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Aerodynamic development of a four-sided ground run-up enclosure for propeller transport aircraft

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Summary

The development of a ground-run up enclosure is described for propeller aircraft of the size of the Lockheed Martin C-130 Hercules and smaller as operated by the Royal Netherlands Airforce. The primary goal of the facility is to obtain up to 14 dB(A) noise insertion loss, to comply with intended acoustical legislation. This requires high sound barrier walls all around the aircraft. Not only heavy acoustical demands exist, the aircraft operator also requires the facility to be operational for outside wind speeds up to 21 knots, independent of wind direction. For the Eindhoven airport - the intended building location - this boils down to an operational availability of 97 % of the time. Under these wind conditions the engine torque fluctuations for the C-130 should stay below 2 % with Maximum Take-Off Power on all 4 engines simultaneously. The paper highlights some of the aerodynamic design considerations behind the facility and the development and validation in 2 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 cross wind directions. The design employs a single aircraft line up direction, as preferred by the operator. Although the facility has been designed in particular for the C-130 aircraft, it could be adapted to fit aircraft like the Boeing 737.

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

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Nomenclature

A_P	=	propeller disk area (equals 13.3 m^2 for the C-130) [m^2]
C_T	=	propeller thrust coefficient, $C_T = \dfrac{T}{\rho_0 \ (nD)^2 \ D^2}$
D	=	propeller diameter [m]

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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_i	=	local air velocity in GRE intake stack [m/s]
V_{in}	=	average air velocity in GRE intake stack [m/s]
V_{ref}	=	propeller slipstream reference velocity, $V_{ref} = \sqrt{\dfrac{2T}{\rho_0 A_P}}$ [m/s]
V_{hr}	=	reference wind speed at Z=10 m full scale, hourly average [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]

Abbreviations:

Beta_m	=	β_m
GRE	=	Ground Run-up Enclosure
IB	=	Inboard
MTOP	=	Maximum Takeoff Power
OB	=	Outboard
RNLAF	=	Royal Netherlands Airforce
RSB	=	Rotating Shaft Balance
[ ]	=	Full-scale dimension

I Introduction

In order 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 (RNLAF) 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. A Grumman Gulfstream IV, which is also operated by 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 Take-Off power simultaneously. This requirement must be satisfied for wind speeds up to 21 kts (10.8 m/s, i.e. 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 start-up phase of the project the RNLAF made a C-130 aircraft available to perform tests at various existing GRE-facilities, both 3-sided and 4-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 were the aircraft could be operated with all engines at MTOP without exceeding existing over-torque fluctuation limits.

