Journal of Aircraft
Vol. 43, No. 3, May–June 2006

Aerodynamic Development of a Ground Run-Up Enclosure for Propeller Transport Aircraft

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The development of a four-sided ground run-up enclosure is described for the Lockheed Martin C-130 Hercules and Fokker 50 as operated by the Royal Netherlands Airforce. The primary goal of the facility is to obtain up to 14 dB(A) noise insertion loss, requiring high sound barrier walls all around the aircraft. Besides, the aircraft operator required the facility to be operational 97% of the time. For Eindhoven airport—the intended building location—this means that the facility must be functional at outside wind speeds up to 21 kn, independent of wind direction. Under these wind conditions the engine torque fluctuations for the C-130 should stay below 2% with maximum takeoff power set on all four engines simultaneously. The paper highlights the aerodynamic design considerations behind the facility and the development and validation in two wind tunnels, the DNW-LST and the DNW-LLF. It is shown that the required overall operational availability has been obtained, despite a small overrun of the torque fluctuation limit for crosswind directions. The design employs a single aircraft line-up direction. Although the facility has been designed in particular for the C-130 aircraft, it could be adapted to fit aircraft like the Boeing 737.

Nomenclature

A_P	=	propeller disk area (equals 13.3 m^2 for the C-130), m^2
C_T	=	propeller thrust coefficient, $= T/\{\rho_0(nD)^2D^2\}$
D	=	propeller diameter, m
n	=	propeller rotational speed, rps
Q	=	propeller torque, Nm
T	=	propeller thrust, N
V_{crit}	=	critical wind speed at which 1.8% torque fluctuation occurs on one of the engines, m/s
V_{hr}	=	reference wind speed at $Z = 10$ m full scale, hourly average, m/s
V_i	=	local air velocity in ground run-up enclosure (GRE) intake stack, m/s
V_{in}	=	average air velocity in GRE intake stack, m/s
V_{ref}	=	propeller slipstream reference velocity, m/s
$V_{10'}$	=	10 minute average wind speed, m/s
Z	=	height above ground, m
β	=	wind direction relative to compass North, deg
β_m	=	wind direction in model axis frame, deg
ρ_0	=	reference air density, kg/m^3
[ ]	=	full-scale dimension

I. Introduction

TO comply with environmental legislation, the ground-bound acoustic noise produced by aircraft run-up tests at Eindhoven Airbase has to be reduced. For this purpose the Royal Netherlands Air Force intends to build a ground run-up enclosure (GRE). This GRE will be used for ground tests of the transport aircraft C-130H30 Hercules and the Fokker 50 and 60. These are all propeller aircraft. A jet aircraft, the Grumman Gulfstream IV, which is also operated by Royal Netherlands Airforce (RNLAF), will occasionally use the facility as well. The program of requirements for the GRE states that torque fluctuations, notably for the C-130, have to stay below 2% (amplitude) with all engines running at maximum takeoff power simultaneously. This requirement must be satisfied for wind speeds up to 21 kn (10.8 m/s, that is, up to 5 Beaufort inclusive) regardless of wind direction. This means that the facility will be operationally available for 97.1% of the time, given the Eindhoven airport wind statistics.

For acoustic reasons the facility must be fully enclosed, as sound insertion losses up to 14 dB(A) have to be obtained. This requires the erection of high noise barriers around the aircraft. Also a single aircraft line-up direction is preferred in view of the infrastructure required otherwise. It is clear that both requirements posed strong restrictions on the aerodynamic design of the facility.

In the startup phase of the project, the RNLAF made a C-130 aircraft available to perform tests at various existing GRE-facilities, both three sided and four sided, to determine the acoustic and aerodynamic suitability of various facilities. During these tests, it appeared that none of these facilities offered sufficient performance to comply with the requirements. Often it was even difficult to find a spot inside the facility where the aircraft could be operated with all engines at maximum takeoff power (MTOP) without exceeding existing overtorque fluctuation limits. These tests also made clear that the 2% torque fluctuation requirement is a very strict one, as the C-130 in free field trials, performed also, shows torque fluctuations of up to 5% already at tail winds of only 8 to 10 kn. Therefore, it was decided to develop a new concept. The aerodynamic design effort was performed in close collaboration between the National Aerospace Laboratory/NLR and International Testing Facilities/ITF Services. Burns and McDonnell International (construction), Netherlands Organisation for Applied Scientific Research-Technical Physics Department (TNO-TPD) (acoustic design), and the RNLAF (civil engineering) were the other partners in this project.

Figure 1 shows the schematic initial concept. The main idea behind the design was that part of the aircraft was located inside a more or less closed channel, as shown in the figure. After some refinements had been made to this concept, it was decided to take up the initial development and conduct proof-of-concept testing in the small (2.25 × 3.0 m) German-Dutch Wind Tunnels-Low-Speed Wind Tunnel (DNW-LST). The main goal of this test was to show

Presented as Paper 2005-0698 at the AIAA 43rd Aerospace Sciences Meeting an Exhibit, Reno, 10–13 January 2005; received 15 March 2005; accepted for publication 26 June 2005.

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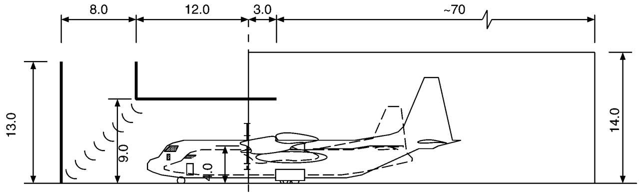


Fig. 1 Sketch initial ground run-up enclosure concept with Lockheed Martin C-130H30 and Fokker 50 aircraft.

that in principle the 2% torque fluctuation requirement could be met, as this was surely not clear initially. The scale of the model, 1:13.5, was dictated by the available 0.3-m-diam propellers compared to the full-scale 4-m ones. Because of the size of a model of this scale, only a half-model (port side) could be tested in the DNW-LST. Also the model was too large to be mounted on the turntable; therefore, only the tailwind condition was tested, being considered the most critical one. Torque fluctuations with varying wind velocity were measured using a rotating shaft balance mounted at the propeller hub.

