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Risk Assessment of Aircraft's Takeoff Overrun or Failure to Clear the Obstacle over the Runway Threshold during Takeoff with All Engines Operative

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Abstract

This article presents a methodology to calculate the risk of aircraft running off the runway or failing to clear the obstacle of 10.7 meters requirements during the take-off operation by means of mathematical modeling. Particularly, the article presented herein provides theoretical quantification of the risk of an aircraft exceeding the predetermined and/or designed runway takeoff length considering the permissible risk value of one accident or incident out of a million operations (10^{-6}). The modeling is demonstrated by means of comprehensive calculation of the Boeing 737-800 aircraft takeoff phases in view of the maximum takeoff weight, the airplane aerodynamic characteristics and the condition of the runway surface. The presented calculation algorithm is paving the way for the methodology of design of runways based on the theory of risk. It is worth noting that the other takeoff scenarios, the takeoff with one engine non-operative engine and the rejected takeoff are also solved. However, these scenarios will be presented separately in different papers.

Keywords

Risk, Runways, Run-Off, Aircraft, Design, Take-Off, Ground-Run, Aircraft Performance, Design

1. Introduction

The existing runway design standards do not take into consideration the probabilistic nature that governs aircraft's performance parameters during the takeoff maneuver. Besides, the existing methods for assessing the probability of aircraft takeoff accidents are subjective in nature and based on non-universal empirical calculations and procedures. This paper provides a theoretical, mathematical and universal method, taking into account the distribution law of the aircraft's performance parameters. These parameters, namely the length of the takeoff ground roll (first phase) and the length of takeoff air section to clear an obstacle (second phase). The theory presented herein, to a certain extent, is part of a global runway design methodology developed by the author covering the runway design parameters based on the theory of risk. Globally, the methodology covers runway' design that adequately answers the risk of overruns during both landing and takeoff, the risk of veer-offs and the risk of landing undershoots. The method is also applicable to assess the residual level of risk at any specific airport and its deviation compared to the recommended design Norms such as the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA). Also, the presented mathematical solutions offer airports' operational and safety management departments a viable tool so that appropriate measurements can be adopted. Finally, it is a methodology not only to assess the risk but also to determine the appropriate runway design parameters such as length, width, slopes and vertical curves. In other words, it is a new approach for runway design.

2. The Takeoff Operation in Brief

All requirements and regulations governing the aircraft takeoff can be found in the national civil aviation regulations such as the United States Federal Aviation Regulations (FAR 14 CFR 25). The International Civil Aviation Organization (ICAO) also presents such regulations in the Airplane Performance Manual (ICAO Doc 10064). Indeed, presently there is a high degree of uniformity between the majorities of the national civil aviation regulations worldwide regarding landing and takeoff requirements. In fact, the declared takeoff distance for runway' is

