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Article

Research on Flight Stability Assessment and Real-Time Early Warning System Based on Energy Management

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Abstract

The aircraft is often difficult to be stably evaluated due to energy fluctuations in the final approach phase. The traditional single-parameter threshold monitoring method is difficult to capture the complex coupling relationship between dynamic energy and potential energy, and the adaptability is insufficient under variable meteorological disturbances. Therefore, this study proposes a new multi-dimensional prediction and evaluation method, which integrates energy management theory and deep learning technology, aiming to improve the early recognition ability of unstable approach under complex meteorological conditions and optimize the energy regulation ability. Firstly, a new stability evaluation framework is constructed from the perspective of energy. Two core evaluation parameters of 'energy altitude' and 'balance energy' are proposed. This method breaks the traditional way of monitoring speed and altitude parameters in isolation. In this paper, a dynamic safety boundary function is designed based on the principle of flight mechanics and civil aviation specifications. The function uses an altitude attenuation mechanism to make the boundary shrink smoothly with the decrease of flight altitude. At the same time, the sliding window statistics and balanced energy triggering mechanism are introduced, which significantly enhances the adaptability of the boundary to various disturbances and effectively overcomes the lag problem of static boundary response. By establishing a multi-dimensional parameter system with energy altitude and balance energy as the core, this study reveals the mechanism of dynamic energy potential energy coupling on approach stability. The hybrid dynamic boundary function realizes the collaborative optimization of physical constraints and data-driven. The research results provide a new theoretical paradigm for solving the evaluation of unstable approach under complex weather, and have important theoretical value and engineering application prospects for ensuring flight safety.

Keywords: final approach; energy management; energy altitude; stability assessment

1. Introduction

The rapid development of the global air transport industry has promoted the growth of air traffic volume. In this context, flight safety has always been the bottom line of civil aviation operation. The statistics of the International Civil Aviation Organization (ICAO) reveal a key phenomenon¹. The approach and landing phase accounts for about 4% of the entire flight process in time, but the probability of flight accident risk accounts for 49.1% of the entire flight accident risk. Among them, unstable approach is widely considered to be one of the main factors that induce serious safety incidents such as controlled flight into terrain and runway excursion. Therefore, it is helpful to predict

the risk in advance by summarizing the main causes and development trends of unsafe events in the approach stage.

The civil aviation supervision system's judgment of stable approach mainly depends on the threshold monitoring of a single flight parameter. However, it is difficult to fully grasp the dynamic change process of aircraft energy state only by focusing on a single parameter. This detection method may cause all single monitored parameters to be within the safe range, and the pilot's response to abnormal energy state perception is judged to be unstable approach. Because the coupling relationship between different parameters is not fully considered in the evaluation, the evaluation results may deviate from the actual operation decision of the pilot. Stable approach requires all relevant parameters to meet the stability standards at the same time. However, there are sometimes cognitive biases in the operation of flight personnel, which leads to insufficient understanding of the hidden hazards of unstable approach and cannot strictly implement the stable approach requirements. Therefore, it is of great significance to study the coupling relationship between the causes of unsafe events in the approach phase to ensure safe landing.

As early as 2006, Yi et al.² built a model based on severity classification and probability calculation, which provided an effective paradigm for quantitative analysis of risks such as energy management failure in the approach stage, and laid an important theoretical foundation for subsequent engineering evaluation. In 2011, the Bazhenov³ deeply explored the mechanism of the digital multi-rate control system on the lateral stability of the aircraft, and pointed out that the sampling frequency of the system should not be less than 50 Hz to ensure the required control accuracy. This discovery provides a key parameter basis for the design of the control algorithm in the approach phase. In 2013, Asadi et al.⁴ constructed a database of trim characteristics of left-wing damaged aircraft. The discovery that the degree of artificial aircraft damage and the flight altitude at that time have a significant impact on the contraction of the approach envelope strongly promotes the exploration of targeted assessment of the risk of damaged aircraft approach. The following year, Nasir et al.⁵ evaluated the aerodynamic characteristics and flight quality of the hybrid wing-body aircraft, and found that the canard configuration can improve the longitudinal static stability of the aircraft. In 2015, Raghu et al.⁶ proposed a reliability evaluation framework for UAV actuator architecture, which verified that the redundant design can successfully reduce the probability of catastrophic failure by 40%.

In recent years, in order to realize the prediction and prevention of unsafe events, some scholars have evaluated the state of aircraft from the perspective of energy management. In 2018, Jiao et al.⁷ constructed an empirical model for unstable approach below 1000 feet, and found that airspeed overrun and channel deviation were the main causes of instability, revealing the profound internal relationship between approach stability and aircraft energy state. In 2019, Hernández-Romero et al.⁸ took environmental factors into account, constructed a wind field uncertainty model, quantified the specific impact of wind shear on the severity of approach conflicts, and provided a novel probabilistic analysis scheme for approach risk assessment under complex meteorological conditions. In 2025, some scholars began to pay attention to the coupling effect between various influencing factors. Du⁹ proposed a double closed-loop sliding mode control strategy, which effectively solved the problem of internal and external coupling in the trajectory tracking task of vertical take-off and landing aircraft. In the same year, the PID controller designed by Dagal et al.¹⁰ was successfully applied to the approach training simulation of Cessna 172 aircraft, which shortened the time for the aircraft to reach a stable state by 30%.

Reducing unstable approach events and ensuring safe landing are of great significance to civil aviation operation¹¹. Existing research has recognized that building a risk assessment system is the research premise, considering the impact of the coupling relationship of various risk incentives is the key to research, and using energy management to achieve aircraft condition assessment is the research basis. The aircraft adjusts the dynamic energy and potential energy by adjusting the engine thrust and pitch attitude. The coordinated change of the two can achieve a stable and controllable decrease in the total energy during the approach and landing phase, and finally meet the energy

conditions necessary for safe landing[12–14]. The International Civil Aviation Organization clearly states that the core of stable approach is to maintain the controllability of the energy state¹, and the change of energy state is affected by multi-source data. Therefore, in order to realize the accurate evaluation of the final approach stability of the aircraft, it is necessary to break through the traditional framework of single parameter monitoring and construct a multi-dimensional evaluation system based on the overall energy state.

