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Emergency Takeoff Charts for Fighter Aircraft

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An important aspect of flight planning is calculating the performance of the aircraft. In particular, the ground performance which consists of takeoff distance, rotation velocity (V_{ROT}) and rejected takeoff (RTO) distance and velocity (V_{AB}) and varies dramatically with the available runway length and aircraft weight.

Recently, an effort has been made to prepare for emergency scenarios in which part of the runway is unavailable for takeoff. Ground performance data has been used to create 'takeoff charts' which present the takeoff risk as a function of two parameters: (i) The available runway; (ii) Aircraft weight. The risk is calculated by evaluating the difference between the rotation velocity and the rejected takeoff velocity for each weight and available runway length. Charts have been produced for fighter aircraft across various Israeli airbases.

The charts present a fusion of multiple parameters into a single all-in-one tool (per aircraft per airbase). This way the decision makers are provided with an immediate evaluation of the risk at emergency takeoffs from partially available runways and with an assessment of the maximum aircraft weight for a safe takeoff from a given runway length.

Keywords

Flight Mechanics, Ground Performance, Takeoff, Rejected Takeoff, Abort Velocity

Nomenclature

t	Time
a	Acceleration
V	Airspeed
x	Horizontal distance
g	Gravity acceleration constant
W	Aircraft total weight
T	Thrust
L	Lift
D	Drag
M	Pitch moment
μ_n, μ_m	Nose (n) and main (m) landing gear friction coefficients
μ_{Total}	A model equivalent friction coefficient
N_n, N_m	Nose (n) and main (m) landing gear normal forces
b	Horizontal distance between nose and main landing gears
c	Horizontal distance between center of gravity and main landing gear
d	Vertical center of gravity height above ground
V_{ROT}	Rotation velocity
V_{AB}	Takeoff abort velocity
V_{BA}	Brake application velocity

I. Introduction

Ground performance is a vital part of flight planning, since each aircraft configuration has its unique rotation velocity (takeoff), abort velocity (rejected takeoff), touchdown velocity (landing) and full braking velocity (rejected takeoff and landing). Takeoff and landing are characterized by transition of the aircraft from one dynamic environment to another, gathering or discarding a large amount of total energy.

The need to reject a takeoff may occur in case of a critical failure at the takeoff stage. Light-weight configurations are able to abort takeoff at any stage during takeoff since they are not limited in available runway length and brake energy limits, thus the abort velocity is equal to the rotation velocity ($V_{AB}=V_{ROT}$). Heavier configurations have limited abort velocities ($V_{AB}<V_{ROT}$) since often the runway is not sufficiently long in order to stop the aircraft before the runway ends. Another consideration which is taken into account is the brake energy limit which dictates a maximum brake application velocity (V_{BA}). Applying the brakes at velocities higher than V_{BA} may result in overheating of the brakes and tire rupture. The maximum brake application velocity is smaller as the aircraft is heavier since the energy absorbed in the brakes is equal to the work carried by the landing gear friction force, which is bigger for heavier aircraft. Another limitation imposed by the brakes is the braking force limit. Since an attempt to reject the takeoff at the rotation velocity (or any velocity in the range $V_{AB}<V<V_{ROT}$) for heavy configurations may result in a loss of an aircraft the velocity range $V_{AB}<V<V_{ROT}$ is referred as the 'death zone'.

In order to reduce the 'death zone' to the minimum possible, arresting systems such as cables (at different positions over the runway) and nets (at the end of the runway) are commonly installed. These systems absorb the kinetic energy of the aircraft (equipped with a hook), bringing it to stop within a few hundred meters. The addition of arresting systems allows reducing the 'death zone' significantly; however, they impose new limitations such as the hook load limit velocity, hook stabilization time and arresting system energy absorption limits. Due to the diversity of arresting systems, their rigging and location along the runway, aircraft manufacturers do not include performance charts in the aircraft Flight Manual for the abort velocity while engaging such a system. Flight Manuals usually include abort velocity charts that refer to an aircraft braking to a full stop, without the aid of any ground arresting system.

