Multi-physics based Simulations of a Shock Absorber Sub-system for PHM

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ABSTRACT

The multi-physics involve Mechanical, Thermal, Hydraulic, and Pneumatic based modeling and simulation of an oleo-pneumatic shock absorber with fault capabilities presented in this paper. The fault simulated in this model is leakage due to eccentricity. The one-dimensional shock absorber system models render loads at different sink velocities. These load values, used in the structural model to do static stress analysis. By using these loads directly from the system model eliminates the error in load computation from the loads group, thereby eliminating the time and cost involved in this activity. The models and static stress analyses are done with both 1-D and 3-D elements. The 3-D landing gear model meshed with using both auto and manual mesh generation options. The consequences of both 1-D, and 3-D models mesh generation are discussed in this paper. The static stress analysis, compared with the experimental results and it is found that the results are within 5% deviation. Based on the static stress analysis computed the life of a landing gear.

1. INTRODUCTION

The modeling and simulation work done for a shock absorber sub-system of an aircraft's tri-cycle landing gear for healthy and fault conditions. The simulations include quasi-static and dynamic simulation of a shock absorber sub-system. Shock absorber is an integral part of a landing gear of an aircraft. A typical shock absorber of a medium utility type aircraft has been chosen for the modeling and simulation. In the case of a quasi-static modeling a ramp load is applied whereas in the case of dynamic the vertical drop velocity provided as an input parameter. The initial adverse events table, constructed by collecting data gathers from findings within the ASRS, FAA, and NTSB data bases and shown in Table 1, from reference "Mary S R, Tolga K, Karen M L, Jeffrey L B, Colleen A W (2010)". "Milwitzky B, and Cook F E, (1952)" has shown the analysis of Landing-gear behavior, indicating that the simplified linear segment variation is adequate for tire deflection characteristics and this followed in this paper.

"James N. Daniels (1996)" developed a FORTRAN program to model, simulates and validated the results with the experimental data.

Table 1 Integrated Vehicle Health Management (IVHM) Adverse Events

Adverse Event Type	Example Damage Condition
Incipient faults	1. Icing conditions in propulsion system 2. Fault of power electronics 3. Turbine engine bearings
Slow progression faults	4. Fatigue cracks on metallic airframe structure 5. Delamination in composites 6. Hydraulic failures 7. Air conditioning and pressurization faults 8. Oil and/or lubrication failures
Intermittent faults	9. Wire chafing failures
Cascading faults	10. Power system faults 11. Control surface faults (aileron, rudder, or elevator) 12. Instrumentation, communication, and navigation failures 13. Fuel system faults
Fast progression faults	14. Engine stall or faults in turbomachinery 15. Landing gear faults 16. Brake and/or anti-skid system faults 17. Lightning- and radiation-related avionics faults

Diagnostic approaches, broadly divided into two types: model-based and data driven as described in "Edward B, Abhinav S, Sriram N, Indranil R, and Kai G, (2011)". This work in the paper considers model-based approach. The system modeling and analyses are done in Siemens' Advanced Modeling Environment Simulation (AMESim) software package. It is a multi-physics domain based package to model Mechanical, Hydraulic, Pneumatic, Thermal, Electrical and Electronic systems and 2-dimensional structures/ bodies. This package based on bond graph theory to model multi-domain components.

In the taxonomy of prognostic approaches as indicated by "Kai Goebel, George Vachtsevanos and Marcos E. Orchard, (2013)" the physics based models is on the top of the triangle. The multi-physics models' being on the top of triangle is presented in this paper show its significance to Prognostics Health Management (PHM).

2. PHYSICS BASED MODELING

Physics-based models employ a physical understanding of the system in order to estimate the remaining useful life of a system. There exist two major challenges in physics based prognostics: 1) the lack of sufficient knowledge on physics of failure degradation and 2) the inability to obtain the values of the parameters in the formulations, as stated by "Eker O F, Camci F, and Jennions I K (2012)". Modeling of a shock absorber is done at different tiers (levels). The first model has lesser number of sub-components. In this a separate pneumatic chamber/ bottle modeled with or without the tyre or tire model. The second level (tier) model is a detailed model having all the four chambers modeled. The third level is a fault model, modeled with a leakage sub-component.