Therefore, this paper will define the core energy parameters such as energy altitude and dynamic energy-potential energy ratio, and establish a model to describe the dynamic evolution of energy state. The research results can provide solid theoretical support for the early identification of unstable approach, optimize the energy control strategy of key airborne equipment such as automatic throttle and flight guidance system, and provide data-driven decision-making basis. The research results have important theoretical value and engineering application prospect for improving the flight safety level under complex and changeable meteorological conditions.

2. Theories and Research Methods

2.1. Dynamics Analysis of the Final Approach Stage

The ICAO clearly stipulates that the aircraft must fly strictly along the prescribed glide path, maintain the speed within the specified range, the vertical descent rate must not exceed 1000 feet/min, and the adjustment of key configurations must be completed before reaching the stable approach point¹. However, in actual flight, pilot manipulation may cause the energy state to get out of control. When the pilot reduces the dynamic energy by reducing the thrust, if the pitch angle is not adjusted in time, the potential energy decline rate may significantly exceed the dynamic energy attenuation, which in turn causes cascading effects on parameters such as altitude, velocity, glide angle and vertical velocity.

The energy state of the aircraft is essentially a comprehensive reflection of its dynamic energy and potential energy. The independent analysis of the two energies is difficult to effectively capture the dynamic synergy. Therefore, the study proposes 'energy altitude (H_e)' and 'balance energy (E_b)'. The H_e converts the dynamic energy into an equivalent altitude and superimposes it with the actual geometric altitude to form a comprehensive energy index with a unified dimension. The E_b is used to quantify the distribution equilibrium of dynamic energy and potential energy.

When the E_b approaches zero, it indicates that the distribution of dynamic energy and potential energy is in an ideal state. If the balance energy exceeds 50 meters, the dynamic energy is considered to be excess, and the excess dynamic energy needs to be converted into potential energy by increasing the pitch angle.

2.2. Energy Management and Constraints

The core control logic of energy management is to achieve energy balance by changing the thrust and pitch angles. In the early days, the influence of thrust and pitch angle on velocity and altitude was discussed separately in aircraft energy management. This method often leads to system failure due to the coupling effect between parameters in complex disturbances. In 2004, the total energy control theory was proposed¹⁵. The total energy change rate was adjusted by changing the thrust, and the conversion ratio of dynamic energy and potential energy was adjusted by using the pitch attitude, which fundamentally solved the problem of energy regulation mismatch.

Based on the quick access recorder (QAR) data of a large number of accidents, the ICAO and the Civil Aviation Administration of China (CAAC) have formulated the constraint standards for the parameters of the final approach phase of the aircraft.

3. Construction of Stability Assessment System Based on Energy Management

3.1. Definition of Energy Parameters

For the stability evaluation of the aircraft in the final approach stage, the traditional method mostly adopts the speed and altitude independent monitoring mode, which has significant limitations. Due to the strong coupling characteristics of flight parameters in the approach phase, the velocity and altitude can be correlated by the conversion of dynamic energy and potential energy. External disturbances often act on velocity and altitude at the same time, and it is difficult to accurately capture the essential characteristics of the energy state only through single parameter or two-parameter independent evaluation. Therefore, H_e and E_b are used as evaluation parameters to realize the synergistic analysis of dynamic energy and potential energy, which provides a quantitative basis for multi-dimensional energy state evaluation.

3.1.1. Definition of Energy Altitude

The stability of the aircraft in the final approach phase is essentially a manifestation of the dynamic balance of dynamic energy and potential energy. Traditional research often analyzes dynamic energy and potential energy independently, which cannot reflect the synergistic relationship. Therefore, this study uses the idea of unified control of total energy to convert dynamic energy into equivalent altitude. The H_e can be obtained by adding the equivalent altitude to the actual altitude, and the total energy reserve of the aircraft can be intuitively characterized by a single parameter.

The important parameters of aircraft descent are listed in Table 1. The forces of the aircraft are shown in Figure 1. The green solid line is the trajectory, TOD represents the top of descent, and CG represents the center of gravity.

Table 1. parameters of aircraft descent.

Name	Symbol	Unit
Horizontal distance	x	m
The geometric altitude from the horizontal plane	h	m
Track angle (the angle between the track and the horizontal plane)	γ	rad
Gravity	W	N
Thrust	T	N
Drag	D	N
Lift	L	N
True air speed	V_T	m/s
Wind speed	V_W	m/s

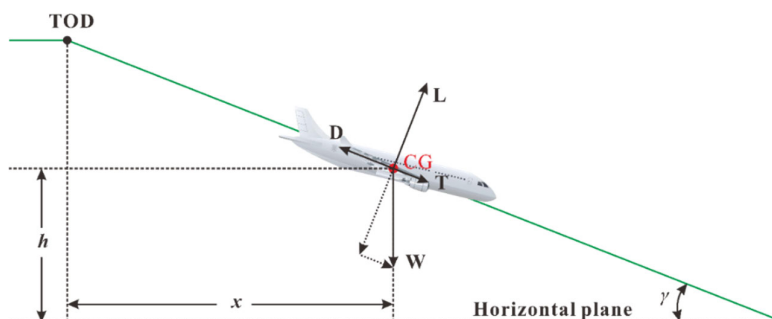


Figure 1. The motion force of the aircraft descending.