The results of this preliminary test were encouraging although a long roof overhang—almost up to the aircraft's vertical tail plane—had to be used to obtain acceptable results. In a subsequent test in the same wind tunnel, a large number of changes were tested to further improve the performance of the design and to limit the final building costs by reducing the roof overhang. This resulted in the basis for the final concept as described in this paper. A separate test in the DNW-LST was performed to test a facility, sized not only to fit the C-130 but also aircraft with significantly larger propellers. As this design proved to offer less performance margin for the C-130, unless special measures and therefore costs were taken, it was not pursued further.

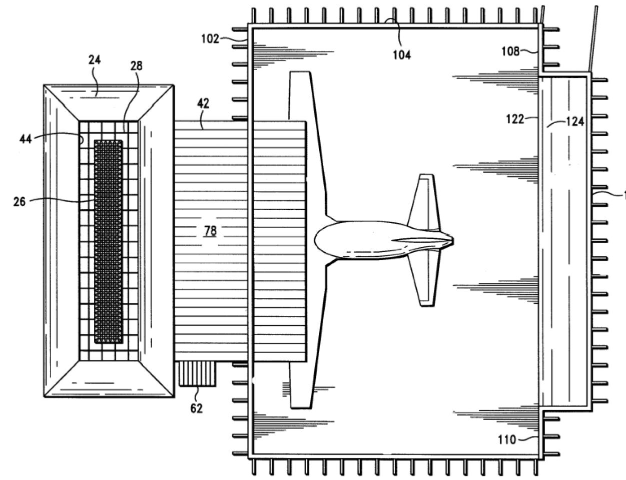
After testing in the DNW-LST brought forward a viable concept, it was taken to the large 9.5 × 9.5 m DNW Large Low Speed Facility (DNW-LLF) wind tunnel for a final validation. This larger wind tunnel allowed testing the full GRE model for all wind directions. The tailwind performance of this model turned out to be excellent, corresponding to the earlier DNW-LST results. However, further refinements were required to the intake stack in order to improve crosswind performance. This resulted in a GRE design complying with the operational requirements for which a patent has been applied for.[1]

The approach using two different wind tunnels resulted in a cost-effective development of this GRE facility. Model scale was kept equal. Therefore port-side engine mounting, including balance instrumentation, as well as some other model parts could be transferred directly from the DNW-LST to the DNW-LLF. The inexpensive DNW-LST proved to be the proper tool for concept testing and rough polishing up of the design, the larger DNW-LLF being used only for the final touches. This paper describes some of the design considerations and shows the final results obtained in the DNW-LLF for the largest aircraft, the C-130.

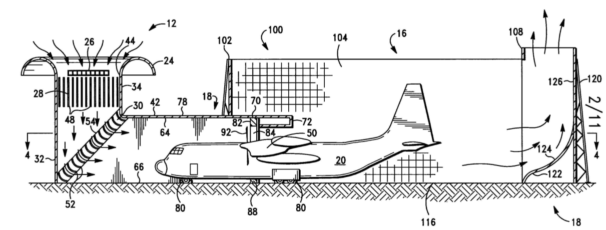
II. GRE Design Considerations

A sketch of the final GRE design layout is shown in Fig. 2. First a general description of the facility layout is given before going into somewhat more detailed design considerations. The aircraft is located partly inside an intake channel. The air is entering this intake channel through a vertical stack with a rounded lip on the intake and a flow rectifier. A screen (26) is centered in the intake opening. Corner vanes guide the flow into the horizontal part of the intake channel before it reaches the propellers. The flow around the propellers is stabilized by the "propring" (82, 84, 88) close to the propeller cross section. The propring consists of a sharp edge projecting from the walls of the intake channel. The flow is then exhausted to the back into the open pen area.

The acoustic requirements for the facility expect sound insertion losses of 14 and 10 dB(A) to be attained in aircraft nose and tail direction, respectively. This is a fairly stringent requirement, especially for a low-frequency noise source like a propeller aircraft. Therefore the pen area is bounded by four walls, 14 m in height. At the back end of the GRE, there is a door with integrated slipstream deflector, allowing entrance of the aircraft into the facility.



b) Top view



a) Side view

Fig. 2 Ground run-up enclosure: final design.

A single aircraft orientation is used, independent of wind direction, as this reduces the size of the facility and the amount of (expensive) concrete platform to be built.

How did the final shape evolve? Looking at the wind field inside a four-sided enclosure, some observations can generally be made: firstly, the inside wind velocities are lower than those outside the enclosure. Secondly, the spatial variation in velocity vectors is large and sensitive to the outside wind conditions, and, thirdly, there can be large time variations in the local wind velocity vector. These wind conditions do not necessarily promote successful test conditions for an aircraft being positioned inside high noise barrier walls. The first observation in principle is favorable as far as engine testing is concerned. The latter two are unfavorable. A variation in wind direction means that the propellers can experience a tailwind component resulting in test run instabilities. These instabilities are further aggravated by the time variations of the local velocity vectors that have a significant low-frequency contribution, determined to a large extend by the main dimensions of the building and the outside wind velocities. The corresponding timescales can be of the order of 1 s or more. Fluctuations at these timescales easily result in unstable engine readings.

Therefore positioning an aircraft inside four walls will not result in a satisfactory run-up performance for all wind directions, if any. The detrimental effects of walls can even be further enhanced by the flow generated by the aircraft propellers themselves inside the enclosure. In the start-up phase of the project, the actual C-130 aircraft was tested in various three- and four-sided run-up enclosures that proved the difficulty of obtaining stable running conditions. It was often difficult to find a spot inside the GRE were the aircraft could run within acceptable limits. Depending on the location, running the aircraft up to MTOP sometimes was impossible because of excessive torque fluctuations. These tests took place at wind conditions well below the required 21 kn.

