Research on Airworthiness Certification and Risk Control of Minimum Unstick Speed for Civil Aircraft

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Abstract: V_{MU} is the minimum speed at and above which the aircraft can safely lift off the ground and continue the takeoff, expressed in terms of calibrated airspeed, and is the basis for formulating other takeoff speeds of the aircraft. As a typical high risk flight test subject, the V_{MU} test is a key concern of the Administrator during airworthiness certification. Based on the takeoff speeds section of CCAR25.107, combined with relevant Advisory Circular, this paper analyzes the requirements of the airworthiness clause of the V_{MU}, analyzes the characteristics of the V_{MU}, gives the airworthiness certification concerns, systematically analyzes the risk and the risk reduction measure of the V_{MU} for civil aircraft. It can provide reference for verifying the airworthiness compliance of the V_{MU} section of civil aircraft.

Keywords: Minimum Unstick Speed; Airworthiness Certification; §CCAR25.107; Risk Control.

1. Introduction

V_{MU} is the minimum speed at and above which the aircraft can safely leave the ground and continue to take off. §25.107 of CCAR-25R4 "Airworthiness Standard for Transport Category Aircraft" requires that the nose wheel lifting speed of the aircraft must be determined according to the V_{MU}, which is also related to other take-off characteristic speeds [1]. Therefore, the determination of V_{MU} is of great significance for the formulation of takeoff speed and takeoff safety assessment of civil aircraft, and is also an important parameter for the selection of aircraft by airlines. V_{MU} is a flight test maneuver for civil aircraft to take off with maximum performance. It's a low-speed and high angle of attack flight test subject under the influence of ground effect.

According to the relationship between the geometric characteristics, stall characteristics and elevator handling efficiency of the test aircraft, the minimum unstick airspeed tests can be divided into three types [2]. Fig. 1 shows the typical curve of the variation of the lift coefficient C_L with the angle of attack α, where θ is the pitch angle.

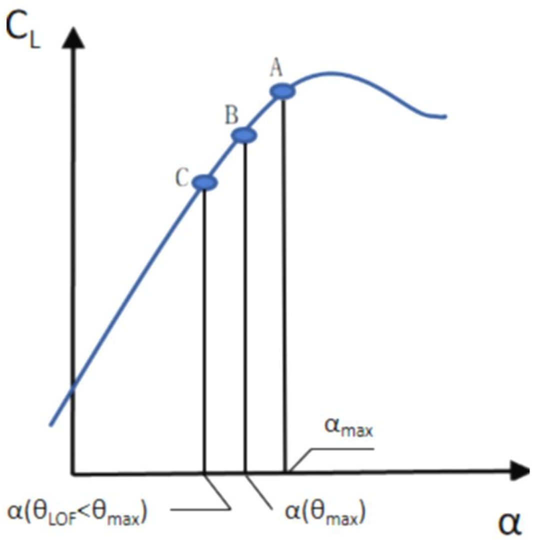

Fig. 1 Lift coefficient curves of typical aircraft

a) Minimum unstick airspeed limited by stall: When the aircraft reaches the lift coefficient at point A in Fig. 1, the tail of the aircraft has not wiped the ground, and if the aircraft continues to increase the Angle of attack, the aircraft will stall before lifting off the ground, then the VMU speed of the aircraft is considered to be limited by stall. There are generally fewer aircraft of this type.

b) Minimum unstick airspeed limited by aircraft geometry (tail wiping) : When the aircraft reaches the lift coefficient at point B in Fig. 1 during takeoff, the tail of the aircraft has wiped the ground and the pitch angle has reached the maximum, then it is considered that the VMU speed of the aircraft is limited by the geometric structure (tail wiping). Most modern civil aircraft belong to this design feature.

c) Minimum unstick airspeed limited by pitch control authority: When the aircraft reaches the lift coefficient at point C in Fig. 1 during takeoff, the pitch control has reached the aft stop, but the tail of the aircraft has not touched the ground and has not reached the maximum lift coefficient, then the VMU speed of the aircraft is considered to be limited by the elevator control authority.

2. Airworthiness Requirements Analysis

Section 25.107 states: "V_{MU} is the calibrated airspeed at and above which the airplane can safely lift off the ground, and continue the takeoff. V_{MU} speeds must be selected by the applicant throughout the range of thrust-to-weight ratios to be certificated. These speeds may be established from free air data if these data are verified by ground takeoff tests."

