Research Article

Emergency Flight Control Based on the Fan Wing

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Received 14 July 2021; Revised 29 September 2021; Accepted 9 November 2021; Published 28 November 2021

Academic Editor: Dakun Sun

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FanWing has been taken to the visual field because of its performance combination of fixed-wing aircraft and helicopter. Its flight mode is currently limited mainly by a remote control, while the research of automated flight control is on the rise. The fan wing could offer lift, thrust, and the additional pitch moment for longitudinal control. At the same time, the roll moment and the yaw moment can be generated by the differential rotation of the cross-flow fan to realize the lateral control. It provides the possibility for its emergency flight control when the aerodynamic control becomes inefficient at a low speed. The difficulties in designing the emergency control system in both the longitudinal and lateral controls are analyzed. And it emphasizes the importance of selecting its center of gravity and the emergency control method of longitudinal control in engineering. The simulation results show that as an emergency flight control system, fan wing control is feasible. The study of the fan wing control will provide a reference solution for its further engineering applications.

1. Introduction

Different from the conventional fixed-wing, rotor, and flapping-wing aircraft, FanWing [1] is a new principle and new concept aircraft. The cross-flow fans are partially embedded within the FanWing airfoil section, which can draw the flow in from the suction surface and exhaust the flow out at the trailing edge regardless of the angle of attack. As a low-speed, large-load, and high-efficiency vehicle, FanWing could share certain fundamental features of both the conventional airplane and the helicopter. As a new unmanned aircraft potentially serving both military and civilian markets, FanWing has a broad prospect [2–4]. SOAR, one project of the European research framework program called Horizon 2020, endeavours to further develop the FanWing ultrashort take-off and landing (USTOL) vehicle to reduce fuel burn and carbon footprint associated with some helicopter and fix-wing airplane. FanWing, as its name, is an aircraft configuration that uses a simple cross-flow fan mounted in the wing to produce lift and forward thrust simultaneously at a low flying speed [5–7]. The research on FanWing is heavily focused on the superiority of the fan wing [8–11]. It is one of the burning issues for FanWing to be controlled. The flight mode of FanWing is currently limited mainly by a remote control, while the research of automated flight control is on the rise. There are still a lot of works to do about theoretical control research and engineering applications.

Unlike the conventional fixed-wing aircraft susceptible to external wind gusts [12, 13], the flight dynamic of FanWing is mainly determined by the rotation speed of the cross-flow fan. By comparison, the flow velocity on the wing has little effect on the forces and moments derived by the fan wing, which is different from the aerodynamic forces that support the conventional fixed-wing airplane in flight. They are mainly determined by the rotation speed of the cross-flow fan, the incoming flow velocity, and the inflow angle of the airflow. As a low-altitude and low-speed aircraft, the aerodynamic forces on FanWing are small, resulting in low efficiency or control failure of the rudder surfaces. In these circumstances, the maneuverability of FanWing can be appropriately improved by the area increase of the rudder surface, the adoption of the tail beam design, the rearward movement of the rudder and the elevator, and other
structural adjustment measures [14]. But the effect is not apparent. So, the control schemes are designed to improve the maneuverability of FanWing in this paper.

In the 1980s, as an emergency control strategy, PCA (Propulsion Controlled Aircraft) proposed specific control ability using throttle modulation, while the conventional flight control system failed. For FanWing, the emergency flight control system is realized using the cross-flow fan instead of the traditional rudder. FanWing can not only provide the thrust but also change the lift and the pitch moment. The flight track control is realized by changing the flight speed through the throttle thrust change in the conventional aircraft [15]. Then, the flight lift is altered, and the longitudinal flight path is controlled. Similar to the conventional aircraft, the FanWing longitudinal control is realized through the forces and moments provided by the cross-flow fan. At the same time, part of the lift is directly generated to control the longitudinal flight trajectory. Since there is a distance between the force action position of the fan wing and the center of gravity, a pitch moment is additionally generated. In comparison, the lateral control system is realized by the differential control of the fan wing [16].

2. Control Efficiency of the Cross-Flow Fan

There are five control variables in FanWing—elevator, aileron, rudder, rotation of the cross-flow fan, and differential rotation of the cross-flow fan. The definitions of the rudder surfaces are shown in Figure 1.

