Study on the Frame Configuration and Optimization Design of Miniature Foldable Electric Vehicle

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Abstract: In order to solve the miniature foldable electric vehicle frame configuration and design problems, the key dimensions and constraints of the frame has been extracted and a single objective optimization mathematical model has been established and optimized by using MATLAB optimization tool kit, basing on the design goals. The 3D model of the frame has been built by SOLIDWORKS and the ADAMS has been used for kinematics simulation analysis. The results show that the optimized folding size of the vehicle has increased by 18%, which meets the design requirements and the stability of the designed mechanism under certain speed conditions is also verified.

1 INTRODUCTION

The concept of intercity vehicles has been proposed to solve the increasingly serious urban traffic problems in recent years. The Hiriko[1], a miniature electric car with a folding frame developed by MIT can realize such functions as shortening wheelbase and zero radius steering. On the basis of Hiriko, EO SCC 2[2-3], developed by DFKI, introduces the idea of modular design, which lays a foundation for the serialized development of the vehicle while realizing the folding and high mobility of the vehicle.

A kind of electric vehicle folding mechanism based on separating frame and rocker slider mechanism is proposed and designed in this paper.

2 FRAME FOLDING MECHANISM CONFIGURATION DESIGN

2.1 Design Objective

According to GB1589-2016 and the same type of vehicles, the goal of parking three electric vehicles in folded state on the parking space of 5-5.5 meters long compact car is realized by controlling the external profile size of the vehicle.

2.2 Design Scheme

The frame is designed as a separate structure that contains front frame, main frame and rear frame. A folding mechanism with the principle of rocker slider is used to lift the main frame, and the main frame drives the front frame to shift, thus reducing the length of the vehicle. Considering the cost and structure interference, the front and rear frame adopt the same frame and the rear frame is designed as the inclined plane where the rear frame meets the main frame. The frame folding scheme (side view) is shown in Figure.1.

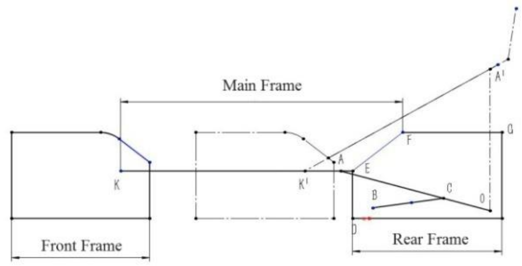

Figure.1: Scheme of foldable frame.

When the vehicle is stopping, the rear frame wheels keep still and the bottom AK of the main frame is parallel to the ground. When the vehicle is folding, the electric servo cylinder BC pushes the back of the main frame which is connected with the rocker OA and then the front frame which is connected with the hinge points K is shifted backward to shorten the length of the vehicle.

2.3 Mathematical Modeling

2.3.1 Vehicle Parameters

On the basis of referring to the national standard for the size of similar types of vehicles and vehicle exterior profile, the main performance parameters of the vehicle are summarized in Table.1.

Table.1: Vehicle parameters.

Category	Value
Vehicle length, mm	2000
Main frame length, mm	1300
Wheel base, mm	1500
Tread, mm	1100
Curb weight, kg	270
Maximum speed, km/h	80

2.3.2 Design Variable

As the frame is a complex structure, the main structural interference factors should be considered in the designing process, and the model should be simplified.

The Cartesian coordinate system as shown in Figure.2 is established at the hinge point O of the rocker and the rear frame. The main dimensions such as the vehicle exterior profile and the outline of the battery pack of the external frame are extracted, which are taken as design variables.

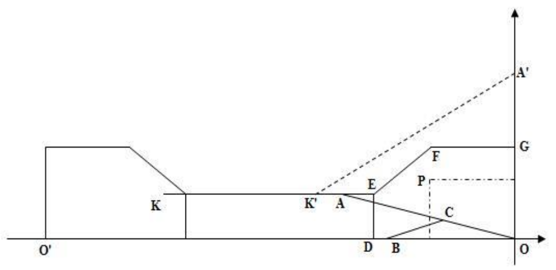

Figure.2: Simple diagram of the folding mechanism.

The value range of design variables are determined by visual design and comparison of vehicle size of the same type that are shown in Table.2.

Table.2: Summary of designing variables.

Variable	Mark	Range	Initial value
Front height of rear frame DE	X_1	0-400mm	150mm
Bevel length of the rear frame EF	X_2	0-400mm	290mm
Length of upper side of rear frame FG	X_3	0-400mm	290mm
Slope angle of rear frame	X_4	30°-60°	45°

2.3.3 Objective Function

In order to reduce the parking space, the wheelbase should be the minimum after folding. The maximum displacement of the point K where the front frame is hinged with the main frame is designed as the objective function. It is assumed that the rocker OA is in the vertical position when the vehicle folding length reaches its maximum.

