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Development of Pilot Mathematical Model in the Preview Manual Control Task

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Abstract: The model for perception of the preview target trajectory is being proposed. The model is a weighted sum of the slopes of the preview target trajectory elements. A procedure for the selection of the weighting coefficients as well as other pilot adaptation parameters is proposed. The results of the mathematical modelling of the pilot-aircraft system corresponding to the preview tracking and ground-based simulation are compared.

Keywords: manual control, pilot model, preview control, pilot-aircraft system, predictive display

1. INTRODUCTION

The replacement of instruments for displays and the use of on-board computers in the second half of the last century prompted a number of studies aimed at finding new ways of displaying information such as "the tunnel in the sky", allowing the pilot to assess the position of the aircraft in space and the future planned trajectory of its motion. The first studies in this area were carried out by Wilkens and Schatterman [V. Wilckens, et. al.(1968)]. They proposed the so-called "channel display" and demonstrated its effectiveness in comparison with the other instruments used for landing. The end of the pioneer era in the research of "the tunnel in the sky" display are associated with investigations of Grunwald [A. J. Grunwald, (1985)] examined the availability and use of control-related information in spatial visual display, the importance of preview of the target trajectory and flight path predictor symbol. The intensive studies of "the tunnel in the sky" including the definition of the tunnel sizes [M. Mulder (1999), M. Mulder, et. Al. (2005)], the integration of the perspective flight path display with path oriented control augmentation [C. Borst, et. al. (2006)]and many other aspects of its design were carried out in the Delft University of technology. The results of all these works are the predictive display which is a combination of the tunnel and predictor. It displays, in addition to the tunnel, a surface MN ("predictive window") moving inside it at the aircraft velocity. The vector of velocity V is projected (Fig. 1) onto this surface.

The determination of the distance L_{pr} from the pilot's eye to the surface MN (or predictive time $T_{pr} = \frac{L_{pr}}{V}$) can be done by the different ways. For example in [G. Sachs, (2000)] it was defined by the traditional feedback control theory to ensure acceptable dynamics of the controlled element dynamics.

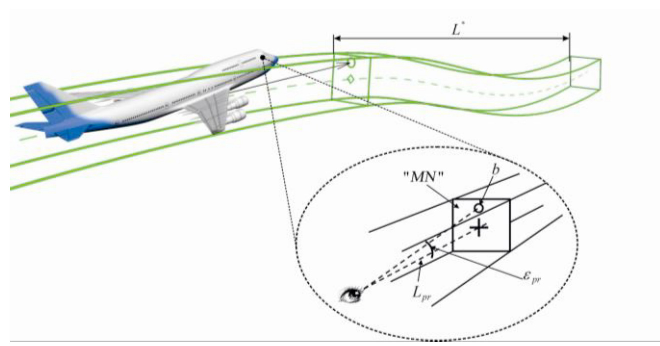

Fig. 1 Predictive display with image of preview trajectory

Another way is proposed at the Moscow Aviation Institute [A.V. Efremov, et al. (2011)]. It is considered briefly in part 2. Practically all studies on predictive display design showed that its use can improve task performance significantly. Taking into account the high efficiency of the predictive display, it seems appropriate to combine the idea of predicting the aircraft path motion, implemented by the predictive display, with the prediction of the preview planned trajectory, located behind the predictive window at a certain distance corresponding to the time interval $(t+T_{pr}; t+T_{pr}+T^*)$, and determine the rational preview time $T^* = \frac{L^*}{V}$. To solve this problem, it is necessary, first of all, to know the model of the pilot's perception of preview target signal.

The major part of the more than seventy-year history of the pilot-aircraft system research was carried out in conditions corresponding to the compensatory tracking task. For this case, the main regularities of his behavior were defined, in particular, adaptation to task variables, and several versions of behavior models (structural model, optimal model, neural network model), and a technique for identification of the characteristics of the pilot were developed. These results were applied to flight control systems, inceptors and displays design widely.

