Structural Design and Fatigue Analysis of a WIG (Wing in Ground) Vehicle

Bandaru Swetha
Assistant Professor, Department of Aeronautical Engineering
VITAM College of Engg. Visakhapatnam, Andhra Pradesh, India

Gundlathoti Sowmya
Department of Aeronautical Engineering
Visakhapatnam, Andhra Pradesh, India

Abstract- This project is a research and design of WIG crafts. The project serves to design, analyze of Wing in Ground (WIG) vehicle. It covers a wide range of engineering work processes and due to the realistic nature and wide scope of the project.

The project starts with the design phase whereby the general shape, design of the WIG craft is determined. This is then followed by the structural design of the WIG craft. In the design phase after the general shape of the WIG craft is determined by mainly non-structural considerations, the structural aspect of the craft is designed, taking into account the loads that it will encounter. The design is then subsequently modeled using the CATIA software. Analyses were carried after the design phase. Software like Msc. Nastran/Patran used to carry out the structural analysis.

Together with theoretical calculations, the WIG craft is analyzed structurally to prevent failure during operation. Due to the small size of the WIG craft and limitations in equipment, static loading is done instead on the craft to obtain the stress values on the WIG craft during flight. It is well known that, under repeated loading or unloading, failure can produced by stresses and that magnitude of these stresses required to produce failure decreases as the number of cycles of stresses increases. This phenomenon of the decreased resistance of a material to varying stresses is called fatigue. We also have done fatigue analysis on WIG craft.

Keywords – Wind in Ground Vehicle, Ground Effect, Fatigue analysis, Patran/Nastran

I. INTRODUCTION

Marine vehicles are classified according to different criteria. One of these is the lifting force required to vertically support the vehicle as shown in fig.1. The lifting force is either static (in the form of water buoyancy or pressurized air cushion) or dynamic (planning surfaces, hydrofoils or lifting wings). The most recent member that has joined marine vehicles family is Wing In Ground effect vehicle (WIG).

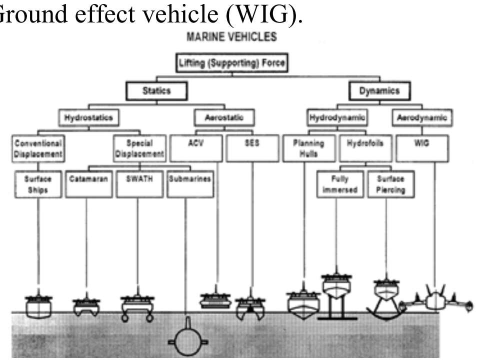


Figure 1. Marine vehicles classification according to supporting force

WIG is an abbreviation of Wing In Ground-effect. A WIG craft sits on a layer of air cushion created by aerodynamics rather than by an engine in the case of a hovercraft. This means that it only exists when the WIG craft has sufficient forward speed. This is called a dynamic air cushion as opposed to the hovercraft's static air cushion. This air cushion reduces the friction drag of the WIG craft with water, which makes it a more efficient vehicle compared to convention marine craft.

WIG craft have been around for decades. In the past 40 years a large number of different WIG craft have been designed and built. However there are still a very limited number of literatures written on it. The effects of ground effect on small-scale vehicles are virtually unexplored. Therefore this project, aims to design, analyze a small scale wing in ground (WIG) craft to demonstrate the effects of ground effect.

A Wing-In-Ground-effect vehicle (WIG) is a craft that is especially designed to take advantage of the reduced drag and increased lift due to ground proximity. Therefore a WIG vehicle will always fly close to the water surface.

The payload per power installed is quite remarkable. A hovercraft typically can lift around 5.8 kgs per kilowatt of engines fitted while a WIG craft can lift around 10 kgs per kilowatt of engines fitted; fig.2. Hence, the main benefits when a craft is operating within ground effect are that speed; payload and fuel economies are considerably more efficient than with traditional boat, plane and helicopter transport.

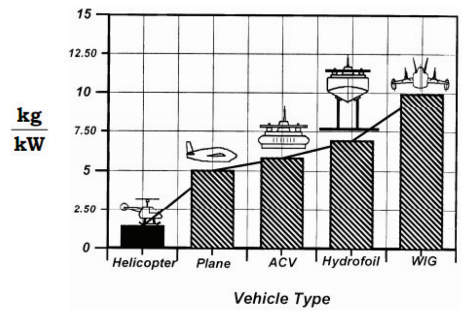


Figure 2. Payload per installed power ratio for different vehicles types.

