Structural Health Monitoring and Life Optimization of an Oleo Strut

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Abstract. The landing gear is one of the most complicated system of the aircraft, comprising of structural members, hydraulics, energy absorption components, brakes, wheels and tires. It is a unique sub system of an undercarriage in an aircraft which is actuated to land the airframe without any damage. One of the critical parts of landing gear is oleo strut or shock strut. A type of hydro-pneumatic (oil and air) component in an aircraft landing gear system that absorbs the landing shock. In the current investigation, an attempt is made to conduct a static structural analysis by establishing design data of an aircraft landing gear oleo strut and analyse its dynamic characteristics and fatigue life using Ansys 14.5. The computed results are validated for different materials and endurance limit. It is found that Al-7178(Aluminium) has maximum number of life cycles for an applied load condition when compared to Ti-6Al-4V and Al-7178(Aluminium) has high factor of safety.

1. Introduction

Aircraft’s major component that is needed to be designed is landing gear (undercarriage). Landing gear is an undercarriage system of an aircraft or spacecraft utilised during take-off and landing. It supports the vehicle on the ground for taxiing, landing and take-off without damage. In fact, landing gear design has several interferences with the aircraft structural design. High Mach aircrafts usually have retractable under carriage systems which fold away during flight to reduce drag. Amongst the various parts of the undercarriage oleo strut one of the important devices which absorb the landing shock as shown in Figure 1. The main function of oleo strut is to absorb and dissipate landing shocks incorporated in a telescopic tube mechanism which absorbs landing shocks but resist re-bound and at the same time protects the aircraft structure, controlling the re-bound (spring back or recoil) movement and to provide cushioning effects during taxiing.
The aircraft structure encounters dynamic loads due to the impact of landing, runway and taxiway unevenness leading to fatigue damage and high stress concentration in the airframe structure. Additionally, ground induced vibrations resulted from ground ride qualities encountered by many conventional transport aircraft require enhanced gear design. The ground induced vibrations and dynamic problems are further magnified for supersonic aircrafts due to increased structural flexibility of the body.

In order to obtain a structure with substantial increase in fatigue life and structural dynamic performance characteristics, it is essential to strive for a design to limit the load applied to the landing gear. One potential method is to design oleo strut to obtain for lighter aircraft application.

A number of researchers have strived to design a landing with better fatigue life and performance characteristics few of which are included here, John et al. [2] developed and programmed a mathematical model of an active control landing gear to improve ground handling qualities and fatigue life of airframe by limiting the loads applied, around 20-30% reduction in wing force results in significant improvement in the fatigue life of the airframe structure. Kuldip Ganorkar et.al [1] conducted a numerical analysis by optimizing the landing gear and evaluating the accurate stresses and displacements. Sreenivas Babu [3] conducted an numerical investigation on landing gear oleo strut with different materials to estimate the distribution of stress and deformation regions. Ayan Dutta et.al [7] carried out a linear static analysis to evaluate natural and forced frequencies of nose landing gear for different loading conditions. Similarly, Alex et.al [8] modified the oleo strut shock absorber design to flatten out or damp shock impulses and dissipate the kinetic energy to enhance the performance characteristics and Rajesh A et.al [6] carried out a static structural and impact analysis to find the stresses, deformation and primary acoustic effects for nose landing gear. Suresh et al [11] have presented an integrated approach for the sustainable development of an automotive component with the implementation of design for environment and design for manufacturing and assembly concept. In this work, the authors conducted a case study in the connecting rod of single cylinder four stroke petrol engines. The concepts initiate to reduce the environmental impact, manufacturing cost, time and weight of the product to address the improvements in sustainable product design and business benefits. This work will helps to improve in aircraft parts also. Rishab choudhary et al. [4] conducted a linear buckling analysis of a landing gear and compares the results with different titanium alloys. They are modelled the landing gear using creo 3.0 and the analysis is conducted using Ansys 19.2.

Antony Samuel Prabhu et al [9] conducted a case study on fatigue and analysis of different wing spar using the CAD and CAE software. This work provides to develop the similar type of aircraft parts.
Antony Samuel Prabhu et al [10] presented a study on crack propagation rate of an aircraft wing spar. This work provides valuable insights to develop such type of landing gear.

Vishnuraj et al [11] presented a case study on

Tuan H et al. [5] conducted a research and formulate the methodology of assessing the maximum impact loading condition that will incur onto an aircraft’s landing gear system via Finite Element Analysis (FEA) method and appropriately determining its structural and impact responses to minimize potential design failures during hard landing (abnormal impact) and shock absorption testing. In this study both static and dynamic loading condition were analyzed, compared, and derived through the Federal Aviation Administration’s (FAA) airworthiness regulations and empirical testing data.

The main objective of the present work is to design an oleo strut of the landing gear and investigate its dynamic characteristics and fatigue life using modal analysis for landing and take-off phase. Among the modal parameter to be studied are the mode shapes, deformation, and natural frequencies of the mode shapes.

2. METHODOLOGY

The basic reference dimensions of the oleo strut are taken from the Tomahawk Piper aircraft and it is modelled with respect to oleo strut and oleo piston.

