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# Aircraft Ground Braking Assistant Control Based on Pilot Control Model

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**ABSTRACT** Aircraft ground braking control is a complex time-varying dynamic problem, especially when there are unexpected disturbances from lateral wind or visual error. Therefore, under some extreme conditions, it is hard for the pilot to control aircraft braking as well as usual without assistant control. This paper solves this problem by proposing a novel assistant control for aircraft ground braking, mainly based on the pilot control model and the LPV theory. And in order to reflect the control characteristics of the pilot, the sensory and control-theoretic model were combined together for controller designing. To test the performance of proposed control method, a real time pilot-in-loop simulation system is constructed. According to experiment results, the proposed assistant control shows better performance than pilot control, for it not only help the pilot to resist disturbance, but also hardly run counter to the pilot's intent.

**INDEX TERMS** Aircraft ground braking, pilot assistant control, pilot-aircraft system, real time simulation, linear parameter variant.

## I. INTRODUCTION

Since there are lots of aircraft accidents during landing, aircraft ground brake control has become one of the most important issues during the landing procedures. Meanwhile, more than 70% of the fatal aviation accidents were due to pilot factors, mainly because of the poor manipulation behavior [1]. Sometimes when aircraft ground braking, unexpected disturbance from lateral wind and pilot visual error would make the condition even harder to deal with [2]. Moreover, the driver assistance system and pilot flight assistance has been researched in several years [3], [4]. Therefore, the pilot assistant control system for aircraft ground braking is also valuable to study.

The research on pilot control model would also be important in this study, because the pilot assistant control problem is highly related to pilot behavior and control mode, and some well-known method for pilot control system synthesis is already widely used in practice, such as model following control [5]. The study in [2] introduced a lot of pilot models in aircraft flight dynamics in details, in which the integrated pilot models mainly including 3 parts: sensory dynamics, biodynamic modelling and control-theoretic pilot models.

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Among these models, the visual system models of sensory dynamics and quasi-linear models of control-theoretic pilot models, discussed by Hess, Kleinman, McReur and Neal-Smith handling qualities criteria [6]–[9], have introduced simple models for visual observation, source of error and pilot dynamics mechanism, which are of referential significance to this paper. And the studies in [10], [11] provides descriptions for concrete control theoretical models such as Gross model and relevant parameters. For vehicle ground braking, especially, reference targets such as inclination of runway sidelines, near and far angle are important for pilot lateral control modelling, which are discussed in [12]–[14]. As for obtaining the pilot model parameters, different estimation methods are introduced in previous researches [15]–[18].

To help the pilot with aircraft ground braking, the assistant controller design need to consider both pilot control behaviors and aircraft ground dynamics. Some studies of driver assistance control for ground vehicle could also be referred to. In [19], to solve the trajectory-following problem under constant velocity, the gross model is used to describe driver behavior and desired lateral deviation is introduced to build the gain schedule  $H_\infty$  robust controller, integrated with vehicle model into a closed-loop driver-vehicle system. However, under aircraft ground braking condition, since the velocity is various, it is better to use near and far angle

to replace the lateral deviation, just as the study in [20]. As discussed above, the disturbance and varying parameters such as velocity must also be considered, therefore, robust control for linear parameter variant (LPV) system could be referred to. Study in [21] introduced the  $H_\infty$  control for LPV system and relevant lemmas, in which the bound real lemma and vertex property lemma convert the controller designing problem to linear matrix inequation (LMI) problem. Based on these theories, a combined control method for direct yaw moment control was proposed in [22], in which a useful performance index was constructed based on  $H_\infty$  theory as the system output.

The main contribution of this paper is that we solved the pilot assistant control problem when aircraft braking under external disturbance, where lateral wind and pilot visual error are mainly considered in this study. To make the assistant control work well with pilot, the control method was based on pilot-aircraft dynamics, including the introduced sensory model and control-theoretic pilot models. During aircraft ground braking, the varying longitudinal velocity makes it an LPV problem. Therefore, the robust controller was constructed using  $H_\infty$  and LPV theory, while relevant lemmas are also introduced. As for results verification, the real-time simulation is now widely used in researches of aircraft brake and flight control [23], [24]. Therefore, the real time pilot-in-loop experiment system is constructed in this paper, which would promote test efficiency significantly. By real-time pilot-in-loop experiments, the proposed assistant control shows better performance than pilot control, for it not only helps the pilot to resist disturbance, but also hardly runs counter to the pilot's intent.

