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CFD Analysis of A Typical Hydraulic Pressure Pipe Line in an Aircraft and Suggest Methods to Optimize its Stress and Vibration

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Abstract- The Hydraulic system of an aircraft is one of the most critical systems which operates essential services like the Control surfaces and Undercarriage system. Operators of Airlines and MROs have frequently complained about premature hydraulic line failures. This paper is aimed at studying the Fluid-Structure Interaction (FSI) of a typical hydraulic pipeline running in tandem with other pipe lines (which is a common feature in Aircraft) and suggest solutions to optimize the stress and vibration in them which is considered as the main factor for such catastrophic failures. Both CFX and FLUENT Solvers are used in our case. The analysis is carried out concerning suitability of material properties and support structure (for a high-speed aircraft) which are under the control of designers and MROs. The Von Misses stress has been simulated and analysed to substantiate various solutions being proposed. The ability of CFD to resolve such practical and field level problems and common snags in aircraft and associated components have made it quite popular among the aviation experts.

Keywords: high speed aircraft hydraulic system, FSI, CFD of hydraulic pipe, CFX solver, FLUENT, active vibration dampers, MRO, von misses stress.

1. INTRODUCTION

Hydraulic pipeline systems range from the very simple ones to very large and quite complex ones. A system may consist of a number of sub-networks separated by differing energy lines or pressure values. In order to study the Head loss and Energy loss across a pipe flow and to design Hydraulic pipelines individually or in manifold configuration, the following notations were used. The notations are shown in figure 1 for a computational sequence flow design.

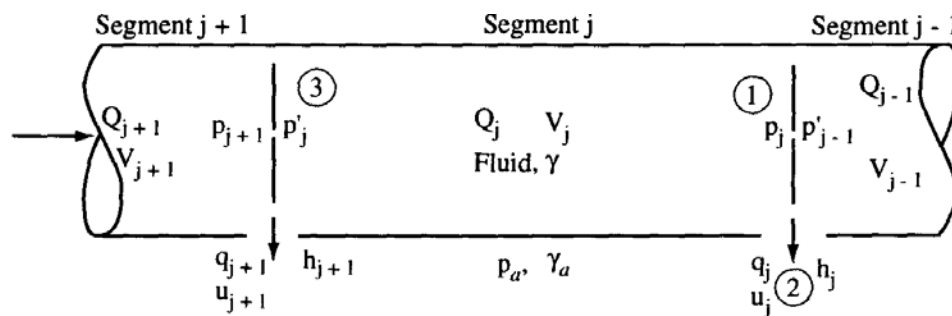


Figure 1: A two port hydraulic pipe segment

The manifold ports and barrel segments are numbered from the downstream end toward the upstream supply head or reservoir, with each port and segment number that is up stream of it denoted by j , which will also be used as a subscript on the other variables to indicate their location. Other variables are Q = discharge in the barrel segment, V = mean velocity in the barrel segment, A = cross-sectional area of the barrel segment, D = diameter of the barrel segment, q = discharge from a port, u = mean velocity through a port, a = cross-sectional area of a port, and d = diameter of a port. The fluid being conveyed has a unit weight of γ . The hydraulic model of flow in a pipe

Has a discrete jump in pressure across a port; just upstream of port j the internal pressure is P_j , and the pressure immediate downstream of the next port is p_j .

We write an energy equation from a point inside the main control volume, point 1 to another instance in the port efflux stream, point 2:

$$-h_j + \frac{V_j^2}{2g} + \frac{P_j}{\gamma} = -h_j + \frac{u_j^2}{2g} + \frac{P_{aj}}{\gamma} + K_L \frac{u_j^2}{2g}$$

In the above equation, K_L is the port head loss coefficient. If we define an energy parameter E at port J as

$$E_j = \frac{P_j - P_{aj}}{\gamma} + \frac{V_j^2}{2g}$$

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Then the fluid exit velocity through the port is given by

$$u_j = \left(\frac{1}{1+k_L} \right)^{1/2} (2gE_j)^{1/2}$$

What makes the hydraulic system of aircraft more complicated is the fact that there is continuous transfer of forces and momentum between the pipe structure and hydraulic fluid (at high pressure of about 3000 Psi). Excitation caused by high frequency pulsation of flow coupled with vibration from equipment around viz Gas Turbine, gear mechanisms, etc. can lead to fatigue failure of these pipes.