2.1. Healthy Model

The healthy model is real system emulation. The healthy model of oleo-pneumatic shock absorber is as shown in Fig. 1. The flow rate equation for an orifice is given by Eq. (1).

$$Q = C_q A \sqrt{\frac{2|\Delta p|}{\rho}} \qquad (1)$$

Where

Q – Flow rate (m^3/s)

C_q – Flow coefficient

A – Surface area of opening (m^2)

Δp – Pressure difference (Pa)

ρ - Air density (kg/m^3)

The efficiency or wave form coefficient, used to describe how square an output curve is. The efficiency is the ratio of square wave output to actual output force for a given application. To compute the area under the curves as shown in Fig. 2 using MATLAB program (www.mathworks.com) the trapz (xv, yv) function. The efficiency is computed using the area under the curve divided by the maximum area. The efficiencies for with and without wheel configurations are 73.333 and 68.071 respectively.

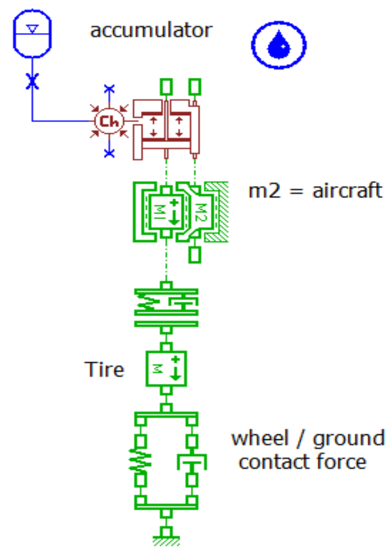

Fig. 1 Level I model of an oleo-pneumatic shock absorber

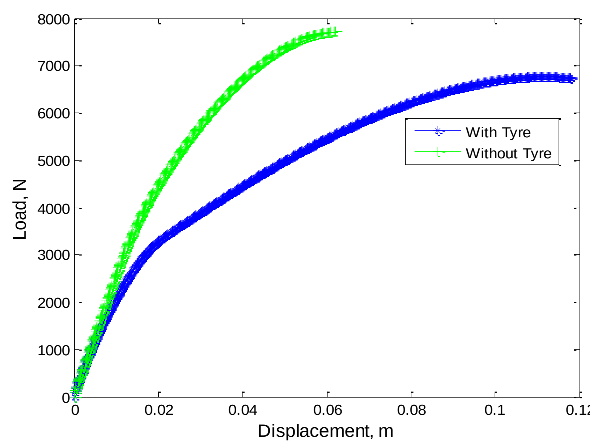

Fig. 2 Efficiencies computation curves

The second level of an oleo-pneumatic shock absorber with its all four chambers is as shown in figure 3. The various parameters for this model used are given in Table 2.

2.2. Build Fault Model

Once the healthy model built and checked for its complete performance, described in section 4, now for the Prognostic Health Monitoring and Management (PHM) require fault model. A healthy model has no provision for fault inception, whereas an unhealthy model has fault or degradation capability built into the model.