V_{MU} is the basis of establishing the take-off characteristic speeds. As specified in the Advisory Circular, the applicant may determine the lowest possible V_{MU} speeds, or may select a higher speed that supports the aircraft take-off performance target values. But the applicant must demonstrate compliance with CCAR25.107(d), (e)(1)(iv), (e)(3) and (e)(4), with indicating that the selected V_{MU} speed will enable the aircraft to lift off the ground safely and continue taking off.

According to section 25.107(e)(1)(iv), when the applicant formulates the rotation speed V_R of the aircraft, it requires that if the aircraft is rotated at its maximum practicable rate at V_R, the resulting lifting off speed V_{LOF} will not be less than 110% of V_{MU} in the all-engines-operating condition,and 105% of V_{MU} determined at the thrust-to-weight ratio corresponding to the one-engine-inoperative condition.According to the analysis and summary of airworthiness sections, the relationship between V_{MU} and the take-off characteristic speeds is shown in Fig. 2. Through this safety margin requirement, the airworthiness sections ensures that the aircraft has sufficient maneuver margin during lifting off ground, sufficient climbing ability after leaving the ground, and sufficient maneuvering ability once one engine fails, so as to ensure the safety of the aircraft during takeoff [3].

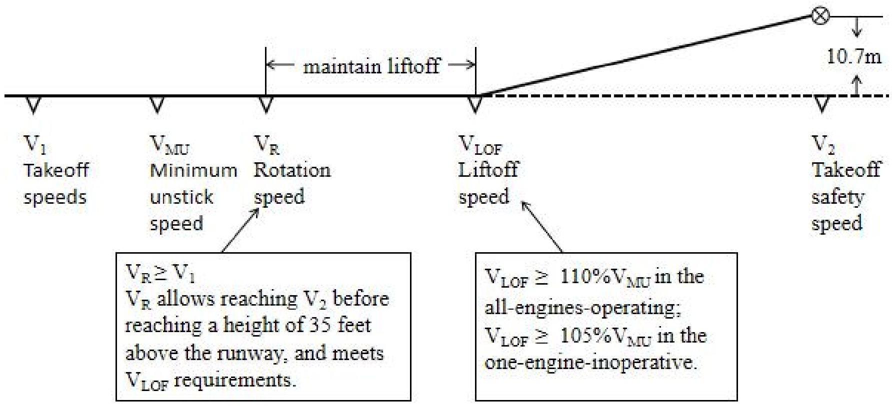

Fig.2 Relationship between V_{MU} and takeoff characteristic speeds

3. Key Concerns of Airworthiness Certification for V_{MU}

3.1 Typical Flight Tests Method

The V_{MU} flight tests method is as follows:

a) Before the flight tests, the engine condition parameters are calculated according to the thrust-to-weight ratio and aircraft weight;

b) The aircraft slides to the take-off line, maintains a complete braking state for 5s, and then runs along the runway;

c) At a speed 20~40kn less than the predetermined V_{MU} speed, the test pilot retracts the throttle to the expected position and pulls the throttle to the end, so that the aircraft begin to lift the nose wheel;

d) The test pilot should observe the tail skis touch indicator light in the cockpit. When the pre-touchdown indicator light turns on, the pilot can pull the rod until the tail skis is basically compressed to the end;

e) Keep the tail skis touching the ground until it lift off the ground, and the pitching attitude cannot be reduced after takeoff;

f) The test adopts all-engines-operating tests to simulate that the critical engine falls, and does not carry out the one-engine-inoperative V_{MU} tests.

3.2 Selection of Center of Gravity

During airworthiness certification, V_{MU} tests are usually conducted with a forward center of gravity. This is because the V_{MU} tests at the forward center of gravity gives a more conservative speeds result, resulting in a safer takeoff characteristic speed. When the aircraft center of gravity is forward, the downward aerodynamic force acting on the horizontal tail is greater in order to achieve the maximum nose-up attitude of the aircraft. For a static aircraft, the aerodynamic force of the horizontal tail is in the opposite direction of the lift of the wing. Therefore, at the same angle of attack, the airplane with the forward center of gravity needs more wing lift to lift off the ground. In other words, in the case of the same aircraft weight and attitude off the ground, the aircraft at forward center of gravity has a higher speed with lifting off the ground.

