Design and Strength Analysis of FSAE Suspension

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Abstract: China FSAE race is introducing the formula racing gradually in the university campus. In order to make FSAE racing have better ride comfort, handling and stability. Design and strength analysis of FSAE suspension was proposed. Firstly, according to the whole layout of FSAE racing, the suspension mode was selected, both front and rear suspension were unequal push rod type double wishbone independent suspensions. Secondly, the main parameters and the orientation structure of the front and rear suspension were preliminarily designed. The wheels alignment parameters selected and all kinds of stiffness, damping coefficient, cross arm length calculation etc. were selected as well. According to the design parameters, the rim and shock absorber suitable, to determine the structure of the suspension’s main components were chosen. Thirdly, the front and rear suspension models were set up by the SolidWorks 3D software. Finally, the analysis of static stress on the main components of FSAE racing using the simulation module was performed. Made the car suspension system so that it meets the design requirements of the FSAE regulations. The paper could provide references for the real vehicle development.

Keywords: FSAE, design, strength analysis, suspension.

1. INTRODUCTION

FSAE racing is a sport with global influence; it is a college student design competition known as the "academic F1". The suspension system is the device connecting the body with wheels. When the body has irrelative motion between the wheels, the motion is constrained by the suspension, all kinds of forces and moments between the wheels and the ground passes to the body through the suspension. The design of the suspension system is an important part of the overall vehicle design, which determines the performance of the racing car.

The car suspension kinematics research started earlier in developed countries. Brazil Sao Paulo University in 2005 for the design of FSAE racing suspension, used the push rod unequal wishbone for both front and rear suspensions, and a multi-body dynamics model was established to analyze the kinematics and dynamics. In 2008, Greece’s Aristotle University had designed the first FSAE race car with front and rear suspension with placing an unequal double wishbone type. The selection principles of the roll center were given and the effects of front wheel alignment parameters on the handling stability were discussed, in order to avoid the cross arm bending, push rod was directly hinged on the steering knuckle.

In recent years, China has also begun to do performance research on college student formula racing. In 2011, South China University of Technology based on the optimization analysis platform ADAMS/Insight, determined the design variables, the design goal, the goal function, and constraint conditions etc. The experiment design and multi-objective optimization design on the front and the rear suspension system respectively were done [1, 2]. In June the same year, the Harbin Institute of Technology’s Li Man did the static and modal analysis of the suspension’s lower arm for FSAE racing [3, 4]. In 2013, Beijing Information Science and Technology University’s Jiang Liman adopted the method to combine the analysis with test, taking the finite element analysis software Hyper Works and LS-DYNA as the calculation tools, the DASP as modal test analysis system and e-DAQ as stress test data acquisition system, to complete more comprehensive static and dynamic characteristics analysis and structural optimizations [5, 6].

Above all, suspension design is a complex process, the type of suspension is determined by the comparison of different characteristics of the suspensions, and then a number of parameters were designed according to the parameter selection and calculation. Then the parts of the suspension is designed and assembled. What will ensure the feasibility and reliability of the design of the suspension used in the racing car?

2. FSAE RACING CAR SUSPENSION DESIGN

According to the requirements of China college student formula race, the race car suspension must have the shock absorber, the suspension travel is not less than 25.4 mm in the case of a racer, and all the connection point can be directly or indirectly seen. Therefore, the FSAE car suspension design should meet the following requirements:

1. Must have the appropriate attenuation vibration ability;
2. Ensures the car has good handling and stability performance;
(3) The light and strong;
(4) Easy operation and control for the driver;
(5) Convenient installation and easy adjustment.

In view of the flexibility and good motion characteristics of the double wishbone layout, the unequal length independent suspension is adopted.

FSAE racing requires the rim diameter shall not be less than 203.2 mm, the commonly used rim sizes are 254 mm and 330.2 mm. Because the 254 mm is small, may not be convenient for the steering column layout and causes stress of the lower arm, therefore the 330.2mm rim is selected. According to the rim size, the selected tire model is type 205/510R13.