The aircraft is regarded as a particle, and its kinematic equation can be expressed as:

$$\begin{cases} \frac{dx}{dt} = V_T \cos \gamma + V_{wx} \\ \frac{dh}{dt} = V_T \sin \gamma + V_{wh} \\ \frac{dV_T}{dt} = \frac{T-D}{m} + g \sin \gamma \end{cases} \quad (1)$$

m is the mass of the aircraft (kg), g is the gravitational acceleration (9.81 m/s²), t is the flight time (s), V_{wx} is the decomposition of the wind speed in the horizontal direction, and V_{wh} is the decomposition of the wind speed in the vertical direction. According to the above equation, it can be obtained:

$$T = \left(\frac{\dot{V}_T}{g} - \gamma \right) mg + D \quad (2)$$

The total energy E_T of the aircraft can be expressed as the sum of dynamic energy E_D and gravitational potential energy E_P :

$$E_T = E_D + E_P = \frac{1}{2} m V_T^2 - mgh \quad (3)$$

In order to achieve dimensional unification, the total energy is equivalent to the 'altitude' form. Assuming that the total energy is completely converted into potential energy, the total energy of unit quality can be obtained:

$$E_T = \frac{V_T^2}{2g} - h \quad (4)$$

The H_e can reflect the total energy reserve state of the aircraft through a single parameter (equivalent altitude). If the energy altitude is high, it indicates that the total energy is excess, which may lead to excessive touch-down speed. If the energy altitude is low, it means that the total energy is insufficient, and there may be risks such as poor anti-disturbance ability.

3.1.2. Total Energy Change Rate

Derivation of formula (4) can be obtained:

$$\dot{E}_T = V_T \frac{\dot{V}_T}{g} - \dot{h} \quad (5)$$

Since $\dot{h} = TAS \sin \gamma$, bring it into formula (5) to get :

$$\frac{\dot{E}_T}{V_T} = \frac{\dot{V}_T}{g} - \sin \gamma \quad (6)$$

Because the descent angle is small. In the instrument landing system (ILS) rule, the standard descent angle is set to 3 degrees. Therefore, $\sin \gamma \approx \gamma$ can be considered. Formula (6) can be rewritten as:

$$\frac{\dot{E}_T}{V_T} \approx \frac{\dot{V}_T}{g} - \gamma \quad (7)$$

Bring Formula (2) into (7):

$$T - D = mg \left(\frac{V_T}{g} - \gamma \right) \quad (8)$$

When the aircraft is in normal flight, the weight change mainly comes from the reduction of fuel. Therefore, the mass of the aircraft is almost unchanged in a short period of time, mg is considered to

be a constant. $\frac{TAS}{g}$ can be used to characterize the changing rate of kinetic energy (m/s). γ (or $\sin\gamma$) can be used to characterize the changing rate of gravitational potential energy (rad). By changing the thrust, the total energy can be directly regulated, and the distribution ratio of kinetic energy and potential energy can be adjusted by changing the track angle γ .

3.1.3. Definition of Balanced Energy

The balanced distribution of kinetic energy and potential energy during flight is the key factor to determine the approach operation. Through the quantitative analysis of the equilibrium degree of kinetic energy and potential energy distribution, it can provide intuitive and real-time reference for pilots, which is helpful to improve the safety and accuracy of approach operation.

The E_b is defined as the difference between potential energy and kinetic energy, which is expressed as:

$$E_b = mgh - \frac{1}{2}mV_T^2 \quad (9)$$

The changing rate of E_b is obtained by simultaneous derivation on both sides of the above formula:

$$\dot{E}_b = mg\dot{h} - mV_T\dot{V}_T \quad (10)$$

By bringing $\dot{h} = V_T \sin \gamma$ into the above formula:

$$\dot{E}_b = mgV_T \left(\sin\gamma - \frac{\dot{V}_T}{g} \right) \quad (11)$$

The mass and V_T of the aircraft are constant in a short period of time. Ignoring its influence, \dot{E}_b can be expressed as :

$$\dot{E}_b = \sin\gamma - \frac{\dot{V}_T}{g} \quad (12)$$

Taking the standard 3° glide angle, 150 knots air speed and no wind condition as the standard, Figure 2 shows the comparison diagram of the balance energy changing rate curve between the measured and standard state of the last 1000 feet approach stage of the aircraft. It is found that the standard curve maintains a stable and regular trend throughout the whole process, and the measured data can respond to the dynamic change of energy change rate in real time. The fluctuation frequency of \dot{E}_b is higher than the traditional parameters such as speed and altitude, which can capture the abnormal energy distribution in advance and provide more timely decision-making basis for pilots.

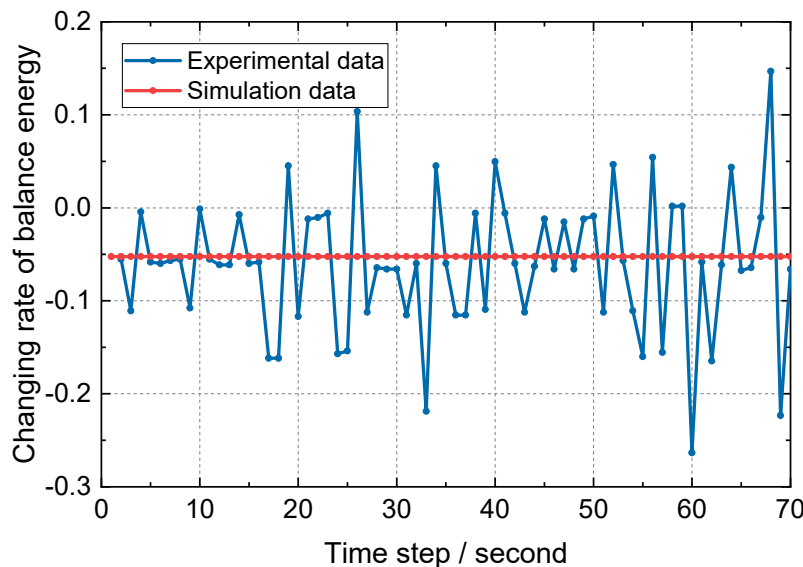


Figure 2. Changing rate of balance energy.

3.2. Construction of Safety Boundary Function

As the key constraint of the evaluation system, the design of the safety boundary function is very important. This study will use the basic theory of flight mechanics, combined with civil aviation regulations and standards, to construct a dynamic boundary function. The function accurately establishes the safety boundary of aircraft energy state through multi-parameter cooperative coupling and adaptive adjustment mechanism, and provides a reliable basis for approach stability evaluation.

