to that from the lower surface, and helical paths, or vortices, result. A whole line of vortices trails back from the wing, the vortex being strongest at the tips and decreasing rapidly to zero at midspan. A short distance downstream, the vortices roll up and combine into two distinct cylindrical vortices that constitute the wingtip vortices. The wingtip vortices trail back from the wing tips and they have a tendency to sink and roll toward each other downstream of the wing. Again, eventually the tip vortices dissipate, their energy being transformed by viscosity. The tip vortices cause additional down flow (or downwash) behind the wing within the wingspan. For an observer fixed in the air, all the air within the vortex system is moving downward (called downwash) whereas all the air outside the vortex system is moving upward (called upwash). An aircraft flying perpendicular to the flight path of the airplane creating the vortex pattern will encounter upwash, downwash, and upwash in that order. The gradient, or change of downwash to upwash, can become very large at the tip vortices and cause extreme motions in the airplane flying through it. An airplane flying into a tip vortex also has a large tendency to roll over. If the control surfaces of the airplane are not effective enough to counteract the airplane roll tendency, the pilot may lose control or, in a violent case, experience structural failure.

A vortex occurs when the high pressure on the bottom of the wing curls around the wingtip into the low pressure on top of the wingtip. The vortex creates a problem in lift because it pushes down on the top of the wing when it curls around it causing it to lose lift. Another type of vortex is caused by angles. When air blows past a corner (for instance where the wing intersects with the fuselage) it spirals. This is because the air hits one side and bounces to the other and it just follows that pattern in a spiral.

WING AND WINGLET GEOMETRY:

The Boeing 737-800 wing without winglet and the wing with winglets have been designed in Catia V5 R20. In order to do that, airfoil (root, midspan and tip) coordinates are picked from the Airfoil investigation website. This coordinates are created in excel sheet and imported into catia.

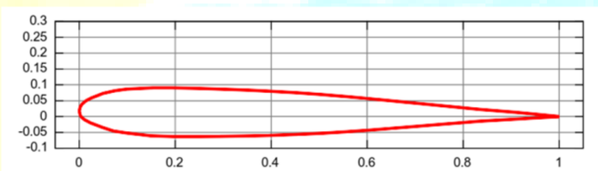


Fig. 2: Airfoil of Boeing 737 Root

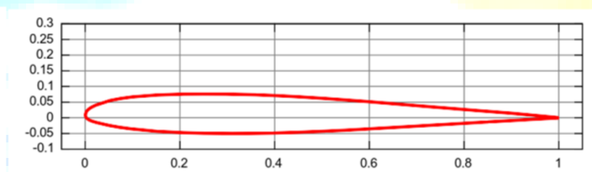


Fig. 3: Airfoil of Boeing 737 Midspan

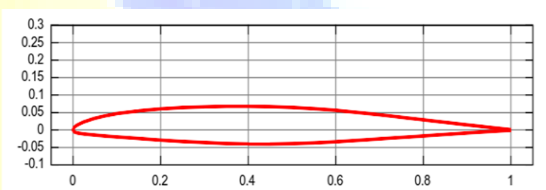


Fig. 4: Airfoil of Boeing 737 Outboard

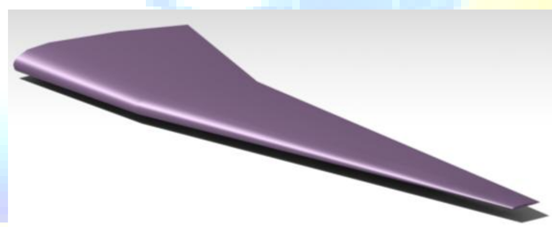


Fig. 5: Wing without winglet

Winglet design:

The geometry of a winglet is defined by three main parameters:

- · Height
- · Sweep angle
- · Cant angle

Wingtip Fence: The wingtip fence is also design with Boeing 737-800 tip airfoil. The upper winglet has sweep angle is 26° and cant angle is 65° and length of winglet is 8 feet 3 inches. The lower winglet has sweep angle is 21° and cant angle is 45° and the length of winglet is 4 feet 5 inches. The Boeing 737-800 wing with wingtip fences as shown in fig 6.

Racked Wingtip: The racked wingtip is design with Boeing 737-800 tip airfoil. The Length of wingtip is extended to 15 feet and swept angle is 53°.The Boeing 737-800 wing with racked wingtip as shown in fig 7.