As shown in Figure 1, the positive rudder is defined in the rearview (from the tail to the nose). An upward left trailing edge of the aileron and a downward right trailing edge of the aileron leads to a negative roll moment, a positive aileron direction. A downward trailing edge of the elevator leads to a negative pitch moment, which is a positive elevator direction. A left trailing edge of the rudder leads to a negative yaw moment, which is a positive rudder direction. And an increased fan wing rotation speed leads to a positive fan wing direction. With the left fan wing rotation speed δn + δnd and the right fan wing rotation speed δn − δnd, the positive fan wing differential direction is defined, which is contrary to the positive aileron direction.

The optimal flight condition, FanWing velocity \( v = 16 \) m/s, and FanWing altitude \( h = 200 \) m are chosen. A coaxial rotation speed \( \delta_n = 100 \text{ r/min} \) and a differential rotation speed \( \delta_{nd} = 50 \text{ r/min} \) pulse signal are given separately to FanWing. The three attitude angles (roll angle acceleration \( \dot{\omega}_x = 88/\text{s}^2 \), yaw angle acceleration \( \dot{\omega}_y = 19/\text{s}^2 \), and pitch angle acceleration \( \dot{\omega}_z = -45/\text{s}^2 \)) impulse responses are sub-
sequently derived, as shown in Table 1.

100 r/min increase of the cross-flow fan rotation speed brings a \(-45/\text{s}^2\) FanWing pitch angle acceleration. Because of the additional pitch-down moment, a negative pitch rate is provided. FanWing tends to head down. Then, due to the change of attitude, FanWing tends to head up. This will be analyzed in detail in the following research contents. By definition, the differential fan wing control is similar to the aileron control but is opposite in sign. 50 r/min increase of the cross-flow fan differential rotation speed brings a good control efficiency that the FanWing roll angle acceleration is \(88/\text{s}^2\) and the yaw angle acceleration is \(19/\text{s}^2\). Generally, the conventional rudder surfaces can be replaced by the fan wing to control FanWing.

3. Model of FanWing

The longitudinal fan wing control is an application of the thrust vector control technology, which changes the direct force on FanWing by the coaxial rotation of both wings. Compared with the elevator control that the flight control is realized by the change of the flight attitude caused by the elevator deflection, the fan wing control can pull the air along the wing and accelerate the air over the wing to produce the demanded thrust, lift, and an additional pitch-down moment. Then, the direct contact between the fan wing rotation speed and the flight attitude is established. The effect of the additional pitch-down moment is directly reflected in the change of the pitch rate. The pitch angle response is affected by both the force and the moment generated by the fan wing. The lateral moments are fundamentally caused by the forces produced by the different rotation speeds of both sides of the fan wing. The lateral control system is realized. The control forces and moments are obtained in the database by the three-dimensional interpolation according to the angle of attack, the sideslip angle, and the fan wing rotation speed. Since the flight speed of FanWing is small, the influence of the incoming flow velocity can
be ignored. The forces and moments generated by the fan wing are given in

\[
\begin{aligned}
F_x^o &= T_y, \\
F_y^o &= T_x, \\
M_x^o &= M_y^o, \\
M_y^o &= M_x^o = M_\theta^o = 0.
\end{aligned}
\]  

(1)

\(T_x\) on the \(ax\) axis is the thrust produced by the fan wing, and \(T_y\) is the \(oy\) axis component of the lift. \(M_x^o\) is the additional pitch-down moment. The forces and moments in Equation (1) are generated by the fan wing coaxial rotation. When there is a differential rotation of the fan wing, the lateral moments are no longer zero. The roll moment is determined by the difference in the lift generated by the fan wing. The yaw moment is determined by the difference in the thrust generated by the fan wing. The force analysis of FanWing is shown in Figure 2.

In Figure 2, six attitude states are sequentially defined as \(\omega_x, \omega_y, \omega_z\) (angle rate components of the body-fixed coordinate) and \(\theta, \gamma, \psi\) (pitch angle, roll angle, and yaw angle), followed by three moments \(M_x, M_y, M_z\) (moment components of the body-fixed coordinate, including the aerodynamic moment and the fan wing moment). The model of FanWing can be divided into longitudinal motion and lateral motion.

