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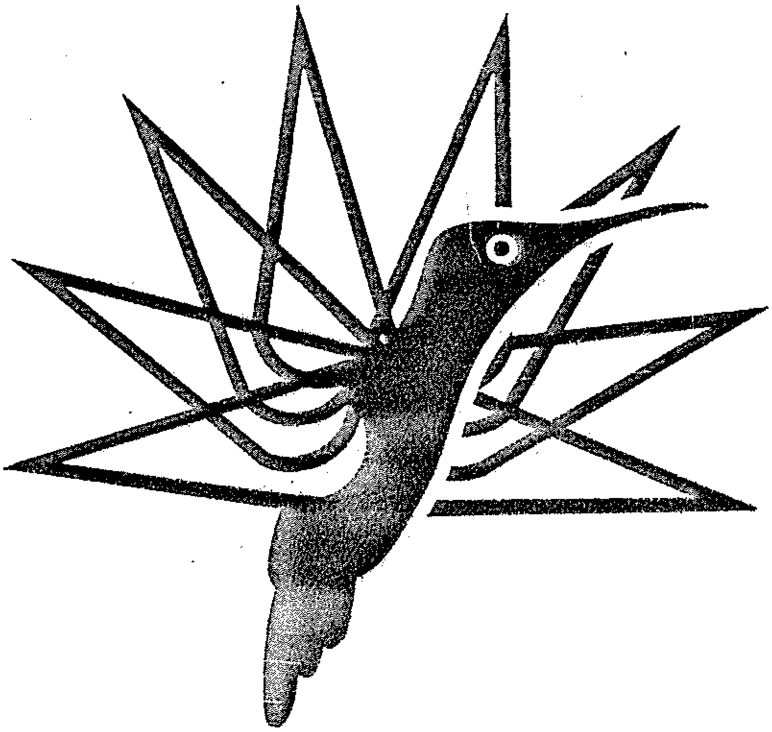

TEST CAPABILITIES OF THE GERMAN-DUTCH WIND TUNNEL DNW FOR ROTORS, HELICOPTERS AND V/STOL AIRCRAFT

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Abstract

As one of the new large aerodynamic facilities in Europe, the German-Dutch Wind Tunnel DNW has entered the commissioning. The DNW is a co-operative project of both the aerospace laboratories DFVLR and NLR and will be also jointly operated. It will belong to the largest and most versatile low speed wind tunnels in Europe and soon efficiently contribute to aircraft and helicopter development work.

This paper describes some typical design features as interchangeable atmospheric test sections with cross sectional areas between 36m^2 and 90m^2 and maximum air speeds in the range of 65 to 150 m/s, slotted working sections and an air exchange system. Reference is made to the main testing equipment, the auxiliaries, and the data management and control system.

The DNW will cover a wide range of testing capabilities including aero-acoustics and testing with real engines. Special attention has been given to comprehensive possibilities of aerodynamical and performance tests also of rotors, helicopters and V/STOL aircraft. In view of prospective high-speed helicopters the size of the test sections had been determined in such a way that sufficiently large rotors can be tested in the whole range of actual forward speeds. The assessment of rotor testing capabilities has been supported by studies on wall interference effects taking into account such parameters as incidence correction, disc loading, model position and flow breakdown conditions. Examples are given for several V/STOL and rotor test set-ups considering different testing objectives.

The present status of construction of the facility is outlined.

Notation

C_L	lift coefficient, $L/q\pi R^2$ (-)
D	rotor diameter, 2R (m)
D.L.	disc loading, $N/\pi R^2$ (N/m^2)
H	test section height, dimension in lift direction (m)†)
L	rotor lift, N cos α (N)
N	resultant force normal to rotor tip-path plane (N)
q	dynamic pressure, $\frac{1}{2}\rho V^2$ (N/m^2)