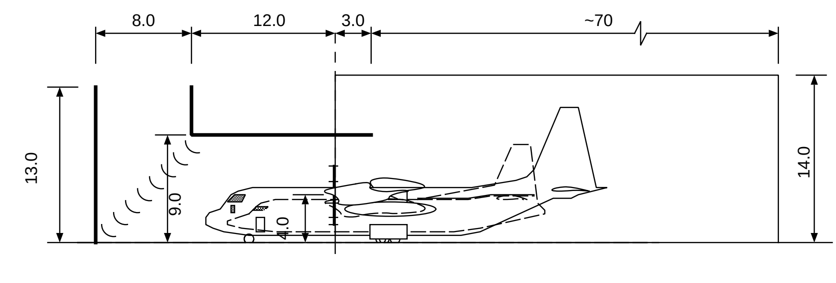


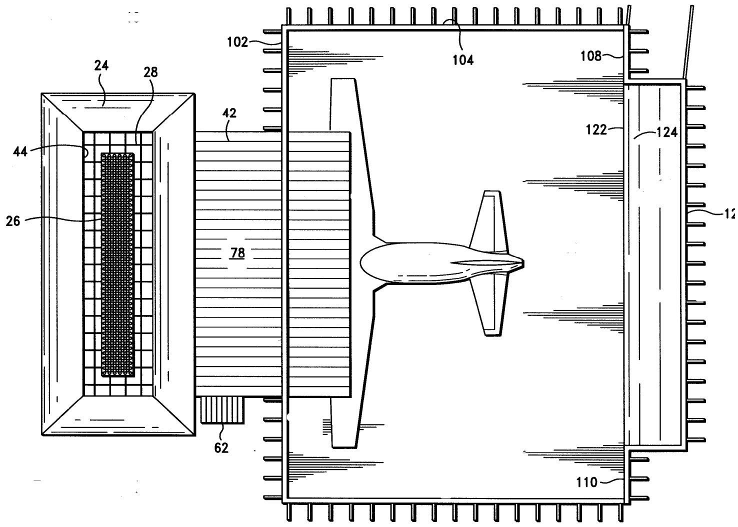
Figure 1. Sketch initial Ground Run-up Enclosure concept with Lockheed Martin C-130H30 and Fokker 50 aircraft.

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 kts. Therefore, it was decided to develop a new concept. This effort was performed in collaboration between the National Aerospace Laboratory NLR, ITF Services and Burns & McDonnell International. TNO-TPD performed the acoustic analysis.

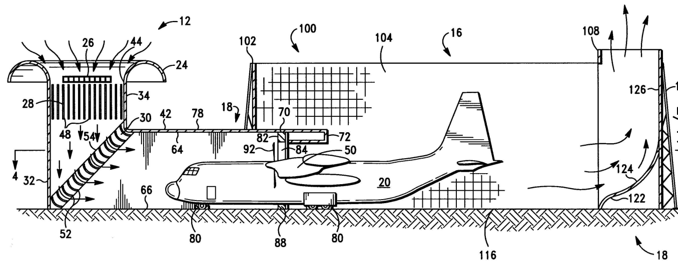
Figure 1 shows the schematic initial concept. The main idea behind the design was that (part of the aircraft) was located inside a more or less closed channel, as shown in the figure. After some refinements had been made to this concept it was decided to take up the initial development and conduct proof-of-concept testing in the small (2.25 m x 3.0 m) DNW-LST wind tunnel. The main goal of this test was to show that in principle the 2% torque fluctuation requirement could be met as this was not clear initially. The scale of the model, 1:13.5, was dictated by the available 0.3 m diameter propellers compared to the full-scale 4 m ones. Therefore, only a half model (port side) could be tested the DNW-LST. As the tail wind condition was considered the most critical one only this one was tested, as the model was too large to be mounted on the turntable. Torque fluctuations were measured using a Rotating Shaft Balance mounted at the propeller hub for various wind velocities. 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 a good result. 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. In a separate test in the DNW-LST also a facility was tested sized to fit aircraft significantly larger then the C-130. 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 the tests in the DNW-LST brought forward a viable concept, it was tested for a final validation in the large 9.5 m x 9.5 m DNW-LLF wind tunnel. This larger wind tunnel allowed testing the full GRE-model for all wind directions. The tail wind performance of this model turned out to be excellent, corresponding to the earlier DNW-LST results. However, further modifications were required to the intake stack in order to improve cross wind performance. This resulted in a satisfactory GRE design for which a patent has been applied for[1].

The approach using 2 different wind tunnels resulted in a cost-effective development of this GRE facility. Model scale was kept equal and therefore engine mounting, including rotating shaft balances, for the port side engines 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 more expensive 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. It is expected that the facility will actually be built in 2005.



b. Top view



a. Side view

Figure 2. Ground Run-up Enclosure: final design.

II GRE design considerations

A sketch of the final GRE design layout is shown in figure 2. The aircraft is located partly inside an intake channel. The air is entering the intake channel through a vertical stack with a rounded lip on the intake, a flow rectifier and a screen centered in the intake opening. Corner vanes guide the flow into the horizontal part of the intake channel, before it reaches the propellers and is exhausted to the back into the open pen area. The flow around the propellers is stabilized by the 'propring' close to the propeller cross section. The propring consists of a sharp edge projecting from the walls of the intake channel.