FSAE racing requires cars wheelbase shall not be less than 1525 mm, wheelbase increased will directly increase the vehicle's weight and is not suitable for the car lightweight requirements. After considering the similarities of a racer with a car; the engine position, tire width, and the length of the cross arm are selected. The wheelbase is initially selected as 1720mm. After determining the wheelbase, the wheel track B will be determined by the empirical formula (1):

\[ B = kL \]  

(1)

where, L is the wheelbase, mm; k is the coefficient, 0.55-0.64.

The initial track is about 1210 mm, in order to increase the inclination angle stiffness of the suspensions the wheel track can increase in a small range to better the lateral stability. The front wheel track is larger than the rear wheel track as it is favorable for fast obstacle avoidance, the original front wheel track is 1240 mm, and the rear wheel track is 1180 mm.

The originally racing car main technology parameters are shown in Table 1.

**Table 1. Car technology parameters.**

<table>
<thead>
<tr>
<th>Parameters/Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car length/mm</td>
<td>2800</td>
</tr>
<tr>
<td>Car height/mm</td>
<td>1260</td>
</tr>
<tr>
<td>Wheelbase/mm</td>
<td>1720</td>
</tr>
<tr>
<td>Front wheel track/mm</td>
<td>1240</td>
</tr>
<tr>
<td>Rear wheel track/mm</td>
<td>1180</td>
</tr>
<tr>
<td>Whole quality/kg</td>
<td>200</td>
</tr>
<tr>
<td>Front and rear wheel load ratio</td>
<td>40:60</td>
</tr>
</tbody>
</table>

Offset frequency has great impact on the suspension's performance. High offset frequency leads to hard suspension, and causing the handling & stability to be good. Low offset frequency leads to soft suspension and resulting in increased ride comfort. In racing car design, a certain degree of ride comfort can be appropriately sacrificed, so a large offset frequency is selected. The front suspension offset frequency is \( f_{o1} = 2.0 \) Hz and the rear one is \( f_{o2} = 2.2 \) Hz. The suspension static deflection is determined by the offset frequency, and the optimum stiffness \( K_r \) can be calculated by formula (2):

\[ f_o = \frac{1}{2\pi} \sqrt{\frac{K_r}{m}} \]  

(2)

where, \( f_o \) is the offset frequency, Hz;

\( K_r \) is optimum stiffness, N/m;

\( m \) is the load of the shaft, kg.

The equivalent stiffness of suspension and tire \( K_s \) can be represented by formula (3):

\[ \frac{1}{K_s} = \frac{1}{K_w} + \frac{1}{K_r} \]  

(3)

where, \( K_w \) is suspension stiffness, N/m;

\( K_r \) is the radial stiffness of the tire, equal to 3e6 N/m.

From formula (3), the front and rear suspension stiffness is 16783 N/m and 29874 N/m, respectively.

Spring stiffness and the effective stroke can be determined by the movement ratio, FOX VAN R type damper is selected as the elastic element. The distance of the upper and low holes is 221 mm, the maximum expansion amount is 71.18mm.

Based on the structure of FSAE car, the handling and operating conditions, FSAE car wheel alignment parameters selection is generally within a range.

Car wheel alignment parameters are generally negative camber angle with negative toe angle. After comprehensive consideration of various factors, FSAE car wheel alignment parameter values are determined, which are shown in Table 2.