†) = Duits-Nederlandse Windtunnel/Deutsch-Niederländischer Windkanal

Q	porosity factor (-)
R	rotor radius, 0.5 D (m)
V	wind speed (m/s)
W	test section width, dimension in spanwise direction (m)+)
x_f	wake impingement distance according to Fig. 8 (m)
Δ_z	distance between rotor centre and test section centre line (m)
α	angle of attack of rotor tip-path plane, referred to tunnel axis (deg)
$\Delta\alpha$	local incidence correction (deg)
$\overline{\Delta\alpha}$	average incidence correction of rotor tip-path plane (deg)
γ	test section width/weight ratio, W/H (-)
ζ	vertical eccentricity of rotor model in the test section, $(2\Delta z/H + 1)^{-1}$ (-)
ρ	air density (kg/m)
σ	ratio of rotor diameter to test section width, D/W (-)
χ	momentum wake skew angle, according to Fig. 8 (deg)
χ_e	effective skew angle of rolled-up wake, according to Fig. 8 (deg)

Subscript:

o	test section

+) Since the definition is related to the model, the meaning of W and H is invers when the model is rolled by 90 degrees in the rectangular 8m x 6m test section.

1. Introduction

About 10 to 15 years ago several European countries leading in aviation identified a great need for new aerodynamic test facilities as the existing wind tunnels regarding size and efficiency no longer meet the requirements of future aeronautical development work. Especially in the low speed regime where problems in connection with take-off and landing characteristics became more and more dominant for optimum design of aircraft, a considerable gap in testing capabilities was evident. Forced by this critical situation projects of four new medium-sized low speed wind tunnels of different technical concepts were initiated. Whereas France and Englang decided for the construction of pressurized tunnels (ONERA F1 and RAE 5m) mainly assigned to higher Reynolds number capabilities, Germany and The Netherlands gave preference to larger atmospheric tunnels (DFVLR GUK and NLR LST 8x6) with a wider range of test capabilities and versatile equipment. For economic reasons the fusion of both these projects had been considered by DFVLR and NLR as well as on government levels. The bilateral co-operation seemed to be an obvious solution also from the technical point of view as both concepts showed similar design features regarding tunnel type, size, and performance and were mutually complementary regarding the tasks and the equipment.

For the joint project venture which was named DNW, the DFVLR and the NLR established a new organisation, the DNW Foundation. The objective of the foundation is to construct, operate, maintain and further develop the wind tunnel facility DNW. The Foundation will carry out wind tunnel investigations under contract on a non-profit basis.

The generally prevailing design principles for the project are:

- high aerodynamic and aero-acoustic qualities
- comprehensive and advanced equipment for a wider range of types of test
- high testing productivity
- flexible and economic operation
- maximum system reliability

The main activities will be focussed on such items as:

- improvement of A/C low-speed characteristics (take-off and landing, safety, economy)
- high-lift devices
- V/STOL aerodynamics
- engine/airframe interfarence
- airframe & engine noise
- rotor aerodynamics
- high-speed helicopters
- flutter tests
- jettison tests
- optimization of full-scale A/C components
- real engines (intake, efflux)
- non-aeronautical investigations

By reviewing potential development programs both on the civil and military side, a share of about 30% of the total prospective work load of the DNW has been estimated for testing V/STOL, helicopters and rotors. These types of tests had, of course, a strong impact on the basic design of the new DNW facility, especially when considering size and performance of the test sections and the choice of testing equipment. The manyfold requirements which a typical V/STOL testing facility should meet are thoroughly discussed in Ref. 1.

2. Description of the facility

2.1 General features

Fig. 1 shows an aerial view of the DNW facility which is located in the North-East-Polder, The Netherlands. Fig. 2 displays the arrangement of the various plant buildings. Central items is the closed tunnel circuit shaped as a slender rectangle in the plan view. The centre line has a total length of 318 m. The testing hall covers the area of the test sections. The large parking hall with a span of about 84 m accommodates all the interchangeable test sections not being in operation. Several smaller halls are annexed to the parking hall, such as the experimental hall (next to the circuit, with all necessary auxiliary supplies for static pre-tunnel tests on models), two model assembly halls and a calibration hall for the external six component balance. The office building also accommodates functional rooms (small work shops, off-line data reduction) and provides direct access to the control room. The control room is close to the test sections for easy observation and houses also the on-line data handling and remote control system.

These buildings are supplemented by a machine hall for the compressed air plant and by a 110/10kV power station. The circuit and the belonging-to installations were the main subjects to a careful aerodynamic design (Fig. 3). General surveys over the DNW project and its technical features are given in summarizing papers (Ref. 2 and 3).

