180km/h급 한국형 틸팅차량의 틸팅 메카니즘 기구동역학 해석

Kinematics Analysis of Tilting Mechanism for Korea Tilting Train with 180km/h Service Speed

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ABSTRACT

곡선부가 많은 국내 기존선의 속도향상을 위한 틸팅차량의 개발은 기존선의 전철화에 따른 고속화를 위해 그 필요성이 부각되고 있다. 일반 고속차량과 다른 주행 메카니즘을 가지고 있는 틸팅차량의 주요 기술을 확보하기 위한 틸팅대차와 틸팅시스템의 개발과 연구는 한국철도의 기술력 향상에 큰 역할을 할 것이다. 180km/h급 한국형 틸팅차량의 틸팅 메카니즘 기구동역학 해석을 통하여 틸팅 대차를 형성하는 주요 파라메터들의 변화에 따른 틸팅 메카니즘의 특성과 영향력을 검토한다. 이를 통하여 최적의 틸팅운동을 수행할 수 있는 주요 파라메터의 값을 제시함으로서 틸팅차량이 요구하는 최적의 틸팅 메카니즘을 구현하고자 한다. 이 연구를 통해서 얻어지는 결과들은 틸팅 대차용 엑츄에이터의 성능 설계와 해석의 기반 자료로 사용되어진다.

1. Introduction

The application of the tilting train is one of the most efficient ways to increase curving speed of train on existing tracks or on mountain railway lines with sharp curves as the conventional railway in Korea. It can increase the running speed and ensure the passenger comfort and safety at the same time. Therefore, the development of tilting train has been paid high attention by many countries in the world. Tilting trains have been operated successfully in many countries such as Italy, Spain, Germany, Sweden, England and so on. The tilting trains possess broad prospects in raising speeds. The kinematics of tilting mechanism for the developing tilting bogie are analyzed to get the optimized parameters of new tilting mechanism. The influences of the parameters of tilting mechanism on the tilting performance are carefully studied.

2. Kinematics Relations of Bogie Tilting Mechanism

The schematic diagram of the tilting car bogie is shown as Fig. 1. The tilting bolster is hanged on the bogie frame through four swing arms and the carbody is sat on the bolster through air springs. The electromechanical actuator which is laid between the bolster and bogie frame will push or pull the bolster according to the control regularity, then the carbody will tilt a certain angle towards the inside of the curved track in order to balance the centrifugal forces during curve negotiation.

It is assumed that there is no relative motions between the bolster and the carbody for the kinematic study, then the tilting mechanism of the bogie is shown as Fig. 2 and θ is the tilting angle. The stationary points A and

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B are fixed on the bogie frame and points *C, D* on the tilting bolster. *EF* is the electromechanical actuator. *E* is the point on the bogie frame and F is the point on the bolster. In the figure, *G, P* and *Q* indicate the carbody gravitational center, titling center and coupler center respectively.

The axis *OYZ* is shown as Fig.2.1 and the origin O is on the middle of *AB*. Let the bolster or carbody tilt a angle θ, then points C, D turn to be C', D' Because the lengths of *AC, BD* and *CD* are invariable, the following kinematic relations can be obtained.

$$(y_{C'}-y_A)^2+z_{C'}^2=((y_C-y_A)^2+z_C^2)^{1/2} \qquad (y_{D'}-y_B)^2+z_{D'}^2=((y_D-y_B)^2+z_D^2)^{1/2}$$
$$(y_{C'}-y_{D'})^2+(z_{C'}-z_{D'})^2=((y_C-y_D)^2+(z_C-z_D)^2)^{1/2} \qquad (z_{C'}-z_{D'})/(y_{C'}-y_{D'})=tg\theta \tag{1}$$

Eq. (1) is nonlinear algebraic equations with four unknown variables $(y_{C'}, y_{D'}, z_{C'}, z_{D'})$ and can be solved by using Newton iteration method. After the coordinates of C', D' are determined, then the coordinate (*y, z*) of any point on the carbody can be calculated. Let the arbitrary point on the carbody be S (y_0, z_0), then *S,C,D* are all on the carbody and will turn to be S', C', D' when the carbody tilts an angle θ. The angles between *SC* and y axis and between *SD* and y axis in the initial position are expressed as

$$\theta_1 = tg^{-1}(\frac{z_S - z_C}{y_S - y_C}), \quad \theta_2 = tg^{-1}(\frac{z_S - z_D}{y_S - y_D}) \tag{2}$$

