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DESIGN, ANALYSIS AND OPTIMIZATION OF FOLDING WING MECHANISM FOR EFFECTIVE UTILIZATION OF AIR SIDE AREA

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ABSTRACT

This paper aims to suggest a solution for the problem of disproportionately lesser growth of airside space with respect to growth of passengers/air traffic by using wing folding mechanism in aircrafts while on ground. A study of air traffic growth was followed by selecting STO-wing mechanism which met with desired requirements.

Boeing 787-8 Dreamliner was selected as base aircraft as it met certain criterion and analysis for mechanism was started. Different mechanisms of implementing STO-wing are discussed, and calculation for rod-lug mechanism which was finally chosen is shown. Its FEM analysis was carried out in ANSYS 14.5 along with mesh sensitivity study. An extensive weight optimization was carried out to make it as commercially viable as possible.

Then advantages and limitations of this type of solution with respect to other probable solutions are discussed and future scope of this endeavor is underlined.

Keywords

STO-wing folding mechanism, FEM, weight optimization, Boeing 787-8 Dreamliner

1. INTRODUCTION

Our envisaged future gives an insight into the skies full of flying machines, and increased traffic. Thus this paper checks the problems arising due to the inevitable traffic growth because of increased preference of air travel, air cargo and trade.

As aircraft traffic is bound to increase there is a requirement to either increase air side area of all airports around the world or reduce the "footprint" of existing or future aircrafts. This paper presents solution of problem in form of a folding wing mechanism for civilian aircrafts which will greatly reduce their "footprint" on ground. So, a STO-wing has been designed keeping in view the future requirements.

The STO-wing mechanism proposed, gives the wing, a degree of freedom about two axes using a single lug-rod arrangement. The foldable portion of the wing can be folded in both horizontal and vertical direction simultaneously with a single lug-rod arrangement movement. Also, the use of composite and titanium materials in this mechanism can compensate for the added weight to some extent.

Once developed, this technique can usher the scope for parking many of the huge airliners at a time in fewer number of terminals, ease in taxing after and prior to landing, passenger comfort and convenience, and many minutes of time saved. To serve the purpose of an efficient flight and ground operations altogether, a folding wing design has been employed to Boeing 787.

2. LITERARY REVIEW

A study was done for past World War-2 era mechanisms, currently used mechanisms in small private aircrafts and also spring loaded mechanisms used in some modern cruise missiles. The naval helicopters and the ship-borne aircraft-carriers have been the pioneer, in the sphere of foldable main-planes and tail-planes. Many patents have been created by the leading designers and manufacturers. The merits and demand of a folding wing mechanism to potentially cease the ill-effects of traffic growth in aviation industry have paved the basis for considering the design.

The concept of folding wings originated with the necessity of room in case of naval fixed-wing aircrafts that operate from the limited deck space. There was a need of space and localization on the hangar and flight decks.

Short Brothers, the world's first aircraft manufacturer, developed and patented folding wing mechanisms for ship-borne aircraft called the Short Folder, the first patent being granted in 1913. The wings were hinged so that they folded back horizontally alongside the fuselage, usually being held in place by latches projecting sideways from the rear of the fuselage.

Later, Grumman F4F Wildcat by Leroy Grumman became the first American built carrier-based aircraft with folding wings. F4F-4 had a STO-wing mechanism which was intensely studied and was a major source for designing the STO-wing mechanism for civilian aircrafts.

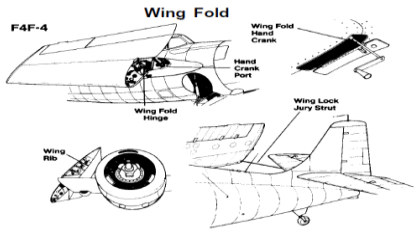

Figure 1. Folding wing mechanism of Grumman F4F-4 Wildcat [9]

The folding wing mechanisms have been concentrated to military and navy aircrafts in order to create room for large number of aircrafts. But with the expansion of the aircraft industry and advent of more passengers & airplanes, the commercial airliners are also facing the need of space on airports.