A way to improve the unsteady torque performance is to uncouple the flow around the propellers as much as possible from the flow inside the pen area by introducing a channel inside which the propellers are located. In that case, the aircraft induces its own flow inside the intake channel, and effective aerodynamic measures can be taken to guide the flow as required. Therefore an intake stack was designed, located at the front end of the facility. A further advantage of such an intake channel is that the sound generated by the propellers can be attenuated close to the source.

The design of the intake channel must be such that large-scale flow separations with their accompanying pressure and flow fluctuations are avoided. These would lead to unstable run-up conditions. Also, the flow velocity over the height of the intake channel should be made as uniform as possible, to reduce load variations on the propeller blade during each revolution. To reduce building size and costs, it was decided to keep the cross section of the vertical intake stack equal to that of the horizontal channel. This resulted in a rather high-aspect-ratio, rectangular shape of the inlet stack. As this compromises the aerodynamic performance in terms of sensitivity to various wind directions, additional measures needed to be taken to ensure a stable intake flow at the propeller location. Therefore, the inlet stack has a rounded intake lip, a flow straightener in the inlet opening, a centered screen on top of the flow straightener, and turning vanes in the corner. In this way a good flow quality at the propellers was achieved at almost all wind directions. The rounded intake lip, the flow straightener, and the centered screen at the inlet limit the local flow separation for various wind directions. The corner vanes improve the uniformity of the flow in the intake channel.

Because the propellers are installed on the aircraft, the presence of the aircraft wing limits the extent of the intake channel. This means that uncoupling from the outside environment cannot be done as well as in case of uninstalled testing. Therefore additional measures are required to stabilize the propeller flow. For this purpose a possible description of the flow around a propeller in ground proximity is given.

A propeller sucks in air from all sides. The ground surface forms a barrier, however. On the ground a stagnation line is formed, separating air drawn in from the front and from behind. In case of tailwind (Fig. 3), the amount of air drawn in from behind increases. This results in an increased instability of this stagnation line because of the always existing interaction between the air drawn in from behind and the propeller slipstream. Moreover, the airflow originating from the unsteady stagnation line area passes through the outer edge of the propeller disk and therefore has a large effect on steady propeller operation.

Although this has not been investigated further, it is not unlikely that blade-tip vortex instabilities amplify the observed instabilities. This situation is somewhat comparable to the vortex ring state that can occur with helicopters in descending flight and that also leads to an unsteady flight behavior. The ratio of descent velocity to hover-induced velocity in that case can be compared to the ratio of tailwind velocity to slipstream velocity. Notwithstanding the fact that this ratio is somewhat larger ($\approx$0.5–1.5) in a typical vortex ring state condition than that for the observed propeller tailwind instability ($\approx$0.1), possibly the effects of vortex instability and deformation from the helical shape become visible already at these tailwind velocity ratios. This instability also affects the airflow drawn in from behind into the propeller disk.

The ground-stagnation-line instability is closely related to the observed torque instabilities in tailwind conditions. This coupling could be verified by means of tuft flow visualizations. The idea then was to reduce the torque instabilities by an artificial stabilization of this ground stagnation line. Various ways of stabilization were tried, but the most effective one proved to be a raised edge, normal to the walls of the intake channel, in the vicinity of the propellers. This feature of the present design is termed the "propring" (item 82 in Fig. 2). Extensive studies have been done on the effectiveness of the propring depending on the axial location and the edge height, but these results are not reported here. The propring significantly improved the performance of the GRE in the critical tailwind conditions.

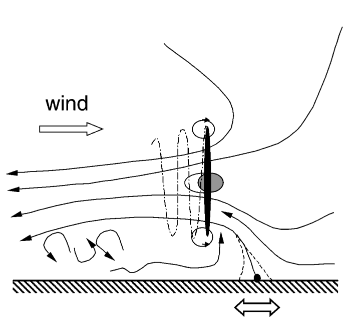


Fig. 3 (Simplified) flow pattern close to propellers in case of tail wind.

As is common practice, a slipstream deflector (being movable to allow entrance of the aircraft into the GRE) is situated at the aft end of the enclosure. This ensures a proper high-momentum vertical discharge of the slipstream air in order to prevent recirculation as much as possible. This high-momentum vertical discharge also acts as an "air curtain" decreasing the detrimental effects of tailwind.

III. Test Setup

The wind-tunnel tests were performed in the DNW-LST 3×2.25 m and the DNW-LLF 9.5×9.5 m. Atmospheric boundary-layer (ABL) simulation was utilized in both tunnels using test-section entrance spires and a floor barrier. This system not only simulates the wind velocity variation with height, but also the (small-scale) turbulence levels. For the DNW-LST the ABL simulation stretched the full test-section height; for the DNW-LLF the simulation only stretched over the lower relevant part of the test-section height to about 2 m [25 m full scale] to limit testing costs (Fig. 4a). As ABL-simulation had not been used before in the DNW-LLF, the validity of this way of ABL simulation was tested in a separate test in the DNW Pilot Low-Speed Wind Tunnel (PLST), being a 1:10 scaled-down model wind tunnel of the DNW-LLF. ABL simulation was tuned such that the atmospheric wind velocity profile corresponded to the mesoscale roughness[2] representative for Eindhoven airport. No effort was made to model small local disturbances, actually present at some distance from the planned facility, like trees and small buildings.

GRE model scale in both tunnels was equal to 1:13.5. Figure 4b shows the full model mounted on the DNW-LLF turntable, to permit testing for all wind directions. Because of the size of the DNW-LST in that tunnel, only a (port-side) half-model could be used, having a fixed (tailwind) orientation. To simulate the Hercules C-130 aircraft propulsion system, four four-bladed, 0.304-m-diam propellers were mounted side by side on top of a strut at positions corresponding to the inboard and outboard engines of the full-scale aircraft (Fig. 4c). These propellers were powered by TDI 1999A air motors. Two smaller TDI 845D air motors powered the starboard-side propellers. As the volume flow of the air driving the engines was small, relative to the airflow passing the propeller disk, the engine drive air was freely exhausted into the flow.