Based on the analysis of the total forces and moments acting on FanWing, the dynamic equations and kinematic equations of FanWing are expressed in Equation (2). The moments of inertia and the cross-product of inertia are, respectively, defined as \(I_x, I_y, I_z, I_{xy}\):

\[
\begin{aligned}
\dot{\omega}_x &= \frac{1}{I_x I_y - I_{xy}} \left[ I_y M_x + I_x (M_y - (I_z - I_x) \omega_z \omega_y) + (I_x^2 + I_y^2 - I_z) \omega_y \omega_z \right], \\
\dot{\omega}_y &= \frac{1}{I_x I_y - I_{xy}} \left[ I_x M_y + I_y (M_z - (I_x - I_y) \omega_z \omega_x) + (I_z^2 + I_y^2 - I_x) \omega_z \omega_x \right], \\
\dot{\omega}_z &= \frac{1}{I_z} \left[ M_x - (I_y - I_z) \omega_y \omega_x + I_{xy} \left( \omega_x^2 - \omega_y^2 \right) \right], \\
\dot{\theta} &= \omega_z \sin \gamma + \omega_z \cos \gamma, \\
\dot{\gamma} &= \omega_x - \tan \dot{\theta} (\omega_z \cos \gamma - \omega_z \sin \gamma), \\
\dot{\psi} &= \frac{\omega_y \cos \gamma - \omega_z \sin \gamma}{\cos \dot{\theta}}.
\end{aligned}
\]  

Figure 2: Force analysis of FanWing.

The optimal remote control flight condition of FanWing is \(v = 16 \text{ m/s}\) and \(h = 200 \text{ m}\), which is chosen as the state point. The formal linearization is carried out to obtain the longitudinal mode eigenvalues and mode parameters, as shown in Table 2.

As seen in Table 2, different from the conventional fixed-wing aircraft, the trim angle of attack of FanWing is negative, which is determined by the structure of FanWing. Because of the pitch-down moment caused by the fan wing, FanWing is usually flying at a negative angle of attack. Its longitudinal mode has prominent long- and short-period characteristics. In comparison, its lateral mode has three major mode characteristics. So, the classical PID method is used in the design of the fan wing control system.

4. Design of the Fan Wing Control System

The design of the fan wing control system is mainly used to assist the conventional rudder surface control or used as an emergency system in case of the control failure of the rudder surfaces. Therefore, the classical PID control method is adopted to design the fan wing control system when the conventional rudder surface fault occurs.
4.1. Design of the Longitudinal Fan Wing Control System.

When the elevator, the main rudder surface, fails, the flight task can be completed by fan wing control. The control variable is the coaxial rotation speed of both sides of the fan wing. The overall structure of the longitudinal control system of FanWing is shown in Figure 3.

A PD fan wing control is adopted in the inner loop to control the longitudinal pitch attitude. And a PID fan wing control is used in the outer loop to stabilize the longitudinal altitude to maintain the FanWing flight path.

4.1.1. Design of the Attitude Control. A PD control is adopted in the attitude control. The control law is formulated in

\[
\delta_n = K_{\omega_z} \omega_z + K_{\vartheta} (\vartheta - \vartheta_i).
\]

In Equation (3), \(K_{\omega_z}\) is the pitch rate feedback gain and \(K_{\vartheta}\) is the pitch angle feedback gain. If the force action position of the fan wing is behind the center of gravity, there is an additional pitch-down moment. When the fan wing control is working, the pitch rate \(\omega_z\) and the rotation speed \(\delta_n\) of the fan wing are the same sign. If the force action position of the fan wing is before the center of gravity, there will be a pitch-up moment. Then the sign of \(\omega_z\) and \(\delta_n\) would be opposite. Different from conventional rudder surface control, \(K_{\vartheta}\) is not necessarily positive or negative.