After the carbody tilts an angle θ, the equations for $S'C'$ and $S'D'$ become

$$tg(\theta_1+\theta) = \frac{z_{S'} - z_{C'}}{y_{S'} - y_{C'}}, \quad tg(\theta_2+\theta) = \frac{z_{S'} - z_{D'}}{y_{S'} - y_{D'}} \tag{3}$$

Thus, the position of arbitrary point S on the carbody can be determined. Then the motions of the carbody gravitational center *G*, coupler center *Q* and actuator driving point *F* with respect to angle θ can be determined by eqs.(2) and (3). The stroke of the actuator can be obtained according to *EF* and EF'. The swing center *P* is the intersection of AC and BD and can be obtained by

$$\frac{z_{P'}}{y_{P'} - y_A} = \frac{z_{C'}}{y_{C'} - y_A}, \quad \frac{z_{P'}}{y_{P'} - z_B} = \frac{z_{D'}}{y_{D'} - y_B} \tag{4}$$

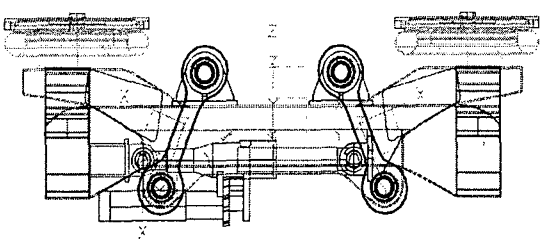


Figure 1. Tilting car bogie

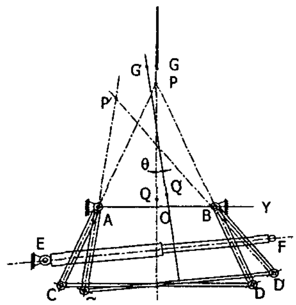


Figure 2. Tilting mechanism

3. Kinematic Analysis and Parameter Study of Tilting Mechanism

Let the initial parameter values of the tilting mechanism to be as follows:

Height of points A, B to rail top: H_1=770 mm

Length of AB: L_1=650 mm (varying range 500~750mm)

Length of AC and BD: L_2=550 mm (varying range 450~650mm)

Angle of swing arm AC, BD to vertical axis: $\alpha=23^0$ (varying range 20^0~25^0)

Height of actuator EF to rail top: H_2=450 mm (varying range 400~600mm)

Length of electromechanical actuator EF: EF=1050 mm

Height of carbody gravitational center G: H_C=1600mm (varying range 1500~1900mm)

Coupler center Q to rail top: H_Q=890 mm

Tilting center P to rail top: H_P=1535.65 mm

Then the initial coordinate of each point is:

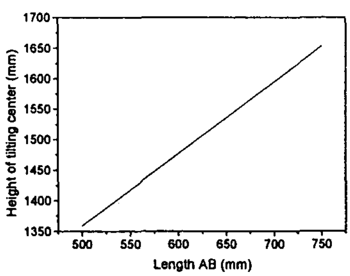
A=(-325,0), B=(325,0), C=(-539.9,-506.28), D=(539.9,-506.28), E=(-625,-320), F=(425,-320), G=(0,830), Q=(0,120), P=(0,765.65).

Thus, the kinematic relation of the tilting mechanism can be calculated when the tilting angle θ changes from $-8^0 \sim +8^0$.

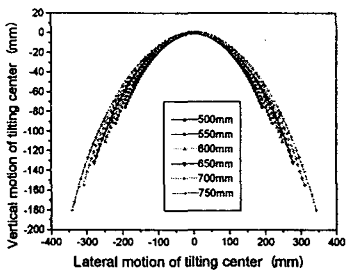
3.1 Influence of Length AB of Tilting Mechanism

When the upper point distance L_l of the four bar mechanism, i.e. length AB, varies at range 500~750mm, the change of height of tilting center to rail top is shown as Fig. 3(a). It can be seen that the height of tilting center increases as the distance L_l increases.