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Since for convenience, and allocation of a larger number of airplanes, the area required is also large. Folding surfaces are rare among land-based designs, and are used on aircrafts that are tall or too wide to fit inside service hangars. Examples include the Boeing B-50 Superfortress and its folding tail. The Saab 37 Viggen and the Boeing 377 Stratocruiser have foldable rear fins that make them lower for entering hangars. The Boeing 777 twinjet wide-body airliner was offered with folding wingtips as for increased fuel efficiency, larger wing spans were developed. And most of the largest commercial airports can handle wingspans of no more than 214 feet (65 meters as defined by the International Civil Aviation Organization), which has been a problem for the massive Airbus A380, a possible beneficiary of our solution.

For design of the wing folding mechanism in two planes in LSA May 2008 project report, the mechanism makes use of a two stage process. In the first step, the trailing edge of the wing rotates up. To achieve this motion, the bolts connecting the main and trailing spars to the fuselage are to be removed. The wing is then free to pivot about an axis running from the strut/main spar connection to the fuselage/main spar connection. In the second step, the wing slides down while being rotated to the rear of the aircraft. In order to maintain correct geometry throughout these processes, the strut connections at the wing are able to rotate about 2 axes, and the strut connection at the fuselage around 3 axes. The main spar/fuselage connection is to be a translating rotating joint, which could be built a rail sliding through a pivoting hook. But still this process required 2 moments which is too much an investment of time and weight and it is done manually [4].

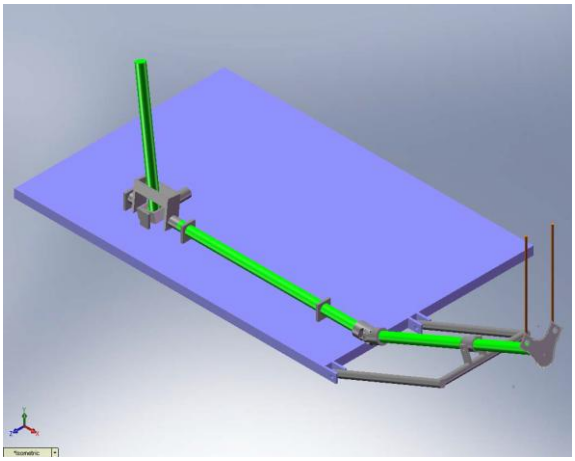
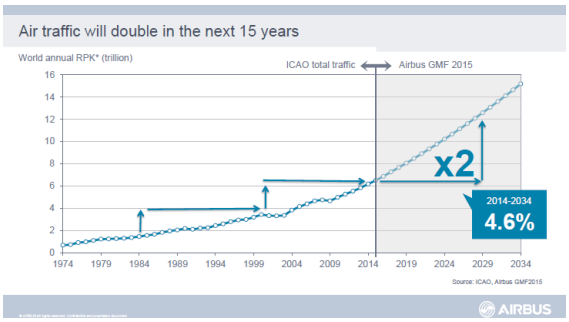


Figure 2. LSA folding wing mechanism [4]

3. METHODOLOGY

Number of passengers travelling by air has folded more than 6 times in last 40 years, not only this, the number of passengers are forecasted to grow by 4.6% every year for next 20 years [1]. This brings us in an urgency to find a solution for coping with this arising problem of air traffic growth which is going to affect our economic and ecologic systems drastically in the coming time.

(a)



(b)

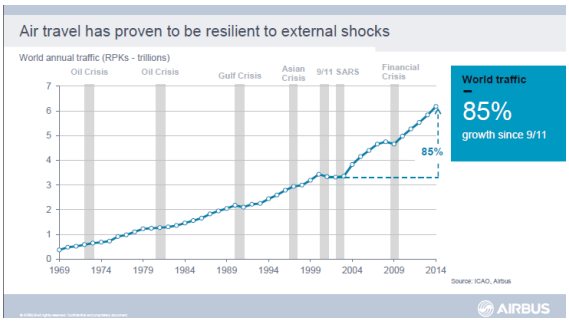


Figure 3. (a)Air traffic growth till 2015 and projected [5].

(b)Resilience of air travel growth to external factors [5]

One solution could be increasing the terminal area of an airport for accommodating more aircrafts, but this solution creates more problems rather than solving the problem at hand. Increasing the terminal area may halt the functionality of an airport, and after increasing the size it will require more number of workers to maintain that size of airport which will eventually increase the budget required to run the airport.