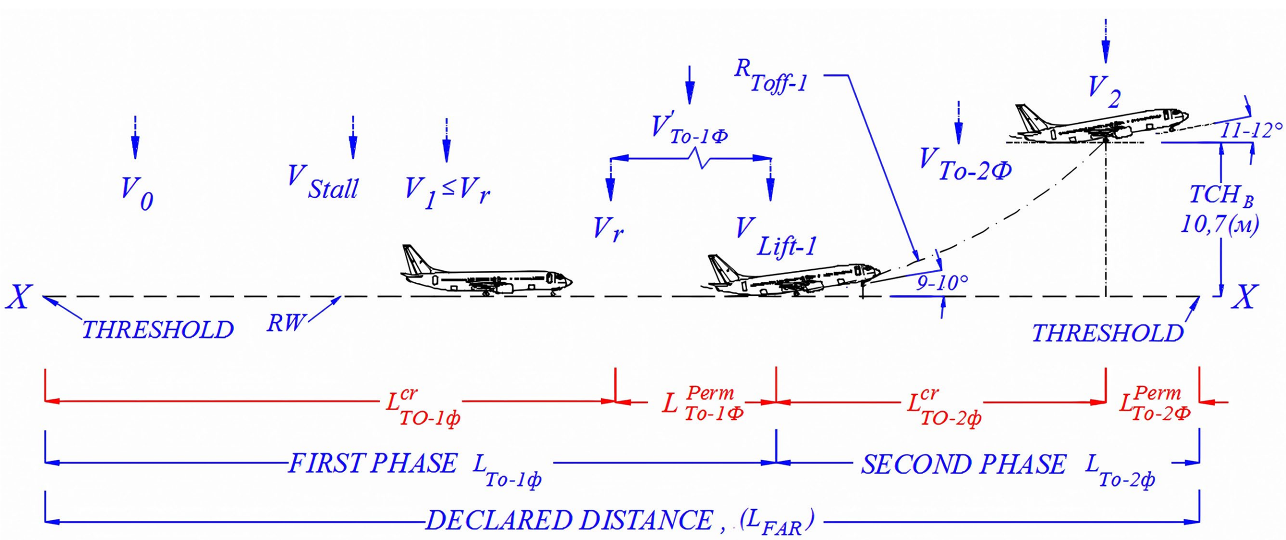

Figure 1. Takeoff side view with all engines operating.

specified by the aircraft manufacturer and consists of 115% of the actual distance (minimum) required to accelerate, lift-off and reach a point 10.7 meters above the runway with all engines operating at a speed known as V_2 [1] [2]. This length, in fact, also covers the required runway distance in case of a rejected takeoff and in case of takeoff with one engine that is inoperable. In fact, our research covered all takeoff scenarios; however, in this paper, we are presenting only the case of takeoff with all engines operating. It is worth noting that from the pilots' perspective, this distance is determined on the basis of the aircraft flight manual and charts, whereas from runway design engineers' perspective, this distance is taken from the Airplane Characteristics for Airport Planning manuals that are produced by the aircraft manufacturer. In **Figure 1**, both takeoff phases, in addition to the main parameters, are presented in confirmation with civil aviation regulations.

2.1. Computing the Risk of Aircraft Exceeding the Declared Takeoff Distance

Verifying the risk of aircraft exceeding the declared takeoff distance known as F.A.R. takeoff runway length requirements through real simulation of Boeing 737-800 aircraft in standard conditions known as the ICAO Standard Atmosphere (ISA).

Initial data:

– Aircraft type Boeing 737-800 (CFM56-7B24 ENGINES AT 24,200 LB SLST);
– Temperature of +15˚C;
– Density of 1225 kg/m^3;
– Mean sea level;
– Takeoff weight 79016 Kg;
– Declared takeoff distance L-F.A.R. 2792.00 m;
– Takeoff flaps 15;
– Zero runway longitudinal slope;
– Aircraft wing area 103.65 meter square;
– The maximum lift coefficient of the aircraft in takeoff configuration, 2.48;
– The drag coefficient value when the lift force is zero, 0.076;
– The wing span; 34.3154, m;
– The wing chamfer angle (between the wing outer edge and the axis perpendicular to the vector of moving direction of the aircraft) 28.25 degrees.

The analysis of measurements indicates that the normal distribution fits both takeoff phases, the ground run phase length and the air phase length. It is worth noting that together, normal distribution as well as the Gram-Charlier distribution laws were examined and both fit takeoff length of such aircraft category. However, due to the limitation, we are presenting the normal distribution case in this paper (**Figure 2**). Fifty four (54) observations (data points) are used to establish the distribution laws of both takeoff phases, ground run and air section.

