Kinematic analysis and simulation of 6-DOF vehicle driving simulator

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Abstract. In order to reasonably design the six degrees of freedom turntable (hereinafter referred
as the transfer table), based on the structure size and motion index parameters of the turntable,
The motion mechanics calculation model was established to simulate and analyze the mechanical
variation curve of singing platform under different motion modes. The analysis shows that when
the upper platform load and the component mass are 3000 kg, the maximum action force of the
rotating platform support moving cylinder is 1376.4 kg.

1. Introduction
The six degrees of freedom transfer platform is a parallel platform that can move within six degrees of
freedom in space 3. It has the characteristics of high positioning accuracy, safe and reliable structure,
and strong load capacity, so it is widely used in the simulation training fields of vehicles, aircraft and
ships [1-3]. To design the six degrees of freedom platform, the kinematic and kinetic characteristics of
the platform should be studied. A large number of literature shows that there is more literature on
kinematic characteristics and less research dynamics. The kinetic research mainly analyzes the force
situation of the platform movement, which is the key to the platform structure design and power source
power selection.

According to the design requirements of the turning platform, the overall mathematical model,
dynamic model are established, and the force situation of 6 moving cylinders is simulated to provide a
basis for the engineering design of the moving cylinder.

2. Platform parameter size
According to the simulation driving training requirements, the platform load is 2000 kg, the platform
base installation size is 2580 mm × 2465 mm, 2500 mm × 2290 mm, the installation surface is 1168 mm
from the ground, the platform installation surface is 1668 mm from the ground, the movement
component weight of the upper platform and moving cylinder is about 1000 kg. According to the design
requirements, the structural parameters [4-6] of the upper and lower platform are shown in Figure 2, the
radius of the lower platform hinge circle R2 is 1055 mm, the short edge length d2 is 310 mm, the radius
of the upper platform hinge circle R1 is 835 mm, and the short edge length d1 is 304 mm. Acceleration
of up and down movement: 0.3g. Acceleration of the front and rear movement: 0.5g. Acceleration of the
left and right movements: 0.5g. Up and down motion distance: ±200 mm. Left and right motion
distance: ±200 mm. Front and rear motion distance: ±200 mm. Horizontal rolling motion
range:±20°. Subduction range of motion:±20°. Range of deflection:±20°. Angle acceleration:110°/s². There are motion parameters of the platform.

Figure 1. Six degrees of freedom transfer platform structure

Figure 2. Vertical view of the platform

3. Mathematical model

3.1 Hinges coordinate calculation

In order to facilitate the description of the spatial position of the six-degrees of freedom platform and the analysis of each moving cylinder, two coordinate systems are established: the brief model diagram of the static coordinate system O₀-X₀Y₀Z₀, moving frame Oₘ-XₘYₘZₘ, is shown in Figure 3.

Figure 3. 6-DOF Turntable coordinate model
3.2 Kinematic reverse solution
The six degrees of freedom transfer platform drives the reciprocating linear movement of the six moving cylinders. Therefore, at the known position and change angle of the rotating table, the length of each moving cylinder can be calculated through the upper platform position, and this process is reverse of kinematics. The force analysis of the moving cylinder thus provides dimensional and structural support.

Defines the upper platform around \(X, Y, Z\) axis rotation angle is \(\alpha, \beta, \gamma\) respectively after RPY transformation, the rotation matrix \(R\) is obtained, the \(O_m\) of the origin of \(O_m-X_mY_mZ_m\) in the fixed coordinate system \(O_s-XsYsZs\) is \((x_p, y_p, z_p)\), after the homogeneous transformation matrix \(T\), a point \(P_i\) in the dynamic coordinate system is set (\(i=1,2,..6\)). The homogeneous coordinate \(P\) in the fixed coordinate system after the above translation and rotation is the value of \(T \times P_i\).