Another solution could be increasing the size of an aircraft, but this would require redesigning of the power, structural and weight considerations of the aircrafts, which can take years to get implemented. Moreover making an aircraft bigger will create a need to re-design an airport, now bigger runways will be required for taking-off and landing such a big aircraft and bigger hangars will be required too. At the same time, the infrastructure, and the runway will need to be altered.

This paper focuses on a much quicker and cost efficient solution. By folding the wings of an aircraft there will be less number of changes needed in design of airports and aircrafts.

3.1 Finalizing the Mechanism

There are many ways in which a wing can be folded, like, simple fold, horizontal fold, vertical fold, multi-fold, STO fold, etc.

3.1.1 Types of wing folding

1. Vertical fold: In this fold the wing is folded in the upward direction from a position on the wing nearer to fuselage. It requires a pushing mechanism to fold the wing along the hinge having longitudinal axis.

2. Multiple fold: It is the type of fold in which the wing is folded multiple times to save space in vertical as well as horizontal direction.

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3. Horizontal fold: It is the lateral folding of the wing in which a section of the wing folds such that it becomes parallel to the fuselage.

(a)

(b)

(c)

Figure 4.(a) Vertical Fold in F/A-18E/F Super Hornet [2]. (b) Multiple Fold in Fairey Gannet (c) Horizontal Fold in Fairey Fulmar

4. STO: It is a type of folding mechanism in which the wing is folded in the aftward direction such that it can move relative to two planes having one degree of freedom in a single movement as shown in the figure 5.

(a)

(b)

Figure 5. (a) and (b) STO-wing in F4F-4 Grumman Wildcat

3.1.2Advantages of STO-wing

Out of these we chose the STO folding mechanism because of reasons discussed as follows:-

A considerable amount of weight can be saved by implementing the STO-Wing mechanism instead of other aft or horizontal axis folding mechanisms currently used in many military and some small 2-8 seater civil aircrafts. As it uses rotation about only one axis using only one lug-rod arrangement rather than using two which would require 2 arrangements connected to 2 separate mechanisms which would also consume twice the power apart from extra weight and valuable space.

It is a relatively simpler mechanism for folding in two planes. Since implementing a vertical fold or horizontal fold possesses a huge challenge in case of large airliners like Boeing 787-8 due to limit on height of hangers. So, aftward fold using STO-Wing mechanism is an efficient way to implement a simple yet effective mechanism.

In this mechanism we have the freedom of adjusting its vertical as well as its horizontal movement just by adjusting rod axis. Its benefit is that we can adjust its vertical displacement in such a way that while folding it does not interfere with the horizontal stabilizer of the airplane.

The mechanism would comprise of a rod-lug structure which could be powered by motors. The part of the wing to be folded is connected with the lug which is attached with the rod. The rod makes 45° angle with respect to two planes. One with the vertical plane along the span of the wing and another with the vertical plane along the chord of the wing, such that the top end of rod is inclined towards the outboard side of wing and rearward side of fuselage to minimize both the lateral and vertical space required when the plane is parked. When this rod is rotated the wing follows the STO folding pattern and moves about two axes [9].

3.2 Finalizing Aircraft

Proper working and feasibility of the mechanism was checked by implementing the mechanism on an existing aircraft. The concept of folding mechanism was introduced early in the field of military aircrafts back at time of World War 2. But as this concept is new to the field of commercial aircrafts, an aircraft which could satisfy these following needs would best be the best candidate. The following are the requirements considered for choosing the aircraft:

- Simpler and easy to understand design.

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- It must be commercial heavy duty aircraft, which could carry a significant amount of payload.
- Accessibility to large number of airports in the world.
- Twin-engine aircraft.

Accommodating a folding wing mechanism in an aircraft would need a lot of initial investment in terms of human, technological and financial resources and to prove that it is commercially viable, a heavy duty aircraft having enough payload capacity to transport both passengers and cargo is needed as a reference aircraft. It should be accessible to most of the airports in the world so as to benefit from its wide range of operation and would finally help it to come out as a commercial success. The part that can be folded in the case of a four engine aircraft is smaller (as it is not technically feasible to place this mechanism in between the two engines), so accommodating this mechanism would not prove to be much beneficial. But in the case of a twin engine aircraft this mechanism would prove to be much beneficial as a significant amount of airside area would be saved.

