180km/h 급 한국형 틸팅차량의 틸팅대차용 엑츄에이터 성능 예측
Performance Prediction of Tilting Actuator for 180km/h Korea Tilting Train

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ABSTRACT

180km/h 급 한국형 틸팅차량의 틸팅 메카니즘 기구동역학 해석을 통하여 얻어진 틸팅 대차를 형성하는 주요 파라메터들의 값을 기반으로 틸팅대차용 엑츄에이터의 성능과 용량을 계산하여 설계에 결과를 반영하고자 한다. 승객의 안락감을 유지하기 위해 차체 틸팅 각가속도에 Sine 연속 함수를 적용하여 차체의 틸팅 제어 패턴을 결정하였으며, 이를 통해 차체의 틸팅 각속도와 틸팅 각의 패턴을 얻어내었다. 또한 이번 연구를 통해 틸팅 메카니즘의 파라메타를 변화하면서 각각의 틸팅각에 따른 Swing bar 와 엑츄에이터에 작용되는 반발력에 대한 영향력을 분석, 검토하였으며, 이에 따른 엑츄에이터의 출력과 변위 속도등의 변화를 조사하였다. 이러한 결과와 틸팅 메카니즘 기구동력학 해석의 결과를 토대로 틸팅차량이 요구하는 최적의 틸팅 운동을 수행하는 파라메타를 결정하였다.

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 kinematics and kinetics of the tilting mechanism for the Korea tilting bogie are analyzed. The kinematics and kinetics relations of the tilting mechanism are derived and the carbody control pattern is determined. The influences of the parameters of tilting mechanism on the tilting performance are carefully studied. Finally the optimized parameters of the tilting mechanism are chosen and the kinematics and kinetics performance are predicted

2. Determination of the Control Pattern of Carbody Tilting

In order to ensure the passenger ride comfort, the angular acceleration ε of carbody tilting should be a continuous function of time t which can be expressed as follows

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$$\varepsilon=\begin{cases}\varepsilon_m \sin\frac{\pi}{T_1}t & 0\le t<T_1\\ 0 & T_1\le t<T_1+T_2\\ -\varepsilon_m \sin\frac{\pi}{T_1}(t-T_1-T_2) & T_1+T_2\le t\le 2T_1+T_2\end{cases} \tag{1}$$

where ε_m is the maximum angular acceleration. T_1 is the time of half sine wave, i.e. the time spent for the carbody velocity from zero to maximum or from maximum back to zero. T_2 is the time of zero angular acceleration, i.e. the time of maintaining maximum velocity. Through integrating eq.(1), the formulas for the carbody tilting angular velocity and tilting angle with respect to t can be expressed as

$$\omega=\begin{cases}\frac{T_1\varepsilon_m}{\pi}(1-\cos\frac{\pi}{T_1}t) & 0\le t<T_1\\ \frac{2T_1\varepsilon_m}{\pi} & T_1\le t<T_1+T_2\\ \frac{T_1\varepsilon_m}{\pi}(1+\cos\frac{\pi}{T_1}(t-T_1-T_2)) & T_1+T_2\le t\le 2T_1+T_2\end{cases} \tag{2}$$

$$\theta=\begin{cases}\frac{T_1\varepsilon_m}{\pi}(t-\frac{T_1}{\pi}\sin\frac{\pi}{T_1}t) & 0\le t<T_1\\ \frac{T_1\varepsilon_m}{\pi}(2t-T_1) & T_1\le t<T_1+T_2\\ \frac{T_1\varepsilon_m}{\pi}[t+T_2+\frac{T_1}{\pi}\sin\frac{\pi}{T_1}(t-T_1-T_2)] & T_1+T_2\le t\le 2T_1+T_2\end{cases} \tag{3}$$

In the above formulas, it can be chosen that the maximum angular acceleration $\varepsilon_m=15^0/s^2$ and the maximum angular velocity $\omega_m=5.0^0/s$. Then we can obtain T_1=0.5236s from eq.(2) and T_2=1.0764s from eq.(3). Therefore the total time spent for the carbody tilting an angle 8^0 is $T=2T_1+T_2=2.1236s$, then the mean value of angular velocity is 3.767^0/s. The control pattern of the carbody tilting is described on Figs. 1~3.

For the tilting train, the carbody tilting action should be finished during the transition curve negotiation. In order that the carbody can reach maximum tilting angle 8^0 when running through the transition curve, the transition curve is required to have a minimum length. Thus the minimum length of transition curve with respect to vehicle forward speed can be calculated and listed in Table 1. For the first car, there always has time delay for the carbody tilting action caused by the measuring and control system. But for the latter cars the time delays can be compensated. The effect of the time delay Δt on the minimum length of transition curve is also considered in Table3.1. It is known that the higher the vehicle speed is and the larger the length of transition curve should be.