The rest of this paper is organized as follows: section 2 presents the study on pilot control model and relevant parameters estimation. Section 3 proposes the pilot-aircraft dynamic system modelling, while section 4 gives the design for LPV assistant controller and introduced relevant theories. In section 5, real-time experiment results for pilot assistant control has been compared with pilot control results to prove the effectiveness of the proposed system.

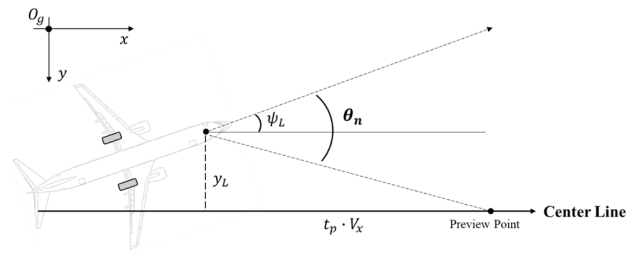
**II. AIRCRAFT-ON-GROUND PILOT CONTROL MODEL**

In this section, an aircraft-on-ground pilot control model based on the preview point of the pilot was proposed, refer to the famous two-point visual control model of vehicle steering. And the key parameters were estimated through a series of pilot-in-loop experiments.

**A. PILOT CONTROL MODEL**

In many studies of vehicle steering situation, the pilot control mechanism is determined by two visual angles  $\theta_{near}$  and  $\theta_{far}$  [20]. As for aircraft ground braking situation, the near angle  $\theta_n$  is derived from the driver position, near preview point and the direction, which is shown as follows:

Where  $V_x$  is the aircraft longitudinal velocity,  $t_p$  is the preview time,  $y_L$  is the lateral deviation,  $\psi_L$  is the direction

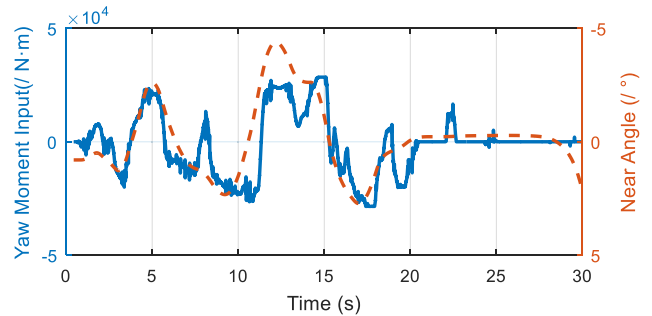


**FIGURE 1. The explanation of near angle  $\theta_n$ .**

angle. Thus, the near angle could be given by:

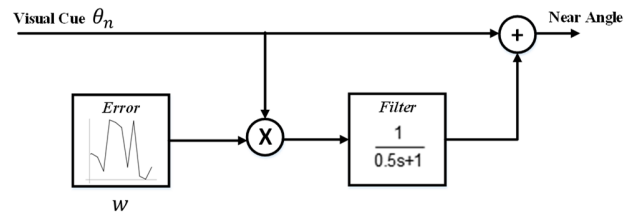
$$\theta_n = \psi_L + \psi_y = \psi_L + \frac{y_L}{V_x t_p} \tag{1}$$

According to two visual angle theory, the pilot's main braking target is to limit the  $\theta_n$  as small as possible while reducing the longitudinal velocity, which means that the larger the near angle is, the larger the pilot input would be. The pilot-in-loop experiment (assuming that  $t_p = 3s$ ) also shows similar phenomenon, the expected yaw moment and near angle are shown as follows:



**FIGURE 2. The comparison between pilot input and near angle.**

And according to the Gross model, which is widely used in the pilot model, the expected torque not only depends on  $\theta_n$ , but also pilot leading and delay time [10]. However, the pilot's observation for near angle  $\theta_n$  might include related error, which is described in Hess's visual perception model [9] as follows:



