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# Aircraft Fuel Manifold Design Substantiation and Additive Manufacturing Technique Assessment Using Finite Element Analysis

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**ABSTRACT**

An aircraft fuel system allows the crew to pump, manage, and deliver aviation- or jet fuel to the propulsion system and Auxiliary Power Unit (APU) of an aircraft. Fuel systems differ greatly due to different performance of the aircraft in which they are installed. The fuel system is designed to provide an uninterrupted flow of clean fuel from the fuel tanks to the engine. The fuel must be available to the engine under all conditions of engine power, altitude, attitude, and during all approved flight maneuvers. Two common classifications apply to fuel systems in small airplanes – gravity-feed and fuel-pump systems and current study focuses on the later one. The auxiliary fuel pump provides fuel under pressure to the fuel/air control unit for engine starting and/or emergency use. After starting, the engine-driven fuel pump provides fuel under pressure from the fuel tank to the fuel/air control unit. This control unit which meters fuel based on the mixture control setting, and sends it to the fuel manifold valve at a rate controlled by the throttle. After reaching the fuel manifold valve, the fuel is distributed to the individual fuel discharge nozzles. The discharge nozzles, which are located in each cylinder head, inject the fuel/air mixture directly into each cylinder intake port. An aircraft's fuel system has a more profound effect on aircraft performance than any other airframe system. Any failure in the fuel manifold will lead to catastrophic aircraft damage and it is very important to consider all the critical flight mission points for design substation. The current project work focuses on the design substantiation of twin engine commercial aircraft engine fuel manifold system to operate satisfactorily under all conditions, such as acceleration and deceleration, temperature, pressure, and flight attitudes. This work also focuses on the alternative manufacturing methodology “Additive Manufacturing Technique” for design optimization using finite element analysis. The proposed methodology will be verified in order to meet the FAA requirements.

Hence in the present investigation attempts have been made on the following major sections fuel manifold design substantiation for temperature and pressure requirement, vibration analysis, high cycle and low cycle fatigue analysis, design optimization using additive manufacturing technique. A comparative study has been made between conventional and additive manufacturing. Analysis results has been correlated based on hand calculated results which indicates less than five percent deviation to satisfy the FAA guidelines.

The rise in number of vehicles had led to many problems like traffic congestion, increase in consumption of fuels, rising travel costs. Considering all these problems we have studied different papers. This paper introduces bike sharing application which will help people to travel on one bike and share their expenses and also reduce pollution.

## INTRODUCTION

The largest and most important fluid system in an aircraft is the fuel pump system. Hence all aircraft projects involve the design of a fuel system to some degree. The objective of this work is to describe how the use of design methods may shorten system development time in the conceptual phase by early introduction of design automation [1]. In this way more concepts can be evaluated in the early stages of aircraft design. Every step in the system development process that can be formalized and automated reduces the time needed from days to minutes or even seconds. Consequently, there is an enormous potential for improvement. The objective is also to minimize the number of mistakes by helping the designer increase his or her understanding of how flight conditions impact the low-level design parameters such as pumps, valves, pipes etc. Fuel pump system mainly used in low and mid wing single reciprocating aircrafts which cannot utilize gravity feed system as the fuel tanks are not located in the engine. Instead in this, one or more fuel pumps are used for fuel migration. There are two basic types of aircraft fuel systems gravity feed system and the pump feed aircraft fuel systems; Gravity feed system is the simplest of fuel systems commonly found in high wing aircraft with a fuel tank in each wing. A gravity feed system is designed with the fuel tanks above the engine and propulsion system, with lines feeding the fuel from the tank to the engine via gravity [2]. Gravity feed fuel tanks do not use any pumps and have a simple shut-off valve system, with some aircraft having the option to manage fuel feed from either left wing, right wing or both tanks simultaneously and For low and mid wing aircraft where the fuel tank car cannot be located above the railway locomotive, a pump feed fuel scheme is necessary, utilizing one or more pump to deliver fuel from the tank to the engine. Usually, this type of aircraft fuel system has two pumps arranged in parallel - an electric and an engine drive pump - to provide a musical accompaniment pump should one fail. As with gravity feed pumps, there is a shut-off valve with selection capabilities.

