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Envelope protection for aircraft encountering upset condition based on dynamic envelope enlargement

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Abstract Upset condition encountered by an aircraft in flight could pose great threat to flight safety, which is of chief importance in civil aviation. The causal factors have the nonlinear and multiple characteristics, and as a result the conventional envelope protection system cannot successfully do with the condition. So dynamic envelope based on differential manifold theory, which can take more coupling factors into account, is proposed as a basis to design a novel envelope protection system. Then the relationship between the dynamic envelope and the control coefficient or pilot command is obtained, and the result shows that the dynamic envelope can be enlarged with the change of control coefficient. Furthermore, quantification of flight security is realized via defining relative distance between flight state and dynamic envelope, which can detect whether there is a risk for an aircraft in flight. Finally, an envelope protection system based on dynamic envelope enlargement is proposed on the basis. NASA's Generic Transport Model encountering hazard gust wind in climbing phase is taken as an example to verify the system's feasibility. The result shows that the system can give a better operation encountering upset condition and to a certain extent reduce the number of accidents or incidents.

1. Introduction

Flight safety as an issue, which cannot be ignored, is of chief importance in civil aviation, and therefore any flight mission must be completed on this basis. In order to develop safety of an aircraft to avoid accidents when encountering abnormal conditions, e.g., a jammed elevator, an engine loss, or abnormal atmospheric phenomenon like icing condition, wind shear, gust, etc., it is of paramount importance to reveal the leading cause and its formation mechanism. Analyzing transport airplane accidents worldwide, we know that the anterior one is summarized as Loss of Control (LOC), whose descriptions can be seen in Refs.[1,2] LOC as a similar cause of many fatal aircraft accidents or incidents[1,3] has been attached more importance by researchers and aviation industry. As for the posterior one, one of significant researches can be summarized that flight with state departing from no less than three of five envelopes can be regarded as LOC occurring; the envelope was

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derived from Quantitative Loss-of-control Criteria (QLC)[2,4] posed by the Boeing Company and the NASA Langley Research Center. In addition, some researchers tried to make a better interpretation for aircraft LOC via reachability analysis,[5–7] bifurcation analysis,[8,9] and nonlinear Region of Attraction (ROA) analysis,[7,10] i.e., methods mentioned above provide a possibility to predict aircraft LOC via posing various flight envelopes, which can be regarded as LOC envelopes, and the final prevention of LOC is implemented by Envelope Protection System (EPS). Hence, the flight envelope plays an important role in the prediction and prevention of LOC.

It is known that flight envelope with upset condition would be shrunk. And EPS with the envelope without taking this disturbance into account would provide pilot or flight control system with wrong control strategy, and finally induce aircraft LOC. The ATR accident of 1994[11] just occurred because of this. In this accident, anomaly of the roll under icing condition occurred at an angle of attack of 5°, which is much lower than the angle of attack limit (18.1°). Hence, it is more necessary to make a development on the conventional EPS with predetermined limits on some parameters. In addition, from Ref.[12], we know that aircraft would stall at a lower angle of attack when the pitch rate is large enough due to the coupling characteristic between various flight states, of which explanations will also be described in Section 4. Furthermore, for a flight control system, the controllable region, LOC envelope, is various with the different control laws. Hence, it is feasible to guarantee the flight state in the envelope via changing control law to enlarge the controllable region. So an accurate estimation of the flight envelope taking coupling multi-factor and control law into account is of primarily importance in the protection system by enlarging envelope.

To make envelope determination meet the qualification above, the formation of flight envelope must be discussed first. The flight envelope is intersection of the dynamic envelope, the structural and comfort envelope, and the environmental envelope.[13] Because flight dynamic is taken into account, the dynamic envelope determination is more difficult, while others can be computed by traditional method. Furthermore, as an important causal factor impacting on the flight envelope, the dynamic envelope is the focus studied by most researchers. One of accepted methods to estimate the dynamic envelope with more coupling multi-factors taken into account is the so-called reachable set theory, which is always utilized to compute a safe set via level set method based on the optimal control theory and reachability analysis or Lagrangian methods relying on the vector field's flow.[14] Considering that a reachable set is also a controllable set for given time horizons and input constraints rather than global time horizons and certain input of a given controller, it is difficult to make a direct connection between the set and control law designed. Alternatively, EPS based on the ROA method can make a better compensation. ROA, a kind of controllable set with certain control law at certain pilot input, which is regarded as the dynamic envelope, can be posed by various methods. And the boundary determination has a direct connection with the Proportional Integral Derivative (PID) controller as a main component in classical control architecture. In addition, although modern control such as robust control, adaptive control, and sliding mode control, which provides a possibility to develop the flight performance and safety, has been considered as an attractive control method for flight control system, unfortunately, due to the limits of the hardware, specifically the computer processor and the large challenges of the flying quality evaluation, almost all flight control laws utilized in modern flight control system are based on the classical control techniques rather than modern control theories.[15] Therefore it is absolutely necessary to make a development on the basis of classical control architecture. Furthermore, considering that the dynamic envelope based on the ROA method has the same potential to predict the LOC as that of the QLC and reachable set theory, it can be regarded as a kind of LOC envelope which is applied to the EPS.

In a word, in order to design an EPS with the classical control architecture via enlarging the dynamic envelope, it is of great importance to determine an accurate envelope, which can predict the LOC and has the direct connection with the control law. In view of these, the organization of the paper is as follows. For a better illumination to this paper's theme, Section 2 first presents an overview of EPS based on dynamic envelope enlargement as well as the technologies needed. And the aircraft, NASA's Generic Transport Model (GTM) longitudinal dynamics, which is taken as an example, is presented in Section 3. In Section 4, the technologies for the EPS proposed are discussed in detail. First, we generalize the differential manifold theory, which can provide an accurate dynamic envelope; then we propose the relationship between the envelope and control law for establishing the dynamic envelope database utilized on the EPS. A quantitative analysis for safety factor and the method for control coefficient change are also proposed in the section. Examples for aircraft under upset condition are discussed in Section 5. Finally, conclusions are drawn in Section 6.

2. Envelope protection system

Fig. 1 illustrates the concept map for LOC envelope protection system based on the envelope enlargement; in the figure, the conventional flight condition is drawn as black solid line, while the red dashed line is for the abnormal condition when the warning signal for envelope departing is detected; furthermore, database scheduled as a process for the whole flight is indicated by green dotted line. The detailed description is as follows.

Step 1. In the normal flight condition, in order to give a prediction for the envelope departing, the warning module provides the degree of safety according to the active envelope and the premeditated safety factor limit. And the system will not turn to Step 2 until the warning signals of envelope departing from warning module are detected. In addition, the module of warning for envelope departing is utilized for judging whether the flight is safe enough or not via plotting curve of safety factor S_f, which indicates degree of safety. And the limit of safety factor is the premeditated separatrix between safety and danger.

Step 2. Enlarge the dynamic envelope via changing the control coefficient or command, which is on the basis of database for dynamic envelope. Note that in order to guarantee that the flight task is completed, the control coefficient alteration is made first of all. Furthermore, the module of envelope database is used to store the dynamic envelope information, which is determined based on the differential manifold theory and has the direct relationship with the control law, pilot command and dynamic model. And from the database, the information