2.2 Choice of test section

Regarding the tasks and the operational requirements of the DNW a closed return circuit and atmospheric test sections were considered the optimum solution. The minimum size of the test sections resulted from the requirements that also powered V/STOL and helicopter models which are rather complex by nature should show true geometrical scaling. Wall interference effects should be kept low in as much as the test results will not become questionable. Further design aspects referred to post-stall investigations, testing of full-scale aircraft components as control surfaces, high-lift flap systems, engine intakes, air brakes, and landing gears at reasonably high Reynolds numbers and moderate speeds.

The envisaged range of wind speed resulted from the requirements that models of high-speed helicopters should be tested and flutter and jettison test be carried out at wind speeds of at least 130 m/s.

An optimization of the various requirements and costing aspects both for construction and operation showed that the tasks can best be distributed over three atmospheric and closed test sections and one open test section. The main design data are:

TYPE OF TUNNEL	CLOSED RETURN CIRCUIT (OVERALL LENGTH OF CENTERLINE: 320m		
SIZE OF WORKING SECTION	9.5mx9.5	8m x 6m	6m x 6m
TYPE OF SECTION	CLOSED	CLOSED AND OPEN	CLOSED
CONTRACTION RATIO	4.8	9.0	12.0
MAX. SPEED (m/s)	62	110 (90)	145
STATIC PRESSURE IN TEST SECTION	ATMOSPHERIC (1 BAR)		
REYNOLDS NUMBER $\times 10^{-6}$ *)	3.9	5.2	5.8
MAIN DRIVE	THYR. SYNCHR. MOTOR; NORMAL RATING: 12.7 M		
AUXILIARY DRIVES	MAINLY FOR COMPR.AIR; ≈ 7 MW		
FAN	SINGLE STAGE; 8 BLADES; DIRECT DRIVE 225 RPM; CONST. PITCH, WIND SPEED CONTROL BY MOTOR		

*) BASED ON V_{max} AND $0.1\sqrt{A}$ (A: TEST SECTION AREA)

MAIN DESIGN DATA

During the first trial runs actual maximum wind speeds of 120 and 150 m/s had been reached in the closed 8m x 6m and 6m x 6m test section respectively.

The test capabilities of DNW for rotary-wing investigations thus allow for practically all generalized rotor models and also for certain detailed rotor models as defined in Ref. 4.

The 8m x 6m and the 6m x 6m test sections have been combined to one convertible test-up. This convertible test section is provided with movable side walls (Fig. 5) and the belonging-to contraction with inserts. The 9.5m x 9.5m test section is a separate arrangement. Each test section arrangment consists of three movable parts: the contraction, the test section and the transition part, with a total length of 44 m. In the open (8x6) test section mode the transition part of 9.5 x 9.5 test section will serve as the collector. All section elements can be moved between the testing and the parking hall by an air cushion transport system (Fig. 4). Further equipment includes breathers, hatches, and synchronized turntables and will allow testing complete and half models as well as 2D wing sections. If a model has to be exchanged the movable part of the contraction will be removed to provide access to the test section.

In order to provide atmospheric conditions in the test sections these have to be vented by breathers. For an optimum breather performance for all three configurations, also under stationary tunnel conditions, perforated plates will be inserted flush in the walls about 2 m upstream of the test sections' end.

In order to minimize the effect of wall constraint and to increase the tolerable size of models all three test sections will be provided with slotted walls. The design aims at a minimization of wall constraint under application of known correction methods. The geometry of the slots had been determined with the aid of a special method for the calculation of lift interference with slotted test sections:

- slot width: variable from 0 to 0.12 m
- pitch: 1m
- length: about two times the test section width
- position: in all four walls, upstream of the breathers

The slots are tapered at both ends to reduce distortions of the boundary layer. A smaller pitch (and consequently a smaller width) would have resulted in more homogeneous conditions near the walls; the slots, however, would be more sensible to viscosity effects.

Ref. 5 provides a more detailed discussion of the aerodynamic design aspects.

2.3 Model support

For model support in the test sections the standard equipment includes:

- a sting support machanism which allows for models to be placed in extreme positions (angle of attack ± 45°, angle of yaw ± 30°); it can also be used in connection with a moving belt ground plane or may serve as a probe support for flow field measurements. Vertical positioning can be performed with a maximum speed of 5 m/s and a deceleration of 5 m/s . This enables the simulation of landing and moderate flare phenomena. The vertical loads are limited to 55 kN and - 15 kN.
- an external six component balance ('platform' type) of high accuracy and with maximum vertical loads of ± 65 kN will be available. For calibration purposes the balance can be moved on air cushions into the calibration hall where a rigid frame construction for applying test loads is installed.