\[
R = \begin{bmatrix}
    \cos \beta \cos \gamma & \sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma & \cos \alpha \cos \beta \sin \gamma + \sin \alpha \cos \gamma \\
    \cos \beta \sin \gamma & \cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma & -\cos \alpha \cos \beta \sin \gamma + \sin \alpha \cos \gamma \\
    -\sin \beta & \cos \beta \sin \gamma & \cos \alpha \cos \gamma
\end{bmatrix}
\]  
(1)

\[
T = \begin{bmatrix}
    x_p & y_p & z_p & 1 \\
    \cos \beta \cos \gamma & \sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma & \cos \alpha \cos \beta \sin \gamma + \sin \alpha \cos \gamma & x_p \\
    \cos \beta \sin \gamma & \cos \alpha \sin \beta \cos \gamma + \sin \alpha \sin \gamma & -\cos \alpha \cos \beta \sin \gamma + \sin \alpha \cos \gamma & y_p \\
    -\sin \beta & \cos \beta \sin \gamma & \cos \alpha \cos \gamma & z_p
\end{bmatrix}
\]  
(2)

3.3 Analysis of motion mechanics
The motion mechanical analysis mainly analyzes the force situation of 6 moving cylinders under different operating posture, analyzes the mechanical change rules of 6 moving cylinders, and provides a theoretical analysis basis for the design of the moving cylinder.

In the process of movement, in addition to the dead weight and load of the upper platform and the components, the platform movement process is also affected by the acceleration and movement torque. Therefore, the analysis of the platform during movement is needed. The forces and moments of the six degrees of freedom platform in the three spatial directions are balanced:

\[
-\sum_{i=1}^{6} F_{zi} + F_g = Mg + M \times \alpha_z
\]  
(3)

\[
\sum_{i=1}^{6} F_{xi} = M \times \alpha_x
\]  
(4)

\[
\sum_{i=1}^{6} F_{yi} = M \times \alpha_y
\]  
(5)

According to the torque balance conditions of the horizontal roll:

\[
\sum_{i=1}^{6} F_{zi} \times y_i = Mg \times y_{z0} + M_t
\]  
(6)

According to the torque balance conditions of the horizontal roll:

\[
\sum_{i=1}^{6} F_{xi} \times x_i = Mg \times x_{z0} + M_t
\]  
(7)

According to the torque balance conditions of the horizontal roll:

\[
\sum_{i=1}^{6} F_{yi} \times x_i + \sum_{i=1}^{6} F_{xi} \times y_i = M_t
\]  
(8)

In: \(\alpha_x\) : The X-axis direction acceleration. \(\alpha_y\) : The Y-axis direction acceleration. \(\alpha_z\) : The Z-axis direction acceleration. \(M_t\) : Horizontal roll torque. \(M_t\) : The torque of pitch direction. \(M_t\) : The torque of yaw direction. \(F_g\) : The gravity of the 6 moving cylinders, unit: N; \(M_t\) : Moment of the moving cylinder on the static coordinate system, unit: N·mm;
For calculation, the platform is rectangular and the size is $a \times b \times c = 1000 \text{mm} \times 1000 \text{mm} \times 50 \text{mm}$. The inertia in the rolling direction:

$$I_z = \frac{1}{3}MR^2 = \frac{1}{12}Mb^2$$  \hspace{1cm} (9)

Horizontal roll torque:

$$M_z = I_z\alpha_z = \frac{1}{12}Mb^2\alpha_z$$  \hspace{1cm} (10)

Similarly, the torque of pitch, yaw direction can be obtained:

$$M_y = \frac{1}{12}Ma^2\alpha_y$$  \hspace{1cm} (11)

$$M_z = \frac{1}{12}M(a^2 + b^2)\alpha_z$$  \hspace{1cm} (12)

Simulation analyzes the force situation of 6 moving cylinders under different operating conditions. Simulation results in typical operating environment are as follows:

Under the horizontal rolling motion, the simulated angular velocity and angular acceleration reach the maximum state, and the simulation results are shown in Figure 4. Translation along the Z-axis, the simulation results are shown in Figure 9. According to the figure, the maximum bearing capacity of the moving cylinder is 1,187.6 kg.

![Figure 4. Plot of kinetic analysis during horizontal rolling motion](image)

![Figure 5. Kinetics analysis during pitch motion](image)
Figure 6. Analysis of the kinetics during yaw motion

Figure 7. Kinetics analysis during the X-axis translation motion

Figure 8. Kinetics analysis during the Y-axis translation motion
4. Conclusion
According to the structural parameters and technical index parameters of the six degrees of freedom platform, the motion mechanics analysis model of the six degrees of freedom platform was established, and performed static analysis and kinetic analysis using MATLAB software. According to the kinetic analysis, the maximum action force of 6 moving cylinders is 1376.4 kg. For the dynamic cylinder design selection, the maximum acting force must be greater than 1500 kg.

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