Steering body-tire angle control strategy optimization of wide-body airplane ground turning

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Abstract. The wide-body airplane's unsynchronous coordination of the inner and outer steering body-tires turning angle during the ground turning process will increase the lateral force of the tires and cause side slip accidents. This paper considers the dissymmetry of the inner and outer steering body-tire turning angles during the ground turning process, calculates the theoretical turning angle mathematical relationship between nose-tire and steering body-tire, optimizes the steering body-tire control strategy from "symmetric turning angle control strategy" to "dissymmetric turning angle control strategy". By comparison, the optimized "dissymmetric turning angle control strategy" can effectively reduce the lateral force of steering body-tires during the ground turning process, decrease the risk of side slip accidents and tire abrasion. Besides, the optimized "dissymmetric turning angle control strategy" can reduce the lateral force difference between the inner and outer steering body-tires during the ground turning process, making the lateral force distribution more balanced, reducing the damage to landing gear structure caused by unbalanced lateral force and extending the service life of body landing gear.

1. Introduction
The safety and performance of airplane are closely related to the ground turning control skill [1]. With the development of large airplane technology, foreign wide-body airplane such as A380 and B747 generally use nose-tire and steering body-tire cooperative turning control when turning on the ground. Since the turning radius of the body landing gear on both sides are different when turning, the inner steering body-tires needs larger turning angle, the outer steering body-tires needs smaller turning angle. If the inner and outer steering body-tires can’t keep synchronous coordination, steering body-tires’ lateral force will increase and cause side slip accidents when the airplane is turning at large angles or high velocity [2]. In this paper, the steering body-tire control strategy is optimized based on the lateral force of tires on body landing gears.

2. Steering body-tire control strategy
The landing gear layout of the certain type wide-body airplane is shown in figure 1. It includes a nose landing gear, two body landing gears, 14 tires in total [3].During the ground turning process, when the nose-tire turn through a certain angle, the steering body-tire will turn rotate a small angle in reverse direction to help nose-tire complete the airplane ground turning action.
2.1. Symmetric turning angle control strategy
At present, the airplane use "symmetric turning angle control strategy" during the ground turning process. When the nose-tire turns $\alpha$, the inner and outer steering body-tire turning angle $\varphi_1, \varphi_2$ calculation method is shown in equation 1. The relationship between steering body-tire’s turning angle $\varphi_1, \varphi_2$ and the nose-tire turning angle $\alpha$ is shown in figure 2. Under this control strategy, the inner and outer steering body-tire angles are equal.

\[
\varphi_1 = \varphi_2 = \begin{cases} 
-0.14 \times (\alpha - 13) & \quad 13 < \alpha < 70 \\
0 & \quad -13 \leq \alpha \leq 13 \\
-0.14 \times (\alpha + 13) & \quad -70 < \alpha < -13 
\end{cases}
\]  

(1)

$$\alpha$$ – tire1, tire2 turning angle ; $\varphi_1$ – tire13, tire14 turning angle ; $\varphi_2$ – tire7, tire8 turning angle.

2.2. Dissymmetric turning angle control strategy
According to the Ackermann principle [4], to ensure the smooth and controllable process of the airplane ground turning, there can only be one turning center point at any time, as shown in figure 3. Based on the airplane landing gear layout, the theoretical turning angle mathematical relationship between nose-tire and steering body-tire turning angle is calculated by equation 2, 3, the result is shown in figure 4.

\[
\varphi_1 = \arctan\left(\frac{L_3}{L_4}\right) = \arctan\left[\frac{L_3}{L_2 \cot \alpha - L_3 / 2}\right]
\]

(2)

\[
\varphi_2 = \arctan\left(\frac{L_3}{L_6}\right) = \arctan\left[\frac{L_3}{L_2 \cot \alpha + L_3 / 2}\right]
\]

(3)
It is calculated that when the nose-tire turning angle is less than 13°, the theoretical turning angles of the steering body-tire on both sides don’t exceed 1°. It can be approximated that the steering body-tires haven’t participated in the turning process at this stage. Besides, the wide-body airplane such as A380, B747 adopt linear steering body-tire control strategy currently. After comprehensive consideration, modifying the theoretical turning angle mathematical relationship between nose-tire and steering body-tire turning angle, obtaining the “dissymmetric turning angle control strategy”, as shown in figure 5. At this point, the angle of nose-tire and steering body-tire satisfies the equation 4, 5. Since the inner steering body-tire turning angle is always larger than the outer under this control strategy, it is called "dissymmetric turning angle control strategy".