The acoustic requirements for the facility expect sound insertion losses of 14, 10 and 3 dB(A) to be attained in aircraft nose, spanwise and tail direction respectively. This is a fairly heavy requirement, especially for a low frequency noise source as a propeller aircraft. Therefore the pen area is bounded by 4 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. A single aircraft orientation is used, independent of wind direction as this reduces the amount of (expensive) concrete platform to be built.

How did the final shape evolve? Looking at the wind field inside a 4-sided enclosure the following observations can generally be made: firstly, the inside wind velocities are lower than those outside the enclosure. Secondly, the velocity vectors vary greatly from spot to spot and are sensitive to the outside wind conditions and thirdly, there may be large time variations in the local wind velocity vector. 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 may experience a tail wind component resulting in 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 time scales may be of the order of 1 second or more.

Therefore positioning an aircraft inside 4 walls will generally not result in a satisfactory run-up performance. The detrimental effects of walls may 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 3 and 4-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. Those tests were done at wind conditions well below the required 21 knots and in many cases it even was impossible to run the aircraft up to the required Maximum Takeoff Power (MTOP) because of excessive torque fluctuations.

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 an intake channel. 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 production by the propellers can be attenuated close to the source. As is common practice, a slip stream deflector (being movable to allow entrance of the aircraft into the GRE) is situated at the aft end of the enclosure. This assures 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 tail wind.

The design of the intake channel should 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. In order 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 assure a stable intake flow at the propeller location. Therefore, the inlet stack has 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 flow straightener and the centered screen at the inlet limit the local flow separation. The corner vanes improve the uniformity of the flow in the intake channel.

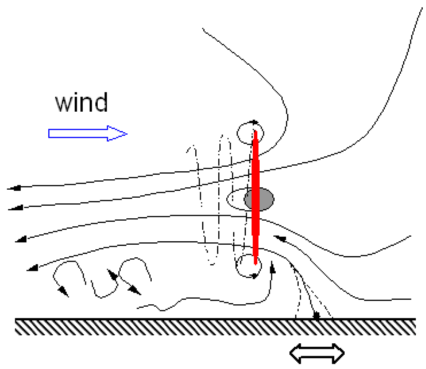
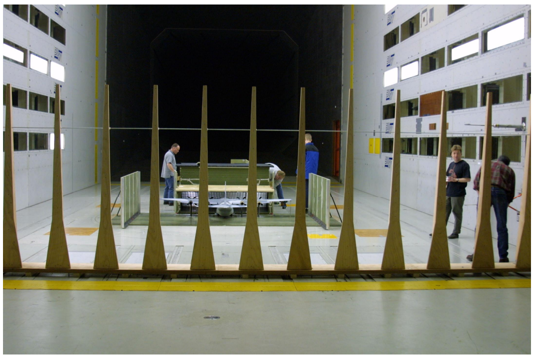
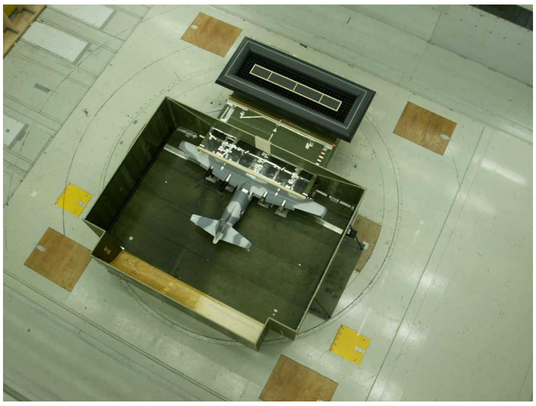


Figure 3. (Simplified) flow pattern close to propellers in case of tail wind.

Due to the fact that the propellers are installed on the aircraft, the aircraft wing limits the extent of the intake channel. This means that uncoupling from the outside environment can not be done as well as in case of uninstalled testing. Therefore additional measures are required to stabilize the propeller flow.



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).

Figure 4. GRE model in the DNW-LLF 9.5 m x 9.5 m test section.