For designing this mechanism suiting to feasibility, calculations and analysis were done. CAD models of Boeing 787 wing and rod-lug mechanism were made using Catia V5. Significant loads like, loads acting while folding and opening of the wing and loads acting on mechanism while in flight were determined. FEM analysis applying the same loads was performed to determine the feasibility of the mechanism. Weight optimization of the mechanism was accomplished by reducing additional weight out of the regions where least stresses were noted.

Accommodating the mechanism in an already designed aircraft would require a section of trailing edge of the static wing to be folded, allowing motion of the foldable part of the wing to the rear-side, and also alterations like changing the position and shape of the fuel tank, reinforcement of spar (as it has been made discontinuous), finding different ways to connect the electrical lines between the two parts of the wing. Also, keeping airfoil shape of the wing intact, proper weight distribution and proper load distribution would pose big challenge.

Accommodating and deciding the location of the folding mechanism inside the wing of aircraft with reasons and calculations

The location of the folding wing has been decided keeping in mind the optimum wing ground swept area. By optimum, it's meant that neither the area should be very small nor it should be very large. The shorter swept area means shorter movable part of the wing which finally result in large ground area covered by the aircraft during parking that contradicts our statement of purpose. And on the other hand if the swept area is increased to a larger value thus moving the mechanism near the root of the aircraft, then there is a good chance of wing tip interfering with the empennage of the aircraft. Moreover, increasing the swept area will also increase the weight of the movable part, this increase in weight will require more torque by the motor attached to it and also a stronger and heavier mechanism decreasing the payload capacity of the aircraft. So an optimum length of the static wing part is required which could keep an equilibrium between the weight and total ground area of an aircraft.

Also the position of the mechanism is determined on the basis of two main concerns, first, its position according to the conditions during flight and second, on the basis of its conditions while standing in the airside area. During the flight conditions the location will be such that its distance will be minimum from the point at which the total reaction force generated by the lift and drag force is acting, this will ensure us that the moment acting on the mechanism is minimum, which further will increase reliability on mechanism during flight. And during the time when the wings are folded, i.e., on ground, the mechanism when placed at a point nearer to the C.G. of the folded part will result in less moment to cope with. And, a shorter length of the folded part will result in lesser distance between the C.G. (of the folded part) and the mechanism. So, an optimum location for placing this is chosen which will ensure equilibrium between inflight and parking conditions.

Position of mechanism in between the thickness of the wing was determined using results of the analysis done in ANSYS, the position giving the least deformation and deflection to the rod while the forces and moments are acting on it was chosen.

For deciding its position along the thickness of the wing, two factors had to be taken into account simultaneously. First, the mechanism should be near the upper or lower surface of the wing so that the moment deforming the rod would be minimum. But this should be limited because mechanism being too near would restrict its motion as is evident from figure 6.

Position of mechanism in chord wise direction is dictated by the location where moment acting on the rod is minimum both when wing is folded and when unfolded. By hand calculations that position came to be at 0.25c.

Taking into consideration the effect of location of folding wing mechanism would have on span of static part of the wing and also on swept area, it is of utmost importance that factors like clearance with respect to horizontal tail, maximum static span required for accommodation at gate, rise in power requirements and structural requirements are taken into account and are accounted for accordingly.

As the location of folding wing mechanism is shifted more towards the root of wing static span decreases which is although desirable, increases the structural and power requirements for mechanism significantly. The mechanism would have to sustain much more moment due to increase in load due to weight of increased folding wing length, weight of components inside wing and possibly fuel tanks and engines. It must be made sure that increase in weight of mechanism to sustain additional load does not overshadow its advantages as additional weight is bound to reduce payload carrying capacity of aircraft meaning less earnings for airlines.

Keeping the above mentioned conditions in mind, with the help of calculation and FEM analysis as discussed below, we have come up with results favoring the positioning, weight and material for the folding mechanism economically and reliably.