II. CFD ANALYSIS OF PIPELINES

The CFD analysis of commonly occurring defects in hydraulic pipelines carrying high pressure hydraulic fluid follows a sequence of technical processes along with scientific data analysis. The processes are explained in brief.

a) Preliminary study phase

It is necessary to study the physical problem analytically prior approaching the modeling and simulation phase. A proper preliminary study of the physical problem will help us individuate the assumptions and simplifications that are acceptable. In our case simplification lead to reduction in geometric complexity while allowing the thermal transfer equations. Hence this phase is fundamental to an accurate simulation result.

b) Geometric modelling

Geometrical models can be either 3D or 2D. It has to be an optimal choice so that it is easy to pass the data to the mesher software.

c) Meshing

Mesher plays an essential role in providing simulation related information to our model. During this process the model was divided into regions and surfaces. For the mesh to be usable all the boundaries relevant to the physical problem must be identified. These features will be used during the simulation setup phase to define fluids, solids and boundary conditions properties. The accuracy of the simulation result is dependent on the mesh geometry to a great extent. *This was evident during our various iterations and subsequently an Optimal.*

d) Solver for Simulation

During this phase we define the properties of all the fluids, solids and boundaries in fine detail. The choice of solver that is most suitable for the particular case is also decided in this phase viz. incompressible flow, compressible flow, steady solution, dynamic solution heat transfer and so on. *We chose SOLID 185 and FLUID 142 for representing our Material*

of pipeline and Hydraulic Fluid respectively. We have defined the initial conditions as encountered by a hydraulic pipeline in an aircraft system (these are the values that the variables take at the beginning of simulation). The solution is accepted through verification and validation.

e) Data visualization and post processing

Post processing data visualization is the most important human interface to understand the analysis. The incremental behaviour of various parameters associated to our analysis like speed, pressure and density need to be visualized. The data compilation and visualization should be such that the value of particular physical parameter can be extracted or derived as per requirement for further detail analysis.

III. EXPERIMENT

In order to carry out the study, a particular hydraulic pipe line, of one of the high-speed aircrafts, which had shown signs of frequently failure was considered. To carry out CFD analysis and stress analysis, we collected various parameters required for initialization as per Aircraft Manual. These parameters are required to be fed exactly as per dimension during mathematical modeling of the pipeline to obtain an accurate and stable solution. The parameters are:

- The Internal and external diameter of the pipeline.
- Viscosity of the fluid flowing through the pipeline.
- The Material of the pipeline.
- Flow rate.
- Pressure and temperature at the inlet of the pipeline.
- Length of the pipeline.
- Pipe profile and its shape.
- Maximum vibration in the equipment bay/zone.
- Distance between support clamps.

The figure given below is the photograph of a frequently failing hydraulic pipeline on the pressure side. This hydraulic pipe supplies required hydraulic pressure to the actuator of flying controls of an aircraft.



Figure 2: Actual photo of Hydraulic pr line of a fighter aircraft



Figure 3: Damage to hydraulic pipelines followed by leakages and Pressure drop



Figure 4: Routing (Zone 1) of a Hydraulic Pipeline and support clamping

IV. PARAMETERS REQUIRED FOR MODELLING

a) We collected various parameters of the specific hydraulic pipeline those were required for pre-processing phase and are tabulated below.

Table 1: Parameters of pipeline for Pre-Processing

S. no.	Parameters	Part no. y.yy.yyyy.yy
1	Internal diameter	8.22mm
2	External diameter	10.22mm
3	Flow rate	185 l/min
4	Length of pipeline	52"
5	Pressure through pipeline	210 kg/cm ²
6	Temp. of hydraulic fluid	-60c to +175 c
7	Distance between clamp	16",26",40.5"
8	Name of fluid	7-50c-3(synthetic oil)

b) Vibrations readings at Zone1

- Engine vibration - 3.4mm/s
- Gear box vibration - 3.8mm/s

c) Fluid properties

- Density at 20c - - 930 kg/m³
- Solidification point - <-70c
- Kinematic viscosity - - 25mm²/s
- Type - - mixture of polysiloxane fluid and organic ether with addition of anti wear additive + antioxidant

It is a known fact that the hydraulic pipelines are to be routed complexly inside an aircraft equipment bay due to space constraint. Also, the various components of the Hydraulic system including actuators are located at distant positions, depending on their utility and design criteria, which causes sufficient length of pipelines to be laid out that further requires support and clamping to hard points on the fuselage. In our case the specific pipeline was clamped to 03 hard points at the bulkhead at mid fuselage. The defects reported by an MRO were of chaffing, crack and dent. On scrutiny it was discovered that the root cause would be excessive stress and vibration and dent being attributed to the process of bending or routing. In order to analyse the vibration related stress and provide a solution, three cases were considered:

a) Effect of choice of material on the stress induced in the hydraulic pipe (in terms of Fluid Structure Interaction - FSI). To ascertain the same, Von Misses stress or Equivalent stress was analyzed with Ti and Steel by customizing SOLID185.

- b) Since the vibration in the hydraulic pipeline can only get transferred to fuselage through the clamp points, two cases were considered for Von Misses stress analysis, one with 3-point support and the

other with 4-point support. The working fluid was chosen to match the technical specification of the Hydraulic fluid of the aircraft that is FLUID 142 with customized properties.

