Design and Analysis of an In-Wheel Suspension System for Tractor

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Abstract
The aim of this work is to study and analyze the suspension system which is placed inside a vehicle's wheel. The In-wheel suspension system isolates the spring mass from excitations similar to conventional suspension systems. In traditional suspension systems, the isolation is provided by spacious and complicated mechanisms, and mainly in the vertical direction. However, the In-wheel suspension system, not only fits the suspension mechanism inside the unused space between a wheel’s rim and hub, but also allows for isolation both in vertical and horizontal directions.

The model evaluates the response of the suspension system and investigates the influence of various design parameters on the in-wheel suspension to analyze its applicability. This reduces the system's complexity and weight while boosting its performance. The 3D model is designed in UNIGRAPHICS NX9 and structural analysis is done in ANSYS 15. The stress, strain and deformation development in the system are analyzed to justify the applicability of In-Wheel suspension system practically.

Keywords: In-wheel, suspension, spring.

1. Introduction
In-Wheel Suspension System:
The IWS concept not only improves the horizontal isolation but also eliminates the spacious suspension mechanisms by embedding the suspension system inside the vehicle's wheel. The development of IWS is based on the idea of fitting the spring and damping elements inside a vehicle’s wheel. Depending on whether the suspension rotates with the wheel or not, the IWS can be classified to: Rotating and Non-Rotating IWS. From another point of view, if the IWS is placed inside a driving wheel, the IWS can be classified to Powered or Non-Powered IWS. A Powered IWS requires an infinite torsional stiffness to transfer tracking or breaking forces to the wheel.

It should also allow the maximum possible wheel travel. For the rotating IWS in addition to the conventional suspension properties, the stiffness fluctuation should be considered as well. The rotation of the suspension system which is embedded inside the vehicle's wheel, changes the orientation of the suspension elements at each rotation angle of the wheel. Consequently, the change in the suspension component's orientation can lead to undesired stiffness fluctuations. These fluctuations are sensed by the sprung mass as periodic vertical or horizontal vibrations when moving on a flat surface. The major challenge in the IWS design is the space limitation. Although road excitation may be in the vertical direction, longitudinal direction, or the lateral direction, current suspension systems mainly isolate vertical forces and disturbances. In many situations, isolation in more than one direction can improve safety and comfort significantly. For instance, the addition of a suspension system that is capable of reacting to longitudinal forces in wheelchairs, bicycles and motorcycles, can reduce the incidents resulting from tipping over upon hitting obstacles. Furthermore, conventional suspension systems usually occupy a significant amount of space. Such space could be used for passenger comfort or the reduction of the overall size and weight of the vehicle. IWS concept is a strong alternative to conventional suspension systems in other applications.

Michelin active wheel (Michelin re-invents the wheel, 2008) and Siemens eCorner (Continental Automotive Systems Inc.) are shown in Figure 2.3 and Figure 2.4. The Michelin active wheel integrates an electrical motor, the power-train, the suspension system, and the braking system inside the wheel. Likewise, Siemens VDO's eCorner concept embeds an automobile's drive-train, shock absorbers, brakes, and steering, into its four wheels. The eCorner removes the need for the traditional engine architecture. Siemens declares "The transition from an internal combustion engine to one Corner wheel hub motor will result in decreased emissions, increased energy efficiency and lower costs for consumers due to the elimination of hydraulic systems to maintain and service." (Continental Automotive Systems Inc.). Although the Michelin and Siemens wheels embed different automobile subsystems, including the suspension system, inside its wheels, but the suspension system is still limited to isolation in the vertical direction.
2. Problem Definition

2.1 Why to provide suspension system to tractors because:

- We can alter the suspension system whenever we require suspension we can activate it remaining times we use it without suspension.
- On road conditions due to high speeds and unevenness in roads shock loads can be absorbed then we can run the tractor in more speeds.
- On form work we restrict the suspension system and make it to work previously
- By using this system we can use tractors for high speed conditions and transportations of goods for long distances in place of lorries, buses and trucks etc.

2.2 Tractors do have suspension/ shock absorption system.

- Tractors are mostly used to pull loads or equipped in farming conditions, if there is a suspension installed, then the ride height will be changing. So it may affect the mass being pulled.
- Consider the tractor is ploughing , there will be load trying to make the tractor stop as its inserted in the ground. This may cause the body of the tractor to tilt backwards (assumed the plough is attached to rear axle).
- This reaction may cause the spring to bend .Also the steering heavily will affect the steering characteristics.