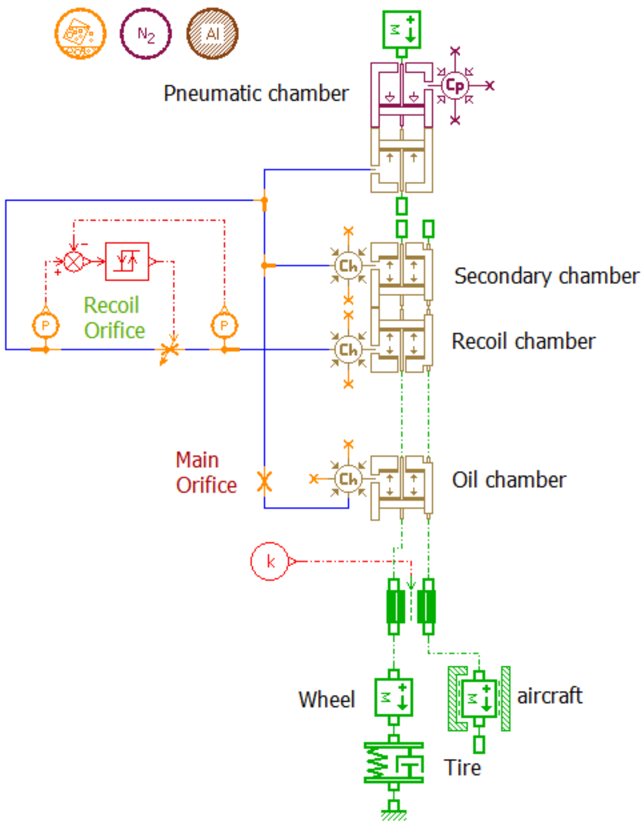

Fig. 3 Level II model of an oleo-pneumatic shock absorber

The unhealthy/ fault model built using sub-component which cater for fault simulation as in fig. 4 (the leakage sub-model part) or this simulated by changing the parameters. The latter one is simple to do but the former requires a sub-component level model built-in the software. If not, the user has to build a custom component that suits the requirement. The leakage part component introduced in the place of a recoil chamber (Fig. 4) is the novelty of this paper. The leakage component fault parameters are given in Table 3. The leakage flow rate equation is given by Eq. 2 this is more complex compared to Eq. 1. The unhealthy behavior is modeled with a leakage component which has feasibility to model leakage with variable length, eccentricity and viscous friction. This component used for the recoil chamber part. The shock absorber shown here is to model the leakage in the recoil chamber which is a common type of fault observed in most of the shock absorbers. Fig. 4 depicts a model of an oleo-pneumatic shock absorber which has mechanical, thermal, pneumatic and hydraulic capabilities built-in. There are four chambers one pneumatic and remaining three are hydraulic. In this model there is a provision to incorporate sensors like displacement, accelerometer and pressure sensors at numerous locations. One typical location is as shown in Fig. 4. A systematic methodology for the design of a Prognostic Health Management system should include a means of selecting and combining a set of data-to-information (sensors) conversion tools to convert machine data into performance-related information to provide health indicators/indices for decision makers to effectively understand the current performance and make maintenance decisions before potential failures occur, presented in “J. Lee, Fangji Wu, Wenyu Zhao, Masoud Ghaffari, Linxia Liao, David Siegel (2013)”.

Table 2 List of various parameters for healthy model

SN	Title	Unit	Default values
I	**Parameters of aircraft**		
1	Sprung (Cradle) Mass	Kg	1824
2	Un-sprung (Wheel) mass	Kg	45
3	Sink Velocity	m/s	3.05
II	**Parameters of chamber**		
4	Oil chamber piston diameter	mm	80
5	Secondary chamber piston diameter	mm	60
6	Recoil chamber piston diameter	mm	15
7	Pneumatic chamber piston diameter	mm	105
8	Pressure	Bar	13.6
9	Pneumatic chamber dead volume	L	0.2
III	**Parameters of main orifice**		
10	Equivalent orifice diameter	mm	9.5
11	Maximum flow coefficient	Null	0.64
IV	**Parameters of Recoil orifice**		
12	Equivalent orifice diameter	mm	6
13	Maximum flow coefficient	Null	0.64
V	**Parameters of spring damper**		
14	Spring rate	N/m	250000
15	Damper rating	N/(m/s)	15000

$$Q = -\frac{\Delta p}{12\mu l_c} r_c^3 \pi d_p \left[1 + \frac{3}{2}\left(\frac{ecc}{r_c}\right)^2 \right] + \frac{v^+ - v^-}{2} r_c \pi d_p \quad (2)$$

Where

Δp – pressure difference between port 2 and port 1: $p_2 - p_1$

r_c – radial clearance defined as, $r_c = d_c/2$

d_p – external piston diameter

l_c – contact length obtained

μ - fluid dynamic viscosity taken at mean pressure

ecc - eccenctricity

v+ and v- correspond respectively to the velocities of the cylinder (envelop) and the piston

Table 3 Various parameters of a fault model

S N	Description	Unit	Value
1	Piston diameter	mm	15
2	Clearance diameter	mm	0.2
3	Contact length	mm	30