The pitch angle feedback gain is determined by the sign of the pitch moment derived by the fan wing. The pitch angle feedback gain is determined by the lift and the additional pitch moment generated by the fan wing, if it is a pitch-up moment. The sign of the pitch angle feedback gain is negative, if it is a pitch-down moment. Since FanWing has good stability, the short-period motion is soon disappeared. So, the angle of attack \(\alpha\) and the pitch rate \(\omega_z\) are stable. The angle of attack decreases to offset the additional pitch-down moment. The pitch angle \(\vartheta\) is determined by both the angle of attack \(\alpha\) and the flight path angle \(\theta\). An additional pitch-down moment is generated by \(\delta_n > 0\); more importantly, the lift and the thrust are also caused by \(\delta_n > 0\). With the increase of the lift, FanWing starts climbing, which leads to a positive flight path angle \(\theta > 0\). And \(\vartheta = \theta + \alpha\). Finally, the sign of the pitch angle feedback gain is uncertain, which is determined by both \(\theta\) and \(\alpha\). If the additional pitch-down moment is significant, the sign of the pitch angle feedback gain is positive. If the lift is significant, the sign of the pitch angle feedback gain is negative.

In most cases, the force action position of the fan wing is after the center of gravity. Finally, the pitch angle feedback gain is determined by both the lift and the additional pitch-down moment generated by the fan wing. So, full consideration should be taken in the structure design of FanWing. And for the stability control of FanWing, the center of gravity should be as close to the force action position as possible.

Table 2: Trim data for FanWing.

| Steady state | \(\alpha = -5.899^\circ\) | \(\delta_e = 5.4439^\circ\) | \(\delta_n = 2986.2 \text{ r/min}\) |
|--------------|----------------|-----------------|-----------------|
| Longitudinal mode | Eigenvalue | Damp | Frequency (rad/s) |
| | \(-2.41 \pm 11.8i\) | 0.2 | 12 |
| | \(-0.42 \pm 0.7i\) | 0.0514 | 0.816 |
| | Eigenvalue | Damp of dutch roll mode | Frequency (rad/s) |
| | \(-0.261 \pm 5.86i\) | 0.0444 | 5.87 |
| Lateral mode | \(-2.21e - 15\) | -0.164 |

Figure 3: Longitudinal fan wing control system.
4.1.2. Design of the Track Control. The final purpose of the longitudinal control is to track the longitudinal trajectory. In the elevator control system, the track control is realized by the attitude control. In comparison, the fan wing control is more direct. The flight trajectory is controlled by the lift generated by the fan wing.

The inner loop of the attitude control system is the pitch attitude control, while the outer loop is the height control. The fan wing control law is designed as follows:

$$\delta_n = K_n^{\text{h}}(h - h_c) + K_n^{\text{th}} \int (h - h_c) \, dt.$$  \hspace{1cm} (4)

In Equation (4), $K_n^{\text{h}}$ is the height feedback gain of the proportional part and $K_n^{\text{th}}$ is the height feedback gain of the integral part. Take climbing as an example. With a given desired flight altitude and a known current flight altitude, the altitude difference $h - h_c$ is negative. The fan wing control is aimed at eliminating the altitude difference. As a result of the lift generated by the increase in the fan wing rotation speed, FanWing will enter into a typical climb. Therefore, the sign (positive or negative) of the fan wing rotation speed and the altitude difference $h - h_c$ is opposite. The altitude feedback gains $K_n^{\text{h}} < 0$ and $K_n^{\text{th}} < 0$, which is different from the conventional rudder surface control.

Generally, the longitudinal control of the conventional rudder surface is realized by changing the FanWing attitude through the corresponding moment caused by the elevator deflection. Then, the aerodynamic forces and the forces generated by the fan wing are affected. The path plan is changed. While in the fan wing control system, the change of the fan wing rotation speed leads to the variation in the lift, which directly acts on the FanWing trajectory. On the contrary, the trajectory tracking is hampered by the additional pitch-down moment.

4.2. Design of the Lateral Fan Wing Control System. Different from the longitudinal control system, the design difficulty of the lateral control system is the selection of control solution when the rudder and the aileron are out of work.

The rudder is mainly used to compensate for the roll motion and increase the damping of the dutch roll motion. And the aileron is primarily used to track the flight heading and maintain the roll angle. The outer loop track control is realized by the inner loop roll angle control. The fan wing differential control can replace the aileron when the aileron fails. But it is used to replace both the rudder and the aileron when the rudder fails.