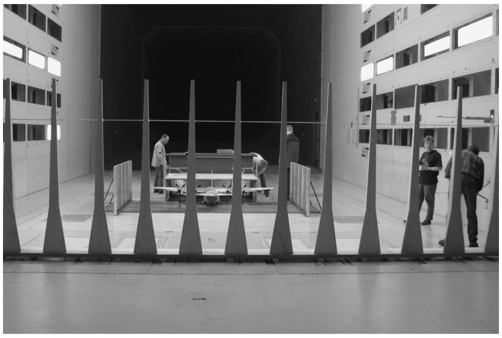
The propeller blades were set at such a pitch angle that a reference slipstream velocity equaled the full-scale one at MTOP, being $V_{\mathrm{ref}} = 65.6$ m/s. This reference slipstream velocity corresponds to the theoretical slipstream velocity at a large distance behind an actuator disk:

$$V_{\mathrm{ref}} = \sqrt{2T/(\rho_0 A_P)}$$

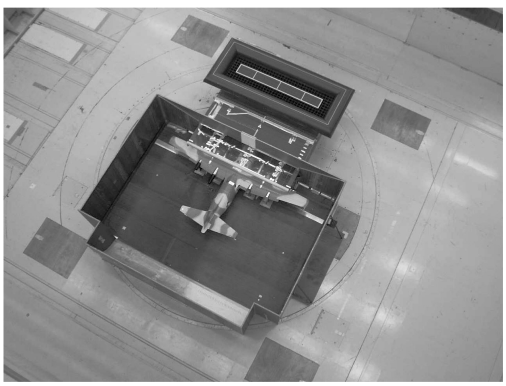
Simulation of the actual slipstream velocity is important, as it is the ratio of slipstream velocity to wind velocity that is an important similarity parameter in this test. Therefore, although it is tempting to use less power to drive the propellers, lowering the slipstream velocity is undesirable as it would result in very low wind-tunnel speeds and therefore decreased measurement accuracy. The thrust coefficient at the given propeller setting corresponds to $C_T = 0.36$.

The carbon-fiber propeller blades were manufactured by NLR,[3] not specifically using the C-130 blade profile but a more advanced design. The propeller solidity number was close to that of the C-130, however. Note that, although thrust has been scaled to the full-scale value, torque, and therefore power, is not properly scaled because of the blade section design of the available propellers being different from the actual propellers. Within limits, this is not critical as is explained later on.

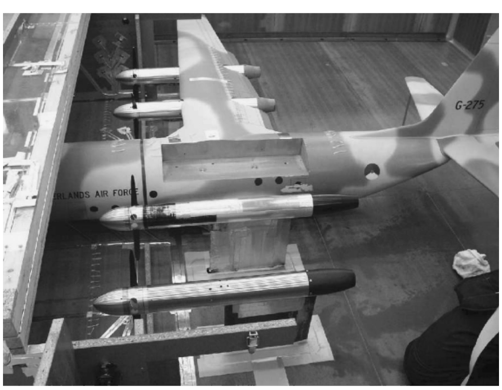
Note also that the propeller blades in the wind tunnel were set at fixed pitch, whereas, with the actual C-130, blade pitch is adjusted continuously to keep torque at the set level. This pitch change is



a) Model being mounted in the test section with atmospheric boundary-layer simulation visible in the front



b) Top view of model on wind-tunnel turntable



c) Engine mounting (port wing and roof removed)

Fig. 4 GRE model in the DNW-LLF.

relatively slow, compared to the quick load changes caused by aerodynamic instabilities, and the full-scale blades are considered as quasi-fixed pitch. Nevertheless, these pitch changes tend to reduce the torque excursions. Therefore the torque fluctuations found in the wind tunnel are comparable to or slightly higher (i.e., on the safe side) then the full-scale ones. This was confirmed by some free-field full-scale/wind-tunnel comparisons for tailwind conditions.

IV. Instrumentation

Wind-tunnel reference velocity was measured using a pitot-static tube at 0.74 m [10.0 m full scale] above the floor, located 2 m behind the spires. The vertical wind velocity distribution in the atmospheric boundary-layer simulation was checked by two other pitot-static probes, one at 2 m [27 m] height and one measuring the undisturbed wind-tunnel velocity at 1 m below the wind-tunnel ceiling at 8.5 m [115 m] height.

Both port-side propellers were equipped with a six-component rotating shaft balance (RSB), developed by NLR[3–5] and capable of measuring propeller torque and thrust directly at the propeller hub. In this way the weighed mass is minimized. This is important, as mass inertia effects have to be minimized to reduce the errors in the measured propeller force fluctuations. The propeller setup on the port side of the aircraft was equal to the one used in the half-model tests in the DNW-LST to ensure reproducibility.

Surface pressures were measured on the inside and outside of various GRE surfaces, to determine the loads on these surfaces. In total 124 pressures were measured and distributed more or less evenly over the GRE model. The pressures were measured by means of electronic pressure scanners. However, the dynamic pressure loads at six positions on structurally critical construction elements (roof overhang and propring) were measured using separate pressure transducers. These were connected with short pressure lines to the inside/outside tap pair at each position to obtain information about the low-frequency behavior (up to a few 100 Hz) of the pressure differences.

Eight total pressure tubes were mounted inside the intake stack to gain an understanding of the velocities and possible flow separations inside the intake. These tubes were located just below the flow straightener, taking care to avoid the wakes of the straightener cell walls.

Finally, to further visualize the flow, tufts were used at critical locations. For this purpose the model was equipped with miniature cameras to observe the flow inside the intake channel.

V. Data Processing

The two port-side RSBs and propeller 1p (once-per-revolution) signals were collected, stored, and processed by the data-acquisition system together with the signals from the six time-variant pressures and the engine parameters that determine the power supplied by the air motors. For verification purposes, the signal of a microphone mounted in the test section was also measured. At each data point these signals were sampled at 2 kHz during 50 s. This enables processing and studying the signals in different ways, for example, using different filter settings.

