



ANALYSIS OF LANDING OPERATION INCLUDING THE EMERGENCY STATES

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Abstract

Air transportation as a fast-growing transport mode provides the constantly innovating constructions. Security is an integral factor in determining the movement of the aircraft. The paper contains an analysis of landing operations including emergency states. Describes the flight rules with inoperative engine. All these parameters have a direct impact on ensuring safety of passengers and crew members.

Keywords: *air transportation, security*

1. Introduction

Air transport plays a major role in the development of world economic activity and remains one of the fastest growing sectors of the international economy. One of the key elements that contribute to the maintenance of civil aviation development is to secure safe, efficient and environmentally sustainable means of transport, at the global, local and regional level.

Air transport is the safest mode of transport, but still air accidents remain inevitable. The causes of air accidents are different and largely dependent on the current flight phase of an aircraft. Most critical phases of flight are takeoffs and landings, due to potentially dangerous proximity of the earth's surface [5]. These two flight phases must be performed with adherence to basic safety rules and the procedures for takeoff and landing must be strictly followed.

2. Characteristics of the landing operations

A very important operation that the aircraft has to perform before coming to a safe standstill is landing [4]. This part of flight can be defined by applying two main guidelines. The first one is meeting the premise that the distance needed to land should not be greater than the distance available. Considering the length available for landing it should be realised that this phase begins at 50 feet above the runway, whereas landing ends once a complete standstill has been reached.

The speed to be achieved when coming to 50 feet should not be less than 123% of V_{SRO} ¹ and not less than V_{MCL} ². This speed is called V_{REF} ³.

Another prerequisite to be fulfilled during the landing operation is to make sure that the aircraft can be quickly taken off the runway while maintaining an appropriate climb angle. Included both in the JARs⁴ and the CS-25⁵, these requirements are slightly complicated and divided into the two parts: for the climb angle of the aircraft with all engines operative and that with one engine inoperative.

With the climb angle values required for the aircraft with all engines operative, the right parameters can be achieved to take off the aircraft and make a go-around. These requirements specify the constant climb angle value of at least 3.2% of the engine power available eight seconds after the initiation of the go-around procedure, but the climb speed has to meet the following conditions [1]:

- 1) should not be less than:
 - a. 108% of V_{SR} ⁶ for aircraft with four engines in which increasing the power results in a substantial reduction of the stall speed,
 - b. 113% of V_{SR} for all other aircraft types,
- 2) should not be less than V_{MCL} ,
- 3) should not be greater than V_{REF} .

The climb angle required after take-off with one engine inoperative is another part of the second requirement included in the JARs and the CS-25 that should be met by the aircraft for safety reasons. This requirement is supposed to ensure the right climb angle for the aircraft with one engine inoperative to go around. For such an aircraft configuration, the constant climb angle should not be less than 2.1% with the operative engine's power sufficient for take-off. This value is referred to the maximum landing weight, the extended landing gear and the climb speed based on the normal landing operation, but it should not be greater than 1.4 of V_{SR} . The described values are reasonable for twin-engine aircraft only. For three-engine aircraft, the climb engine should not be less than 2.4%, whereas for four-engine aircraft, it should not be less than 2.7%. It should be noted that all climb angle values are referred to the air, i.e. they depend on weather conditions.

The JARs specify the climb angle requirements in more detail, concluding that the weight of the aircraft climbing after a failed landing should be sufficient to achieve the projected climb angle values. If this weight were exceeded, the aircraft would not be capable of meeting the requirements in this respect.

Landing takes place not only in the air, but also on the ground [2, 3]. The most important issues in this segment are the criteria for the length of the distance necessary for landing. The regulations state that the pilot has to make sure that the weight of the aircraft for the correctly estimated time required for landing enables a complete standstill from a height of 50 feet and falls within:

- 60% of the available landing distance for turbojet aircraft,
- and 70% of the available landing distance for turboprop aircraft.

Landing is that stage of flight when the aircraft reaches a height of 50 feet above the runway before it comes to a complete standstill. Such landing can be divided into two stages. One relates

¹ V_{SRO} – indicative landing stall speed

² V_{MCL} – minimum landing speed at which the aircraft with one engine inoperative is controllable

³ V_{REF} - the speed values associated with achieving V_{SRO} and V_{MCL}

⁴ JARs (Joint Aviation Requirements) – European aviation regulations of the Joint Aviation Authorities

⁵ CS 25 – Certification Specifications 25 – specifications of the European Aviation Safety Agency for large passenger aircraft.