In this thesis, the structural aspects of the WIG craft will be covered. Including the structural design, fatigue analysis.

A. Ground Effect –

Ground effect can be divided up into two distinct regimes, ram and normal ground effect. Ram ground effect occurs where the wing is at an altitude of h/c=0.1 or less. Here the wing is so close to the ground that the trailing edge of the wing is creating a sealed envelope. The airfoil is operating on a trapped cushion of air, using the same principal as a hovercraft. As the airfoil's altitude increases, it enters what is normally considered to be normal ground effect. This regime extends from just above the "ram wing" height (h/c>0.1) to approximately half the wings span off the ground.

Ground-effect on WIG, a dynamic hovercraft without the need of a heavy skirt, or lift engines. The dynamic self-stable ground effect cushion of lift is created by its own forward passage. Stripped down in this way, WIG is a very simple concept comprising an aerodynamic hull form, an air propulsor and a rudder. Indeed, ground effect' can be simply demonstrated by laying a piece of card on a table; given a flick it can be sent skimming on a dynamic cushion of air.

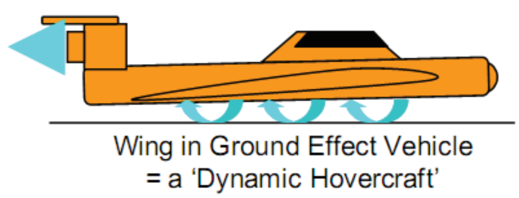


Figure 3: The WIG - a 'dynamic' hovercraft, without skirt or lift engines

II. PROPOSED ALGORITHM

A. Structural Design –

The WIG craft can be considered as an air vehicle. One main difference between the WIG craft structures and materials and other engineering structures and materials lies in the weight. The main influential force in this WIG craft design is to reduce weight and at the same time being strong enough to withstand the forces acting on it during flight. Therefore materials in general for the small scale WIG craft must have a high strength to weight ratio so as to be deemed suitable for the WIG craft application.

The WIG craft structures must be designed to ensure that every part of the material is used to its full capability. This leads to the use of airframe structures, which requires the assembly, and joining of numerous parts together. Most of the size and shape of the WIG craft structural component are determined based on non-structural considerations, thus the structure must also maintain the shape of the design. The WIG craft is thus also designed taking into accounts the dimensions of the required components, weight and availability of these various components.

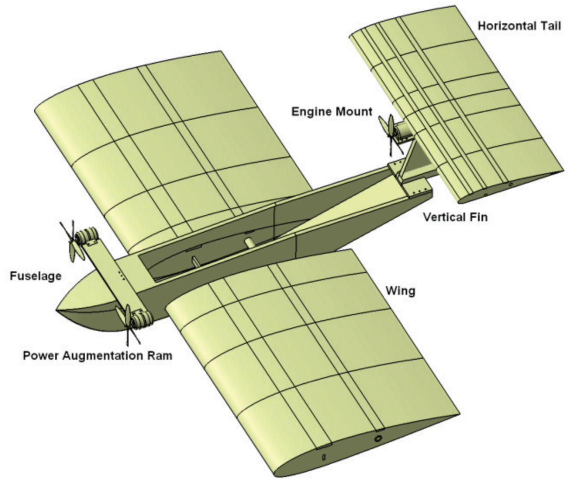


Figure 4. Structure of Wing in Ground Vehicle

B. Finite Element Analysis –

The finite element is a numerical technique for solving a set of different simultaneous algebraic equations with imposed boundary conditions for analyzing structures. Usually the problem addressed is too complicated to be solved satisfactorily by classical analysis methods. The method was originally applied to the problems of structural mechanics, heat conduction, magnetic and electric fields, lubrication and others. However, the finite element method is an approximately technique based on the solutions of the equations. Care must be taken to ensure that the approximations are appropriate. Complex, unsolvable structures are broken into simple, solvable structures or shapes [triangle, quadrilateral, tetrahedron, and hexahedron] and finding solutions through FEM. It is also defined as: "The process of dividing domain having infinite number of degree of freedom into a structure having finite number of degree of freedom"

C. Steps Involved in Msc.Patran –

I. Geometry:

Wing in Ground Vehicle is designed using a CAD tool CATIA V-5 and imported into the MSC Patran.