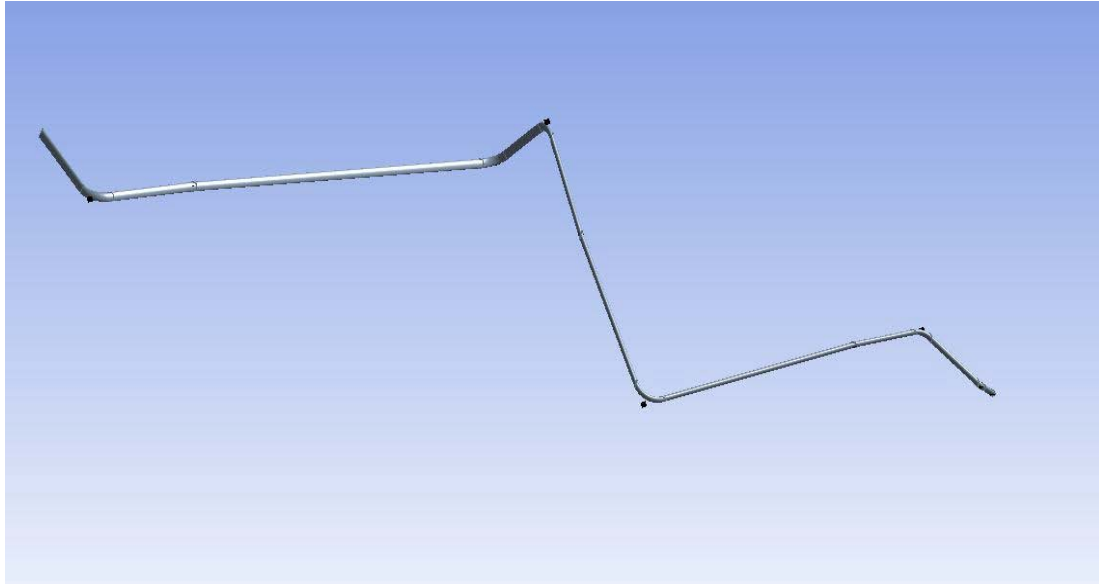


Figure 5: 3D Solid Model of the Hydraulic pipeline with 4-point clamp constraints

V. FLUENT ANALYSIS

As we deal with high pressure hydraulic fluids, which in our case are about 20 Mpa, the interactions between fluids and the walls of pipe lines that surround them cannot be neglected. When FSI occurs, fluid flow interacts with a physical structure, which in turn changes the fluid flow. This two-way interaction loop continues through multiple cycles, possibly resulting in structural damage and less-than-optimal flow. Traditional fluid flow

simulation doesn't account for this interaction, so simulation results may be incomplete and even misleading. Thus accurate analysis of structural vibrations and fluid transients in pipes should be based on FSI mechanism. In our paper, ANSYS FLUENT SOLVER and ANSYS Mechanical have been combined to solve the FSI problem.

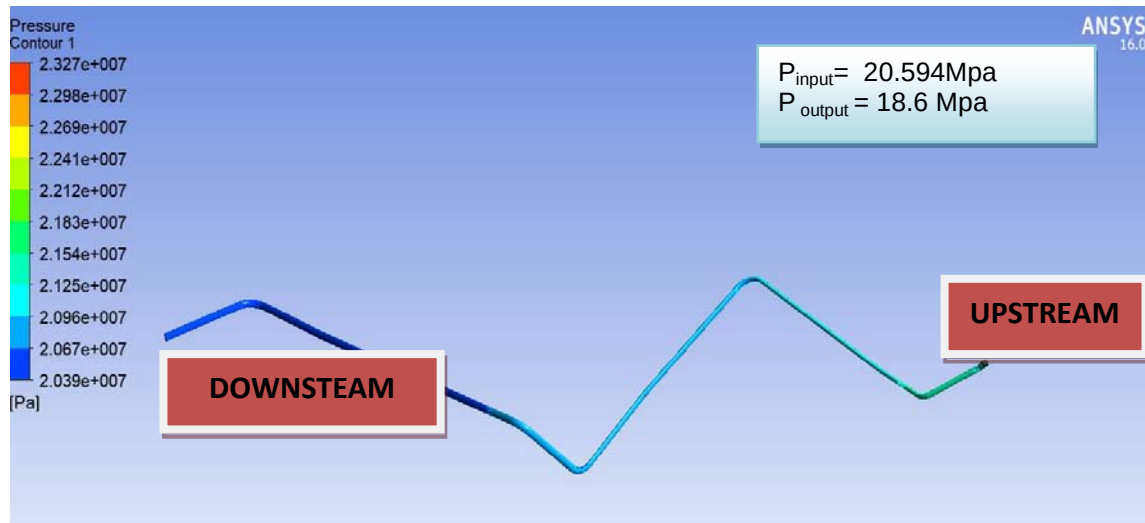


Figure 6: Wall Pressure

- a) Three Support Hydraulic Pipe system

During this phase of the experiment the Hydraulic flow in the specific pipeline was simulated with the present configuration of 3 support clamps.