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However, not all piloting tasks can be assigned to compensatory tracking tasks. In particular, when tracking a target flying against the background of clouds or the earth, the pilot perceives the input signal *i(t)*, in addition to the error signal, forming the so-called pursuit tracking task. When flying through mountain gorge or while driving a car, the operator sees the future trajectory $i(t+T^*)$ with preview over a certain time interval T^*. In one of the first studies [L.D. Reid, et al. (1972)] of such a case, it was shown that the perception of the future planned (target) trajectory leads to a significant decrease in tracking error at values T^* not exceeding 2 ÷ 3 seconds. A further increase in it practically does not reduce a tracking error.

The investigations of pilot-aircraft system in preview tracking task is a subject of intensive studies carried out by the group of scientists from the Delft University of technology during more than the last two decades. In these investigations they exposed a set of the regularities of human operator behavior by the identification of characteristics describing the operator responses on the input and error signals and by their mathematical modeling [K. van der El, et al. (2016), (2017), (2018), (2018)]. In particular these studies allowed to define the optimum preview time, to expose the human responding on near and far points that are located ahead on the previewed target, influence of linear perspective preview display and controlled element dynamics on human operator characteristics in preview manual control task and many other results.

The present article is devoted to the mathematical modeling of pilot behavior in preview manual control task by modification of pilot structural model proposed in [A.V. Efremov, et al. (2011)] for investigations of compensatory tracking task. The model corresponds to the task of the predictive path tracking carried out in condition of preview plane trajectory located behind the predictive window. Such model is necessary for explanation of results of experimental investigations and definition of previewed information parameters.

2. DEFINITION OF PREDICTIVE TIME T_{pr}

In [A.V. Efremov, et al. (2011)], it was proposed to project the predicted path angle to the display screen $\gamma_{pr} = \gamma + \dot{\gamma}\frac{T_{pr}}{2}$. Here $\gamma, \dot{\gamma}$ - are the path angle and its derivative. Then the dynamics of the controlled element dynamics in the longitudinal channel is determined by the angle $\varepsilon_{pr} = \gamma_{pr} + \frac{\Delta H}{L_{pr}}$, described by the following transfer function:

$$W_c^*(s) = \frac{K_c(T_{pr}s^2 + 2s + \frac{2}{T_{pr}})}{s^2(s^2 + 2\zeta\omega + \omega^2)} \quad (1)$$

A block diagram of the pilot-aircraft system corresponding to such controlled element dynamics is shown in Fig. 2. In this block diagram, not only the controlled element dynamics depends on the predictive time T_{pr} (or L_{pr}), but the other variables of this system as well. Namely, the input signal $\frac{i(t+T_{pr})}{L_{pr}}$ and the transfer function determining the ratio between aircraft altitude and path angle

$$W_c = \frac{H}{\varepsilon_{pr}} = \frac{2V}{T_{pr}s^2 + 2s + \frac{2}{T_{pr}}} \quad (2)$$

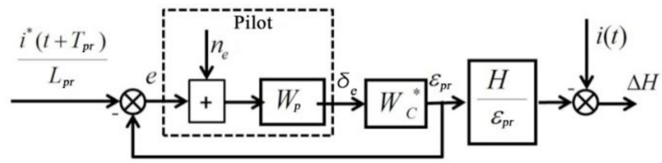

Fig. 2. Structural scheme of the pilot - aircraft system

The analysis shows that the predictive time T_{pr} has a different effect on all these variables, and, consequently, on the characteristics of the aircraft-pilot system. The optimal value T_{pr} was defined in [A.V. Efremov, et al. (2011)] by minimization of the error variance $\sigma^2_{\Delta H}$. For that purpose a modified Hess structural model [R. Hess, (1977)] was used, the parameters of which in the visual and proprioceptive channels are selected by minimizing the error dispersion σ_e^2 for each value T_{pr} [A.V. Efremov, et al. (2011); A.V. Efremov, et al. (2018)] Further calculation $\sigma^2_{\Delta H} = f(L)$ allowed to find the optimal solution. In papers [A.V. Efremov, et al. (2011); A.V. Efremov, et al. (2018)] it is shown that pilot-aircraft system model given in fig. 1 allows obtaining not only qualitative but also quantitative coincidence with the results of mathematical modeling, in which both frequency response characteristics and mean square of error signal were measured.

3. PRELIMINARY RESEARCH ON THE EFFECT OF PREVIEW TIME T^*

In the case that the pilot perceives the additional preview target trajectory on the interval $[t+T_{pr}; t+T_{pr}+T^*]$, the task of pilot-aircraft system modeling becomes more complicated. Here it is necessary to take into account the perception of this information and simulate the reaction of the pilot to it, as well as to the error signal.