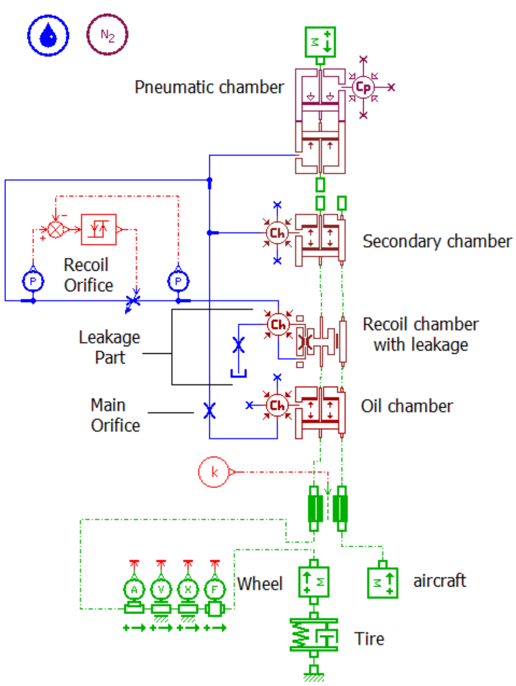

Fig. 4 Level III fault simulator model of shock absorber

3. DYNAMIC SIMULATIONS

For the healthy and fault model, the dynamic simulation for an interval of two seconds, it is observed that the temperature range does vary up to a maximum of 120^0 C in the pneumatic chamber and in the case of all the hydraulic chambers the temperature maintained within 22^0 C (shown in Fig. 5). The leakage introduction represents the fault model of an oleo-pneumatic shock absorber of an aircraft. Here the leakage model presented with an external orifice provided for the leakage sub-component. The leakage orifice diameter is 1.5 mm. The graph shows that the displacement destabilizes the aircraft. The diverging phenomenon seen due to leakage is as shown in figure 6.

Dynamic simulation carried out for the healthy model. The various sink velocities considered are 1, 2, 3.05, and 4 m/s. The third velocity corresponds to 3.05 m/s corresponds to 10 ft/ sec this is the maximum allowed as per the Federal Aviation Regulations (FAR). The loads obtained from these simulations are fed into the structural model. This process of load computation eliminates the error in load computation. The magnitude of the load is an important factor. Here the load magnitude is one direction only. In the case of lateral drift landing all three x, y, and z components of loading exist. The loading in all three directions viz., the vertical, drag, and side load happens in a lateral drift landing case as described in the report by "Krishna Lok, Pulak Chakrabarti, Satish Chandra (2012)". The resultant magnitude is important. The various magnitudes of vertical force for different sink velocities are shown in Fig. 7.