Table 1. Minimum length of transition curve v.s. speed V*

V (km/h)		100	120	140	160	180	200	220
Min. length (m)	Δt=0.0s	59.0	70.8	82.6	94.4	106.2	118.0	129.8
	Δt=0.1s	61.8	74.1	86.5	98.8	111.2	123.5	135.9
	Δt=0.2s	64.5	77.5	90.4	103.3	116.2	129.1	142.0
	Δt=0.3s	67.3	80.8	94.3	107.7	121.2	134.6	148.1

4. Dynamic Model of Tilting Mechanism

The forces acted on the carbody by the tilting mechanism is shown as Fig.4. In the figure, F indicates the output force of the actuator, F_1 and F_2 are the tensile force of the swing arms, Mg is the half carbody weight. The

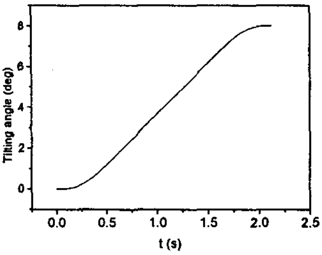


Fig.1 Carbody tilting angle

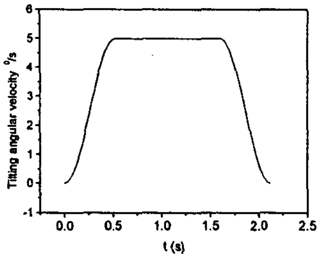


Fig.2 Carbody tilting angular velocity

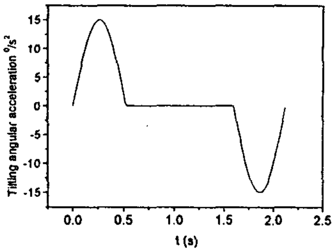


Fig.3 Carbody tilting angular acceleration

coordinates of C', D', G', F' are obtained by the kinematics relation of the tilting mechanism. The length $\overline{G'T}$ and $\overline{G'S}$, angles θ_1 and θ_2 of left and right swing arms, actuator angle β, and angles α_1 and α_2 of $G'C'$ and $G'D'$ to horizontal plane can be easily calculated. During the carbody tilting process, the lateral wind force on the carbody towards the inside of the curved track can also be considered. The lateral wind force F_e can be calculated by the time of wind pressure P_f and carbody side wall area A, that is $F_e=AP_f$. The roll moment acted on the carbody by the wind force can be expressed as

$$M_f = L[(H_C - H_0)^2 - (H - H_C)^2]P_f \cos\theta / 2 \tag{4}$$

where L、H_0、H and H_C indicate the length of carbody, the height of carbody and the height of carbody center of gravity respectively. Let the maximum unbalanced centrifugal acceleration of the carbody on circular curved track be g_m=2.0 m/s^2, then the unbalanced centrifugal acceleration on the transition curve can be expressed as $g_m\theta/8$ approximately. Thus, the dynamic equations of the half carbody model can be derived as below:

$$\begin{cases} M\ddot{y} = F\cos\beta + F_1\cos\theta_1 - F_2\cos\theta_2 + Mg_m\theta/8 + F_e \\ M\ddot{z} = F\sin\beta + F_1\sin\theta_1 + F_2\sin\theta_2 - Mg \\ I\ddot{\theta} = F\overline{G'T} + F_1(\cos\theta_1\overline{G'C'}\sin\alpha_1 - \sin\theta_1\overline{G'C'}\cos\alpha_1) - \\ \qquad F_2(\cos\theta_2\overline{G'D'}\sin\alpha_2 + \sin\theta_2\overline{G'D'}\cos\alpha_2) + M_f \end{cases} \tag{5}$$

where M and I are the half carbody mass and moment of inertia. The lateral and vertical acceleration of the carbody can be derived according to the tilting angle θ and the instantaneous rotary center S of carbody.

$$\ddot{y} = -\ddot{\theta}\overline{G'S}\cos\theta, \qquad \ddot{z} = -\ddot{\theta}\overline{G'S}\sin\theta \tag{6}$$

Substituting the above equation into eq.(5), the unknown forces F, F_1 and F_2 can be solved. Then the output velocity and power of the actuator can be calculated by

$$V_a = \dot{\theta}\overline{ST}, \quad P_a = FV_a \tag{7}$$

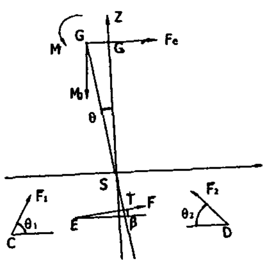


Fig.4. Forces acted on carbody

6. Parametric Determination, Kinematics and Kinetics Prediction

Through the parameter studies for the kinematics and kinetics of the tilting mechanism, the influence of the parameters on the performance indices of the tilting mechanism can be decided. Then in consideration of the space in the bogie and the possibility of the parameter realization, the optimized parameters of the tilting mechanism can be finally chosen as below:

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

Length of AB: L_1=680 mm

Length of swing arm AC and BD: L_2=505 mm

Angle of swing arm AC, BD to vertical axis: α=23.33^0

Height of electromechanical actuator EF to rail top: H_2=430 mm

Length of electromechanical actuator EF: EF=1050 mm

Carbody gravitational center G to rail top: H_C=1700mm

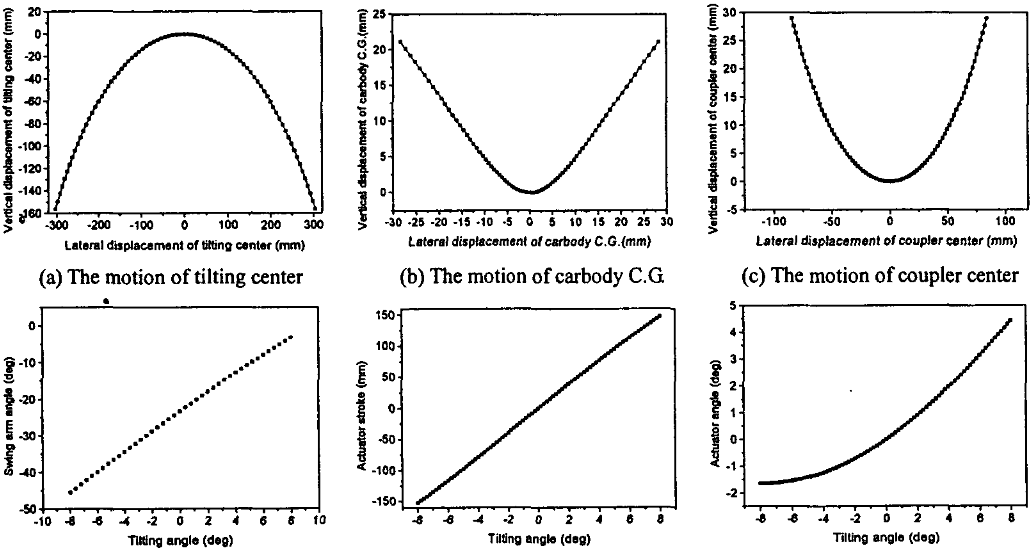
Coupler center Q to rail top: H_Q=890 mm

Tilting center P to rail top: H_P=1558.33 mm

The effect of the side wind force on carbody is considered in this section. The maximum side wind speed is 30m/s. Then side wind pressure P_f can be calculated by wind speed × air density × air resistance coefficient. Normally the air density is 1.29kg/m^3 and air resistance coefficient is 1.0. The parameters of the carbody sectional shape are L=23.03m, H_0=0.9245m, H=3.6895m. Two cases of without wind (P_f=0) and with wind (P_f=0.378 kN/m^2) are considered for the calculations.

6.1 Motion of Tilting Mechanism for chosen parameters

When the tilting angle θ varies at -8^0~+8^0, the motion of the tilting center of the tilting mechanism is shown as Fig.5(a). It is known that the maximum lateral and vertical displacements of the tilting center are: ±303.42 mm, -156.42 mm.



(a) The motion of tilting center (b) The motion of carbody C.G (c) The motion of coupler center

(d) The motion of swing arm angle (e) The stroke of actuator (f) The angular motion of actuator

Figure 5. Motion of tilting mechanism for chosen parameters at various tilting angle (θ = at -8^0~+8^0)

When the tilting angle θ varies at -8^0~+8^0, the motion of carbody center of gravity is shown as Fig. 5(b). It is known that the maximum lateral and vertical displacements of the carbody center of gravity are: ±28.41 mm, 21.514 mm.

When the tilting angle θ varies at -8^0~+8^0, the motion of coupler center of gravity is shown as Fig.5(c). It is known that the maximum lateral and vertical displacements of the coupler center are: ±84.32 mm, 29.03 mm.

When the tilting angle θ varies at -8^0~+8^0, the motion of swing arm angle of the tilting mechanism is shown as Fig.5(d). It can be seen that the range of motion of the swing arm angle is: -45.52^0~ -3.31^0.