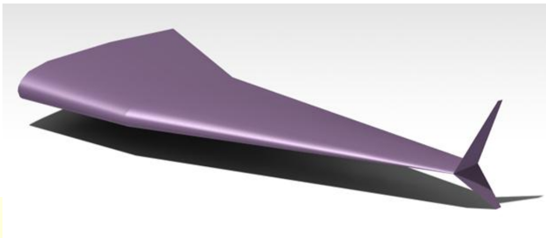


Fig. 6: Wing with Wingtip fence

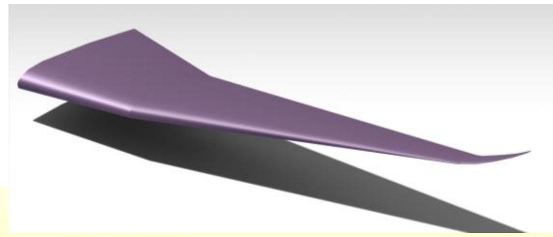


Fig. 7: Wing with Racked wingtip

The wing areas of these models are shown in table 1.

Wing	No Winglet	Wingtip fence	Racked Wingtip
Area (mm^2)	152.775	153.557	156.753

Table 1: Wing Areas

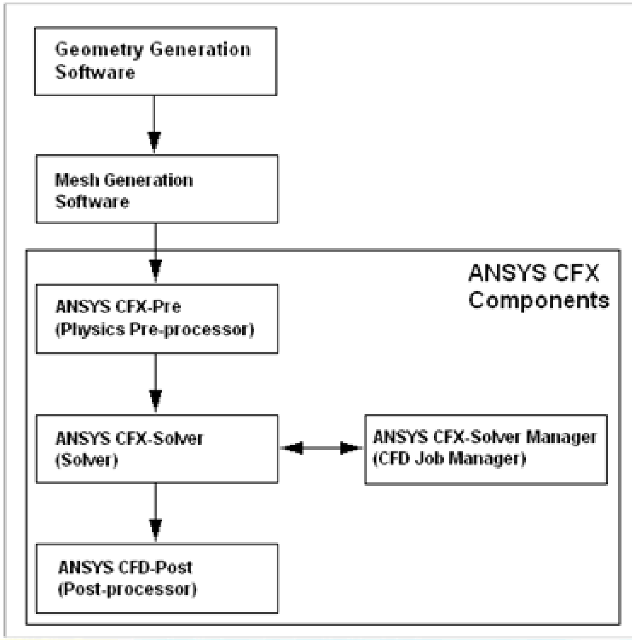
These wing areas will be used to work out drag coefficient C_D, lift coefficient C_L.

COMPUTATIONAL FLUID DYNAMICS:

Computational Fluid Dynamics (CFD) is a computer-based tool for simulating the behavior of systems involving fluid flow, heat transfer, and other related physical processes. ANSYS CFX is a general purpose Computational Fluid Dynamics (CFD) software suite that combines an advanced solver with powerful pre- and post-processing capabilities.

The Structure of ANSYS CFX:

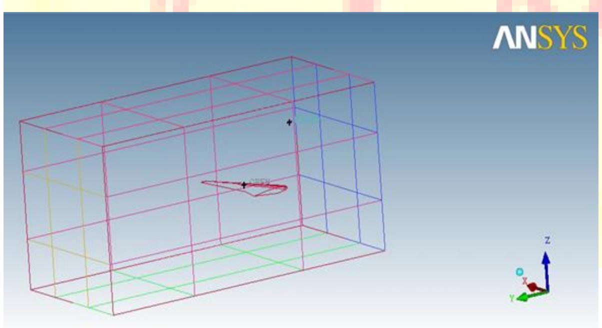
The set of equations solved by ANSYS CFX are the unsteady Navier-Stokes equations in their conservation form. ANSYS CFX consists of four software modules that take a geometry and mesh and pass the information required to perform a CFD analysis.



PROCESS INVOVED IN ANSYS CFX:

Creating Domain and Meshing (in ICEM CFD):

The model is imported in ICEM CFD from Catia V5 R20. To import, we have to convert '.cat shape' file to 'stl' format. Create the domain in ICEM CFD. The control volume (domain) will be wind tunnel. The dimensions of the control volume are 30mm in X, 65mm in Y, 32mm in Z as shown in fig 8. Now create parts such as inlet, outlet, top boundary, surface, symmetry, symmetry1, fluid, orfn as shown in fig. Now we mesh entire domain with tetrahedral mesh as shown in fig 9, the '.prj' file is generated.



