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Design and Development of Front Air Fork Suspension System for Two-Wheeler

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Abstract : A front suspension is capable of absorbing the vibrations produced at wheel due to irregular ground surface on which rider ride the bike. By this way, vibrations do not be transmitted to the bike rider. Conventional Front fork system uses helical spring to absorb the vibrations which include major cost of Suspension system & also increase the weight of the Front fork unit. In this invention, the front fork includes two vertical leg assemblies as a shock absorbing unit which is made by a group of components that operates by means of suspension oil & a gaseous fluid. Internal floating piston is used to separate an oil chamber from the other gaseous fluid chamber. The front fork also includes a simple mechanical blocking system which is further used to generatedamping force.
Keywords: Front suspension, absorbing vibration, helical spring, suspension oil, gaseous fluid, Internal floating piston, Damping force

I. INTRODUCTION

There are many challenges coming in the way of automobile makers. Especially bikes are the trendy thing & people are demanding the changes in the bike. Suspension is the system of springs, shock absorbers and linkages that connects a vehicle to its wheels and allows relative motion between the two. Conventional Suspension system uses helical coil springs to absorb vibration energy generated due to uneven road condition whereas dampers are used to control the spring movement. It is the major part in automobile to maintain ride quality& comfort. Control of excessive suspension movement without shock absorption requires stiffer springs, which would in turn give a harsh ride as well as it adds more weight in suspension system. Addition of weight reduces the fuel efficiency. As the bike manufacturers demands lighter suspension with improved performance and fuel efficiency, we replaced heavy helical springs with pressurized nitrogen gas. Hydraulic oil used to achieve damping force whereas pressurized nitrogen gas gives assembly load. Introduced internal floating piston to separate suspension oil and pressurized nitrogen gas.

In this, we are going to use conventional telescopic front fork suspension for our research. The mechanical parts (helical spring) have been replaced by internal floating piston and by the fluids such as Front fork oil & pressurized Nitrogen gas which carry out a complete absorption of vibration energy produced due to uneven road condition.

II. CONSTRUCTION OF FRONT AIR FORK

In this research we are developing conventional front fork suspension without spring (Front Air fork). Piston along with Fork pipe assembly, rebound spring & bottom case is fastened with the help of socket headed bolt against bottom case. A part of Fork pipe assembly fits inside the bottom case & moves telescopically in it. DU bush is provided to guide the fork pipe while reciprocating in bottom case. It reduces metal to metal contact between fork pipe outer diameter & bottom case inner diameter. Oil seal is provided to seal the oil inside the front air fork & not to allow oil to leak. Dust seal used to avoid the interruption of dust & mud inside the front air fork assembly.

Internal floating piston (IFP) is used as fluid separating member. It isolates front fork oil from pressurized nitrogen gas. IFP is designed in such a way that it will reciprocate on inner diameter of Fork pipe. IFP reciprocate along with a pneumatic seal on pressurized gas chamber side & another hydraulic seal on oil chamber side. IFP having a rubber valve which is used to remove air trapped below the IFP, while assembling.

O-ring is provided on the periphery of Fork bolt to avoid nitrogen gas leakage from gas chamber to atmosphere. By using syringe needle, through rubber valve one can fill pressurized nitrogen gas inside the fork pipe gas chamber.

Nitrogen gas as Pneumatic fluid is compressible in nature whereas Oil is a non-compressible fluid. By increasing or decreasing the volume of gas inside the gas chamber we can decrease or increase the pressure of gas inside gas chamber. This pressurized gas can be act as a load carrying pneumatic spring &hence we can achieve required assembly load.

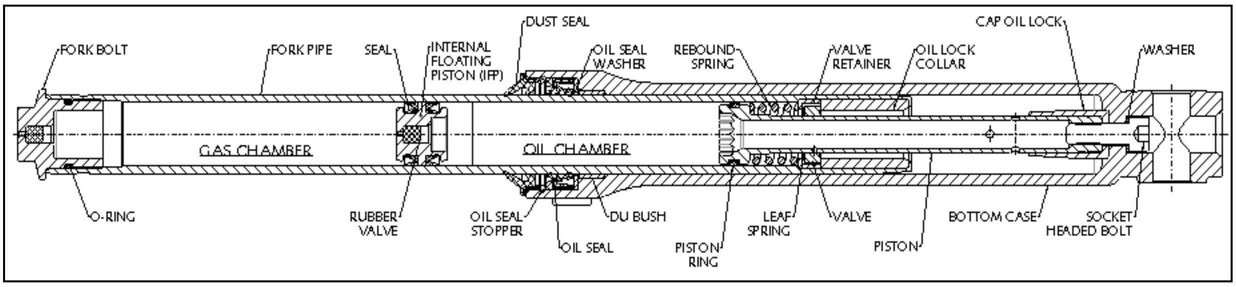


Fig. 1: Nomenclature of Air front fork

III. PROBLEM DEFINITION &METHODOLOGY

The purpose offront air fork is to provide a sensitive, dynamic and high capacity suspension that offers superior ride quality. A nitrogen reservoir with variable volume gives up a spring with non-linear force-deflection characteristics. In this way the resulting system does not possess any frequencies and associated dynamic instabilities, which need to be suppressed through extensive damping in conventional suspension systems.