The reference wind-tunnel speed was determined behind the atmospheric boundary-layer simulation system using the pitot-static probe at 0.74 m above the floor, corresponding to 10 m full scale. Data were not corrected for wind-tunnel blockage. Blockage leads to an increase in effective wind velocity around the model not only as a result of the presence of the model but also because of the reversing propeller slipstream for tailwind conditions. For the LLF, the effective velocity increase caused by blockage is estimated to be around 10 to 15% at 21 kn reference wind speed, depending on the wind direction. Not correcting for blockage thus creates an additional wind velocity safety margin. For the smaller LST blockage obviously was large, but this was considered acceptable in view of the exploratory character of these tests.

If the propellers are operated in a condition without dominant second-order flow effects (for instance, significant blade flow separation), a linear propeller static thrust/torque response can be assumed. Figure 5 shows that this is indeed the case. This allows equating relative torque fluctuations with relative thrust fluctuations:

$$\Delta Q/Q = \Delta T/T$$

Despite mounting the RSB close to the propeller blade root and thereby limiting the weighed mass moment of inertia, torque fluctuations cannot be measured directly as these are still overly affected

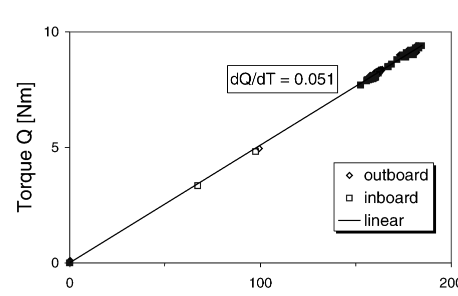


Fig. 5 Linear propeller thrust vs torque relation.

by the inertia of the rotating propeller system. The air motors driving the propellers deliver a constant power. A time-variant propeller loading, resulting in a change in aerodynamic torque on the blades, will therefore result in an increase or decrease of propeller rpm. And, although these rpm variations were small, they resulted in inertia effects on the torque reading, as can be explained as follows. Because of the propeller mass inertia, an increase in rpm will be measured by the RSB as a torque increase. This torque increase partly compensates the aerodynamic torque reduction giving rise to that same rpm increase, thus resulting in a decrease in measured torque excursions as the RSB measures the sum of both. Thrust fluctuations are not affected by this phenomenon (apart from the small forces caused by fore/aft bending of the propeller blades). Therefore, thrust is a better measure for the torque fluctuations that occur. In this test torque fluctuations, as measured by the RSB, were about 15% of the actual fluctuations as determined from the thrust readings. More detailed information on this effect can be found in Ref. 6.

The mechanical torque measurement system of the actual C-130 aircraft has a limited dynamic response. The response of the torque indicators in the cockpit was determined using a video recording of the readings in a tailwind situation with instationary run-up conditions. Analysis of these recordings shows fluctuations up to 0.7 to 1 Hz at maximum (−3-dB point).[7] Therefore, given the model scale of 1:13.5, reproduction of the full-scale behavior of the torque and thrust signals was obtained by low-pass filtering the time signals from the wind-tunnel test at 10 Hz.

Torque fluctuation levels are defined in the same way as for the full-scale aircraft, namely, as half the maximum peak-peak value occurring in the measured signal. To reduce the effect of individual outliers, the high and low peaks have been determined by averaging the 50 highest and 50 lowest time signal samples respectively, each equaling 0.05% of the total number of samples. The fluctuation level is expressed as a percentage of the mean thrust/torque value.

VI. Error Estimates

The accuracy of the RSBs used is 0.3% full scale (400 N) in measured thrust and 0.3% full scale (40 Nm) in measured axial torque. For the given ranges of the balances, this results in a thrust uncertainty of ±1.2 N and a torque uncertainty of ±0.12 Nm. As the thrust and torque in the test amount to around 180 N and 9 Nm, the errors in the static thrust and torque are 0.7 and 1.3%, respectively.

As far as the fluctuating quantities are concerned, these errors depend mainly on the duration of the thrust time signal measurement, as thrust instabilities can be missed during very short measurements. The minimum time required for a reliable thrust fluctuation measurement depends on the lowest frequency in the thrust spectrum. For the present test this was in the order of a few tenths of hertz for the larger fluctuations, and, therefore, a 50-s signal acquisition time was chosen. The results confirm this choice, as repeatability in this test was found to be within 0.1%.

Some differences exist between model and full-scale situation: the model propeller blades were not exactly equal to the actual C-130 ones. Furthermore, the engines were mounted on struts that are not present in full scale and constant instead of variable propeller pitch was used. Reynolds effects might also have had some influence on the aerodynamics of certain parts of the model (e.g., on the rounded intake lip). Errors introduced by the preceding factors are difficult to quantify. Therefore it was decided to assign a safety margin of 0.2% to the thrust (torque) fluctuation data.

The reference wind velocity was determined from a pitot-static tube mounted at a relatively short distance behind the atmospheric boundary-layer simulation system (order 2 m). Preferably, this tube would have been at a position further downstream, but then upstream interference by the GRE model on the probe readings could not be excluded. Although wind velocity measurement with a pitot-static tube and the available pressure transducers can be performed within 0.5% accurate, some inaccuracy in wind velocity can result if the tube is located at a position where the wakes of the individual spires did not fully merge yet. And although earlier tests on spires have shown a very quick restoration of two-dimensional flow, velocity variations of a few percent are considered realistic at the given probe location. However, the dominant error in velocity will be caused by wind-tunnel blockage leading to a 10–15% low velocity reading at 21 kn in the DNW-LLF. So, the actual wind velocity will be slightly higher than the one shown, and therefore the data are on the conservative, safe side.

VII. Results

A. Torque Fluctuations

A rough check of the validity of the measurements was made by comparing the full-scale torque measurements with the C-130 aircraft positioned in the free field in tailwind conditions with wind-tunnel results for the same situation. In this case full-scale torque fluctuations rise to around 5% (amplitude) at a tailwind of around 8 to 10 kn. This situation was simulated in the smaller DNW-LST and led to similar results, although at slightly lower indicated tailwind velocity. The discrepancy in velocity can, however, be caused by the reduced measurement accuracy at these low wind speeds and the disturbance of the wind-tunnel reference system by the (reversing) propeller slipstream. Further, the wind-tunnel results were found comparable to full scale in the sense that the torque fluctuations were lower in the case of only two engines at MTOP instead of four engines. The latter being attributed to reduced interference between the engines.