2.4 Special equipment

In order to make full use of the basic V/STOL and rotor testing capabilities the DNW will be equipped with various auxiliaries, e.g.:

- compressed air plant with a capacity of 6 kg/s for continuous operation and 35 kg/s for intermittent operation, 100 bars dis charge pressure at the model.
  Compressed air will be used for engine flow simulation, high-lift systems, drive of suction systems (ejectors) and pneumatic motors.
- air exchange system (throttle and hatches)
- tunnel cooling (heat exhanger, re-cooling system)
- moving belt for ground simulation (width: 6m, length: 7m, maximum belt speed: 60 m/s), designed to bear jet impingements of powered lift models
- q-stopper as a rapid flow deceleration device for flutter tests
- scoop for sucking off hot and/or contaminated gas from the test sections
- rotor drive; preference will be given to pneumatic motors because of the favourable ratio of power to weight and volume (Ref. 6).

2.5 Data management

In particular testing sophisticated powered models is exacting safety and productivity. Therefore a close interface between the experimenter and the model through a remote control system and an on-line data system is necessary. These requirements are met by a distributed computer system. The data acquisition and processing system is divided into two compound computer systems (Fig. 6). The on-line branch is mainly used for actual tunnel testing and controlling while the off-line branch is mainly charged with supporting tasks such as model check-outs, calibration, and post-processing of test data.

2.6 Aero-acoustic features

As future aircraft and helicopter design will take into account noise consideration still more seriously, aero-acoustic measurements on models in wind tunnels may probably become an essential part of the devlopment work, especially concerning airframe and rotor noise. The measurement of this type of noise necessitates exacting test provisions as low back-gound noise level and the possibility to determine the far field noise.

According to the present state-of-the-art, DNW found an open jet (8x6 contraction) within an anechoic testing hall the most promising solution for far-field measurements. A proper location of the microphones in the testing hall requires distances from the model of at least once the jet width for 'fly-over' and twice the jet width for the sideline position. To obtain an anechoic environment the walls, the ceiling, and the floor will be covered by noise absorbing material.

In order to reduce the fan noise prepagated to the testing hall acoustic treatment has been applied to the turning vanes of the first and fourth corner, i.e. downstream and upstream of the test section. The estimated back-ground noise based on tests in a 1:10 model tunnel will be about 73 dB and hence will be below the specification (85 dB). Fig. 7 7 shows that the noise of an aircraft model can be clearly identified above 1 kHz.

Because of the large size and of the good aerodynamic and aeroacoustic properties in like manner, the DNW meets the requirements of far field noise testing in a unique way.

3. Assessment of rotor testing capabilities

3.1 Introductory remarks

In order to obtain a first impression of the maximum allowable model dimensions and the testing limits for helicopter and rotor testing in the several DNW test sections, an exploratory investigation has been undertaken on wall interference effects (Ref. 7). This study was based mainly on presently available knowledge of wall effects in closed-wall test sections, and was supplemented by the utilization of a special computer program for lift interference in slotted-wall test sections (Ref. 8).

For the DNW test sections in closed configuration wall-interference data and testing limits can be drawn respectively from the well-known analytical method due to Heyson (Ref. 9 to 11) and from the so-called flow breakdown criteria derived empirically by Rae and Shindo (Ref. 12 and 13). Both these sources are particularly useful for the present purpose, since Heyson as well as Rae and Shindo proceeded from the lifting rotor as a typical example of a V/STOL configuration. A summary discussion on interference problems in V/STOL testing has been given in Ref. 14.

Inherent in wind tunnel testing of helicopter rotors is a large variety of possible operating conditions. In accordance with Heyson's model of a lifting rotor, they can be simplified, however, and may be expressed by quantities like the disc loading, the lift coefficient C_L, the wake skew angle χ, etc. One of the basic assumptions is that forces tangential to the rotor tippath plane are neglected. Thus, in fact a lifting 'actuator disc' is considered, having only a resultant normal force N which can be resolved in the usual way into a lift and a drag force when the rotor is at incidence with respect to the forward velocity. For the specific relationships between C_L, χ and α the reader is referred to Ref. 11.