⁶ V_{SR} – stall speed used to determine other speeds of the aircraft as a percentage reference.

to the time when the aircraft is in the air and the other to the time when the landing gear constantly touches the ground. In a projection onto the ground plane, the airborne part usually is 1000 feet and specific steps have to be taken within this distance. After reaching a height of 50 feet the pilot completely reduces the thrust of the engines and raises the nose of the aircraft. With such a configuration in place, the main wheels of the aircraft are the first to touch the runway when landing. One should also bear in mind that descent techniques vary depending on the aircraft and will be totally different for lightweight aircraft and different for large aircraft, e.g. operated by transport companies.

Another landing stage relates to the ground part, which comprises the movement of the aircraft from touchdown until a complete standstill [10]. Similar to the airborne part, there are specific operations that have to be performed. After the wheels of the main landing gear touch the ground, reverse thrust and an appropriate flap configuration can be used. By introducing such solutions, the aircraft can securely lose speed. Nevertheless, in reality the aircraft cannot come to a complete standstill on the runway, but only at a certain location beyond it. Therefore, the aircraft is brought to an appropriate minimum speed so as to reach the destination point.



Fig. 1. Landing Descent Diagram

Another factor affecting the characteristics of aircraft movement during landing is resistance force. This force is responsible for the reduction of forward progression. The two forms of this force should be taken into consideration when landing: aerodynamic resistance force and wheel rolling resistance.

Wheel resistance force and braking force are further components affecting the total resistance. The first force relates to the resistance of the wheels rolling down the runway, whereas the second one to the resistance generated by applying the brake shoes to the brake disc. The wheel rolling resistance comes to analysis when the first wheels of the main landing gear touch the ground. As the lift force in the initial landing phase on the ground, immediately after touchdown, is still significantly low, the rolling resistance will not be so efficient as it is when the lift force decreases. It is so because the force of gravity is somewhat balanced by the lift, resulting in a low efficiency of such resistance. If you change the flap configuration, the lift force decreases, increasing the share of the rolling resistance in the total impact of resistance forces. An increase in this force can be observed for the entire time of the retarded movement down the runway, and its maximum value can be recorded just before a complete standstill.

The resistance force generated by the wheel brakes is several times higher than the resistance caused by reverse thrust and approximately two and a half times higher than that caused by the wheels rolling. A prerequisite for achieving such a high braking efficiency is, however, a proportionally high wheel rolling speed because it will not be possible to obtain such a high braking force without a relatively high abrasion of the wheels against the ground. Therefore, right after touching the runway, when the rolling resistance is low, the brake efficiency will be low as

well. Such a correlation between rolling resistance and braking force implies the pilot's need to get rid of the lift force during touchdown.

3. Identification of the parameters during the flight phase

For more detailed analysis was performed to identify landing operations as part of the research process. It was prepared computer identification of parameters, which consist of developing the mathematical model using the results of the measurements carried out on a real object. Simplified scheme of identification process can be presented as shown on below figure [11, 12].