All the above mentioned constrains, together with initial conditions such as runway height, temperature, condition (dry/wet) and wind velocity, make the task of calculating the abort velocity for a given configuration quite complex. The complexity of the problem can be handled by using an adequate numerical scheme which takes into account the limitations, initial conditions and aircraft dynamics. The problem is solved by an in-house simulation described thoroughly in the following chapter.

II. Methodology

The simulation developed in order to take into consideration all of the above parameters and constraints has only one degree of freedom (x coordinate), with the dynamics of the pitch axis neglected. The moment equation is used in order to calculate the nose and main landing gear reactions. Control parameters such as the throttle and stabilator angle are assumed constant and given as an input per the corresponding flight phase (e.g. stabilator angle of 0° during takeoff and full trailing edge up during braking). A diagram of the forces acting on the aircraft is given in Figure 1:

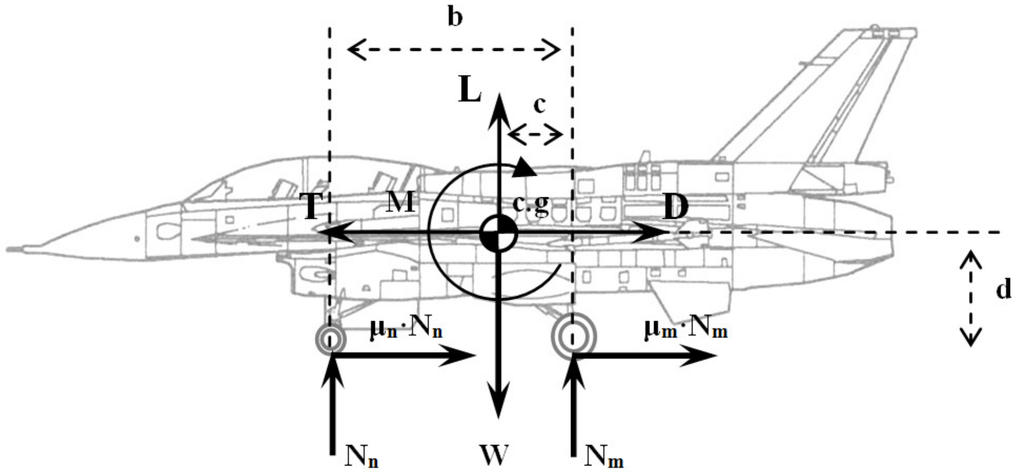

Figure 1. A diagram of the forces acting on the aircraft

The corresponding equations describing the dynamics of the aircraft are:

$$\begin{aligned} &\Sigma F_x : \tfrac{W}{g} a = T - D - \mu_{Total}(W - L) \\ &\Sigma F_y : N_m + N_n = W - L \\ &\Sigma M : (\mu_n N_n + \mu_m N_m)d + N_m c - N_n (b - c) = M \end{aligned} \tag{1}$$

$$\mu_{Total} = \frac{\mu_m \left(b - c + \dfrac{M}{W - L} \right) + \mu_n \left(c - \dfrac{M}{W - L} \right)}{b + d(\mu_m - \mu_n)} \tag{2}$$

where μ_{Total} models the total friction force acting on the aircraft.

The calculation is performed by numerical integration of the following equation:

$$a = \frac{d^2 x}{dt^2} \tag{3}$$

Calculation of takeoffs is performed by acceleration in full power until lift-off. Calculation of rejected takeoffs involves defining additional parameters such as:

a. The decision time required for the pilot to identify the problem, determine the adequate response and reject the takeoff. It is common to use 3 seconds as decision time.
b. The type of the failure: critical or engine. The difference between the two is that in the course of critical failure the engine continues to provide thrust during the decision time while in engine failure the thrust decays immediately at the failure. Critical failures are usually assumed since they impose more severe abort velocities.
c. Type of arresting system (cable/net/none) – each arresting system has unique energy absorption limitations which are implemented by a velocity limitation at the location of the arresting system.