**FIGURE 3. Hess visual cue perception model.**

Therefore, referring to Gross model, Hess model and the driver model provided in [27], we presented a pilot model as follows:

$$M_d = \frac{K_c (1 + t_L s)}{1 + t_L s} e^{-t_d s} \theta_n \left( 1 + \frac{w}{0.5s + 1} \right) \tag{2}$$

where  $M_d$  denotes the expected yaw moment output of the pilot, and the larger is the  $\theta_n$ , the larger  $M_d$  is.  $K_c$  is the

pilot gain constant, reflecting the driving habits.  $t_L$  is the leading time constant, which is related to the predictive ability of the pilot.  $t_l$  is the neuromuscular lag time, related to the inertial characteristic of pilot. Using two pada approximation  $(1 + t_L s) \approx e^{t_L s}$  and  $e^{-t_d s} \approx \frac{1}{(1+t_d s)}$ , the model would transfer into:

$$M_d = \frac{K_c}{(1 + t_l s)(1 + t_d s)} e^{t_L s} \left( \psi_L + \frac{y_L}{V_x t_p} \right) + a' \quad (3)$$

where  $a'$  is the combined error from the visual cue and model. Considering the study in [19], since the time lag  $t_l$  and the time delay  $t_d$  are small, and  $e^{t_L s} \left( \psi_L + \frac{y_L}{V_x t_p} \right) = \psi_L + \frac{y_L}{V_x(t_p+t_L)}$ , the model could also be described as:

$$M_d \approx \frac{K_c}{1 + T_d s} \left( \varphi_L + \frac{y_L}{V_x T_p} \right) + d' \quad (4)$$

where  $T_d = t_l + t_d$ ,  $T_p = t_L + t_p$ ,  $d'$  represents the combined error in this model. Therefore, the continuous time model could be described as:

$$\dot{M}_d = -\frac{1}{T_d} M_d + \frac{K_c}{T_d} \psi_L + \frac{K_c}{T_d T_p} \frac{y_L}{V_x} + d' \quad (5)$$

### B. PILOT CONTROL PARAMETERS ESTIMATION

According to the continuous time pilot control model as equation (5), the discrete time model could be defined as follows:

$$\left( 1 - \frac{\Delta t}{T_d} \right) M_d(t) + \frac{K_c \Delta t}{T_d} \psi_l(t) + \frac{K_c \Delta t}{T_p T_d} \cdot \frac{y_L(t)}{V_x(t)} - M_d(t + \Delta t) + d' = 0 \quad (6)$$

where  $\Delta t$  denotes the interval time. Referring to study in [16], using the pilot-in-loop experiment data, the pilot control parameter could be estimated by solving the Least Squares question as follows:

$$\min J = \sum_{k=1}^n \left[ K_1 M_{fd}((k) \Delta t) + K_2 \psi_L(k \Delta t) + K_3 \frac{y_L(k \Delta t)}{V_x(k \Delta t)} - M_{fd}((k+1) \Delta t) \right]^2$$

$$s.t. K_1 < 1, K_2 < 0, K_3 < 0 \quad (7)$$

Which could also be described as follows;

$$\min \frac{1}{2} x^T H x + f^T x$$

$$s.t. A x < b \quad (8)$$

where,  $x = [K_1 \ K_2 \ K_3 \ K_4]^T$ ,  $A = \text{diag}(1, 1, 1, 1)$ ,  $b = [1 \ 0 \ 0 \ 0]^T$ . And  $K_1 = 1 - \frac{\Delta t}{T_d}$ ,  $K_2 = \frac{K_c \Delta t}{T_d}$ ,  $K_3 = \frac{K_c \Delta t}{T_p T_d}$ . Therefore, the key parameter would be calculated as  $T_d = \frac{\Delta t}{1-K_1}$ ,  $K_c = \frac{K_2 T_d}{\Delta t}$ ,  $T_p = \frac{K_c \Delta t}{K_3 T_p}$ . The estimation experiment was taken on the pilot-in-loop simulation system

described in section 5, and relationships between longitudinal velocity and lateral deviation in different experiments are as follows:

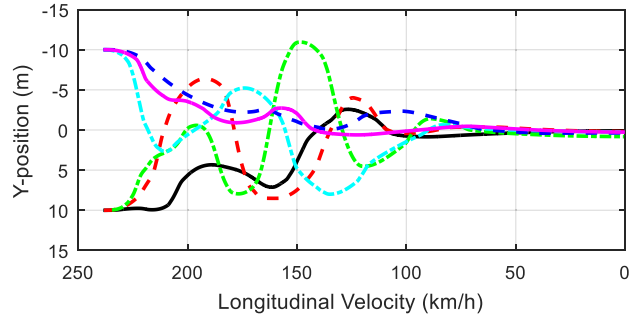


FIGURE 4. Lateral deviation variation during braking.

