DESIGN AND VALIDATION USING FLIGHT DATA OF A METHOD FOR PREDICTING THE GROUND RUN REQUIRED FOR TAKE-OFF

David Zammit-Mangion, Martin Eshelby
College of Aeronautics, Cranfield University, Bedfordshire, England.

Keywords: *take-off, performance monitoring, performance prediction.*

Abstract

The role of a take-off performance monitor is to determine whether the take-off manoeuvre is developing as desired or otherwise. Depending on design criteria, the system usually either compares the achieved performance against a pre-determined threshold, or else looks ahead and attempts to predict the future performance along the run. Whilst offering significant advantages over the former, the latter type relies on accurate prediction and the capability of looking as far ahead as possible to provide early warning of any impending anomaly to the crew. This paper discusses the predictive approach adopted in the design of a performance monitoring algorithm and presents the results obtained from flight testing using the College of Aeronautics' Jetstream-100 flying laboratory.

1 Introduction

In order to take-off, an aircraft must accelerate down the runway and achieve an airspeed allowing it to become airborne and climb away over any obstacles. Further to this basic requirement, Part 25 (Group A) certified aircraft must be capable of also successfully[1] completing the take-off attempt if an engine failure is experienced at any stage during the run. This effectively requires the attempt to be rejected if failure is experienced at low speeds early on in the run, since the reduced thrust will not be sufficient to allow the aircraft to become airborne within the remaining length of the runway. If, instead, the failure is experienced towards the end of the run, the take-off is continued on the grounds that insufficient runway will be available to bring the aircraft to a halt in time. This implies that the aircraft must have the necessary excess thrust installed in order to ensure that it can still accelerate to the scheduled airspeed and achieve a minimum positive climb once the engine has failed.

The take-off run can therefore be seen to consist of two stages, namely an initial stage during which the run must be aborted if an anomaly is detected, and a final stage in which the run must be always continued (unless the aircraft is clearly not airworthy). The critical point dividing the two stages of the run is identified as the decision speed V_1 (Figure 1).

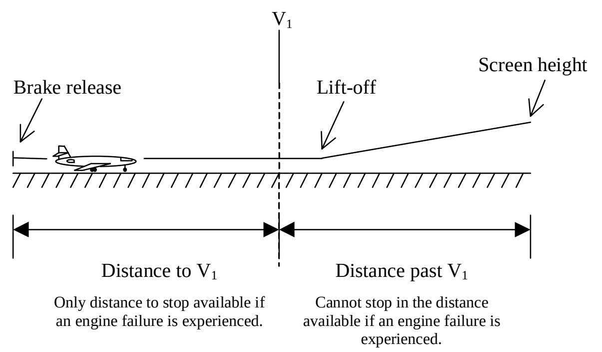

Figure 1: The decision speed V_1 as a point of no return during take-off.

[1] A takeoff attempt is in this text defined as successful if the manoeuvre is completed without an accident, and unsuccessful otherwise.

Aircraft take-off performance is often measured in terms of key distances required to reach salient points during the take-off attempt. To this effect the regulations define three distances - the take-off run required (TORR), the take-off distance required (TODR) and the accelerate-stop distance required (ASDR). TORR is the distance from brake release required (or allowed for) for the aircraft to lift off the runway, TODR is the distance required to achieve screen height[2], whilst ASDR is the distance required from brake release to bring the aircraft to a halt if the run is aborted at V_1, the latest possible moment (Figure 2). Likewise, airfields are required to declare their available distances, referred to as TORA, TODA and ASDA respectively. Safety is then assured during take-off by ensuring that the required distances fit within those available.

The regulatory bodies are understandably sensitive to the issue of distance requirements for take-off. They require aircraft manufacturers to demonstrate the field performance of an aircraft type by declaring TORR, TODR and ASDR for all operating conditions. This data is then made available to the aircraft operators, who are in turn required to ensure that the aircraft is only dispatched if the calculated TODR, TORR and ASDR fit within the field lengths available on the runway from which the takeoff is to be made. If excess runway is available, operators are allowed to execute the take-off at reduced thrust, thereby effectively increasing the required distances to match those available. This is a common procedure adopted in non-restricting conditions as it prolongs engine life and also favours noise abatement policies.