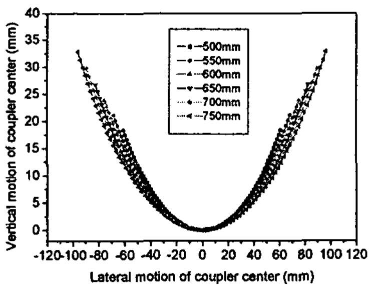
When the upper point distance L_l of the four bar mechanism varies at range 500~750mm and the tilting angle θ at $-8^0 \sim +8^0$, the motion of tilting center can be seen from Fig. 3(b). It can be known from the calculation results



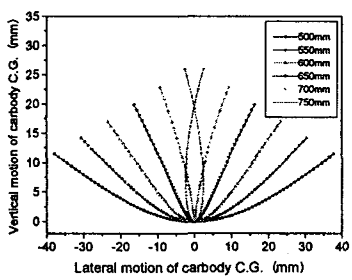
(a) The height of tilting center



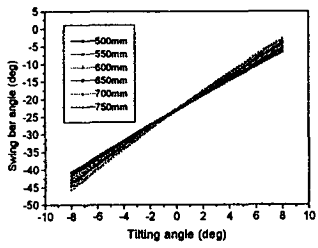
(b) The motion of tilting center



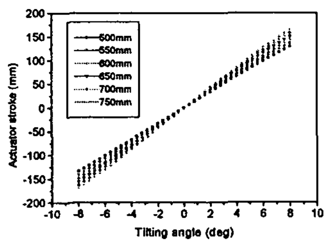
(c) The motion of carbody center of gravity



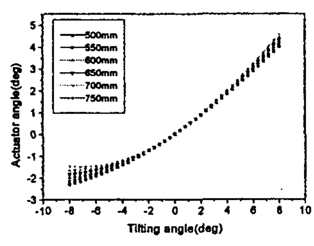
(d) The motion of coupler center



(e) the swing arm angle



(f) the actuator stroke



(g) the actuator angle

Figure 3. Influence of L_l on tilting mechanism

that the lateral and vertical motions of the tilting center increases as the distance L_1 increases. Thus if want to reduce the motion of the tilting center, the distance L_1 should not be too large.

When the upper point distance L_1 of the four bar mechanism varies at range 500~750mm and the tilting angle θ at $-8^0 \sim +8^0$, the motion of carbody center of gravity can be seen from Fig. 3(c). It can be known from the results that large L_1 will increase the vertical motion of the carbody center of gravity and small L_1 will increases the lateral motion. Thus the value of L_1 should be appropriately chosen.

When the upper point distance L_1 of the four bar mechanism varies at range 500~750mm and the tilting angle θ at $-8^0 \sim +8^0$, the motion of coupler center is shown as Fig. 3(d). It can be seen that the larger the L_1 is, the larger the lateral and vertical motions of coupler center are. Therefore, the chose of reasonable small value of L_1 can reduce the motion of coupler center.

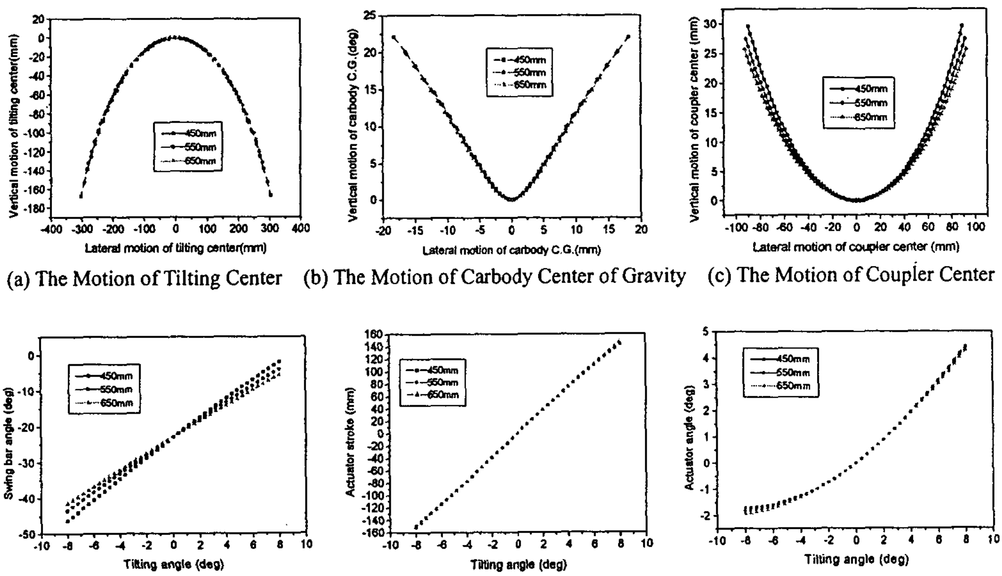
When the upper point distance L_1 of the four bar mechanism varies at range 500~750mm and the tilting angle θ at $-8^0 \sim +8^0$, the change of vertical angle of the swing arm is shown as Fig. 3(e). It can be seen that the larger the L_1 is, the larger the change of the swing arm angle is. When L_1=750mm and $\theta=8^0$,the swing arm tends to be vertical, i.e., the swing arm angle tends to be zero.