Since the fan wing differential control is adopted instead of the rudder in the dutch roll motion, the fan wing differential control regulates both moments on the $\text{ax}_n$ axis and the $\text{ay}_n$ axis. The aileron control will be disturbed. What is more, the efficiency of the fan wing differential control is higher than that of the aileron. It leads to a large compensation deflection of the aileron, even larger than the aileron deflection range. Therefore, it is not advisable to replace the rudder alone with the fan wing differential control. When the rudder fails, the fan wing differential control is needed to simultaneously replace both the rudder and the aileron. The overall structure of the lateral control system of FanWing is shown in Figure 4.

4.2.1. Fan Wing Differential Control Instead of the Aileron. The fan wing control law is designed as follows:

$$\delta_r = K_r^{\omega_y} \omega_y,$$

$$\delta_n = K_n^{\text{rd}}(y - y_c) + K_n^{\text{rrd}} \omega_x,$$  \hspace{1cm} (5)

$$\gamma_c = K_c^{\text{r\gamma}}(\psi - \psi_c) + K_c^{\text{r\gamma\gamma}}(z_c - z).$$

The realization of the control system is similar to that of the aileron control. But since the definition of the positive direction is opposite, the feedback gain is negative except $K_n^{\text{rrd}}$ and $K_c^{\text{r\gamma\gamma}}$. With a given desired roll angle $y_c(y - y_c < 0)$, the fan wing differential rotation speed will be positive $\delta_n > 0$ from Equation (5). It means an increased rotation speed at the left wing while a decreased rotation speed at the right wing. A positive roll moment is then provided because of the increased lift at the left side and the decreased lift at the right side. The $K_n^{\text{rrd}}$ effect is earlier than $K_c^{\text{r\gamma\gamma}}(y - y_c)$, which plays a damping effect with a negative fan wing differential rotation speed.

4.2.2. Fan Wing Differential Control Instead of Both the Aileron and the Rudder. The fan wing control law is designed in

$$\delta_n = K_n^{\text{rd}} \omega_y,$$

$$\delta_n = K_n^{\text{rrd}}(y - y_c) + K_n^{\text{rrd}} \omega_x,$$  \hspace{1cm} (6)

$$\gamma_c = K_c^{\text{r\gamma}}(\psi - \psi_c) + K_c^{\text{r\gamma\gamma}}(z_c - z).$$

There are four inputs in the lateral control system, including aileron $\delta_a$, rudder $\delta_r$, fan wing coaxial rotation speed $\delta_n$, and fan wing differential rotation speed $\delta_{nd}$. $\delta_n$ is the trim value, and $\delta_{nd}$ is the control input in the fan wing lateral control.

In general, the control principle of the fan wing control and the traditional rudder control is the same in the FanWing lateral control. The lateral control is realized by the roll moments and the yaw moments generated by the control structures. So, the fan wing differential control is similar to the aileron control and has better efficiency.

4.3. Simulation of the Emergency Flight Control System. With a constant fan wing rotation speed, the rudder surface control can be realized. At the same time, FanWing can also be controlled by the fan wing. We assume that the traditional rudder surface fails in the level flight state. In this case, the failed rudder surface can be replaced directly by the fan wing. So, no more simulation verification is needed in this case. The issue studied in this paper is that the rudder surface fails in the climbing/sliding or turning state. In this case, the rudder surface is still working.
Take climbing as an example. A 50 m height deviation is given. We assume that the elevator fails at $t = 30\, \text{s}$. The longitudinal nonlinear simulation is shown in Figure 5.

From Figure 5, the fan wing longitudinal control can be used as the emergency flight control of FanWing. Figure 5(d) is the pitch angle rate simulation. The fan wing control system starts to work at $t = 30\, \text{s}$ when the elevator fails. The elevator stays at the broken position shown in Figure 5(c). Because of the additional pitch-down moment, FanWing climbs with a nose-down attitude. With an approximate path angle of $2.4^\circ$, the elevator works out, and the fan wing joins in at $t = 30\, \text{s}$. Since the fan wing rotation speed increases, a bigger path angle of 5.1° is provided. A positive lift and a negative pitch moment are produced by increasing the fan wing rotation speed, leading to decreased pitch angle at $t = 30\, \text{s}$ shown in Figure 5(a). Then, with the increasing path angle, the pitch angle grows. There is a strong coupling between the altitude control shown in Figure 5(b) and the pitch angle control. So, some control performances of the pitch angle are sacrificed for guaranteeing a stable altitude control. The climbing process of FanWing is different from that of the conventional airplane in the fan wing control system. The control of the pitch angle is realized by changing the flight path angle caused by the fan wing lift. The climbing process is as follows.

