CYCLONE Fluid Dynamics

Criteria for crosswind variations during approach and touchdown at airports

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Joint Symposium of DFG FOR 1066 and DLR-Airbus $C^2A^2S^2E$
"Simulation of Wing and Nacelle Stall"
Braunschweig, Germany, December 2014

Abstract

Landing in adverse wind conditions in a major airport can sometimes result in incidents, which in some cases can be attributed to the local infrastructure. The measurement of the representative wind near a runway and touchdown zone is discussed including the influence of the built environment on the wind conditions and how representative they are. Localised rapidly changing wind conditions, or building induced turbulence, will result in aircraft attitude changes (and occasionally with consequences like hard landings, pod strikes or go-arounds). The development of the original crosswind criterion and the extended criteria which limit the crosswind and headwind variations, are presented and their application to the built environment of airports is discussed.

1 Introduction

An analysis by the Flight Safety Foundation of approach-and-landing accidents between 1980 and 1996 contains the following conclusions [1, 2]:

- There were 287 fatal approach-and-landing accidents and 76 serious incidents (occurrences during 1984–1997).
- Adverse wind conditions (the presence of strong crosswinds, tailwinds and wind shear) are involved in one-third of approach-and-landing accidents.
- Two-thirds of the overruns or excursions occurred with at least two of the weather factors; rain, fog and/or crosswind present.
- 85% of crosswind incidents and accidents occur at landing.

R. Radespiel et al. (eds.), *Advances in Simulation of Wing and Nacelle Stall*,
Notes on Numerical Fluid Mechanics and Multidisciplinary Design 131
Springer Verlag, 2016, pp. 167-187, DOI: 10.1007/978-3-319-21127-5_10

The important role of crosswinds during landings is obvious. The major factors during these excursions are: a non-stabilized approach; excess airspeed; (intentionally) landing beyond the intended touch down point; impaired braking action due to a slippery or contaminated runway; or other changed conditions existing at the time of landing [3]. More information on runway excursions, both veer-offs and runway overruns at takeoff and landing, identified by the Flight Safety Foundation can be found in [4].

Major airports are always located near areas of economic activity where passengers need terminals, and freighters need cargo terminals. Then there is a whole range of services complementing the infrastructure. A successful airport attracts businesses and developers, and some of them would preferably like to be located on the runway itself. This pressure of the built environment on airport operations can result in larger objects being built nearer to the runways. These objects have to comply to the Obstacle Limitation Surfaces (OLS), and they shouldn't affect the Instrument Landing System (ILS). However, these larger objects can also influence the wind measurements, and even impact the operations on the runways in high winds.

In 1993 a Test Run Facility was built at Amsterdam Airport Schiphol for wide body aircraft and some time afterwards in December 1994 to March 1995 pilots started to report 'increased turbulence' when they approached Runway 27 with a strong south to south-westerly wind. Until one day after three missed approaches by three very diverse aircraft, a Fokker 100, a Boeing 737, and a DC-10, the airport immediately issued a notice prohibiting the use of Runway 27 in the event of strong south-westerly winds (larger than 25 kts).

Subsequently a model of the Test Run Facility was tested in the NLR LST wind tunnel and trailing vortices were discovered in 1995, and their strength and, more important, the depth of the wake were measured in 1996. The fluctuating wind and wake interact, and the outcome is perceived by the pilot as turbulence. The wake crossed the glidepath at an altitude between 60 and 80 m (higher than 200 ft, well before the flare).

The measurements were used in 1996 for off-line simulated approaches with a Fokker 100, which showed the major role of the wake (and not the vortices which originate from the facility). In 1998 the Test Run Facility was also studied numerically and the results were in agreement with the wind tunnel measurements (the streamlines showing the two vortices are shown in Figure 1; they have been produced using the RANS solver 'dolfyn').

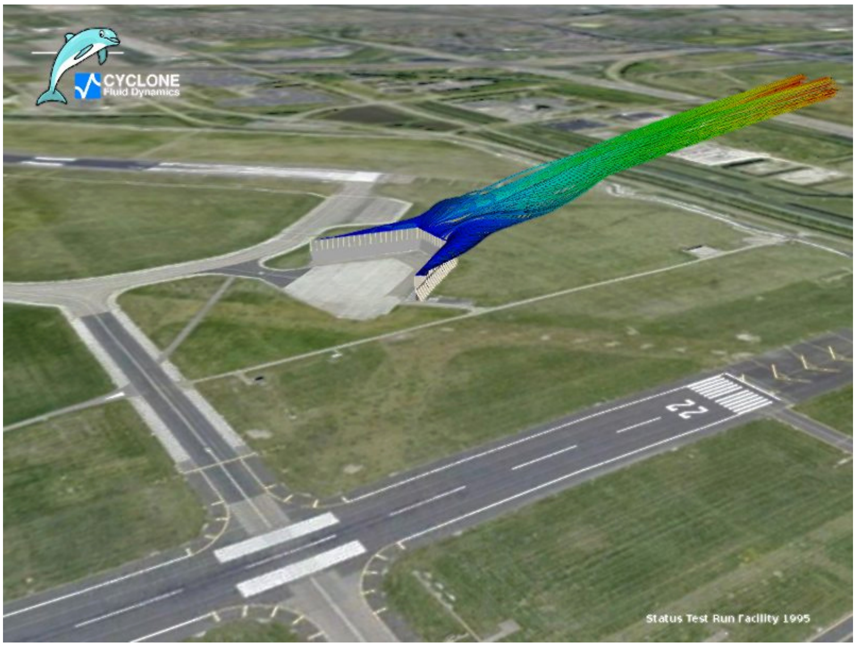

Figure 1: Vortices behind a Test Run Facility with 16 m high walls in 1995

Together with the original pilot reports and recorded wind data of the day with the three go-arounds, these studies formed the basis of the original 'seven knots criterion'.

Originally it ran "From the very limited amount of flight reports which could be related to the Test Run Facility, it was concluded that problems occurred at wind speeds above 22 kts. (...) This resulted in a critical wind speed of 20 knots (for wind 210). (...) Given these (absolute) wind speeds and the wind tunnel data it is seen that pilots start experiencing problems as soon as the maximum velocity defect in the wake exceeds 8.8 and 7.5 kts, which led to the (conservative) '7-kts criterion'."[1] Shortly thereafter it was adjusted to a stricter limit of 7 kts crosswind change and a crosswind component of 25 kts.