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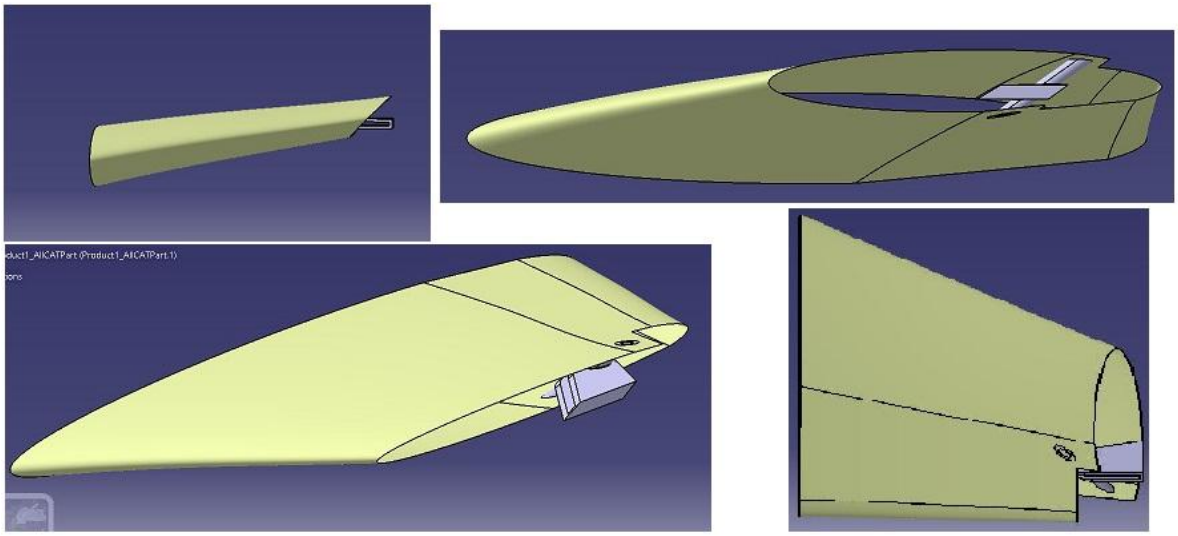

Figure 6. Depicting location of the mechanism on CAD model of B-787 wing (showing front, side, isometric and bottom view, clockwise from top)

4. CALCULATIONS

For calculations elemental square area method was used. In this, scaled plan view of Boeing 787-8 was divided into square elements of side 0.1913 m each and the squares falling inside a particular section were summed up and used for further calculations.

Net wing area = 2 × (62.6 + 76.734) m^2 = 278.689 m^2

Gross wing area = Net wing area + Fuselage covered area = 278.669 + 69.1929 = 347.19 m^2

Maximum payload capacity = 2233714 N [6]

Wing loading = (2233714/278.689) = 8015.077 N/m^2

Static wing lifting force = 501743.82 N

Folding wing lifting force = 615028.92 N

After considering the load factor (n=2.5)

Static wing maximum lifting force = 1254359.55 N

Folding wing maximum lifting force = 1562572.3 N

Moment acting on the lug-rod arrangement due the Portion 2 lift and drag forces:

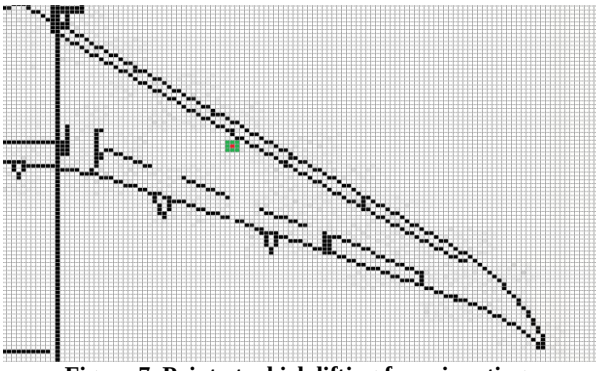

Figure 7. Point at which lifting force is acting

Moment on lug-rod arrangement = (Lifting Force of Portion 2) × (Distance b/w lug-rod arrangement and point of force)

Distance b/w lug-rod arrangement and point of force = $\sqrt{(7.0781)^2 + (0.5739)^2}$ = 7.1013 m

Moment on lug-rod arrangement = 1562572.3 × 7.1013 = 11096338.59 N-m

5. FEM

To analyze the Structure used for folding mechanism, the analysis was performed using static structural toolbox of ANSYS 14.5.

Analysis along with Weight Optimization

As one of the major setbacks in installation of folding mechanism in commercial aircrafts is the weight. STO wing folding mechanism was chosen based on these weight considerations. This mechanism is lighter and gives more efficient two-axes folding simultaneously than other mechanisms. This weight was further optimized by changing the materials. This optimization is based upon material and shape alterations. Lighter materials, out of those used in the industry were analyzed if they could be subjected to the stress calculated and showed deformation in the allowable limit. Titanium showed the best results.