As shown in Fig.4, with large initial lateral deviation, the pilot would not limit the deviation as soon as possible when velocity is still higher than 100 km/h. To obtain the pilot control model, the Least Squares question in Eq.(7) is solved, and the observation results are shown as follows:

TABLE 1. Pilot control parameter estimation results.

	Pilot 1			Pilot 2			Pilot 3		
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
$K_c$	-3124	-3639	-4564	-3378	-3495	-2973	-3396	-3108	-3802
$T_d$	1.44	1.04	1.04	2.15	1.19	1.19	1.07	1.43	1.12
$T_p$	5.73	4.70	4.20	13.84	6.14	6.31	7.81	10.47	11.56

The experiments were taken by 3 pilots and each one tested for 3 times. The results 1-3, 4-6 and 7-9 above were from pilot 1-3 independently. By evening the results, we selected the parameters for control designing as  $K_c = -3704$ ,  $T_d = 1.37$  s and  $T_p = 5.5$ s.

### III. PILOT-AIRCRAFT DYNAMIC SYSTEM MODELLING

In this section, to design the pilot assistant controller, the whole pilot-aircraft dynamics system was proposed, in which the pilot braking model previously proposed is combined with an aircraft reference model.

#### A. AIRCRAFT REFERENCE MODEL

In the study of aircraft ground dynamics, similar to vehicle dynamics, the linear 2 DOF vehicle model could be referred to [25-26]. And the control reference model is shown as follows:

$$x_r = [v_y \ r]^T, u_r = M_r,$$

$$\dot{x}_r = A_r x_r + B_r u_r + C_r f \omega,$$

$$A_r = \begin{bmatrix} \frac{K_f + K_r}{m V_x} & \frac{a K_f - b K_r}{m V_x} - V_x \\ \frac{a K_f - b K_r}{I_z V_x} & \frac{a^2 K_f + b^2 K_r}{I_z V_x} \end{bmatrix},$$

$$B_r = \begin{bmatrix} 0 \\ \frac{1}{I_z} \end{bmatrix}, C_r = \begin{bmatrix} \frac{1}{m} \\ 0 \end{bmatrix} \quad (9)$$

where  $x_r$  and  $u_r$  denote the state vector and control output of reference model independently,  $v_y$  denotes the aircraft lateral velocity,  $r$  is the yaw velocity.  $M_t$  is the total yaw moment output by controller, and  $M_t = M_d + M_e$ , where  $M_d$  is the pilot input and  $M_e$  is the additional yaw moment.  $f_\omega$  is the lateral error from air resistance and lateral stiffness which are hard to be measured.  $K_f$  and  $K_r$  represent the front and rear lateral stiffness independently.  $m$  is the total mass of aircraft.  $a$  and  $b$  independently represent the distance from the center of gravity (C.G) to the Nose wheel and main wheel.  $I_z$  is the yaw inertia about the C.G.

**B. PILOT-AIRCRAFT AUGMENTED SYSTEM**

Based on the aircraft reference model and the pilot control above, the system was extended to a pilot-aircraft augmented system, where the state vector is  $x = [v_y \ r \ y_L \ \psi \ M_d]^T$ .  $w$  is the system input error, mainly comprised of lateral error  $f_\omega$  and gross error  $d'$  of the pilot control model. To create a linear parameter system, the variables  $\theta = V_x$  and  $\varphi = \frac{1}{V_x}$  were introduced. Therefore, the augmented system would be described as follows:

$$\begin{aligned}
 x &= [v_y \ r \ y_L \ \psi \ M_d]^T, w = \begin{bmatrix} f_\omega \\ d' \end{bmatrix}, u = M_e \\
 \dot{x} &= A(\theta, \varphi)x + B_1w + B_2u \\
 A(\theta, \varphi) &= \begin{bmatrix} \frac{K_f+K_r}{m}\varphi & \frac{aK_f-bK_r}{m}\varphi - \theta & 0 & 0 & 0 \\ \frac{aK_f-bK_r}{I_z}\varphi & \frac{a^2K_f+b^2K_r}{I_z}\varphi & 0 & 0 & \frac{1}{I_z} \\ 1 & 0 & 0 & \theta & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & \frac{K_c}{T_d T_p}\varphi & \frac{K_c}{T_d} & -\frac{1}{T_d} \end{bmatrix}, \\
 B_1 &= \begin{bmatrix} \frac{1}{m} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}, B_2 = \begin{bmatrix} 0 \\ \frac{1}{I_z} \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{10}
 \end{aligned}$$

Thus, the pilot-aircraft augmented system become the linear system of variant parameter  $\theta$  and  $\varphi$ . During the aircraft ground braking, the longitudinal velocity  $V_x$  would change continuously, which creates a linear parameter variant (LPV) problem of  $\theta$  and  $\varphi$ . Therefore, in the following part of this paper, the LPV assistant controller was designed to solve this problem.