\[
\varphi_1 = \begin{cases} 
-0.72 \times (\alpha - 42) & 50 \leq \alpha \leq 70 \\
-0.16 \times (\alpha - 13) & 13 < \alpha < 50 \\
0 & -13 \leq \alpha \leq 13 \\
-0.16 \times (\alpha + 13) & -50 < \alpha < -13 \\
-0.72 \times (\alpha + 42) & -70 \leq \alpha \leq -50 \\
-0.126 \times (\alpha - 13) & 13 \leq \alpha \leq 70 \\
0 & -13 < \alpha < 13 \\
-0.126 \times (\alpha + 13) & 70 \leq \alpha \leq -13 
\end{cases}
\]  

\( \varphi_2 \) – tire1, tire2 turning angle; \( \varphi_1 \) – tire13, tire14 turning angle; \( \varphi_2 \) – tire7, tire8 turning angle.

Comparing figure 5 & figure 4, figure 3 & figure 4, the optimized "dissymmetric turning angle control strategy" is much closer to the \( \alpha & \varphi_1, \varphi_2 \) theoretical relationship than the "symmetric turning angle control strategy". So the optimized "dissymmetric turning angle control strategy" is more suitable for ground turning control of the airplane.

3. Ground turning motion model

Based on the ground turning motion of the airplane, the following assumptions are made for the kinetic model: the airplane keeps the height of the gravity center unchanged during the turning process; and the fuselage is parallel to the ground [5]; using the trajectory of the airplane’s gravity center to represent the airplane’s trajectory; airplane ground turning is usually low-speed movements, the aerodynamic forces influence can be ignored [6]; ignoring the instantaneous center's own acceleration influence [7]; the multi-tire landing gear is simplified as a single tire [8].

Taking any moment of the airplane's ground turning as analysis scene, the airplane’s force situation is shown in figure 6. Establish a fixed ground coordinate system \( xoy \) and a dynamic coordinate system \( x'o'y' \).
Figure 6. Ground turning force analysis diagram.

$F_E$ – Engine thrust, $F_G$ – Head resistance, $N_N$ – Lateral force of nose landing gear;

$N_M$ – Lateral force of body landing gear, $T_N$ – Friction force of nose landing gear;

$T_M$ – Friction force of body landing gear, $\alpha$ – nose tire turning angle, $o'$–Airplane gravity center,

$V_C$ – Velocity of airplane, $L_B$ – Distance between body landing gear.

3.1. Analysis of airplane ground motion

The airplane's velocity along the $x, y$ direction and angular velocity around the $z$ axis is:

$$a_x = dV_x / dt = d^2 x / d^2 t = dV_C / dt \cdot \cos(\beta + \sigma) - V_C \cdot \sin(\beta + \sigma) \cdot (d\beta / dt + d\sigma / dt)$$

$$a_y = dV_y / dt = d^2 y / d^2 t = dV_C / dt \cdot \sin(\beta + \sigma) + V_C \cdot \cos(\beta + \sigma) \cdot (d\beta / dt + d\sigma / dt)$$

$$a_z = dw / dt = dV_C / dt \cdot \sin \beta / b + V_C \cos \beta / b \cdot d\beta / dt$$

3.2. Analysis of airplane ground turning forces

The airplane's resultant force along the $x, y$ direction and torque around the $z$ axis is:

$$F_x = F_E - F_G - T_M - N_N \sin \alpha - T_N \cos \alpha$$

$$F_y = N_M + N_N \cos \alpha - T_N \sin \alpha$$

$$M_z = N_N \cdot (a \cos \alpha - e) - T_N a \sin \alpha = -N_M b$$

3.3. Airplane ground motion equation

The airplane's motion equation along the $x, y$ direction and around the $z$ axis is:

$$F_x = F_x' \cos \sigma - F_y' \sin \sigma = ma_x$$

$$F_y = F_x' \sin \sigma + F_y' \cos \sigma = ma_y$$

$$M_z = Ja_z$$

Establish force balance equation along the $o'n$ direction:

$$mV_C^2 / \rho = N_M \cos \beta + N_N \cos(\alpha - \beta) - T_N \sin(\alpha - \beta) - (F_E - F_G - T_M) \sin \beta$$