3.2.1. Static Boundary Restrictions Based on Civil Aviation Regulations

The core goal of the final approach is to maintain a stable airspeed, a 3 ° sliding angle and a reasonable energy state, and finally achieve a safe touchdown. The energy state of this stage needs to meet the 'double decreasing' rule - the total energy decreases continuously with the decrease of altitude, and the distribution of kinetic energy and potential energy needs to be balanced. Therefore, the design of the boundary function needs to focus on the core parameters such as energy altitude and balanced energy, and take into account the dynamic stability requirements and actual constraints.

The static boundary is the 'bottom line constraint' of the safety envelope. Its design should strictly follow the civil aviation regulations and flight mechanics principles to ensure the safety of the energy state under ideal conditions. According to the relevant requirements of the Flight Standards Division of the Civil Aviation Administration of China, the target approach speed (V_{app}) is used as the core reference, and the actual flight speed must be accurately maintained in the range of $V_{app}-5$ to $V_{app}+10$. From the perspective of ensuring the pilot's operating margin and re-flight energy reserve, it is required that the decline rate in the final approach phase must be controlled within 1000 feet/min, and sufficient adjustment time should be reserved for the pilot.

In the final approach phase, the setting of the energy altitude boundary is an important part of ensuring safe landing. Taking the runway entrance as the key node, the safety constraints are constructed based on the principle of energy conservation. When the aircraft arrives at the runway entrance, the total energy needs to meet the requirements of safe landing, and the safety lower limit of energy altitude is derived accordingly. In order to ensure the smooth landing of the aircraft from the energy point of view and ensure that the aircraft has the appropriate energy reserve at the end of the approach, there is the following formula:

$$E_{T,thr} = \frac{1}{2}mTAS_{thr}^2 + mgh_{thr} \quad (13)$$

Here, $E_{T,thr}$ is the total energy of the runway entrance, TAS_{thr} is the allowable vacuum speed of the runway entrance, and h_{thr} is the allowable altitude of the runway entrance.

The initial safety envelope is an energy static boundary (E_{static}) defined based on the physical model. In order to match the operation logic of 'lower altitude and stricter energy control' in the approach phase, the altitude attenuation function $f(h)$ is introduced to dynamically adjust the static boundary:

$$f(h) = \exp\left(-\frac{h_{ref} - h_{x,y,z}}{h_{ref}}\right) = \exp\left(\frac{h_{x,y,z}}{h_{ref}} - 1\right) \quad (14)$$

Here, h_{ref} is to increase the stable altitude of 1000 feet on the basis of the airport elevation, which is used as a reference point to compare with the current actual flight altitude. $h_{x,y,z}$ means the current position altitude. The range of E_{static} is as follows :

$$E_{static} \in \left\{ \left[E_{T,tre} - \Delta E_{min} \times f(h) \right], \left[E_{T,tre} + \Delta E_{max} \times f(h) \right] \right\} \quad (15)$$

$E_{T,tre}$ represents the trend baseline fitted according to the global energy altitude. ΔE_{min} means the minimum energy corresponding to the lower limit of energy altitude fluctuation. When the speed is lower than the standard 5 knots, the corresponding altitude after conversion to equal energy potential energy is less than 20 meters. The meaning of ΔE_{max} is the maximum energy corresponding to the upper limit of energy altitude fluctuation. that is, the speed exceeds the standard 10 knots, and the corresponding altitude after conversion to equal energy potential energy is 42 meters.

In higher airspace, the flight trajectory is difficult to be affected by obstacles. Therefore, the upper boundary of energy altitude is wide, which can contain the natural fluctuation of energy during normal flight. As the trajectory of the aircraft continues to decline, the tolerable fluctuations at the lower boundary of the altitude continue to narrow in an exponential decay manner. This function design can realize the smooth transition of the boundary and effectively avoid the judgment deviation caused by the sudden change of the boundary.

Figure 3 shows the trend baseline $H_{T,tre}$ and its static boundary diagram. The initial position of the static upper boundary is 42 meters higher than the trend line, and the initial position of the static lower boundary is 20 meters lower than the trend line. Over time, the upper boundary gradually approaches the trend baseline, and the distance from the lower boundary to the trend line shrinks to 15.2 meters within 30 seconds and remains parallel to the trend baseline after 30 seconds. The change trend of the range between the static upper boundary and the lower boundary can be divided into two parts. The first 30 seconds are the dynamic narrowing stage. After 30 seconds, it turns to the parallel descent stage. Which provides a reference frame for the energy altitude monitoring range during the aircraft approach.

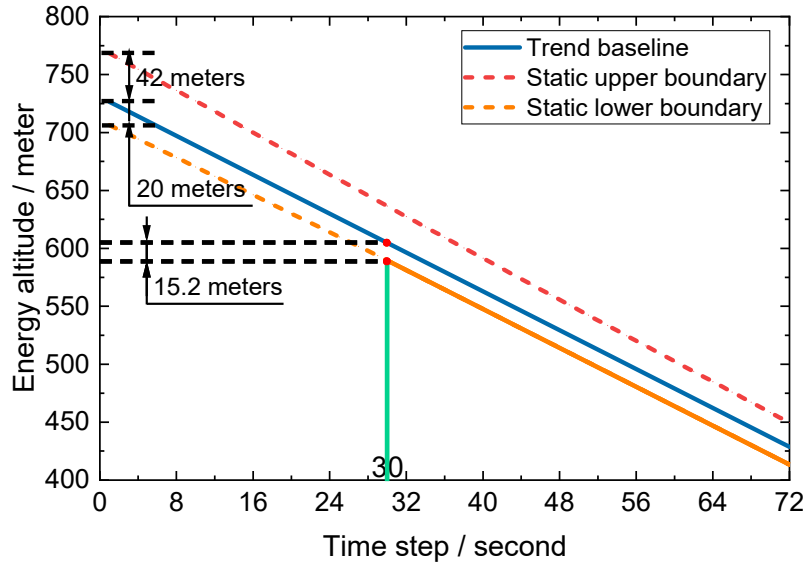


Figure 3. Trend Baseline and Static Boundary Diagram.

