Aircraft Ground Braking Assistant Control Based on Pilot Control Model

YAQI DAI, LIANGYAO YU, (Member, IEEE), JIAN SONG, LANIE ABI, AND SHENG ZHENG
Department of Automotive Engineering, Tsinghua University, Beijing 100084, China

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.

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 on 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 $\theta_{\text{near}}$ and $\theta_{\text{far}}$ [20]. As for aircraft ground braking situation, the near angle $\theta_{\text{near}}$ is derived from the driver position, near preview point and the direction, which is shown as follows:

Where $V_L$ is the aircraft longitudinal velocity, $t_p$ is the preview time, $y_L$ is the lateral deviation, $\psi_L$ is the direction angle. Thus, the near angle could be given by:

$$\theta_{\text{near}} = \psi_L + \psi_y = \psi_L + \frac{y_L}{V_L} t_p \quad (1)$$

According to two visual angle theory, the pilot’s main braking target is to limit the $\theta_{\text{near}}$, 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:

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

$$M_d = \frac{K_c (1 + t_L s)}{1 + t_s} e^{-t_w s} \theta_{\text{near}} \left(1 + \frac{w}{0.5s + 1}\right) \quad (2)$$

where $M_d$ denotes the expected yaw moment output of the pilot, and the larger is the $\theta_{\text{near}}$, 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. \( t_I \) is the neuromuscular lag time, related to the inertial characteristic of the pilot. Using two-pada approximation \((1 + t_L s) \approx e^{t_L s} \) and \( e^{-t_L s} \approx (1 + t_L s) \), the model would transfer into:

\[
M_d = \frac{K_c}{(1 + t_I s)} e^{t_L s} \left( \frac{y_L}{V_s l_p} \right) + d' \quad (3)
\]

where \( d' \) 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 \( e^{t_L s} \left( \frac{y_L}{V_s l_p} \right) = -T \), the model could also be described as:

\[
\dot{M}_d = \frac{K_c}{1 + T_d s} \left( \psi_L + \frac{y_L}{V_s l_p} \right) + d' \quad (4)
\]

where \( T_d = t_I + t_d, T_p = t_I + t_p, d' \) represents the combined error in this model. Therefore, the continuous time model could be described as:

\[
\dot{\psi}_d = -\frac{1}{T_d} M_d + \frac{K_c}{T_d} \psi_L + \frac{K_c y_L}{T_d T_p V_s} + d' \quad (5)
\]

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:

\[
\left(1 - \frac{\Delta t}{T_d}\right) M_d (t) + \frac{K_c \Delta t}{T_d} \psi_L (t)
\]

\[
+ \frac{K_c \Delta t}{T_p T_d} y_L (t) - M_d (t + \Delta t) + d' = 0 \quad (6)
\]

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:

\[
\min J = \sum_{k=1}^{n} \left[ K_1 M_d ((k) \Delta t) + K_2 \psi_L ((k) \Delta t)
\]

\[
+ K_3 \frac{y_L ((k) \Delta t)}{V_s ((k) \Delta t)} - M_d ((k + 1) \Delta t) \right]^2
\]

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

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, \( x = \begin{bmatrix} K_1 & K_2 & K_3 & K_4 \end{bmatrix}^T, A = \text{diag}(1, 1, 1, 1), b = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}^T \). And \( K_1 = 1 - \frac{\Delta t}{T_d}, K_2 = \frac{K_c \Delta t}{T_d}, K_3 = \frac{K_c y_L}{T_p V_s}, \) \( K_4 = \frac{K_c \Delta t}{T_p T_d} \). 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:

\[\text{FIGURE 4. Lateral deviation variation during braking.}\]