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

Although not 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 may occur with helicopters in descending flight and that also leads to an unsteady flight behavior. Although the ratio of descent velocity to hover-induced velocity for that condition is somewhat larger ($\approx$ 0.5-1.5) than that for the observed propeller tail wind instability ($\approx$ 0.1), vortex instability and deformation from the helical shape may be present already at these tail wind velocity ratios. Vortex instability also affects the airflow drawn in from behind into the propeller disk.

The instability in ground stagnation line is closely related to the observed torque instabilities in tail wind conditions. This coupling could be verified by means of tuft flow visualizations. An important feature of the present design therefore is the so-called 'propring' (item 82 in figure 2). This propring consists of a vertical raised edge, normal to the walls of the intake channel, in the vicinity of the propellers. This edge stabilizes the flow separation at the walls close to the propellers. The propring significantly improved the performance of the GRE in tail wind conditions.

III Test set-up

The wind tunnel tests were performed in the DNW-LST 3 m x 2.25 m and the DNW-LLF 9.5 m x 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 LST the ABL simulation stretched the full test section height, for the 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. 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 1:10 scale wind tunnel of the LLF. ABL-simulation was tuned such that the atmospheric wind velocity profile corresponding to a mesoscale roughness[7] representative for Eindhoven airport was simulated. No effort was done 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 4 shows the full model mounted on the DNW-LLF turntable, to permit testing for all wind directions. Due to the size of that tunnel in DNW-LST only a (port side) half model could be used, having a fixed (tail wind) orientation. To simulate the Hercules C-130 aircraft propulsion system, four 4-bladed, 0.304 m diameter 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. 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_{ref} = 65.6 m/s. This reference slipstream velocity corresponds to the theoretical slip stream velocity at a large distance behind an actuator disk. Simulation of the actual slipstream velocity is important, as it is the ratio of slipstream velocity to wind velocity that is a relevant similarity parameter in this test. Although its 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's. The thrust coefficient at the given propeller setting corresponds to C_T = 0.36.

The carbon fiber propeller blades were manufactured by NLR[4], 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 full-scale, torque, and therefore power, is not properly scaled due to 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 blades pitch is adjusted continuously to keep torque at the set level. This pitch change is relatively slow, compared to the quick load changes due to aerodynamic instabilities and the full-scale blades are considered as quasi-fixed pitch. Therefore the torque excursions found in the wind tunnel are comparable to or slightly higher (i.e. on the safe side) compared to full scale. This was confirmed by some free field full scale / wind tunnel comparisons for tail wind conditions.

An impression of the Fokker 50/60 performance was obtained by running only the inboard propellers of the C-130 model. The diameter of the C-130 propellers is about 12% larger than that of the Fokker ones (4.11 m versus 3.66 m). Also the propeller axis location for the C-130 is close to but somewhat higher (4.05 m versus 2.99 m) and slightly more outboard (5.0 m versus 3.5 m) compared to the Fokker 50/60.

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 6-component, rotating shaft balance (RSB), developed at NLR[2,3,4] and capable of measuring propeller torque and thrust directly at the propeller hub. This is important, as mass inertia effects have to be minimized in order to measure propeller force fluctuations, as will be explained later on. The propeller set up on the port side of the aircraft was equal to the one used in the half model tests in the DNW-LST, to assure reproducibility.

Surface pressures were measured on the inside and outside of the GRE, to determine the loads on the various surfaces. In total 124 pressures were measured, 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 6 positions on structurally critical construction elements (roof overhang and propring) were measured using separate pressure transducers connected to the inside/outside tap pair at each position to obtain information about the low-frequency (up to a few 100 Hz) behavior of the pressure differences.

8 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.

Flow visualization was done by means of minitufts. For this purpose the model was equipped with miniature cameras to observe the flow inside the intake channel.

V Data processing

The 2 port side RSB and propeller 1p (once-per-revolution) signals were collected, stored and processed by the data acquisition system together with the signals from the 6 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 seconds. This enables processing and studying the signals in different ways, e.g. using different filter settings.