i. Steel pipe with 3 Support Clamps

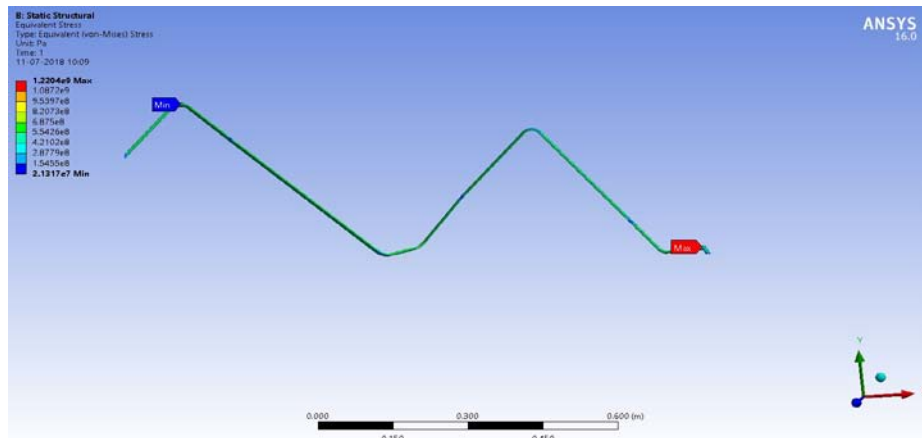


Figure 7: Equivalent Stress (Steel)

ii. Steel pipe with 3 Support Clamps considering Vibration

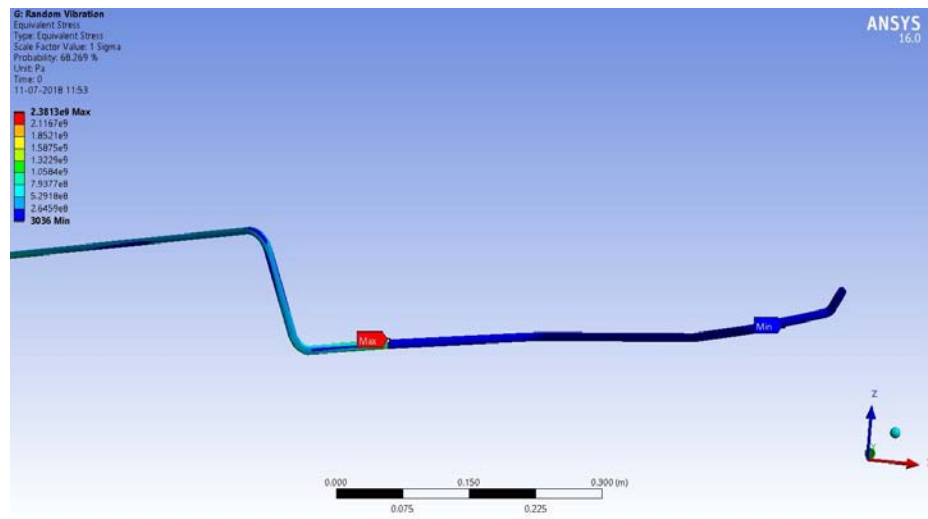


Figure 8: Equivalent Stress (Vibration = 3.8 mm/s)