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:

\[\text{TABLE 1. Pilot control parameter estimation results.}\]

| Pilot 1 | Pilot 2 | Pilot 3 |
|--------|--------|--------|
| Test 1 | Test 2 | Test 3 | Test 4 | Test 5 | Test 6 | Test 7 | Test 8 | Test 9 |
| \(K_c\) | -5124 | -5639 | -4664 | -3378 | -4959 | -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:

\[\begin{bmatrix}
\dot{x}_r \\
\dot{y}_r \\
\dot{u}_r \\
\dot{c}_r
\end{bmatrix} = A_r \begin{bmatrix}
x_r \\
y_r \\
u_r \\
c_r
\end{bmatrix} + B_r \begin{bmatrix}
x_r \phi \\
y_r \phi \\
u_r \phi \\
c_r \phi
\end{bmatrix}, \]

\[A_r = \begin{bmatrix}
\frac{mV_x}{I_c} & 0 & 0 & 0 \\
\frac{mV_x}{I_c} & \frac{aK_f - bK_r}{I_c V_x} & \frac{aK_f}{I_c V_x} & \frac{a}{I_c V_x} \\
0 & 0 & \frac{1}{I_c} & \frac{1}{I_c} \\
0 & 0 & \frac{1}{I_c} & \frac{1}{I_c}
\end{bmatrix}, \]

\[B_r = \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}, \]

\[C_r = \begin{bmatrix}
1 & 0 & 0 & 0
\end{bmatrix} \]
where $x_r$ and $u_r$ denote the state vector and control output of reference model independently, $v_r$ denotes the aircraft lateral velocity, $r$ is the yaw velocity. $M_r$ is the total yaw moment output by controller, and $M_l = M_d + M_e$, 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 $x = \begin{bmatrix} v \ r \ y \ \psi \ M_d \end{bmatrix}^T$, $w$ 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 $\theta = V_s$ and $\varphi = \frac{1}{V_s}$ were introduced. Therefore, the augmented system would be described as follows:

$$x = \begin{bmatrix} v \ r \ y \ \psi \ M_d \end{bmatrix}^T, \quad w = \begin{bmatrix} f_\omega \\ d' \end{bmatrix}, \quad u = M_e$$

$$\dot{x} = A(\theta, \varphi)x + B_1w + B_2u$$

$$A(\theta, \varphi) = \begin{bmatrix} \frac{k_f + k_r}{m} \varphi & \frac{a k_f - b k_r}{m} \varphi - \theta & 0 & 0 & 0 \\
\frac{a k_f - b k_r}{l_z} \varphi & \frac{a^2 k_f + b^2 k_r}{l_z} \varphi & 0 & 0 & 1 \\
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & \frac{K_c}{T_d T_p} \varphi & \frac{K_c}{T_d} & 1 \end{bmatrix}$$

$$B_1 = \begin{bmatrix} 1 \\ 0 \\ m \\ 0 \\ 0 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 \\ 1 \\ l_z \\ 0 \\ 0 \end{bmatrix}$$  

(10)

Thus, the pilot-aircraft augmented system become the linear system of variant parameter $\theta$ and $\varphi$. During the aircraft ground braking, the longitudinal velocity $V_s$ 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 $M_l$. 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 $\theta_s$, 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:

$$z = Cx + Du$$

$$C = \begin{bmatrix} 1 \\ 0 \\ Q_2 \end{bmatrix}, \quad D = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$  

(11)

Therefore, $\|z\|^2 = \begin{bmatrix} x^T Q x + u^T R u \end{bmatrix}$, 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 $\gamma$, $\|z\| < \gamma \|\omega\|$, $J$ would be minimal, the upper bound of $J$ could be also as small as possible.

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

$$\dot{x} = [A(\theta, \varphi) + B_2K(\theta, \varphi)]x + B_1w$$

$$z = [C + DK(\theta, \varphi)]x$$  

(12)
Therefore, the main objective of controller design is to create $H_{\infty}$ a performance for this system, as well as limit the performance index $J$.

### B. $H_{\infty}$ AND LPV THEORY

For the LPV system controller designing, the Bound real lemma and Vertex property lemma are important theoretical basis [7]. The Bounded real lemma would transfer the $H_{\infty}$ performance problem to a Linear Matrix Inequality (LMI) problem, and then make it possible to be solved in MATLAB. And the Vertex property lemma extended the $H_{\infty}$ performance problem to a Linear Matrix Inequality (LMI) problem, and then make it possible to be solved in MATLAB. These two lemmas are shown as follows:

**Lemma 1**: (Bounded real lemma) for the continuous time transfer function $G(s) = D + C(sI - A)^{-1}B$. The following statements are equivalent:

(a) $A$ has asymptotic stability and the system has quadratic $H_{\infty}$ performance $\gamma$, $\|D + C(sI - A)^{-1}B\|_{\infty} < \gamma$.