As just explained, torque fluctuations are determined from the measured thrust fluctuations. Figure 6 shows the port-side engines torque fluctuation as a function of relative wind direction for the final GRE configuration. All engines are operating at MTOP. Zero-degree wind direction corresponds with headwind, and 180 deg with tailwind. The plot is valid for a reference wind speed of 21 kn, corresponding to the requirement value. As a reference, torque fluctuation at zero wind is also given (dashed lines). The outboard engine shows very low fluctuations, around 1%, for all wind directions. The inboard engine is seen to perform well for almost all wind directions, except for a small overrun of the 2% requirement at wind angles around 110 and 280 deg. These are the wind directions where the wind is almost 90 deg cross to the facility. This behavior is related to the relatively long and narrow cross section of the intake opening. The velocity measurements, performed inside the vertical intake channel, indicate that the flow along the front wall of the vertical intake stack is close to separation at these wind directions (discussed further on). Figure 6 also shows some points at which repeat data have been taken, showing the excellent reproduction of the test results.

There might be various reasons for the inboard engine being worse. Because the propring has to be interrupted on the floor to allow space for the undercarriage, the separation zone for the inboard propeller can be less stabilized. Also the presence of the aircraft fuselage—obviously without propring—can further deteriorate this stability. This can explain why the inboard engine shows stronger fluctuations. Moreover, the outboard propeller is able to draw in air from the outside where the propring on the GRE intake channel sidewall further stabilizes the flow. The tests in the DNW-LST have shown the importance of this side wall propring for the stable operation of the outboard engine.

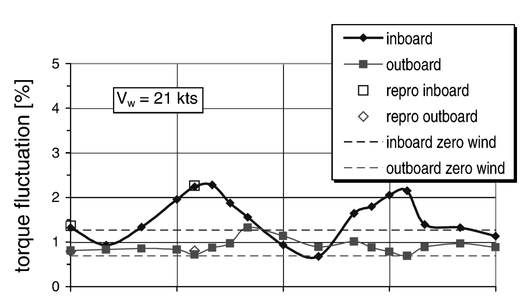


Fig. 6 Torque fluctuations final configuration as function of wind direction, all engines at MTOP.

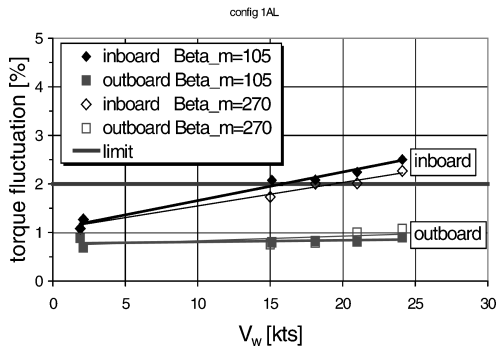


Fig. 7 Torque fluctuations final configuration as function of wind velocity, all engines at MTOP.

The inboard engines on the actual aircraft show a similar sensitivity. For tailwind conditions the fluctuations on the inboard engines are about twice those of the outboard engines. This further supports the correspondence between full-scale situation and model test.

The agreement for tailwind with the DNW-LST test results (not shown) is very satisfactory, despite the exploratory nature of and the relatively large wind-tunnel blockage during these tests. For a comparable configuration the fluctuations amounted to just above 1% in the DNW-LST and around 1% in the DNW-LLF supporting the validity of the chosen development path.

Not only wind direction but also wind velocity was varied. This was done at the two most critical wind directions: $\beta_m = 105$ and 270 deg. The results, given in Fig. 7, show an uneventful, almost linear gradual decrease of inboard fluctuations with decreasing wind velocity. This shows that it is unlikely that there is a sudden flow separation taking place inside the intake stack at increasing wind speeds. The outboard engine fluctuation seems to be nearly independent of wind velocity.

Tests have also been performed with only the inboard engines running. These tests were done to get an impression of the Fokker 50/60 behavior inside the GRE. The diameter of the C-130 propellers is about 12% larger than that of the Fokker ones (4.11 m vs 3.66 m). Also the propeller axis location for the C-130 is somewhat higher (4.05 m vs 2.99 m) and more outboard (5.0 m vs 3.5 m) compared to the Fokker 50/60. At some wind directions, especially quartering headwind, the fluctuations are higher than those for the C-130. A larger flow separation being present in the intake stack was identified as the main cause for this. As the 2% torque fluctuation requirement is relaxed for this aircraft, this larger fluctuation could be accepted. The C-130 is also sometimes tested with two engines running at MTOP; however, in that case the other engines are not switched off but are running at a lower power. The throttled-down engines still induce about 50% of the airflow at MTOP, and therefore it can be expected that the fluctuations are clearly lower than those for the pure two-engine case.

B. Intake Velocities

As mentioned earlier, the performance of the GRE is strongly related to the quality of the flow through the intake channel. Disturbances to the flow pattern, occurring there, have a good chance of advecting through the propeller cross section and resulting in undesirable behavior. To get some idea on the quality of the flow, eight total pressure tubes were installed inside the intake stack at 8.5-m full-scale height in an effort to measure the air velocities in this cross section. Note that these results should be considered approximate as disturbances by the flow rectifier cell walls located above the tubes might have occurred (although care was taken to mount the tubes such that the wakes of these cell partitions were avoided as well as possible). Also, the total pressure tubes will not indicate proper velocities if flow reversal occurs or if turbulence levels are high. Finally, all tubes were mounted at a full-scale distance of 1.1 m to the sidewalls, so that no velocity information is available in the center of the intake cross section, that is, below the screen. Nevertheless, it is considered useful to present the information as it explains some of the torque fluctuation behavior shown before.