In order to develop a model of perception of the input preview signal $i(t+T_{pr}+T^*)$ transmitted to the display screen, a series of experiments were performed in which the continuation of the tunnel located behind the predictive window at various time intervals T^* was demonstrated on the screen. After each experiment pilots were surveyed in order to identify the main factors influencing their perception. The survey and measurements revealed that pilots use information about the derivative of the preview target trajectory. The influence of the remote segments of the trajectory is taken into account by the pilot to a lesser extent than the influence of closely located segments. Experimental studies were performed on the ground-based simulator of the Pilot-Vehicle Lab (PVL) of MAI equipped with a wide-angle stereoscopic computer generated visual system (Fig. 3).

All experiments were performed for the same dynamics (eq. 1). The parameters of the transfer function were the following: $\omega = 2.4 \sec^{-1}, \xi = 0.64, T_{pr} = 0.7 \sec$. It was shown in [A.V. Efremov, et al. (2011)] that value $T_{pr}=0.7sec$ for configuration characterizing by the same ω, ξ. Such controlled element dynamics was used in the current studies too. Three human operators participated in the experiments. One of them is a pilot having a rich experience in flying qualities evaluations. Each operator had performed ten runs for each investigated parameters and the results of experiments were averaged.

Fig. 3 The ground-based simulator of the MAI PVL

The simulated external situation corresponded to a landing task. The predictive display in the form of a tunnel of the different lengths, a predictive window and a projection of the predicted velocity vector were displayed on the simulator screen. The results of the experiments were processed in order to obtain frequency, spectral and integral characteristics in accordance with the algorithms and software given in [Efremov A.V. et al., (1996); Efremov A.V., et al. (1992)].

The purpose of these experiments was to determine the appropriate length of this corridor $L^* = VT^*$. If the corridor is too short then the pilot will not receive enough information, and a considerable length of the corridor will either be useless or cause difficulty of perception with a complex preview trajectory. The experiments were performed with a polyharmonic input signal $i = \sum_{k=1}^{15} A_k \cos \omega_k t$. The amplitudes A_k, frequencies ω_k and their number k were chosen from the conditions of the equivalence of the distribution of power to the distribution of random signal characterizing by the spectral density $S_{ii} = \frac{K^2}{(\omega^2 + (0.5)^2)^2}$ in the frequency band $0.262 \le \omega \le 15.708$ which is more important for the pilot. The results of these experiments (Fig. 4) allowed to get the optimal length L^*_{opt} and also demonstrated that the visualization of a segment of a preview trajectory of sufficient length $L^* > L^*_{opt}$ does not improve task performance (σ_e^2), but even worsens it somewhat.

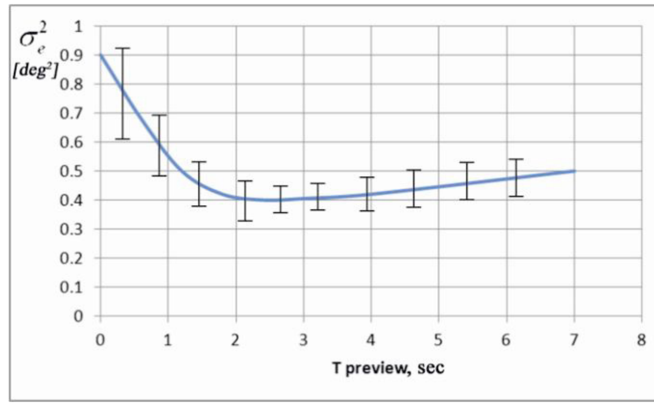

Fig. 4 Influence of preview time on piloting accuracy

In addition to improving task performance, the pilot describing function $W_p(j\omega) = \frac{c(j\omega)}{e(j\omega)}$, obtained under the conditions of perception of additional preview information, demonstrates their difference from the describing function measured under the conditions of the compensatory task (Fig. 5), i.e. in the absence of a tunnel image behind the predictive window.