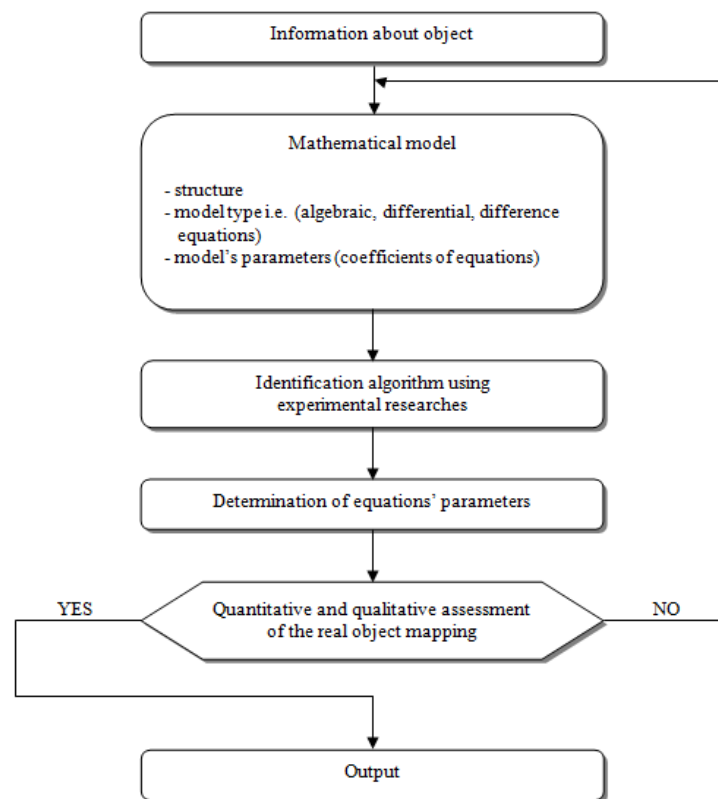


Fig. 2. Scheme of identification. Source: own elaboration

The model in its generality is represented by:

- the structure, expressed by mathematical provisions, block diagrams, joint matrices, flow diagrams or graphs;
- the values of model parameters (coefficients of equations).

The chosen structure depends on the scope of application of the built model. The simpler the structure is the easier the computation procedures are and potentially there is a bigger possibility of interpreting the obtained results [12]. Of course, there is a certain limit of simplifications, which if it is exceeded the model will not map the real object or process. However, in most technical applications, the structure of an object or a process is known and the knowledge which has to be gained is limited to the numerical values of certain parameters (coefficients of equations directing the dynamics of the process, the coefficients of linear or nonlinear model) and / or numerical values of state variables. Then the problem of identification is reduced to the estimation of the process parameters and / or its state. Sometimes detailed knowledge of the process or the object is required, what cause that identification will lead to state estimation [6, 7].

During identification [9] of the mathematical models parameters are sought using the method of the least sum of the squares of the errors. In accordance with this method functional F is determined:

$$F = \sum_{i=1}^N \varepsilon_i^2, \quad (1)$$

$$\varepsilon_i = y_i - y_{Mi} \quad (2)$$

where:

y_i - output signal from the object,

y_{Mi} - input signal of model,

ε_i - difference between output signal from the object and model,

N - number of measurements.

In this article the model reproduces the true airspeed during landing phase. This form of the model is sufficient for the purpose of the study i.a. runway occupancy time or other type of research aiming to increase throughput and safety in the area of the airport [4]. Aircraft's flight parameters used to develop the model come from flight data recorder of Embraer 170. These parameters include i.a.: indicated airspeed and ground speed, barometric altitude, geographical coordinates, course, pitch and roll angle, longitudinal and normal acceleration, Mach number, thrust, flaps/landing gear position, the total mass of the aircraft [7]. To develop the model the characteristic parameters were recorded for flights to and from Warsaw Chopin Airport, for landing on runway 33 with the same STAR (standard terminal arrival route). Data recorded from the moment when the plane reaches the speed of 220 knots during approach to the moment of landing has been taken into account. This way, the beginning of the landing phase has been defined for the purpose of the modeling, depending on the configuration (landing gear position, flaps, wings' mechanization). Searched model includes segments of landing phase presented in Table 1. Figure 2 presents the landing scheme with specification of the characteristic segments.

Table 1. Description of the individual segments of the landing phase

Segment	Beginning of the segment	End of the segment
I	indicated airspeed 220 kt, flaps position 0	indicated airspeed 180 kt, flaps position 1
II	indicated airspeed constantly equals 180 kt, flaps position 2	
III	Indicated airspeed decreases below 180 [kt]	indicated airspeed equals 160 kt, flaps position 3, lower the landing gears
IV	indicated airspeed equals 159 kt and steadily decreasing, flaps position 5	indicated airspeed equals 130 kt
V	indicated airspeed constantly equals 130 kt	
VI	indicated airspeed equals 129 kt and steadily decreasing	indicated airspeed steadily decreasing to 30 kt

Source: own elaboration kt - knot (1 [NM/h]), NM - nautical mile (1852 [m]).