A non-linear spring rate is one for which the relation between the spring's compression and the force exerted cannot be fitted adequately to a linear model.The spring constant k can be calculated as follows:

$$k = \frac{Gd^4}{8D^3N}$$

As k= spring rate or spring constant, d = wire diameter, G = spring's shear modulus, N = Total number of coils
D = Mean coil diameter of spring
But in non-linear spring, the spring force is depending on change in volume, pressure of gas inside the system, cross-sectional area of gas chamber &gas specific heat ratio.
The formula used to calculate the spring force (F) as a function of displacement (x).

$$F= P1 * \left(\frac{V1}{V1-V2}\right)^{\gamma} * A_{IDF}$$

As,
F =Air spring force (N), P1= Pressure inside the system, V1= Initial volume of gas inside the suspension
V2= Volume of gas after displacement of suspension, V1-V2 = Change in volume of gas
A_{IDF} = Floating piston area or Fork pipe inside area (m2), γ = Specific heat ratio

Mathematics of the spring design
Spring rate is a ratio used to measure how resistant a spring is to be compressed or expanded during the spring's deflection. The magnitude of the spring force increases as deflection increases according to Hooke's Law. Briefly, this can be stated as

$$\boxed{F = -kx}$$

Design of Front Air Fork suspension

I. **Front fork length calculation:** To determine length of components whose assembly should be fitted on the vehicle in the given length

Parameter	Symbol	Value
Free Extended length (L Free)	L_F	449.2 mm
Collapsed length (L Min)	L_M	373.2 mm
Axle hole to Cap oil lock bottom	L_{AC}	25 mm
Axle hole to BTA root	L_{AB}	28 mm
Cap oil lock dead height	H_C	3 mm
Inner tube Caulking Height	H_{IC}	46 mm
Oil lock collar + Valve retainer height	H_{SS}	44 mm
Piston head height	H_P	12 mm
Fork bolt dead height	H_{BD}	23 mm
Diff. in Inner tube plt& Spinning length	H_{ISL}	1 mm
Rebound Spring free length	L_{RF}	23.3 mm
Rebound spring rate	k_R	25.31 N/mm
Rebound spring solid length	L_{RS}	15.4 mm
Limb pre-compression	P_L	8.2 mm
Average air spring rate (Assumed)	k_{AS}	6 N/mm

a) **Spinning allowance, D_{SA}** = Inner tube Caulking Height – (Oil lock collar + Valve retainer height)
$= H_{IC} - H_{SS} = 46 – 44 = 2$ mm

b) **Rebound Spring stroke, L_{SR}**= Rebound Spring free length - Rebound spring solid length
$= L_{RF} - L_{RS} = 23.3 – 15.4 = 7.9$ mm

c) **Equilibrium position, E** =

$$\frac{(\text{Rebound Spring rate} * \text{Rebound Spring stroke}) - (\text{Avg. air spring rate} * \text{Limb precompression})}{\text{Rebound Spring rate} + \text{Avg. air spring rate}}$$

$= [(k_R * L_{SR}) – (k_{AS} * P_L)] / (k_R + k_{AS}) = \frac{(25.31 * 7.9) - (6 * 8.2)}{25.31+6} = 4.8$ mm

d) **Rebound spring assembly height @ L_{Free}, L_{RA}**
= Rebound spring solid length + Equilibrium position
$= L_{RS} + E = 15.4 + 4.8 = 20.2$ mm

e) **Extended length of Front fork limb:** The maximum length of front fork that can be achieved when there is pit / depression on the road. At this position of limb, rebound spring is at solid stage, L_{Max} = Free Extended length + Equilibrium position $= L_F + E = 449.2 + 4.8 = 454$ mm

f) **Stroke of Front fork @ L_{Max}, S_{Max}**= Free Extended length – Collapsed length
$= L_{Max} - L_M = 454 - 373.2 = 80.8$ mm

g) **Stroke of Front fork @ L_{Free}, S_{Free}**$= L_{Free} - L_M = 449.2 - 373.2 = 76$ mm