The velocities inside the stack have been scaled with V_{ia}. This is the average air velocity in the intake, assuming that all of the air going through the propeller disks is entering the intake stack (which is not the case). As the intake stack cross section equals 213.75 m^2, this average velocity is equal to

$$V_{ia} = 4A_P(V_{ref}/2)/213.75$$

With four engines at MTOP this amounts to $V_{ia} = 8.1$ m/s.

Figure 8 shows the velocities inside the intake stack for the four-engine MTOP and $V_w = 21$ kn case. The small arrow indicates the relative wind direction. Only half of the wind rose is shown, as symmetry is assumed. This assumption also allows mirroring the pitot-tube data relative to the symmetry plane of the facility, using the data obtained at the "mirrored" wind direction to get a more complete picture. Then, effectively there are measurements at 14 different locations, which still is clearly not sufficient to catch the flowfield in detail. Especially data are missing in the center of the intake. Nevertheless, some idea is obtained on the flow behavior in the intake.

It is seen that the dimensionless velocities V_i/V_{ia} in general are between 0.7 and 2.5. The average velocity seems to be above one, but, because of the center intake screen, there will be a velocity defect in the center of the cross section. This is not reflected in the figure because of the absence of pitot data there. In general it is observed that the highest velocities occur along the upwind wall, except for headwinds ($\beta_m = 0$ deg). The lowest and most critical velocities are found on the front wall for $\beta_m = 90$–120 deg. These are also the wind directions showing the largest torque fluctuations.

At 105 deg there seems to be a rather sharp velocity drop off along the back wall of the intake when crossing the centerline. Apart from a partial flow separation, this might also be indicative of some other kind of flow feature (possibly the effect of a vortex) causing the observed fluctuation levels. This drop off is also observed somewhat at some other wind directions. Referring to earlier remarks, however, it might also be that the pitot tube at this location is hit by a wake from the rectifier above. So, some prudence is called for here in interpreting the data.

C. Operational Availability of the Facility

The program of requirements states that the facility must be operable at (10-min average) wind speeds up to and including 21 kn (i.e., up to and including 5 Beaufort). The reason for this is that the facility should only become unavailable as a result of high wind speeds for very limited amounts of time. The availability of the present design can be estimated from the long-term wind statistics for Eindhoven, as collected by the Royal Netherlands Meteorological Institute KNMI.[2]

To determine the operational availability, for each 30-deg-wind sector the wind speed is determined at which the 2% fluctuation level is reached. A 0.2% safety margin is taken between wind-tunnel experiment and full scale as discussed in Sec. VI. Therefore, for the wind-tunnel experiment this critical wind speed is taken as the one where 1.8 % fluctuation occurs on any one of the four engines of the airplane. For this purpose a linear relation L between wind speed and fluctuation level, as shown in Fig. 7, was assumed to hold for the other wind directions as well. The linear relation was determined using the data at 0 and 21 kn wind speed. The critical wind speed V_{crit} then follows from

$$\text{fluctuation} = L(V_w, \beta), \qquad 1.8\% = L(V_{crit}, \beta)$$

As only the port-side engines were equipped with a RSB, the behavior of the starboard engines has been obtained by assuming symmetry in wind direction, relative to the GRE symmetry plane. This involves the assumption of propeller direction of rotation being of minor influence to the fluctuation results. This is supported by full-scale tests, showing no significant different behavior between port- and starboard side engines.

The critical wind speed, estimated in this way, is shown in Fig. 9 for the case with inboard (IB) and outboard (OB) engines running at MTOP. The horizontal axis shows the actual compass wind