For the aircraft with limited pitch control authority, it may not be possible that the aircraft, at extreme forward center of gravity and normal trim, achieve the maximum possible attitude off the ground. During airworthiness certification, the applicant is allowed to conduct tests at a later center of gravity. According to AC25-7D, the center of gravity tolerance should be controlled within 7% of the entire center of gravity range of the aircraft [4]. After that, the applicant shall revise the V_{MU} values obtained at these center of gravity positions. The formula (1) can be used to convert the lift coefficient corresponding to the V_{MU} at the test center of gravity to the lift coefficient corresponding to the V_{MU} at the standard center of gravity position:

$$C_{LVMU\_B} = C_{LVMU}\left[1 + \frac{MAC}{L_H}(C_{G\_B} - C_G)\right] \tag{1}$$

In formula (1): C_{LVMU_B} is the lift coefficient corresponding to the V_{MU} at the standard center of gravity, C_{LVMU} is the lift coefficient corresponding to the V_{MU} at the test center of gravity, MAC is mean aerodynamic chord. L_H horizontal tail lever, C_{G_B} is the standard center of gravity, C_G is the test center of gravity.

The applicant can use these revised V_{MU} values to establish the take-off characteristic speed, but airworthiness certification shall require the applicant to demonstrate safe flyaway characteristics, in order to check that the relaxed V_{MU} standard does not ignore the possible problems arising from the operational changes of the aircraft limited with the pitch control authority. The minimum speed liftoff demonstrated for safety should be at least 5 knots below the normally scheduled liftoff speed. Taking a certain type of aircraft as an example, theoretical analysis before V_{MU} flight tests suggested that V_{MU} of this aircraft belonged to the type limited by aircraft geometry, but during V_{MU}

tests, it was found that the test should be carried out in the type limited by pitch control authority. Therefore, the test points and criteria for security demonstration are added.

3.3 Determination of Minimum Thrust-to-weight Ratio

According to the theoretical analysis of V_{MU} speeds formula (2), there is an approximate linear relationship between the V_{MU} speeds and the thrust-to-weight ratio of the aircraft.

$$V_{MU} = \sqrt{\frac{2W\left[1 - \frac{T}{W}\sin(\alpha + \psi)\right]}{\rho S C_{LVMU}}} \tag{2}$$

In formula (2): W is the weight of the aircraft, T is for engine thrust, α is the angle of attack corresponding to the V_{MU}, ψ A is the engine mounting angle, ρ is air density, S is the reference area of the wing.

V_{MU} speeds must be selected by the applicant throughout the range of thrust-to-weight ratios to be certificated [5]. There are two methods to adjust the range of thrust-to-weight ratio of the aircraft: keep the weight of the aircraft fixed, interpolate the engine thrust according to the engine speeds; The engine thrust is fixed and the thrust-to-weight ratio is changed by the mass of the aircraft. According to AC25-7D, the minimum thrust-to-weight ratio in V_{MU} tests should meet the requirements of the climb gradient of the aircraft after an engine failure. In order to ensure the safety of tests, the applicant can simulate the push-to-weight ratio of one-engine-inoperative condition in tests by using the all-engines-operating condition. When one engine is failed in tests, the failed engine will create drag, the minimum thrust-to-weight ratio obtained will be slightly larger. Therefor, with using the all-engines-operating condition to simulate one-engine-inoperative condition, The minimum thrust-to-weight ratio obtained will be smaller.

Before the V_{MU} tests, it is necessary to verify whether the minimum thrust-to-weight ratio obtained by the calculation and analysis can meet the requirements of the climb gradient in the take-off. The applicant can use the determined engine speed and predicted minimum ground clearance speed for the first and second stages of takeoff flight tests, and perform climb gradient checks in the air. If the climb gradient obtained by using a certain engine thrust is greater than the required climb gradient in regulations, the minimum thrust-to-weight ratio corresponding to that thrust is considered reasonable.

3.4 Tail Skis Unit

The tail skis unit is also one of the concerns in the V_{MU} tests airworthiness certification. In V_{MU} tests, the key criteria of success is whether the tail of the aircraft wipes the ground or not and the time of wiping the ground. In order to avoid damage to the tail structure of the aircraft, the tail skis unit is usually installed on the bottom of the aircraft tail before the V_{MU} tests to realize the aircraft tail wiping. Tail skis unit mainly includes rocker arm friction block assembly, buffer assembly and indicator system. Tail skis unit used by a certain type of aircraft is shown in Fig. 3.