(b) There exists positive definite solution $X$ to the matrix inequality and for the whole space holds:

$$H = \begin{bmatrix} XA + A^T X & XB & C^T \\ B^T X & -\gamma I & D^T \\ C & D & -\gamma I \end{bmatrix} < 0$$ \hspace{1cm} (13)

**Lemma 2**: (Vertex property lemma) for the polytopic LPV plant as follows:

$$\dot{x} = A(\theta, \phi)x + B(\theta, \phi)w$$
$$y = C(\theta, \phi) + D(\theta, \phi)w$$ \hspace{1cm} (14)

where the vertices are $H(\theta_i) = \begin{bmatrix} A(\theta_i) & B(\theta_i) \\ C(\theta_i) & D(\theta_i) \end{bmatrix}$, $i = 1, \ldots, r$. The following statements are equivalent:

(a) The LPV system is stable with quadratic $H_{\infty}$ performance $\gamma$ within the state space all along.

(b) There exists a single matrix $X > 0$ satisfying the system of LMIs as follows on vertices: $H(\theta_i) < 0$, $i = 1, \ldots, r$.

In the following parts, these two lemmas are utilized to design the LPV controller.

### C. CONTROLLER DESIGNED

By introducing $P_1 = X^{-1}$ and $P_2 = KX^{-1}$, the LMI in equation (13) would be transferred into linear system of $\theta$ and $\varphi$ as follows:

$$LMI(\theta, \varphi) = \begin{bmatrix} A(\theta, \varphi)P_1 + B_2 P_2(\theta, \varphi) + P_1 A(\theta, \varphi)^T + P_2(\theta, \varphi)^T B_2^T & B_1 & P_1 C^T \\ * & -\gamma I & 0 \\ * & * & -\gamma I \end{bmatrix} < 0$$ \hspace{1cm} (15)

Therefore, referring to lemma 1 and 2 and study in [6], the LPV controller design problem could be described as:

$$\min \gamma^2$$

$$LMI(\theta, \varphi) < 0$$

$$(\theta_i, \varphi_i) = \begin{bmatrix} \left( \frac{V_{\max}}{V_x}, \frac{1}{V_x} \right), & \left( \frac{V_{\max}}{V_x}, \frac{1}{V_x} \right), \\
\left( \frac{V_{\min}}{V_x}, \frac{1}{V_x} \right), & \left( \frac{V_{\min}}{V_x}, \frac{1}{V_x} \right) \end{bmatrix}$$ \hspace{1cm} (16)

And the feedback function is $K(\theta, \varphi) = P_2P_1^{-1}$. Once the feedback matrixes on vertices are solved, the control law feedback $K(\theta, \varphi)$ could be calculated based on 4 vertex results, using the difference equation as follows:

$$K(\theta, \varphi) = \sum \frac{|\theta_i - \theta| |\varphi_i - \varphi|}{(\theta_{\max} - \theta_{\min})(\varphi_{\max} - \varphi_{\min})} \cdot K((\theta_i, \varphi_i))$$ \hspace{1cm} (17)

Therefore, the control law would be $M_e = u(\theta, \varphi) = K(\theta, \varphi) \cdot x$, and the total yaw moment output is $M_t = M_d + M_e$.

### V. REAL-TIME EXPERIMENT RESULTS FOR PILOT ASSISTANT CONTROL

In this section, the real-time pilot-in-loop experiment system is introduced, which is the experiment environment for the pilot control parameter estimation and assistant controller tests. The results of pilot-in-loop experiment with assistant controller are also shown in following parts.
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 barking 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.
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 $M_f$ 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 $M_f$ is also large. And as velocity and near angle decreasing, the difference also decreased. Moreover, along the aircraft braking period, the direction of output $M_f$ 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.