Another case of suspected low-level wind effects by buildings occurred in Hong Kong International Airport on 23 August 2008. On that day, Typhoon Nuri brought gale force north-northwesterly winds to Hong Kong [5].

The unobstructed anemometer at the western end of the north runway recorded a wind speed of about 36.9 kt (19 m/s), whereas the corresponding anemometer at

[1] J. Gooden, NLR, 1998.

Figure 2: Isolated hangars nearby a touchdown zone

the western end of the south runway had a wind speed of about 23.3 kt (12 m/s). The crosswind at the unobstructed north runway was rather high so that the pilot decided to land at the south runway. However, two aircraft reported a hard landing at the south runway. According to the pilot report from one of the aircraft, the plane appeared to 'drop out of the sky' before landing, and experienced flipping to the right shortly after landing and passing out of the hangars to the left. It was believed that the hangars might have caused turbulent airflow over the touchdown zone at the western end of the south runway. In Figure 2 the touchdown zone and the hangars are visible. Today, pilots are warned when landing in northwesterly/northerly winds with a background speed of about 15 knots or more, of the possibility of building-induced turbulence and windshear effects over the touchdown zone.

Other examples of similar landings were reported from London Gatwick with a A300 [6], a B737 in Canberra [7], a B747 in Manchester 2008 [8], and an A300 in 2011 on East Midlands Airport [9]. The case with an unexpected gust was the go-around of an A320 in Hamburg, 2008 [10] (the gust was not very surprising due to the topography of the airport and the prevailing wind). Finally, in the end of 2008, a sudden gust in Denver resulted in an runway excursion of a B737 whilst taking off [11].

2 Measuring wind near a runway

The theory of (neutral) atmospheric boundary layers, and especially the logarithmic profile near the surface, forms the basis of the theories presented here. There is a relationship between the mechanical turbulence and the fluctuating wind velocity σ_u as a result of friction by the type of surface, farmland, objects, and built environment. From a certain threshold onwards, mechanical turbulence scales linearly with the wind velocity and depends on the surface friction, or environment, only. In other words, it depends on the history of the wind over the last kilometres, hence it can differ at any given point for each wind direction. Bad weather with storm fronts, showers, or hail, can amplify the fluctuations. This is not considered here.

The environment influences anemometer readings and gust factors, and this was recognised and quantified more than 40 years ago (see e.g. [12, 13]), followed by the first anemometer exposure corrections based on peak gusts by Wieringa [14, 15], and noting that the 1973 WMO guidelines on anemometer obstructions are rightfully 'recommended' only. In any case measurements have to be reduced to WMO standards (unobstructed at 10 m height, and using a $z_0 = 3$ cm).

Later Beljaars concentrated on the measurement chain and the measurement of gustiness with an alternative model (which can also be used to characterize the exposure error of wind stations [16, 17]), followed by Verkaik and others [18, 19]. The results below are based on their work. The increase of computing and storage resources made the Beljaars approach possible today, however the Wieringa model is still useful in cases where detailed anemometer recordings are not available.

The gustiness of the wind is a measure of the turbulence intensity which is in turn related to the roughness history of the boundary layer over the upstream terrain. The velocity profile of a neutral boundary layer without displacement is a function of the friction velocity u_τ and the aerodynamic roughness coefficient z_0,

$$U(z) = \frac{u_\tau}{\kappa} \ln\left(\frac{z}{z_0}\right) \quad , \tag{1}$$

with κ as von Kármán's constant (approximately 0.40∼0.42).

In the lowest 10% of the atmospheric boundary layer the shear stress τ is considered to be (almost) constant, and equal to the shear stress τ_0 at the ground (it has to be). The friction velocity is defined as $u_\tau = \sqrt{\tau_0/\rho}$ using the density ρ.

The wind spectrum, the fluctuations, and gusts, are related to each other. The fluctuations are, especially in a neutral atmosphere, Gaussian and the integration of Kaimal's spectrum results for the standard deviation of the fluctuations in the direction of the wind [18, 19]:

$$\sigma_u = \left[\frac{105}{33} \cdot \frac{3}{2}\right]^{1/2} \cdot u_\tau = 2.185\, u_\tau = f_{\sigma_u}\, u_\tau \tag{2}$$

with $f_{\sigma_u} = 2.185$ (close to Panofsky's value [20]).

Using equation 1 and equation 2 the turbulence intensity can be defined to be

$$i(z) = \frac{\sigma_u}{U(z)} = \frac{f_{\sigma_u}\, \kappa}{\ln\left(\frac{z}{z_0}\right)} \quad , \tag{3}$$

and for an anemometer measuring at 10 m height this results in

$$i(10) = \frac{f_{\sigma_u}\, \kappa}{\ln\left(\frac{10}{z_0}\right)} \quad . \tag{4}$$

In other words, the measured turbulence intensity by an anemometer is only directly related to the upstream history of the approaching boundary layer, and will in general be direction dependent.

In Figure 3 the turbulence intensity footprints of two anemometers next to a runway are shown. The anemometer data (a record of wind speed and direction every second over 6 years) has been filtered and processed.

In total about 400 million pairs were processed.

The final step consisted of collecting only the data sets with an average wind speed larger than 6 m/s. These sets of wind direction, wind speed, and the corresponding standard deviation were distributed over 36 wind directions.

The end result of the before mentioned process is a distribution of turbulence intensity as a function of wind direction, as it has been measured by the anemometers (albeit without taking the anemometer characteristics into account). Consequently also the aerodynamic roughness length z_0, and the exposure correction F [21] are also known at this stage (in this case there are no seasonal influences). Here only the turbulence intensity is relevant.