iii. Titanium pipe with 3 Support Clamps without Vibration

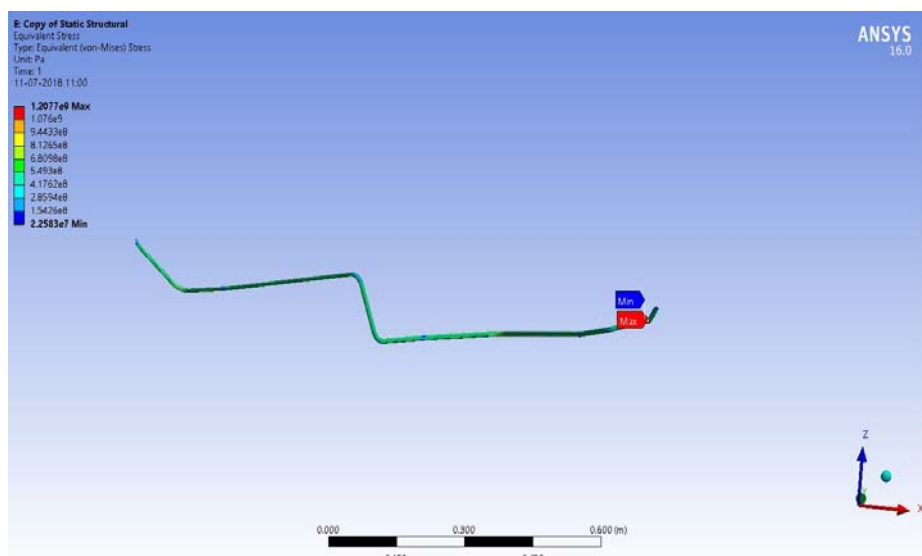


Figure 9: Static Structural Stress

iv. Titanium Pipe with 3 Support Clamps with Vibration

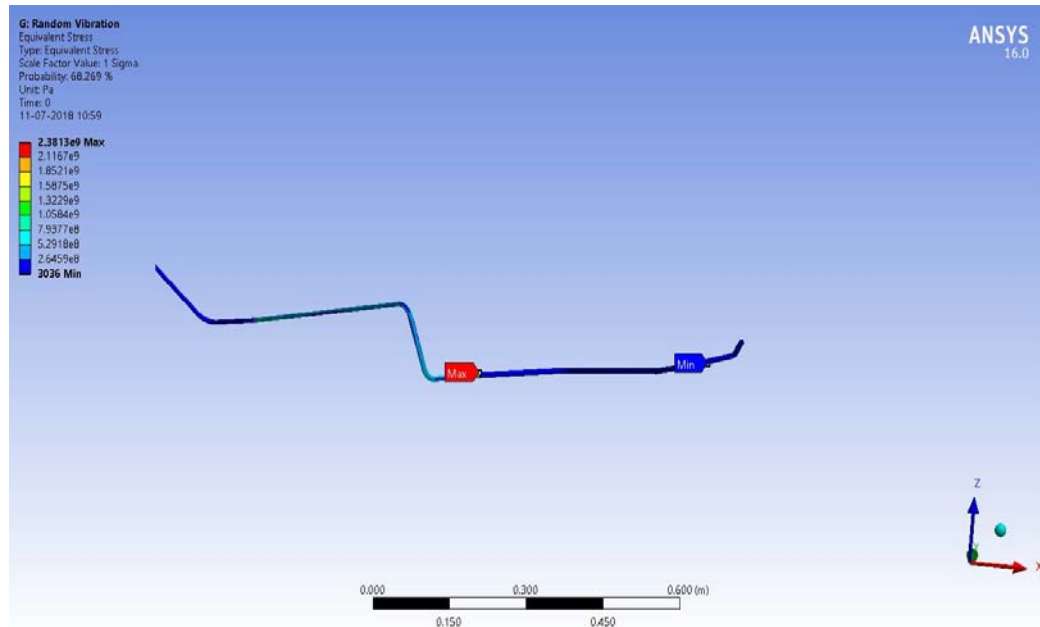


Figure 10: Equivalent Stress (Vibration = 3.8 mm/s)

b) Four Support Hydraulic Pipe system

Subsequently the specific pipeline was considered with 4 supports with hard point attachment on the aircraft bulkhead frame to ensure transfer of dynamic forces to fuselage from the pipelines.

The equivalent stresses on the pipeline in static condition and with surrounding vibrations were simulated for comparison. The simulation figures are appended below.