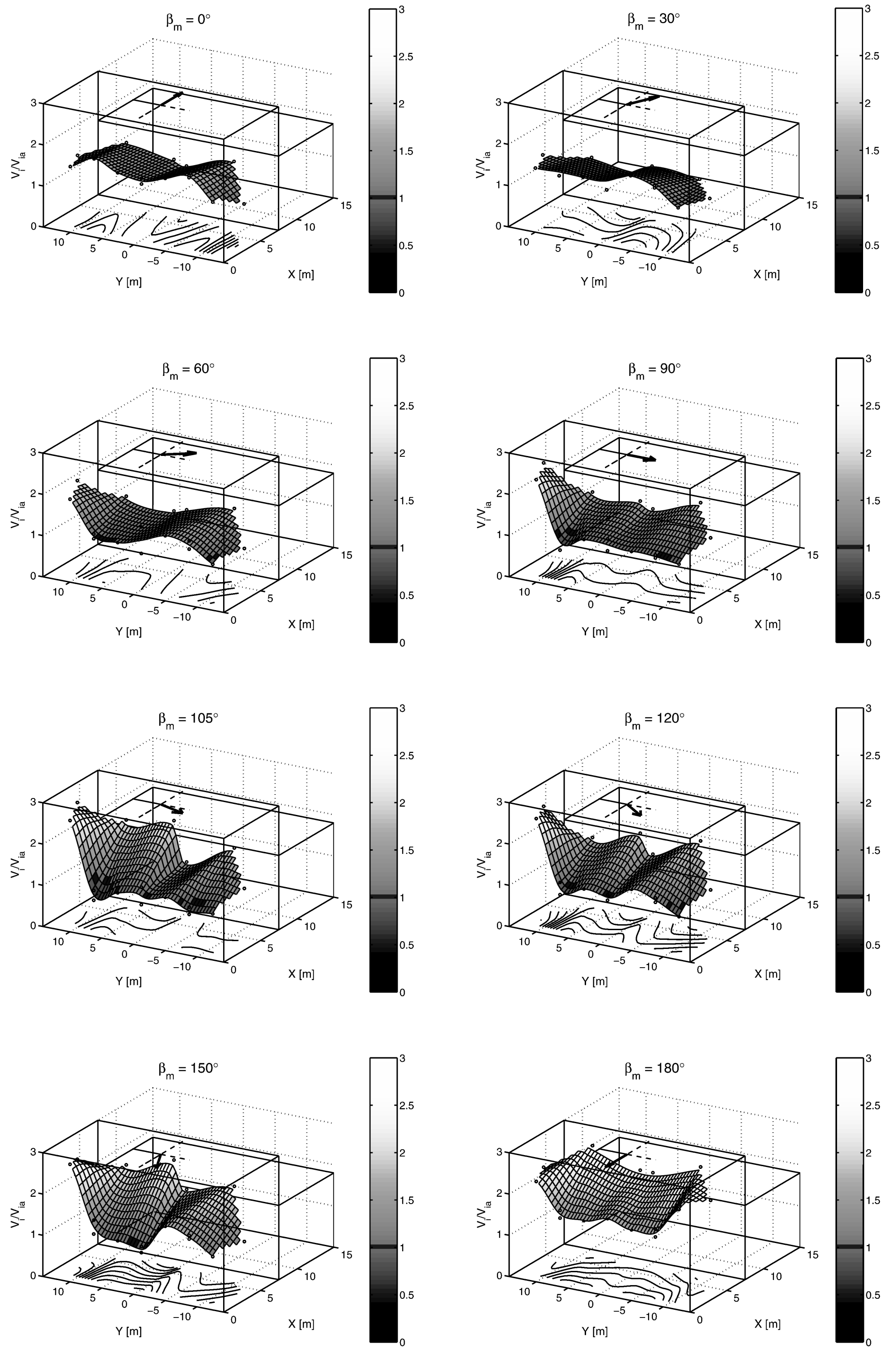


Fig. 8 Velocities inside intake stack for various wind directions (inboard and outboard running).

direction; the one relative to the facility is indicated inside the figure. This figure takes the facility to be oriented in the 240-deg direction, as planned. If the critical wind speed exceeds 21 kn, then there is a gain relative to the requirements and vice versa. It is seen that losses occur for the crosswind conditions ($\beta = 140$ and 340 deg), as can be expected from the fluctuation data, but gains occur for the other wind directions.

From these data the number of hours is determined for each compass rose sector during which the wind speed stays below the critical wind speed. This gives the operational availability of the facility design as it is. A correction for the difference between 10-min average and hourly average has been applied here. The hourly average wind V_{hr} is slightly lower than the (maximum) 10-min average during that hour because of the unsteady nature of the wind. Taking the relation between both wind speeds as given in Ref. 8 for inland terrain: $V_{10'} = 1.12\ V_{\mathrm{hr}}$, this allows estimating the number of hours per year during which the 10-min averaged wind speeds exceed a certain value.

Overall a $V_{\mathrm{crit}} = 21$ kn flat performance equals a 97.1% usability, corresponding to 8508 h/year. For the actual design the availability equals 8575 h/year, equaling 97.8%. This means that the overall operational availability of the facility with all engines at MTOP is even slightly better than the requirements, despite the slight deficiencies for crosswind.

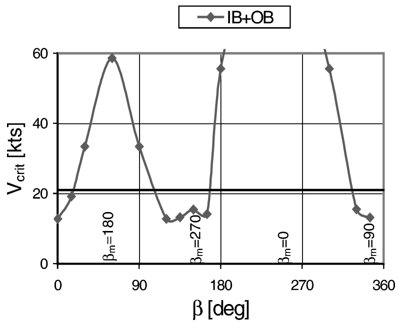


Fig. 9 Critical wind speeds as a function of wind direction.

VIII. Use by Other Aircraft

The present GRE is designed primarily for use by the Lockheed Hercules C-130 and the Fokker 50/60. Nevertheless, its use is not limited to these aircraft. The size of the design is such that other propeller aircraft of a size comparable to the C-130 and also jet-aircraft like the Boeing 737, Airbus A320, or Fokker 100 could use the facility, possibly after small modifications. Also using the facility for occasional testing of fighters as the F16 is considered by RNLAF. Ground-based run-up tests on jet aircraft in general also must be performed with headwind. The present facility would allow these aircraft to be tested in a single run-up orientation. Moreover, the structure surrounding the engines allows for an optimal sound reduction. The fixed positioning of the aircraft would also allow for added sound absorption, for example, by Helmholtz resonators built into the facility to reduce tonal noise. It is expected that the facility of the present size can be adopted for propeller aircraft much smaller than the C-130 with local modifications to the propring to obtain optimal propeller inflow conditions. The exploratory tests in the DNW-LST have shown that a GRE-design, large enough to fit the A400M, could be modified in this way to obtain satisfactory performance for the C-130.

IX. Conclusions

The paper describes the aerodynamic development and testing of a GRE concept for the Lockheed Martin C-130 and Fokker propeller transport aircraft of the Royal Netherlands Airforce in the DNW-LST and DNW-LLF wind tunnels. The approach using two different wind tunnels resulted in a cost-effective development of this GRE facility. The inexpensive small DNW-LST proved to be the proper tool for concept testing and rough polishing up of the design, the large DNW-LLF being used only for the final touches. The performance of the designed facility was judged on the basis of torque-fluctuation levels at 21 kn outside wind speed for the C-130 case. These fluctuations have been measured using rotating shaft balances, mounted at the propeller hub.

Further, wind-tunnel test results show the following:

1) Tailwind performance is excellent, and the initial half-model wind-tunnel tests in the smaller DNW-LST and the final full model test in the DNW-LLF are in excellent agreement for this wind direction.

2) The operational availability of the facility has been estimated, using the long-term wind statistics for Eindhoven airbase. It is shown that the availability amounts to 97.8% of the time for the C-130 4-engines maximum takeoff power case. This is slightly better than the flat 21 kn 2% program of requirements equivalent operational availability (97.1%), despite maximum torque fluctuation levels just exceeding the 2% limit as specified in the program of requirements for the C-130 in four engines maximum takeoff power operation.

3) Highest torque fluctuation levels occur for crosswind situations. This could be attributed to the reduced performance of the intake stack at these wind directions. Ways to improve the design here have been indicated, but were not pursued further as the operational availability requirements were satisfied with the present design.

Acknowledgments

The authors thank Robert van der Tang (Royal Netherlands Air Force) and Mike Roark (Burns and McDonnell, Inc. Kansas City) for the permission to publish the work described in this publication. The work was performed under contract for the Royal Netherlands Air Force.

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