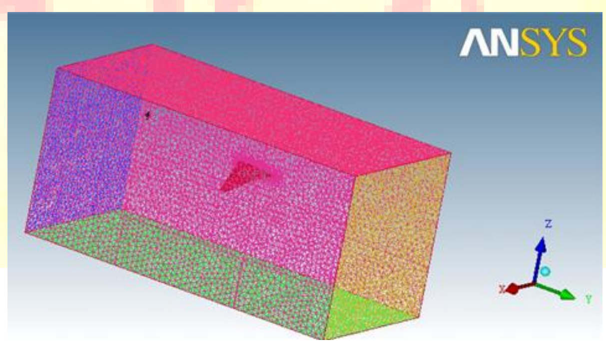


Fig. 8: Parts of the Domain **Fig. 9: Meshing**

Boundary condition (in CFX- Pre):

Import mesh file in to CFX- Pre as shown in fig 10. CFX-Pre is used to define simulations. Analyses, which consist of flow physics, boundary conditions, initial values, and solver parameters, are also specified. A full range of boundary conditions, including inlets, outlets and openings, together with boundary conditions for heat transfer models and periodicity, are all available in ANSYS CFX through CFX-Pre.

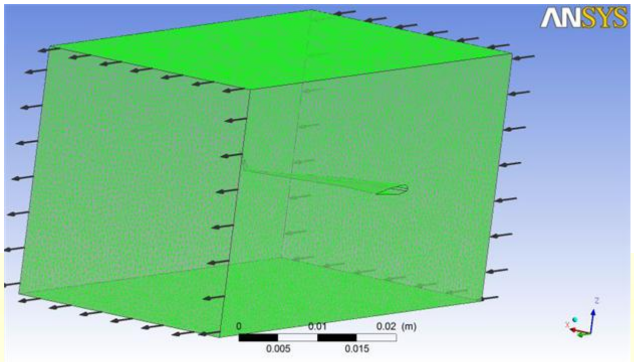


Fig. 10: Domain in CFX-Pre

K-Epsilon model was picked since it is a two equation model that works very well in these kinds of problems. The flow regime is subsonic. The velocity inlet for take off is 264.3 ft/sec (M=0.2730) and for cruise is 760.053 ft/sec (M=0.785). The Cartesian velocity components are given to specify the different angle of attacks. Basically, vorticity magnitude, pressure and drag coefficient must be calculated to compare the performance wing model without winglet and with wingtip fence. The solver control is set as advention scheme is high resolution and turbulence numeric is high resolution. The .cfx file is generated here.

Iterations (in CFX- Solver):

CFX-Solver solves all the solution variables for the simulation for the problem specification generated in CFX-Pre. One of the most important features of ANSYS CFX is its use of a coupled solver, in which all the hydrodynamic equations are solved as a single system. The coupled solver is faster than the traditional segregated solver and less iterations are required to obtain a converged flow solution.

Define the run by giving '.cfx file'. The solution is converged as a result of among iterations. The .def file is generated. After convergence, the CFD post will open automatically. The wing and the wing with winglets will be analyzed in CFX at different angles of attack. The models will be studied when the aircraft is taking off and cruise with different angles of attack between 0 and 16 degrees.

Visulalizing Results (in CFX- Post):

CFD-Post provides state-of-the-art interactive post-processing graphics tools to analyze and present the CFX simulation results. To check the results in any where in domain we have to create planes.

To measure vorticity magnitude around wing and winglets, we create seven planes with a distance as in percentage of root chord of the wing (as in table 2) as shown in fig 11.

Plane No.	% of Root chord (7.88mm)	Distance from leading edge of wing
Plane 1	0	0
Plane 2	25	1.97
Plane 3	50	3.94
Plane 4	75	5.91
Plane 5	100	7.88
Plane 6		10
Plane 7		12

Table 2: Planes in percentage of root chord of the wing

To measure the pressure, we create six planes with a distance as in percentage of wing span (as in table 3) as shown in fig 11.

Plane No.	% of Wing Span (17.16 mm)	Distance from root of the wing
Plane 1	0	0
Plane 2	25	4.29
Plane 3	50	8.58
Plane 4	75	12.87
Plane 5	100	17.16
Plane 6		18