h) **Fork pipe spinning length, L_{PS}** = L Free – Stroke @ L_{Free} – Axle hole to BTA – Bolt collar height
$= L_F – S_{Free} - L_{AB} = 449.2 – 76 – 28 = 345.2$ mm

i) **Fork pipe plated length, L_{FP}** = Fork pipe spinning length + Diff. in Inner tube plated & Spinning length
$= L_{PS} + H_{ISL} = 345.2 + 1 = 346.2$ mm

j) **Piston length, L_P** = Piston head height + Rebound spring assembly height @ L_{Free} + Inner tube Caulking Height + Stroke of Front fork @ L_{Free} + Axle hole to BTA root - Axle hole to cap oil lock bottom - Cap oil lock dead height - Diff. in Inner tube plated & Spinning length
$= H_P + L_{RA} + H_{IC} + S_{Free} + L_{AB} - L_{AC} - H_C - H_{ISL} = 12 + 20.2 + 46 + 76 + 28 – 25 – 3 – 1 = 153.2$ mm

II. Design of Front air fork parts

1. **Design of Fork pipe:** Fork pipe of Front air fork is structural member as well as it undergoes clamp load of Under bracket & Upper bracket. In working condition, it undergoes tensile & compressive loading due to up-down motion of Front fork.

a) Permissible nominal stress,

$\sigma_P = \frac{UTS}{FOS} = \frac{790}{5} = 158$ N/mm^2

b) When the fork pipe is subjected to axial tensile force, the tensile stress is given by,

$\sigma_t = \frac{P}{\frac{\pi}{4}(OD_I^2 - ID_I^2)} = \frac{981}{0.785*(29.95^2 - 24^2)} = 3.857$ N/mm^2

c) When the fork pipe is subject to bending moment the bending stress is given by

$\sigma_b = \frac{M_b y}{I} = \frac{198358.2*14.975}{23210.36} = 127.98$ N/mm^2

i. $M_b = P * X = 981 * 202.2 = 198358.20$ N.mm

ii. $I = \frac{\pi}{64}(OD_1^4 - ID_1^4) = \frac{\pi}{64}(29.95^4 - 24^4) = 23210.36$ mm^4

d) Total normal stress on Fork pipe is

$\sigma_1 = \sigma_t + \sigma_b = 3.857 + 127.98 = 131.87$ N/mm^2

The design will be safe if the σ_1 is less than permissible nominal stress σ_P

So $\sigma_1 \le \sigma_P = 131.87 \le 158$ N/mm^2

Hence the Outer diameter 29.95 mm & Inner diameter 24 mm are safe for fork pipe manufacturing.

2. **Design of Outer tube**

Outer tube is another structural member which must sustain maximum bending load on it. In working condition, it undergoes compressive & bending loading condition. Outer tubes add aesthetic gracefulness in bike suspension.

a) Permissible tensile stress,

$\sigma_P = \frac{UTS}{FOS} = \frac{240}{5} = 48$ N/mm^2

b) When the outer tube is subjected to axial tensile force, the tensile stress is given by,

$\sigma_t = \frac{P}{\frac{\pi}{4}(OD_O^2 - ID_O^2)} = \frac{981}{0.785*(38.5^2 - 30.06^2)} = 2.16$ N/mm^2

c) When the outer tube is subject to bending moment the bending stress is given by

$\sigma_b = \frac{M_b y}{I} = \frac{102024*19.25}{67768.35} = 28.98$ N/mm^2

i. $M_b = P * X$ = 981 * 104 = 102024 N.mm

ii. I $= \frac{\pi}{64}(OD_O^4 - ID_O^4) = \frac{\pi}{64}(38.5^4 - 30.06^4) = 67768.35\ mm^4$

d) Total normal stress on outer tube is

$\sigma_1 = \sigma_t + \sigma_b$ = 2.16 + 28.98 = 31.14 N/mm^2

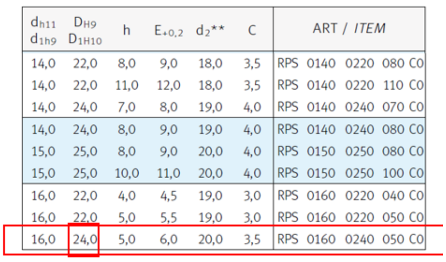
The design will be safe if the σ_1 is less than permissible tensile stress σ_P