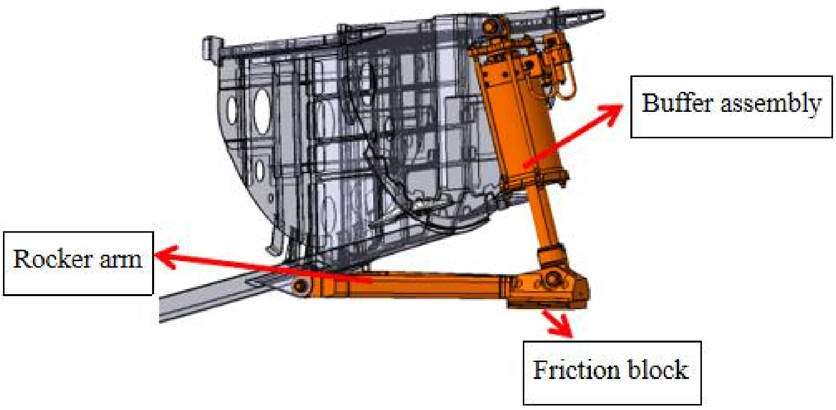

Fig. 3 Tail skis unit used by a certain type of aircraft

The indicator system controls the indicator lights installed in the cockpit to turn on and off through the tail skis touchdown logic, indicating pilots of the situation of the tail skis wiping ground. When the pre-touchdown indicator light is on, the pilot can slowly pull and control the rod. When the touchdown indicator light is on, it indicates that the tail skis buffer is basically compressed to the bottom and the aircraft is in maximum ground clearance attitude. For the V_{MU} tests with added trim on the horizontal tail, the aircraft has a relatively high pitch angle velocity when approaching the tail skis touchdown, which will result in a very short time interval between the tail skis pre-touchdown signal and the tail skis touchdown signal. The tail skis pre-touchdown signal may not even serve as a warning, and it is worth the extra attention for the applicant in the tail skis design.

In the tail skis modification airworthiness review, the Administrator pays special attention to the tail skis modification design, the applicant should focus on the following aspects:

a) The strength impact analysis of the tail skis unit on the structural change of the aircraft shall be completed;

b) Analysis of the influence of tail skis unit on aircraft aerodynamic characteristics should be completed;

c) The tail skis unit should be avoided from touching the ground twice;

d) The tail skis unit should be able to effectively protect the tail area of the aircraft that may wipe the ground during the flight tests;

e) The tail skis shall have appropriate anti-collision measures to prevent the tail of the aircraft from hitting the runway;

f) The tail skis and the aircraft should be firmly and reliably connected to prevent the parts from wearing off and damaging the aircraft structure, or falling onto the runway;

g) The tail skid friction block will generate a lot of heat and spark in the process of wiping the ground, so the friction block should have good wear resistance and flame retardant characteristics, and poor thermal conductivity;

h) The tail skis shall provide pilots with accurate and continuous pre-touchdown signal and touchdown signal.

4. Risk Analysis and Control of V_{MU} tests

4.1 Risk of Tail Wiping During the Takeoff Running

According to the V_{MU} tests method, the pilot needs to control the aircraft nose-up to the maximum angle of attack. The rear fuselage is very close to the runway, which poses a risk of interference with the ground and may cause the aircraft tail wiping the ground,with damaging the aircraft structure seriously. (There are very few aircraft that have already stalled before the tail wiping the ground, and this article will not discuss it.)

Risk control measures: Install a tail skis unit at the tail to prevent the aircraft structure from wiping the ground. Install a tail skis indicator system in the cockpit with displaying pre-touchdown signals and touchdown signals, to remind the pilot of the touchdown status of the aircraft tail. Before the V_{MU} tests, the pilots should be familiar with the pitch angle limitations of the aircraft. The crew should closely cooperate, the main pilot controls, and the co pilot closely monitors the aircraft's status (key parameters such as: angle of attack, direction, speed, pitch angle, roll angle, and engine status). Continuous ground takeoff can be used to train the pilots to maintain a certain pitch angle during the takeoff, enhancing the V_{MU} test technique [5]. It should be carried out in a gradual manner, first conducting tests under conditions of medium and high thrust-to-weight ratio, and then transitioning to tests with low thrust-to-weight ratio. The pilots can rotate the wheels when the aircraft is at a low speed, then reach the maximum pitch attitude of the aircraft at a lower pitch rate. During the tail of wiping the ground, the pilot should not forcefully pull the rod to prevent the tail from colliding with the ground. It is possible to consider installing high-speed cameras near the airport runway to assist in assessing the integrity of the tail structure.

4.2 Risk of the Tail Wiping After Lifting Off the Ground

According to AC25-7D, In the speed range from 96 to 100 percent of the actual liftoff speed, at least 50% time the aft under-surface of the aircraft should be in contact with the runway. Before the aircraft liftoff, due to the protection of the tail skis unit, the pitch rate of the aircraft is almost zero. During the period from takeoff to a height of 10.7m, AC25-7D requires that the pitch angle of the aircraft should not be smaller than the moment of takeoff, so the rod needs to be kept in a backward position. At the moment of takeoff, without the protection of the tail skis, the instantaneous pitch rate of the aircraft will be relatively high. If the aircraft is not well controlled, it will be quickly rotated, causing the position near the tail of the fuselage to wipe the ground. Especially at tests with high thrust-to-weight ratios, the touchdown time may be very short, which greatly tests the piloting skill.