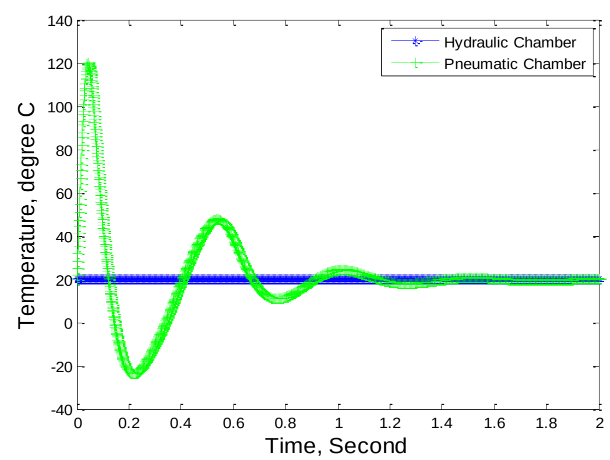

Fig. 5 Variation of temperature in two chambers

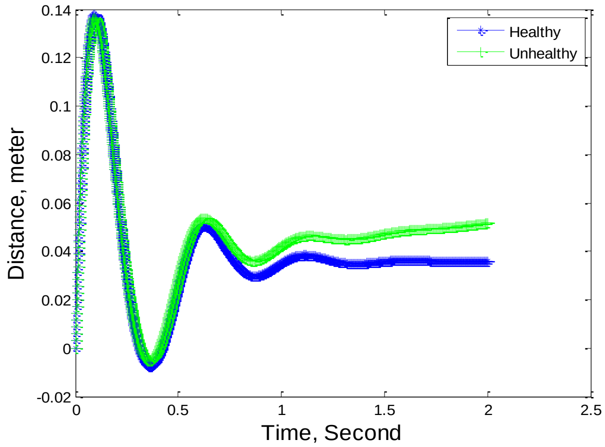

Fig. 6 Aircraft displacement for different conditions

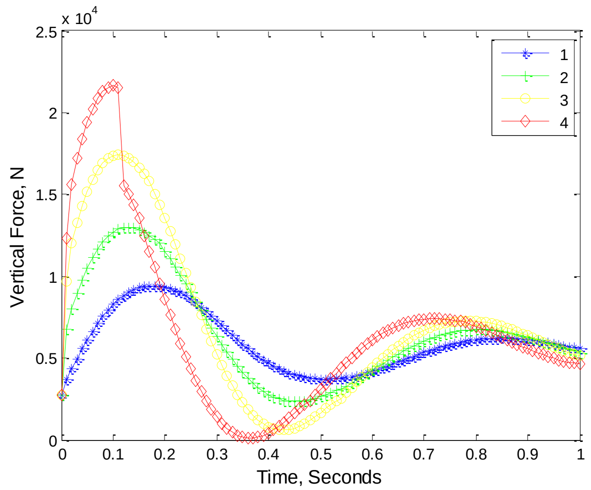

Fig. 7 Vertical force magnitudes for various sink velocities

4. EXPERIMENTAL VERIFICATION

The healthy model is validated through experimental results of a drop test. The experimental comparison curves shown for the displacement, vertical force (load) and pressure are in figures 8, 9, and 10 respectively. They do show a good comparison. The vertical force comparison is similar to that shown by "Cai-Jun X, Yu H, Wen-Gang Q, and Jian-Hua D, (2012)".

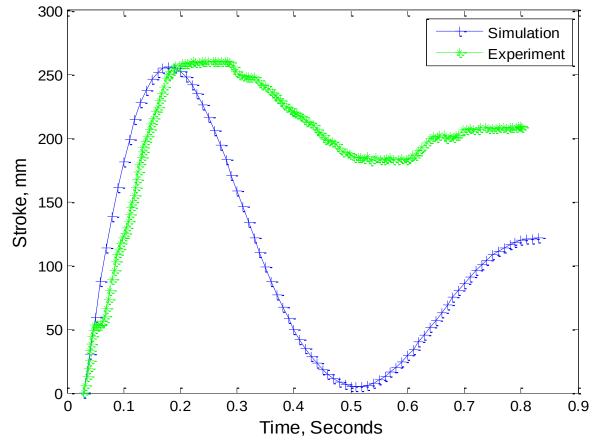

Fig. 8 Shock absorber stroke displacement versus time

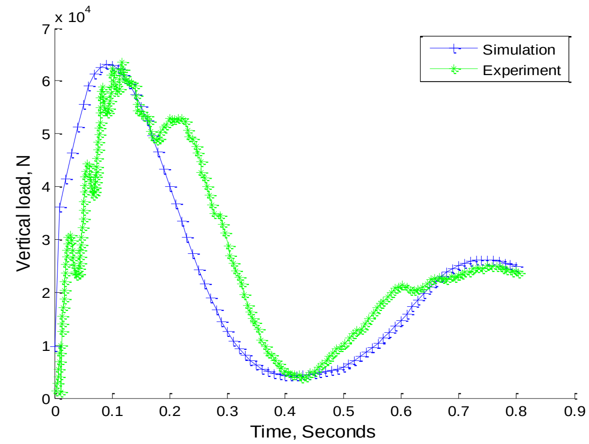

Fig. 9 Comparison curves for vertical load versus time data

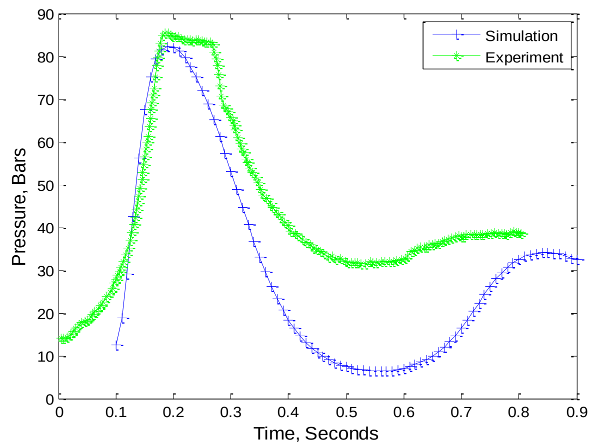

Fig. 10 Comparison curves for pressure versus time data

5. CO-SIMULATION

The combination of structural and system based models simulation coined as co-simulation. The output force magnitude from the physics based model is input to the structural model. The structural model of landing gear, made up of two materials their properties are indicated in Table 4. Aluminum is the material for upper and lower toggle links and the remaining part of the structure is of Steel material. For the structural modeling of landing gears has been done using CATIA. The meshing part is done using Hypermesh package (www.altair-india.in) and analysis in Abaqus. The fundamental static finite element equation is given in Eq. 3.