REFERENCES

[1] R. Mori and S. Suzuki, “Modeling of pilot landing approach control using stochastic switched linear regression model,” J. Aircr., vol. 47, no. 5, pp. 1554–1558, Sep. 2010.
[2] M. Lone and A. Cooke, “Review of pilot models used in aircraft flight dynamics,” Aeron. Sci. Technol., vol. 34, pp. 55–74, Apr. 2014.
[3] M. Lu, K. Wevers, and R. Van Der Heijden, “Technical feasibility of advanced driver assistance systems (ADAS) for road traffic safety,” Transp. Planning Technol., vol. 28, no. 3, pp. 167–187, Jun. 2005.
[4] C. Maag, D. Mulbacher, C. Mark, and H.-P. Kruger, “Studying effects of advanced driver assistance systems (ADAS) on individual and group level using multi-driver simulation,” IEEE Intel!. Transp. Syst. Mag., vol. 4, no. 3, pp. 45–54, Fall. 2012.
[5] A. Tomczyk, “Shaping indirect flight control system properties for general aviation aircraft,” J. Aeron. Eng., vol. 24, no. 1, pp. 59–71, Jan. 2011.
[6] D. McRuer and E. Krendel, “Mathematical models of human pilot behavior,” Advisory Group Aerosp. Res. & Develop., Neuilly-sur-Seine, France, Tech. Rep. GARDograph AGARD-AG-188, 1974, p. 83, no. 1.
[7] T. Neal and R. Smith, “An in-flight investigation to develop system design criteria for fighter airplanes,” Flight Dyn. Lab., Wright-Patterson Air Force Base, Tech. Rep. AFFDL-TR-70-74, 1970.
[8] D. L. Kleinman, S. Baron, and W. H. Levison, “An optimal control model of human response part I: Theory and validation,” Automatica, vol. 6, no. 3, pp. 357–369, May 1970.
[9] R. A. Hess, “Simplified approach for modelling pilot pursuit control behaviour in multi-loop flight control tasks,” Proc. Inst. Mech. Eng., G, J. Aeron. Eng., vol. 220, no. 2, pp. 85–102, Feb. 2006.
[10] M. Jirgl, M. Havlíkova, and Z. Bradac, “The dynamic pilot behavioral models,” Procedia Eng., vol. 100, pp. 1192–1197, 2015.
[11] J. Boril, R. Jalovecky, and R. Ali, “Human-machine interaction and simulation models used in aviation,” in Proc. 15th Int. Conf. MECHATRONIKA, Dec. 2012, pp. 1–4.
[12] D. D. Salvucci and R. Gray, “A two-point visual control model of steering,” Perception, vol. 33, no. 10, pp. 1233–1248, Oct. 2004.
[13] R. Mori and S. Suzuki, “Neural network modeling of lateral pilot landing control,” J. Aircr., vol. 46, no. 5, pp. 1721–1726, Sep. 2009.
[14] C. Sentouh, P. Chevrel, F. Mars, and F. Claveau, “A sensorimotor driver model for steering control,” in Proc. IEEE Int. Conf. Syst., Man Cybern., Oct. 2009, pp. 2462–2467.
[15] A. C. Trujillo and I. M. Gregory, “Pilot stick input estimates from attitude commands as indicator of systemic changes,” J. Guid., Control, Dyn., vol. 40, no. 4, pp. 998–1012, Apr. 2017.
[16] E. Lavretskyy, “System identification (ID): CDS 270–L,” Class Notes, California Inst. Technol., Pasadena, CA, USA, 2008.
[17] A. Trujillo and I. Gregory, “Preliminary exploration of adaptive state predictor based human operator modeling,” in Proc. AIAA Modeling Simulation Technol. Conf., Aug. 2012.

FIGURE 9. Time to line comparison.
A. Trujillo and I. M. Gregory, “Wetware, hardware, or software incapacitation: Observational methods to determine when autonomy should assume control,” in Proc. 14th AIAA Aviation Technol., Integ., Operations Conf., Jun. 2014.

J. Wang, G. Zhang, R. Wang, S. C. Schnelle, and J. Wang, “A gain-scheduling driver assistance trajectory-following algorithm considering different driver steering characteristics,” IEEE Trans. Intell. Transp. Syst., vol. 18, no. 5, pp. 1097–1108, May 2017.