So $\sigma_1 \le \sigma_P$ = $31.14 \le 48\ N/mm^2$

Hence the Outer diameter 38.5 mm & Inner diameter 30 mm are safe for Outer tube

3. Internal floating piston design & Pneumatic seal selection

As the designed inter diameter of Fork pipe is Ø24 mm, we have selected Pneumatic seal from the catalog of Atric seals. Refer below image



d_{h11} / d_{1h9}	D_{H9} / D_{1H10}	h	$E_{+0,2}$	d_2**	C	ART / *ITEM*
14,0	22,0	8,0	9,0	18,0	3,5	RPS 0140 0220 080 CO
14,0	22,0	11,0	12,0	18,0	3,5	RPS 0140 0220 110 CO
14,0	24,0	7,0	8,0	19,0	4,0	RPS 0140 0240 070 CO
14,0	24,0	8,0	9,0	19,0	4,0	RPS 0140 0240 080 CO
15,0	25,0	8,0	9,0	20,0	4,0	RPS 0150 0250 080 CO
15,0	25,0	10,0	11,0	20,0	4,0	RPS 0150 0250 100 CO
16,0	22,0	4,0	4,5	19,0	3,0	RPS 0160 0220 040 CO
16,0	22,0	5,0	5,5	19,0	3,0	RPS 0160 0220 050 CO
16,0	24,0	5,0	6,0	20,0	3,5	RPS 0160 0240 050 CO

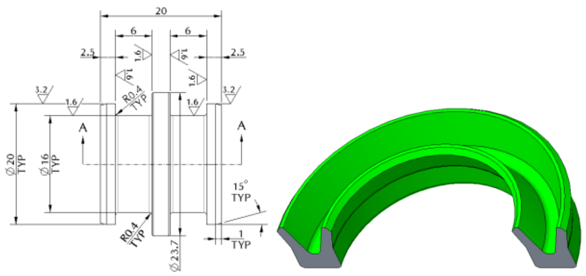


Fig. 2: Dimensions of IFP on basis of selection of pneumatic seal

III. Assembly load & oil volume calculation

This calculation is for single limb of Front air fork suspension

Parameter	Symbol	Value
Inner tube		
Outer Dia.	OD_I	29.95 mm
Inner Dia.	ID_I	24 mm
Total Length	L_I	346.2 mm
Caulking Dia.	ID_C	26 mm
Caulking Length	L_C	46 mm
Inner tube overlap dist.	L_{IO}	145.6 mm
Outer tube		
Inner Dia.	ID_O	30.06 mm
Inner dia. length	L_O	198.5 mm
Guide bush fitment dia.	ID_G	33 mm
Guide bush step length	L_G	10.5 mm
Oil seal fitment ID	ID_S	42 mm
Oil seal fitment length	L_S	12.6 mm
Total Volume of child parts	V_{CT}	53.33 cc
Piston		
Outer dia.	OD_P	14 mm
Inner dia.	ID_P	10.5 mm
Stroke	S_{FF}	76 mm

a) Air Volume inside Inner tube up to Oil seal top, V_{IA}

$= \frac{\pi}{4} * ID_I^2 * (L_I - L_{IO})$ = [0.785* 24^2 * (346.2-145.6)] / 1000 = 90.75 cc

b) Volume of Inner tube at caulking length, V_C

$= \frac{\pi}{4} * (OD_I^2 - ID_C^2) * L_C$ = [0.785*(29.95^2- 26^2) * 46] / 1000 = 7.98 cc

c) Total Volume of Inner tube inside outer tube, V_I

$= \frac{\pi}{4} * (OD_I^2 - ID_I^2) * (L_{IO} - L_C) + V_C$ = [0.785 *(29.95^2-24^2)* (145.6-46)]/1000 + 7.98 = 33.10 cc

d) Air volume at BTA length, V_{O1} $= \frac{\pi}{4} * ID_O^2 * L_O$ = [0.785 * 30.06^2 * 198.5] / 1000 = 140.87 cc

e) Air volume at Guide (DU) Bush length, V_{O2} $= \frac{\pi}{4} * ID_G^2 * L_G$ = [0.785*33^2*10.5]/1000 = 8.98 cc

f) Air volume at Oil seal length, V_{O3} $= \frac{\pi}{4} * ID_S^2 * L_S$ = [0.785*42^2*12.6]/1000 = 17.46 cc

g) Total volume of Air Inside Outer tube, V_{OA} $= V_{O1} + V_{O2} + V_{O3}$ = 140.87 + 8.98 + 17.46

= 167.31 cc

h) Total Air volume in Inner tube & Outer tube (Air Volume in limb without child parts),