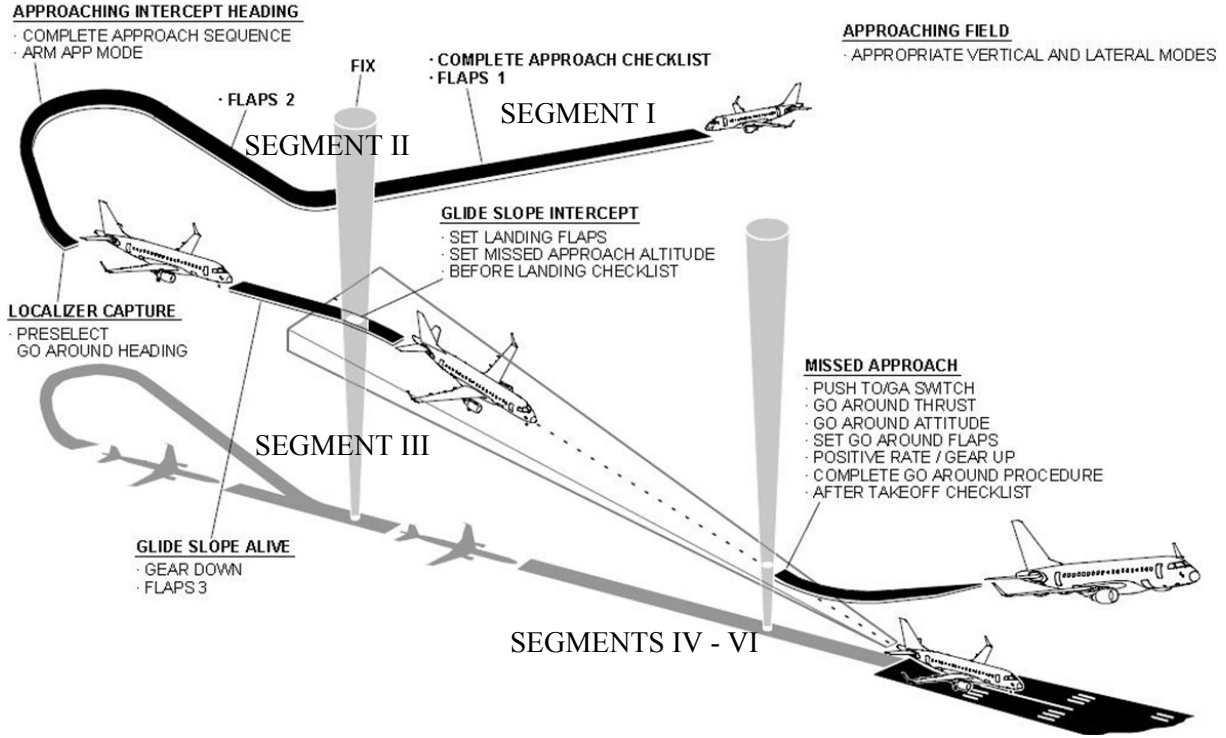


Fig. 3. Scheme of aircraft landing operation. Source: own elaboration

In this case, from the purpose of mathematical modeling point of view, the flight speed characteristics are interesting. Model mapping speed variation V_{i+1} at the time $i+1$ has the form:

$$V_{i+1} = \underline{x}_i \underline{a} \quad (3)$$

where:

\underline{x}_i - row matrix inputs for i - th time moment with elements,

$$\underline{x}_i = [x_{1i}, x_{2i}, x_{3i}, \dots, x_{7i}] = [1, t_i, t_i^2, s_i, t_i s_i, V_{i-1}, V_i] \quad (4)$$

\underline{a} - seeking vector of model's parameters (3) described as;

$$\underline{a}^T = [a_1, a_2, a_3, \dots, a_K] \quad (5)$$

t_i - i - th time moment of the flight [s],

s_i - segment's number for i -th time moment ; $s = 1, 2, \dots, 6$; $i = 1, 2, \dots, N$.

Data obtained from flight data recorder are a discrete form and in order to be able to use the received data sequence in further calculations they were subjected to the interpolation process. Flight parameters characteristic were interpolated using a polynomial. It is essential to determine polynomial parameters using the points of characteristic of this polynomial. The value calculated in the middle of timestamp interval is taken as a value of the interpolated characteristic. In the next step, interpolation is performed similarly as in the previous points, with a shift by one timestamp. In the article interpolation for 9 points was applied, based on points obtained from the measurement, using a polynomial of degree 2. Examples of interpolated characteristics are shown in Fig. 4.