3.2 Model size and operating conditions in view of flow breakdown

Especially for rotor models a relative large amount of empirical information has been built up concerning the flow breakdown phenomenon (Ref. 12 and 13). 'Flow breakdown' is reserved to a test condition in closed test sections where the flow is distorted to such an extent (by recirculation effects) that the measured results are no longer corrigeable, and thus are meaningless in terms of any equivalent free-air condition. Because of this absolute character of the associate test limit, its implications for model size and operating conditions are given priority in the present considerations.

Following Heyson (Ref. 11), a generalized formula for the onset of flow breakdown is used:

$$\chi = \arctan\,(2\sigma\gamma\zeta(x_f/D)_{min})$$

According to Heyson $(x_f/D)_{min}$ has the value 1.25 for a rectangular test section with $\gamma = 4/3$ and $3/4$, but the value 1.75 for a square test section ($\gamma = 1$). The above-mentioned formula and the numerical values of $(x_f/D)_{min}$ have been derived from experimental results for a rotor at small incidence angles. As a consequence, the flow breakdown limit is actually not so sharply defined as is suggested above and may become even invalid at large (negative) rotor angles of attack.

In Fig. 8 to 10 the allowable model size and operating conditions are summarized on the basis of Heyson's generalized flow breakdown criterion. In Fig. 8 the favourable effect of a vertical model eccentricity $\Delta z/H$ is shown for the several DNW test sections. This effect may have no general validity in wide rectangular tunnels ($\gamma \gtrsim 1.5$). Rae's orginal results (Ref. 12) seemed to confirm this tendency. Recently however, new experimental results were published (Ref. 13) of the effect of a vertically off-centered model in a closed rectangular test section with $\gamma = 1.5$ which show a different trend. It was concluded there, that any off-centre position, either below or above the centre line, will suffer a loss of the usable testing range, the central model location thus being an optimum. Because this feature in wide tunnels is ascribed to the close presence of the ceiling, introducing local flow separation at the ceiling or at least a deterioration of the inflow to the rotor, the favourable effect of $\Delta z > 0$ may remain valid in square and high test sections ($\gamma \leq 1$). But for the 8m x 6m test section with $\gamma = 4/3$ the actual effect of $\Delta z > 0$ is subject to doubt.

Another, even more striking, result is the increase of the usable testing range of the 8m x 6m test section when the model is rolled by 90 degrees, such that the rotor tip-path plane is vertical and thus the axis of rotation is horizontal. As can be seen in all diagrams of Fig. 8 through 10, the 6m x 8m test section with $\gamma = 3/4$ turns out to be even more favourable than the much larger 9.5m x 9.5m test section. It will be shown in the next section, however, that rotation of a large model in the rectangular 8m x 6m test section, so that $\gamma = 3/4$ instead of $\gamma = 4/3$, causes a strong increase of the wall corrections, and flow breakdown may turn out to be not the critical limit in that case.

Also the decrease of the testing possibilities with increasing rotor angle of attack α, as shown in Fig. 10, is for large α subject to some doubt, since the magnitude of this effect is derived from Heyson's generalized formula and is, strictly speaking, not actually measured by Rae and Shindo (their measurements were restricted to $-7^\circ \leq \alpha \leq 7^\circ$).

Finally, it should be noted, that the susceptibility to flow breakdown of the 8m x 6m and 9.5m x 9.5m test sections may be remedied by using the moving belt ground plane according to known criteria for V/STOL testing.

3.3 Wall interference corrections in closed test sections

Although the existing wall interference correction methods for models with large downward wake deflections leave much to be desired, Heyson's approximate theory for V/STOL models seems to be very useful for the present purpose, the more so, as the basic mathematical model is clearly inspired on a lifting rotor.