II. Meshing:

Once we have imported or created the geometry, we can create and verify the finite element mesh using a powerful suite of meshing tools.

There are two types of meshing the objects:

- Isomesh
- Paver

Generally Isomesh is preferred over Paver mesh being more accurate and quad elements preferred over tri elements as later being stiffer overestimates the results.

Creating the elements:

It is the most complex part of a stress analysis; it can be done using 1-D, 2-D or 3-D elements depending on complexity of component as well as its thickness. If thickness is more than 5mm so 2- D mesh is ruled out and 3-D mesh is to be done.

1-D elements: CROD, CBAR, CBEAM
2-D elements: CQUAD (Isomesh), CTRI (Isomesh)
3-D elements: CHEX, CWED, CTET

Here every component in this structure is meshed by using CQUAD4 and CHEX elements and Size of mesh is decided by performing Convergence Analysis as per which accuracy of result is directly proportional to number of elements to a point after which it starts decreasing. After meshing of the component is over, we create 1- D Beam or Rod element for load transfer around holes to simulate the bolts.

Create mesh seed at the connecting surfaces to maintain the continuity; mesh seed can be tabular (to retain same number as present on the edge) or uniform (defining new number of seeds).

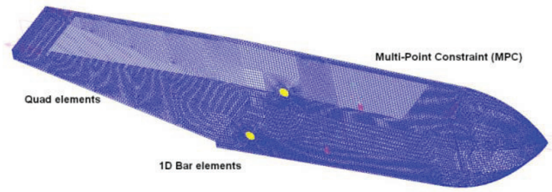


Figure 5. Meshing of Fuselage

III. Materials and Properties –

Material Selection:

As mentioned earlier, being an air vehicle, the weight of the WIG craft is an important factor in the design. Other than being light, the craft must be able to float on water as well; making density of the materials used for construction a considered factor. To allow or a light craft to be able to withstand all the forces experienced, a material that has a high strength to weight ratio must also be selected. Stiffness of the material is also important, as it is unwise for the WIG to deform tremendously during operation. Another factor that need to be considered include corrosion caused by exposure to weather and water that the WIG craft would come into contact with. The effect of corrosion is serious as it is likely to degrade the material strength and this may cause failure. Other factors would include availability and cost.

Aluminium-Zinc 7010-T7451:

Young's Modulus: 70000N/mm

Poisson Ratio = 0.3

Composition :

Zinc..6.20

Magnesium..2.30

Copper 1.75

Zirconium 0.13

Aluminum ....Base

Table - 1 Material Properties

S.No.	**Material**	**Elastic Modulus** (E, GPa)	**Poisson Ratio** (v)	**Density** (ρ,Mg/m^3)
1	Al-Zn 7010-T7451	70000	0.3	2.7
2	Steel	210000	0.3	7.799
3	Carbon Fiber Reinforced Plastic	1500	0.28	1.5

The Materials application is where we define the materials for our analysis model. A material model is a group of material properties that describe what our model is made of (such as steel or aluminum) and the attributes of that material (stiffness, density, and so on). Once we define the materials for our model, we will assign them to model regions.

Table - 2 Structural Properties

S.No.	**Component**	**Object**	**Type**
1	Bolts, Front Spar, Rear Spar & Stringers in Horizontal Tail, Rear Spar & Shaft in Wing	1D	Beam
2	2D Skin, Ribs, Front Spar in Wing, Structure of Fuselage	2D	Shell
3	Remaining Structures	3D	Solid

IV. Simulating Forces and Boundary Conditions–

The finite element analysis tests a particular model's reaction to particular loads and constraints imposed as boundary conditions. Loads are environmental factors such as force, pressure and inertial loads. Boundary conditions are described in terms of degrees-of-freedom, that are the directions in which the edges of the model are free to move in 3D space, along a translational (straight-line) or a rotational path.