The TODR, TORR and ASDR calculated by the operator are actually predictions of the distances required under the assumed or expected operational conditions. The precise definitions of these distances include several leeways and factors of safety introduced to allow for any adverse variations in performance when the take-off is actually attempted. These include variations in aircraft performance normally experienced in a large type fleet, different piloting skills and responses, and discrepancies between dispatch (assumed) and actual weight. Further leeway is allowed for variations in reported or scheduled meteorological and other operational conditions.

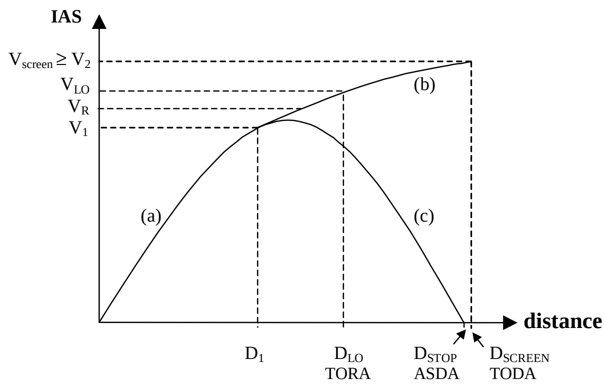

Figure 2: Minimum takeoff performance characteristic and the V-speed technique.

(a) Acceleration to V_1, all engines operative (AEO). Sufficient runway is available to bring the aircraft safely to a halt if the run is aborted. In the event of an engine failure the run must be aborted as insufficient runway is available to allow the aircraft to lift off or reach screen height within the remaining runway distances (TORA/TODA).

(b) Acceleration past V_1 to V_R, V_{LO} and V_2. The aircraft becomes airborne before TORA and achieves screen height before the end of the runway (TODA). The aircraft is too fast and too far down the runway to be brought to rest in the remaining distance if an engine fails. Aircraft scheduled performance, however, allows the aircraft to achieve screen height even if an engine failure is experienced at any time.

(c) Run aborted at V_1. This is the latest point along the run at which the take-off may be aborted. The aircraft is brought to rest in ASDA using the retarding mechanisms allowed for by regulation. V_1 consequently defines a 'point of no return'.

[2] The screen height is the clearance height above any obstacles, currently 35ft for take-offs from dry runways and 15ft for wet runways.

Whilst large leeways increase safety by increasing the probability of a successful take-off, they increase the cost of operations by either requiring longer runways than would otherwise be necessary[3] or else by restricting aircraft in the fuel and pay loads[4] they take on. The amount of total leeway allowed for is, in effect, intended to strike a balance between the two opposing interests, resulting in what to date has been judged as an acceptable safety record and satisfactory operational costs.

When attempting the take-off the crew follow well defined procedures which are standard worldwide. Once the thrust is set to the desired value, the aircraft is allowed to accelerate down the runway whilst the pilot not flying (PNF)[5] monitors the engine instruments and the ASI, calling out V_1, V_R and V_2 as the aircraft transits the salient airspeeds. At V_R the pilot flying (PF) rotates the aircraft at the desired rotation rate to the target attitude and, as the aircraft unsticks, it climbs out at the predetermined airspeed. This is usually achieved by flying on instruments such as the airspeed indicator (ASI) and Flight Director to control attitude and airspeed.

2 The dangers of poor performance

A crucial aspect of the take-off procedure (herein referred to as the V-speed technique) is that whilst monitoring the progress of the run, the crew observe the aircraft's airspeed but have no instrument providing information of the aircraft's position on the runway. As a result, they cannot objectively judge whether the aircraft's performance is within the scheduled threshold - that is, whether the aircraft will lift off and achieve screen height within the scheduled values of TORR and TODR respectively, or, in the case of a rejected run, is capable of coming to a stop within the calculated ASDA. They only have their intuition and experience to go by, and considering the fact that they operate different aircraft in continuously changing operating conditions, detecting subtle under-performance would at best be described as difficult. In any case, such judgement is invariably subjective which, in the authors' opinion, is not satisfactory in critical conditions.