The oleo strut with different material properties is modelled in CATIA V5 software as shown in Figure 2, and numerical analysis is done by using ANSYS Workbench 14.5. All of the boundary conditions of the Landing Gear Oleo strut such as the mass, connections, mechanical properties are defined. Governing equation’s like Von-misses stress theory, Principle stress theory is used to calculate the maximum and minimum stress analysis on the given oleo strut with the meshed nodal points.[6]

![Figure 2 CAD model of (a). Oleostrut (b). Oleo piston](image)

3. THEORETICAL CALCULATIONS

Impact load on the aircraft can be evaluated using impact force equations and von-misses stress theory, results in three directional stress, strain and deformation with respect to the theoretical and
computational dynamics [2]. In order to attain the impact load the touch down velocity and the stall velocity are obtained.

- From landing performance, we know that the touch down velocity

\[ V_{TD} = 1.15 \cdot V_{STALL} \]

- the stalling speed of P-40 Tomahawk aircraft is 57 m/s

\[ V_{STALL} = 57 \text{ m/s} \]

\[ V_{TD} = 65.55 \text{ m/s} \]

- From kinematics of equations,

\[ v = v_0 + at \]

- From Newton's 2nd law of motion,

\[ F = ma \]

Thus, impact force nose landing gear is found to be 1687694N and impact force on each landing gear is 843847N.

\[ \sigma_a = \left( P_i r_i^2 - P_o r_o^2 \right) / \left( r_o^2 - r_i^2 \right) \]

\( \sigma_a \) = stress in axial direction (MPa, psi) = 106.59 Mpa

\( P_i \) = internal pressure in the tube or cylinder (MPa, psi) = 7424E+4

\( P_o \) = external pressure in the tube or cylinder (MPa, psi) = 843.85E+3

\( r_i \) = internal radius of tube or cylinder (mm, in) = 76 mm

\( r_o \) = external radius of tube or cylinder (mm, in) = 98.6 mm

\[ \sigma_c = \left[ \left( P_i r_i^2 - P_o r_o^2 \right) / \left( r_o^3 - r_i^3 \right) \right] - \left[ \frac{r_o^3}{r_o^3 - r_i^3} \right] \left( P_o - P_i \right) / \left( r_i^2 \left( r_o^3 - r_i^3 \right) \right) \]

where

\( \sigma_c \) = stress in circumferential direction (MPa, psi) = 243.04 Mpa

\( r \) = radius to point in tube or cylinder wall (mm, in) \((r_i < r < r_o)\) = 87.3 mm

maximum stress when \( r = r_i \) (inside pipe or cylinder)

Von mises stress \( = \sqrt{\frac{(P_1 - P_2)^2 + (P_2 - P_3)^2 + (P_3 - P_1)^2}{2}} \)

\( = 136.6 \text{ Mpa} \)

where \( P_1, P_2, P_3 \) are principal stresses.
3.1 Factor of Safety, $[Nfs]$  
According to definition factor of safety is equal to margin of safety minus one. Factor of safety helps to give more amount of safety for the given loading conditions.

Here, 

$S_{yp} =$ yield strength, $S_{avg} =$ average stress 
$S_r =$ Reversing stress, $K_f =$ geometric stress concentration factor. 
$Se =$ endurance strength(for Tensile strength < 1400 MPa. i.e., $Se= 0.5 \text{ tensile strength}$  
Tensile strength >1400MPa. i.e., $Se=100\text{kpsi or 700Mpa}$)

$$N_{fs} = \frac{S_{yp}}{S_{avg} + S_r, k_f \left( \frac{S_{yp}}{S_{r}} \right)}$$  
$$S_{avg} = \frac{S_{max} + S_{min}}{2}$$  
$$S_r = \frac{S_{max} - S_{min}}{2}$$

4. Material Properties  
For the Analysis of the oleo strut three different type’s materials like Titanium (Ti-6Al-4V), Structural Steel and Aluminium (Al-7178) are considered. The poisons ratio, Tensile strength and Youngs modulus is taken from materials data handbook [6] as shown in Table 1.

| SL | Material Properties | Tensile Strength (MPa) | Poisson’s Ratio | Young’s Modulus (MPa) |
|----|---------------------|------------------------|----------------|----------------------|
| 1  | Titanium (Ti-6Al-4V)| 880                    | 0.35           | 100                  |
| 2  | Structural Steel    | 250                    | 0.3            | 20000                |
| 3  | Aluminium (Al-7178)| 275.8                  | 0.33           | 70000                |

5. Analysis Of Aluminium Piston  
The numerical analysis is done considering the landing gear oleo strut as a cantilever beam. Figure 3 represents the analysis of the aluminium piston. The results had been obtained with respect to Equivalent Stress, Damage, Life Cycle, and Safety Factor.

The boundary conditions for aluminium piston are imposed as one end fixed and the other end is applied with the impact force of 1687694N as shown in Figure 3.a.