i. Steel pipe with 4 Support Clamps without Vibration

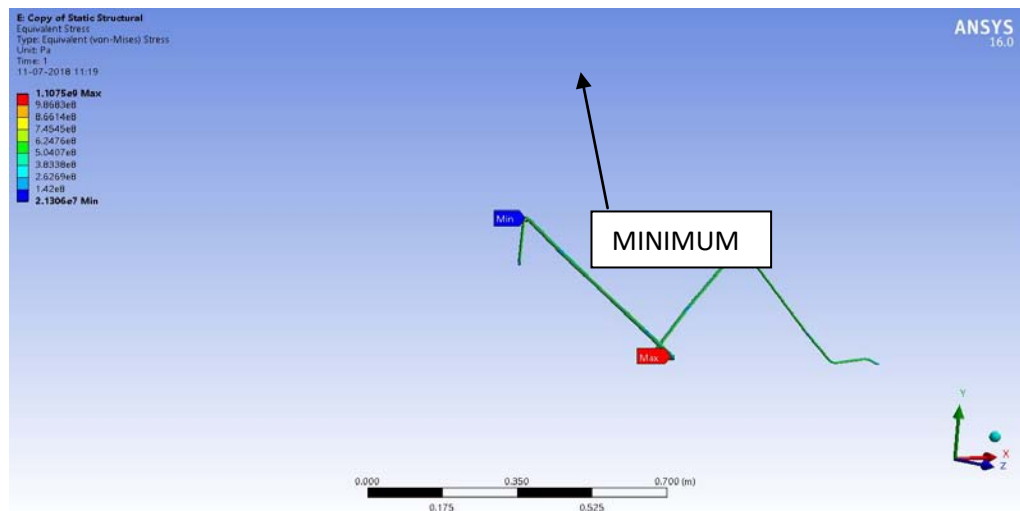


Figure 11: Equivalent Stress

ii. Steel pipe with 4 Support Clamps considering Vibration

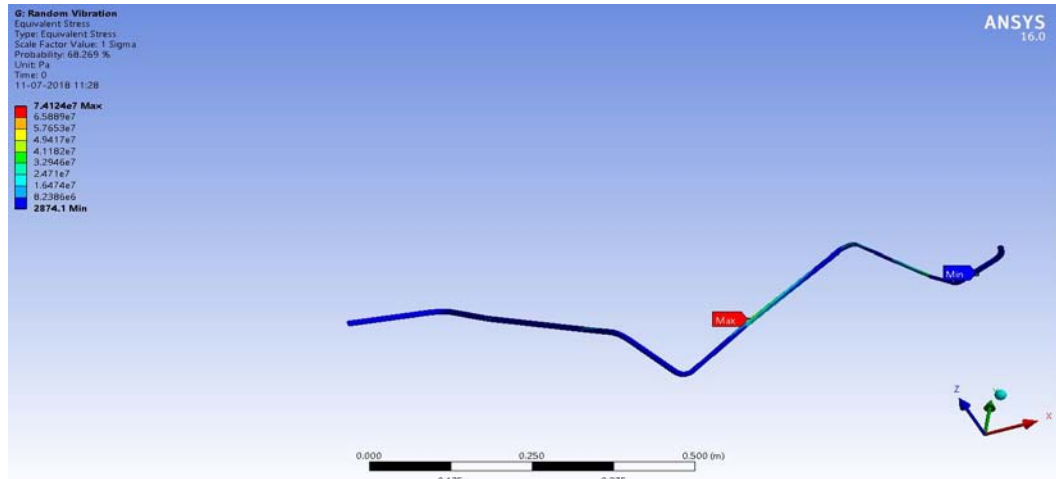


Figure 12: Equivalent Stress (Vibration = 3.8 mm/s)