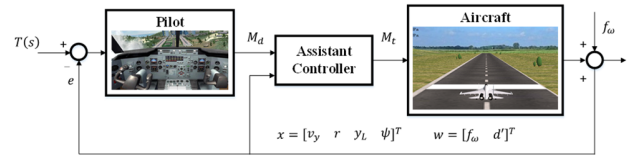
**IV. PILOT-AIRCRAFT DYNAMIC SYSTEM MODELLING**

In this section, we designed an assistant controller mainly based on  $H_\infty$  and LPV theory. And a method was presented to calculate the feedback matrix. Related lemmas are also described to explain the controller design principles.

**A. CONTROL SYSTEM DEFINITION**

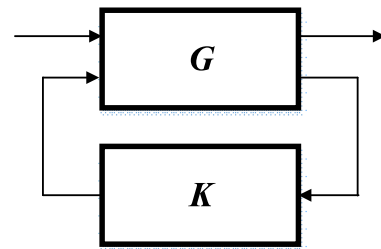
As we discussed in sections 1 and 2, as manipulate the high speed aircraft to brake on the ground, the disturbance from

wind and the error from visual cue would make the pilot controlling more difficult. Therefore, the assistant controller was proposed, which would receive the state variables, adjust the additional yaw moment  $M_e$  and output the total yaw moment  $M_t$ . In the control system diagram, the controller is arranged between the pilot expected output and the aircraft braking actuator. The control system structure is shown as follows:



**FIGURE 5. The assistant control system diagram.**

The error  $e$  is the near angle  $\theta_n$ , and  $T(s)$  is the control objective of the pilot. Since most state variables could be obtained on board sensors such as IMUs, we adopt state feedback control in this paper and the feedback vector was  $y = x$ . The system would be simplified as follows:



**FIGURE 6. State feedback controller.**

Where  $G$  is the augmented controlled system,  $K(\theta, \varphi)$  is the feedback matrix, which is the function of  $\theta$  and  $\varphi$ . And referring to study in [6], to design the performance index directly, the system output  $z$  in this paper is proposed as follows:

$$\begin{aligned}
 z &= Cx + Du \\
 C &= \begin{bmatrix} \frac{1}{Q^2} \\ 0 \end{bmatrix}, D = \begin{bmatrix} 0 \\ \frac{1}{R^2} \end{bmatrix} \tag{11}
 \end{aligned}$$

Therefore,  $\|z\|_2^2 = \left\| \begin{bmatrix} Q^{\frac{1}{2}}x \\ R^{\frac{1}{2}}u \end{bmatrix} \right\|_2^2 = x^T Qx + u^T Ru = J$ , which could also be considered as performance index  $J$ , where  $Q$  and  $R$  are the penalty matrix of state vector and control output. If the quadratic  $H_\infty$  performance exists, there would be a positive real number  $\gamma$ ,  $\frac{\|z\|_2}{\|\omega\|_2} < \gamma$ . Thus, there would be  $J = \|z\|_2 < \gamma \|\omega\|_2$ . Since the disturbance  $\omega$  has an upper bound, if  $\gamma$  could be minimized, the upper bound of  $J$  could also be as small as possible.