2.3 Function of An In-Wheel Suspension System

- We can alter the suspension system whenever we require suspension we can activate it remaining times we use it without suspension.
- On road conditions due to high speeds and unevenness in roads shock loads can be absorbed then we can run the tractor in more speeds.
- On form work we restrict the suspension system and make it to work previously
- By using this system we can use tractors for high speed conditions and transportations of goods for long distances in place of lorries, buses and trucks etc.

3. Design of An In-Wheel Suspension System

3.1 Design Consideration

By considering the kinematics of assembly:

- The spokes of an assembly has diameter of 50mm. We are replacing spokes with spring suspension system with 50 mm diameter and for requirement we can make some changes to get the required motion. It needs a two roller pair on each spoke.
- The replaced spoke and the parts are as shown in figure. The thickness of plate is to carry the spring load. So its thickness is half of its diameter of the shaft.
- Here we aren’t considering the design of rim and rim dimensions taken by standard rim dimensions of tractor.
- The materials for all components can be taken from the already existing wheel components of tractor.
- In this project we are considering only static and structural analysis, further to develop this concept different analysis to be needed.

Model description:

- The system consists of a planar mechanism with eight moving bodies:
  - Rim: which is pinned to the ground and has only one rotational degree of freedom?
  - Hub: which is connected to the rim via six links and has all of the three planar degrees of freedom with respect to the rim?
  - Six arms: Those are used to connect the rim and the hub together.

3.2 Design of Rim and Hub

Let, ‘t’ be the thickness of the rim in mm and ‘B’ be the width of rim in mm, then the ratio of thickness to width from the design and data book is given as

\[(\frac{t}{B}) = 0.5 - 1.25\]

Let, ‘d_h’ be the diameter of the hub in mm and ‘d_s,’ be the diameter of the shaft in mm and ‘L’ be the length of the hub in mm.

- Diameter of the hub, \(d_h = 2.5d_s\)
- Length of the hub, \(L = 2d_h - 2.5d_s\)
- Inside thickness \(= \frac{d_s}{2}\)

Let ‘N’ be the speed of the engine in ‘rpm’ and ‘T’ be the engine torque in ‘N-m’ and ‘D’ be the diameter of the rim in ‘m’, the
Power, \( P = \frac{2\pi NT}{60} \)

Velocity at maximum speed, \( V = \frac{\pi DN}{60} \)

Angular velocity, \( \omega = \frac{2\pi N}{60} \)

The average energy delivered by the engine shaft per revolution
\[
E_a = \frac{1000 \times P_{\text{max}}}{N}
\]

But, \( E_a = I \times \frac{c}{2} \times C_i \)

Here, \( I \) = mass moment of inertia in kg-mm²

\[ I = mR^2 \]

Where \( m \) =volume × density

3.3 Design of spoke:
If each spoke take tangential force, \( P \) in N

Then,

Torque=\( P \times R \)

Where, \( R \) = radius of the rim in mm

Bending moment, \( M_b = F \left( \frac{Rh}{2} \right) \)

Where,

\( F = P \) = tangential force on a spoke in newtons

\( D_h \) = diameter of the hub in mm

Moment of inertia of a circular cross section,

\[ I = \frac{\pi \times d^4}{64} \text{ in mm}^4 \]

Where, \( d \) = diameter of the spoke in mm

Bending stress, \( \sigma_b = \frac{M_b}{I} \)

Where, \( Z \) = polar moment of inertia in mm

3.4 Design of spring:

Let,

\[ G = \text{rigidity modulus in N/mm}^2 \]

\[ \sigma_t = \text{tensile stress in N/mm}^2 \]

Shear stress, \( \tau = \frac{\sigma_t}{2} \text{ in N/mm}^2 \)

Let,

\[ K = \text{Walh's factor or stress concentration factor} \]

\[ K = \frac{4C-1}{4C-4} + \frac{0.615}{C} \]

\[ \tau = \text{maximum shear stress induced in the wire} \]

\[ \tau = K \left( \frac{BP}{\pi d^2} \right) \]

Diameter of the coil in mm, \( D = C \times d \)

\( C \) = spring index

\[ \delta = \text{be the deflection in mm} \]

then, \( \delta = \frac{BPd^4}{Gd^4} \)

\( n \) = Number of active coils

\[ \text{Solid length} = n \times d \text{ in mm} \]

\[ \text{Free length} = (\text{solid length + total gap} + \delta) \]

\[ \text{Pitch, } P = \frac{\text{free length}}{n-1} \]

4. Materials Used and Design Calculations:
The material considered for making of suspension system is grey Cast Iron due to following reasons.

- The ability to produce sound castings economically in complex shapes such as water cooled engine blocks.
- Good machinability even at wear resisting hardness levels and without burring.
- High vibration damping as a power transmission cases.
- Dimensional stability under differential heating such as in brake drums and discs.