Table 3: Planes in percentage of the wing span

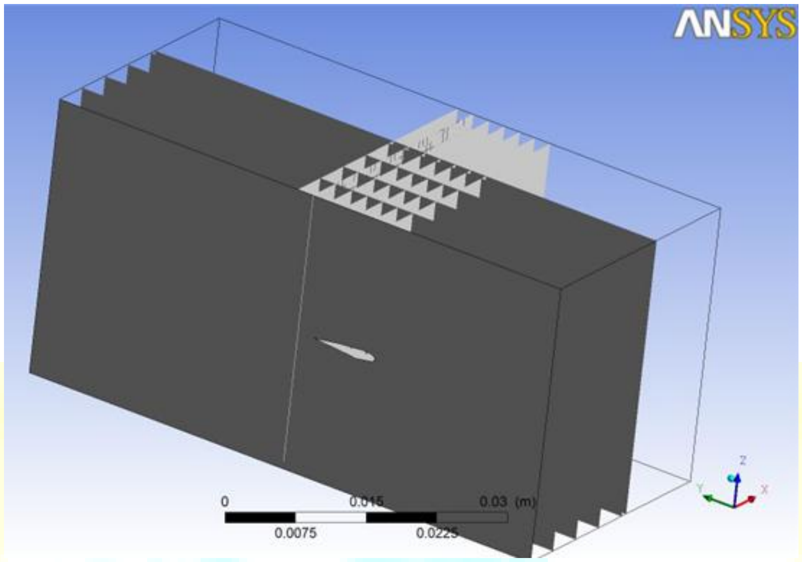


Fig. 11: Planes in the Domain

CFD Analysis of wingtip vortices development:

To study wingtip vortices development, wing will be analyzed at 0° and 4° angles of attack in cruise condition. At 0° angle of attack, my wing is not able to generate an enough lift coefficient to develop wingtip vortex. In fact, the drag coefficient is higher than the lift coefficient at 0 degrees in cruise. Lift coefficient C_L, at 0° is equal to 0.0000123204 and drag coefficient C_D at 0° is equal to 0.000911279, therefore the ratio C_L / C_D is equal to 0.013519425. Despite the fact C_D is higher than C_L the aircraft will not produce positive lift. So wingtip vortices are not created for wing at 0° angle of attack in cruise.

At 4° angle of attack in cruise, the value of C_L equal to 0.122901 N and the value of C_D equal to 0.0962416 N and then, the value of C_L / C_D equal to 1.277005197. My wing model at 4° is able to generate a positive lift and therefore, wingtip vortices can be developed. At 0°, there is no wingtip vortex, since the wings are not operating at positive lift. Besides, the ratio C_L / C_D is less than 1. At 4°, as the ratio C_L / C_D is higher than 1 there is wingtip vortices development. A wing generates wingtip vortices, as it is able to produce a ratio C_L / C_D higher than 1. Vortices form due to the difference pressure between the lower and upper surface in a wing. As my wing model works at 0°, there is no difference pressure between lower and upper surface and so there is no lift and no wingtip vortices. The difference pressure between lower and upper surface in a wing generates lift and therefore wingtip vortices. The difference pressure gets higher at 8 degrees. Of course, when the angle of attack increases the difference pressure goes up too.

Effect of Vortices: It is absolutely important to measure vorticity magnitude when to know the velocity curl. The maximum sum of vorticity magnitude value is produced by wing and, the minimum value by wingtip fence.

		Sum of the Velocity Curl at 0° in Take off							
Model	Plane 1	Plane 2	Plane 3	Plane 4	Plane 5	Plane 6	Plane 7		domain
	0	1.97	3.94	5.91	7.88	10	12		
Wing	1.430E+07	6.170E+07	6.348E+07	5.973E+07	5.746E+07	3.854E+07	1.735E+07		7.105E+07
Wingtip Fence	2.226E+07	7.421E+07	8.612E+07	9.618E+07	9.431E+07	6.672E+07	3.485E+07		1.736E+08
Racked Wingtip	1.727E+07	3.668E+07	4.072E+07	4.668E+07	4.601E+07	3.397E+07	2.388E+07		1.465E+08
		Sum of the Velocity Curl at 4° in Take off							
Model	Plane 1	Plane 2	Plane 3	Plane 4	Plane 5	Plane 6	Plane 7		domain
	0	1.97	3.94	5.91	7.88	10	12		
Wing	1.888E+07	6.504E+07	6.656E+07	6.278E+07	6.009E+07	4.155E+07	2.088E+07		7.235E+07
Wingtip Fence	2.886E+07	8.044E+07	9.278E+07	1.035E+08	1.018E+08	7.370E+07	4.191E+07		2.028E+08
Racked Wingtip	2.252E+07	4.160E+07	4.556E+07	5.141E+07	5.076E+07	3.859E+07	2.819E+07		1.477E+08
		Sum of the Velocity Curl at 8° in Take off							
Model	Plane 1	Plane 2	Plane 3	Plane 4	Plane 5	Plane 6	Plane 7		domain
	0	1.97	3.94	5.91	7.88	10	12		
Wing	2.564E+07	7.236E+07	7.355E+07	6.963E+07	6.659E+07	4.765E+07	2.672E+07		7.760E+07
Wingtip Fence	3.601E+07	8.739E+07	9.961E+07	1.105E+08	1.087E+08	8.064E+08	4.858E+07		2.062E+08
Racked Wingtip	2.911E+07	4.792E+07	5.170E+07	5.753E+07	5.686E+07	4.449E+07	3.367E+07		1.495E+08
		Sum of the Velocity Curl at 12° in Take off							
Model	Plane 1	Plane 2	Plane 3	Plane 4	Plane 5	Plane 6	Plane 7		domain
	0	1.97	3.94	5.91	7.88	10	12		
Wing	3.287E+07	7.895E+07	8.003E+07	7.609E+07	7.294E+07	5.391E+07	3.312E+07		8.260E+07
Wingtip Fence	4.505E+07	9.608E+07	1.084E+08	1.193E+08	1.177E+08	8.961E+07	5.731E+07		2.105E+08
Racked Wingtip	3.702E+07	5.544E+07	5.917E+07	6.479E+07	6.422E+07	5.156E+07	4.041E+07		1.522E+08
		Sum of the Velocity Curl at 16° in Take off							
Model	Plane 1	Plane 2	Plane 3	Plane 4	Plane 5	Plane 6	Plane 7		domain
	0	1.97	3.94	5.91	7.88	10	12		
Wing	3.273E+07	7.804E+07	7.910E+07	7.522E+07	7.211E+07	5.339E+07	3.294E+07		8.166E+07
Wingtip Fence	4.486E+07	9.508E+07	1.072E+08	1.179E+08	1.163E+08	8.871E+07	5.695E+07		2.073E+08
Racked Wingtip	3.689E+07	5.499E+07	5.867E+07	6.419E+07	6.362E+07	5.118E+07	4.018E+07		1.502E+08