When the upper point distance L_1 of the four bar mechanism varies at range 500~750mm and the tilting angle θ at $-8^0 \sim +8^0$, the change of actuator stroke is shown as Fig. 3(f). It can be seen that the larger the L_1 is, the larger the change of actuator stroke is. Therefore L_1 can not be too large if want to have small actuator stroke.

When the upper point distance L_1 of the four bar mechanism varies at range 500~750mm and the tilting angle θ at $-8^0 \sim +8^0$, the change of actuator angle is shown as Fig. 3(g). It is known that the L_1 has a little influence on the actuator angle.

3.2 Influence of Length L_2 of Swing Arm

When the length L_2 of the swing arm varies at range 450~650mm and the tilting angle θ at $-8^0 \sim +8^0$, the motion of tilting center can be seen from Fig. 4(a). It can be known from the calculation results that the lateral and vertical motions of the tilting center increases as the length L_2 decreases. Thus if want to reduce the motion



(a) The Motion of Tilting Center (b) The Motion of Carbody Center of Gravity (c) The Motion of Coupler Center

(d) The Swing Arm Vertical Angle (e) The Actuator Stroke (f) The Actuator Angle

Figure 4. Influence of L_2 on tilting mechanism

of the tilting center, the length L_2 should not be too short.

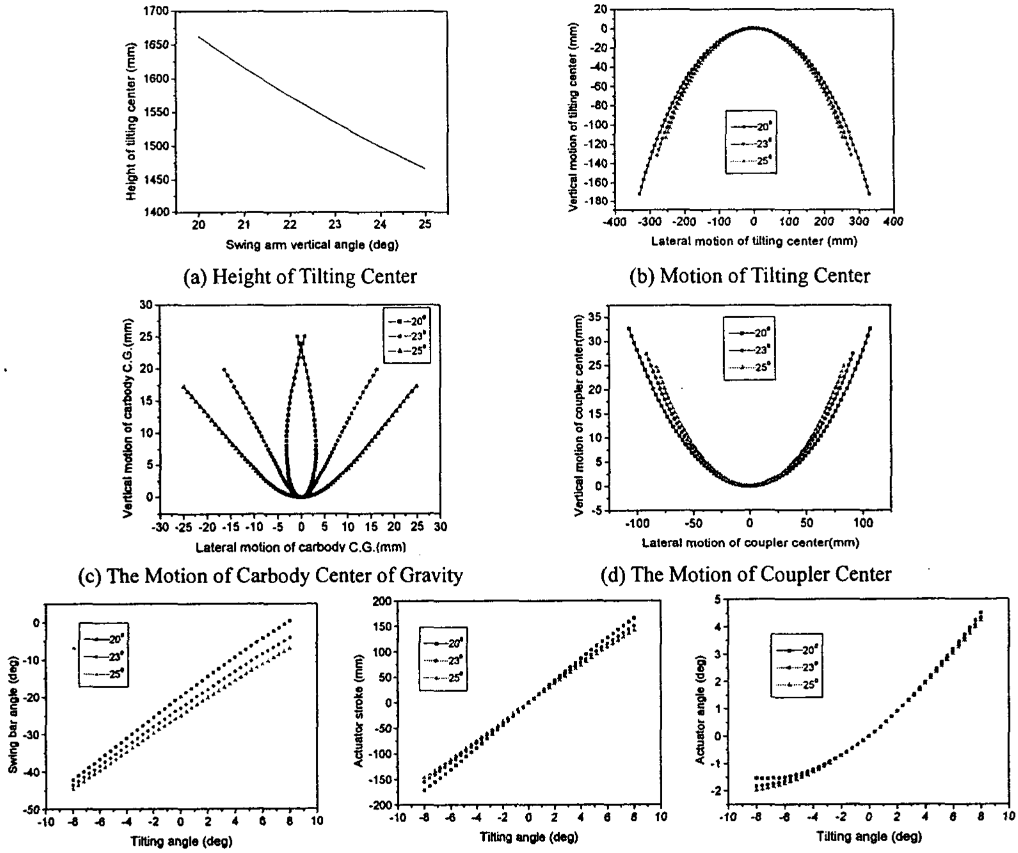
When the swing arm length L_2 of the four bar mechanism varies at range 450~650mm and the tilting angle θ at -8^0~$+8^0$, the motion of carbody center of gravity can be seen from Fig. 4(b). It can be known from the results that short L_2 will increase the lateral and vertical motions of the carbody center of gravity. Thus the value of L_2 should not be chosen too short.