## EXPERIMENTAL DETAILS

### Materials Used

In the present investigation, austenitic stainless steel G321 has been used similar to type 304 but with titanium addition of at least five times the carbon content. The titanium addition reduces or prevents carbide precipitation during welding [800-1500°F (427-816°C)] service. It also improves the elevated temperature properties of the alloy. **Table 1** gives the mechanical properties of stainless steel. **Table 2** gives the mechanical properties based on additive manufacturing.

**Table 1.** Mechanical properties of the stainless steel.

| DESCRIPTION | VALUES |
|---|---|
| Elastic Modulus | 193 GPa |
| Poisson’s ratio (υ) | 0.3 |
| Density (ρ) | 8027 kg/m$^3$ |
| Yield Strength ($\sigma_y$) | 206 MPa |
| Tensile Strength | 517 MPa |
| Material Endurance Strength | 144.5 MPa |

**Table 2.**Mechanical properties based on additive manufacturing.

| DESCRIPTION | VALUES |
|---|---|
| Yield Strength ($\sigma_y$) | 103 MPa |
| Tensile Strength | 258.5 MPa |
| Material Endurance Strength | 72.3 MPa |
| Material Allowable LCF Fatigue Strength for 25,000 Cycles | 51.1 MPa |

The following steps give the work methodology employed in the present investigation:

- Aircraft fuel manifold has been analyzed for pressure loading conditions and failure criteria is based on material yield strength.
- Fuel manifold has been substantiated for low cycle fatigue requirement for 25000 cycles.
- Detailed dynamic/vibration analysis including modal analysis is performed to validate the design for engine vibration loads.
- High cycle fatigue assessment has been performed using SN method to ensure the Aircraft Fuel Manifold design meets the fatigue life requirement of infinite life. Goodman curve will be plotted to verify the design for infinite fatigue life.
- Aircraft fuel manifold design assessment using additive technology is performed.

### Static Analysis

The Static Structural Analysis of Fuel Manifold is carried out for three loading requirements i.e. as per the guidelines of TSO – C135 Standards. The manifold will be always subjected to internal pressure due to the presence of fluid inside the manifold. The three loading requirements are:

- Normal Working Pressure Requirement

- Proof Pressure Requirement
- Burst Pressure Requirement

The stress observed in the Fuel Manifold must be within the material yield or ultimate strength limit. Static requirements for Fuel Manifold are listed in **Table 3**.

As per FAA:

Proof pressure = 1.33 × Normal Working Pressure

Burst pressure = 2 × Normal Working Pressure

**Table 3.**Static load requirements.

| Static Load Conditions | Pressure (MPa) |
|---|---|
| Maximum Operating Pressure | 0.165 |
| Proof pressure | 0.220 |
| Burst pressure | 0.330 |

## RESULTS AND DISCUSSION

### Static Analysis Results

The fuel manifold tube ends are constrained in all degrees of freedom. The constrained locations are identified based on the clamping locations of manifold routing [3]. Therefore, the maximum displacement of 0.0001 mm is observed at tube end due to effect of pressure and plug load as shown in total deformation **(Figures 1 and 2)**.

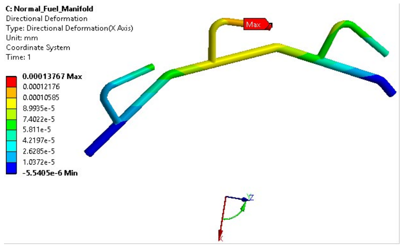


**Figure 1.** Total displacement plot.

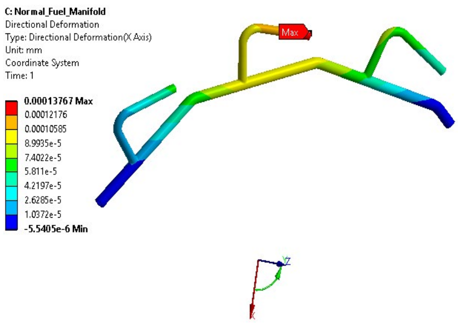


**Figure 2.** Radial directional deformation.

### Analysis–Results Summary – Pressure Analysis

**Table 4.** Details of pressure analysis.

| Load Case | Max Stress Region | Max Stress, MPa | Material Allowable Yield / Ultimate strength, MPa | Factor of Safety | Margin of Safety = FOS–1 |
|---|---|---|---|---|---|
| Normal Working Pressure | Straight Section | 1.44 | 204.8 | 99.3 | 98.3 |
| | Bend Radius | 0.49 | | 99.8 | 98.8 |
| Proof Pressure | Straight Section | 1.92 | 204.8 | 99.1 | 98.1 |
| | Bend Radius | 0.71 | | 99.7 | 98.7 |
| Ultimate Pressure | Straight Section | 2.89 | 517 | 99.4 | 98.4 |
| | Bend Radius | 0.94 | | 99.8 | 98.8 |

Aircraft fuel manifold design is having a maximum stress less than material allowable strength and there by having a significant margin of safety [4]. This being the linear analysis, results can be linearly extrapolated from normal working pressure for proof and ultimate cases. Current Fuel Manifold design meets the Finite Aviation Administration requirements for pressure loading **(Table 4)**.