V_{AW} $=V_{OA}+V_{IA}-V_I$ = 167.31 + 90.75 – 33.10 = 224.96 cc

i) Total Air volume inside limb (Air volume in limb with all child parts),

V_A $=V_{AW}-V_{CT}$ = 224.96 – 53.33 = 171.64 cc

j) Oil volume, V_O = 111 cc

[In this analytical calculation, Oil volume is assumed initially. After doing trials & errors we get exact Oil volume at which we get required assembly load (Air force or axial load or Assembly load)]

k) Remaining volume of air inside limb, V_1 = 171.64 – 111 = 60.64 cc

l) As front fork displacement changes, air force also get changes. Displacement is directly proportional to Air force (Assembly load)

Let assume, Front fork displaced by **10 mm** means it consumed its 10mm stroke, D_S

So Displacement volume of Front fork @ 10 mm,

V_2 $= \{[\frac{\pi}{4} * OD_I{}^2 * D_S] - [\frac{\pi}{4} * (OD_P{}^2 - ID_P{}^2) * D_S]\}$

$= \{[0.785*29.95^2*10]-[0.785*(14^2-10.5^2)*10]\} / 1000$ = 6.37 cc

Air properties:

1. Pressure of compressed air filled in limb assy. to achieve required pre-compression, P1 = 2.5 bar (This value can be decided on the basis of required pre-compression of Front fork. It can be achieved by trials & errors method)

2. Isentropic Index (Ratio of Specific heats), □ = 1.4

m) Pressure inside front fork at 10 mm displacement, P_2 $= P_1 * (\frac{V1}{V1-V2})^{\gamma} = 2.5 * (\frac{60.64}{60.64-6.37})^{1.4} = 2.92$bar

n) Air force at 10 mm displacement, F_{10}= Pressure * Area = $(P_2 * \frac{\pi}{4} ID_I{}^2) / 10$

$= (2.92 * 0.785 * 24^2) / 10 = 132.1$ N

Similarly, we can get the Air force @ Front fork stroke (S_{FF}), F_{Stroke}

o) So, Displacement volume of Front fork @ free stroke, V_{2S}

$= \{[0.785*29.95^2*76]-[0.785*(14^2-10.5^2)*76]\} / 1000 = 48.42$ cc

p) Pressure inside front fork at free stroke, P_2 $= 2.5 * (\frac{60.64}{60.64-48.42})^{1.4} = 23.57$ bar

Air force at free stroke displacement, F_{Stroke} $= (23.57 * 0.785 * 24^2) / 10 = 1066.1$ N

A. Static structural analysis:

A static analysis result of structural displacements, stresses and strains and forces instructures for components caused by loads will give a clear idea about whether the structureor components will withstand for the applied maximum forces. If the stress values obtained inthis analysis crosses the allowable values, it will result in the failure of the structure in thestatic condition itself. To avoid such a failure, this analysis is necessary.

a. Structural analysis of outer tube:

1. Selection of Meshing and element size: Add meshing to Leg assembly with mesh element size 8 mm with no. of nodes 291516 and elements 180491.