The projection length of the main frame bottom face AK:

$$|x_{K'}| = \sqrt{(1200 - x_2\cos x_4)^2 - (\sqrt{x_1^2 + (x_2\cos x_4 + x_3 + 50)^2} - x_1)^2}$$

The maximum displacement of the hinged point K of the main and front frame after folding:

$$|KK'| = x_3 + 1250 - \sqrt{(1200 - x_2\cos x_4)^2 - (\sqrt{x_1^2 + (x_2\cos x_4 + x_3 + 50)^2} - x_1)^2}$$

The model objective function expression:

$$goal(x) = \min(-|KK'|) = \min\left(\sqrt{(1200 - x_2\cos x_4)^2 - \left(\sqrt{x_1^2 + (x_2\cos x_4 + x_3 + 50)^2} - x_1\right)^2} - x_3 - 1250\right)$$

2.3.4 Constraint Conditions

1. Vehicle length constraint

To control the vehicle size, the total length of the vehicle frame should be less than 2000mm. Design variables should satisfy the relation:

$$1300 - 100 + 2(x_2\cos x_4 + x_3) - x_2\cos x_4 \leq 2000$$

After simplifying, the relation:

$$x_2\cos x_4 + 2x_3 \le 800 \quad (1)$$

2. Limit point interference constraint

In the process of frame folding, there should be no interference between the hinge point A of lifting bar and the limit position point F of auxiliary frame, and the length of lifting bar should be longer than the length from point O to point F. The dimension constraint relation:

$$\sqrt{x_3^2 + (x_1 + x_2\sin x_4)^2} - \sqrt{x_1^2 + (x_2\cos x_4 + x_3 + 50)^2} \le 0 \quad (2)$$

3. Frame interference constraint

After folding, the front and rear frames should not interfere. As the point K is not the limit position of the front frame, when the frame reaches the limit position, the clearance between the point K and the rear frame is reserved for 120mm.The dimension constraint relation:

$$|x_K| \ge x_2\cos x_4 + x_3 + 120$$

After simplifying, the relation:

$$x_2\cos x_4 + x_3 + 120 - \sqrt{(1200 - x_2\cos x_4)^2 - \left(\sqrt{x_1^2 + (x_2\cos x_4 + x_3 + 50)^2} - x_1\right)^2} \le 0 \quad (3)$$

4. The battery interference constraint

Due to the use of hub motor drive technology, the space of the front and rear frame is mainly occupied by the battery pack, so the interference of the battery pack should be considered in the design of the frame.

The equation of the straight line EF can be get from the point E(- $x_2\cos x_4 - x_3$, x_1)and point F($-x_3$, $x_1 + x_2\sin x_4$).

The liner equation:

$$y = \tan x_4(x + x_2\cos x_4 + x_3) + x_1$$

To ensure that the limit position point P （-520，180）of the battery pack does not interfere with the ramp of the auxiliary frame, point P should be below the right of the linear EF in the coordinate. The constraint relation can be obtained from the position relation:

$$200 - \tan x_4(-260 + x_2\cos x_4 + x_3) - x_1 \le 0 \quad (4)$$

5. Front and rear frame size constraint

Considering the size of battery pack and folding mechanism of vehicle size, the outer profile height of auxiliary frame is preliminarily determined to be 300-500mm. Constraint relation:

$$x_2\cos x_4 + x_3 - 500 \le 0 \quad \text{and} \quad 300 - x_2\cos x_4 - x_3 \le 0 \quad (5)$$

The length of the front and rear frame is 400-600mm.And the constraint relation:

$$x_1 + x_2\sin x_4 - 600 \le 0 \quad \text{and} \quad 400 - x_1 - x_2\sin x_4 \le 0 \quad (6)$$

6. Constraint of the lifting bar inclination

Rotation of the rocker plays a major role in frame folding. In order to ensure that the pressure angle of the rocker is not too large, its inclination angle relative to the X-axis of the coordinate system is set within 10-30° . The constraint relation:

$$\frac{x_1}{x_2\cos x_4 + x_3 + 50} - \tan 30° \le 0 \quad \text{and} \quad \tan 10° - \frac{x_1}{x_2\cos x_4 + x_3 + 50} \le 0 \quad (7)$$

3. MATLAB OPTIMIZE DESIGN AND MODELING SIMULATION

3.1 Multivariable Optimization

The mathematical model of frame folding optimization belongs to the problem of single objective multivariable optimization.

The normalized form[4]:

min F(X)
s.t
AX ≤b
AeqX = beq
C(x) ≤ 0
Ceq(X) = 0
lb≤ X ≤ub

The function fmincon is invoked to solve the problem. The basic format of the function command：

[x,fval,exitflag,output]=fmincon(@objfun,x0,A,b,Aeq,beq,lb,ub,@confun)

By writing the M file of the objective function and the constraint function, the optimization results can be obtained by establishing the main program solution:

x =149.2821 400.0000 226.7949 0.5236
fval = -778.9473
exitflag =1

The result (exitflag =1) shows that the first-order optimality condition of variable satisfies the tolerance range. According to the optimized result, the folding length of the frame will reach 778.95mm, which will reach one-third of the length of the whole vehicle. The summary results of design variable optimization are shown in Table.3.

Table.3: Optimization results of designing variable.

