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SPECTRAL ANALYSIS OF AUTOCORRELATION FUNCTIONS OF ROLL AND PITCH ANGLES

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Abstract*—This article addresses issues related to assessing the impact of a pilot's psychophysiological stress on the quality of aircraft piloting techniques. The quality of aircraft control was evaluated through changes in flight parameters, specifically the roll and pitch angles during the landing approach. The study utilized the analysis of autocorrelation functions of the controlled parameter and their spectra. The proposed mathematical apparatus allows tracking the moment when the pilot's psychophysiological stress increases to the point of emotional instability, constructing a function of its influence on the quality of aircraft piloting. This method is necessary for improving crew training for special situations in flight.*

Index Terms—Human factor; parameter amplitude; autocorrelation functions; spectrum analysis; flight piloting technique.

I. INTRODUCTION

A significant number of aviation incidents are caused by pilot errors, especially during critical flight phases. The International Civil Aviation Organization (ICAO) has classified the main types of aviation incidents, with a substantial portion falling into categories such as Loss of Control (LOC), Controlled Flight Into Terrain (CFIT), and Approach and Landing Accident (ALA) [1].

The automation of control processes helps reduce the cognitive load on pilots, as the amount of information per unit of time increases during landing approaches, while the human operator's (pilot's) capabilities for perception, comprehension, and processing of information are limited. The pilot's attention and reaction to aircraft deviations approach their physiological threshold, exceeding which can lead to an aviation incident. Therefore, when considering the economic efficiency and regularity of flights, it is essential to prioritize the primary qualitative indicator of civil aviation activity–flight safety.

Flight safety involves the continuous identification of hazardous factors and risk management. Hazardous factors during landing can include bringing the aircraft to critical flight conditions, which, under low altitude and low-speed conditions, leads to the risk of aircraft stalls.

Preventing the aircraft from reaching critical conditions during landing requires constant monitoring and improving crew training quality.

It is known that an aircraft stays airborne due to the lift force (L), which is generated by the wing and is a result of pressure differences. The lift force depends on the air density (ρ), the velocity of the air relative to the wing (V), the wing area (S), and the lift coefficient (C_L), which is expressed by the equation [2]:

$$L = \frac{\rho V^2}{2} \cdot SC_L .$$

The air density (ρ) within the vertical cross-section of the glide path changes little, and the wing and fuselage area (S) of the aircraft remains almost constant, so they have minimal impact on the change in lift force. The lift force is more significantly affected by the aircraft's airspeed (V) and the lift coefficient of the aircraft's aerodynamic surfaces (C_L), which is a function of the angle of attack of the wing [3]. Additionally, a parameter that accounts for the combination of all forces acting on the aircraft is the load factor (n), which characterizes the aircraft's maneuverability. A reduction in lift force to a level below the aircraft's weight leads to a loss of altitude (Fig. 1), and a sharp decrease in lift force results in a stall and a subsequent fall. Therefore, one of the main dangers for an aircraft is a stall due to a critical reduction in lift force (L).

Landing an aircraft consists of a descent segment and the actual landing distance. During the descent phase, the aircraft follows a sloping trajectory downward from the approach altitude to the flare height of about 15 meters above the ground, maintaining a constant descent speed (V_L) that should exceed the stall speed (V_S) by 1.3 times.

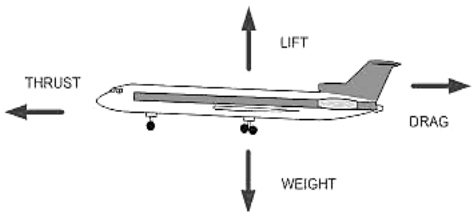


Fig. 1. Forces Acting on an Aircraft

During the landing approach, risk factors that can lead to a loss of lift and a stall at low altitudes include [3]:

- loss of airspeed;
- critical angles of attack;
- exceeding weight limits;
- critical roll angles;
- influence of weather conditions.