The three curves, spanning 2 years each, coincide to a large extent for both anemometers, indicating a good reproducibility, and is proof that the turbulence is predominantly mechanical. The lowest turbulence intensity values are present in the direction of the runway (and the corresponding z_0 values are $2 \sim 3$ cm, the value for

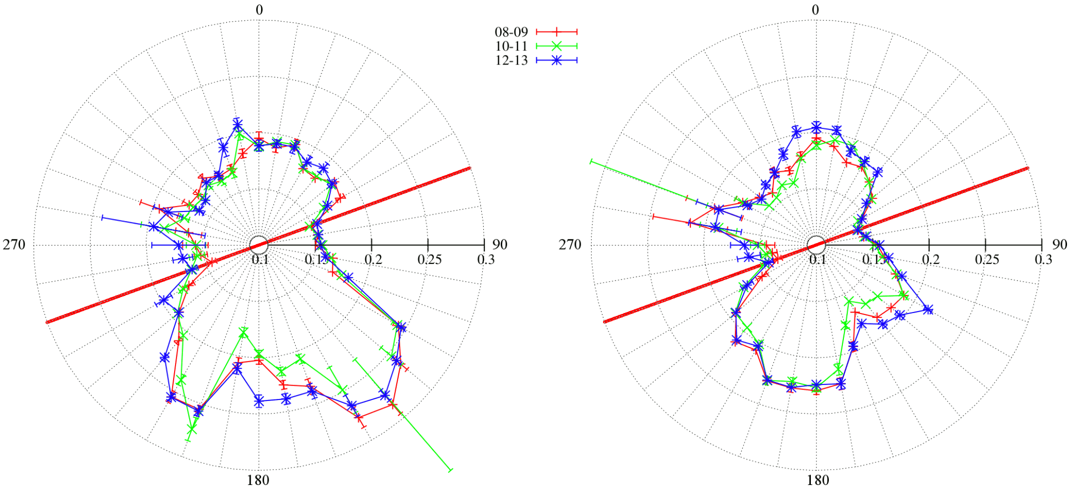

Figure 3: Two anemometer footprints along a runway

grass along runways). Parts of the environment show turbulence intensity values of around 20%, which corresponds to a z_0 of approximately 12 cm. The largest difference between the two footprints is for south-eastern winds; the top anemometer shows values of around 27% ($z_0 \approx 30$ cm) in that direction, whereas the lower right anemometer shows a considerably lower value of 18%. Now assume a measured 25 kt crosswind from the south-east, then for the left anemometer the standard deviation σ_u would be about 6.8 kt, whereas σ_u of the right anemometer would be about 4.5 kt. The corresponding maximum 3σ gusts are 20.4 kt, respectively 13.5 kt. Note that due to the turbulence, the measured wind velocity will differ for both anemometers (about 2.8 kt).

This example shows the difficulties involved with a 'representative' wind measurement of a runway. The built environment in the immediate vicinity of the runway, or anemometer, alters the wind measurement (despite generously meeting the WMO obstruction rules). On the other hand, anemometer footprints can give an insight into the slowly changing developments around the runways (on and around the airport); the changes for the south-eastern winds in the right anemometer of Figure 3 can be attributed to a newly built terminal building. Other examples of anemometer footprints can be found in [22].

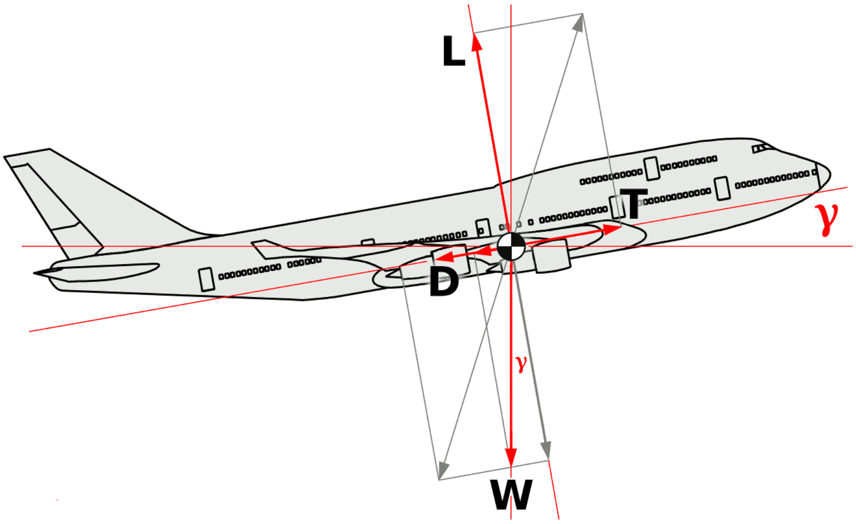

Figure 4: Balanced forces in climb

3 Forces on aircraft and crosswind approaches

An aircraft has six degrees of freedom; three translational, along the three principal axes (front – back, left – right, and up – down), and three rotational, about these axes (pitch, roll, and yaw, controlled respectively by the elevators, ailerons, and the rudder). The origin of the axes is defined on the aircraft's centre of gravity (c.g.).

The motion of the aircraft, or of its centre of gravity, is described by using Newton's laws of motion. There are four forces acting on the aircraft; the lift (L), drag (D), thrust (T), and weight (W). When all the forces are balanced, then the aircraft does not accelerate or rotate (see Figure 4). When landing, on a glidepath with $\gamma = -3°$, the lift is – due to the small angle – almost equal to the weight. At the end of the glide path the elevator is pulled, the angle of attack increases, and therefore the lift increases and the aircraft enters a curved path (the flare) towards a smooth touchdown.

In a quiescent air or in case with headwind only, and a steady and balanced straight flight, there are no side forces. Consider a landing aircraft and a drop in headwind, or a tailwind gust (with equal strength across the span). In effect this lowers the velocity over the wing and correspondingly the lift lowers as well. Hence the aircraft will drop and its attitude (pitch) will change (without rolling or yawing). After a short while a new equilibrium is found. When this happens just before touchdown the result will be a firm landing.

Two common non-straight flight manoeuvres are the flare and the level turn. Aircraft are turned by banking. Movement of the ailerons causes the aircraft to roll and then turn, where the rate of turn depends on the airspeed and the bank angle. As the aircraft banks during a controlled turn, the lift vector can be considered to rotate about the roll axis, reducing the vertical lift component. To execute a level turn, elevator input is increased slightly on entry to the turn and reduced on exit from the turn to minimize any change of altitude in a turning manoeuvre. This is a normal, clean and intended manoeuvre.