**Table 2. Wheel alignment parameters.**

<table>
<thead>
<tr>
<th>Alignment Parameter</th>
<th>Camber Angle°</th>
<th>Kingpin Inclination°</th>
<th>Caster Angle°</th>
<th>Toe Angle°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front suspension</td>
<td>-1</td>
<td>4</td>
<td>4</td>
<td>-1</td>
</tr>
<tr>
<td>Rear suspension</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Offset frequency is an important parameter in suspension design. Front offset frequency \( n_q \) and rear \( n_b \) can be obtained by the formula (4):

\[ n_q = \sqrt{\frac{k_q}{m_q} \cdot \frac{1}{(2\pi)}} \], \[ n_b = \sqrt{\frac{k_b}{m_b} \cdot \frac{1}{(2\pi)}} \]  

(4)

where,

\( k_q \) is front suspension stiffness, N/m;

\( k_b \) is rear suspension stiffness, N/m;

\( m_q \) is sprung mass of front suspension, kg;
\( m_R \) is sprung mass of rear suspension, kg.

For FSAE racing car, the main objective is to complete the race, the requirement of the ride comfort is low and so the selection of the offset frequency is larger than the general car’s. The initial front suspension offset frequency is 2.0 Hz, and the rear one is 2.2 Hz.

For the independent suspension, roll angle stiffness can be represented as:

\[
C_\phi = \frac{1}{2} K_i B^2 \tag{5}
\]

where, \( B \) is the wheel track, mm;
\( K_i \) is the line stiffness of the suspension, N/mm.

Generally speaking, if the roll angle stiffness is larger, the handling and stability will be better and the corresponding ride comfort will be less. Under the effect of 0.5g lateral stiffness, the roll angle should be controlled in the range of 2° to 5°. The same roll angle stiffness will affect the handling and stability, so the rear suspension roll angle stiffness is smaller than the front.

When the roll center is high, the roll torque will be smaller, so that the body-roll angle decreases accordingly. But roll center is too high and can cause wheel track to get larger when the body tilts, reducing the service life of tires. Because FSAE car chassis is very low, so front suspension roll center is set to 30mm and the rear roll center is set 47 mm.

The trim center of double wishbone typed independent suspension can be obtained by using the method of drawing. The intersection point of the extension of the upper and lower wishbone rotating shafts is the trim center.

In the process of general double wishbone independent suspension design, the low cross arm is longer than the upper cross arm, so that the arrangement of the engine is conducive. In order to ensure the handling and stability, the ratio of the upper and low cross arm length is generally about 1.0. The ratio of front and rear are chosen to be 0.81 and 0.86, respectively.

Through the above description and preliminary design calculation, the front and rear suspension parameters are shown in Table 3.

<table>
<thead>
<tr>
<th>Name</th>
<th>Front Suspension</th>
<th>Rear Suspension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offset frequency/Hz</td>
<td>2.0</td>
<td>2.2</td>
</tr>
<tr>
<td>roll center height/mm</td>
<td>29</td>
<td>46</td>
</tr>
<tr>
<td>Push rod length/ mm</td>
<td>546</td>
<td>495</td>
</tr>
<tr>
<td>Upper cross arm length/mm</td>
<td>401</td>
<td>409</td>
</tr>
<tr>
<td>Low cross arm length/mm</td>
<td>493</td>
<td>475</td>
</tr>
<tr>
<td>Free length of the damper/mm</td>
<td>300</td>
<td>310</td>
</tr>
<tr>
<td>Kingpin caster angle°</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Kingpin inclination angle°</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Toe angle°</td>
<td>-1.0</td>
<td>0</td>
</tr>
<tr>
<td>Camber angle°</td>
<td>-1.0</td>
<td>-1.0</td>
</tr>
</tbody>
</table>

### 3. MODELING AND ASSEMBLY

The current popular 3D software SolidWorks is used to model and lay the foundation for the analysis of the strength of the follow-up.

Because FSAE car is a rear wheel drive with the front end only steering, so the design of the front and rear steering knuckle is different. Upper and lower bolt holes of the steering knuckle are installed on the outside ball head pins of the upper and lower control arms, respectively, with the the being hole and the shaft shoulder in the middle. The lower side of knuckle arm is installed on the outside ball pin of steering tie rod and the upper side is the support installed to the brake clamp. Because the rear wheel drive, increases the intensity on the beam, two cross arms are designed. Accordingly, there are two mounting points on the upper end of the rear steering knuckle; the column 3D models are shown in Fig. (1).