$$[K]\{q\} = \{f\} \tag{3}$$

Where, [K} – global stiffness matrix

{q} – global nodal displacement vector

{f} - global nodal force vector

Table 4 Material properties for landing gear

S N	Description	Steel	Aluminum
1	Modulus of elasticity (GPa)	210	72
2	Poisson ratio	0.25	0.3
3	Ultimate tensile strength (MPa)	1230	480

5.1. One-dimensional model

The one-dimensional structural model with beam elements of a Nose landing gear is as shown in figure 11. The various beam profiles for this gear listed in a Table 5.

Table 5 Beam pipe section profiles and their dimensions

S N	Component	Beam cross-section profiles	
		Radius, mm	Thickness, mm
1	Cylinder	57.5	9.5
2	Piston	39.55	5.0
3	Stub-axle	49	9.5
4	Actuator	22.15	5.6
5	Pintel Pin	25.5	7.0
6	Yoke	30.0	5.0
7	Axle	25.5	7.0

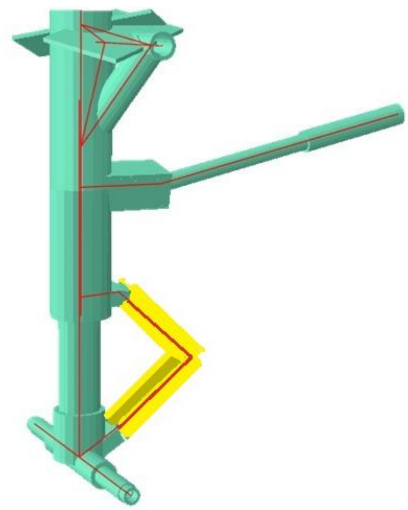

Fig.11 One-dimensional superimposed with beam profile

5.2. Three-dimensional model

A three-dimensional (3D) model of a nose landing gear's nomenclature, mesh, boundary conditions (BC), and loading is shown in figure 12. A typical auto mesh model has tetrahedral elements the number of nodes 47 995 and elements as 1 63 364 whereas the manual mesh has number of nodes 2 91 321 and hexa-8, tria-3, and tetrahedral elements as 5 95 753. It is observed that the manual mesh has more than three times that of the auto mesh's number of nodes and elements. The stress and fatigue analysis work done by "Krishna Lok S and Abdul Waheed A (2014)" presented in their earlier paper.

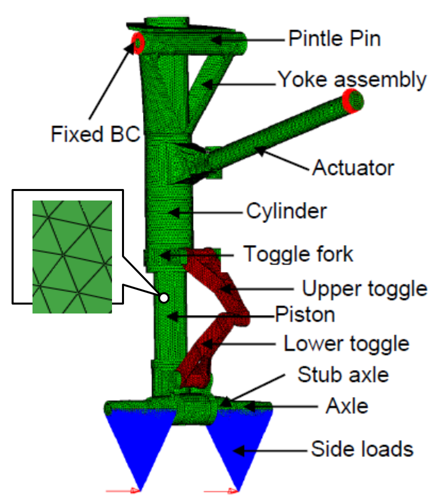

Fig.12 Nomenclature, FE model, BCs, Material, and Loads

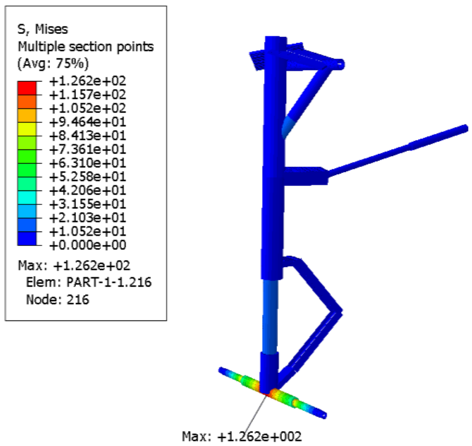

Fig. 13 Stress contours on a Nose Landing Gear

Table 6 Stress magnitudes for different sink velocities

Sink velocity (m/s)	Vertical force (N)	Displacement (mm)		von-Mises stress (MPa)	
		1D	3D	1D	3D
1	9073	0.357	0.321	67.14	68.39
2	12608	0.496	0.459	93.30	94.97
3.05	17060	0.670	0.603	126.20	128.60
4	21304	0.838	0.753	157.60	160.50