Now consider a straight level flight in quiescent air with a sudden kick against the rudder pedals that soon return back to the centred position. The rudder deflects and as a result the aircraft will yaw, and whilst doing so the side of the wing which sweeps forward will have a higher lift than the wing side which sweeps backward. Hence the aircraft will roll, and this movement is damped by the wing dihedral. The yawing motion is damped by the tail fin and the sweepback (in crosswind conditions the tail fin is responsible for weathervaning the aircraft into the wind). The wing then yaws backward and the aircraft rolls back. The combination of rolling, slipping, and yawing oscillations is less damped than the pure motions will be. These motions can be invoked by a sudden rudder or aileron disturbance, but can also be the result of a sudden drop of crosswind (deficit, wake), or a gain of crosswind (gust).

Any amount of cross- or sidewind introduces a (drag) force d which literally blows the aircraft off course. This force has to be counteracted in order for the aircraft to remain on track for touchdown and the runway.

The side force d can be compensated by tilting, thus lowering the upwind wing into the crosswind as in Figure 5. The aircraft is rolled and to prevent the fuselage weathervaning into the wind vector opposite rudder is needed.

Obviously, the maximum bank angle during touchdown is limited. It depends on aircraft configuration (with some indicative examples in Figure 10), undercarriage and shock absorbers, wing inertia (wing bending during touchdown), rudder limits (maximum deflection) and finally some safety margin. As the vertical stabilizer is of importance to this approach, it is easy to estimate the maximum amount of crosswind which can be managed. The maximum amount of crosswind that can be handled with this approach is determined for example by the unseparated airflow around the vertical stabilizer, the maximum defection of the rudder, and engine intake stall.

Another method to compensate for the side force d relies on the engines (see Figure 6). A heading towards the wind is established with the wings level so that the

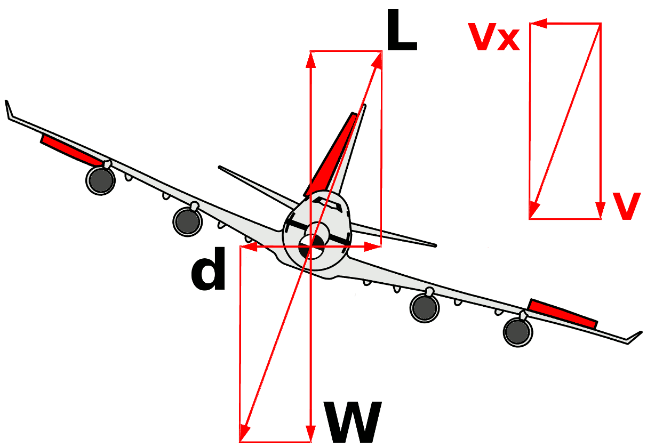

Figure 5: Forces in a wing down approach

airplane's ground track remains aligned with the centreline of the runway. The crab angle is maintained until just prior to the flare and touchdown as most undercarriages cannot withstand the extra stresses involved with crabbed landings. In strong crosswind conditions, it is sometimes necessary to combine the crab technique with the sideslip technique.

Both methods rely on the presence of the side force d. But when a wake is encountered this force suddenly disappears. Then the tilted lift and yawed thrust forces result in a turn and an additional roll into the wind and lowering the upwind wing. Next when a wake has been passed the crosswind conditions are re-established and the motions are reversed. When this happens just before or during touchdown, it will surely raise the cockpit workload. The combination of the extra yawing and rolling motions is more disorientating than the case with a headwind change. Of course, in the case of a crosswind gain, or gust, the motions are opposite.

When landing with an oblique crosswind, both the crosswind and headwind components can vary due to turbulence. If a gust, or a deficit, is in the direction of the wind then the resultant components are easily decomposed. The disturbances are then a combination of both the symmetric and asymmetric responses. Expect to observe pitching, rolling, yawing, dropping and slipping, et cetera in these circumstances.

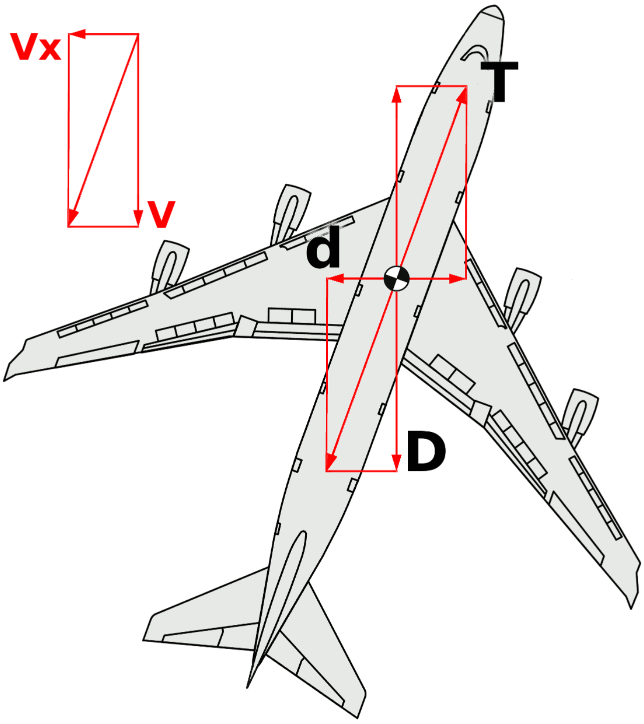

Figure 6: Forces in a crabbed approach

4 Maximum Demonstrated Crosswind landing

According to the US FAR 25 and the European CS 25 regulations, airliners have to comply with the following: "For landplanes and amphibians, a 90-degree cross component of wind velocity, demonstrated to be safe for takeoff and landing, must be established for dry runways and must be at least 20 knots or 0.2 times the staling speed during landing (VS0), whichever is greater, except that it need not exceed 25 knots." [23]

None of the major aircraft manufactures consider the Maximum Demonstrated Crosswind landing to be limiting. It is demonstrated using the maximum wind which occurred during trials and tests. Airlines are free to pose their own crosswind limits, and some of them do.

Flight tests of airliners are normally carried on specialised, not too busy, airports. In the USA, NASA's Neil A. Armstrong Flight Research Center[2] facilities, located at Edwards Air Force Base are used (Figure 11). In Europe, the airport of Keflavik in Iceland is a popular resort for test flights (Figure 12). What both sites have in common is a very empty environment; the salt plains of Rogers Lake in the Mojave desert, and the open seas and treeless environment of Keflavik.