1. We assume that a height deviation signal $\Delta h > 0$ is given (FanWing is climbing). The fan wing rotation speed increases $\Delta \delta_w$. A negative additional pitch moment is then produced, which leads to a reduction of the pitch rate $\Delta \omega_\alpha$. The angle of attack decreases $\Delta \alpha$ to offset the additional pitch-down moment. In the conventional airplane, there is an increased angle of attack caused by the positive pitch moment generated by the elevator. So the lift is generated, and the flight path angle is changed, then the pitch angle increases. Unlike the conventional airplane, an additional pitch-down moment is caused first by $\Delta \delta_w$, that the pitch angle decreases $\Delta \theta$. 

2. At the same time, a lift is generated by $\Delta \delta_n$. FanWing has a positive flight path angle rate $\Delta \dot{\theta}$. Since FanWing has good stability, the angle of attack is stable. So, the flight path goes upward. With the increase in $\Delta \theta$, the pitch angle increases $\Delta \theta'$. However, the lift $T_y$ and the thrust $T_x$ generated by $\Delta \delta_n$ are the primary issues. Because the effect of the lift is more potent than that of the additional pitch-down moment in this paper, $|\Delta \theta'| > |\Delta \theta''|$, $\theta$ increases gradually

3. With the increasing $\theta$ and decreasing $h$, the fan wing rotation speed reduced until $\Delta \delta_n = 0$. Then, the forces and the moments generated by the fan wing are null $\Delta T_x = \Delta T_y = \Delta M_z = 0$. But FanWing is still climbing at a specific path angle at this point

4. The altitude difference signal is less than the pitch angle deviation signal, making the fan wing rotation speed callback and leading to an opposite $\Delta \delta_n'$. With the decrease of the fan wing rotation speed, the additional pitch-down moment decreases, and then, the pitch rate increases, and the pitch angle increases again

5. Because of the decrease of the fan wing rotation speed, the lift and the pitch angle are reduced until $\Delta h = \Delta \theta = 0$. The fan wing rotation speed returns to the equilibrium position $\Delta \delta_n = 0$. And the FanWing altitude control is realized

In the lateral subsystem, a 50 m lateral deviation is given. We assume that the rudder and the aileron fail at $t = 10\, \text{s}$. The lateral nonlinear simulation is shown in Figure 6.

From Figure 6, the fan wing lateral control can be used as the emergency flight control of FanWing. Figure 6(a) is the angle simulation, and Figure 6(b) is the angle rate simulation. As an extreme case, the aileron and the rudder are both out of work. The aileron and the rudder constantly work at the broken deflection shown in Figure 6(c). So, a state of continually adjusting is shown in Figure 6(d). But in most cases, there is only one broken rudder surface at a time. If the aileron fails, it can be replaced by the fan wing. If the rudder fails, the rudder and the aileron would be replaced by the fan wing simultaneously. And in this case, the aileron would still work so that a return-to-zero order would be supplied to the aileron. The repeated adjustment does not take place.
Figure 5: Longitudinal nonlinear simulation.
Figure 6: Lateral nonlinear simulation.
5. Conclusion

(1) This paper introduces the emergency flight control of FanWing with the fan wing control and can obtain favorable effects from the case above. The practical and measurable physical quantities are adopted in the design of the control system, which has strong engineering practicality.

(2) The difficulty in designing the longitudinal emergency control system lies in the design of the feedback gain, whose polarity is determined by the forces and moments generated by the fan wing. The additional pitch moment has a significant influence on the fan wing control system design. And the FanWing structure design is substantial. For the stability control of FanWing, the center of gravity should be as close to the force action position as possible.

(3) When the rudder fails, the fan wing differential control is needed to replace both the rudder and the aileron simultaneously and not as a standalone replacement of the rudder.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

We would like to acknowledge helpful information obtained from the FanWing company. This work was supported in part by the National Natural Science Foundation of China under Grant 61903183 and in part by the Nanjing Institute of Technology high level introduction of talents Research Fund under Grant YKJ201942.

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