4.1 Design Calculations for In-Wheel Suspension System

Massey Ferguson MF240-50HP

- Type = Diesel Engine
- No. of cylinders = 03
- Bore = 91.4 mm
- Shaft diameter = 35 mm
- Stroke = 127 mm
- Compression Ratio = 16.5:1
- Maximum engine power at 250 rpm = 50HP
- Maximum torque at 1400 rpm = 172 N-m

Dimension of tyre:
- Front tyre = 6.00-16 W
- Rear tyre = 13.6-28.2 W
- Weight = 4015-4485 pounds
- 2WD wheel base = 76.1 inch (193 cm)
- 4WD wheel base = 77 inch (195 cm)

4.2 Design of Rim

Material: Grey Cast Iron

Young’s modulus (E) \( \text{(MN/m}^2) \) = 100 ×10⁻³

Modulus of Rigidity (G) \( \text{(MN/m}^2) \) = 41.4×10⁻³

Poisson’s Ratio \( (\mu) \) = 0.211

Density \( (\rho) \) \( \text{ (Kg/m}^3) \) = 7200

From design data book

\[ \left( \frac{C}{B} \right) = 0.5 - 1.25 \]

Where, \( t \) = thickness

- Hub diameter \( (d_h) = 2d_s \)
- \( d_s \) = diameter of the shaft

\( B \) = width

- Length of the Hub \( (L) = 2d_s - 2.5d_s \)

Calculations

Maximum Power \( = 50 \text{ H.P at 250 rpm} \)

Torque, \( T \) = 172 N-m at 1450 rpm

\[ P = \frac{2\pi NT}{60} = \frac{2\pi \times 1450 \times 172}{60} = 26.5 \text{ KW} \]

At \( T = 172 \text{ N-m, } P_{\text{max}} = 36 \text{ KW} \)

- Shaft diameter, \( d_s = 80 \text{ mm} \)
- Hub diameter, \( D = 200 \text{ mm} \)
- Length of hub, \( L = 180 \text{ mm} \)
- Inside thickness = \( \frac{d_s}{2} = 40 \text{ mm} \)

- Velocity at maximum speed, \( V = \frac{\pi DN}{60} = \frac{\pi \times 1.5 \times 1450}{60} = 20 \text{ m/sec}^2 \)
For Grey Cast Iron

- **Weight** = 69800 N/m³
- **Maximum Energy**, \( E_a = \frac{1000 \times P_{max}}{N} = \frac{1000 \times 36}{250} = 8640 \text{ N-m} \)
- **Angular velocity**, \( \omega = \frac{2\pi N}{60} = \frac{2\times \pi \times 1450}{60} = 28 \text{ rad/sec} \)

But,
- \( E_a = I \times \omega^2 \times C_s \)

\( 8640 = I \times 28^2 \times 0.2 \)

\( I = 55.10 \text{ kg-m}^2 \)

But,
- **Mass** (m) = volume \( \times \) density

\( 98 = (2 \times \pi \times R) \times (b \times t) \times 7200 \)

And \( b = 1.2t \)

\( 98 = 2 \times \pi \times \frac{0.75 \times 1.2t \times t}{106} \times 7200 \)

\( t^2 = 2.407 \times 10^3 \)

\( t = 49 \approx 50 \text{ mm} \)

\( b = 1.2t = 1.2 \times 50 = 60 \text{ mm} \)

### 4.3 Design of Spokes

Let,

The tangential force taken by each spoke = F

- **Torque**, \( T = F \times R \)

From

\[ P = \frac{2nNT}{60} \]

\( 36 \text{ KW} = \frac{2 \times \pi \times 250 \times T}{60} \)

\( T = 1375 \text{ N-m} \)

\( F = \frac{T}{R} = \frac{1375}{0.75} = 1834 \text{ N} \)

Let us take F value as 2000 N

Now,

- **Bending moment**, \( M_b = F \left( R - \frac{D}{2} \right) \)

\[ = 2000 \times (0.75 - \frac{0.2}{2}) = 1300 \text{ N-m} \]

Material: Grey Cast Iron

Ultimate tensile strength \( \sigma_{ut} \) \( (MN/m^2) \): 200MPa

For C.I,

- \( \sigma_b = \frac{\sigma_{ut}}{2} = \frac{200}{2} = 100 \text{ N/mm}^2 \)
- **Moment of Inertia**, \( I = \frac{\pi \times d^4}{64} \)

From

\[ \sigma_b = \frac{M_B}{I} \]