It is a widespread assumption that the validity of this theory will extend generally up to the flow breakdown limit. This might lead to the conclusion that the maximum model size could be based solely upon this limit. It can be shown, however, that the validity of the calculation method in predicting the wall-induced velocity field may not always be a sufficient condition that satisfactory corrections can be deduced. Quite rightly, it was stated by Heyson (Ref. 11), that the magnitude of nonuniformity of the wall interference in the neighbourhood of the model may often cause one of the most severe limits on the usable testing range of a given wind tunnel. It is very difficult, however, to define such a limit in some practical usable form or to derive corrections at a certain accepted level of nonuniformity. It is for this reason that already in the early stages of design of the DNW the possibility of creating the use of slotted walls was an important item.

In the present section some results of wall-interference calculations, performed by using a few of the computer programs published by Heyson (Ref. 9), will be presented, principally to reveal some consequences of a certain choice of model size in terms of both average values and distributions over a rotor model of the principal wall correction on incidence ($\Delta\alpha$). In these calculations an axisymmetrical triangular disc-load distribution is assumed, i.e. a normal-force distribution which is independent of the azimuth angle but which varies linearly with the radius. Further details are given in (Ref. 10).

The average wall correction on rotor incidence, $\overline{\Delta\alpha}$, as a function of rotor diameter is shown in Fig. 11 for $\alpha = 0$ and for conditions in which flow breakdown starts affecting the data in the closed configuration of the various DNW test sections. This means, since flow breakdown onset varies with model size, test section geometry, model height, etc., that in Fig. 11 as well as in some of the subsequent diagrams, the test conditions (e.g. C_L) are not only different for different curves, i.e. for different test sections and model heights, but vary also along each individual curve with the rotor diameter. Therefore these diagrams can not be used for a comparison of the testing capabilities of the several DNW test sections on the basis of a certain acceptable magnitude of the wall corrections. On the other hand, it may be concluded indeed, that testing of large models, up to the flow breakdown limit in the 6m x 8m ($\gamma = 3/4$) and 6m x 6m test section inevitably leads to large wall corrections and that increasing model height, causes a further increase of the corrections. As a tentative, preliminary conclusion it may even be stated, that a vertical model arrangement in the 8m x 6m test section often cannot be recommended, because the gain in maximum allowable lift coefficent or in minimum allowable wind speed which according to Fig. 8 through 10 can be obtained by rolling the model by 90 degrees in the 8m x 6m test section is accompanied by a doubling of the wall corrections. Obviously the 9.5m x 9.5m test section turns out to be most favourable if only small corrections due to wall interference will be admitted.

Rather than the average value of the correction, the nonuniformity, i.e. the variation of $\Delta\alpha$ over the model, is important for the decision what magnitude of wall interference might be acceptable.

In Fig. 12 the variation of the incidence correction $\Delta\alpha$ along the longitudinal X' axis in the tip-path plane is shown for model rotor diameters of 3.5 and 4.0 m in several test section configurations. Also here conditions are considered at the onset of flow breakdown in the closed configuration. The specific value of C_L is indicated at each curve as a measure of the test condition considered. From these results it is obvious that the longitudinal variation of $\Delta\alpha$ is almost linear but may become very large, in particular in the closed rectangular ($\gamma = 3/4$ and $\gamma = 4/3$) test section. Although the large 9.5m x 9.5m test section shows a significantly smaller nonuniformity, it is clear that the large longitudinal gradient $\delta\Delta\alpha/\delta x'$ is inherent to models of large longitudinal extent in closed test sections and that, especially when relative large model sizes are pursued, it deserves at least as much attention as the flow breakdown limit.

A striking result is shown by the lowest curve of Fig. 11 which belongs to the case that ceiling and side walls of the 8m x 6m ($\gamma = 4/3$) test section would be removed, thus creating a so-called 'closed-on-bottom-only' test section. Obviously the large longitudinal nonuniformity as well as the large average value of $\Delta\alpha$ is greatly reduced. This may be considered as an indication that a kind of wall modification (e.g. by applying slotted walls) may be applied as a means of creating a more homogeneous wall interference.

Besides the cases shown, also other calculations have been performed for instance the correction on dynamic pressure, lateral distributions of $\Delta\alpha$ and Δq_o, effects of non-zero values of the rotor angle of attack α, etc. From these results it was found that the lateral variation generally is not large but may become significant for large models ($D/W > 0.5$). Also the effect of α deserves attention, since wall interference effects turn out to increase generally with increasing α. Again the large 9.5m x 9.5m test section induces the smallest interference effects, as expected.