The reference wind tunnel speed was determined behind the atmospheric boundary layer simulation system at a height above the wind tunnel floor, corresponding to 10 m full scale using the pitot-static probe at that height. Data was not corrected for wind tunnel blockage. Blockage leads to an increase in effective wind velocity around the model as a result of the presence of the model and the reversing propeller slipstream. In this test this was considered an additional safety margin. For the LLF blockage is estimated to be around 10 to 15% at 21 kts reference wind speed, depending on the wind direction. For the smaller LST it was obviously larger, but this considered acceptable in view of the exploratory character of these tests.

As the propellers are operated in a condition without dominant 2^{nd} order flow effects (e.g. significant blade flow separation) a linear propeller static thrust/torque response may be assumed. Figure 5 shows that this is indeed the case. This allows equating relative torque fluctuations with relative thrust fluctuations:

$$\frac{\Delta Q}{Q} = \frac{\Delta T}{T}$$

Torque fluctuations can not be measured directly as these are still overly affected by the inertia of the rotating propeller system (despite the mounting of the RSB close to the propeller blade root, thereby limiting the weighed mass moment of inertia). These inertia effects come into play due to small propeller rpm fluctuations as a result of time variant propeller loading and constant engine power. At constant engine power a reduction in aerodynamic torque on the blades will result in an increase in propeller rpm. Due to the propeller mass-inertia an increase in rpm will be measured by the RSB as a torque increase. This torque increase due to mass-inertia effects partly compensates the aerodynamic torque reduction giving rise to the 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 effect (apart from the small effect of fore/aft bending of the propeller blades). More detailed information on this effect can be found in Ref.5.

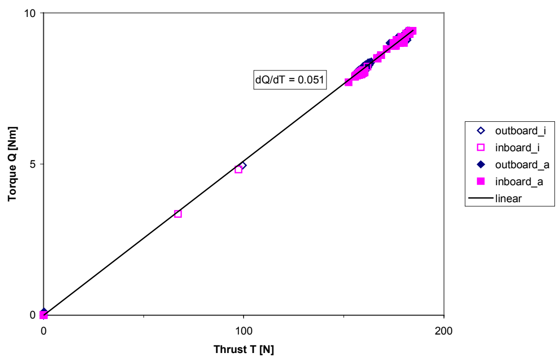


Figure 5. Linear propeller thrust vs. torque relation.

Proper filtering simulates the limited dynamic response of the mechanical torque meters of the actual C-130 aircraft. The torque indicators of the C-130 show fluctuations up to 0.7 to 1 Hz at maximum (-3dB point)[6]. 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 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 as the average of 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 RSB's 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 may 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 Hz 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 may also have had some influence on the aerodynamics of certain parts of the model. Errors introduced by the above 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 may 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 2D flow, velocity variations of a few percent are considered realistic. The dominant error in velocity will be caused by wind tunnel blockage however, leading to a 10-15% low velocity reading at 21 kts 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

As a rough check of the validity of the measurements a comparison was made with full-scale torque measurements with the C-130 aircraft positioned in the free field in tail wind conditions. In this case torque fluctuations rise to around 5% (amplitude) at tail wind of around 8 *kts*. This situation was simulated in the smaller DNW-LST and led to similar results, although at slightly lower tail wind velocity. However, at these low wind speeds the accuracy of the wind speed is less, among other things owing to disturbance of the wind tunnel reference system by the (reversing) propeller slipstream at these low wind speeds. Also the wind tunnel results were found comparable to full scale in the sense that the torque fluctuations were lower in case of only 2 engines at MTOP instead of 4 engines. The latter being attributed to reduced interference between the engines.