\( 100 = \frac{1300 \times 10^3}{\frac{3d^4}{32}} \)

\( d^3 = 132416.91 \)

\( d = 50.96 \text{ mm} \)

i.e. dia. of the spoke = 51 mm

### 4.4 Design of spring

Total load = 10000 kgs on 2 sides

Load on one side = 5000 kgs

\( P_{max} = 50000 \text{ N on each spring} \)

\( P = 40000 \text{ N} \)

Material

Oil hardened tempered steel or carbon steel

\( G = 81370 \approx 82000 \text{ N/mm}^2 \)

Max deflection, \( \delta = 70 \text{ mm} \)

Gap between the springs = 5 mm

- For higher loads spring index, \( C = \frac{D}{d} = 4 \)

### 4.5 Calculation of wire diameter

\( G = 82000 \text{ N/mm}^2 \)

\( \sigma_i = 1000 \text{ N/mm}^2 \)

\( \tau = \frac{\sigma_i}{2} = 500 \text{ N/mm}^2 \)

\( K = \text{Walh's factor} \)

\[ K = \frac{4c^4 - 1}{4c^4 - 4} + \frac{0.615}{c} \]

\( K = 1.2525 \)

\( \tau = \text{maximum shear stress induced in the wire} \)

\[ \tau = K \left( \frac{BP}{GD^2} \right) \]

\( 500 = \frac{1.2525 \times b \times 50 \times d}{G D^2} \)

\( d^2 = 1275.78 \)

\( d = 35.93 \text{ mm} \)

Diameter of the coil, \( D = C \times d \)

\( = 4 \times 36 \)

\( D = 144 \approx 145 \text{ mm} \)

From,

\[ \delta = \frac{8BPd^3n}{6Gd^4} \]

\( 70 = \frac{8 \times 50 \times 145^3 \times n}{82 \times 10^3 \times 36^4} \)

Number of active coils, \( n = 8 \)

For square and grounded end,
Total number of turns, \( n' = n + 2 \)
\[ n' = 8 + 2 = 10 \]

Solid length = \( n \times d \)
\[ = 10 \times 36 = 360 \text{ mm} \]

Free length = (solid length + total length + \( \square \))
\[ = 360 + 70 + 45 = 475 \text{ mm} \]

Pitch, \( p = \frac{475}{n'-1} \)
\[ = \frac{475}{10-1} \]
\[ p = 52 \text{ mm} \]

5. Modeling of In-Wheel Suspension System by NX 9
NX, formerly known as NX Unigraphics or usually just U-G, is an advanced high-end CAD/CAM/CAE software package originally developed by Unigraphics, but since 2007 by Siemens PLM Software. NX is abbreviated as Next Generation.

Modeling of components
The modeling of components can be done by using the calculated dimensions of each component.

Hub: Hub, which is connected to the rim via six links and has all of the three planar degrees of freedom with respect to the rim.

Spoke: Six arms that are used to connect the rim and the hub together.

Rim: which is pinned to the ground and has only one rotational degree of freedom.

Assembly model:

6. Finite Element Analysis of In-Wheel Suspension System
FEA has become a solution to the task of predicting failure due to unknown stresses by showing problem areas in a material and allowing designers to see all of the theoretical stresses within. This method of product design and testing is far superior to the manufacturing costs which would accrue if each sample was actually built and tested. In practice, a finite element analysis usually consists of three principal steps.

6.1 Generic Steps to Solving any Problem in ANSYS:
Like solving any problem analytically, you need to define
(1) Your solution domain,
(2) The physical model,
(3) Boundary conditions and
(4) The physical properties.
You then solve the problem and present the results. In numerical methods, the main difference is an extra step called mesh generation. This is the step that divides the complex model into small elements that become solvable in an otherwise too complex situation. Below describes the processes in terminology slightly more attune to the software

Build Geometry
Construct a two or three dimensional representation of the object to be modeled and tested using the work plane coordinates system within ANSYS.

Define Material Properties
Now that the part exists, define a library of the necessary materials that compose the object (or
project) being modeled. This includes thermal and mechanical properties.

Generate Mesh
At this point ANSYS understands the makeup of the part. Now define how the Modeled system should be broken down into finite pieces.

Apply Loads
Once the system is fully designed, the last task is to burden the system with constraints, such as physical loadings or boundary conditions.

Obtain Solution
This is actually a step, because ANSYS needs to understand within what state (steady state, transient... etc.) the problem must be solved.

Present the Results
After the solution has been obtained, there are many ways to present ANSYS’ results, choose from many options such as tables, graphs, and contour plots.