iii. Titanium Pipe with Four Support Clamps

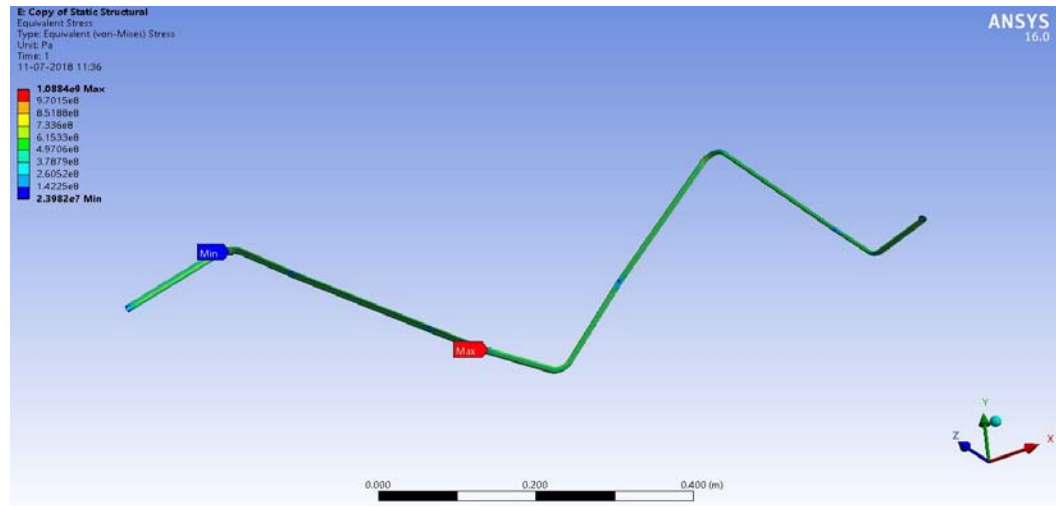


Figure 13: Equivalent Stress

iv. Titanium Pipe with Four Support Clamps with Vibration

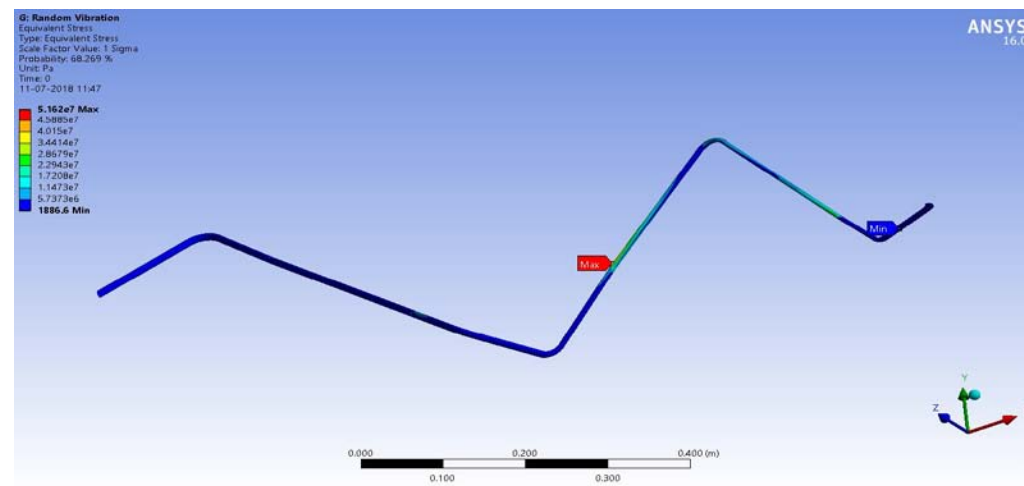


Figure 14: Equivalent Stress (Vibration = 3.8 mm/s)

VI. RESULTS

After the simulation with help of ANSYS and both CFX, FLUENT Solver, the equivalent stress distribution through the length of the pipeline was

scrutinized for abnormality and the location of maximum stresses were identified. The simulation data are tabulated below in Table 2.

Table 2: Results Table

Test	Steel with 3 support	Titanium with 3 support	Steel with 4 support	Titanium with 4 support
Static structural analysis (stress)	1220.4Mpa	1207 Mpa	1107.5 Mpa	1088 Mpa
Random vibration analysis(stress)	2381.3 Mpa	2381 Mpa	74.12 Mpa	51.62 Mpa

VII. ANALYSIS REPORT

Below mentioned are few of the common factors that can affect the health of Hydraulic pipelines which carry high pressure hydraulic fluid. The Hydraulic system plays an extremely vital role in aircraft operation. These common mistakes may be avoided for deterioration of hydraulic pipelines and any further catastrophic failure.

a) Manufacturing Process and Handling

Pipes are required to be casted as per routing. No further bending should be carried out by using primitive methods like hammering. It has been proved through various experiments that bending of pipeline causes severe stress concentration at the point of bend that may cause crack initiation (Griffith energy criteria)

It has been observed that external force is applied in order to fix pipeline into the system/ routing in the equipment bay. This external force is applied either by bending the pipeline or by hammering. This leads to increase in residual stress inside the body which reduces strength of material. Finally, it leads to crack initiation and propagation.

When external forces or hand pressure is applied on the pipeline to fix the pipeline then it reduces the distance between the pipelines. Sometimes pipelines come in contact with each other. It leads to the chaffing of material. Pipelines rub against each other, causing erosion of the surface and eventual failure. The transfer of vibration and other dynamic loads can cause deterioration of pipelines.



Figure 15: Pipelines Rubbing Against Each Other due to Zonal Vibration

i. Clamping or Support System

Due to Fluid Structure Interaction coupled with Vibration, these hydraulic piping systems become highly responsive, leading to amplified vibrations and fatigue failures. With low-damped systems, the vibration Ring-down time after the initial event can be severely long. Damping is a proven solution to control vibration and is used extensively in the automotive and aerospace industries.

In most of the aircraft systems NT (Nylon Titanium Composite Clamps) material are used as support system. Studies have shown that flour plastic gasket can reduce the vibration to some extent. The complexity of source of vibration that exists in an aircraft certainly requires an active Vibration Dampers with damping material liner and wear pad. One such active Damper available in the market (DamperX) is shown in Fig 16.

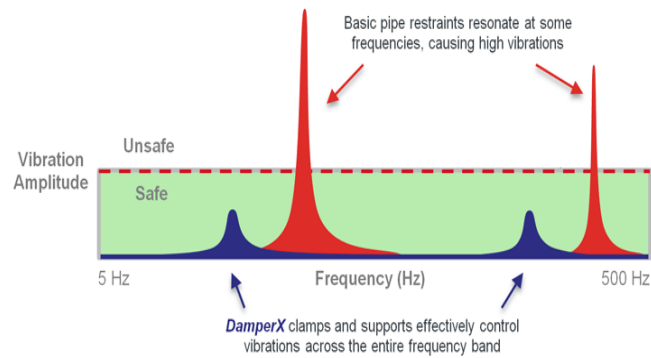


Figure 16: Anti Vibration Damper

ii. Pipe Hanger or Pipe Support

A pipe support or pipe hanger is a designed element that transfers the load from a pipe to the supporting structures. The four main functions of a pipe support are to *anchor, guide, absorb shock, and support a specified load*. Pipe supports used in high or low temperature applications may contain insulation materials. The overall design configuration of a pipe support assembly is dependent on the dynamic loading factor and operating conditions.