Assume in these conditions a very low aerodynamic roughness coefficient of $z_0 =$ 2 mm for the Armstrong Flight Research Center. Using equation 4 this will result in a turbulence intensity of only 10% (which will be representative along all the salt lake runways). Using a measured crosswind of 25 kt again, the standard deviation will only be 2.5 kt and the maximum gust of $2\sigma = 5$ kt (95% of the gusts) to $3\sigma = 7.5$ kt (99.7% of the gusts) will still be lower than the gust reporting threshold.

It will be no surprise that every aircraft type has its own Maximum Demonstrated Crosswind guidelines. In Table 1 an overview is given of some published demonstrated crosswind take-offs and landings. The values provided at the top of the list differ from the rest as they show the average wind and the gust level during the flight tests. The other values have to be considered either as the average or as a maximum crosswind including a small amount of gusts.

As an example one can analyse both the Airbus A380 values (the highest values, including gusts, in the overview). The crosswind flight test program was carried out at Keflavik. If the reported gust values are assumed to be twice the standard deviation, then the turbulent intensity during the tests was only about 15 to 17%, which

[2] Formerly known as Dryden Flight Research Center.

Model	Takeoff	Landing	Remarks and source
A320	29 G38	33 G38	A320 FCTM
A330	32 G40	32 G40	A330 FCTM
A340	27 G35	27 G37	A340 FCTM
A380	39 G51	42 G56	at Keflavik [24]
F50	33	33	dry
F100	30	30	estimated
MD80	28	30	dry
MD90	30	30	dry, estimated
MD11	35	35	[25]
B733/../5	40	40	737 FCTM
B736/../9	34	40	without winglets 737-NG FCTM
B736/../9	36	40	with winglets 737-NG FCTM
B736/../9	25	40	wet runway 737-NG FTCM
B757/B767	40	40	dry runway 757/767 FCTM
B757/B767	25	40	wet runway 757/767 FCTM
B744	40	36	dry runway 747-400 FCTM
B744	25	32	wet runway 747-400 FCTM
B777	22 - 40	45	dry (dep. weight & cg) 777 FCTM
B777	20 - 40	40	wet (dep. weight & cg) 777 FCTM
B787	20 - 40	TBD	dry (dep. weight & cg) 787 FCTM

Table 1: Overview of demonstrated crosswinds in knots of various airliners (mainly based on Flight Crew Training Manuals)

is a value that suits the open featureless landscape around the airport. Nevertheless, Airbus recommends a lower limit.

Other features in Table 1 are: the values of dry runways (higher friction) are of course higher than wet runways (or even worse conditions, like contaminated or slippery runways). The values for take-off are less or equal to the demonstrated landing crosswinds (taking into account an engine failure). The Boeing 737 has a higher demonstrated crosswind for landing on dry runways than the larger Boeing 747. Finally, a maximum value for a dry runway could be 36 kts (B747), 38 kts (A320), or 40 kts (B737); with 38 kts as a kind of ‘average’.

5 Extended seven knots criterion

The initial formulation which restricted the crosswind changes to seven knots was motivated by the wind tunnel measurements in 1996. Later NLR carried out an offline and piloted simulator study on the original criterion.

Simulators or engineering models and simulations, however, are not a suitable tool to explore the flare and ground part of a landing or take off. Deficiencies in mathematical ground effect models, undercarriage and runway models, and atmospheric boundary layer model in combination with the motion and visual cues of a simulator result in insufficient confidence in the evaluation of the results. Therefore limits based on pilot evaluations in a simulator may prove significantly different (optimistic in most cases) from realistic values [26, 11, 27].

In simulator tests carried out by the US National Transportation Safety Board (NTSB) two pilots were able to 'take off' in a 737 with a staggering 60 kt crosswind, stating they required more rudder correction but felt they had more than enough rudder authority available to accomplish the manoeuvre [11]. Assume a take-off speed of 160 kt and a 60 kt crosswind component this results in an angle of attack for the vertical stabilizer of 20 degrees. In order to reach 160 kt, the aircraft has to pass the lower speeds, for example at 120 kt the angle of attack would have been 26.5 degrees.

In the original definition of the criterion nothing has been specified about the size, shape, or gradients of crosswind changes (nor runway conditions, as they were irrelevant). When a deficit is built up over a long distance (i.e. with a low gradient) then an aircraft can accommodate to the changing conditions. In such cases the criterion does not apply. Wakes, or deficits, can be accompanied by crosswind surpluses as well. Instead of limiting the crosswind deficit, it might be more appropriate to limit the crosswind change.

From the beginning, the criterion applied to the approach and the complete runway (plane along the runway centreline, below 200 ft). In contrast to the NLR study which focussed on the approach and touchdown only [28]. However, the restrictions of this study are due to the simulator and it does not automatically imply that the criterion should be limited to this flight (and landing) phase only. For example in case of a go-around (airborne or almost touched down) it takes a while before the engines have spun up to full power (this effect has not been taken into account in the study). Other examples are long landings, extended flares, and the take off phase (the critical transitional phase when the aerodynamic forces of ailerons and rudders are not sufficiently efficient for directional control, and the runway friction is reduced due to the increasing lift of the wings).

The NLR offline and piloted simulator study used a 20 kt crosswind. In the 2006 report the variation in mean wind speed due to wind disturbing structures must remain below 7 knots along the aircraft trajectory at heights below 200 ft. In 2010 it was refined by including a distance criterion, stating that the speed deficit change of 7 knots must take place over a distance of at least 100 m [28]. Furthermore across the aircraft track the speed deficit due to a wind disturbing structure must remain below 6 knots over at least the same distance (restricting to 7 knots with a 25 kt crosswind is 7% more strict). Hence, the study confirms the original criterion.

Using a width criterion for a deficit (wake), or surplus (gust), introduces a new problem: how to define the width? Especially in typical complex crosswind conditions, in contrast to a single isolated object, this can be a very difficult task. At the start, and at the end, of a major wake the deficit increases, and decreases, rapidly respectively. The minimum and maximum peaks of the gradients clearly define the main part of a wake or gust (see the examples below).