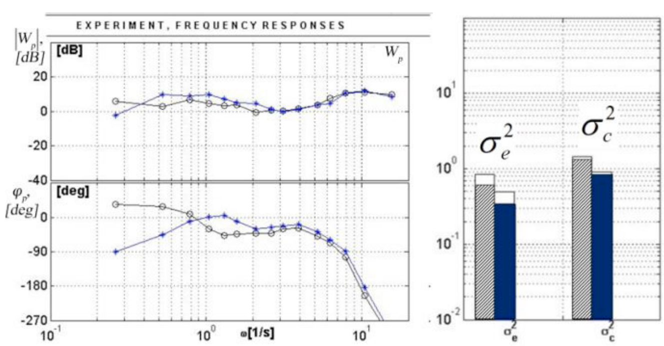

Fig. 5 Pilot describing function $W_p(j\omega)$ and integral characteristics in compensatory (—o—o—, ▨) and preview (—+—, ■) tasks

When tracking with preview (fig. 5), an increase in the pilot amplitude frequency response in the low-frequency band, as well as an additional phase lead in the crossover frequency band is noticeable.

4. PILOT MODEL FOR TRACKING WITH PREVIEW

Taking into account the above survey of pilots on the use of information on the curvilinear trajectory located behind the predictive window, as well as the obtained preliminary experimental results, a model of its perception was proposed in the form of an additional signal $\nu(t)$ summed with the error signal $e(t)$ (Fig. 6).

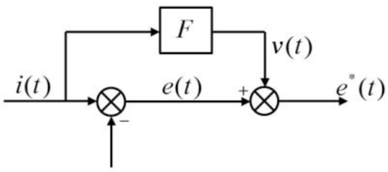

Fig. 6. Pilot model in preview tracking task

Here F is the operation applied to the input $i(t)$ allowed to get the following signal $\nu(t)$

$$\nu(t) = K_1 \frac{[i(t+\Delta t) - i(t)]}{\Delta t \cdot V} + K_2 \frac{[i(t+2\Delta t) - i(t+\Delta t)]}{\Delta t \cdot V} + ... \qquad (3)$$

This signal is essentially a weighted sum of the slopes in trajectory segments of the same length $\Delta t \cdot V$, shown in Fig. 7 and determines the process of perception of the future planned trajectory by the pilot.

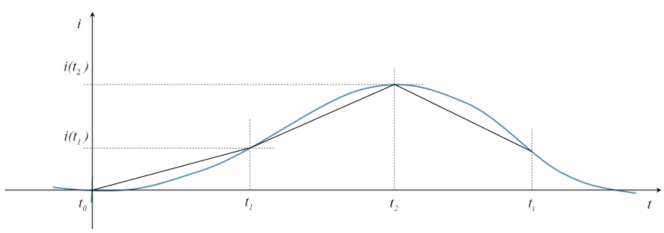

Fig. 7 Formation of signal $\nu(t)$

The weights K_i determine the degree of importance for the pilot the average slopes of trajectory parts, located at different distances behind the predictive window. The preliminary ground-based simulations were performed for two kinds of information presented on the display. One of them was the signal $e^*(t) = e(t) + \nu(t)$. The weighting coefficients K_i in eq. 3 were equal to (4.5, 5, 3, 2, 1) and Δt=0.4 sec. Such conditions corresponding to the compensatory tracking task. The other one was the case in which the predictive window, projection of predictive path angle and preview trajectory were demonstrated on the display screen. In the both cases the same input polyharmonic signal was used. The results demonstrated quite similar pilot describing functions (Fig. 8).

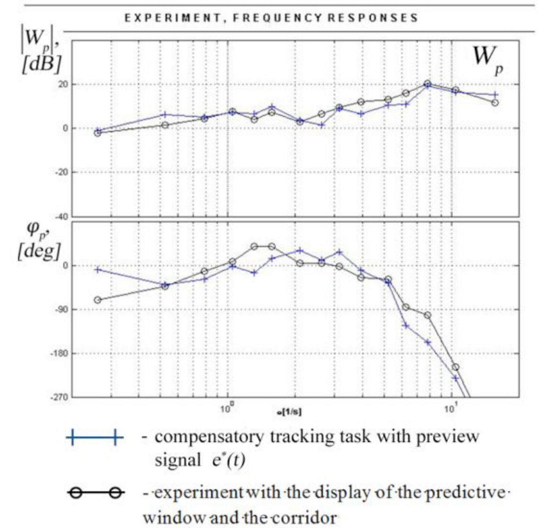

Fig. 8 Pilot describing function for two types of information

For the mathematical modeling of pilot-aircraft system corresponding to the compensatory task, the modification of the Hess's structural model was developed in [A.V. Efremov, et al. (2011)] and shown in Fig. 9. It is the quasi linear model for which all nonlinear unstationary effects of pilot behavior are related to the noises $\tilde{n}_e$ and $\tilde{n}_{\dot{e}}$.