In combination with the above equations, the lateral force of the body landing gear is:

$$N_M = -\frac{d\alpha}{dt} \frac{V_C \cos^2 \beta}{L \cos^2 \theta} - T_N \frac{g_3(\alpha)}{g_1(\alpha)} + (F_E - T_M) \frac{g_3(\alpha)}{g_1(\alpha)} + \left( \frac{mV_C^2 \cos \beta}{r} \right) \frac{g_4(\alpha)}{g_1(\alpha)}$$
\[
g_1(\alpha) = \frac{1}{J \cos \beta} \left[ b + \frac{\cos \beta (a \cos \alpha - e)}{\cos (\alpha - \beta)} \right] + \frac{\sin \beta \cos \beta \sin \alpha}{bm \cos (\alpha - \beta)} + \frac{\sin^2 \beta}{bm^2 \cos^2 \beta} \left[ 1 - \frac{\cos \beta \cos \alpha}{\cos (\alpha - \beta)} \right]
\]

\[
g_2(\alpha) = \frac{1}{J \cos \beta} \left[ a \sin \alpha - \frac{\sin (\alpha - \beta) (a \cos \alpha - e)}{\cos (\alpha - \beta)} \right] - \frac{\sin \beta}{bm} \left[ \cos \alpha \cos (\alpha - \beta) + \sin (\alpha - \beta) \sin \alpha \right]
\]

\[
- \frac{\sin^2 \beta}{bm \cos^2 \beta} \left[ \sin \alpha - \frac{\sin (\alpha - \beta) \cos \alpha}{\cos (\alpha - \beta)} \right]
\]

\[
g_3(\alpha) = \frac{1}{J \cos \beta} \left[ \frac{\sin (\alpha - \beta) (a \cos \alpha - e)}{\cos (\alpha - \beta)} \right] - \frac{\sin \beta}{bm} \left[ 1 - \frac{\sin \beta \sin \alpha}{\cos (\alpha - \beta)} \right] - \frac{\sin^2 \beta}{bm \cos^2 \beta} \left[ \sin \beta \cos \alpha \right]
\]

\[
g_4(\alpha) = \frac{1}{J \cos \beta} \left[ \frac{(a \cos \alpha - e)}{\cos (\alpha - \beta)} \right] + \frac{\sin \beta}{bm \cos (\alpha - \beta)} - \frac{\sin^2 \beta}{bm \cos^2 \beta} \cos \alpha
\]

\[N_{M1} : N_{M2} = (r + L_B / 2) : (r - L_B / 2)
\]

3.4. Lateral force calculation of steering body-tire

The calculation method of each tire’s lateral force of multi-tire landing gear can be found in the aircraft design manual. To calculate the actual lateral force of steering body-tire, the steering body-tire turning angle influence need to be taken into account [9], as shown in figure 7. The calculation formula of the actual lateral force and friction force of the steering body-tire satisfies the equation 22, 23.

![Figure 7. Steering body tire force analysis diagram.](image)

\[
N_{M1} = N_m \cos \varphi_i + T_m \sin \varphi_i
\]

\[
T_{M1} = T_m \cos \varphi_i - N_m \sin \varphi_i
\]

4. Setting of ground turning conditions

According to literature review, to ensure that there is no side slip during ground turning, the velocity of a foreign trunk airplane during ground turning is controlled below \( 18km/h \) \((5m/s)\), and a regional airplane is controlled below \( 24km/h \) \((6.67m/s)\) [10]. In conclusion, the ground turning velocity of the airplane selected in this paper is \( 3m/s \), \( 5m/s \) and \( 7m/s \), and the nose-tire turning angle’s range is \( 20^\circ \) - \( 70^\circ \) [11].

5. Comparative analysis of body landing gear tire lateral force

5.1. Comparative analysis of steering body-tire’s lateral force

The body landing gears include four steering body-tires, tire 7, tire 8 on the outer body landing gear, tire 13, tire 14 on the inner body landing gear. The lateral force calculation results are shown in the table 1, table 2.