As explained above, thrust fluctuations are interpreted as torque fluctuations. Figure 6 shows the port side thrust fluctuation as a function of relative wind direction for the final configuration with all engines operating at MTOP. Zero degrees wind direction in this plot corresponds with head wind, 180 degrees with tail wind. The plot is valid for a reference wind speed of 21 kts, corresponding to the requirement value. As a reference, torque fluctuation at zero wind is also given (dashed lines). The outboard engine is seen to have 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 degrees. These are the wind directions where the wind is almost 90° 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.

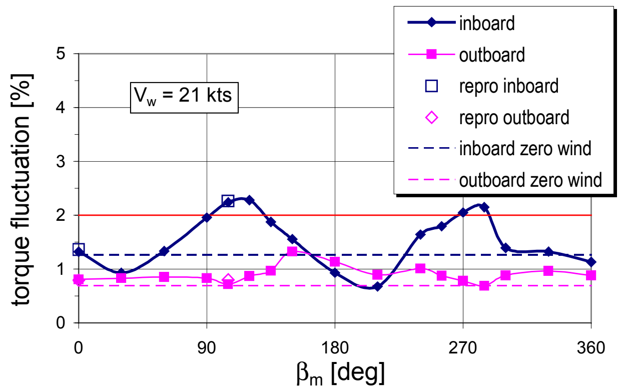


Figure 6. Torque fluctuations final configuration as function of wind direction, all engines at MTOP.

There may 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 – may further deteriorate this stability. This may 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. Earlier tests in the DNW-LST have shown the importance of this side wall propring for the stable operation of the outboard engine.

Finally, the intake flow velocity measurements give some indication that the flow is closer to separation there, possibly resulting in larger instability in the center of the intake channel. It is interesting to remark that the inboard engines on the actual aircraft show a similar sensitivity. For tail wind 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 tail wind with the DNW-LST test results (not shown) is very satisfactory, despite the exploratory nature of 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: β_m = 105° and 270°. The results, given in figure 7, show an uneventful, gradual decrease of inboard fluctuations with decreasing wind velocity. The outboard engine fluctuation seems to be nearly independent of wind velocity. A straight line has been fitted through the data points.

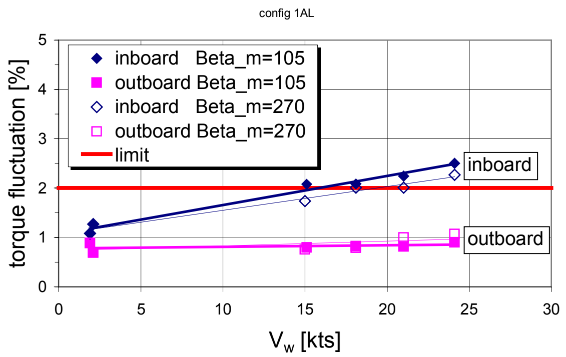


Figure 7. Torque fluctuations final configuration as function of wind velocity, all engines at MTOP

Tests have also been performed with only the inboard engines running. These tests were done to obtain an impression on the single engine Fokker 50/60 performance. At some wind directions, especially quartering head wind, 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.

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. In order to get some idea on the quality of the flow, 8 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 may 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 distance of 1.1 m full scale to the sidewalls, so no velocity information is available in the center of the intake cross section, i.e. 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 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:

$$V_{ia} = \frac{4\,A_P\,\dfrac{V_{ref}}{2}}{213.75}$$

With 4 engines at MTOP this amounts to V_{ia} = 8.1 m/s.