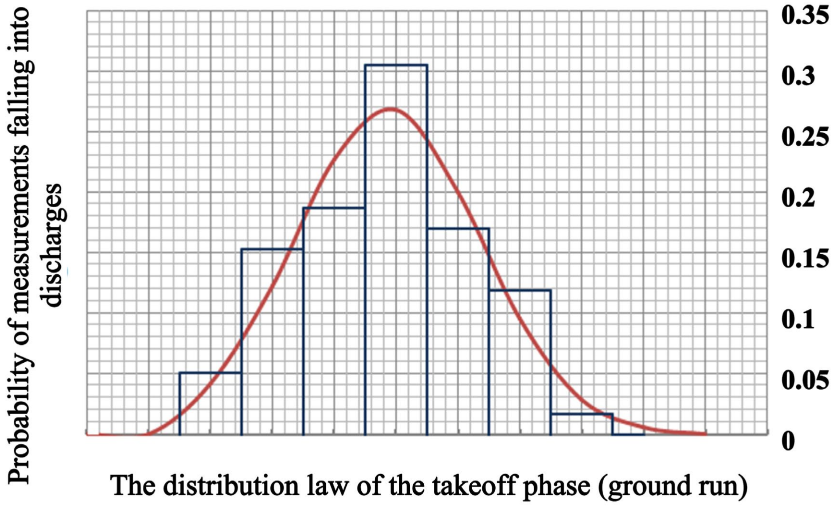

Figure 2. Takeoff run length distribution law, normal distribution vs empirical distribution function.

2.2. Calculation Procedure

A takeoff with all engines running and precisely at the limit of the first phase (ground phase), the pilot performs the following actions [3] [4]:

– Initiating the command "rotation", where the pilot signals the decision to begin the takeoff procedure (1 second);
– Having heard the command, the second pilot pulls the control towards himself (1 second);
– The aircraft begins to rotate, which smoothly continues at a speed of 3˚ per second and in 4 seconds reaches a typical lift-off angle of 9˚ - 12˚.

Acknowledging that the time required for the aircraft to rotate is $t_{B1} = 6$ seconds and understanding that the length for which the risk of 50% the aircraft overrun beyond the expected accelerate distance is the minimum length of the takeoff ground run, the critical length value of the takeoff first phase (the ground run) is determined using the expression (1), *m*:

$$L_{TO-1\Phi}^{cr} = \frac{V'_{TO-1\Phi} \times t_{B1}}{3.6} + \frac{V_r^2}{3.6^2 \times 2 \times a_{B1}}, \quad (1)$$

$$L_{TO-1\Phi}^{cr} = \frac{(265.23 + 277.86) \times 6}{2 \times 3.6} + \frac{265.23^2}{3.6^2 \times 2 \times 2.08} = 1759.4$$

where V_r (km/h) is the speed at which the rotation of the aircraft, during takeoff ground run, should be initiated. Upon FAA rules, this speed is set with respect to the stalling speed of the aircraft in the takeoff configuration V_{st-63} according to the following's relationships:

$$V_r = 1.05 V_{st-63} = 1.05 \times 3.6 \times \sqrt{\frac{2 M_{TOF} g}{C_{y\max} \rho S_w}}, \quad (2)$$

$$V_r = 1.05 \times 3.6 \times \sqrt{\frac{2 \times 79016 \times 9.8066}{1.225 \times 103.65 \times 2.48}} = 265.23 \text{ km/h};$$

where:

M_{TOF} —the maximum take-off weight, kg;

ρ —air density;

S_w —aircraft wing area;

$C_{y\max}$ —the maximum lift coefficient of the aircraft in takeoff configuration;

t_{B1} —the time required to rotate the aircraft.

Using formula (3) we determine the acceleration within the takeoff first phase, from the moment of movement initiation when the speed is zero and the runway longitudinal slope is zero (the angle $\theta^{\circ} = 0$) until the aircraft lift-off when reaching V_{lift}.

$$a_{B1} = \frac{1}{M_{TOF}}\left(T_{To} - \frac{1}{2}\rho V_r^2 S_w\left(C_{DT} - C_{LTO}\left(f_{B1} + \varphi_{B1}\right)\right) - M_{TOF}\, g\cos\theta\left(f_{B1} + \varphi_{B1}\right)\right) \quad (3)$$

$$a_{B1} = \frac{1}{79016}\left(219469.29 - \left(\frac{1}{2}\times 1.225\times\left(\frac{265.23}{3.6}\right)^2 \times 103.65\left(0.512 - 2.48\left(0.0340 + 0.4803\right)\right)\right)\right.$$
$$\left. - 79016\times 9.81\times 1\times\left(0.0340 + 0.4803\right)\right)$$

$$a_{B1} = 2.28\ \text{m/s}^2$$

The aircraft lift coefficient in take-off configuration during ground roll C_{LTO}, is calculated using the known aerodynamic formula:

$$C_{LTO} = \frac{2M_{TOF}}{319.324\times\rho\times S_w C_{LTO-\max}^2} = 2.48 \quad (4)$$

$C_{LTO-\max}$ —the predetermined maximum lift coefficient at take-off configuration and maximum angle of attack.