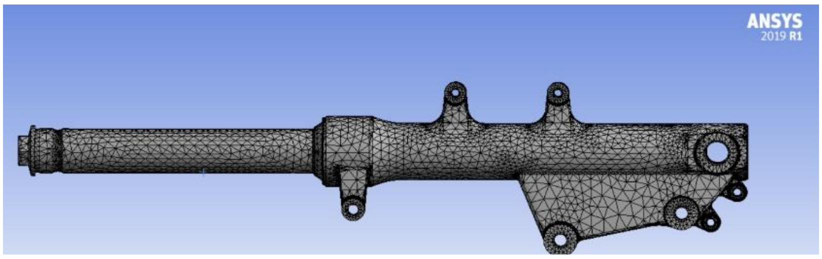


Fig.3: Meshing of Leg Assembly

2. Assign the Fix support & Force on the meshed Leg assembly as per the actual loading conditions

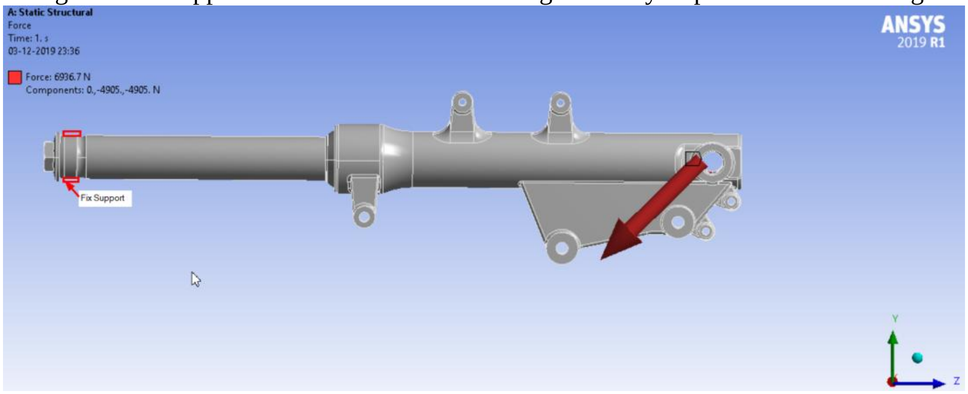


Fig.4: Fix support & Loading conditions of Outer tube

3. Total deflection, Equivalent Von mises Strain & Equivalent Von mises stress observed on the modelled Leg assembly & its component through the analysis by solving equations of boundary conditions assigned to this FEA problem.

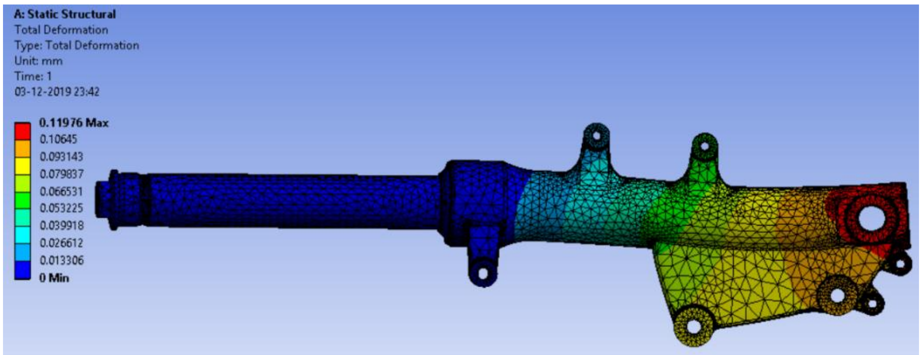


Fig.5: Total deflection

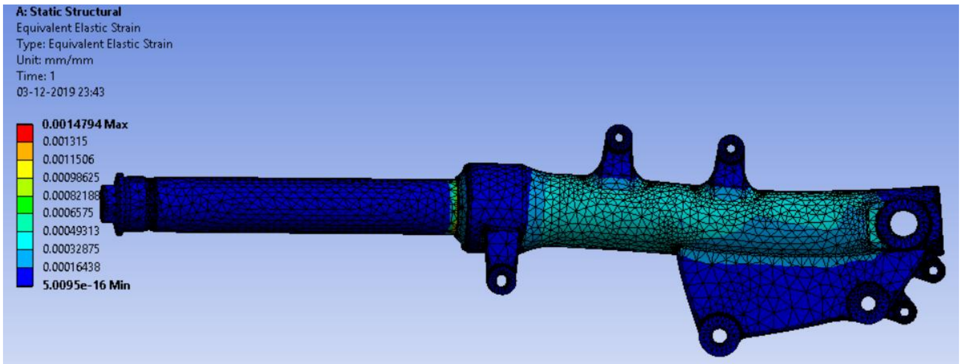


Fig.6: Equivalent Von mises strain

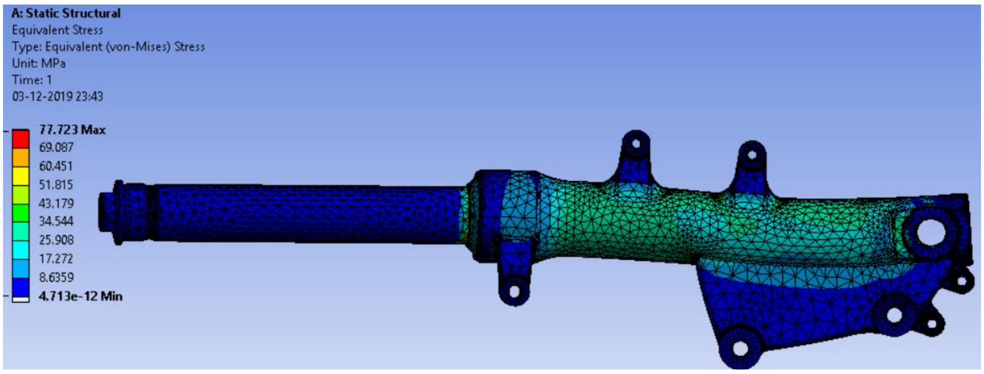


Fig.7: Equivalent Von mises stress

From above FEA analysis we get to know that the design of Fork outer tube is passing the design margin as appeared stresses are less than YTS of Outer tube.

$$77.723 < 240 \text{ MPa}$$

The difference in analytical calculations & FEA results is because we can consider only simple geometries in hand calculations whereas FEA involves model with all features (ribs, fillets, bosses, etc)

b. Fork pipe tube structural analysis:

1. Selection of Meshing and element size:Add meshing to Leg assembly with mesh element size 8 mm with no. of nodes 56403 and elements 32224.