Force on Engine Mount:

a)Force due to Engine (downward Force) F_{DW} = Weight = 0.08*9.81= 0.78N~0.8N

b) Trust Exerted by motor F_t = 2.6N

Force on Horizontal Tail:

Lift force (inertial loads) on Horizontal tail = 0.4*9.81 =3.924N

Force on Vertical Fin:

a) Lift force of Horizontal Tail = 0.4*9.81 =3.924N

b) Resultant Stress of Engine Mount = 1.22 N/mm^2

Force on Wing:

Lift force (inertial loads) on wing = 2*9.81 = 19.62N

Force on Fuselage:

a) Trust Exerted by each motor F_t = 2.6N

Due to the presence of 2 motors, Trust Exerted by motors F_t = 2.6*2 = 5.2N

b) Lift force (inertial loads) of wing = 2*9.81 = 19.62N

c) Resultant stress of Vertical fin = 1.38N/mm^2

V. Tailoring The Model For a Selected Analysis Code–

Analysis is done in MSc/Patran by selecting OP2/XDB data output file.

VI. Running A Finite Element Analysis (In Msc. Nastran) –

This file is submitted for solving to MSc/Natran by selecting required output file. The *.bdf file is generated. Processing is done using MSC/Natran; the command prompt is :

```
scr =yes   old=no     news = no
```

VII. Compiling the Analysis Results–

Now *.op2 /xdb file is submitted to MSC/ Patran for post processing by select result file from nastran.

Checking the results

Various stress, force, displacement plots are available which can be accessed by clicking on Result icon and choosing Plot Markers in it.

D. Fatigue Analysis –

Fatigue analysis of WIG involves Stress – Life (S-N) approach. It is made up of Al-Zn alloy and its specification is 7010-T7451. The WIG is a critical and safe life vehicle. The stresses obtained from the finite element static stress analysis using MSC Patran/Nastran. For fatigue analysis, maximum principle stress is considered for getting mean stress and alternative stress. The fatigue symmetric load spectrum of the WIG vehicle is given in Fig.6 .

The fatigue analysis of the WIG is done using MS-EXCEL. To calculate the each 'g' number of cycles to failure has been calculated using Goodman diagram i.e. Constant life curve of the Al - Zn alloy ,AMS 4205, 7010 - T7451. The damage of the component for each 'g' is found out by using the ratio of occurrences/hour to the number of cycles to failure (N_f). The total damage (D) is calculated by summation of all the 'g's. Finally, the unfactored life of the component is estimated by taking the reciprocal of the total damage (1/D). Factored life of the component is calculated by dividing the obtained unfactored life by a scatter factor 5.0.

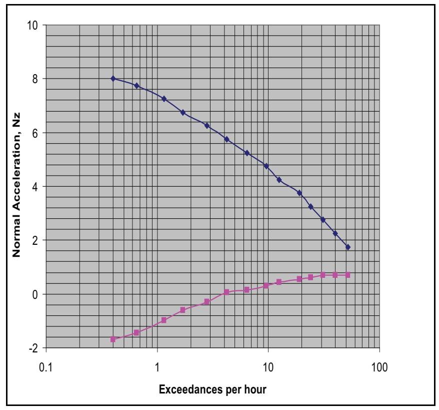


Figure 6. Fatigue Load Spectrum of Typical Trainer Aircraft

III. RESULT AND DISCUSSIONS

A. Stress analysis results –

The Stress analysis of Wing in Ground vehicle has been carried out by using Finite Element Software MSC PATRAN and MSC NASTRAN. The results are shown below.