3.4 Application of slotted walls

For some time past a numerical method is available at NLR for the calculation of wall interference due to lift in three-dimensional test sections provided with slotted or perforated walls of finite length (Ref. 8).

The computer program described in Ref. 8 has been developed from a theoretical analysis by Slooff and Piers (Ref. 15) and was intended to serve as a practical tool to predict the effectiveness of slotted walls in low speed wind tunnels. The method proceeds from a source-panel singularity distribution as a representation of the tunnel walls and is based on a modified form of the classical linear homogeneous boundary condition due to Baldwin et al (Ref. 16). The modification as described and argued in (Ref. 15) was introduced as a consequence of the finite length of the ventilated (slotted or perforated) part of an actual test section.

Typical of the linear homogeneous boundary condition is the existence of two coefficients, the slot parameter K and the porosity or viscosity parameter Q. The latter presents some difficulties because, unlike the parameter K, its magnitude cannot be predicted from the actual slotted wall configuration. Unfortunately, the calculated wall interference is highly dependent on Q, and so a large amount of uncertainty exists about the characteristics of any new slotted wall test section. In addition, the validity of the linear boundary condition itself is also subject to discussions, particularly when large disturbances are created by the model in the test section flow.

In view of these shortages in the analytical prediction methods, a very flexible design was chosen for the DNW test sections, enabling a continuous variation of the open area ratio beteen 0 and 12% for all four walls.

An example of the effect of slotted walls on the longitudinal distribution of the incidence correction $\Delta\alpha$ is shown in Fig. 13, based on calculations for a 4m diameter rotor in the 8m x 6m ($\gamma = 4/3$) test section. It has been assumed that all four walls have identical characteristics, i.e. equal values of K and Q. For K a constant value belonging to an open area ratio of 12% was chosen; whereas Q was varied between the values Q = 0.5 and Q = 0.9, being a conceivable range.

In view of these and other results of exploratory calculations, which show a simular trend, it is believed that the slotted walls in the DNW test sections will answer the expectations for V/STOL testing, since both the nonuniformity and the large average values of the incidence correction can be assumed to decrease substantially. In addition the flow breakdown limits may be shifted to higher lift coefficients.

Though the basic fluid dynamics of a slotted-wall arrangement is not yet fully understood practical experience in other wind tunnels (e.g. Boeing-Vertol 20' x 20' (Ref. 1)) has proven the benefits of such fittings. Even the removal of working section panels (Ref. 17), if carried out carefully, can yield a substantial increase in the maximum allowable downwash angle and keep the tunnel flow free from recirculatory interference. Further research is needed, however, in order to obtain reliable correction procedures for the specific form of wall interference which will remain insuch cases.

4. Rigs for V/STOL and rotor models

After some aspects of test section lay-out and suitable model sizes have been reviewed the possibilities of actual model mountings will be briefly discussed. The availability of three closed test sections with various interchangeable floor sections, an open test section, and two alternative standard model supports (external balance and sting support) provides a great flexibility of model mounting arrangements. The kind and objective of the test and the type of model can individually be taken into account. Fig. 14 shows some typical examples of test set-ups for powered V/STOL and rotor models.

Ex. A illustrates a rear-sting mounted model with an internal balance and the use of the moving belt ground plane. The arrangement meets particular requirements regarding tests in ground proximity, avoidance of flow breakdown at low wind speeds, and flare simulation. Ex. B shows the external balance underneath the test section floor, with a strut-mounted model. Half models are mounted vertically on the external balance (Ex. C).

Ex. D to F refer to some set-ups for rotors and helicopters. Any complete model in the open jet can be supported either by the sting support or the external balance. Ex. D and E show in a rather principle way how tilting rotors can be mounted, especially when a vertical position of the rotor disc is preferred.

Fig. 15 summarizes various feasible combinations of model support and test sections. Preparatory check-outs and no-wind calibration and testing of powered models which often form a considerable part of the overall testing time, can be carried out to a large extent outside the tunnel, i.e. in the experimental hall. This will drastically contribute to test cost-effectiveness.

As an example for an actual model arrangement in the convertible 8m x 6m/6m x 6m test section the DFVLR rotor and helicopter test stand (Ref. 18) is shown on Fig. 16.