**Analysis Results Summary with Additive Manufacturing–Pressure Analysis**

**Table 5.** Analysis–results with additive manufacturing-pressure analysis.

| Load Case | Max Stress Region | Max Stress, MPa | Material Allowable Yield / Ultimate strength, MPa | Factor of Safety | Margin of Safety = FOS–1 |
|---|---|---|---|---|---|
| Normal Working Pressure | Straight Section | 1.44 | 103.0 | 71.5 | 70.5 |
| | Bend Radius | 0.49 | | 210.2 | 209.2 |
| Proof Pressure | Straight Section | 1.92 | 103.0 | 53.6 | 52.6 |
| | Bend Radius | 0.71 | | 145.1 | 144.1 |
| Ultimate Pressure | Straight Section | 2.89 | 258.5 | 89.4 | 88.4 |
| | Bend Radius | 0.94 | | 275.0 | 274.0 |

Aircraft fuel manifold design is having a maximum stress less than material allowable strength and there by having a significant margin of safety based on additive manufacturing **(Table 5)**.

**Harmonic Analysis**

***Fuel manifold vibration analysis***

Harmonic analysis is performed for Fuel Manifold design. Base excitation technique is used in the current analysis methodology. Acceleration load of 1G (9810 mm/s$^2$) is applied in all three directions lie, X, Y and Z-direction. Global damping ratio of 2% (0.02) is used in the current analysis based on the prior test correlation study. Mode superposition method is used to solve the harmonic analysis **(Figure 3)**.

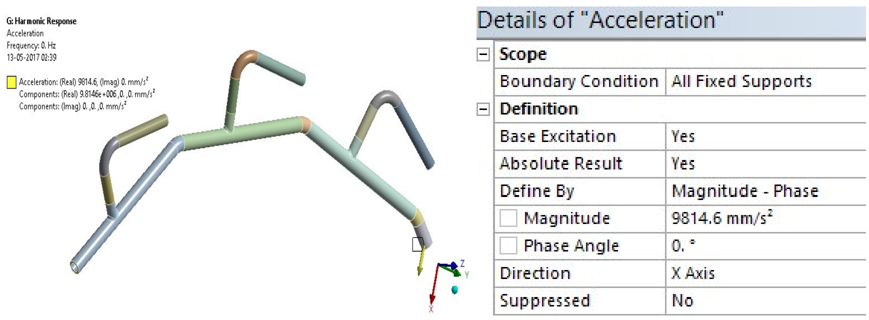


**Figure 3.**Effect of acceleration.

**Fatigue Analysis**

The majority of component designs involve parts subjected to fluctuating or cyclic loads. Such loading induces fluctuating or cyclic stresses that often result in failure by fatigue [5]. About 95% of all structural failures occur through a fatigue mechanism **(Table 6)**. Fatigue Assessment of Aircraft Fuel manifold at alternating Stress at 251.3 Hz.

**Table 6.** Fatigue analysis–results summary.

| Frequency (Hz) | Max Stress Region | Max Alternating Stress, MPa | Material Endurance Strength for 1E6 Cycles, MPa | Fatigue Factor of Safety | Fatigue Strength Margin |
|---|---|---|---|---|---|
| 251.3 | Bend Radius | 112.50 | 72.30 | 0.64 | -0.36 |
| 621.1 | Bend Radius | 116.85 | 72.30 | 0.62 | -0.38 |
| 743.4 | Bend Radius | 60.00 | 72.30 | 1.21 | 0.21 |