The numerical simulations of the original 16 m high Test Run Facility can be used as an initial guess. Despite the fact that the wake crossed the glidepath at an altitude of over 200 ft, the go-arounds indicate that that the disturbance was significant. The corresponding crosswind gradients of ± 5 kt/30m are therefore a lower limit (see Figure 7). The numerical simulation of the northerly winds around the hangars in Hong Kong in 2008 showed that the gradients should be lower than ± 3 kt/30m. Currently a limit of 2.5 kt/30m is used. The NLR studies indicate that headwind changes should be treated in the same way as crosswind changes. The extended crosswind criteria limit the headwind changes, with a crosswind component of 25 kt, to 7 knots. The corresponding gradients are limited to 2 kt/30m (slightly more restrictive than the crosswind criteria). The criteria are based on the decomposition of the velocity components. As oblique winds can be more disorientating, it may be worthwhile to restrict in the future the changes in the direction of the wind to seven knots (and limiting its gradient).

The current procedure, based on an experience of over 60 projects on various airports, is to verify that the maximum crosswind change remains below seven knots, and if exceeded, the maximum rate of change should be less than 2.5 kt/30m. It must also be verified that the maximum headwind change remains below seven knots, and if exceeded the maximum rate of change should be less than 2.0 kt/30m. The evaluation is carried out with a crosswind component of 25 knots.

See Figure 8 for an example of an oblique crosswind evaluation. Of course, in a

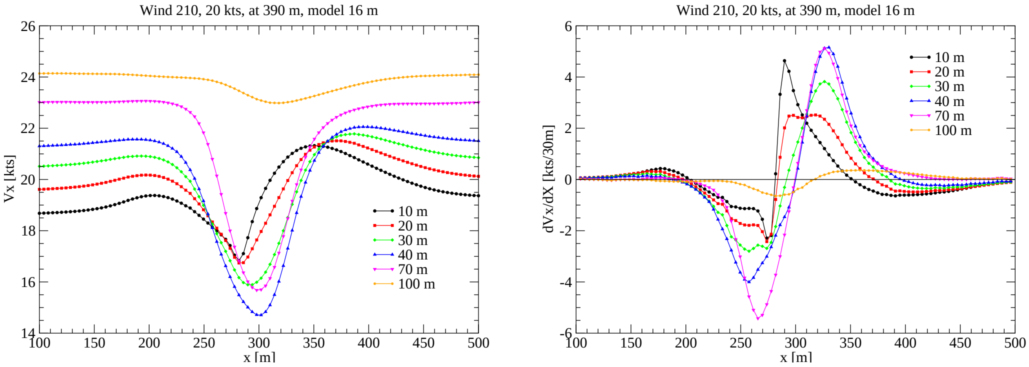

Figure 7: Crosswind changes and gradients of the 1995' Test Run Facility

pure crosswind case the headwind changes, and the corresponding gradients, are insignificant. On the other hand, the built environment normally does not have an impact on winds parallel to the runway. Therefore, the infringement of the headwind criteria is rare.

The criterion is generic and applies to all aircraft, in any condition or configuration.

6 Influence of the built environment

The airport infrastructure can be considered as additional 'roughness elements', and when they are close to the runway, the influence of these individual 'roughness elements' (hangars, terminals) are perceivable at the runway centreline. The further away an object is, the more it will blend into the (almost) homogeneous background turbulence.

The scale of the wakes and turbulence introduced by the built environment is much smaller, and localised, than the effects of, for example, a microburst; a downburst that covers an area less than 4 km along a side with peak winds that last 2–5 minutes (as such a phenomenon only recognised recently). A microburst has spatial dimensions of multiple span lengths, whereas wakes and gusts are in the order of span lengths. Wakes and gusts which are considerably smaller than the wing span, will have almost no impact. Because of the limited size of wakes, on-board radars and other meteorological equipment are generally not able to detect them well.

It will be clear that a light mast, or an advertising column, will only produce a

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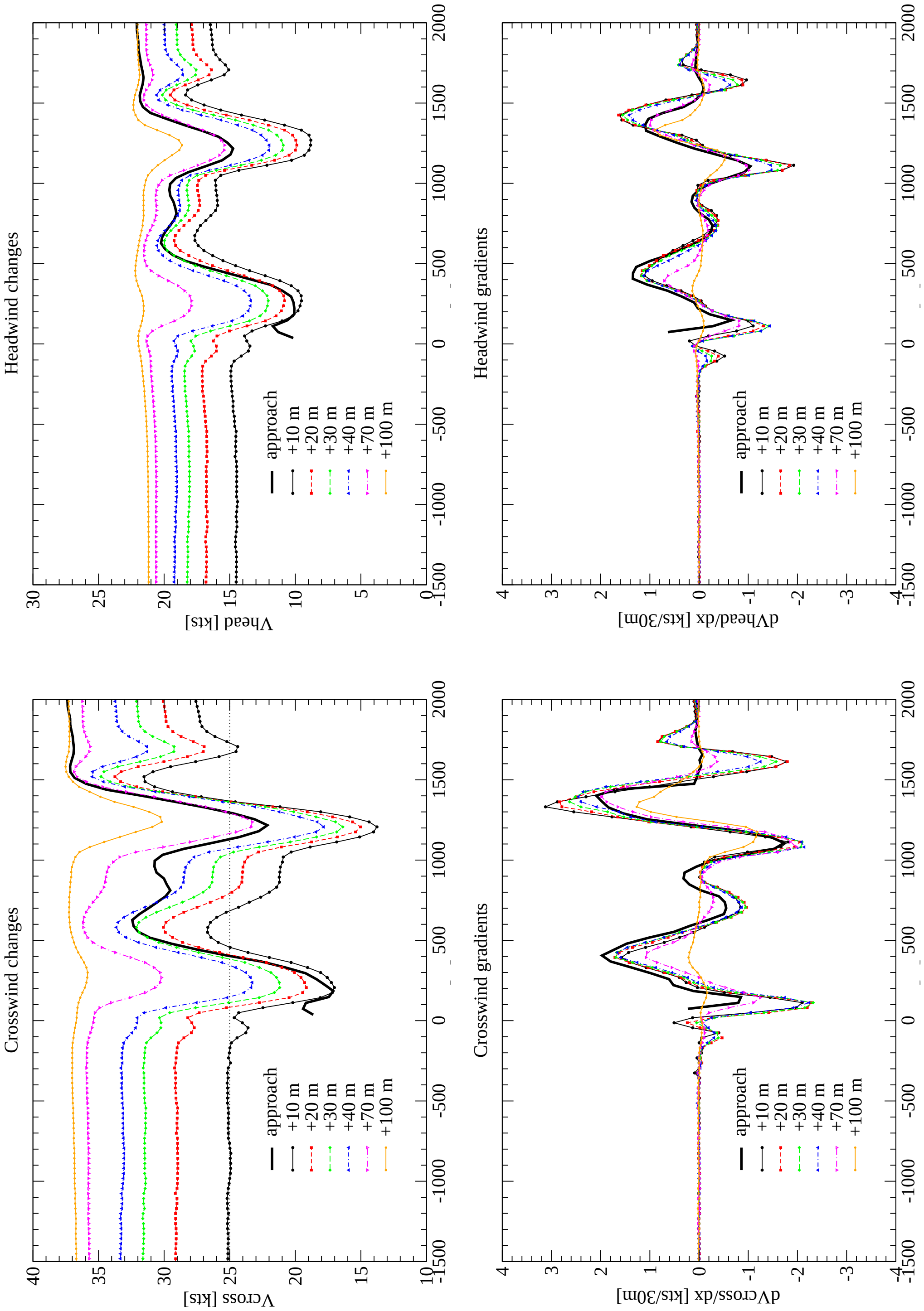