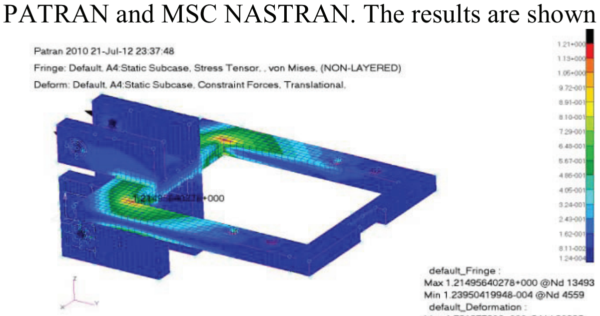


Figure 7. Von mises Stress on Engine mount

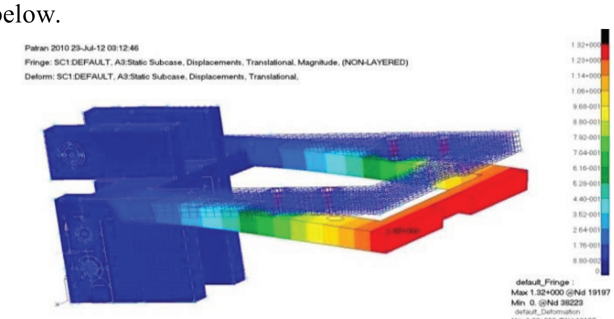
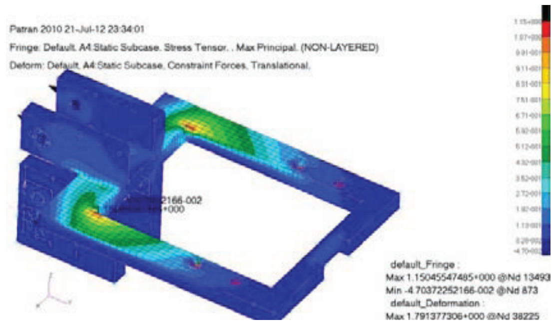
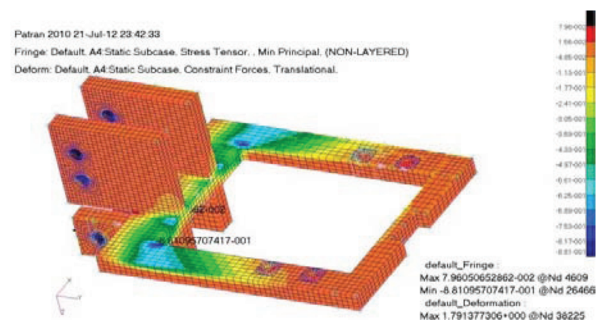