The whole operation involving take-off is effectively an open-loop action where once the dispatch conditions are calculated the aircraft is assumed to perform within particular performance limits and really left at that. It is very possible, therefore, that the aircraft may be under-performing without the crew being aware that they might not be meeting one or more of the runway distance constraints. Due to the significant amount of leeway - particularly that of allowing for an engine failure at V_1 when no engine failure is experienced – an aircraft which is under-performing will most likely take-off successfully and this masks the seriousness of the issue. Poor take-off performance may be the result of a variety of shortcomings, including variations in piloting technique, inaccurate weight calculations, mis-set thrust and variations between actual and scheduled ambient temperature, pressure and wind.

Although it is unlikely that poor performance alone will result in an unsuccessful take-off, if an incident is experienced, the attempt is then more likely to result in an accident. Several runway excursions and failed take-offs in which poor performance has been a major contributory factor have in fact occurred, the most well known of which probably being Air Florida's fatal Flight 90 on 13 January 1982. The aircraft took off and, for a number of reasons, stalled and crashed less than a mile from the runway. The NTSB accident report [1] states that the although the aircraft achieved V_1 and the target lift-off speed, it used 5400ft of runway instead of the 3500ft expected of a normal aircraft of the type at the dispatch weight and existing environmental conditions. It also states that the performance was below normal from the beginning of the takeoff roll.

[3] Longer runways involve higher construction and maintenance costs.

[4] The take-off distances required can be shortened by reducing the take-off weight.

[5] Part 25 certified aircraft require a two man crew, one of which (PF) will have control of the aircraft whilst the other (PNF) assists the PF by monitoring the progress of the run.

This accident could well have been averted if the crew were informed that the aircraft was under-performing.

3 The role of the performance monitor

In the light of the above discussion the role of the performance monitor would be to provide objective performance information on the development of the take-off run in order to assist the crew in their on-going decision up to V_1 to continue with the run or otherwise. In the current V-speed technique, the crew are well trained to identify any discrete anomaly, obvious problem or unsatisfactory engine performance and then to take positive action as appropriate. In this environment the authors believe that the take-off performance monitor should be sensitive to, and optimised for, the detection of subtle under-performance which is otherwise difficult to detect. The information provided will supplement that already available to the crew and result in a more comprehensive situational awareness. In order to exploit the instrument's potential, a monitor should predict the future performance of the run, looking as far ahead as possible. This will reduce the probability of having to abort a take-off late in the run to V_1, which is not only a relatively high risk manoeuvre, but also likely to disrupt operations and may result in delays and financial loss. It is also highly desirable that the instrument integrate seamlessly with the V-speed technique so as not to disrupt current procedures and facilitate instrument certification.

The ultimate goal of a take-off performance monitor is to ensure safety during the manoeuvre. Besides the obvious advantage of contributing to the improvement of the safety record in aviation, the performance monitor may also offer commercial advantages to operators. By indicating the performance during take-off, less leeway in the scheduled distances may be necessary so it would be possible to permit aircraft to take-off at higher dispatch weights whilst maintaining current safety standards. In order to provide such benefits, however, the performance monitor will have to have demonstrated sufficient reliability so that no false or misleading information be generated as to result in the unnecessary rejection of take-off runs or, more seriously, lead to the development of a dangerous situation or an accident.