After defining the parameters, the simulation first checks whether the abort velocity is equal to the rotation velocity by running an arrested takeoff with $V_{AB}=V_{ROT}$. If this scenario results in exceeding the limitations, the calculation is continued by calculating two arrested takeoffs based on initial guesses of the abort velocity ($V_{AB,1}$, $V_{AB,2}$) and then performing an iterative process involving the secant method, in order to find the maximal abort velocity satisfying all the constraints:

$$V_{AB,n+1} = V_{AB,n} - f_n \frac{V_{AB,n} - V_{AB,n-1}}{f_n - f_{n-1}} \quad (4)$$

The definition of the function f_n depends on the type of the rejected takeoff. When the calculation involves an arresting system, it is defined as the difference between the velocity at the arresting system and the velocity limitation of the arresting system. When the calculation is without arresting systems it is defined as the difference between the rejected takeoff distance and the runway length.

If the calculation involves an arresting system, the algorithm checks whether the hook is stabilized (locked in full down position) prior to engagement into the system. If the hook is not stabilized, the abort velocity is decreased in a manner allowing the hook to stabilize before engagement. The calculation is performed using the secant method when the function f_n is defined as the difference between the distance where the hook is stabilized and the location of the arresting system.

The braking force limitation is implemented during the braking stage by checking whether the braking force achieves the limitation. In case the limitation is achieved, the friction coefficient is corrected accordingly to obtain the maximum available braking force.

The braking energy limitation is implemented after initial convergence of the abort velocity. First, convergence is achieved as described above, without imposing the limitation of the maximum brake application velocity. Afterwards, the abort velocity is reduced to obtain the maximum available braking energy. The calculation is performed using the secant method when the function f_n is defined as the difference between the brake application velocity and its limitation.

The logical flowchart of the rejected takeoff calculation is summarized in Figure 2:

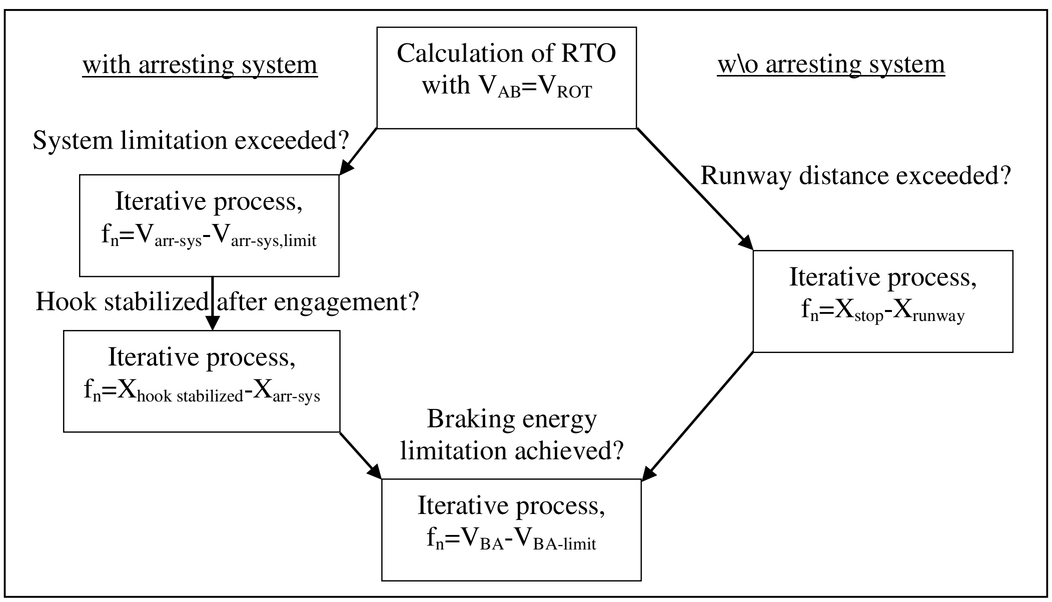

Figure 2. logical flowchart of rejected takeoff calculation

The simulation is implemented in Matlab and its databases have been calibrated on the basis of time histories of takeoffs and arrested takeoffs at various conditions.

III. Results

An example of a rejected takeoff without the use of arresting systems, with the aircraft stopping at the end of the runway, is described in Figure 3. The abort velocity is marked as "Failure recognition" and the maximum braking effort is achieved after 3 seconds which assess the time required for the pilot to identify the problem, determine the adequate response and reject the takeoff. The abort velocity in this case is limited by the available runway length.