3.2.2. Data Driven Dynamic Boundary Correction

The static boundary gives the energy range in the ideal scene. However, in real operation, complex and changeable meteorological conditions are often encountered, and the static boundary is difficult to adapt to the dynamic fluctuation of energy. Therefore, this study takes the Quick Access Recorder (QAR) data of an international airport from 2015 to 2020 as the research object, deeply mines the key information, and proposes a dynamic boundary correction strategy combining energy altitude and equilibrium energy. The sliding window statistical technology is used to capture the data characteristics, and the trend analysis method is used to optimize the safety envelope contour, so that the boundary setting can better adapt to the complex environmental conditions, and improve the environmental adaptability and practical application value of the evaluation system.

1. Data pre-processing

In order to accurately analyze the characteristics of energy data, the linear fitting method is used to extract the trend baseline $H_{T,tre}$, which can effectively separate the long-term trend and short-term fluctuation in the data. By calculating the residual $H_{T,res}$, the short-term deviation of the energy altitude relative to the ideal trend can be visually presented. This data processing avoids the interference of trend factors on quantile calculation and ensures the accuracy of subsequent analysis. The residual formula is as follows:

$$H_{T,res} = H_{T,thr} - H_{T,tre} \quad (16)$$

The Z-score standardization of the residuals can eliminate the influence of the dimensional differences of different parameters, so that the parameters can be compared and analyzed at a unified scale, which lays a foundation for the subsequent construction of the dynamic boundary correction model. The standardized treatment is as follows:

$$X_{norm} = \frac{X - \mu X}{\sigma X}, (X \in \{H_{T,res}, B_e\}) \quad (17)$$

Here, X represents any parameter that is standardized, X_{norm} represents the standardized parameter. μX and σX are the mean and standard deviation of the parameter X , respectively.

2. Dynamic boundary correction method

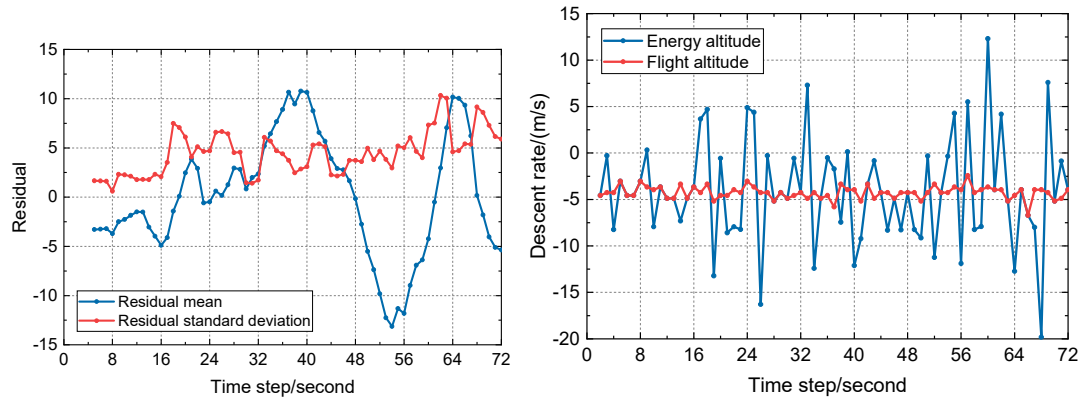
(1) A sliding window with a length of 5 seconds is used to extract the following features:

- Residual mean value μ_{res} : The average level of energy fluctuations in the window, reflecting short-term fluctuations, for anomaly detection.
- Residual standard deviation σ_{res} : measures the dispersion degree of energy fluctuation. The larger the standard deviation is, the more violent the fluctuation is.
- Energy altitude drop rate β : ensure that the drop rate meets the energy gradient requirements for stable approach:

$$\beta = \frac{H_{e,end} - H_{e,start}}{t_{end} - t_{start}} \quad (18)$$

Here, $H_{e,start}$ is the energy altitude at the final moment, $H_{e,end}$ is the energy altitude at the initial moment, t_{end} is the final moment, and t_{start} is the initial moment.

The extracted data is shown in Figure 4. Figure 4a shows the residual mean and standard deviation at different times, while Figure 4b shows the rate of decrease in energy altitude and flight altitude at different times.



(a) Mean and standard deviation of residuals (b) Gradient of energy altitude decrease

Figure 4. Sliding Window Feature Extraction.

(2) Dynamic boundary adjustment rules:

Calculate the 5% and 95% quantiles of the residuals within the window based on the residual quantiles, using the following formula:

$$\begin{cases} H_{T,upper} = H_{T,tre} + (Q_{0.95} + 1.5\sigma_{res}) \times f(h) \\ H_{T,lower} = H_{T,tre} + (Q_{0.05} - 1.5\sigma_{res}) \times f(h) \end{cases} \quad (19)$$

Here, $Q_{0.05}$ and $Q_{0.95}$ are typical fluctuation ranges for capturing residuals, that covering 90% of the data. σ_{res} provides 1.5 times the safety margin for residuals, which can avoid false alarms.

$H_{T,upper}$ and $H_{T,lower}$ are static upper boundary and static lower boundary, respectively. $H_{T,tre}$ means the energy altitude descent curve fitted based on actual flight data. The dynamic margin is shown in Figure 5. The window size in Figure 5 is 5 seconds. After calculating the residuals, arrange them in ascending order and extract the 5% and 95% quantiles.

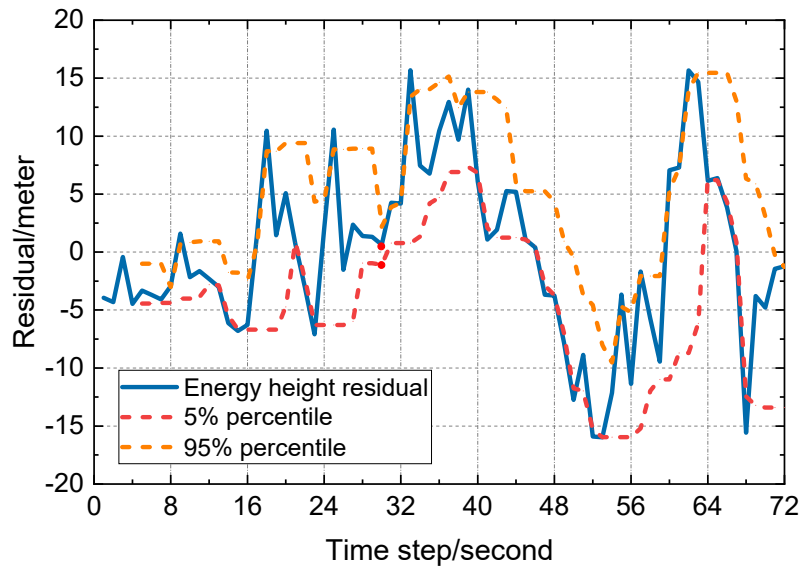


Figure 5. 5% and 95% quantiles of residuals within the window.