Figure 3.b. represents the equivalent stress, where minimum stress of about 79.66 MPa is noticed around the mid-section of the piston for the aluminum material and the maximum stress of 437.58 Mpa is observed near the fixed end. Figure 3.c. represents the damage occurred in the piston with respect to the applied loading condition. The maximum damage is observed near the mid-section of the oleo piston. Comparing the stress and damage Figure 3.c. it shows that where the maximum stress is
occurring the maximum damage is also noticed at the maximum stress concentration area. Due to the applied loading condition the maximum damage is occurred, with respect to the maximum damage the oleo piston can withstand for a maximum life cycle of 6987 as shown in Figure 3.d. Comparing with respect to life expectancy the minimum safety factor of 0.08611 value is obtained as shown in Figure 3.e.

![Figure 3 Analysis of Aluminum Piston](image)

**Figure 3** Analysis of Aluminum Piston
6. Analysis of aluminium (strut):

![Figure 4 Analysis of Aluminum Strut](image)

Figure 4 represents the analysis of the aluminium strut. The boundary conditions for aluminium piston are imposed as one end fixed and the other end is applied with the impact force of $8.43 \times 10^5$ N as shown in Figure 4.a.

Figure 4.b. represents the equivalent stress, where minimum stress of about $2.22 \text{MPa}$ is noticed throughout the length of the strut expect at the fixed end for the aluminum material and the maximum stress regions of $161.28 \text{MPa}$ are observed near the fixed end. Figure 4.c. represents the damage occurred in the strut with respect to the applied loading condition. Due to the applied loading condition the maximum damage is occurred, with respect to the maximum damage the oleo strut can withstand for a maximum life cycle of $1 \times 10^9$ as shown in Figure 4.d. Comparing with respect to life expectancy the minimum safety factor of $0.12383$ value is obtained as shown in Figure 4.e.

7. Estimation of Endurance Limit by Graphical Method Piston Aluminium

Figure 5 represents the S-N curve, plotted between the Stress Amplitude Vs Number of Life cycles. Generally, the S-N curve is high for endurance limit for low of stress amplitude cycles. [6]

From the Figure 5, it is noticed that with decrease in stress concentration on the material the life increases.
8. Estimation Of Endurance Limit By Graphical method Strut Aluminium

Figure 6 shows the maximum endurance limit when the curve is flat. As there is a reduction in stresses acting on the material leads to increase in the life of the material.
9. Result Comparison

9.1.1 Fatigue Life for an Applied Load of 843847N

The table 2 shows the results of the fatigue life for different materials with respect to the Piston and Strut component of the aircraft landing gear.

| Materials          | Piston | Strut |
|--------------------|--------|-------|
| Aluminium(Al-7178) | 2e+05  | 1e+09 |
| Titanium(Ti-6al-4v)| 1.71e+0| 2e+05 |
| Structural Steel   | 1e+06  | 1e+06 |

9.1.2 Endurance Limit for an Applied Load of 843847N

Table 3 shows the result of the endurance limit for different materials with respect to the Piston and Strut component of the aircraft landing gear.

| Material          | Piston | Strut |
|-------------------|--------|-------|
| Aluminium(Al-7178)| 0.7e+8 | 2.1e+01|
| Titanium(Ti-6al-4v)| 7.25e+7| 2.1e+08|
| Structural Steel  | 1.8e+8 | 2.32e+8|

9.1.3 Factor of Safety for an Applied Load of 843847N

Table 4 shows the result of Factor of safety for different materials with respect to the Piston and Strut component of the aircraft landing gear.

| Material                  | PISTON | STRUT |
|---------------------------|--------|-------|
| ALUMINIUM(AL-7178)        | 1.75   | 1.24  |
| TITANIUM(TI-6AL-4V)       | 1.76   | 0.35  |
| STRUCTURAL STEEL          | 0.99   | 0.59  |
10. Comparison

- From the obtained results fatigue life, it is evident that Al-7178 (Aluminium) has maximum number of life cycles for an applied load condition when compared to Ti-6Al-4V materials used.
- From the obtained results of Factor of safety, it is evidenced that Al-7178 (Aluminium) has high factor of safety.

11. Conclusion

- Stress analysis plays very important role in finding structural safety and integrity of the structure. The stress analysis of the oleo strut is carried out and equivalent stress is identified on piston and strut at fixed end which is found out to be lower than the yield strength of the material.
- The fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. Fatigue life calculation is carried out for the prediction of the structural life of oleo strut.
- Factor of safety indicates safety margin of the structure which indicates how much stress life cycles that a structure can have.
- Materials subjected to stresses below the endurance limit will never fail under cyclic loading.
- Stress life testing is the most common type of fatigue testing and is designed to determine the safe or infinite life or fatigue strength of a material or component.
- Since Al-7178 is identified to have better properties like factor of safety and fatigue life with low weight and ease fabrication and offers good machinability and responds well to resistance welding.

12. Future Scope

- This work focuses on estimation of fatigue life for determining the number of load cycles that a material can withstand.
- According to tabulated results of each materials, it can be used for future reference.
- The deformation of piston and strut is not included, so it becomes research area to perform frequency analysis by using deformation.
- Static load condition is given prior importance in this project, so it provides opportunities for analysis under dynamic load condition.

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