Table 4: Sum of the velocity Curl in Take off

		Sum of the Velocity Curl at 0° in Cruise							
Model	Plane 1	Plane 2	Plane 3	Plane 4	Plane 5	Plane 6	Plane 7		domain
	0	1.97	3.94	5.91	7.88	10	12		
Wing	7.899E+07	1.498E+08	1.448E+08	1.507E+08	1.994E+08	1.513E+08	6.024E+07		4.126E+07
Wingtip Fence	5.086E+07	1.968E+08	2.323E+08	2.588E+08	2.536E+08	1.743E+08	8.129E+07		4.190E+08
Racked Wingtip	3.740E+07	9.257E+07	1.036E+08	1.201E+08	1.181E+08	8.261E+07	5.380E+07		3.270E+08
		Sum of the Velocity Curl at 4° in Cruise							
Model	Plane 1	Plane 2	Plane 3	Plane 4	Plane 5	Plane 6	Plane 7		domain
	0	1.97	3.94	5.91	7.88	10	12		
Wing	4.580E+07	1.809E+08	1.817E+08	1.676E+08	1.587E+08	1.048E+08	4.035E+07		1.421E+08
Wingtip Fence	7.035E+07	2.157E+08	2.500E+08	2.820E+08	2.772E+08	1.949E+08	1.015E+08		4.904E+08
Racked Wingtip	5.313E+07	1.075E+08	1.182E+08	1.345E+08	1.324E+08	9.659E+07	6.676E+07		3.327E+08
		Sum of the Velocity Curl at 8° in Cruise							
Model	Plane 1	Plane 2	Plane 3	Plane 4	Plane 5	Plane 6	Plane 7		domain
	0	1.97	3.94	5.91	7.88	10	12		
Wing	6.788E+07	1.994E+08	2.026E+08	1.912E+08	1.824E+08	1.288E+08	7.004E+07		1.882E+08
Wingtip Fence	9.311E+07	2.372E+08	2.716E+08	3.040E+08	2.993E+08	2.176E+08	1.242E+08		5.219E+08
Racked Wingtip	7.417E+07	1.274E+08	1.380E+08	1.540E+08	1.521E+08	1.157E+08	8.491E+07		3.464E+08
		Sum of the Velocity Curl at 12° in Cruise							
Model	Plane 1	Plane 2	Plane 3	Plane 4	Plane 5	Plane 6	Plane 7		domain
	0	1.97	3.94	5.91	7.88	10	12		
Wing	8.972E+07	2.198E+08	2.225E+08	2.109E+08	2.018E+08	1.481E+08	8.982E+07		2.054E+08
Wingtip Fence	1.213E+08	2.645E+08	2.992E+08	3.316E+08	3.276E+08	2.465E+08	1.516E+08		5.390E+08
Racked Wingtip	9.881E+07	1.512E+08	1.617E+08	1.773E+08	1.759E+08	1.390E+08	1.066E+08		3.655E+08
		Sum of the Velocity Curl at 16° in Cruise							
Model	Plane 1	Plane 2	Plane 3	Plane 4	Plane 5	Plane 6	Plane 7		domain
	0	1.97	3.94	5.91	7.88	10	12		
Wing	1.069E+08	2.331E+08	2.345E+08	2.215E+08	2.122E+08	1.578E+08	9.886E+07		2.017E+08
Wingtip Fence	1.448E+08	2.892E+08	3.240E+08	3.589E+08	3.561E+08	2.738E+08	1.757E+08		4.865E+08
Racked Wingtip	1.286E+08	1.812E+08	1.919E+08	2.076E+08	2.072E+08	1.695E+08	1.351E+08		3.657E+08