On the other hand, considering feedback matrix  $K(\theta, \varphi)$ , the closed-loop system could be described as follows:

$$\begin{aligned}
 \dot{x} &= [A(\theta, \varphi) + B_2K(\theta, \varphi)]x + B_1w \\
 z &= [C + DK(\theta, \varphi)]x \tag{12}
 \end{aligned}$$





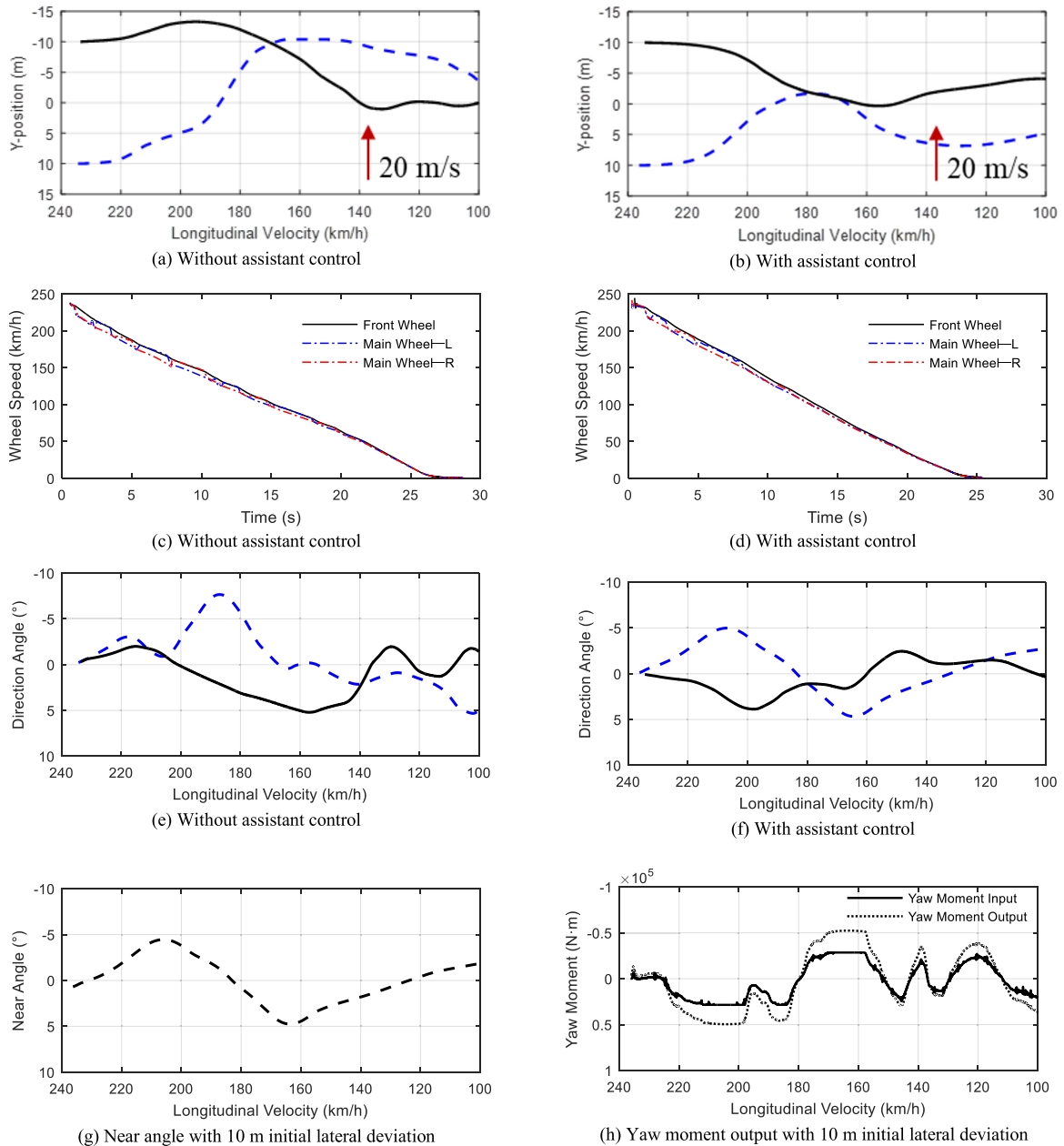


FIGURE 8. Control results comparison.

**A. PILOT-IN-LOOP SYSTEM DEFINITION**

The relevant experiments are taken on the pilot-in-loop system as follows:

As shown in figure 7 (a), the pilot-in-loop system is mainly comprised of the pilot control platform, control module, aircraft simulation system and braking actuator. The main aircraft dynamics for simulation were run on NI PXI at real time. The simulation model mainly considers aircraft ground brake condition, ignoring some of the aerodynamics and caring more about road friction. Focusing on the relationship between pilot braking input and output, the platform only prepared pedal input for pilot, without nose wheel steering input and rudder input.