When swing arm length L_2 of the four bar mechanism varies at range 450~650mm and the tilting angle θ at -8^0~$+8^0$, the motion of coupler center is shown as Fig. 4(c). It can be seen that the length L_2 has a little effect on the motions of coupler center. Large L_2 will increase the lateral motion of coupler center and reduce the vertical motion.

When the swing arm length L_2 of the four bar mechanism varies at range 450~650mm and the tilting angle θ at -8^0~$+8^0$, the change of vertical angle of the swing arm is shown as Fig. 4(d). It can be seen that the use of large L_2 is advantageous to reduce the change of swing arm.

When swing arm length L_2 of the four bar mechanism varies at range 450~650mm and the tilting angle θ at -8^0~$+8^0$, the change of actuator stroke is shown as Fig. 4(e). It can be seen that the length L_2 has a little effect on the change of actuator stroke.

When swing arm length L_2 of the tilting mechanism varies at range 450~650mm and the tilting angle θ at -8^0~$+8^0$, the change of actuator angle is shown as Fig. 4(f). It is known that the L_2 has a little influence on the actuator angle.



(a) Height of Tilting Center

(b) Motion of Tilting Center

(c) The Motion of Carbody Center of Gravity

(d) The Motion of Coupler Center

(e) The Swing Arm Angle

(f) The Actuator Stroke

(g) The Actuator Angle

Figure 5. Influence of Swing Arm Vertical Angle on tilting mechanism

3.3 Influence of Swing Arm Vertical Angle

When the initial swing arm vertical angle α varies at 20^0~25^0, the height of tilting center to rail top is illustrated in Fig. 5(a). It is known that the larger the swing arm angle is, the lower the height of tilting center is.

When the initial swing arm vertical angle α varies at 20^0~25^0 and the tilting angle θ at -8^0~+8^0, the motion of tilting center v.s. θ can be seen from Fig. 5(b). It is known that the lateral and vertical motions of the tilting center decreases as the angle α increases.

When the initial swing arm vertical angle α varies at 20^0~25^0 and the tilting angle θ at -8^0~+8^0, the motion of carbody center of gravity v.s. θ is shown as Fig. 5(c). It can be known from the results that large α will increase the lateral motion and small α will increase the vertical motion. Therefore the value of α should be chosen appropriately.

When initial swing arm vertical angle α varies at 20^0~25^0 and the tilting angle θ at -8^0~+8^0, the motion of coupler center with respect to θ is shown as Fig. 5(d). It can be seen that the larger the angle α is, the smaller the lateral and vertical motions of coupler center are. Therefore using large angle α can reduce the motions of the coupler center.