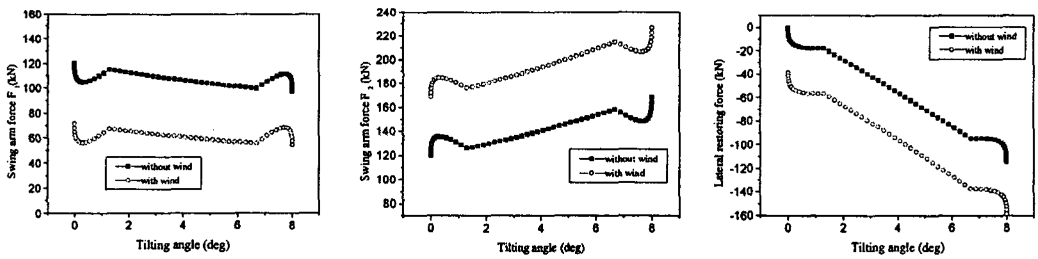
When the tilting angle θ varies at -8^0~+8^0, the stroke of the actuator is shown as Fig.5(e). It is known that the stroke of the actuator is: -152.11 ~147.80 mm.

When the tilting angle θ varies at -8^0~+8^0, the change of the actuator angle is shown as Fig.5(f). It can be seen from the result that the range of the actuator angular motion is: -1.64 ^{0}~4.44^0.

6.2 Reaction Force of Tilting Mechanism for chosen parameters

When the tilting angle θ varies at 0~8^0, the swing arm forces of the tilting mechanism are shown as Fig.6(a) and Fig.6(b). It can be seen that the maximum forces of swing arm AC and BD are: F_1=120.2kN (without wind), 71.47kN (with wind); F_2=168.3kN (without wind), 227.0kN (with wind).

When the tilting angle θ varies at 0~8^0, the lateral restoring force of the tilting mechanism is shown as Fig.6(c) It can be seen from the calculating results that the maximum lateral restoring force is: -114.5 kN (without), -158.8 kN (with wind).

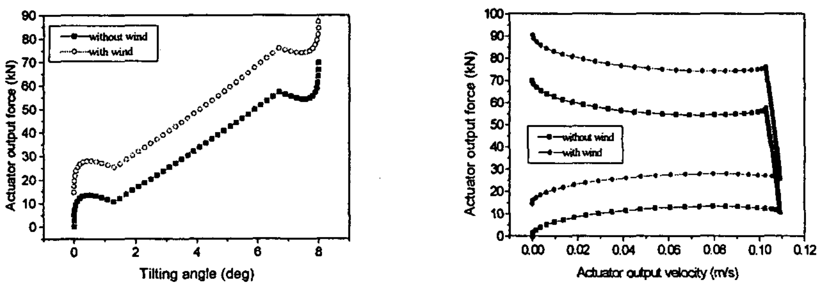


(a) The swing arm force F_1 (b) The swing arm force F_2 (c) The Lateral restoring force

Figure 6. Reaction Force of Tilting Mechanism for chosen parameters at various tilting angle (θ = at -8^0~+8^0)

6.3 The actuator force for chosen parameters

When the tilting angle θ varies at 0~8^0, the actuator force of the tilting mechanism is shown as Fig.7(a) and Fig.7(b). It can be seen from the calculating results that the maximum actuator output forces arw: 69.7 kN



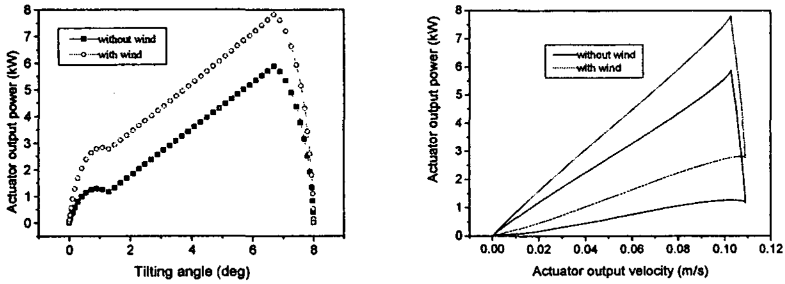
(a) For various tilting angle (b) For various actuator output velocity

Fig.7. Actuator output force

(without wind), 90.28 kN (with wind).

When the tilting angle θ varies at $0\sim8^0$, the actuator output power of the tilting mechanism is shown as Figs. 8 (a) and (b). It can be seen from the calculating results that the maximum actuator output powers are: 5.88 kW (without wind), 7.81 kW (with wind).

When the tilting angle θ varies at $0\sim8^0$, the actuator output velocity of the tilting mechanism is shown as Fig.9. It can be seen from the calculating results that the maximum actuator output velocity is: 0.109 m/s.



(a) For various tilting angle (b) For various actuator output velocity

Fig.8. Actuator output power

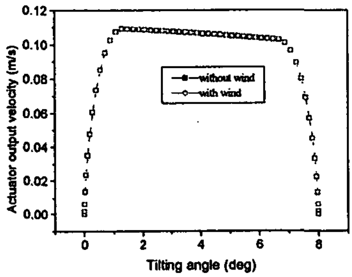


Fig.9. Actuator output velocity

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