C_{DT} —the corresponding drag coefficient is:

$$C_{DT} = C_{D0} + k_0 C_{LTO}^2 = 0.512 \quad (5)$$

T_{To} —the thrust force (kg·m/s^2) required to achieve at least the takeoff safety speed V_2 that must be attained at 10.7 meters height above the end of the runway (above the threshold). Upon regulation $V_2 = 1.2V_{st-63}$, so the minimum thrust force is determined by the expression: [5]-[7]

$$T_{To} = \frac{1}{2}\rho V_2^2 S_w C_{D0} + \left(\frac{\left(M_{TOF}\, g\right)^2}{0.5\rho V_2^2 S_w}\right)\left(\frac{1}{\pi e AR}\right) \quad (6)$$

$$T_{To} = 0.5\times 1.225\times\left(\frac{303.12}{3.6}\right)^2\times 103.65\times 0.0268$$
$$+\left(\frac{\left(79016\times 9.81\right)^2}{0.5\times 1.225\left(\frac{303.12}{3.6}\right)^2\times 103.65}\right)\left(\frac{1}{3.1416\times 0.36\times 5.68}\right)$$
$$= 219469.29$$

AR —is the wing aspect ratio, the wing span to its area.

$$e = 4.61\left(1-0.045\left(\frac{u^2}{S_w}\right)^{0.68}\right)\left(\cos\Delta_{LE}\right)^{0.15} - 3.1, \tag{7}$$

where C_{D0} —is the drag coefficient value when the lift force is zero;

K_0 —the drag correction factor;

e —the Oswald wing efficiency factor;

u —the wing span;

S_w — the wing area;

Δ_{LE} —the wing chamfer angle (between the wing outer edge and the axis perpendicular to the vector of moving direction of the aircraft).

The values of the coefficient of friction φ_{B1} and the coefficient of rolling resistance f_{B1} at the given speed V are determined, respectively, to be 0.4803 and 0.034. The friction value φ used in the formula presented below is established based on FAA system of runway surface friction threshold to initiate runway surface rehabilitation. FAA sets this value to the order of 0.52. The coefficient of friction is determined according to the formula:

$$\varphi_{B1} = \varphi - \beta_\varphi V, \tag{8}$$

the coefficient β_φ is tabulated in Appendix 2 [8];

V —the speed of the aircraft at the moment of takeoff km/h;

f —the calculated values of the rolling resistance coefficients are established according to dependence:

$$f_{B1} = f_{20} + K_f V, \tag{9}$$

f_{20} —the values of the rolling resistance coefficient at the aircraft speed tabulated in Appendix 3 [8];

K_f —This coefficient is taken from the note to Appendix 3 [8].

The critical value of the length of the takeoff air section, takeoff second phase, with all engines operating from the point at which the aircraft lifts the ground to the point at which the aircraft crosses the threshold at an altitude 10.7 meters above the runway $L^{cr}_{TO-2\Phi}$ (m) is calculated using the following relationship [9]:

$$L^{cr}_{TO-2\Phi} = \sqrt{\left(2\times R_{Toff-1}\times TCH_B\right)-\left(TCH_B\right)^2}, \tag{10}$$

$$L^{cr}_{TO-2\Phi} = \sqrt{\left(2\times 20199.3\times 10.7\right)-\left(10.7\right)^2} = 657.38$$

where R_{Toff-1} —the radius of the flight path curve from the aircraft liftoff and until it clears an obstacle equal to a height of 10.7 meters in accordance with the civil aviation flight safety standards, (see **Figure 1**) and determined by the formula [9] [10], m:

$$R_{Toff-1} = \frac{V_{stall}^2}{g\left(n_1-1\right)} = \frac{252.6^2}{g\left(1.322-1\right)} = 20199.3, \tag{11}$$

where n_1 —the coefficient of load factor, the ratio of the aircraft's lift to its weight force. When the aircraft takeoff with all engines operating this coefficient is determined as follows:

$$n_1 = \frac{L}{W} = 1.322, \tag{12}$$

Hence, the takeoff runway length in standard day ISA conditions $L.F.A.R._{Toff}$ (M) is calculated:

$$L.F.A.R_{Toff} = 1.15\left(L^{cr}_{TO-1\Phi} + L^{cr}_{TO-2\Phi}\right) = 2779.3$$

It is worth noting that our calculation shows almost the same value as that declared on the Boeing Airplane Characteristics for Airport Planning. 2779.3 Vs. 2792.00 meters.

During takeoff with all engines operating, the 15% (required by regulations) added to the critical length value reflects the sum of the permissible deviation of the takeoff operational length in both phases, ground run stretch (first phase) and air stretch to clear the obstacle of 10.7 meters (second phase) (**Figure 1**). Since all operational speeds have a linear dependence with respect to the stall speed in the takeoff configuration, it is fair to calculate the permissible deviation of the operational length of the first and second phases, respectively, as follows:

$$L^{Perm}_{TO-1\Phi} = 0.15 L^{cr}_{TO-1\Phi} = 263.913, \tag{13}$$

$$L^{Perm}_{TO-2\Phi} = 0.15 L^{cr}_{TO-2\Phi} = 98.607, \tag{14}$$

Thus the operational estimated distance, for which the risk of the front wheels of the aircraft runoff over the calculated distance, from the starting point to the point where the aircraft lifts off the ground (when the aircraft becomes airborne), with all engines operating, should be determined as per the regulation rule, m:

$$L_{TO-1\Phi} = 1.15 L^{cr}_{TO-1\Phi} = 2023.3$$

The standard deviation of the aircraft's take-off critical length with all engines operating in the first phase (ground acceleration run), can be established by differentiating the formula of the critical length (1) by the speed of movement, the friction coefficient, the pilot's reaction time and the regulated decision speed at its limit:

$$\sigma_{L^{cr}_{TO-1\Phi}} = \sqrt{\left(\frac{t_{BP}}{3.6}\right)^2 \sigma^2_{V'_{TO-1\Phi}} + \left(\frac{V_r}{a_{B1}}\right)^2 \sigma^2_{V_r} + \left[\frac{V_r^2}{2\left(\pm i + a_{B1}\right)^2}\right]^2 \sigma^2_{\varphi_{B1}} + \left(\frac{V'_{CP-BB\text{Д}}}{3.6}\right)^2 \sigma^2_{t_{BP}}}, \tag{15}$$

$$\sigma_{L^{cr}_{TO-1\Phi}} = \sqrt{\left(\frac{6}{3.6}\right)^2 \times 4.27^2 + \left(\frac{73.67}{2\times 2.08}\right)^2 \times 4.18^2 + \left[\frac{73.67^2}{2\times 2.08^2}\right]^2 \times 0.02^2 + \left(\frac{271.54}{3.6}\right)^2 \times 0.9^2}$$
$$= 100.839$$

where— $\sigma_{V'_{TO-1\Phi}} = 4.27$, $\sigma_{V_r} = 4.18$, are respectively, the standard deviations of the average speed of the aircraft during the rotation sub-phase, the speed of the aircraft at the moment the nose wheel gear is raised (m/h). These values are calculated using the relationship: $\sigma_V = (0.05 \times V) + 0.5$;

$\sigma_{\varphi_{B1}} = 0.02$ —the standard deviations of the coefficient of runway surface friction (pre-calculated);

$\sigma_{t_{BP}} = 0.09$ —the standard deviations of the pilot reaction time (pre-calculated);