According to table 1, the optimized "dissymmetric turning angle control strategy" can reduce the lateral force of tire 7, tire 8, and the lateral force reduction effect is more obvious when the airplane is
turning at large angles or high velocity.

According to table 2, the optimized "dissymmetric turning angle control strategy" can reduce the lateral force of tire 13, tire 14, and the lateral force reduction effect is more obvious when the airplane is turning at large angles or high velocity. Besides, the lateral force falling range of tire 13, tire 14 is bigger than tire 7, tire 8.

Table 1. Lateral force of tire 7, tire8.

| Nose tire turning angle (°) | Velocity (m/s) | Lateral force of tire7 (N) | Falling range | Lateral force of tire8 (N) | Falling range |
|----------------------------|----------------|-----------------------------|---------------|-----------------------------|---------------|
|                            | Symmetric     | Dissymmetric                |               | Symmetric                  | Dissymmetric |
| 20                         | 3              | 6249                        | 6098          | 2.41%                      | 9328          | 9107          | 2.38%          |
| 30                         | 3              | 9597                        | 9359          | 2.48%                      | 14285         | 13940         | 2.42%          |
| 40                         | 3              | 13278                       | 12943         | 2.52%                      | 19743         | 19258         | 2.46%          |
| 50                         | 3              | 17501                       | 17046         | 2.60%                      | 26012         | 25354         | 2.53%          |
| 60                         | 3              | 22335                       | 21720         | 2.75%                      | 33199         | 32307         | 2.69%          |
| 70                         | 3              | 26017                       | 25232         | 3.02%                      | 38658         | 37518         | 2.95%          |
| 70                         | 5              | 72016                       | 69785         | 3.10%                      | 107655        | 104347        | 3.07%          |
| 70                         | 7              | 141013                      | 136614        | 3.12%                      | 211152        | 204591        | 3.11%          |

In conclusion, the optimized "dissymmetric turning angle control strategy" can effectively reduce the lateral force of steering body-tires, and the lateral force reduction effect is more obvious when the airplane is turning at large angles or high velocity. It's beneficial to decrease the risk of side slip accidents and tire abrasion.

5.2. Comparative analysis of two sides steering body-tire’s lateral force difference

The lateral force difference calculation results are shown in table 3.

Table 3. Lateral force difference between two sides steering body-tire.

| Nose-tire turning angle (°) | Velocity (m/s) | Symmetric | Dissymmetric | Falling range |
|-----------------------------|----------------|-----------|--------------|---------------|
| 20                          | 3              | 2142      | 2098         | 2.08%         |
| 30                          | 3              | 5394      | 5266         | 2.39%         |
| 40                          | 3              | 11405     | 11042        | 3.18%         |
| 50                          | 3              | 23034     | 22104        | 4.04%         |
| 60                          | 3              | 48707     | 45580        | 6.42%         |
| 70                          | 3              | 121953    | 107481       | 11.87%        |
| 70                          | 5              | 343845    | 298157       | 13.29%        |
| 70                          | 7              | 676683    | 584172       | 13.67%        |
According to table 3, the optimized "dissymmetric turning angle control strategy" can decrease the lateral force difference between the inner and outer steering body-tires, making the lateral force distribution more balanced, reducing the damage to landing gear structure caused by unbalanced lateral force and extend the service life of body landing gear.

6. Conclusion
This paper considers the dissymmetry of the inner and outer steering body-tire turning angles during the ground turning process, optimizes the steering body-tire control strategy from "symmetric turning angle control strategy" to "dissymmetric turning angle control strategy". By comparison:

(1) The optimized "dissymmetric turning angle control strategy" can effectively reduce the lateral force of body landing gear’s steering body-tires, decrease the risk of side slip accidents and tire abrasion.

(2) The optimized "dissymmetric turning angle control strategy" can decrease the lateral force difference between the inner and outer steering body-tires, making the lateral force distribution more balanced, reducing the damage to landing gear structure caused by unbalanced lateral force and extend the service life of body landing gear.

In conclusion, the optimized "dissymmetric turning angle control strategy" can improve the safety of airplane ground turning and provide reference for the study of wide-body airplane ground control method.

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