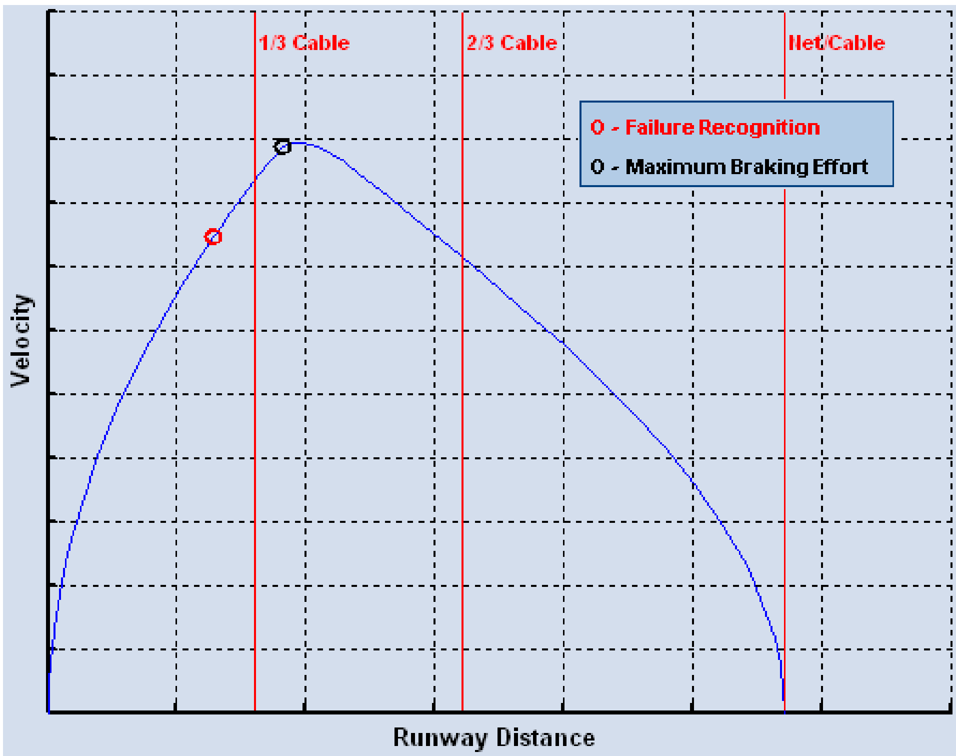

Figure 3. Rejected takeoff without arresting systems (with omission of classified data)

An example of a rejected takeoff without the use of arresting systems, with the aircraft stopping before the end of the runway, is described in Figure 4. The abort velocity in this case is limited by the braking energy limitation.