C. Sentouh, A.-T. Nguyen, M. A. Benloucif, and J.-C. Popieul, “Driver-automation cooperation oriented approach for shared control of lane keeping assist systems,” IEEE Trans. Control Syst. Technol., vol. 27, no. 5, pp. 1962–1978, Sep. 2019.

Z. Shuai, H. Zhang, J. Wang, J. Li, and M. Ouyang, “Combined AFS and DYC control of Four-Wheel-Independent-Drive electric vehicles over CAN network with time-varying delays,” IEEE Trans. Veh. Technol., vol. 63, no. 2, pp. 591–602, Feb. 2014.

L. Waszniowski, Z. Hanzálek, and J. Doubrava, “Aircraft control system validation via Hardware-in-the-Loop simulation,” J. Aircr., vol. 48, no. 4, pp. 1466–1468, Jul. 2011.

J.-W. Jeon, K.-C. Lee, D.-H. Hwang, S.-H. Lee, J.-H. Lee, and Y.-J. Kim, “The research of real-time test of brake-by-wire system for aircraft using HILS & dynamometer system,” in Proc. 30th Annu. Conf. IEEE Ind. Electron. Soc. (IECON), vol. 2, Nov. 2004, pp. 1710–1715.

Y. Dai, J. Song, L. Yu, Z. Lu, S. Zheng, and F. Li, “The lateral control during aircraft-on-ground deceleration phases,” Aerosp. Sci. Technol., vol. 95, Dec. 2019, Art. no. 105482.

B. Aksun Guvenc, T. Bunte, D. Odenthal, and L. Guvenc, “Robust two degree of freedom vehicle steering controller design,” in Proc. Amer. Control Conf., vol. 11, Jun. 2001, pp. 13–18.

W. van Winsum, K. A. Brookhuis, and D. de Waard, “A comparison of different ways to approximate time-to-line crossing (TLC) during car driving,” Accident Anal. Prevention, vol. 32, no. 1, pp. 47–56, Jan. 2000.

YAQI DAI received the B.Sc. degree from Tsinghua University and Science, China, in 2014. He is currently pursuing the Ph.D. degree in mechanical engineering with the State Key Laboratory of Automotive Safety and Energy, Tsinghua University, China.

His research interests include aircraft ground dynamics, vehicle dynamics control, hardware-in-loop simulation, and robust control.

LIANGYAO YU (Member, IEEE) received the B.E. and M.S. degrees in automotive engineering and the Ph.D. degree in mechanical engineering from Tsinghua University, Beijing, China, in 1997, 1999, and 2007, respectively. He has seven years of full-time industrial research experience with the Tsinghua Automotive Engineering Institute, Beijing, from August 2001 to December 2008. Since December 2008, he has been an Associate Professor with the Department of Automotive Engineering, Tsinghua University. He is the author/corresponding author/coauthor of more than 60 peer-reviewed articles in journals and conference proceedings. He is the holder of more than 20 patents. His research interests include modeling, estimation, and control of vehicle dynamical systems; advanced braking systems; electric vehicles; vehicle electronics; in-vehicle networks; energy harvesting; and mechatronic systems. He is a member of the Society of Automotive Engineers.

JIAN SONG received the B.E., M.S., and Ph.D. degrees in mechanical engineering from Tsinghua University, Beijing, China, in 1982, 1986, and 1992, respectively. Since 2000, he has been a Professor with Tsinghua University. His research interests mainly include vehicle dynamics and control, automotive powertrains, and control.

LANIE ABI received the B.Sc. degree from the Changchun University of Technology and Science, China, in 2014. He is currently pursuing the Ph.D. degree in mechanical engineering with the State Key Laboratory of Automotive Safety and Energy, Tsinghua University, China.

His research interests include vehicle dynamics modeling, identify and control, and unmanned commercial vehicle control.

SHENG ZHENG received the B.Sc. degree from the Beijing Institute of Technology, China, in 2016. He is currently pursuing the Ph.D. degree in mechanical engineering with the State Key Laboratory of Automotive Safety and Energy, Tsinghua University, China.

His research interests include vehicle dynamics modeling, identify and control, and unmanned heavy commercial vehicle control.