There is no thumb rule for number of supports to be used on particular pipeline. Generally, support is placed on the longer and straight pipelines. So, an attempt was made to observe stresses by increasing no. of supports. It was found out that stress could be reduced by 32 times, by increasing the support points by 30% while keeping the material of pipeline same.

iii. Changing Material of Pipeline

Pipeline is subjected to high pressure (210 kg/cm²) and vibration. So, Material strength was also considered as a reason of failure. Titanium was considered as a replacement of steel. It was found that with 4 no. of clamps, stresses in steel pipeline are 1.4 times titanium (as compared to 32 times decrease in equivalent stress due to an additional support clamp). It proves that material performance is satisfactory. So, there is no need to change material from steel to titanium.

VIII. CONCLUSION

The use of Hydraulics for operation of various components of an aircraft viz Control surfaces, Undercarriage etc is inevitable. With increase in AUW, the hydraulic system gets more and more bulky and complexity of pipeline system also increases. The flying envelope and max speed of the aircraft also decides the aerodynamic forces on various Control surfaces which in turn decide the robustness of the Hydraulic system. As these dynamic forces increase, the system requirement also becomes more stringent. We used CFX and FLUENT Solver to simulate the flow through a specific hydraulic pipeline which has a history of failing

frequently. The conclusion of our experiment along with recommendation is appended below:

- Locations of occurrence of maximum stress were obtained from Von Misses stress analysis to optimize the support clamp positions.
- With increase in no. of support clamps (in our case 3 to 4), stresses on the hydraulic pipeline reduced drastically. With proper and iterative simulation, the exact positions of support clamps were ascertained.
- In case of steel, when supports are increased from 3 to 4 then stress is reduced by 32 times from 2381.3 Mpa to 74.12 Mpa.
- Changing the material from steel to titanium didn't have any profound effect on reduction of Equivalent stress in pipeline. However, stress reduced from 74.12 Mpa to 51.62 Mpa (with 4 Supports).
- In order to reduce the vibration stress and reduce the chance of failure, an additional 4th support clamp is proposed for the specific hydraulic pipeline as shown below.

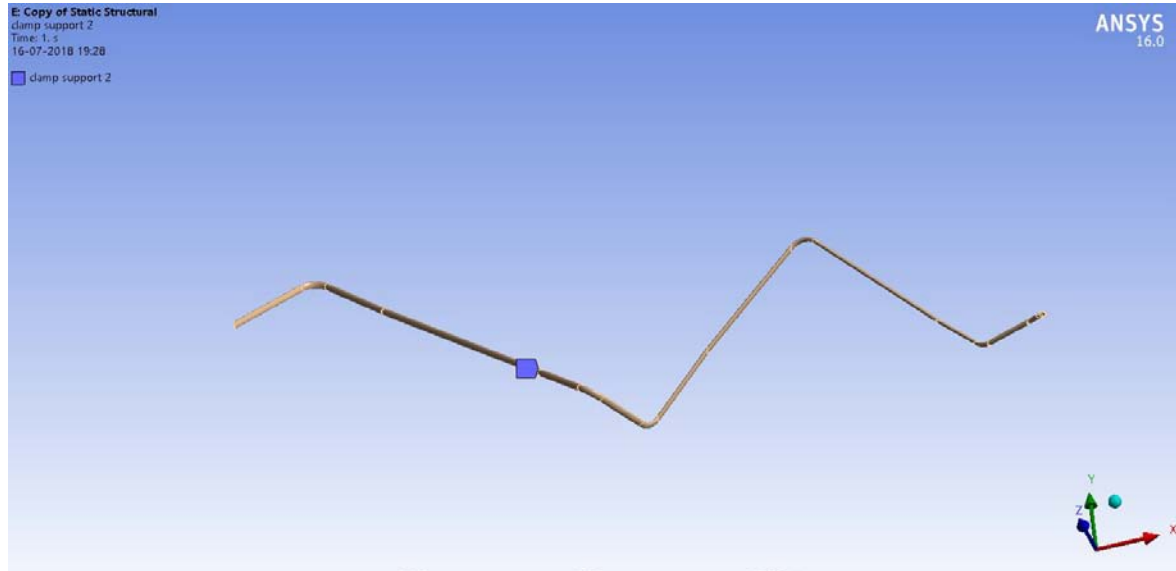


Figure 17: Location of the 4th Support

- vi. Implementation of standardization
 - i. The hydraulic pipelines need to be of standard size and shape (pre-fabricated). No external force should be applied on the pipelines after fitment i.e. cold work is not permitted.
 - ii. Spacing between the pipelines should be standardised.
- 5. Modeling of high-pressure gas transmission lines by J. K. van Deen and S. R. Reintsema.

The hydraulic pipelines are subjected to higher dynamic stresses due to combinatory force of high pressure, temperature and vibration. Hence, clamping of these pipelines using active vibration dampers on main frame or bulkhead of aircraft should be explored. In order to avoid chaffing between pipelines, better pipeline routing may also be explored during design phase.

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