Balanced energy triggers tightening boundary mechanism: if the difference between the balance energy change rate B_e and the standard value within the window is greater than 0.15rad and lasts for 2 seconds, it is determined that the energy distribution is unbalanced. At this time, the tightening boundary formula (20) will be triggered, and the dynamic boundary will be tightened to warn of abnormal energy distribution in advance. The enlarged region shown in Figure 6.

$$H_{T,upper} \leftarrow H_{T,upper} \times 0.95, \quad H_{T,upper} \leftarrow H_{T,upper} \times 1.05 \quad (20)$$

This mechanism improves the accuracy of early warning by balancing the continuous anomaly recognition of energy and focusing boundary adjustments on energy allocation rather than fluctuation amplitude.

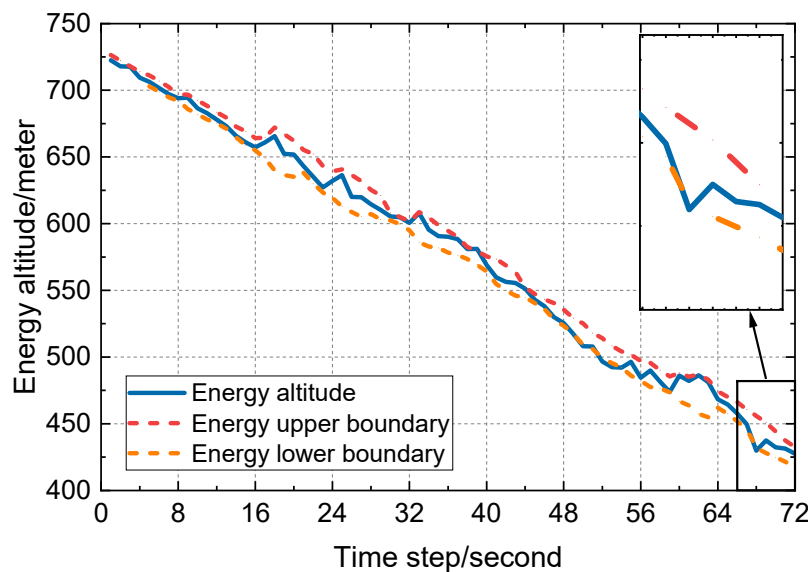


Figure 6. Data-driven dynamic boundaries.

3.3. Comparative experiment

3.3.1. Mixed boundary method

In this study, the approach data of a B777 flight at an international airport on April 5, 2015 were selected. The data completely recorded the flight parameters in the final approach stage, including the core indicators such as airspeed, descent rate, N1 speed, energy altitude, etc. The data recording frequency is 1 times per second. The data include various disturbances such as normal meteorological conditions, weak turbulence, and mild wind shear, which can fully demonstrate the typical characteristics of energy fluctuations during the approach process. There is no sensor failure or key data missing in the data recording process, and the sampling frequency and accuracy of important parameters such as space velocity and altitude are strictly in line with the ICAO standard.

The data preprocessing steps are as follows: 3σ criterion is used to eliminate abnormal points caused by sensor noise. The core parameters such as energy altitude and balance energy are standardized by Z-score to ensure the consistency of model input. Continuous data from the altitude range of 415-1415 feet are extracted to focus on the key stages below the stable altitude.

Figure 7 shows the time series visualization results of experimental data, which shows the relationship between energy altitude and dynamic boundary and static boundary. In the figure, the blue curve is the measured energy altitude, the red solid line is the dynamic upper boundary, the orange solid line is the dynamic lower boundary, the red dotted line is the static upper boundary, and the orange dotted line is the static lower boundary. The yellow column represents the warning state (label 1), and the red column represents the warning state (label 2). The important parameters of the warning event are monitored are shown in the Table 2. It can be seen from the figure that the energy altitude briefly breaks through the dynamic upper boundary at 48:45 (48 minutes and 45 seconds), triggering a yellow alert. And then at 48:58 (48 minutes and 58 seconds), the energy altitude is lower than the dynamic lower boundary for 3 seconds and breaks through the static boundary, triggering a red warning. The visualization results intuitively reflect the evolution process of energy state from fluctuation to imbalance, which provides a key basis for anomaly location.