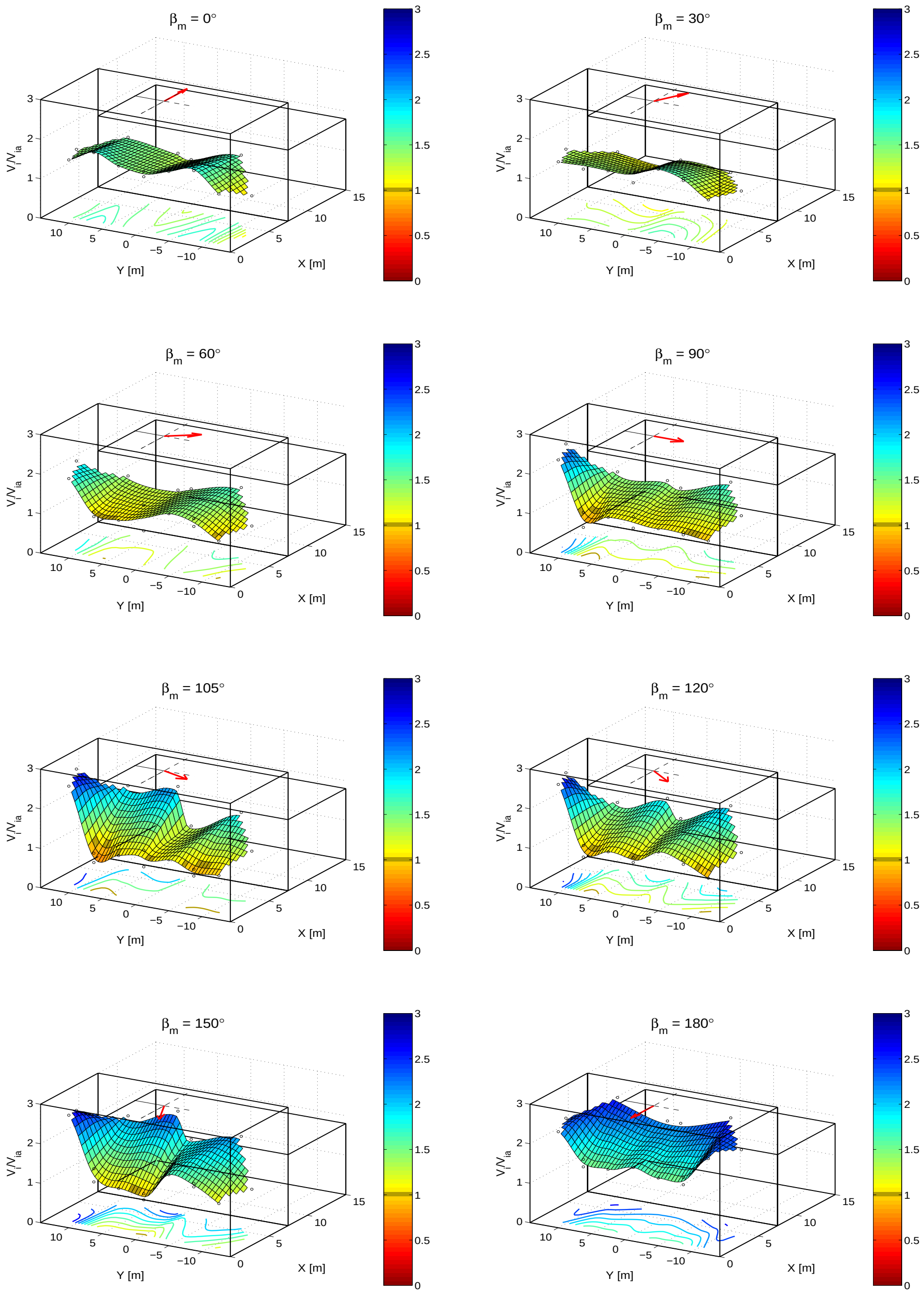


Figure 8. Velocities inside intake stack for various wind directions (IB and OB running).

Figure 8 shows the velocities inside the intake stack for the 4-engine case. The small arrow indicates the 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. Effectively there are measurements at 14 different locations, which is clearly not sufficient to catch the flow field 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 latter number may seem high but, due to the center intake screen, the velocities in the heart of the cross section will be lower. This is not reflected in the figure due to the absence of pitot data there. In general it is observed that the highest velocities occur along the upwind wall, except for headwinds (β_m = 0°). The lowest and most critical velocities are found on the front wall for β_m = 90°-120°. These are also the wind directions showing the largest torque fluctuations.