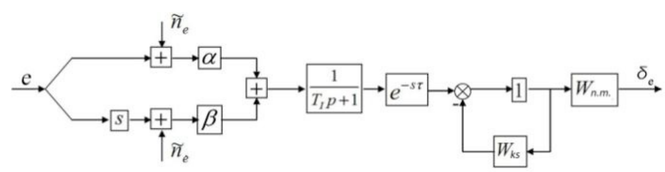

Fig. 9 Pilot structural model

The models of their spectral densities taking into account the influence of perception threshold are the following:

$S_{\tilde{n}_e \tilde{n}_e} = \pi K_{ne} \sigma_e^2$ and

$S_{\tilde{n}_{\dot{e}} \tilde{n}_{\dot{e}}} = \pi K_{n\dot{e}} \sigma_{\dot{e}}^2$,

where $K_{ne} = \frac{0.01}{K_e^2}$, $K_{n\dot{e}} = \frac{0.01}{K_{\dot{e}}^2}$. $K_e = erf\left(\frac{\Delta}{\sigma_e}\right)$ and $K_{\dot{e}} = erf\left(\frac{\Delta}{\sigma_{\dot{e}}}\right)$ are the equivalent coefficients obtained as a result of statistical linearization.

In the mathematical modeling the time delay τ was equal to 0.4 sec. The increased value of this parameter is explained by the central stick used in experiments. The separate set of experiments demonstrated that its use is accompanied by higher time delay (up to 0.2 sec) in comparison with the side stick.

The transfer function $W_{ks} = \frac{K_n p^2}{T_n^2 p^2 + 2T_n p + 1}$ is the model of the pilot's adaptation to proprioceptive information and

$W_{n.m.} = \frac{\omega_{n.m.}^2}{p^2 + 2\xi_{n.m.}\omega_{n.m.}p + \omega_{n.m.}^2} \cdot \frac{1}{\frac{1}{\omega_{n.m.}}p + 1}$ is the dynamics of the neuromuscular system ($\omega_{n.m.} = 12$ 1/sec, $\xi_{n.m.} = 0.1$).

The selection of the parameters of the pilot model ($K_L = \alpha$, $T_L = \frac{\alpha}{\beta}$, K_n, T_n) was implemented by minimizing the error variance

$$\sigma_e^2 = \sigma_{e_n}^2 + \sigma_{e_i}^2. \tag{4}$$

The calculation of the variance of the error for the case $K_{ne} = K_{n\dot{e}}$ was carried out according to the equation [Efremov A.V. et al., (1996)]:

$$\sigma_e^2 = \frac{\sigma_{e_i}^2 + T_L^2\sigma_{\dot{e}_i}^2}{\frac{1}{K_{n_e}} - \int_0^\infty |\Phi(j\omega)|^2 d\omega} \int_0^\infty \frac{|\Phi(j\omega)|^2}{1 + T_L^2\omega^2} d\omega, \tag{5}$$

where $\Phi(j\omega)$ is the describing function of the closed system of the pilot-aircraft system.

Then, the procedure of minimizing the variance of the total error σ_e^2 is based on a multi-parameter global optimization of the variance of the total error value (random search method), where the parameters of the pilot model K_L, T_L, K_n, T_n were defined with accuracy 0.001. The procedure developed by the authors for selecting its parameters, which determine the response of the pilot to visual and proprioceptive information in the absence of an additional signal $\nu(t)$, as well as a random input signal $i(t)$, is given in [A.V. Efremov, et al. (2018)].

For the case when the perceived signal is $e^*(t) = e(t) + \nu(t)$ shown in Fig. 6, the choice of parameters of the pilot model, including the coefficients K_i, should be refined.