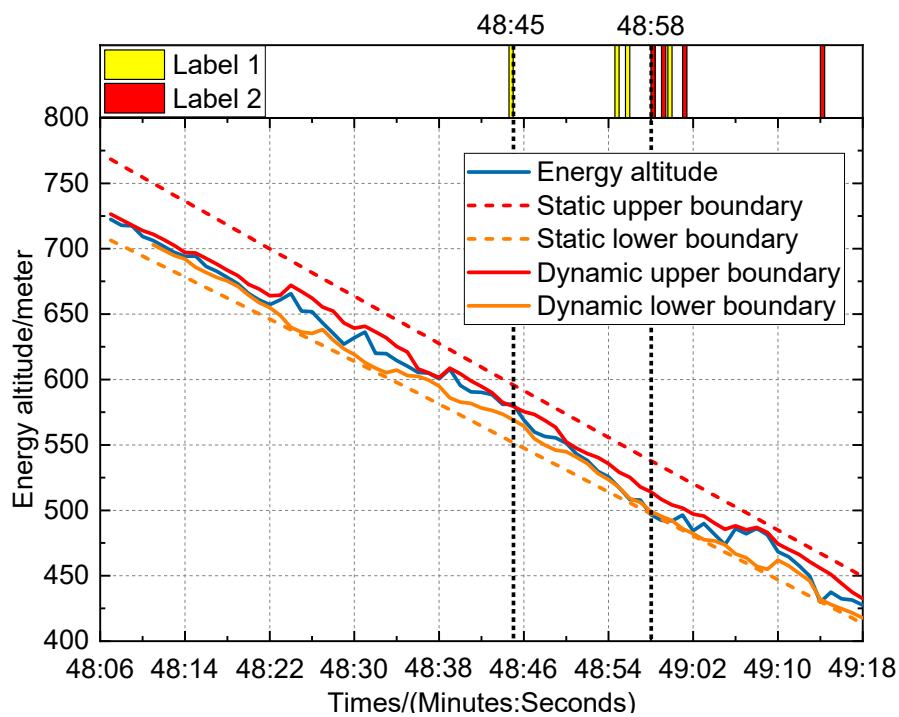


Figure 7. Timing visualization results and output label positioning.

In the verification of the alert state (label 1), at 48 minutes and 45 seconds, due to the influence of turbulence, the energy altitude instantaneously breaks the dynamic upper boundary, and the early warning system quickly triggers the warning prompt and transmits the energy fluctuation signal to the pilot in time. From 48 minutes and 55 seconds to 56 seconds, the energy altitude is lower than the dynamic lower boundary for two seconds, and the system remains on alert. This design sets aside a reasonable operation reaction time for the pilot. Entering the warning state stage (label 2), from 48 minutes and 58 seconds to 59 seconds, the energy altitude falls below the static boundary for two seconds, triggering a warning alarm. At 49 minutes and 01 second, the system issued a warning again. At 48 minutes and 58 seconds, the pilot increased the engine thrust from 58% to 60%, which fully verified the high consistency between the warning logic and the actual operation in the time series. After 49 minutes and 10 seconds, the energy altitude returns to the dynamic envelope range, and the warning label is automatically reset to 0. This process proves that the early warning mechanism can not only accurately respond to abnormal flight conditions, but also return to the monitoring normal after the energy state returns to normal, effectively avoiding false positives and omissions, and ensuring the continuous and stable operation of the system.

Table 2. The important parameters of the warning events.

Times	Correct airspeed (kt)	Descent rate (ft/min)	Rotating speed N1	Energy altitude (ft)	Reason	Label
48:45	152	-808	56.12	1906.4	Higher than the dynamic upper boundary	1
48:55	147	-864	56.50	1697.3	Below the dynamic lower boundary	1
48:56	146	-848	56.83	1667.3	Below the dynamic lower boundary	1
48:58	145	-816	58.00	1629.4	Below the static lower boundary	2
48:59	145	-808	58.62	1615.4	Below the static lower boundary	2
49:00	146	-784	59.50	1614.3	Below the dynamic lower boundary	1
49:01	148	-720	60.50	1628.3	No anomaly (continuous anomaly in the first three seconds leads to system warning)	2
49:14	145	-944	52.81	1410.4	Below the static lower boundary	2

3.3.2. Traditional Evaluation Model

In order to deeply verify the advancement and practicability of the hybrid boundary method, it is compared with the traditional single-parameter threshold method and the pure data-driven model lacking physical constraints. Through multi-dimensional index comparison and scenario verification, the performance differences of different methods in energy state assessment are systematically analyzed.

1. Single parameter threshold method

The single parameter threshold method is the mainstream method for the evaluation of stable approach in the current civil aviation field, which mainly monitors two independent numerical parameters: speed and descent rate. The experimental data are shown in Figure 8 and Figure 9. The speed of the flight is always stable at 145-152 kt during the approach process, and the descent rate is maintained at -720 ft/min~-944 ft/min. The traditional method determines this approach is “stable approach” (label 0).

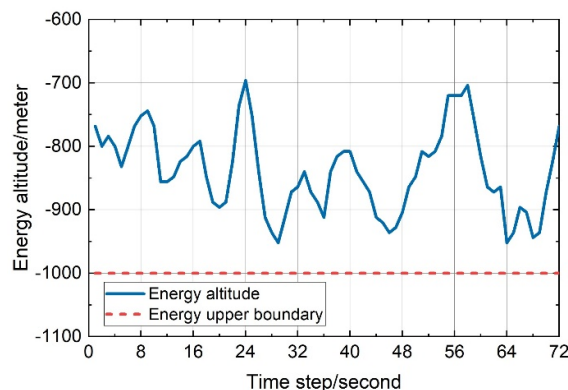


Figure 8. Decline rate and safety boundary.

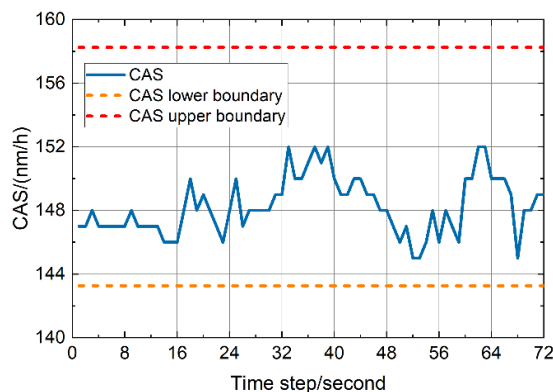


Figure 9. Correct airspeed and safety boundary.

As shown in Figures 8 and 9, from 48 minutes 58 seconds to 49 minutes 01 seconds, traditional parameters indicate that all indicators of the aircraft are within the normal range. However, the energy boundary function constructed in previous section (Figure 7) clearly shows that the energy altitude continuously breaks through the dynamic lower boundary and static boundary. This contradictory phenomenon exposes the inherent flaws of the traditional single parameter threshold method: this method only isolates and judges whether a single parameter meets the standard, and cannot identify the potential risks caused by the interaction between parameters. In sharp contrast, the multi parameter fusion method proposed in this study can more accurately reveal the true state of energy by comprehensively considering the dynamic relationship between energy parameters, effectively compensating for the shortcomings of traditional methods.