4 Design concept

The best way of monitoring the progress of the take-off run is clearly to continuously predict and update the actual expected TODR, TORR and ASDR during the run. The calculated margins between the predicted and scheduled values are then a measure of the viability, or risk factor, associated with the run and the decision to continue or abort. It is clear in these circumstances that prediction accuracy is of great importance if the system is to provide precise and reliable information to the crew. The distance covered in the acceleration phase[6] can be determined with sufficient accuracy largely because, during this time, the more significant parameters affecting performance either remain constant or have a known characteristic. This, however, cannot be said of the latter parts of the run. In the continued take-off case, the distances required to lift-off and to the screen height are very sensitive to the accuracy and technique the PF uses to rotate the aircraft and fly it off the runway. Since the aircraft will be travelling faster during the latter parts of the run, even a slight delay in pilot input may result in significant distance variations. The rejected take-off case is more complicated because not only is the actual time the pilot requires to retard the thrust levers and activate all the braking mechanisms unknown, but other significant parameters such as the braking capacity of the aircraft cannot be determined in advance with sufficient accuracy or confidence.

It is not surprising, therefore, that faced with the difficulty of predicting the various relevant distances with the desired accuracy several different approaches have been adopted in an attempt to avoid depending on so many

[6] The acceleration phase here is defined as the run to V_R in the AEO continued-run case, and the run to V_1 in the case of either a rejected run or a one engine inoperative (OEI) continued-run case.

unknown parameters. At least one design [2] has focused on the comparison of the distance gone with its scheduled counterpart without predicting future performance. Although relatively simple, such a comparison alone is not capable of providing early identification of a problem which may result in unacceptable performance later in the run. A common alternative philosophy has been to monitor ‘secondary’ parameters such as acceleration [3,4] or time-to-salient-airspeed[7] [5] to obtain an impression of the progress achieved, yet for various reasons beyond the scope of this paper this philosophy has largely fallen out of favour. One clear disadvantage of relying solely on such parameters without further processing is the difficulty of reliably relating the monitored (and displayed) parameters to distance requirements.

The SAE Aerospace standard [6] for take-off monitors defines non-predictive monitors as Type I. Type II are those monitors which predict only the continued take-off situation, although the effects of an engine failure are taken into account, whilst Type III also predict, on the basis of reported or estimated runway conditions, the ability to abort the take-off by predicting the stopping distance required. It is clear that Type III monitors provide the most comprehensive view of the progress of events. A number of recent monitor designs [7,8,9,10] have in fact exhibited Type III features in an attempt to provide as complete a performance awareness as possible to the crew. For the continued-run case, two of the designs [7,8] only predict the performance for the acceleration phase whilst the Boeing design [10] also estimates the post-acceleration phase distances required. All these designs also predict the point at which the aircraft is brought to rest if the run is aborted. This calculation of the deceleration phase is based on the estimated braking performance assumed to be available in the event of a rejected run and must allow for nominal delays in pilot reaction. Besides that it is questionable whether any of the post-acceleration-phase predictions can be calculated with sufficient accuracy[8], the very fact that standard values are used in the calculations suggests that these predictions could be interpreted merely as an update (or variation) of the scheduled performance calculated before dispatch. It is in fact the authors’ opinion that they should be treated as such since strictly they are not predictions of the actual run. There also seems to be little point in calculating and using predictions which rely on parameters which are only as accurate as those used in the calculation of the scheduled distances.

In these circumstances it is therefore justified to use the scheduled distances for post-acceleration-phase runway allowances. The use of the distances in context is also conservative from a safety point of view since the distances are the worst-case distances allowed for by regulation and are therefore the longest one should expect whilst remaining confident that the desired safety record will be achieved. If considered necessary, the scheduled distances may at most be updated during the run if any parameters are known to differ from the values assumed during pre-dispatch calculation.

This approach effectively reduces the monitoring problem to predicting only the distance required for the acceleration phase of the run. The logic then used in the assessment of performance is presented in Figure 3. The prediction is extended to the decision speed V_1, rather than the rotation speed V_R, because of the former’s relevance to the V-speed technique.