Firstly analysis was performed using stainless steel just to form a base line. After that analysis was performed using Al 7075-T6 and titanium. Taking into account both reasonable cost factor and less weight, Titanium was chosen as the final material.

To reduce the stress, fillets were applied and some modifications were made in final design to obtain the following properties of lug and rod. Furthermore, the shape and thickness were altered and analyzed for least difference in stress distribution and utmost decrease in the system weight. Eventually, with this optimization we have reduced 40% of the original weight of the mechanism.

Shown below is a table (See Table 1) consisting physical properties of rod and lug design. The mesh generated and force application is shown in Figure 8 and figure 9 respectively.

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Table 1. Physical properties of rod and lug design

Properties	Rod	Lug
Volume	1.0193e+008 mm³	2.2621e+008 mm³
Mass	470.9 kg	1045.1 kg
Centroid X	27646 mm	27905 mm
Centroid Y	9503.2 mm	10145 mm
Centroid Z	4500.3 mm	4418.4 mm
Moment of Inertia Ip1	3.784e+006 kg·mm²	2.3522e+008 kg·mm²
Moment of Inertia Ip2	1.5412e+008 kg·mm²	1.2552e+008 kg·mm²
Moment of Inertia Ip3	1.5422e+008 kg·mm²	3.4683e+008 kg·mm²

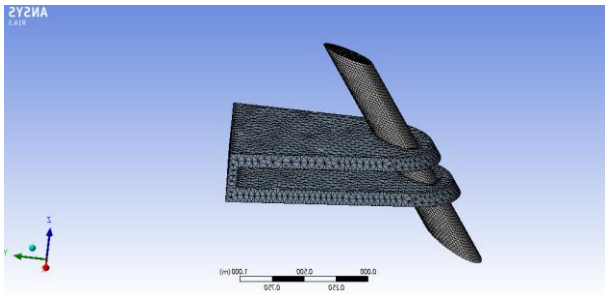

Figure 8. Meshing Done for both Lug and Rod

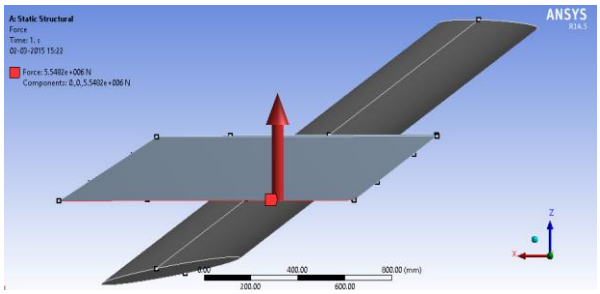

Figure 9.Application of Force to stimulate moment due to Lift

It showed total deformation of 0.488 m when load factor was taken as 2.5 (i.e. L= 2.5 * W) for which the moment obtained was 11096338.59 N-m acting on a point 0.25c from leading edge where our mechanism would be located. Figure 10 and Figure 11 below show the total deformation and equivalent stress.

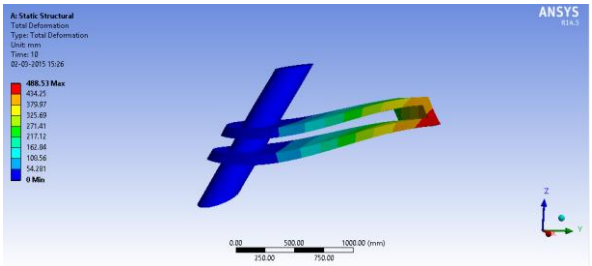

Figure 10. Total Deformation

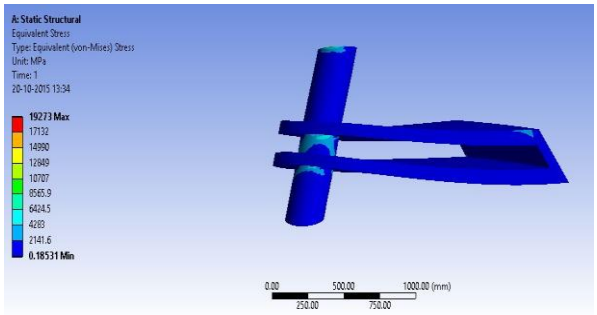

Figure 11. Equivalent (Von-Mises) stress

After varying thickness and material of lug in effort to save weight and analyzing these cases weight was obtained as 1516.0 Kg.