Materials and their Properties
Type of material: Grey cast iron
Young's Modulus (MPa): 1.1e+005
Poisson's Ratio: 0.28
Bulk Modulus (MPa): 83333
Shear Modulus (MPa): 42969
Ultimate tensile strength (Mpa): 240

6.2 Static Structural Analysis of Assembly:
Procedure:
1. Click on the ANSYS workbench 15 icon on desktop.
2. Select static structural in Analysis system tool box, a dialog box is opened Select Engineering Data, specify the new materials and enter their properties as mentioned in above tables by clicking on engineering data sources tool click on project icon.
3. Right click on Geometry option from a dialog box Select Import Geometry Browse the master rod geometry Right click on Model option in dialog box and select Edit.
4. Click on different parts of body and add materials to different parts.
5. Right click on Mesh Select method, Select Geometry as whole body and then Select method as Tetrahedrons and click on OK.
6. Specify boundary conditions by right click on ‘Static Structural’ and then insert fixed support at base road and rim outer surface apply 50,000 N force at Hub of the assembly and click on OK.
7. Right click on Solution Click on Insert Click on Equivalent stress and deformation etc, right click on Solution and click on solve.

6. Results and Discussion
The deformation distribution in the In-Wheel suspension system is shown in fig 3. The result shows that the deformation is higher at the center (Hub) and decreasing towards the rim. The maximum deformation developed is found to be 0.02015mm, which developed close to the hub. Comparing to the normal suspension system the deformation in the In-Wheel suspension system has been distributed to all suspension springs which reduce the maximum deformation development. In this system the hub is flexible which can readjust its position according to the load action on the wheel rim and there by the effect on all springs can happen instead of one or two springs taking the entire action. In conventional suspension system the suspension springs are capable of taking higher loads only in the direction of axis of the spring. But in this In-Wheel suspension system, it can withstand the load in different directions. Based on the line of action of load, the spring which is close to the direction of line of action of load takes the higher deformation changes.

Fig 3. Total Deformation distribution.
The principal tensile stress distribution and principal shear stress distribution in the In-Wheel suspension system are shown in figs 4 and 5. It is observed that the spokes are under action of higher stress development compared to the springs. This is due to that the springs are flexible compare to the spokes. The maximum tensile stress developed is observed to be 7.996MPa, which is far less than the allowable yield point (tensile stress) of the grey cast iron (98MPa). The principal shear stress developed is found to be 4.226MPa, which is far less than the allowable shear stress of grey cast iron (180MPa). This represents that the system is safe. Also it is observed that all the spokes are not under action of...
same level of stress development. It shows that though the stress developed is distributed, the distribution is not uniform, because, it depends on the line of action of direction of load. Particularly it is observed those are opposite to point of action of load on wheel rim are under higher stress development. Among the six spokes half the spokes are bearing the majority of load, which can be observed in the fig (with red, yellow and green color formation on three spokes). The half of the spokes of the wheel on one side of line of action of load direction, which are approaching the point of contact of load action, are under higher stress development. Obviously wheel rim passing over the point of action of load makes the hub to be pushed about its support (Spokes) towards rim, which results in higher stress development in respective spokes. Thus providing spring supporting in radial direction improves the load bearing capacity of the suspension system by distributing the load among all provided supported springs and spokes.

Fig 4. Maximum principal stress distribution.

Fig 5. Maximum principal shear stresses distribution.
The principal elastic strain and shear strain developed in the In-Wheel suspension system are shown in figs 6 and 7. The strain distribution in the suspension system resembles same as stress distribution. The maximum elastic strain developed is 6.58X10^{-5} and maximum shear strain developed is found to be 9.83X10^{-5}. Therefore the strain developed is very less and thereby the design is acceptable. The maximum strain developed spoke is the respective spoke which is almost opposite to the point of action of load and whose axis is close to the line of action of load direction.

Fig 6. Maximum principal elastic strain

Fig 7. Maximum principal shear strain

7. Conclusions
From the analysis carried following conclusions are drawn:
- The developed tensile and shear stresses are distributed among all the suspension springs and supporting spokes, which reduces the maximum principal stress (Both tensile and shear nature) development.
- The maximum principal stress developed is 7.996MPa and maximum principal shear stress is 4.226MPa, which are far less than that of allowable stresses of considered grey cast iron material.
- The deformation is distributed among all suspension springs and maximum deformation is observed to be 0.02015mm, which is within acceptable limit.
The maximum elastic and shear strains developed are found to be $6.58 \times 10^{-5}$ and $9.83 \times 10^{-5}$.

Thus the stress, deformation and strain development is taken up by more than one spring and spoke which results in improvement of performance of In-wheel suspension system.

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