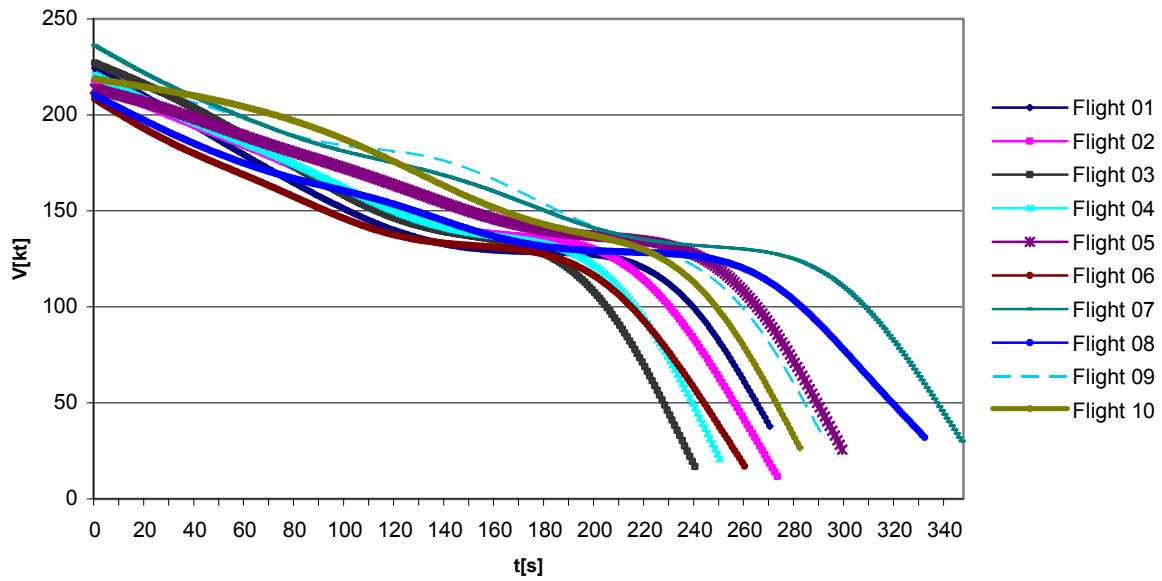


Fig. 4. Interpolated characteristics of indicated airspeed during landing for selected aircraft landing.
Source: own elaboration

For numerical reasons it is profitable to use standardized parameters for modeling (reduced to characteristic with values from the interval (0-1)). Normalization process is presented below. Normalized value of characteristic \bar{x}_{1i} in the individual moments of flight is determined as follows:

$$\bar{x}_{1i} = \frac{x_{1i} - x_{1\min}}{\Delta x_1} \quad (6)$$

where:

$$i = 1, 2, \dots, N$$

$$\Delta x_1 = x_{1\max} - x_{1\min}$$

Inverse dependence has formula

$$x_{1i} = \Delta x_1 \cdot \bar{x}_{1i} + x_{1\min}$$

Analogous dependencies define residual normalized elements of matrix (4) and normalized flight speed.

Model parameters for normalized data can be determined from dependencies of the following equation (4), (6)

$$\underline{a} = (\underline{U}^T \underline{U})^{-1} \underline{U}^T \underline{Y} \quad (7)$$

where \underline{U} indicates matrix, which in each row contains the flight parameters \underline{x}_i in the consecutive moment of time (1, 2, ..., N), where N represents number of analysed moments of time.

$$\underline{\underline{U}} = \begin{bmatrix} 1, & \bar{t}_1, & \bar{t}_1^2, & \bar{s}_1, & \bar{t}_1 \bar{s}_1, & \bar{V}_0, & \bar{V}_1 \\ 1, & \bar{t}_2, & \bar{t}_2^2, & \bar{t}_2 \bar{s}_2, & \bar{s}_2, & \bar{V}_1, & \bar{V}_2 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 1, & \bar{t}_i, & \bar{t}_i^2, & \bar{s}_i, & \bar{t}_i \bar{s}_i, & \bar{V}_{i-1}, & \bar{V}_i \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 1, & \bar{t}_{N-1}, & \bar{t}_{N-1}^2, & \bar{s}_{N-1}, & \bar{t}_{N-1} \bar{s}_{N-1}, & \bar{V}_{N-2}, & \bar{V}_{N-1} \end{bmatrix} \quad (8)$$

$$Y^T = [V_2, \quad V_3, \quad \dots \quad \dots \quad \dots \quad \dots \quad V_N]$$

Due to characteristic of true airspeed recorded by flight data recorder and the method of determination of the coefficients of the model equations the coefficient obtained from equation (7) are treated as random variables. Interesting information about the accuracy of mapping the actual flight parameters by model are in the determined quantitative and qualitative indicators. The basis for their determination are the differences between the outputs of the model and the object. Expressions determining the coefficient of identification quality was specified assuming that the disturbances are characterized by: a normal distribution, zero mean value, are stochastically independent and have constant variance. To check whether these differences are characterized by a normal distribution, i.a. the Kolmogorov compatibility test can be applied. Detailed information concerning the identification of emergency states including will be the subject of further publications.