Figure 8. Displacement of Engine Mount

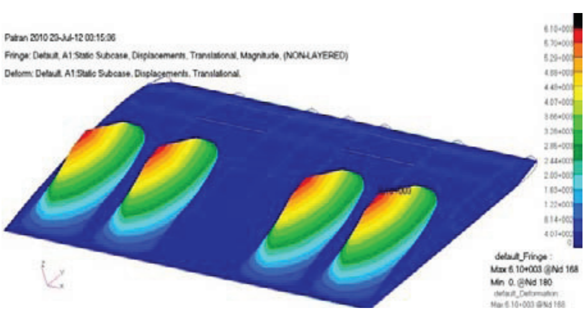


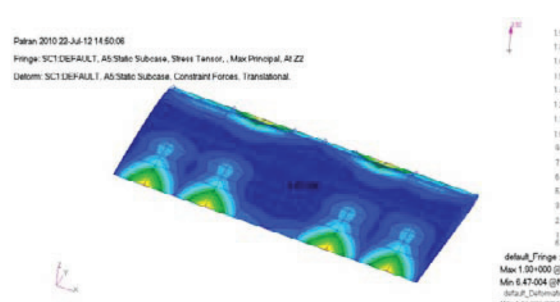


Max. Principal Stress of Engine Mount is 9.91-001 MPa

Figure 9. Max. Principal Stress of Engine Mount

Figure 10. Min. Principal of Engine Mount





Max. Principal Stress of Horizontal Tail is 1.68+000 MPa

Figure 11. Displacement of Horizontal Tail

Figure 12. Max. Principal Stress of Horizontal Tail

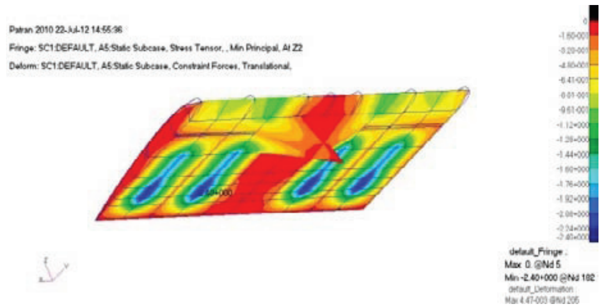


Figure 13. Min. Principal Stress of Horizontal Tail

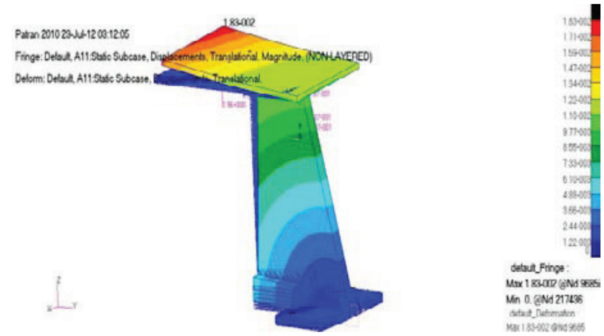
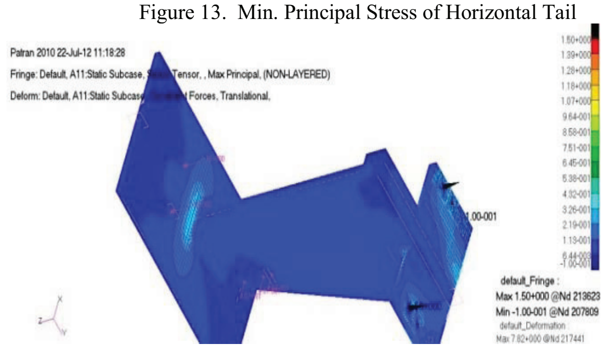


Figure 14. Displacement of Vertical Fin



Max. Principal Stress of Vertical Fin is 4.32-001 MPa

Figure 15. Max. Principal Stress of Vertical Fin

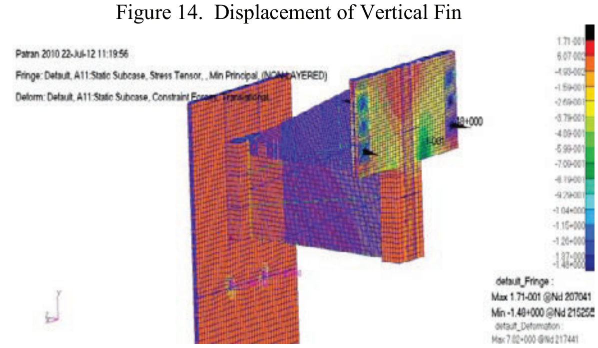


Figure 16. Min. Principal Stress of Vertical Fin

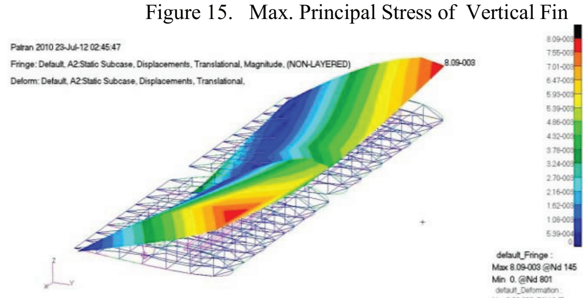
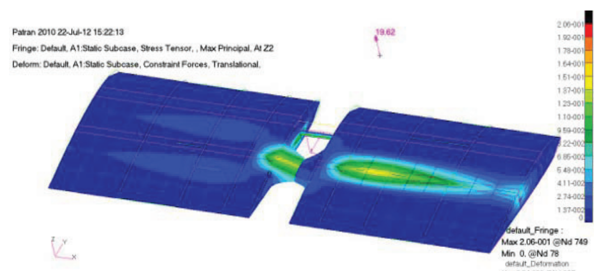