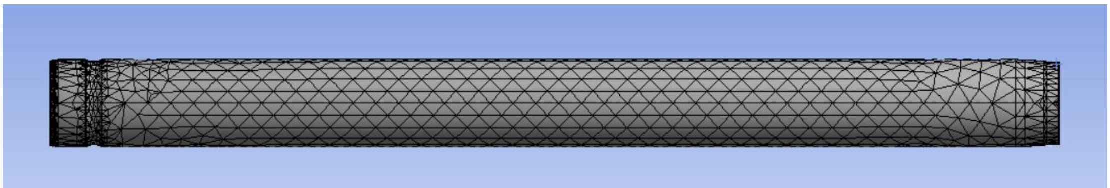


Fig.8: Meshing of Fork pipe & main Piston rod Assembly

2. Assign the Fix support & Force on the meshed Leg assembly as per the actual loading conditions

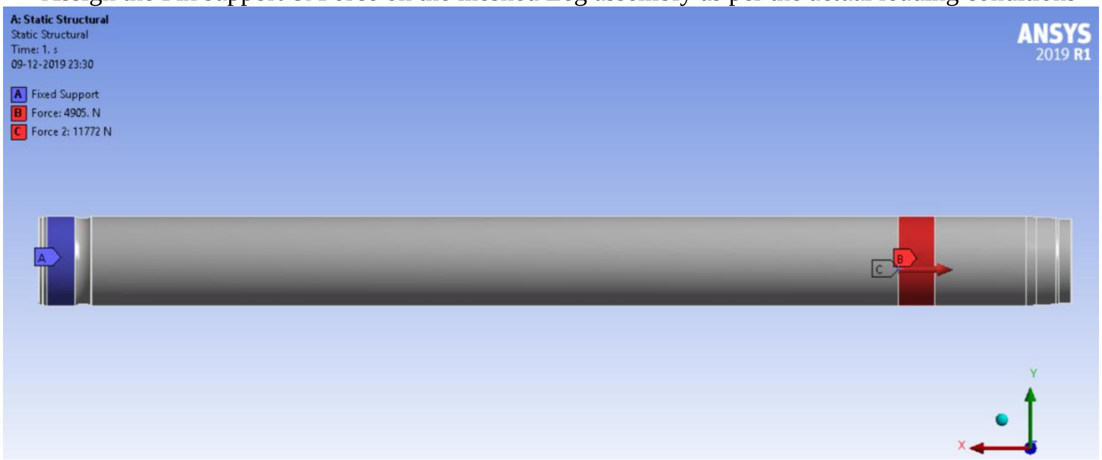


Fig. 9: Fix support & Loading conditions for Fork pipe analysis

3. Total deflection, Equivalent Von mises Strain & Equivalent Von mises stress observed on the modelled Leg assembly & its component through the analysis by solving equations of boundary conditions assigned to this FEA problem.

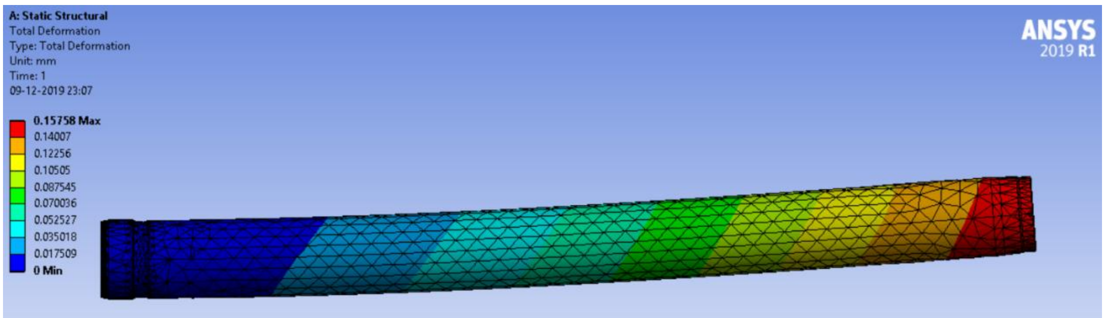


Fig. 10: Total deflection (Fork pipe)