Design variable	Length, mm			Angle,°
	X1	X2	X3	X4
Initial value	150	290	290	45
Optimum value	149	400	226	30
Range of optimization,%	0.67	37.9	22.1	33.3

3.2 3D Modeling

According to the requirement of light weight and strength of the frame, the standard channel steel is adopted for the assembly modeling, and the rigid point factor of the suspension is ignored in the preliminary modeling. The virtual prototype modeling of the whole frame of the frame is carried out with SOLIDWORKS software, as shown in Figure.3a and Figure.3b. The lifting of frame rocker depends on the extension of actuator's pushing.

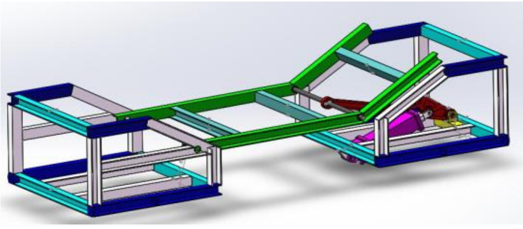

Figure. 3a: The working condition of the frame.

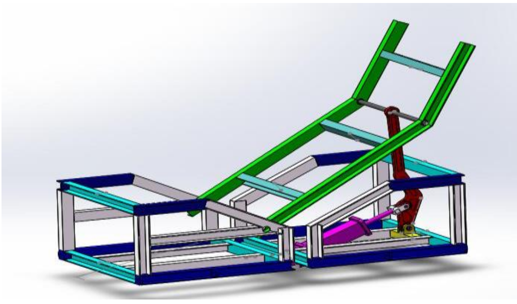

Figure.3b: The folded state of the frame when parking.

The 3D modeling of frame is imported into ADAMS software and the source part model is divided into front frame, main frame, rear frame, connection, rod, linear actuator and connection first-class parts by Boolean operation.

The ADAMS model in Figure.4 is obtained after pre-processing.

Figure.4: ADAMS model of the car chassis.

3.3 Simulation Settings

In order to achieve the frame from acceleration start to slow down the stillness of the folding process, the ADAMS built-in STEP function is added in the simulation of linear actuator and the connection to simulate the movement speed. The movement simulation time is set to 6 seconds.

The STEP function is shown below:

step(time,0,0,2,36.4)+step(time,2,0,4,0)+step(time,4,0,6,-36.4)

The STEP Function meaning：The moving pair accelerates from static to 36.4mm/s in 0-2s time, moves at a constant speed of 36.4mm/s for 2-4s,and the speed is reduced to 0 in 4-6s.

3.4 Simulation Results and Analysis

3.4.1 Frame Folding Analysis

The center of mass of the front frame is used to be the reference point to measure its displacement in the folding direction. The displacement of the front frame under the initial size is compared with that of the optimized front frame. The comparison results are shown in Figure.5.

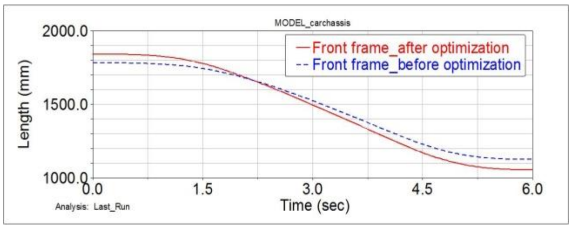

Figure.5 :Displacement of the front frame.

As can be seen from the Figure 6, the folding length of the frame, that is, the displacement of the front frame increases from 657mm to 775mm.Compared with the results of MATLAB model, the error after optimization is less than 1%, indicating that the virtual prototype modeling meets the requirements.

3.4.2 Linear Actuator Motion Analysis

The linear actuator stroke, rocker rotation angle and angular velocity images are shown in Figure.6.

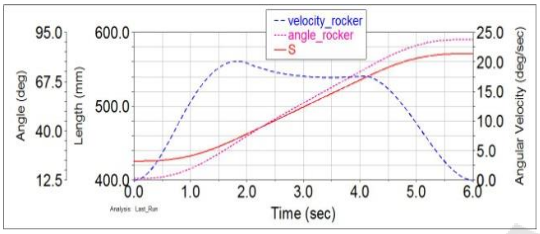

Figure.6: The angular, velocity of the rocker and the elongation of the line actuator.

As can be seen from the image, the maximum displacement of the linear actuator S is 145mm, which satisfies the maximum stroke of the selected linear actuator of 152mm. The maximum rotation angle of the rocker is 91, which is similar to the 90 rotation angle of the rocker in the mathematical model. At the beginning and ending of the motion, the displacement of the linear actuator changes gently and the angular velocity of the rocker is not accelerated or decelerated rapidly.

4 CONCLUSIONS

1. The folding length optimized by MATLAB has increased by 18% compared with that before optimization and is more than one third of the length of frame. The folding effect of frame meets the design requirements.

2. The comparison between MATLAB calculation results and ADAMS simulation results shows that the modeling error is less than 1%, which reflects the reliability of this model.

3. The variation of motion parameters of key components of folding mechanism shows the stability of the designed mechanism at a certain speed.

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