Figure 17. Displacement of Wing



Max. Principal Stress of Wing is 1.37-001 Mpa

Figure 18. Max. Principal Stress of Wing

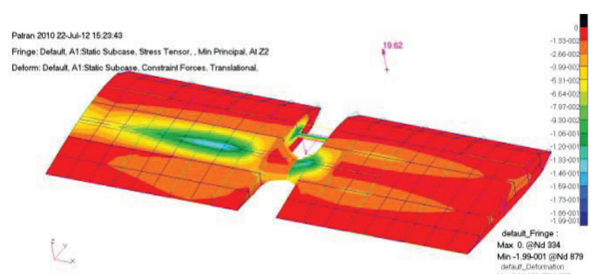


Figure 19. Min. Principal Stress of Wing

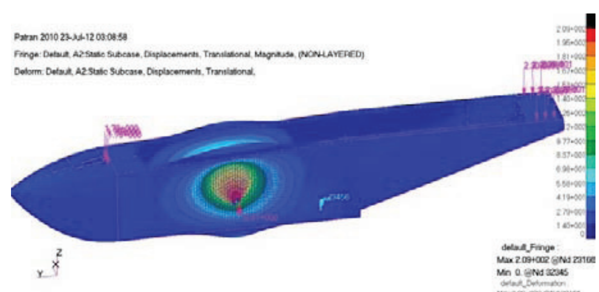
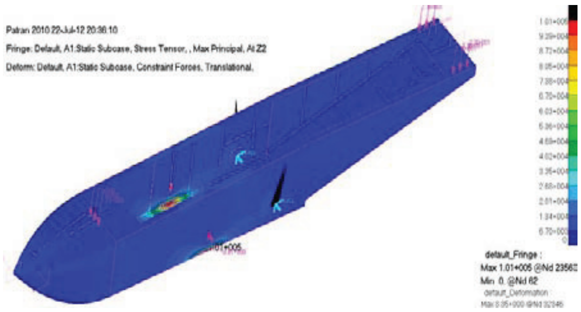


Figure 20. Displacement of Fuselage



Max. Principal Stress of Fuselage is 2.68+004 MPa

Figure 21. Max. Principal Stress of Fuselage

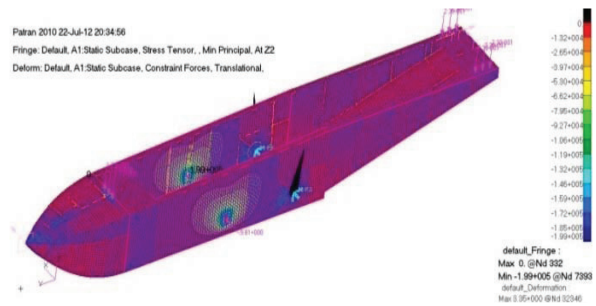


Figure 22. Min. Principal Stress of Fuselage

B. Classical Fatigue Analysis –

For WIG vehicle, load factor lies between 1g to 2g.
Mean G = (Average G_{max} + Average G_{min})/2
Alternative G = (Average G_{max} - Average G_{min})/2
Mean Stress = Max. principle stress * mean G
Alternative Stress = Max. principle stress * alternative G
Occurance = Difference between two successive exceedance per hour
Total Damage for all components , D = Σn/Nf = 1.962E-06
Unfactored fatigue life L = 1/D =5.0968E+05
Factored fatigue life in hours = L / Scatter factor = 1.019E+05 hrs
Therefore, factored fatigue life of the WIG vehicle is 1.019E+05 hrs.

C. Fatigue Life Calculation using MS Excel –

Table – 3 Fatigue Life for Engine Mount

G max	G min	Exceedances per hour	Average G max	Average G min	Mean 'G'	Alternative 'G'	Mean Stress	Alternative Stress	Occurances per hour	No. of cycles to failure	Damage per hour
2	0.7	45									
1.75	0.7	52	1.875	0.7	1.2875	0.5875	0.18505	0.08444	7	7.15E+08	9.79E-09
1.5	0.75	56	1.625	0.725	1.175	0.45	0.16888	0.06467	4	7.90E+08	5.06E-09
1.25	0.8	60	1.375	0.775	1.075	0.3	0.1545	0.04312	4	8.40E+08	4.76E-09
								Total Damage =			1.96E-08
								Un Factored fatigue life =			5.10E+07
								Scatter Factor =			5
								Factored fatigue life in Hrs =			1.02E+07

Table – 4 Fatigue Life for Horizontal tail

G max	G min	Exceedances per hour	Average G max	Average G min	Mean 'G'	Alternative 'G'	Mean Stress	Alternative Stress	Occurances per hour	No. of cycles to failure	Damage per hour
2	0.7	45									
1.75	0.7	52	1.875	0.7	1.2875	0.5875	0.3137	0.14315	7	4.86E+08	1.44E-08
1.5	0.75	56	1.625	0.725	1.175	0.45	0.2863	0.06976	4	6.24E+08	6.41E-09
1.25	0.8	60	1.375	0.775	1.075	0.3	0.26193	0.07309	4	7.00E+08	5.71E-09
								Total Damage =			2.65E-08
								Un Factored fatigue life =			3.77E+07
								Scatter Factor =			5
								Factored fatigue life in Hrs =			7.54E+06