Mesh sensitivity study

To get accurate results mesh sensitivity study was conducted for both total deformation and equivalent Von-Mises stress [8]. Finally a value approximate to converging value was selected and taken as approximate result. The results obtained are presented below in figure 12 and figure 13:

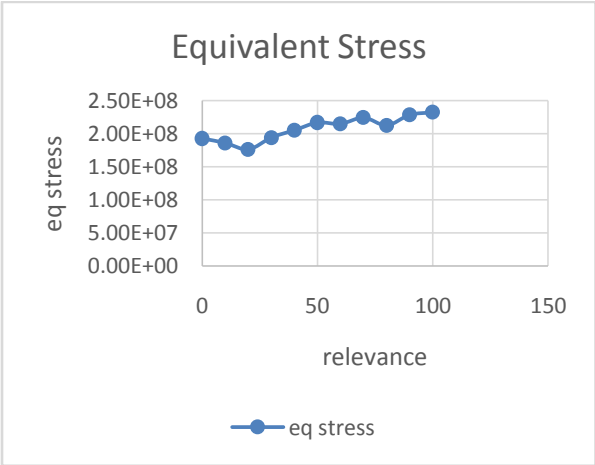

Figure 12. Mesh sensitivity study plot of stress

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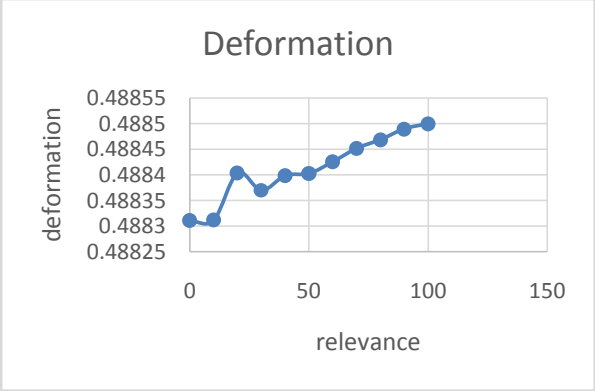

Figure 13. Mesh sensitivity study plot of deformation

6. CONCLUSION

Increasing population and economy, call for improvement in air industry services. Our envisaged future gives an insight into the skies full of flying machines, and increased traffic. Thus, there is a need to resolve the issue of pertaining traffic by traffic-accommodation and sky bridges. The idea of foldable wings underlines the demand of space and land resource management. This in turn save the land and forest resources. Along with ease in taxing, limited number of gates and terminals, and customer convenience, this also solves the problem of adjusting with the limited space norms authorized by International Civil Aviation Organization. Based upon all the calculations, the proposed mechanism of lug-rod arrangement and its location suit to Boeing 787-8 for highest speed and maximum possible load factor. The movement and feasibility of the joint has been verified in Catia and Finite Element Analysis was done in ANSYS 14.5.

To incorporate the folding mechanism inside the wing, some technical challenges have to be dealt with, such as introducing discontinuity in spar at the location at which the mechanism is attached, design and installation of locking mechanism required separately for inflight and ground, re-design and adjustment of fuel and electrical lines through wing, re-designing of rib cut-outs. On the economical side, accommodating a folding wing mechanism in an aircraft will reduce the inevitable need of further expansion of airports, moreover this mechanism can be added to already existing aircrafts which will prove to be much more feasible than designing and manufacturing a completely new aircraft. As the footprint of an aircraft will be reduced, the number of gates on a particular airport can be allowed to increase, which will finally cut the extra costs of transporting passengers and cargo to aircraft parking area. In the follow up papers, case study of different bigger and smaller airports around the globe will be done to find out the different types of practical pros and cons of this mechanism and calculation of the approximate cost cutting will be done.

A statistical case study over various airports, number of aircrafts parked at gates, rate of shuttle services required, and the average time taken by passengers from airport terminal to boarding the aircraft, before and after incorporating the wing folding mechanism, can be generated to cite the functionality and feasibility of folding mechanisms in numerals.

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