When the true airspeed (TAS) is lost, the lift force will decrease. To maintain lift at a level sufficient to compensate for the weight, it is necessary to increase the lift coefficient (C_L), which means increasing the angle of attack (α). Therefore, the slower the speed, the greater the angle of attack should be until the lift coefficient reaches its critical maximum value ($C_{L\max}$), and the angle of attack becomes critical (αS). Further increasing the angle of attack will result in a sharp decrease in the lift coefficient and an aircraft stall. In this case, the stall speed can be determined by the expression:

$$V_S = \sqrt{\frac{2L}{\rho C_{L\max} S}}.$$

To maintain the aircraft in level flight, i.e., with a constant vertical load factor (n_{ZW}), the lift force (L) must compensate for the weight of the aircraft (W).

$$n_{ZW} = \frac{L}{W} = 1.$$

Landing with an exceeded landing weight ($n_{ZW} < 1$) leads to an increase in the calculated stall speed (V_{SR}).

$$V_{SR} = \frac{V_{L\max}}{\sqrt{n_{ZW}}},$$

Therefore, the minimum landing speed ($V_{L\min}$) needs to be increased as well. This factor is relevant for landing aircraft after an emergency takeoff when the fuel quantity is maximal.

Critical roll angles (γ = AOR) during landing affect the lift force of the aircraft. During a roll, the lift force (L) is divided into components, where the vertical component (L_V), which compensates for the weight of the aircraft, becomes smaller. As a result, the aircraft starts to lose altitude with a sliding motion towards the tilted wing, which is dangerous at low altitudes (Fig. 2), so it is necessary to increase the lift force [4]. At a roll angle of γ = 45°, to stabilize the altitude, the lift force should increase by a factor of 1.4.

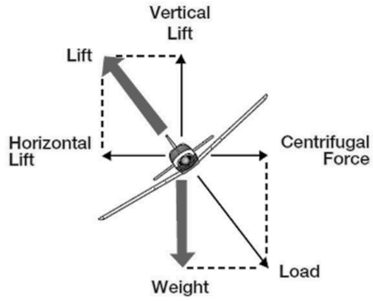
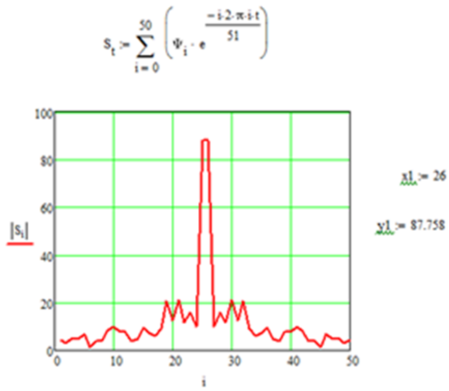


Fig. 2. Dependence of lift force on roll angle LV = f(γ).

The increase in the number of aviation incidents in recent years is due to the growing degree of automation of aircraft to simplify crew operations. This leads to a loss of piloting skills by the crew in extreme conditions, which is evident when automated control systems fail, especially at low altitudes and speeds during landing approaches. Therefore, the detection of deteriorating piloting skills should be a priority among measures to enhance flight safety.

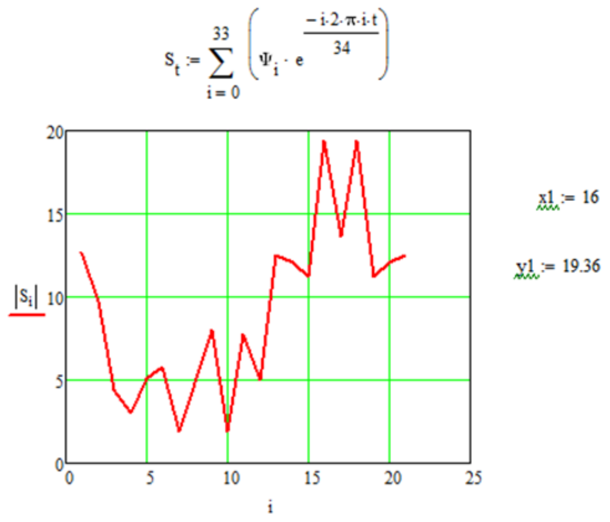
II. Problem Statement

After preliminary evaluation of the piloting technique quality by the airline pilots, we will select the most indicative flights [5]. Additionally, flights during landings at the complex *X* airport are of interest. We will conduct spectral analysis of the autocorrelation functions of the roll angle of these flights (Fig. 3).



