Experimental Analysis for Determination of Longitudinal Friction Coefficient Function in Braking Tractor Semi-trailer

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1. INTRODUCTION

The movement of the vehicle depends on the tire-road forces Fₓ, Fᵧ, F⟂. The tire-road forces Fₓ, Fᵧ, F⟂ are usually determined by the tire model and they depend on the tire-road friction coefficient [1-3].

\[ Fₓ(t) = Fₓ(t)φₓ(t) \] (1)

\[ Fᵧ(t) = Fᵧ(t)φᵧ(t) \] (2)

Therefore, the longitudinal friction coefficient function by time can be determined:

\[ φₓ(t) = \frac{Fₓ(t)}{Fₓ(t)} \] (3)

Thus, in order to determine the longitudinal friction coefficient function \( φₓ(t) \), \( Fₓ(t) \) and \( Fᵧ(t) \) should be known [4].

2. THEORETICAL BASES

The method of separating structure of the multi-object system for the vehicle dynamic model \( \frac{1}{4} \) is used as shown in Figure 1, the equation of vehicle movement is as follows [5]:

\[ m\ddot{x} = F_{C} + F_{K} \]
\[ m_{a}\ddot{z} = F_{CL} - (F_{C} + F_{K}) \]
\[ (m + m_{a})\ddot{x} = F_{x} + F_{w} \]
\[ F_{z} = F_{G} + F_{CL} \]

Or

\[ \begin{cases} F_{x} = (m + m_{a})\ddot{x} - F_{w} \\ F_{z} = F_{G} + m\ddot{z} + m_{a}\ddot{z} \end{cases} \] (5)

The longitudinal slip coefficient of the wheel by time is determined by the following Equations (6) and (7).

The longitudinal slip coefficient of the wheel when braking [6, 7]:

\[ s_{x}(t) = \frac{\tau_{y} φ_{y}(t) - \ddot{x}(t)}{\dot{x}(t)} ; \tau_{y} φ_{y}(t) < \ddot{x}(t) ; -1 < s_{x} < 0 \] (6)
The longitudinal slip coefficient of the wheel when accelerating [5, 6, 8]:

\[ s_x(t) = \frac{r_d \dot{\phi}(t) - \ddot{x}(t)}{r_d \Phi(t)} \quad ; \quad r_d \dot{\phi}(t) > \ddot{x}(t) ; 0 < s_x < 1 \quad (7) \]

So in order to determine the longitudinal friction coefficient function of the wheel according to the longitudinal slip coefficient \( \varphi_x(s_x) \), the longitudinal friction coefficient function by time \( \varphi_x(t) \) should be known as in formula (3) and the longitudinal slip coefficient function by time \( s_x(t) \) as in formula (6,7). The longitudinal friction coefficient function according to the longitudinal slip coefficient is shown in Figure 2 [9, 10].

3. EXPERIMENT AND SIMULATION

3.1. Experiment  In this paper, a 6-axle tractor semi-trailer was chosen for experiment. During the experiment, the braking systems of the axles I, II, III, IV, V were adjusted to stop working. The diagram for installation of the experimental sensor is shown in Figure 3.

To determine the longitudinal friction coefficient function of the wheel according to the longitudinal slip coefficient \( \varphi_x(s_x) \), the following 6 parameters were experimentally determined: Measurement of the longitudinal velocity of the tractor semi-trailer \( (\dot{x}) \) by Kistler GPS sensor (1); measurement of the longitudinal acceleration \( (\ddot{x}) \) and vertical acceleration \( (\dddot{z}) \) of the tractor semi-trailer by MMA7361LC-XYZ sensor (2,3); measurement of the vertical acceleration \( (\dddot{z}) \) of the axle by MMA7361LC-XYZ sensor (4); measurement of the wheel angular velocity \( (\dot{\phi}) \) by Sharp Rotary Encoder sensor (5); weighing the un-sprung mass \( (m_s) \) and the sprung mass \( (m) \) with ULSTRALIM electronic balance (6). Diagram of the measurement system, signal reception and braking experimental result processing of the tractor semi-trailer are shown in Figure 4 [11, 12].

Let the tractor semi-trailer moved steadily on the dry asphalt at a speed of 50 km/h and then brake to let the tractor come to a complete stop. Based on 6 parameters determined by the experiment, the computer processed and output graphs \( F_C(t), F_Z(t), F_{CL}(t), s_x(t), s_i(t), \varphi_x(s_x) \) as shown in Figures 5, 6, 7 and 8. The longitudinal friction coefficient function of the wheel according to the longitudinal slip coefficient \( \varphi_x(s_x) \) is shown in Figure 9.

The experimental results show that the value and shape of the graphs \( F_C(t), F_Z(t), \varphi_x(t), s_x(t), s_i(t) \) are consistent with the theoretical rules. When braking the tractor semi-trailer on the dry asphalt, the maximum longitudinal friction coefficient is \( \varphi_{xmax}=0.89 \) and the minimum longitudinal friction coefficient is \( \varphi_{xmin}=0.72 \),
the value of the longitudinal friction coefficient was determined by experiment equivalent to theoretical value.