When the aircraft ground braking simulation begins, pilot would catch visual cue from the control platform and give expected output  $M_d$  using braking pedal. The proposed assistant controller was deployed in the control module, and by switching the controller on or off, the comparing experiments could be taken. Besides, the actuator could create real braking pressure as feedback.

**B. PILOT-IN-LOOP EXPERIMENT RESULTS**

The experiment results are as shown in figure 8. To simulate the lateral error  $f_{\omega}$ , the lateral wind was set to be about 20 m/s in the simulation system. The initial longitudinal velocity was about 240 km/h and the initial lateral deviation was also given

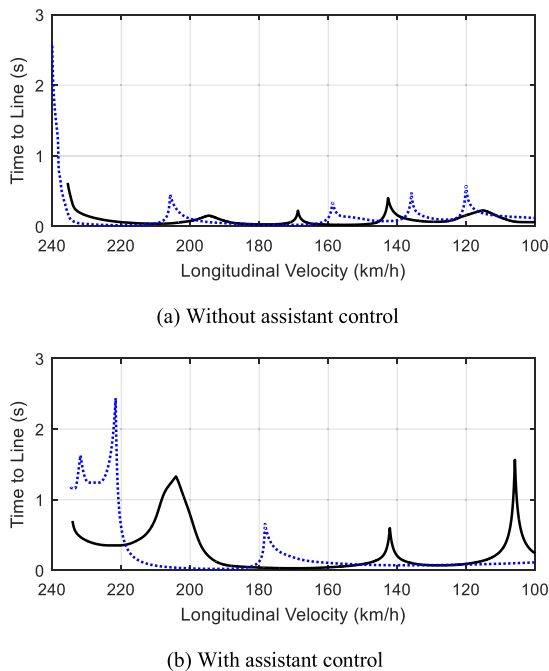


FIGURE 9. Time to line comparison.

in each experiment. As shown in figure 4, it is more difficult for the pilot to control the lateral dynamics when velocity is higher than 100 km/h. Therefore, the working range of the assistant controller was set to [100 km/h, 240 km/h]. Results are as follows:

From figure 8. (a)-(b), in each kind of experiment, the lateral deviations of two round tests were 10 m and -10 m independently. Comparing (b)/ (f) to (a)/ (e), the pilot would limit the maximum of lateral deviation and direction angle better. And the capacity of resisting lateral disturbance has promoted, since the overall shift along the wind direction is more obvious in (a) than (b). And (c)-(d) shows that applying the assistant controller, the time of aircraft braking decreased. Figure 8. (g) shows some mechanisms by plotting the pilot input  $M_d$  and controller output  $M_t$  together, as well as displaying the variation of near angle. As the initial near angle is large and quickly changed when velocity is larger than 150 km/h, the difference between  $M_d$  and  $M_t$  is also large. And as velocity and near angle decreasing, the difference also decreased. Moreover, along the aircraft braking period, the direction of output  $M_t$  is always the same as input  $M_d$ , which means the controller would hardly run counter to the pilot's intent.

Referring to study in [27], to evaluate the aircraft braking results quantitatively, the key index Time to Line Crossing (TLC) was introduced. TLC is the time before aircraft run out off the runway under fix velocity and direction angle at the moment. Therefore, larger TLC would reflect a better performance of the pilot control system. In this study, to show the most extreme condition during braking, we extract the minimum TLC of every 1 s and the results are as follows:

As shown in figure 9, the TLC of tests with assistant control is much larger in general, especially when longitudinal

velocity is still high. This result shows that the proposed assistant control would help the pilot to keep the aircraft lateral safety during braking.

## VI. CONCLUSION

In this paper, a novel assistant control based on pilot control model was proposed to solve the pilot control problem when aircraft ground brake under resistance and error. The proposed pilot assistant control was based on  $H_\infty$  and LPV theory, considering external disturbance and various aircraft velocity. To assist pilot in control aircraft ground braking, the whole pilot-aircraft dynamics system was also proposed to construct the control reference model. As for pilot control modelling, the two visual angle theory is used and relevant parameters are estimated. By real-time pilot-in-loop experiments, the proposed assistant control shows better performances than pilot control, for it not only helps the pilot to resist disturbance, but also hardly runs counter to pilot's intent.

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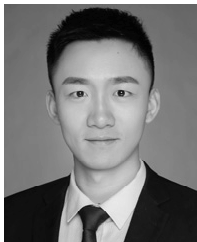
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