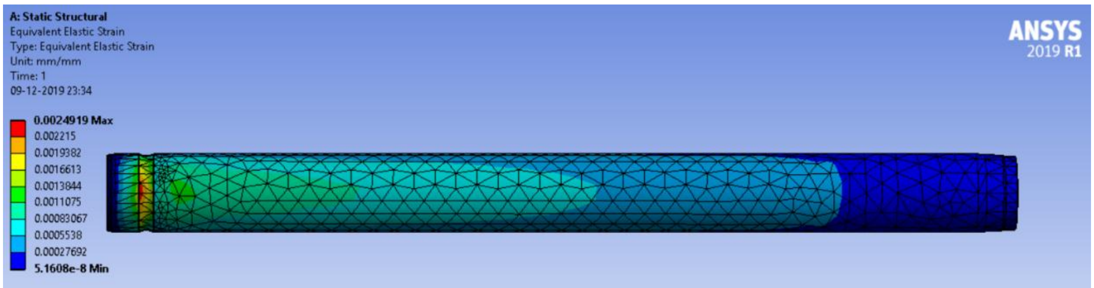


Fig. 11: Equivalent Von mises strain (Fork pipe)

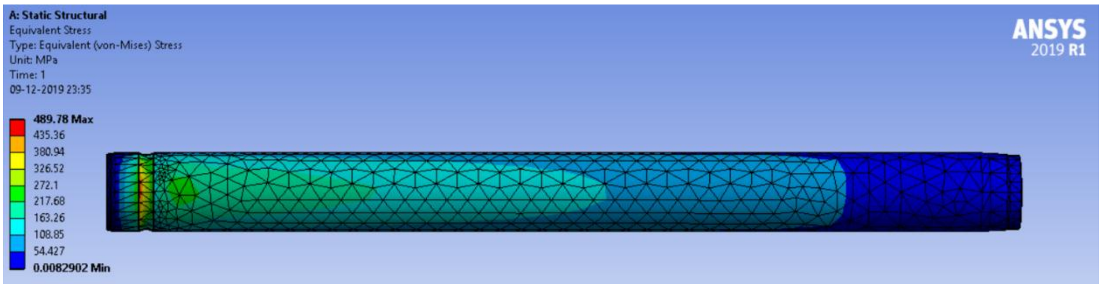


Fig. 12: Equivalent Von mises stress (Fork pipe)

From this FEA analysis we get to know that the design of Fork pipe is passing the design margin with 493.65 MPa stresses with 1200 kgf axial & 500 kgf bending loading.
489.78 < 648 MPa
Axial load 1200 kgf has taken as this value is given by customer for checking spinning strength of Fork pipe & also to check strength of impact loading of piston & rebound spring on fork pipe.
Both the structural members (Outer tube & Fork pipe) of Front air fork suspension are having good design margin. So, the design of Front air fork is safe.

B. Results of actual Performance test

Summary results of Axial load(s) measured on Limb assemblies of Front air fork.

Disp. (mm)	Limb assy 1 RH	Limb assy 1 LH	Limb assy 2 RH	Limb assy 2 LH
0	90.068	112.574	113.1	113.1
2.3	110.702	116.885	116.99	117.02
10.0	124.455	132.005	131.9	132.2
20.0	147.28	157.153	157.02	157.45
30.0	193.74	191.743	192	192.59
40.0	242.27	242.42	242.16	243.05
50.0	320.644	320.298	319.79	321.23
60.0	443.634	453.665	454.87	455.43
70.0	728.159	726.113	724.26	730
74	928.191	923.779	921.23	929.6
75	1853.292	987.989	991.69	994.31

Note: Forces are in N

IV. CONCLUSIONS & FUTURE SCOPE

I. Conclusions:

- The designed Front air fork is passing the acceptance criteria in analytical calculations, experimental trials& FE analysis.
- The suspension with pressurized nitrogen gas can sustain more than 3g condition load of vehicle.
- Air front suspension can provide around same results when compared to conventional front suspension, but it is observed that the overall weight of suspension reduced by around 200 gm (Weight of main spring) as main spring eliminated & IFP used in it is of Aluminum material which is light in weight.
- Overall manufacturing cost of suspension reduced as the main spring eliminated
- This suspension provides smoother ride & enhance riding performance by reducing frictional losses & noise of suspension.

II. Future scope:

Now a day due to increased trend of bikes, riders are interested in adjusting the preload of suspension. To provide this facility bike manufacture/ rider can use below options

- Can insert more pressurized nitrogen gas in suspension through rubber plug of fork bolt/bolt cap on the top of Fork pipe & also can reduce preload by inserting syringe in it.
- Can provide a spring-loaded piston arrangement below fork bolt/ bolt cap whose knob should appear outside the fork bolt. This arrangement helps to increase dead volume of air front fork which increases the pressure of nitrogen gas inside the fork pipe. This will help to increase preload

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