A comparison of displacement and stress magnitudes are given in Table 6 for one (1D) and three dimension (3D) models at different sink velocities. Corresponding to the sink velocity of 3.05 m/s case, the stress contour plot is shown in Fig. 13 for 1D case. Based on the stress magnitude, using S-N approach, computed the minimum life of landing gear is 1E06. This clearly indicates the landing gear has safe life.

6. CONCLUDING REMARKS

The work presents the multi-physics model based simulation of an oleo-pneumatic shock absorber for a typical aircraft for PHM.

Lesson learnt that it is essential to do good number of simulation before building the real shock absorbers. Have good interactions between designer and manufacturer. To arrive at the optimum configuration of the shock absorber components like cylinder and piston, etc. Earlier landing gear shock absorber developed without the any of the software models, now we have good packages, gaining the insight before developing an actual one.

Using the co-simulation concept the load computation errors get minimized.

One and three-dimensional landing gears stress models render stress magnitude values within the maximum deviation of 2 percent.

From the static stress analysis it is observed that axle is the most critical component.

For the considered loading cases computed the life of a nose landing gear.

Future work planned is to work closely with the industry with the usage of powerful software packages, developing a best landing gear for future generation aircraft.

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REFERENCES

Mary S R, Tolga K, Karen M L, Jeffrey L B, Colleen A W (2010), Assessment of the State of the Art of Integrated Vehicle Health Management Technologies as Applicable to Damage Conditions, National Aeronautics and Space Administration (NASA), Glenn Research Center, Cleveland, Ohio 44135, NASA/TM-2010-216911

Milwitzky B, and Cook F E, (1952) Analysis of Landing-gear behavior, NACA TN 2755, Washington D C.

James N D, (1996) A Method for Landing Gear Modeling and Simulation with Experimental validation, NASA Contractor Report 201601, June 1996.

Edward B, Abhinav S, Sriram N, Indranil R, and Kai G, (2011) Experimental Validation of a Prognostic Health Management System for Electro-Mechanical Actuators, Infotech@Aerospace, 29-31 March 2011, AIAA 2011-1518.

Kai Goebel, George Vachtsevanos and Marcos E. Orchard, in Chapter 4: Prognostics of Integrated Vehicle Health Management the Technology, 2013 SAE international http://books.sae.org ISBN 978-0-7680-7952-4, edited by Ian K. Jennions.

Eker O F, Camci F, and Jennions I K (2012) Major Challenges in Prognostics: Study on Benchmarking Prognostics Datasets, European Conference of Prognostics and Health Management Society 2012.

J. Lee, Fangji Wu, Wenyu Zhao, Masoud Ghaffari, Linxia Liao, David Siegel (2013), Prognostics and health management design for rotary machinery systems — Reviews, methodology and applications, Mech. Syst. Signal Process. http://dx.doi.org/10.1016/j.ymssp.2013.06.004.

Federal Aviation Regulations (FAR) part 25, Airworthiness Standards Transport Category Airplanes, May 2009 Edition.

Krishna Lok Singh, Pulak Chakrabarti, Satish Chandra, Report on Computation of NLG and MLG Landing Loads, NCAD/DQ-04/0005/2012, 21March 2012.

Cai-Jun X, Yu H, Wen-Gang Q, and Jian-Hua D, (2012) Landing-Gear Drop-Test Rig Development and Application for Light Airplanes, Journal of Aircraft, Vol. 49, No. 6, November-December 2012, DOI: 10.2514/1.C031913

Krishna Lok S and Abdul Waheed A (2014), Stress and Fatigue Damage Computation of a Nose Landing Gear, Int. J. Fracture & Damage Mechanics 1-10, Journal Pub, vol. 2 Issue 1.

BIOGRAPHIES

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