2. A pure data-driven model without physical constraints

The pure data-driven model trains dynamic boundaries with the help of Fast Access Recorder (QAR) historical data, which exposes significant limitations due to the lack of embedded physical constraint mechanisms in flight mechanics. The data-driven visualization results are shown in Figure 10. Compared to Figure 7, the model experienced multiple boundary anomalies during the approach process. For example, at the 34th and 52nd seconds, there is an unreasonable contraction of the

dynamic boundary, and the dynamic lower boundary is abnormally higher than the energy height trend line. At the same time, the dynamic upper boundary is below the trend line, causing normal fluctuations in flight parameters to be incorrectly marked as abnormal states. At the critical stage of approaching the end 67 seconds and altitude below 500 feet, the boundary expands abnormally, and the dynamic boundary is lower than the static boundary, which completely fails to meet the strict requirements for energy accuracy in the low altitude segment. More seriously, compared to Figure 7, the pure data-driven model without physical constraints did not trigger any warning signals during the period of 48 minutes and 58 seconds to 49 minutes and 01 seconds, which resulted in significant risk underreporting and fully highlighted the negative impact of the lack of physical constraints on the reliability of the model.

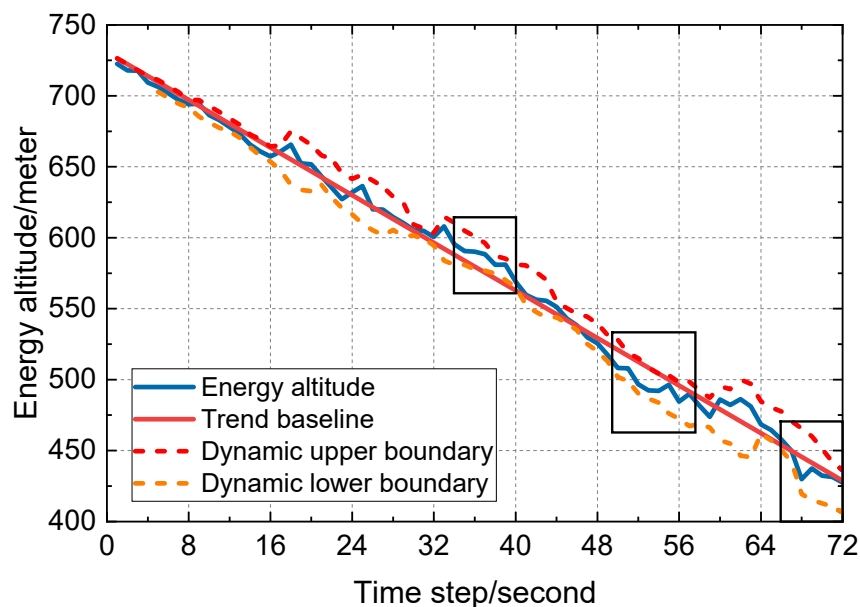


Figure 10. Energy altitude and dynamic boundaries (purely data-driven).

Pure data-driven models overly rely on data training and lack physical laws to support them, making it difficult to accurately identify the intrinsic relationship between height and energy changes. This makes it difficult for the dynamic boundaries constructed to meet the requirements of real flight scenarios, ultimately leading to warning failures in complex energy fluctuations, highlighting the indispensable role of physical constraints in flight safety assessment.

Therefore, this study innovatively integrates the height attenuation function and physical constraints, theoretically ensuring that the boundary function not only conforms to the principles of flight mechanics, but also can be dynamically adjusted according to the actual flight altitude. The height decay function gradually tightens the boundary as the height decreases, while the physical constraints frame the scientific boundary of energy changes. The synergistic effect of the two ensures the rigor of the evaluation system.

Traditional static boundaries are limited by a single parameter evaluation mode, making it difficult to fully reflect the flight energy state; Pure data models have weak generalization ability in complex scenarios due to the lack of physical constraints. In contrast, the hybrid boundary method proposed in this study has the following advantages: by integrating multidimensional parameters, it not only breaks through the limitations of single threshold evaluation, but also accurately identifies the energy imbalance hidden behind the data when a single parameter meets the standard. Innovatively integrating physical constraints with data-driven technology, the boundary function can achieve smooth dynamic adjustment based on flight altitude and adapt to changing flight environments. At the same time, the warning mechanism based on temporal logic can trigger

responses in advance during the risk germination stage, reserve sufficient operational time for pilots, and demonstrate stronger environmental adaptability and system stability.

4. Conclusions

The stability assessment of the final approach phase of an aircraft, as the riskiest stage in the entire flight cycle, is crucial for ensuring flight safety. The traditional single parameter threshold monitoring method is unable to capture the coupling relationship between kinetic energy and potential energy, as well as the energy fluctuation characteristics under complex disturbances, which makes it difficult to meet the needs of modern civil aviation for high-precision and multi-dimensional stability evaluation. This article focuses on this core issue and systematically conducts research on the stability of aircraft final approach based on energy management. The main tasks completed are as follows:

1. Constructed a stability evaluation standard system from the perspective of energy. By defining “energy height” and “balanced energy”, the limitations of traditional “velocity height” dual parameter independent monitoring have been overcome, providing a quantitative basis for multidimensional analysis of energy states.

2. Based on the principles of flight mechanics and civil aviation regulations, a dynamic safety hybrid boundary function was designed that integrates physical constraints and data-driven approaches. The smooth contraction of boundaries with decreasing height is achieved through a high attenuation mechanism, and the adaptability of boundaries is optimized by using sliding window statistics and balanced energy triggering mechanism, which solves the problem of insufficient response of static boundaries to complex disturbances.

3. Integrate multidimensional parameters (airspeed, altitude, descent rate, energy change rate, etc.) to establish a mixed boundary, breaking through the limitations of single threshold evaluation and accurately identifying energy imbalance hazards under the surface standard of parameters. At the same time, innovative integration of physical constraints and data-driven technology enables the boundary function to achieve smooth and dynamic adjustment based on flight altitude, adapt to changing flight environments, and demonstrate stronger environmental adaptability and system stability.

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