From a distance perspective, the decision speed V_1 is related to a point on the runway, herein defined as the *critical distance* D_{crit}. Hence the critical distance is defined as the scheduled distance-to-V_1. The monitor would during the take-off attempt estimate the actual distance-to-V_1, herein defined as the *decision distance* D_1. The viability of the take-off attempt is obtained by comparing D_1 to D_{crit}, the

[7] Time-to-salient airspeed has been largely adopted as a manual performance measure technique.

[8] SAE AS-8044 recommends that ‘the probability that TOPM system tolerances will, of themselves, cause an error greater than ±5 percent in the apparent all-engine operating takeoff distance to rotation speed shall be 0.01 or less’. The authors are of the opinion that the accuracy of the post-acceleration-phase predictions must match this accuracy if they are to be meaningful.

distance margin available giving a measure of leeway or safety associated with the particular run.

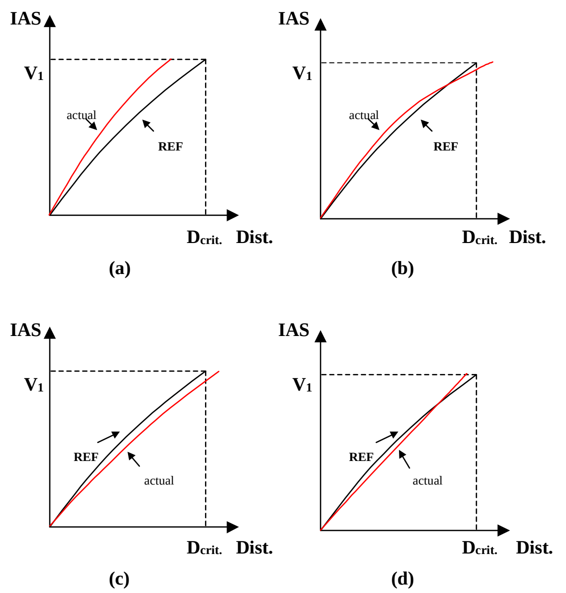

Figure 3: Four possible performance characteristics compared to scheduled performance-to-V_1.

(a) Normal situation where performance is superior to regulated (reference line). V_1 is achieved before D_{crit}, adding to the leeway in distance still available. The probability of a successful take-off is therefore higher than that assumed during the pre-dispatch calculations.

(b) Performance superior to regulated in initial stages but poor acceleration in the latter part of the run will not allow V_1 to be reached before D_{crit}. Poor acceleration coupled with a reduction in the distances available post-V_1 seriously jeopardises the probability of a successful take-off. Early prediction is required if the run is to be aborted at low speed.

(c) Performance inferior to regulated throughout run. Result similar to (b).

(d) Initial performance below scheduled but acceleration allows V_1 to be achieved before D_{crit} (eg. rolling take-off). Satisfactory performance increases the probability of successful take-off , similar to (a).

Defining the scheduled braking distance as the distance required to bring the aircraft to a halt from V_1, a worst-case scenario, it is this distance plus the distance-to-V_1 which then constitutes the *actual predicted* ASDR. Likewise, in the continued-run situation, the distance-to-V_1 plus the scheduled V_1-to-lift-off and V_1-to-screen height distances then become relevant as the *actual predicted* TODR and TORR. Clearly the worst case allowed for by regulation – that of a critical engine failure at the earliest possible instance to allow the attempt to be continued (V_1) must be allowed for in these calculations.

Using the SAE classification of take-off performance monitors, such an approach can be effectively classified as Type III because although only the distance-to-V_1 is actually predicted, the TODR, TORR and ASDR are implicitly compared with TODA, TORA and ASDA respectively.

5 The equations of motion

For the purpose of calculating the distance to V_1 the aircraft is usually modelled as a point mass exposed to linear forces (Figure 4).

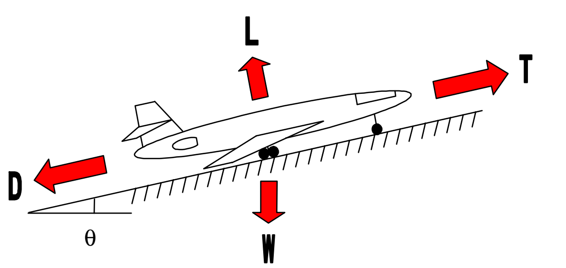

Figure 4: The forces acting on the point mass model of the aircraft during take-off.