Table – 5 Fatigue Life for Vertical Fin

G max	G min	Exceedances per hour	Average G max	Average G min	Mean 'G'	Alternative 'G'	Mean Stress	Alternative Stress	Occurances per hour	No. of cycles to failure	Damage per hour
2	0.7	45									
1.75	0.7	52	1.875	0.7	1.2875	0.5875	0.08066	0.0368	7	1.17E+09	5.98E-09
1.5	0.75	56	1.625	0.725	1.175	0.45	0.07362	0.02819	4	1.45E+09	2.76E-09
1.25	0.8	60	1.375	0.775	1.075	0.3	0.06735	0.01879	4	1.90E+09	2.11E-09
								Total Damage =			1.09E-08
								Un Factored fatigue life =			9.22E+07
								Scatter Factor =			5
								Factored fatigue life in Hrs =			1.84E+07

Table – 6 Fatigue Life for Wing

G max	G min	Exceedances per hour	Average G max	Average G min	Mean 'G'	Alternative 'G'	Mean Stress	Alternative Stress	Occurances per hour	No. of cycles to failure	Damage per hour
2	0.7	45									
1.75	0.7	52	1.875	0.7	1.2875	0.5875	0.0256	0.01167	7	2.40E+09	2.92E-09
1.5	0.75	56	1.625	0.725	1.175	0.45	0.0234	0.00894	4	2.88E+09	1.39E-09
1.25	0.8	60	1.375	0.775	1.075	0.3	0.02136	0.00596	4	2.93E+09	1.37E-09
								Total Damage =			5.68E-09
								Un Factored fatigue life =			1.76E+08
								Scatter Factor =			5
								Factored fatigue life in Hrs =			3.52E+07

Table - 7 Fatigue Life for Fuselage

G max	G min	Exceedances per hour	Average G max	Average G min	Mean 'G'	Alternative 'G'	Mean Stress	Alternative Stress	Occurances per hour	No. of cycles to failure	Damage per hour
2	0.7	45									
1.75	0.7	52	1.875	0.7	1.2875	0.5875	5004.53	2283.618	7	7.65E+06	9.15E-07
1.5	0.75	56	1.625	0.725	1.175	0.45	4567.24	1749.15	4	7.95E+06	5.03E-07
1.25	0.8	60	1.375	0.775	1.075	0.3	4178.54	1166.09	4	8.30E+06	4.82E-07
								Total Damage =			1.90E-06
								Un Factored fatigue life =			5.26E+05
								Scatter Factor =			5
								Factored fatigue life in Hrs =			105263.2

IV.CONCLUSION

The Wing in Ground vehicle is designed in CATIA V5 R19 software. Stress analysis of a Wing IN Ground vehicle is carried out using finite element software package MSC PATRAN/NASTRAN.

- Stress analysis of the WIG vehicle shows the stresses are well within the material allowable limits.
- Displacements are well within the limits.
- The stress analysis of WIG vehicle shows that, it is satisfactory from the strength considerations.

The fatigue analysis of WIG vehicle is done through by classical analysis using MS Excel. By using the maximum principal stress, number of cycles to failure is calculated using constant life curve of Al-Zn aluminum alloy material.

The damage of the component is found out by using the ratio of number of occurrences per hour (n) to the number of cycles to failure (N_f).

Finally, the unfactored fatigue life of the component is estimated by taking the reciprocal of total damage is 1.962E-06 hour.

Factored fatigue life of the component is calculated by dividing the unfactored fatigue life by a scatter factor of 5.0. Therefore the factored life of WIG vehicle is 1.019E+05 hrs, which is more than the required life is 5E+04 hours. Hence the component is safe from fatigue considerations.

REFERENCES

[1] N.Moore, Professor P A.Wilson, A J.Peters, "An Investigation into Wing in Ground effect Airfoil geometry".

[2] Ng Dyi En Benedict, "Structure design and analysis for a small-scale wing in ground (WIG) vehicle".

[3] Juhee Lee, Chang-suk Han, and Chang-Hwan Bae " Influence of Wing Configurations on Aerodynamic Characteristics of Wings in Ground Effect", Journal of Aircraft Vol. 47, No. 3, May– June 2010.

[4] YANG Wei, YANG Zhigang, "Schemed Power-augmented Flow for Wing-in-ground Effect Craft in Cruise", Chinese Journal of Aeronautics ,December 2010.

[5] Kohama et al,"Levitation Control of AERO TRAIN"

[6] Robert Stone , "Fatigue Life Estimates Using Goodman Diagrams"

[7] Jarkko Tikka Patria "Fatigue Life Evaluation of Critical Locations in Aircraft Structures using Virtual Fatigue Test"