a)

Fig. 3. Listing of the calculation of the spectrum of the unnormalized autocorrelation function: (a) is the Pilot 1. Flight 12. Antalya. Heading 185 degrees. (After the 4th turn for landing, t = 240 s); (b) is the Pilot 2. Flight 7. Antalya. Heading 2 degrees. (After the 4th turn for landing, t = 100 s); (c) is the Pilot 2. Flight 11. X. Heading 270 degrees. (After the 4th turn for landing, t = 60 s); (d) is the Pilot 3. Flight 17. N. Heading 47 degrees. (After the 4th turn for landing, t = 260 s)



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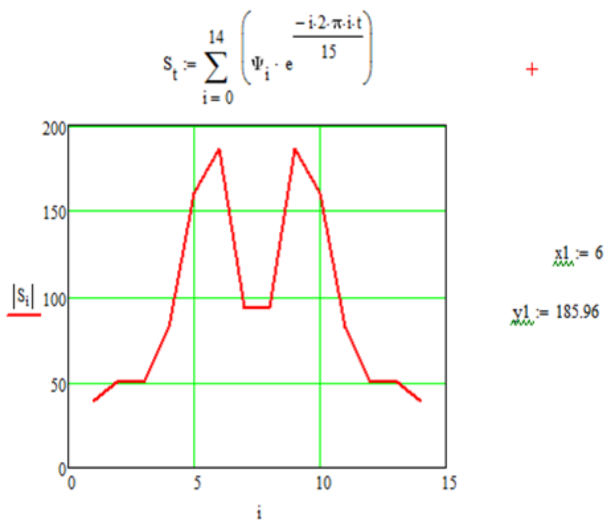

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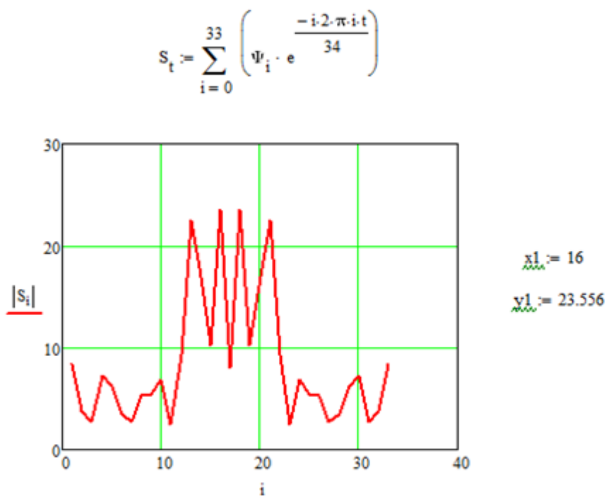

d)

Fig. 3. End. See also p. 101

TABLE I. CALCULATION OF SPECTRA OF UNNORMALIZED AUTOCORRELATION FUNCTIONS SAMPLES OF FLIGHTS WITH DIFFERENT GLIDE PATH LENGTHS

Pilot's namber	**The name of the airport of landing**	**Flights after the 4th turn for landing**
1	Antalya. Heading 185 degrees. (After the 4th turn for landing, t = 240 s).	87.758
2	Antalya. Heading 2 degrees. (After the 4th turn for landing, t = 100 s).	19.36
2	X. Heading 270 degrees. (After the 4th turn for landing, t = 60 s).	185.96
3	Pilot 3. Flight 17. N. Heading 47 degrees. (After the 4th turn for landing, t = 260 s).	23.556