Table 5: Sum of the velocity Curl in Cruise

Drag Coefficient and Lift Coefficient improvement:

The main aim of my project is to check how winglets are able to reduced drag coefficient. The following table show wing models drag coefficient is reduced when winglets are linked to wingtips with different angles of attack, between 0º and 16º in take off and cruise.

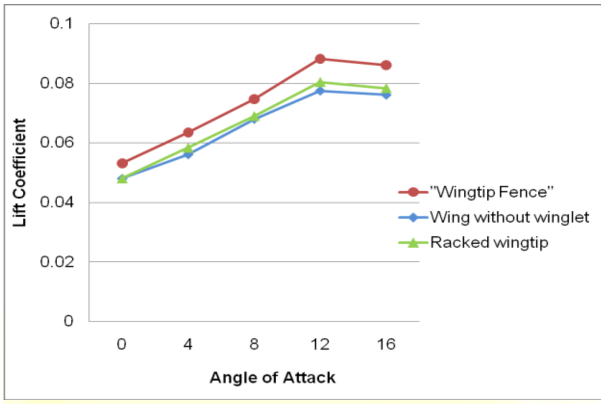
We observe that drag coefficient decreases of wingtip fence and racked wingtip when compared with wing. The drag coefficient of wingtip fence is very small.

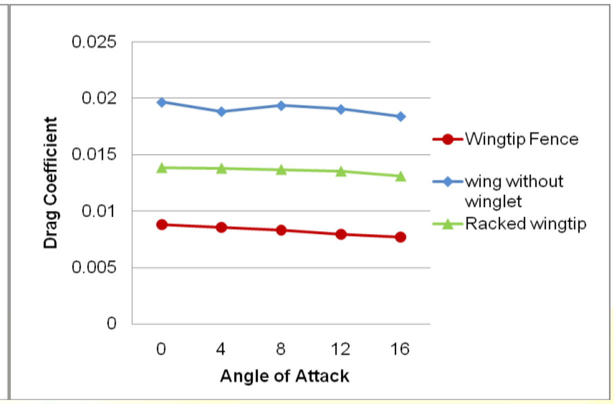
The table 6 also shows the best C_D improvement and C_L improvement of wingtip fence and racked wingtip. The wingtips vortices intensity is related to lift. If the wing is working with high angles of attack the lift is increased. Therefore, we can expect winglet works better with large angles of attack, since the wingtip vortex reduction will be higher. Wingtip fence works better in all angles of attack. The best winglet is wingtip fence because of it is able to reduced C_D conveniently, and the best drag coefficient reduction occurs when it is working.