Resolving along the runway:

$$T - D - W \sin\theta = ma \qquad (1)$$

The total drag D comprises the aerodynamic drag and rolling friction:

$$D = \frac{1}{2}\rho v^2 S C_D + \mu (W - \frac{1}{2}\rho v^2 S C_L) \qquad (2)$$

The true air speed (TAS) v differs from the ground speed v_g by the longitudinal component of the wind velocity v_w:

$$v = v_g + v_w \qquad (3)$$

The acceleration is therefore expressed, in terms of ground speed, as:

$$a(v_g) = \frac{T(v_g + v_w) - \left[\frac{1}{2}\rho S(C_D - \mu C_L)\right](v_g + v_w)^2 - W[\sin\theta + \mu]}{m} \qquad (4)$$

This equation is integrated to obtain the distance run to V_1:

$$D_1 = \int_0^{V_1 - V_w} \frac{m v_g}{T(v_g + v_w) - \left[\frac{1}{2}\rho S(C_D - \mu C_L)\right](v_g + v_w)^2 - W[\sin\theta + \mu]} dv_g \qquad (5)$$

Strictly, v_W is a function of time and θ is a function of distance (runway position). The average value of the former is often considered whilst if the runway slope changes, the integral can be split into two or more components with approximately constant slope. Ambient temperature and pressure (air density), together with aircraft weight and the aerodynamic coefficients, can be assumed to be constant throughout the run.

Equation 5 can either be computed algebraically or numerically using step-wise integration.

6 Flight testing and results

The algorithm predicting the distance to V_1 has been developed and tested using the College of Aeronautics' Jetstream-100, a Group B[9] performance aircraft with a take-off run to V_R (V_1 limit) of about 400m, achieved in around 16s, depending on operational conditions. All runs were carried out on Cranfield University's runway 22/04 at various weights varying from light (4200kg) to heavy (5700kg). Ten runs were carried out to validate the algorithm with results summarised in Table 1. Figure 5 presents the aircraft performance characteristics and the algorithm prediction accuracy of a typical run.

7 Discussion and conclusion

The results from the 10 runs (Table 1) indicate that the maximum prediction error achieved during the second half of the run is on average 6.5m, or 1.60% of the total run. The maximum error within the last 5 seconds of the run is on average 4.3m, or 1.07%. Assuming the errors are random and therefore have a normal distribution, 2.3 standard deviations will cover 99% of the population. Using the values of Table 1, the accuracy of the instrument is expected to be, on 99% of the runs, within:

2.9% (11m) in the second half of the run
1.9% (7m) in the last 5s

These results are well within the requirement of SAE AS-8044 which specifies a minimum accuracy of 5% on 99% of the runs to V_R.

The increase in accuracy towards the latter part of the run is to be expected since as the run progresses the algorithm is not required to look so far ahead. This reduction in error is exhibited in Figure 5 but is not so evident in the result presented in Figure 6. On that particular run, the aircraft is likely to have experienced a very slight unexpected disturbance in the last

[9] The Jetstream-100 is certified under BCAR Section K (Group C) but is capable of Group B performance.

part of the run which the algorithm would have sensed as it occurred. The resulting error due to this contribution is estimated to be about 3m and could be the result of a very slight change in wind speed or direction, a slight oscillation of the aircraft as the undercarriage is alleviated of the weight, or a similar discrete change.

The error characteristics presented in Figures 5 and 6 also exhibits a high frequency (10Hz) oscillation of the order of ±1m. This is most probably due to the quantisation error in the digitising equipment sampling at 20Hz on board the aircraft.

The prediction algorithm requires airspeed as one of the input parameters since it looks forward to the target *indicated airspeed* of V_1. The airspeed indicator on most aircraft starts indicating correctly at about 35kt, which is just under 7s in most of the runs.