The definition of the weighting coefficients K_i (eq. 3) was carried by the interactively. At the first step the values K_L, T_L, K_n, T_n were defined for the initial values of K_i (K_1=0,1; $K_2 = K_3 = K_4 = \ldots$=0) and variance of error was calculated too. Due to the fact that the signal $\nu(t)$ is a polyharmonic input signal which is not a random continuous input signal characterizing by the spectral destiny, the calculation of the variance of error correlated with the input $\sigma_{e_i}^2$ was realized by the numerical integration of the pilot-aircraft system model (Fig. 2). The total variance of error was calculated according to eq. 5 [A.V. Efremov, et al. (2018), Efremov A.V. et al., (1996)]. At the next step the values of each parameters K_i was changed to Δ=0,1 in interval (0,..,10) and procedure for the definition of pilot's parameters and calculation of variance σ_e^2 was repeated. The final values of parameters K_i corresponded to the minimum variance σ_e^2 . These values are given in Table 1.

Table 1. Values of coefficients K_i

K_1	K_2	K_3	K_4	K_5	K_6	K_7
4	4.8	4.2	3.1	1.8	0.6	0.2

The values K_i given in table 1 demonstrate that it does not make sense to take into consideration more than six segments of the trajectory because the value of gain coefficient K_7 is very small and it doesn't influence on the result practically.

The dependence of task performance on time T^* for the calculated values K_i is shown in Fig. 10. It is seen that an increase in time T^* leads to a significant decrease in the variance of the tracking error to $T^* \cong 2.5$ sec. Further growth of T^* does not lead to a decrease in the error and even causes, as in the experiment, some increase in the variance of the tracking error. The same tendency was obtained in experiments too.

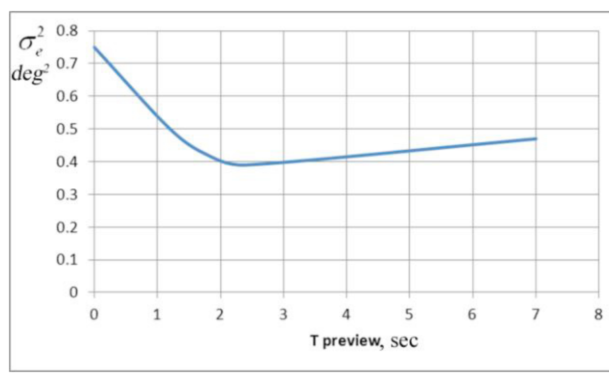

Fig. 10 Influence of predictive time

The frequency response characteristics calculated for the obtained values K_i and other parameters of the pilot model demonstrate fairly good agreement with the frequency and integral (variance of error σ_e^2 and error of inceptor deflection σ_c^2) characteristics obtained in the experimental investigation (Fig. 11).

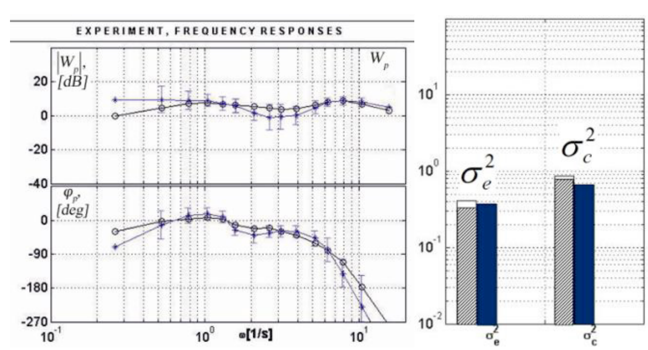

Fig. 11 Comparison of experiment (⊖—⊖ , ▨) with mathematical modeling (+—+ ,■)

5. CONCLUSIONS

The pilot model describing his behaviour in a preview tracking task is based on the assumption of the pilot perceiving a change in the planned trajectory shown on the screen of the predictive display.

The developed algorithm for selecting pilot model parameters allowed to get results close to the results of a ground-based simulation. In particular, the existence of an optimal value of predictive time of T_{pr} =2.2÷2.5 sec was demonstrated.

The use of the preview trajectory with the predictive display allows improving the accuracy of the predictive path angle tracking up to 2.5 times in comparison with the compensatory display.

6. ACKNOWLEDGMENTS

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