		Wing					
	Lift(N)	Drag (N)	Cl	Cd	Cl/Cd		
Take off							
α=0°	0.028178	0.0115555	0.0479668	0.019671557	2.4383835		
α=4°	0.032933	0.0110733	0.0560612	0.018849356	2.97417058		
α=8°	0.0399015	0.0113809	0.0679236	0.019373658	3.50597703		
α=12°	0.0454675	0.0111887	0.0773985	0.01904682	4.06359172		
α=16°	0.0446622	0.0108204	0.0760276	0.01841936	4.12759184		
Cruise							
α=0°	0.00001232	0.00091128	2.536109E-6	0.00018759	0.01351943		
α=4°	0.122901	0.0962416	0.02508469	0.019643373	1.2770052		
α=8°	0.336083	0.0907886	0.06941994	0.018755437	3.7013235		
α=12°	0.385901	0.0891681	0.08007362	0.018502187	4.32779194		
α=16°	0.324347	0.0918723	0.06772329	0.019182832	3.5304114		
			Wingtip Fence				
	Lift(N)	Drag (N)	Cl	Cd	Cl/Cd	Cd improvement%	Cl improvement %
Take off							
α=0°	0.0313298	0.00520007	0.05306053	0.008806782	6.02496235	55.230884	9.59984757
α=4°	0.037484	0.00505955	0.06348334	0.008569676	7.40790434	54.53597	11.69147685
α=8°	0.044099	0.00491136	0.07468659	0.008317328	8.97963745	57.06888	9.055159701
α=12°	0.0521142	0.0046952	0.08826123	0.007951508	11.099936	58.25283	12.30747634
α=16°	0.0508529	0.00454208	0.08612507	0.007692385	11.1961466	58.2375	11.72419366
Cruise							
α=0°	0.259569	0.0392748	0.05316095	0.008043705	6.60901289	–	–
α=4°	0.314983	0.0382472	0.063962146	0.007766683	8.23529625	60.46156126	60.78197564
α=8°	0.374116	0.0367268	0.076892649	0.007548517	10.1864577	59.75291325	9.718365926
α=12°	0.444458	0.0348001	0.091754416	0.007184172	12.7717454	61.17122803	12.73050008
α=16°	0.547292	0.0323815	0.113692005	0.006726789	16.9013782	64.93328514	40.43267159
			Racked Wingtip				
	Lift(N)	Drag(N)	Cl	Cd	Cl/Cd	Cd improvement%	Cl improvement %
Take off							
α=0°	0.0289909	0.00836975	0.04809826	0.013886095	3.46377149	29.4102	0.2733155
α=4°	0.0352037	0.00834067	0.05840579	0.013837849	4.22072751	26.58715	4.01431091
α=8°	0.0416051	0.00827388	0.06902624	0.013727039	5.02848721	29.145858	1.59742
α=12°	0.0484976	0.00818108	0.08046146	0.013573076	5.92801956	28.73836	3.806741762
α=16°	0.0472496	0.00791939	0.07839093	0.013138911	5.96631867	28.667928	3.0148
Cruise							
α=0°	0.241095	0.065761	0.04837065	0.013193562	3.6662313	–	–
α=4°	0.294847	0.0655022	0.05865248	0.013030034	4.50132969	33.66702348	57.23166352
α=8°	0.352495	0.06486	0.070971708	0.013058979	5.43470545	30.37287108	2.186459991
α=12°	0.414789	0.0640407	0.083883634	0.012951082	6.47695916	30.0024262	4.54202306
α=16°	0.494115	0.0644374	0.100552442	0.013113016	7.6681399	31.64191815	32.64878639

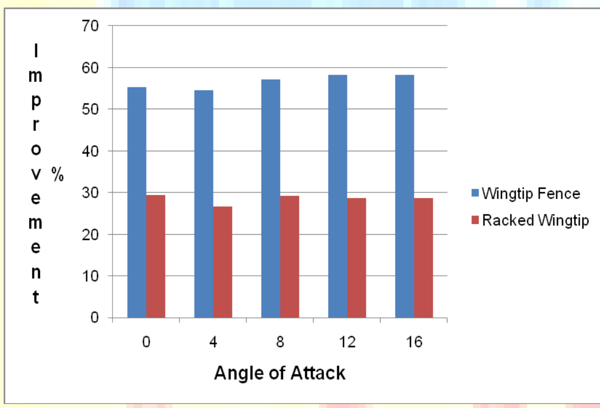
Table 6: Improvement of Lift and Drag Coefficient for all models

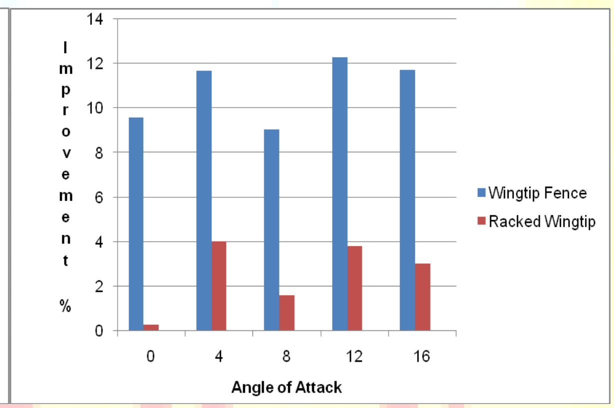
In Take off:





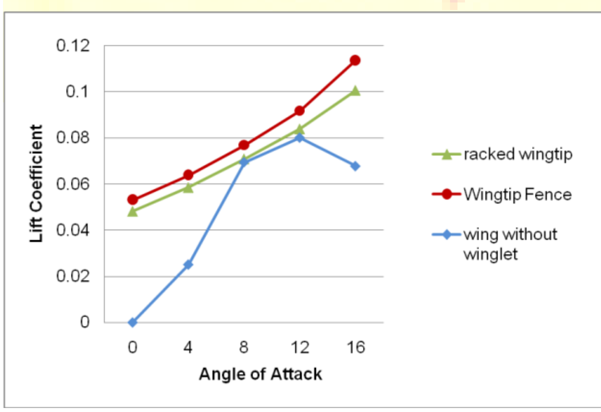
Graph 1: Lift Coefficient versus AOA in Take off **Graph 2 : Drag Coefficient versus AOA in Take off**

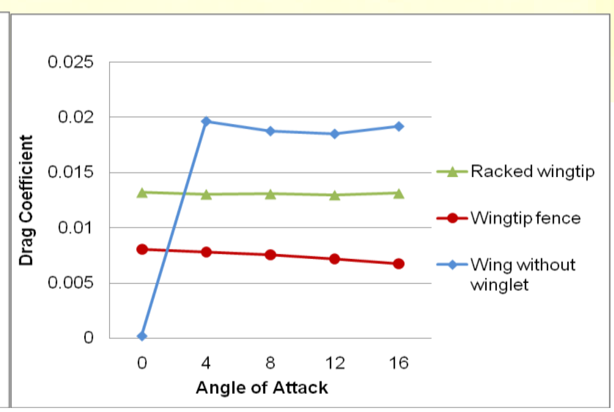




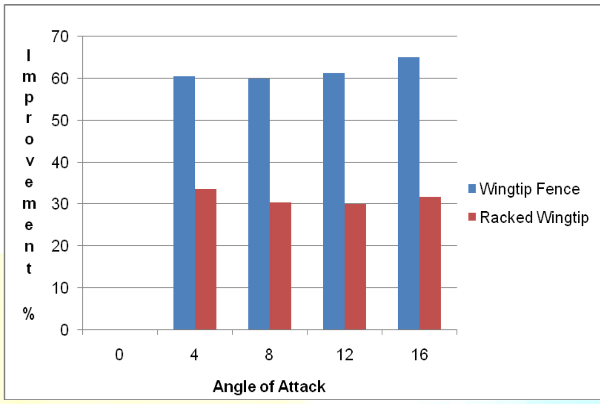
Graph 3: C_D improvement in Take off **Graph 4: C_L improvement in Take off**

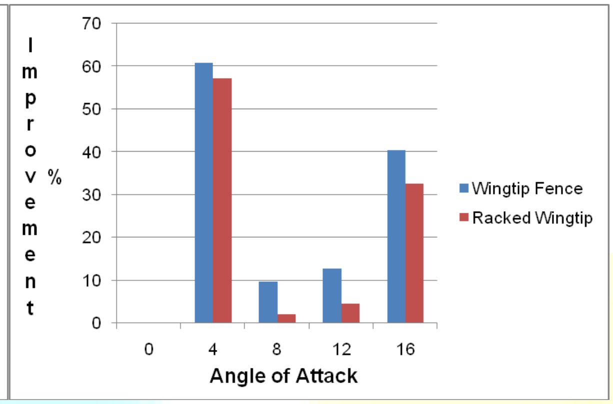
In Cruise:





Graph 5: Lift Coefficient versus AOA in Cruise   Graph 6: Drag Coefficient versus AOA in Cruise





Graph 7: C_D improvement in Cruise   Graph 8: C_L improvement in Cruise

CONCLUSION:

The wingtips vortex are developed as a wing is able to produce a ratio C_L/C_D higher than 1. If ratio C_L/C_D is less than 1, there are no wingtip vortices since the wing is not operating a positive lift. To produce a ratio C_L/C_D higher than 1, the pressure of the lower surface must be higher than the pressure of the upper surface, as can be seen from graphs. The difference pressure between lower and upper surface in a wing generates lift and therefore wingtip vortices produced. The velocity curl on the wing increases respect to angle of attack due to the lift increases as the angle of attack goes up.

The function of the winglet is to reduce the size of the vortex. Winglet is used to deflect the vortex and the vortices are deflected far over the wing. As the velocity curl increase the vorticity magnitude decrease. The two wing models with winglet are able to decrease the vorticity magnitude in the Planes. Therefore, the induced drag C_{Di} goes down in all my wing models with winglet. Wingtip fence and racked wingtip are able to reduce wing drag coefficient at several angles of attack (0°-16°) in take off and cruise. The best winglet is wingtip fence since it is able to reduce drag coefficient and vorticity magnitude. According to this project can affirm that wingtip fence and racked wingtip are tools that improve aircraft's performance when the aircraft is take off and cruise at different angle of attacks.

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