Although this study involved only a preliminary investigation of the prediction accuracy of the algorithm, the results indicate that the algorithm is valid and can be used successfully as the core of a performance monitoring system on transport category aircraft.

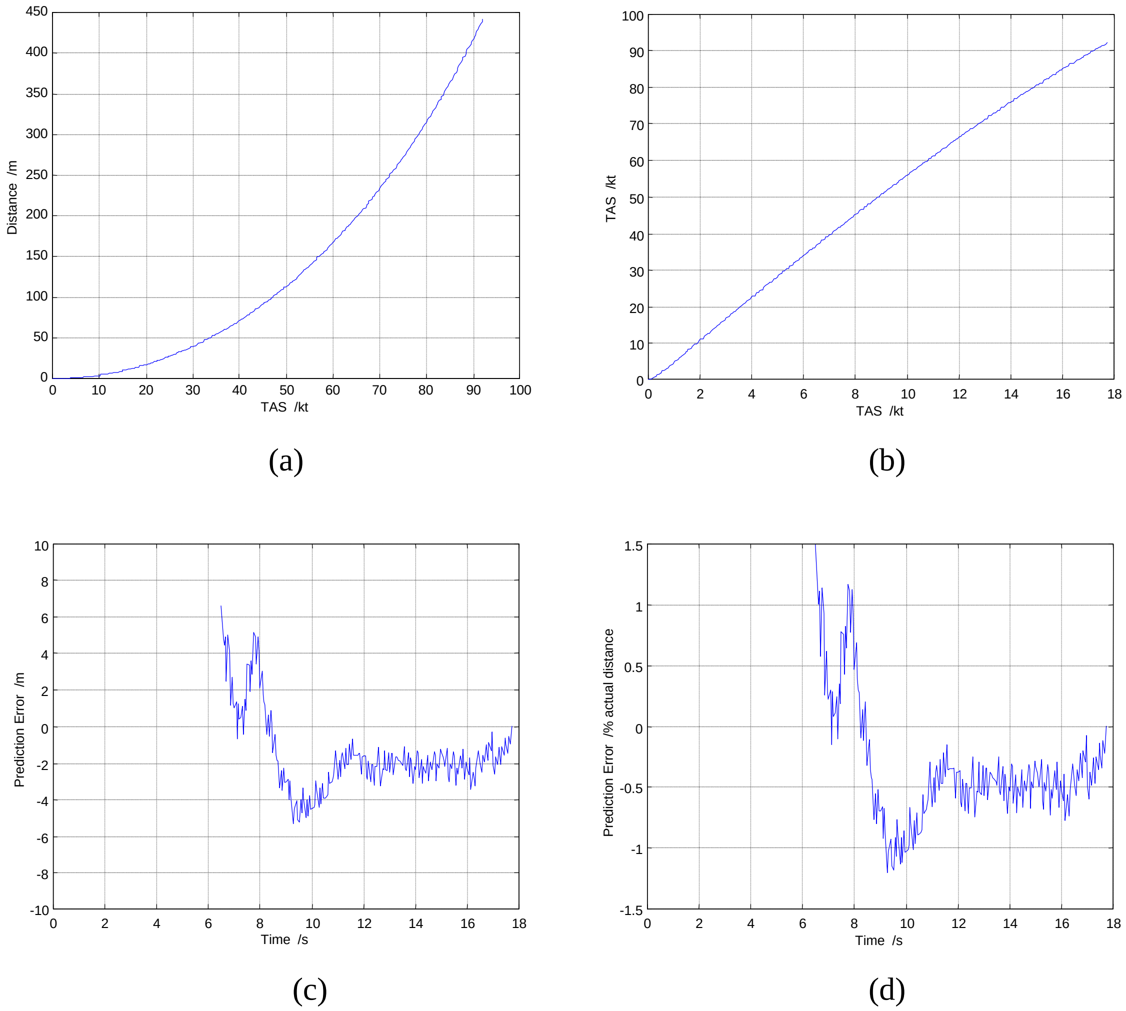

Figure 5: A typical Jetstream-100 ground roll and algorithm prediction error.