Figure 8: Cross- and headwind changes and gradients behind an object

small wake and they will not impact the crosswind conditions along the runway centreline. In general isolated objects or buildings not wider than 30 m will not cause problems. A corresponding height criterion is defined by a 1:35 plane, starting from the (extended) runway centreline; when a normal building does not protrude through this plane it will probably have no influence on the operations. Note that high sharp and isolated walls can produce abnormal wakes and vortices. General recommendations are difficult to formulate, but when a building protrudes through a 1:20 plane it will influence the crosswind conditions.

If one assumes that the maximum demonstrated crosswind U_{dem} is a limit including gusts (and not a guideline) then

$$U_{\text{x}} + \Delta U \leq U_{\text{dem}} \tag{5}$$

where the average crosswind is U_{x} and all fluctuations are summed together in ΔU.

When long term anemometer data is available, the anemometer footprints will produce the turbulence intensity i for each wind direction. Assume for simplicity that the wind components can be directly derived by decomposing the fluctuating wind velocity. Furthermore, suppose that these fluctuations can be assumed to be homogeneous (at least along parts of the runway, for example the touchdown zone). Then, as wakes scale with the wind velocity, the departures from the homogeneous background turbulence can be covered by an constant factor C:

$$U_{\text{x}} + f_s\, i\, U_{\text{x}} + C\, U_{\text{x}} \leq U_{\text{dem}} \quad , \tag{6}$$

or

$$U_{\text{x}} \leq \frac{U_{\text{dem}}}{1 + f_s\, i + C} \quad , \tag{7}$$

in which the average crosswind is a function of the turbulence intensity i, multiplied by a factor f_s (with the option to add an additional attenuator or amplifier for weather related phenomena), and a constant C. Of course, the maximum fluctuation can be limited as well:

$$U_{\text{x}}\, (f_s\, i + C) \leq \Delta U_{\text{x}_{\text{max}}} . \tag{8}$$

The conditions of the Test Run Facility can be recovered by setting the factor $f_s = 2$ and the constant C to 7/25. The result is shown in Figure 9 (including the optional limit set by Equation 8).

Flight tests are regularly carried out at featureless sites. In these cases the turbulence intensity is low (eg. less than 17%), and the constant C can be set to zero (the factor f_s remains 2). Examples, without gusts, are shown as dashed lines in Figure 9.

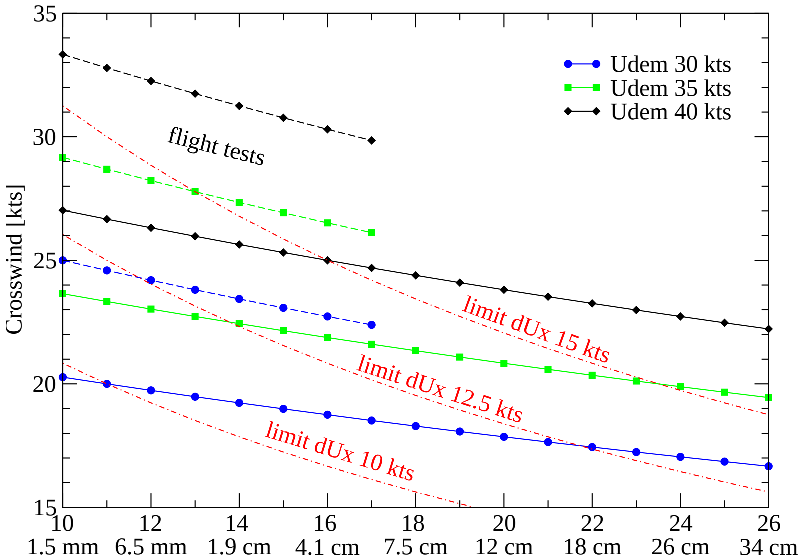

Figure 9: Maximum runway crosswind limits as a function of the environment

Consider a hypothetical airport located on reclaimed land, with open waters on one side ($i = 10\%$, $C = 0$), and the terminals and rural developments on the other side ($i = 22\%$, $C = 7/25$). Then for an airliner, with $U_{\text{dem}} = 35$ kts, the crosswind limit for wind over water is 29.2 kts, and with wind approaching over the built environment equals 20.3 kts (both gusting to 35 kt, with the latter approaching a gust of 15 kt).

7 Conclusions

The influence of the built environment on crosswind landings is obvious. The infrastructure close to an approach and runway (terminals, hangars et cetera) of large/international airports will alter the background turbulence of the incoming (cross)winds, and alter the anemometer readings as well (and in general how representative these measurements are).

The original 'seven knot criterion' was derived from an isolated wake at some altitude (higher than 200 ft, well before the flare).

A strict enforcement of the 'seven knots criterion' would result in a very restricted, and unrealistic, airport operation. The 'extended crosswind criteria' limits the headwind changes as well and takes into account the gradients. The current procedure is to verify that the maximum crosswind change remains below seven knots. If exceeded, the maximum rate of change should be less than 2.5 kt/30m. Due to the possibility of oblique winds, the maximum headwind change is checked to ensure it remains below seven knots. If exceeded the maximum rate of change should be less than 2.0 kt/30m. The evaluation is carried out with a crosswind component of 25 knots. It is therefore a relative criterion and originally geared towards airliners, however as it is scalable it can be used for lighter aircraft as well.