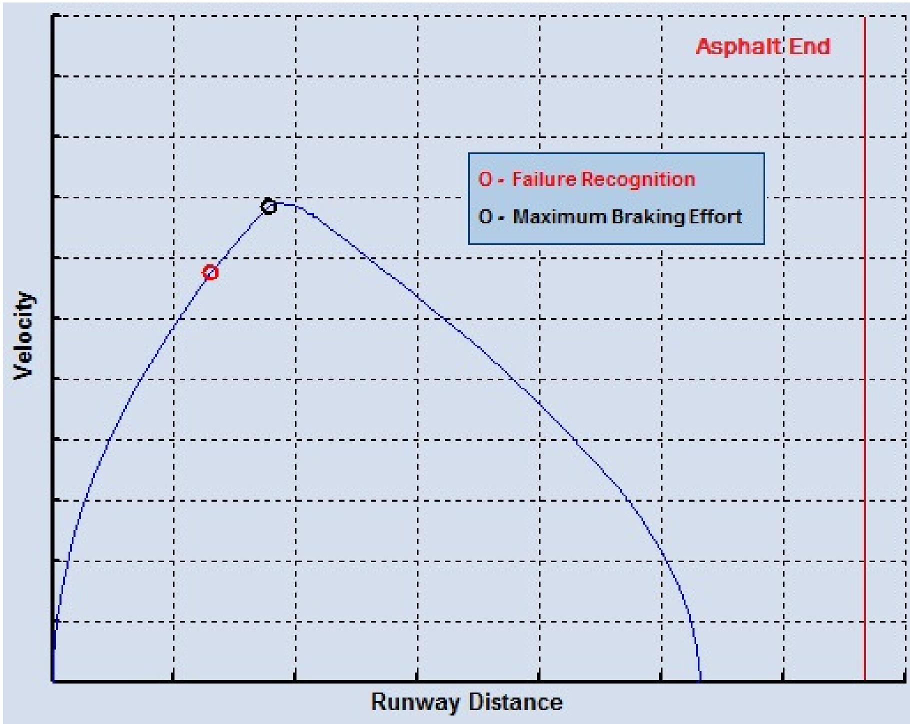

Figure 4. Rejected takeoff without arresting systems (with omission of classified data)

Examples of rejected takeoffs with the use of arresting systems such as net, 1/3 (approach end) and 2/3 (departure end) cables, are described in Figure 5. The abort velocity corresponding to the 2/3 cable and net arresting systems is limited by the arresting system limitation. The abort velocity corresponding to the 1/3 cable arresting system is limited by the hook stabilization time.

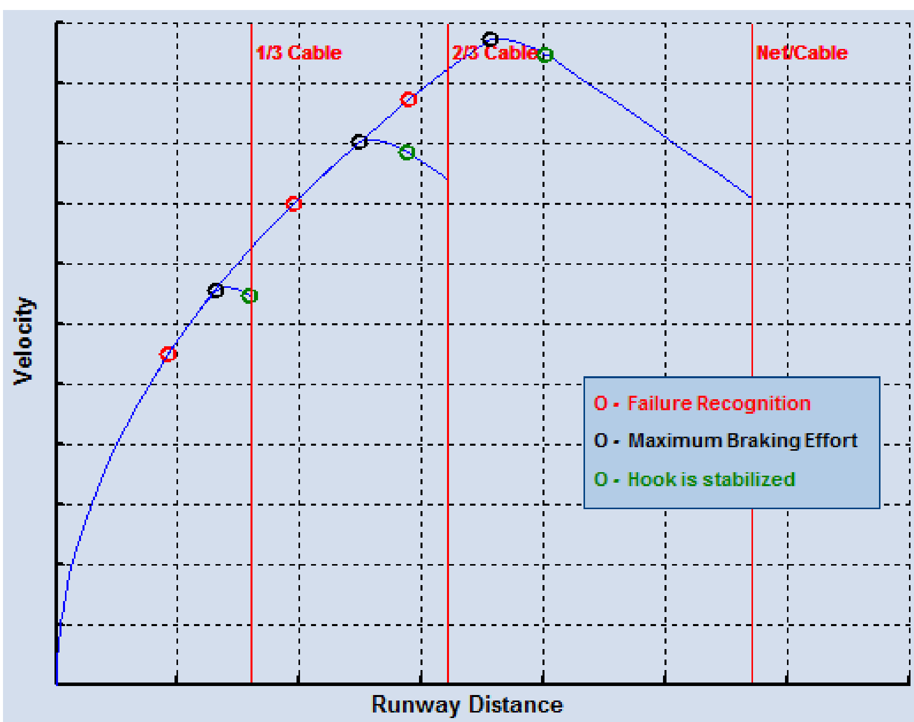

Figure 5. Rejected takeoff with arresting systems (with omission of classified data)

Recently, during an effort to prepare for emergency scenarios in which part of the runway is unavailable for takeoff, the simulation was utilized to create 'takeoff charts' which present the takeoff risk as a function of two parameters: (i) The available runway; (ii) Aircraft weight. The risk is evaluated according to the size of the 'death zone', $V_{ROT} - V_{AB}$. Since it is impossible to predict which part of the runway is available for takeoff, the abort velocity was calculated without arresting systems, ensuring to obtain the strictest risk.