At 105° there seems to be a rather sharp velocity drop off on the back wall of the intake when crossing the centerline. Apart from a partial flow separation, this might also be indicative of some 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-minute average) wind speeds up to and including 21 knots (i.e. up to and including 5 Beaufort). The reason for this is that the facility should only become unavailable due to 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 given by the Royal Netherlands Meteorological Institute KNMI (Ref. 7).

In order to determine the operational availability, for each 30°-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 section VI. Therefore, for the wind tunnel experiment this ‘critical’ wind speed is taken as the one where 1.8 % fluctuation occurs on *one* of the 4 engines of the airplane.

For this purpose a linear relation L between wind speed and fluctuation level, as shown in figure 7, was assumed to hold for the other wind directions as well.

$$\begin{aligned} fluctuation &= L(V_w, \beta) \\ 1.8\% &= L(V_{crit}, \beta) \end{aligned}$$

The relation then was determined for the given wind direction using the fluctuation data at zero wind speed and those at 21 kts. As only the port side engines were equipped with a RSB, the behavior of the starboard engines has been assumed symmetrical 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.

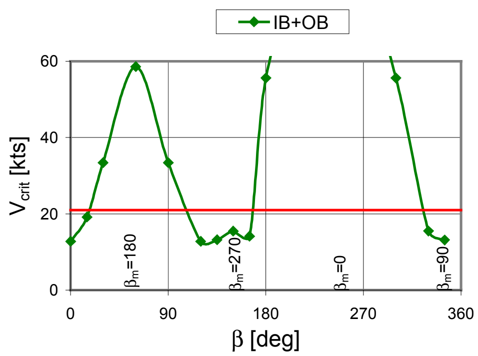


Figure 9. Critical wind speeds as a function of wind direction.

The critical wind speed, estimated in this way, is shown in figure 9. The horizontal axis shows the actual compass wind direction; the one relative to the facility is indicated inside the figure. This figure takes the facility to be oriented in the 240° direction, as planned. If the critical wind speed exceeds 21 kts, then there is a gain relative to the requirements and vice versa. It is seen that losses occur for the crosswind conditions (β = 140° and 340°), as discussed before.

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-minute average and hourly average has been applied here. The hourly average wind V_{hr} is slightly lower than the (maximum) 10-minute average during that hour, due to the unsteady nature of the wind. Taking the relation between both wind speeds as given in Ref. 8 for inland terrain: $V_{10'} = 1.12\, V_{hr}$, this allows estimating the number of hours per year during which the 10 minute averaged wind speeds exceeds a certain value.

Overall the gains and losses relative to a V_{crit} = 21 kts flat performance - corresponding to a 97.1% usability - are as given in the following table:

	IB + OB [hrs/yr]
gain (wind directions with $V_{crit} > 21$ *kts*)	213
loss (wind directions with $V_{crit} < 21$ *kts*)	-146

This means that the overall operational availability of the facility at all engines MTOP is even slightly better than the one corresponding to the requirements, despite the slight deficiencies for cross wind.

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 head wind. 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 e.g. by Helmholtz resonators built into the facility to reduce tonal noise. It is expected that use of the facility for propeller aircraft much smaller than the C-130 will require 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 to obtain satisfactory performance for the C-130 in this way.

IX Conclusion

The paper describes the aerodynamic development and testing of a GRE concept for the propeller transport aircraft of the Royal Netherlands Airforce in the DNW-LST and DNW-LLF wind tunnels. The approach using 2 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 kts wind speed (reference height = 10 m full scale) for the Lockheed Martin C-130 Hercules case. These fluctuations have been measured using Rotating Shaft Balances, mounted at the propeller hub.

Further, wind tunnel test results show that:

- Tailwind performance is excellent and in good agreement with results obtained in the earlier half model wind tunnel tests in the smaller DNW-LST.
- Highest torque fluctuation levels occur for cross wind situations.
- 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 MTOP case. This is slightly better than the flat 21 kts 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 4-engines MTOP operation.
- The intake design is critical for good performance of the facility. The present design can still be improved but in view of the operational availability, this was not pursued further.

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