As a result, the permissible coefficient of variation of the critical run length during takeoff in the first phase is determined according to the formula:

$$C_v^{L^{KP}_{ВВД-1Ф}} = \frac{\sigma_{L^{cr}_{TO-1Ф}}}{L^{cr}_{TO-1Ф}} = \frac{100.839}{1759.42} = 0.057\,, \tag{16}$$

The coefficients of variation of the operational (permissible) and critical (minimum) lengths are comparable and equal $C_v^{L^{cr}_{TO-1Ф}} = C_v^{L_{TO-1Ф}}$ and the operational estimated distance as per regulation requirements ($L_{TO-1Ф}$) is known. Hence, the standard deviation of the operational length of the first phase is determined from the expression, *m*:

$$\sigma_{L_{TO-1Ф}} = C_v^{L_{TO-1Ф}} \times L^{Perm}_{TO-1Ф} = 0.057 \times 263.913 = 15.13\,; \tag{17}$$

The observation of the experimental data shows excellent agreement between the normal distribution and the empirical probability law, when analyzing the statistical data, in addition to small coefficients of asymmetry and eccentricity calculated based on Gram-Charlier distribution. So the normal distribution law is applicable for mathematical modeling of the risk assessment of an aircraft takeoff length of both phases. Hence, the risk of the aircraft going beyond the regulated operational takeoff run distance, under normal operating standard conditions (ISA), with all engines operating is calculated according to Equation (18) below:

$$r_{TO-1Ф} = 0.5 - Ф\left(\frac{L_{TO-1Ф} - L^{cr}_{TO-1Ф}}{\sqrt{\sigma^2_{L_{TO-1Ф}} + \left(\sigma_{L^{cr}_{TO-1Ф}}\right)^2}}\right), \tag{18}$$

$$\begin{aligned} r_{TO-1Ф} &= 0.5 - Ф\left(\frac{2023.3 - 1759.4}{\sqrt{15.126^2 + 100.839^2}}\right) = 0.5 - Ф(2.58823) \\ &= 0.5 - 0.49532778 = 0.00467 \end{aligned}$$

Thus, the risk of the aircraft overrun beyond the expected acceleration distance is 4×10^{-3} (4 incidents per 1000 operations).

By determining the risk of the aircraft exceeding the takeoff length of the first takeoff phase, we move to the second takeoff phase (the air phase) to calculate the risk of exceeding the expected horizontal length in order to clear the 10.7 meters obstacle when crossing the threshold.

The standard deviation of the critical length of the second phase during takeoff with all engines running can be determined by differentiating the formula of horizontal critical length of the second phase (5) by the average speed of the aircraft during the takeoff air phase:

$$\sigma_{L^{cr}_{TO-2Ф}} = \sqrt{5.128058 \times V_{stall} \times \sigma_{V_{stall}}}\,, \tag{19}$$

$$\sigma_{L^{cr}_{TO-2Ф}} = \sqrt{5.128058 \times 4.01 \times (252.6/3.6)} = 37.98$$

Therefore, the permissible coefficient of variation of the critical length of the second phase is determined by the formula:

$$C_v^{L^{KP}_{ВВД-2\Phi}} = \frac{\sigma_{L^{cr}_{TO-2\Phi}}}{L^{cr}_{TO-2\Phi}} = \frac{37.98}{657.38} = 0.06, \tag{20}$$

At the boundary limit the variation coefficients of both, the operational (permissible) and critical parameters of the takeoff air phase length are equal to each other:

$$C_v^{L^{KP}_{ВВД-2\Phi}} = C_v^{L_{TO-2\Phi}}$$

and the permissible deviation of the operational length of the second phase is

$$L^{Perm}_{TO-2\Phi} = 0.15 L^{cr}_{TO-2\Phi} = 98.607, \tag{21}$$

So the standard deviation of the calculated distance along the trajectory of the air section becomes:

$$\sigma_{L_{TO-2\Phi}} = C_v^{L_{TO-2\Phi}} \times L^{Perm}_{TO-2\Phi} = 0.06 \times 98.606 = 5.7$$