4. Emergency Landing

It happens in aviation that emergency landing has to be made during flight or when landing. Maximum safety and minimum risk for the aircraft crew and passengers, and where possible, the integrity of the fuselage have to be ensured in such a situation. There are many emergencies, from a slight degrading of aircraft performance to large (often catastrophic) structural damage to the aircraft or power units. It is also possible that the speed at which the aircraft performance is compromised will determine the type of action to be taken. Nevertheless, all considerations of what to do should be made early enough for the pilots to retain full (or slightly limited) control over the aircraft. In extremely dangerous emergencies it is most often the engine which becomes damaged (or stops operating for various reasons) or the aircraft structure becomes destroyed. Such a situation forces immediate landing, with the need to ensure the proper spatial orientation of the aircraft. If there is no opportunity to land in an area specially designed for this purpose or in a landing field within the aircraft's range, it has to land on an unsuitable surface such as field or water.

Statistically, emergency landing on water ends up in most cases successfully, but the subsequent survival of passengers and crew members and the assistance they can receive depend on many factors. As it appears from the data compiled by the UK and US aviation, 88% of water landings result in few or no injuries to pilots and passengers. Sporadically, deaths during emergency landing on water are caused by subsequent circumstances such as drowning. The success of water landing depends to a large extent on what kind of preparations have been made. The survival of passengers and crew members after landing is contingent on how soon they receive assistance, which can be ensured only through good communication between pilots and rescue services when starting an approach to land on water. Ditching is an intentional landing on water, but not an uncontrollable collision. Passenger injuries can be reduced only by maintaining an

appropriate body posture when the aircraft touches the water surface. It is also compulsory to wear a life-jacket and the crew has to give details on what the passenger can expect and what they should do after landing.

If emergency landing has to be made in the sea or ocean, it is recommended to land along waves, if any, or their crests. Nevertheless, if the wind force exceeds 35-40 knots, the waves may reach a height of even ten feet. Then the most appropriate thing is to land 'against the wind'. The force of hitting the water will in any case be much stronger than that that can be felt during normal runway landing. It is recommended, therefore, to carry out such an emergency operation with the lowest possible speed (landing gear retracted), at such a height that the tail is the first part of the aircraft to touch the surface of the water. The aircraft should sit smoothly on the water. If the height and approach speed are correct, one or two minor hits are inevitable before the main collision. The impact may result in a high rotational speed of the aircraft with an equally high increase in load factor G and finally the immersion of the nose below the water surface, exacerbating this effect even more. In reality, the effects of this situation may be compounded, as the water level rises with the wave and may lead to an uncontrollable tilt of the aircraft. It is a major adverse consequence, but taking the right decision quickly and making meticulous preparations before landing will prevent the effects of this declaration. After emergency water landing the aircraft will very quickly lose its speed, and if the structure of the fuselage is not substantially damaged, it should float on the water surface for a certain time. The certain time is understood as a period from when the aircraft loses its speed and gets stabilised on the water surface until the crew and passengers leave the aircraft.

5. Flying with an Inoperative Engine

The first basic rule for the aircraft with one engine inoperative is to achieve the best climb performance. This performance is defined as the so-called speed V_{YSE} ⁷. After retracting the flaps and landing gear and protecting the engine, the aim is just to achieve the best possible climb performance and parameters while avoiding lateral drift.

For single or multiple engine aircraft with all engines inoperative, lateral drift is eliminated by setting the aircraft so that the indicator on the measuring gauge showing the turn and angle of roll is in its central position. This is the only prerequisite for achieving 'zero' lateral drift, and with such a setting, the aircraft represents the lowest possible air resistance profile achievable.

In multiple engine aircraft with one engine inoperative, putting the said indicator in its central position will not already reflect the 'zero' lateral drift due to asymmetric thrust. In fact, there is no such device that would show the pilot which conditions have to be met in respect of basic flight parameters to eliminate lateral drift. Obviously, if the aircraft does not move around its vertical axis, the minimisation of lateral drift will be limited to bringing the aircraft into a certain angle of roll and setting the turn indicators. All data contained in the *Aircraft Flight Manual* that refer to the situation in which one engine is inoperative are specified for eliminated lateral drift. Such procedures can be accepted for use even if zero lateral drift is close to naught.