Risk control measures: Before the V_{MU} tests, the applicant should use theoretical calculations to determine the maximum pitch angle at which the tail touches the ground at different heights off the ground, to ensure that there is no risk of the tail damage caused by the moment the aircraft lifting off; Before the formal tests, the pilot should gradually approach the ground wiping angle for takeoff, while assisting in high-speed photography to observe whether there is a risk of wiping ground for the tail; During the V_{MU} tests, the pilot cannot make significant pull rod movements at the moment the aircraft lifting off [6].

4.3 Risk of Aircraft Deviating From the Runway

During the V_{MU} tests, the aircraft should maintain a high angle of attack with liftoff the ground attitude on the runway for a period. During this period, the pilot's field of view is limited, making it difficult to observe the heading deviation during the takeoff running. Moreover, the crew's attention is mainly focused on controlling the changes in the pitch attitude, making it easy to overlook the control of heading deviation. Once the pilot intervenes too late to completely stop the aircraft's deviation trend, it will cause the aircraft to deviate from the runway, and in severe cases, the aircraft may be damaged and the pilot may be injured.

Risk control measures: Before the V_{MU} tests, the aircraft's braking system, front wheel steering system, engine, etc. should be checked for normal operation, and the tire pressure should be kept consistent; The pilot should raise the seat appropriately as needed to ensure sufficient cockpit view and facilitate observation of aircraft heading changes; The crew should allocate their energy reasonably, and a dedicated person should pay attention to changes in the aircraft's heading, promptly remind test pilots to immediately increase thrust to complete takeoff, when the aircraft heading deviates more than half of the runway width; The V_{MU} tests should be conducted strictly in accordance with the required crosswind wind speed limit; It is possible to consider installing external cameras outside of the aircraft to monitor the heading deviation during the takeoff. Ground monitors are responsible for reminding the crew to avoid excessive heading deviation.

4.4 Risk of Stall

In AC25-7D, it is stipulated that during V_{MU} tests, the aircraft is permissible to lift off at a speed that is below the normal stall warning speed, provided no more than light buffet is encountered. However, when the aircraft approaches the ground, it is affected by ground effect, resulting in increased lift, reduced drag, and early stall. This is mainly due to the blocking effect of the ground on the downward airflow. The ground effect decreases rapidly with increasing ground clearance, and it is generally believed to be out of the ground effect when the aircraft reaches a height equal to its wing span. When the aircraft lifts off the ground, the weakening of the ground effect will lead to a decrease in the bow torque, causing the aircraft to tend to head up, resulting a further increase of the angle, closer to the stall state.

Risk control measures: Before the V_{MU} test, the applicant should conduct ground effect wind tunnel tests to evaluate the impact of ground effect on the stall angle-of-attack, and provide a briefing to the pilots; Before the V_{MU} tests, the applicant should complete the stall tests flight and the minimum control speed tests in the air; Before the V_{MU} tests, the impact of the stall warning should be evaluated [7]; The pilots should gradually approach the wiping angle for takeoff running, with feeling the lateral trim and attitude maintenance characteristics of the aircraft, and gradually approach the wiping angle for takeoff, with familiarizing the handling characteristics, to eliminate the risk of stall finally; Increasing thrust can delay the turning of the lift line, so it is recommended to use high thrust for familiarity flight tests; After the aircraft lifts off the ground, the pilot should closely monitor the changes of the angle of attack and the stall warning, and if the angle of attack increases rapidly, the pilot should slowly push the rod to reduce the possibility of stall characteristics; For aircraft with fly-by-wire flight control system, the change of control law should be avoided during the V_{MU} tests, so as to reduce the change of aircraft control characteristics and the adverse impact on the operation of pilots.; After the aircraft lifts off the ground, it is not necessary to quickly retract the landing gear. After the aircraft lifts off the ground, the landing gear should not be retracted in a hurry, and the test operation can be considered completed when the altitude above the ground is more than 30m.

5. Conclusion

According to the requirements of §CCAR25.107 for V_{MU} tests, this paper gives three categories of V_{MU} speeds, analyzes the airworthiness requirements of V_{MU} tests in detail combined with AC25-7D, and discusses the key concerns in the process of civil aircraft V_{MU} airworthiness certification. Finally, this article provides a detailed analysis and summary of risk control measures for the four risks involved in the V_{MU} tests, to provide reference for civil airworthiness certification and risk control of V_{MU} tests.

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