Thus, the quintile value (u) of Laplace function $\Phi(u)$ of the takeoff horizontal length of the second phase becomes known as:

$$U = \frac{L_{TO-2\Phi} - L^{cr}_{TO-2\Phi}}{\sqrt{\sigma^2_{L_{TO-2\Phi}} + \left(\sigma_{L^{cr}_{TO-2\Phi}}\right)^2}}$$

Then the risk of the aircraft exceeding the horizontal length of the takeoff air segment under normal operating standard conditions (ISA) with all engines operating is as follows:

$$r_{TO-2\Phi} = 0.5 - \Phi\left(\frac{L_{TO-2\Phi} - L^{cr}_{TO-2\Phi}}{\sqrt{\sigma^2_{L_{TO-2\Phi}} + \left(\sigma_{L^{cr}_{TO-2\Phi}}\right)^2}}\right), \tag{22}$$

$$\begin{aligned} r_{TO-2\Phi} &= 0.5 - \Phi\left(\frac{755.99 - 657.38}{\sqrt{5.7^2 + 37.98^2}}\right) = 0.5 - \Phi(2.56777) \\ &= 0.5 - 0.49488168 = 0.0051 \end{aligned}$$

Thus, the risk of the aircraft exceeding the horizontal length of the takeoff air segment is 5×10^{-3} (5 incidents per 1000 operations).

Note that Laplace function $\Phi(u)$ could be determined from Appendix 3 in Ref. [8].

Finally, understanding that during takeoff, two consecutive risk situations are arising, where each situation has its own independent parameters, the value of total risk is determined via the formula:

$$r_{TO} = r_{TO-1\Phi} + r_{TO-2\Phi} - r_{TO-1\Phi} \times r_{TO-2\Phi} = 0.01, \tag{23}$$

Thus, the risk of the aircraft exceeding the declared takeoff distance (F.A.R. take off runway length) is 1×10^{-2} (1 incident per 100 operations). It becomes obvious that a runway length of 2792 meters does not meet the required permissible risk value of 1 incident per one million operations 1×10^{-6}.

By iteration, adding 350 meters to the takeoff distance (F.A.R. take off runway length), resulting in minimizing the risk of aircraft running off the runway or failing to clear the obstacle of 10.7 meters requirements during the takeoff operation by means of mathematical modeling. We'll demonstrate it.

Using Equation (18), the recalculation of the risk of the Boeing 737-800 going beyond the regulated operational takeoff run distance, under normal operating standard conditions (ISA), with all engines operating is:

$$r_{TO-1\Phi} = 0.5 - \Phi\left(\frac{2278.33 - 1759.4}{\sqrt{15.126^2 + 100.839^2}}\right) = 0.5 - \Phi(5.08904977)$$
$$= 0.5 - 0.49999924 = 0.00000076$$
$$r_{TO-1\Phi} = 7.6 \times 10^{-7}$$

Using Equation (22), the recalculation of the risk of the Boeing 737-800 exceeding the horizontal length of the takeoff air segment under normal operating standard conditions (ISA) with all engines operating is:

$$r_{TO-2\Phi} = 0.5 - \Phi\left(\frac{851 - 657.38}{\sqrt{5.7^2 + 37.98^2}}\right) = 0.5 - \Phi(5.041605)$$
$$= 0.5 - 0.49999918 = 0.00000082$$
$$r_{TO-2\Phi} = 8.2 \times 10^{-7}$$

Therefore, the value of total risk is

$$r_{TO} = r_{TO-1\Phi} + r_{TO-2\Phi} - r_{TO-1\Phi} \times r_{TO-2\Phi} = 0.0000058\,,$$
$$r_{TO-2\Phi} = 5.8 \times 10^{-6}$$

3. Conclusion

The integration, of both the aerodynamic characteristics of aircraft during the takeoff in addition to considering the conditions of the runway surface in the mathematical algorithm of risk calculation, are both key factors in determining the critical parameters of the quintile of Laplace function. Consequently, a higher confidence value is achieved in calculation the runway takeoff length in respect to the permissible risk value. In other words, the inclusion of all independent parameters affecting the minimum required takeoff distance provides more real results.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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