An example of a takeoff risk chart can be seen in Figure 6. The green area corresponds to aircraft having $V_{AB}=V_{ROT}$. As demonstrated in the figure, this occurs for light weight aircraft on long available runways. The 'death zone' where $V_{AB}<V_{ROT}$ is divided to three areas that represent its magnitude, with three values of $V_{ROT} - V_{AB}$ that were selected as the dividers between the yellow, orange and red areas. The divider between the red and the black areas represents the takeoff distance of the aircraft, meaning that aircraft cannot takeoff in the black area.

When assessing the risk for a given weight, it can be observed that starting from a particular weight, as the available runway distance is increased there is a certain distance where the risk (i.e. the 'death zone') ceases to reduce. This occurs due to the braking energy limitation which limits the abort velocity as demonstrated in Figure 4.

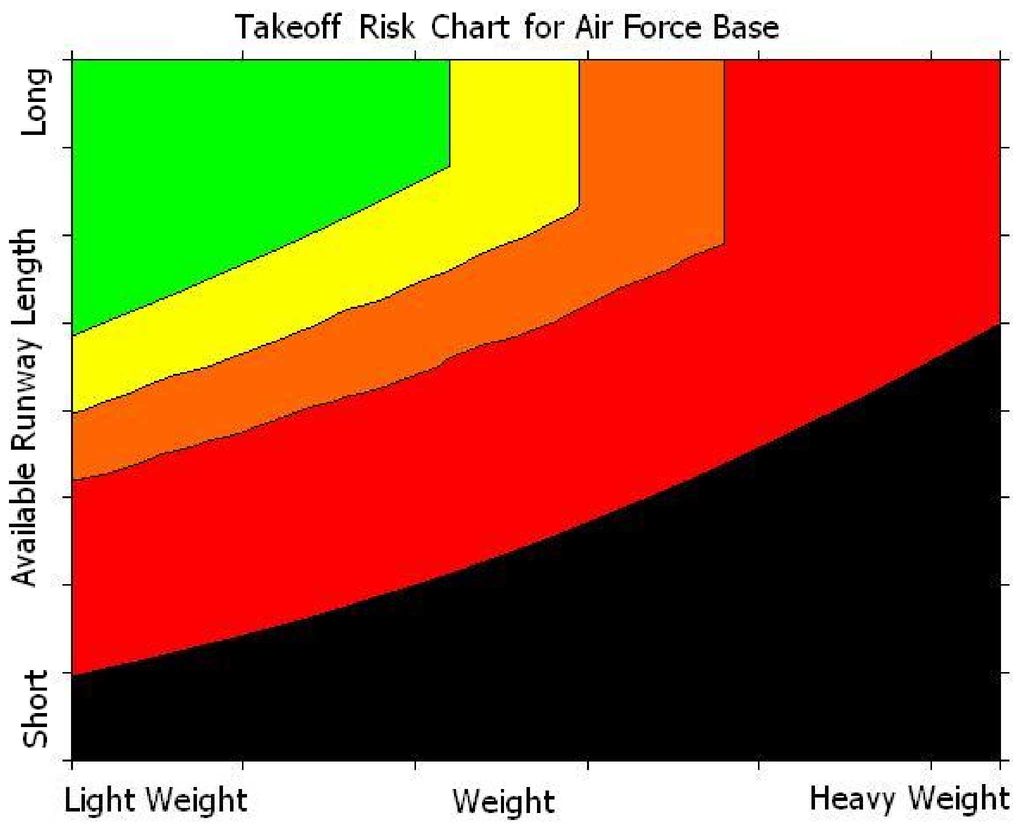

Figure 6. Takeoff risk chart (with omission of classified data)

IV. Conclusions

In order to handle the complicated task of takeoff and rejected takeoff calculations under various limitations, initial conditions and aircraft dynamics, an in-house simulation was developed.

The simulation was utilized to create ‘takeoff risk charts’ which present the takeoff risk as a function of the available runway and the aircraft weight. The charts, which are a fusion of multiple parameters into a single all-in-one tool (per aircraft per airbase), provide decision makers with an immediate evaluation of the risk at emergency takeoffs from partially available runways and assess the maximum aircraft weight for a safe takeoff from a given runway length.

Possible expansions of this work may include creating ‘takeoff risk charts’ with the use of arresting systems and studying the effect of their locations on the charts. Another possible expansion is the creation of ‘landing risk charts’.

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