Let's consider the difference in maximum amplitudes of spectra of unnormalized autocorrelation functions during landing approaches at Antalya airport between flights after the 4th turn for landing.

$$K_n = \frac{87.758 - 19.36}{87.758 + 19.36} = 0.63853.$$

Let us consider the difference in the maximum amplitudes of the spectra of non-normalized autocorrelation functions during the approach to airport X and N after the 4th turn before landing.

$$K_n = \frac{185.96\text{-}23.556}{185.96 + 23.556} = 0.77514.$$

Let us consider the difference in the maximum amplitudes of the spectra of non-normalized autocorrelation functions during the approach to airport X and N after the 4th turn before landing.

During the approach to Antalya airport, all pilots adhere to the limitations set by the Flight Operations Manual (FOM). The bank angle limitation is 28° according to the FOM. After the 4th turn for landing, the first pilot shows maximum values of unnormalized spectra, while the second pilot shows minimum values. During the landing at airport X, the bank angle for the second pilot reached 20 degrees. This is due to a shallow glide path during landing. The pilot's technique resembles a "damped sinusoid." The pilot demonstrated high-quality piloting skills. However, a less experienced pilot in this situation could have struggled. It is worth noting that such a shortened glide path may lead to increased psychophysiological stress. For an untrained pilot in this regard, this could result in a deterioration of piloting skills.

The data analysis of unnormalized (*u*) spectra of autocorrelation functions [6] of pitch angle during the landing approach of Boeing 737 NG aircraft under normal flight conditions is presented in Table II.

TABLE II. THE DATA ANALYSIS OF UNNORMALIZED (U2) SPECTRA OF AUTOCORRELATION FUNCTIONS OF PITCH ANGLE

Flight number	y
1	9.108
2	5.462
3	5.1336

These data show that there are no significant changes in piloting technique quality during a normal glide path.

The deterioration of piloting technique quality on the glide path is directly related to the deterioration of landing quality [7].

Therefore, it is necessary to conduct crew training for in-flight emergencies on comprehensive aircraft simulators [8]. Crews should be given failures on the simulator before entering the glide path. This increases the psychophysiological stress on the crew members. A similar situation occurs in real flights during landing approaches with a shortened glide path.

III. CONCLUSIONS

Critical roll and pitch angles can lead to the risk of loss of lift. This is especially dangerous at low altitudes, i.e., on the glide path. Analysis of autocorrelation function spectra of roll and pitch angles in real flights has led to the conclusion that there is a deterioration in piloting technique quality with a shortened glide path. This deterioration does not occur with a normal glide path. The deterioration in piloting technique quality is associated with increased psychophysiological stress on crew members. Crew training in this area should be conducted on a comprehensive aircraft simulator. Before entering the glide path, comprehensive failures should be simulated, leading to psychophysiological stress on the crew. The positive outcome of training will be uniform amplitude indicators of roll and pitch angles both with and without simulated failures.

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Ю. В. Грищенко, О. О. Чужа, Т. С. Соломаха. Спектральний аналіз автокорреляційних функцій кутів крену та тангажу

У статті розглянуто питання, пов’язані з оцінкою впливу психофізіологічного напруження пілота на якість техніки пілотування літаком. Якість керування повітряним судном оцінювалася за допомогою зміни параметрів польоту, а саме кутів крена і тангажу під час заходу на посадку літака. Для проведення дослідження використовувався аналіз автокореляційних функцій контрольованого параметра і їх спектри. Запропонований математичний апарат дає можливість відстежити, в який момент психофізіологічне напруження пілота зростає до стану емоційної нестабільності, побудувати функцію його впливу на якість пілотування літака. Цей метод необхідний для покращення підготовки екіпажів до особливих ситуацій в польоті.

Ключові слова: людський фактор; амплітуда параметру; автокореляційні функції; аналіз спектрів; техніка пілотування політів.

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