Conclusions

The article contains a preliminary review of aircraft landing operations. The real phenomena occurring within the airfield can be examined using various methods. One of them is tests using mathematical models. An issue related to these tests is assessments and simulations of aircraft movement dynamics. As it is generally the case for mechanical systems, these tests can be conducted in many ways.

⁷ V_{YSE} - the speed for which the aircraft with one engine inoperative is to achieve the best climb performance.

In terms of the quality with which real aircraft flights are mapped, it is interesting to verify the stability of the model. In this case stability is understood as the consistency of the flight speed timings derived from the model with similar timings of real flights under variable initial conditions. The characteristics and procedure in emergencies as well as the rules for flying with one engine inoperative are described.

An important aspect is to create appropriate documentation that can be used for a detailed analysis of emergencies. Unfortunately, no data are available to identify and map the flight in such settings. Reports and documents prepared after emergencies result in more aircraft checks, however. Emergencies are followed by experts' continuously reviewing such reports, official flight manuals published by manufacturers and aviation manuals and regulations regarding aircraft control during asymmetric thrust. As a result, many imperfections and shortages have been identified and eliminated. When reading these imperfect documents, pilots, instructors, teachers and writers create incomplete and consequently incorrect V_{MC} ⁸ speeds, which has surely caused many aviation accidents.

The most important conclusion that should be drawn from all the amendments and additions made to aviation documentation over the years is that speed V_{MC} specified in the flight manuals accompanying an aircraft is used by the pilots of multiple engine aircraft in reality, when flying with an inoperative engine, but it is not just a constant value specified in these operating guidelines. Pilots assume a constant value of this speed, but in reality this speed largely depends on the roll and power settings. The standardised speed V_{MC} to which pilots so often refer is determined for a straight preservative flight, assuming the worst possible variant of variables affecting this speed and a angle of roll of 3-5° from the failed engine side and the maximum one for takeoff. The actual speed V_{MC} can reach values that are even 60 times higher than those specified in operating instructions if the angle of roll does not remain at an appropriate level in relation to the failed engine. As a result, such a situation may lead to a loss of control over the aircraft and finally a catastrophe. Unfortunately, the influence of the angle of roll on the minimum speed at which the aircraft is controllable is not clearly specified in flight manuals (except perhaps for a few cases), aviation regulations or any other documents regarding performance.

The V_{MC} speed mentioned in operating instructions is the minimum speed that is necessary only to control the aircraft, it is surely not a manoeuvring speed and it is valid as long as the angle of roll used to determine this speed is maintained.

It is important to be fully prepared for an emergency during flight. Unfortunately, no clear answer exists, but complying with the following recommendations will certainly increase the chances for the pilot to take correct, appropriate and considered decisions in a critical moment:

- all information regarding the flight mechanics of multiple engine aircraft has to be presented to aviation students, regulatory authorities, aircraft accident investigators, authors of manuals and operating instructions, companies that design flight simulators, instructors and all other people engaged in the operations of multiple engine aircraft. All would understand then that the most critical manoeuvres after realising that a power unit is inoperative is to configure the rudder and wing ailerons properly so as to reduce speeds V_{MC} and V_2 down to safe pre-calculated values.
- the most important conditions of the flight technique used to determine the values of the V_{MC} speed should be properly combined based on the FARs/CS 23 and 25 as well as operating and flight instructions. All techniques of test flights are available from the FAA⁹ and EASA¹⁰ Test Flight Manuals, but for unexplainable reasons they have never been applied by pilots to revisions of the regulations.

⁸ V_{MC} – minimum speed that is needed only to control the aircraft.

⁹ FAA – Federal Aviation Administration – an agency of the US Department of Transportation responsible for all the civil aviation regulations in the United States.,

¹⁰ EASA – European Aviation Safety Agency.

A full analysis of all mechanical aspects would increase the correctness of the information presented in operating instructions, flight manuals and specialist books. The pilot should keep abreast of technological progress in this domain, which is the basis for ensuring an increasingly higher security threshold both for passengers and crew members as well as for the environment. The ability to proceed correctly in a critical situation and take the most appropriate and secure decision is a key part in ensuring safety.

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