When the initial swing arm vertical angle α varies at 20^0~25^0 and the tilting angle θ at -8^0~+8^0, the change of vertical angle of the swing arm with respect to θ is shown as Fig. 5(e). It can be seen that the smaller the initial angle α is, the bigger the change of swing arm angle is. When $\alpha=20^0$ and$\theta=8^0$, the swing arm passes the vertical position.

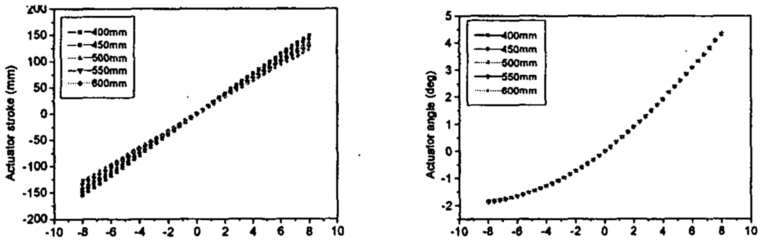
When the initial swing arm vertical angle α varies at 20^0~25^0 and the tilting angle θ at -8^0~+8^0, the change of actuator stroke v.s. θ is shown as Fig. 5(f). It is known that larger angle α can reduce the actuator stroke.

When the initial swing arm vertical angle α varies at 20^0~25^0 and the tilting angle θ at -8^0~+8^0, the change of actuator angle with respect to θ is shown as Fig. 5(g). It is known that the initial angle α has a little influence on the actuator angle.

3.4 Influence of Actuator Height to Rail Top

It is obvious that the change of height of actuator to the rail top has no effect on the motions of tilting center, carbody center of gravity, coupler center and swing arm angle, but has influence on the actuator stroke and actuator angle.

When the height of actuator varies at 400~600mm and the tilting angle θ at -8^0~+8^0, the change of actuator



(a) The actuator stroke (b) The actuator angle

Figure.6. The influence of height of actuator on the actuator stroke and angle

stroke v.s. θ is shown as Fig. 6(a). It is known that the higher the height of actuator to the rail top is, the smaller the actuator stroke is. Therefore, from the viewpoint of reducing actuator stroke, the height of actuator should be relatively large.

When the height of actuator to the rail top varies at 400~600mm and the tilting angle θ at -8^0~+8^0, the change of actuator angle with respect to θ is shown as Fig. 6(b). It is known that the height of actuator has a little influence on the actuator angle.

3.5 Influence of Height of Carbody Center of Gravity to Rail Top

It is obvious that the change of height of carbody center of gravity to rail top has no effect on the motions of tilting center, coupler center, swing arm angle, actuator stroke and actuator angle, and only has influence on the motion of carbody center of gravity.

When the height of carbody center of gravity to the rail top varies at 1500~1900mm and the tilting angle θ at -8^0~$+8^0$, the motion of carbody center of gravity with respect to θ is shown as Fig. 7. It is known that the increase of height of carbody center of gravity will increase the lateral motion of carbody center of gravity and slightly reduce the vertical motion of carbody center of gravity.

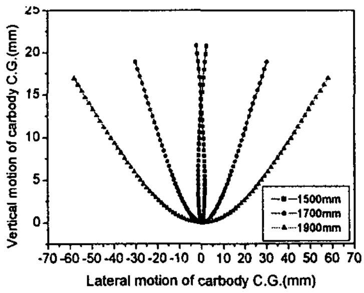


Figure 7. Influence of height of carbody C.G. on carbody C.G. motion

4. Conclusion

- The height of tilting center increases as the distance L_1 increases and the swing arm vertical angle decreases.
- The lateral and vertical motions of the tilting center increases as the distance L_1 increases and the distance L_2 decreases. Thus if want to reduce the motion of the tilting center, the distance L_1 should not be too large and the distance L_2 not too small.
- The large L_1 will increase the vertical motion of the carbody center of gravity and small swing arm vertical angle α will increase the vertical motion of it.
- The larger the L_1 is and the smaller the swing arm vertical angle is, the larger the change of actuator stroke is. Therefore L_1 cannot be too large and α not too small if want to have small actuator stroke.
- The increase of height of carbody center of gravity will increase the lateral motion of carbody center of gravity and slightly reduce the vertical motion of carbody center of gravity.

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This project about the development of tilting train for speed up in conventional railroad is supported by KNR (Korean National Railroad).