3.2. Simulation

Matlab-Simulink software was used to investigate and compare the longitudinal friction coefficient function of the wheel according to the longitudinal slide coefficient \( \phi_x(s_x) \) determined by experiment and the function \( \phi_x(s_x) \) simulated according to Ammon tire model on the same type of road with the maximum longitudinal friction coefficient \( \phi_{x_{\text{max}}} = 0.89 \) and the minimum longitudinal friction coefficient \( \phi_{x_{\text{min}}} = 0.72 \) [4, 5]. The results of function simulation \( \phi_x(s_x) \) by experiment and according to Ammon tire model are shown in Figure 10. The survey results showed that the average error between experiment (the longitudinal friction coefficient function \( \phi_x(s_x) \) determined by experiment) and theory (the longitudinal friction coefficient function \( \phi_x(s_x) \) determined by Ammon tire model) was about 17%.

The function \( \phi_x(s_x) \) determined by experiment and function \( \phi_x(s_x) \) determined by Ammon tire model were used as an input to the dynamic survey model of the tractor semi-trailer as in Figures 11 and the system of dynamic equations of the tractor semi-trailer as formulas (8-49).
The system of dynamic equations of the tractor semi-trailer are as follows [5]:

\[
\begin{align*}
    m_{c1}\ddot{x}_{c1} &= F_{x1} - F_{wx1} - F_{kx1}(i = 1 - 3) \\
    m_{c1}\ddot{y}_{c1} &= F_{y1} - F_{wy1} - F_{ky1}(i = 1 - 3) \\
    J_{zc1}\ddot{\psi}_{c1} &= (F_{x1} + F_{kx1} + F_{wx1} - F_{ky1} - F_{ky1}l_{k1} + (F_{kx1} - F_{ky1}l_{k1})b_{1}) \\
    m_{c2}\ddot{x}_{c2} &= F_{x2} + F_{kx2}(i = 4 - 6) \\
    m_{c2}\ddot{y}_{c2} &= F_{kx2} - F_{y2}(i = 4 - 6) \\
    J_{zc2}\ddot{\psi}_{c2} &= (F_{x2} - F_{kx2}b_{1} + F_{kx2}k_{2} - F_{kx2}l_{k2})(i = 4 - 6) \\
    m_{c1}\ddot{x}_{c1} &= F_{ci} + F_{ki} - F_{kx1}(i = 1 + 3) \\
    J_{yc1}\ddot{\phi}_{c1} &= (F_{ci} + F_{ki}b_{1} + F_{kx1}l_{k1} - F_{kx1}h_{k1} - M_{ij}(i = 1 + 3) \\
    m_{c2}\ddot{x}_{c2} &= F_{ci} + F_{ki} + F_{kx2}(i = 4 + 6) \\
    J_{yc2}\ddot{\phi}_{c2} &= -(F_{ci} + F_{ki}b_{1} + F_{kx2}h_{k2} - F_{kx2}k_{2} + M_{ij}(i = 4 + 6) \\
    J_{xc1}\ddot{\beta}_{c1} &= (F_{kx1} + F_{ci} - F_{kx1} - F_{kx1}h_{k1})w_{l} + M_{kx1}(i = 1 + 3) \\
    J_{xc2}\ddot{\beta}_{c2} &= (F_{kx1} + F_{ci} - F_{kx1} - F_{kx1}h_{k1})w_{l} - M_{kx2}(i = 4 + 6) \\
    m_{ai}\ddot{z}_{ai} &= F_{xci} + F_{kci} - F_{kx1}(i = 1 + 6)
\end{align*}
\]

Graphs of force F₁, F₂ surveyed by Matlab-Simulink software with the input function \( \phi_x(s_x) \) determined by experiment and Ammon function are presented in Figures 12 and 13. The survey results showed that when the input function \( \phi_x(s_x) \) determined by experiment and Ammon function were used, the average error of force \( F_1 \) was 11,81% and the average error of force \( F_2 \) is 19% and 25%.

The obtained results determined by the experiment had shapes and values consistent with theoretical rules as well as research results of many other authors [8, 11, 12].
4. CONCLUSION

The longitudinal friction coefficient function \( \phi_x(s_x) \) can be determined by measuring the longitudinal velocity of the vehicle \( (\dot{x}) \), the longitudinal acceleration of the vehicle \( (\ddot{x}) \), the vertical acceleration of the body \( (\ddot{z}) \), the vertical acceleration of the axle \( (\ddot{\varphi}) \), the wheel angular velocity and weighing the vehicle weight. The experimental results can be used to study the dynamics of the tractor semi-trailer and other types of vehicles on actual roads.

5. REFERENCES

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Persian Abstract

ضریب اصطکاک طولی پارامتر بسیار مهمی برای محاسبه دینامیک خودرو است. از ضریب اصطکاک طولی نظری اغلب برای بررسی پویایی خودرو استفاده می‌شود. با این حال، ضریب اصطکاک طولی به‌ویژه در حالت حرکت در جاده واقعی تغییر می‌کند. در این مقاله روش آزمایشی برای تعیین ضریب اصطکاک طولی نیمه تریلر تراکتور در جاده ارائه شده است. نتایج آزمایش نشان داد که هنگام ترمز نیمه تریلر تراکتور روی آسفالت خشک، حداکثر ضریب اصطکاک طولی \( \phi_{x_{\text{max}}} = 0.89 \) و حداقل ضریب اصطکاک طولی \( \phi_{x_{\text{min}}} = 0.72 \) می‌باشد. از نرم‌افزار Matlab-Simulink برای شبیه‌سازی سیستم‌های دینامیکی استفاده شد. نتایج تحقیقات نشان داد که مدل‌های تک‌محوری نمی‌توانند به‌طور کامل ضریب اصطکاک طولی را توصیف کنند.