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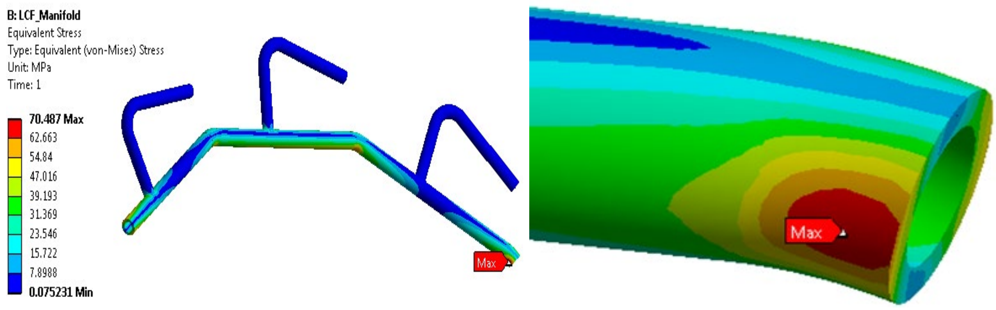


**Figure 4.** Mean stress plot.

- The maximum Von-Mises stress of 70.5 MPa is observed at bend radius **(Figure 4)**.

Mean Stress $\sigma_m = \frac{\sigma_{max}+\sigma_{min}}{2}$ = 70.5 MPa.

## GOODMAN CURVE

As per finite aviation administration requirement, Aircraft Fuel Manifold design needs to have infinite fatigue at maximum take-off condition [6]. Goodman curve is plotted against alternating stress vs. mean stress to validate the design at maximum take-off condition as shown in **Figure 5**. Aircraft fuel manifold design alternating stress falls within the Goodman line and there by having an infinite design life of more than 1E6 cycles at 251.3 Hz.

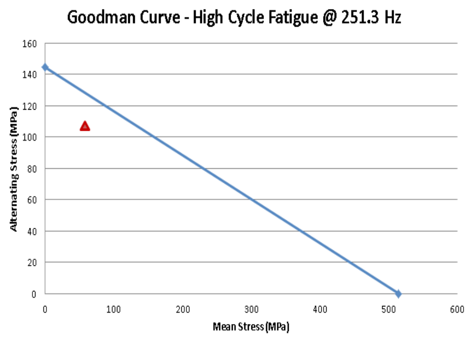


**Figure 5.** Goodman curve.

## FATIGUE ANALYSIS RESULTS SUMMARY

**Table 7.** Fatigue analysis–results summary.

| Frequency (Hz) | Max Stress Region | Max Alternating Stress, MPa | Material Endurance Strength for 1E6 Cycles, MPa | Fatigue Factor of Safety | Fatigue Strength Margin =FOS-1 |
|---|---|---|---|---|---|
| 251.3 | Bend Radius | 112.50 | 144.50 | 1.28 | 0.28 |
| 621.1 | Bend Radius | 116.85 | 144.50 | 1.24 | 0.24 |
| 743.4 | Bend Radius | 60.00 | 144.50 | 2.41 | 1.41 |

Current fuel manifold design is having a maximum alternating stress less than the material allowable endurance strength for 1E6 cycles. Hence Fuel Manifold design is having a positive fatigue strength margins and meets the fatigue design requirement **(Table 7)**. Current fuel manifold design is does not meet the fatigue strength requirement based on additive manufacturing technique. Maximum alternating stress is more than the material allowable endurance strength for additive manufacturing component and there and having a negative fatigue strength margins.

## CONCLUSION

Studies carried out on aircraft fuel manifold design substantiation and additive manufacturing technique assessment using finite element analysis" indicate the following:

- Baseline design of aircraft fuel manifold meets low cycle fatigue requirement.

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- Current aircraft fuel manifold design meets the optimum solution with regards to acceptable low cycle fatigue and high cycle fatigue as per the FAA design requirements.
- The analysis for the Aircraft Fuel Manifold confirms the design substantiation based on finite element analysis.
- Normal working pressure - Successfully meets material yield requirement.
- Proof pressure loading - Meets the requirements with positive design margins against the material yield limit.
- Burst pressure loading - Meets the requirements with positive design margins against the material ultimate strength.
- Low cycle fatigue - Successfully meets material fatigue strength for 25,000 cycles.
- High cycle fatigue assessment– Aircraft Fuel Manifold is having positive fatigue strength margin and there by having infinite design life at max take-off condition. Successfully meets Goodman requirement.
- Additive manufacturing technique – Material is reduced by 50% considering the manufacturing unknown variables. Design meets pressure requirement against the material yield and ultimate strength. However, design can be further optimized to meet the low cycle and high cycle fatigue strength requirements.

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