Limiting the average crosswind changes to seven knots can be derived from the anemometers and a given maximum demonstrated crosswind. This value is therefore independent of any turbulence modelling, or any other modelling.

The Airbus A320 Flight Crew Training Manual states “With a good reported braking action, the maximum demonstrated crosswind at landing is 33 knot, with gusts 40 to 38 knot” apart from the very low margin of five knots for the turbulence, these values leave de facto no room for additional building induced turbulence. As most of the crosswinds incidents occur during the flare and/or actual touchdown; the touchdown zone especially should be free from major disturbances.

The ‘anemometer oriented view’ of the ‘seven knot criterion’ is that it limits the local departures from the homogeneous background turbulence levels. If there was only a homogeneous background turbulence along approach and runway (e.g. an empty desert), then an anemometer could be put everywhere along a 2 to 4 km long runway and still measure ‘representative’ values. The criterion limits the (allowable) inhomogeneity.

The ‘aircraft oriented view’ of the criteria specifies that given the maximum demonstrated crosswind (incl. gusts) landing guidelines of some popular airliners in the order of 38 to 40 kt, and a steady crosswind component of 25 kt, then a crosswind gust is limited to approximately 14 kt. About half of the crosswind gust originates from the homogeneous background turbulence (rural environment), and what remains is produced by the very local individual nearby building induced wakes and gusts. Hence, the original definition of the criterion cannot be considered as too conservative.

The crosswind take-off guidelines are equally strict, if not more stringent, than the crosswind landing guidelines and therefore the criteria are applicable to the approach, touchdown zone, high speed roll-out and a plane defined by the centreline of the runway.

The criterion which limits the additional crosswind change cannot be considerably lower than seven as this would impose impracticable restrictions on the crosswind conditions along the approach and runway. Nor can it be any higher without exceeding the crosswind guidelines of several popular airliners.

Weather related gusts – gusts which can be considerably stronger than the mechanically, or friction, generated gusts – can lead to further operational restrictions. Of course, flight tests are normally not carried out when severe weather fronts pass the airfield.

The previous conclusions are valid for runways with ‘good’ reported braking action (best friction coefficient and normal directional control [3]). Only in these conditions the maximum demonstrated crosswind guidelines hold. The combination of a contaminated runway and a strong crosswind increases the risk of a veeroff by a factor of up to 9 [27]. As both the turbulent fluctuations and the building induced effects scale linearly with the crosswind it is possible to cater for contaminated runways as well.

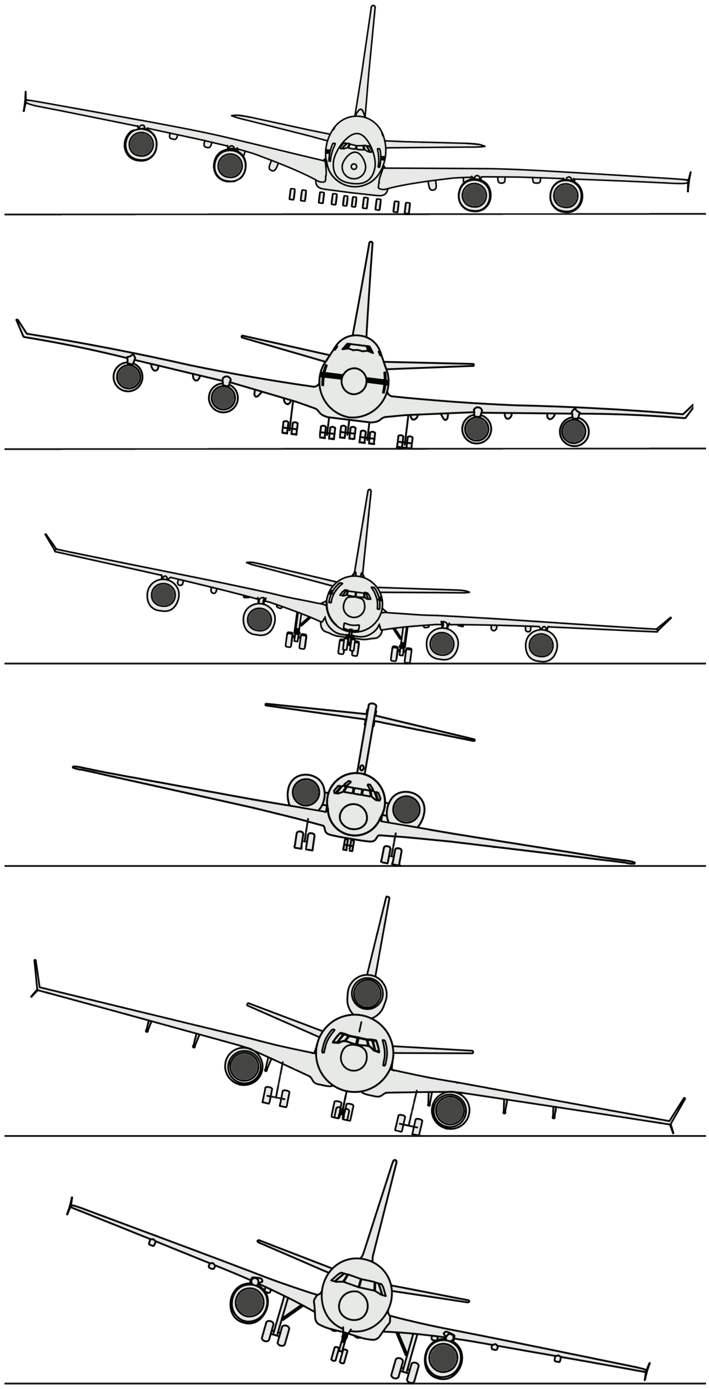

Figure 10: Influence of configuration on maximum bank angle

Figure 11: Unobstructed runways at Rogers Dry Lake near Armstrong Flight Research Center (Source: Wikipedia, Public Domain)

Figure 12: Unobstructed runways at Keflavik Airport (Wikipedia, Author SuperJet International)

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R. Radespiel et al. (eds.), *Advances in Simulation of Wing and Nacelle Stall*,
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Springer Verlag, 2016, pp. 167-187, DOI: 10.1007/978-3-319-21127-5_10