Run #	End speed /kt	Run distance /m	Run time /s	Max. estimate error* Last 50% of run /m	Max. estimate error* Last 50% of run /%	Max. estimate error* Last 5s of run /m	Max. estimate error* Last 5s of run /%
1	88.7	391.0	17.0	8.1	2.07	3.3	0.84
2	86.6	371.5	16.2	7.1	1.91	6.3	1.70
3	86.8	386.1	17.2	3.4	0.89	3.4	0.89
4	92.0	440.6	17.7	4.9	1.11	3.4	0.77
5	94.8	483.0	19.0	7.5	1.55	3.1	0.64
6	88.8	373.2	15.4	10.9	2.92	4.0	1.07
7	93.6	437.6	17.1	5.0	1.14	5.0	1.14
8	96.5	443.3	16.8	6.5	1.47	3.3	0.74
9	88.8	350.5	14.6	5.3	1.51	5.3	1.51
10	90.0	403.7	16.6	5.8	1.44	5.8	1.44
			Average	6.5	1.60	4.3	1.07
			Std. Dev.	2.0	0.55	1.1	0.35

Table 1: Summary of the ten Jetstream-100 runs monitored.

* The prediction estimate maximum error is the maximum absolute variation between the actual run distance (column 3) to the target end speed (column 2) and that predicted to be required at any time during the time period specified.
The percentage error is based on the actual run distance.

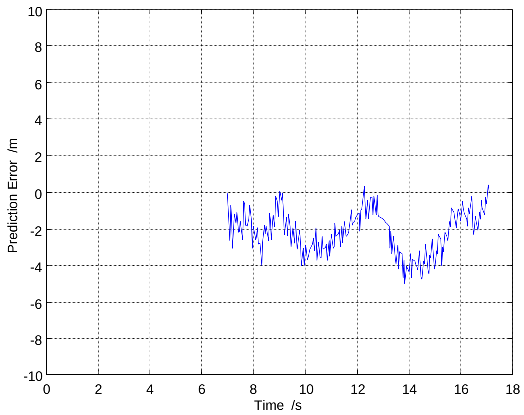

Figure 6: Prediction error of a run showing a disturbance experienced at about 13s.

References

[1] Anonymous. *Aircraft Accident Report. Air Florida Inc. Boeing 737-222, N62AF. Collision with 14th Street Bridge near Washington International Airport, Washington, D.C., January 13, 1982.* NTSB report no. NTSB-AAR-82-8, 1982.

[2] Grover J H H. Take-off instrument for assessing achieved performance during take-off and a take-off accident analysed in context. *8th Int. Aerospace Instrumentation Symposium*, Cranfield University, England, 1975.

[3] Morris G J and Lina L J. *Description and preliminary investigation of an instrument for detecting subnormal acceleration during take-off.* NACA TN-3252, 1954.

[4] Zinn S V. *Develop acceleration and brake monitor system.* DoT, FAA report no. FAA-RD-72-112, 1972.

[5] Fearnside K. Instrument aids for take-off. *J. RAeS*, Vol. 67, pp 544-551, 1963.

[6] Anonymous. *Takeoff performance monitor (TOPM) system, airplane, minimum performance standard for.* SAE, Aerospace Standard AS-8044, 1987.

[7] Cleary P J et al. *Aircraft performance margin indicator.* European Patent Application no. 85200988.8, 1986.

[8] Srivatsan R and Downing D R. *Development of a takeoff performance monitoring system.* NASA-CR-178225, 1987.

[9] Khatwa R. *The development of a take-off performance monitor (TOPM).* Ph.D. Thesis, Bristol University, 1991.

[10] Coquin L et al. *System for deriving an anomaly signal during the take-off of an aircraft.* US Patent no. 5,668,541, 1997.