![Fig. 1. Front and rear column models.](image1)

Control arm is composed of two steel pipe welded by a design angle, there is a short tube in the welding corner. There is another short small diameter steel tube in this short steel pipe, they are welded together. Low control arm installs the push rod, so above the junction of the two steel pipes the steel bracket welds with an open bolt hole in the middle. Because the force of the low control arm is larger, the steel bracket welds at the junctions of suspension control arms. The upper and low control arms are shown in Fig. (2).

![Fig. 2. Upper and low control arm models.](image2)

Due to the push rod, anti roll bar of front and rear suspension are arranged in a different way, the shape of the front and rear rocker arms are also different. Front and rear rocker are four hinged, the rocker is made by 45# steel by a wire-cutting process. Front and rear rocker arms are shown in Fig. (3).

![Fig. 3. Upper and low control arm models.](image3)

Push rod is a steel pipe with thread at both ends, which connects the ball handle of ball head pin and the rocker arm with the steel bracket of the low cross arm. Both hinged threads are adjusted to change the length of the push rod according to different road conditions, effectively changing the clearance of the car from the ground to make the car in an optimal state. Push rod is shown in Fig. (4).
Fig. (3). Front and rear rocker arm models.

Fig. (4). Push rod model.

Front and rear anti-roll bars are U type. The vertical bar connects with the horizontal bar by the ball head pin and with a replaceable torsion bar, which can be adjusted conveniently for roll stiffness, as shown in Fig. (5).

The tires type is 205/510R13, as shown in Fig. (6).

Fig. (5). Anti-roll bar model.

Fig. (6). Wheel rim model.

FOX VAN R type damper is selected as elastic the element. The model and real part are shown in Fig. (7).

Fig. (7). Model and real picture of damper.

The 3D models of main parts are imported into SolidWorks software to assemble. Constraints are added between the components to make an assembly. The front and rear suspension 3D assembly models are shown in Figs. (8, 9).

Fig. (8). Front suspension assembly model.

Fig. (9). Rear suspension assembly model.

4. STRENGTH ANALYSES OF MAIN PARTS

The force on the rocker arm, support plate of low swimming arm and column can be very large when the suspension is working, so a strength analysis will be performed.

Rocker arm material is 45# steel, and the yield strength is 6.20422e8 N/m². Before calculating the stress, the maximum stress value is used to simulate from the security perspective, front and rear equivalent stress is displacement shown in Fig. (10).

Fig. (10). Equivalent stress displacement of front and rear of the rocker arm.

The maximum displacement of front rocker arm is 4.451 e-3 m and the rear one is 3.433 e-3 m, and the maximum deformations is very small, which can meet the design requirements.

Rocker arm material is 45# steel, and the yield strength is 5.56402e8 N/m². Before calculating the stress, the maximum stress value is used to simulate from the security perspective, equivalent stress displacement of low support plate is shown in Fig. (11). The maximum displacement is
1.996e-3m, and the maximum deformation is very small, which can meet the design requirements.

The column material is aluminum alloy 2024, and the yield strength is 7.58291e7 N/m². Before calculating the stress, the maximum stress value is used to simulate from the security perspective, front and rear column equivalent stress displacements are shown in Fig. (12). The maximum displacement of front column is 5.802e-3m and the rear one is 3.766e-3m, and the maximum deformations are very small, which can meet the design requirements.

SolidWorks software is used for modeling and assembly of the suspension’s main components. The Simulation Xpress module is used to analyze static stress of FSAE car suspension main mechanical parts, including rocker arms, low support plate and columns. By analysis it shows, that the design of FSAE car suspension system can satisfy the performance requirements, which provides the design method and parameters support for building real car model.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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