5. Status of construction

On July 1, 1976, the construction activities have commenced at site. Two years later most of the civil work and the furnishing of the circuit were completed. In May 1979, the 'wind-on' phase has been started successfully showing that the specified performance data at the first go-off even could be exceeded. The systems are operating satisfactorily hitherto.

Currently tests with a helicopter model and further flow calibration and acceptance tests are being carried out; the calibration of the external balance (half-model mode) approaches finalization. By the turn of this year a series of calibration and comparative tests with several large sting mounted A/C models, including a new Airbus model specially designed for DNW, will begin. Contractual tests are scheduled in the first half of 1980, followed by the commissioning of 9.5 x 9.5m test section and the external balance in the complete model version.

6. Concluding remarks

1) The German-Dutch Wind Tunnel DNW belongs to the largest and most advanced low speed tunnels in Europe featuring unique aerodynamic and aero-acoustic testing capabilities for a wide range of types of tests.

2) Most of the standard equipment as four interchangeable test sections with a wide range of maximum wind speeds and various model supports, and most of the equipment, e.g. compressed air plant, auxiliary drives, moving belt ground plane, slotted working sections, are specially designed for or most suitable for V/STOL, helicopter, and rotor testing.

3) The 9.5m x 9.5m test section is most suitable for investigations in low speed rotor aerodynamics due to lowest incidence corrections.

4) The lowest allowable speeds with regard to flow breakdown are achieved in the 8m x 6m test section with rotors mounted vertically.

5) Application of moving belt ground plane and slotted walls will increase the usable range of test parameters by shifting flow breakdown on-set to lower speeds and by reducing wall-induced corrections.

7. References

1) F.D. Harris, Aerodynamic and Dynamic Rotary Wing Model Testing in Wind Tunnels and Other Facilities, AGARD-LS-63, March 1973, Paper No. 7.

2) M. Seidel, F. Jaarsma, Der Deutsch-Niederländische Windkanal, Luftfahrtforschung und Luftfahrttechnologie, Statusseminar 1977, Bundesministerium für Forschung und Technologie, pp. 222 - 241; also: DNW-TR-77-165, 1977.

3) M. Seidel, F. Jaarsma, The German-Dutch Low Speed Wind Tunnel DNW, The Aeronautical Journal, pp. 167 - 173, April 1978.

4) I.A. Simons, H. Derschmidt, Wind Tunnel Requirements for Helicopters, AGARD-R-601, April 1973, Paper No. 7.

5) F. Jaarsma, M. Seidel, The German-Dutch Wind Tunnel DNW, Design Aspects and Status of Construction, 11th ICAS Congres, September 1978, Paper No. B3-07.

6) G.O. Albrecht, Factors in the Design and Fabrication of Powered Dynamically Similar V/STOL Wind Tunnel Models, AGARD-LS-63, March 1973, Paper No. 7A1.

7) R.A. Maarsingh, Model Sizes, Testing Limits and Wall Effects for Helicopter Rotors in the DNW, Memorandum NLR AI-79-008, 1979.

8) A.L. Bleekrode, Lift Interference at Low Speeds in Wind Tunnels with Partly Ventilated Walls, Memorandum NLR WD-75-085, 1975.

9) H.H. Heyson, Fortran Programs for Calculating Wind Tunnel Boundary Interference, NASA TM X-1740, 1969.

10) H.H. Heyson, Use of Superposition in Digital Computers to Obtain Wind Tunnel Interference Factors for Arbitrary Configurations; with Particular Reference to V/STOL Models, NASA TR R-302, 1969.

11) H.H. Heyson, Rapid Estimation of Wind Tunnel Corrections with Application to Wind Tunnel and Model Design, NASA TN D-6416, 1971.

12) W.H. Rae Jr., An Experimental Investigation of Wind Tunnel Wall Corrections and Test Limits for V/STOL Vehicles, University of Washington, Rep. 73-2, 1973.

13) S. Shindo, W.H. Rae Jr., Low Speed Test Limit of V/STOL Model Located Vertically Off-Center, J. Aircraft 15, pp. 253 - 254, April 1978.

14) M. Carbonaro, Interference Problems in V/STOL Testing at Low Speeds, AGARD-CP-174, March 1976, Paper No. 40.

15) J.W. Slooff, W.J. Piers, The Effect of Finite Test Section Length on Wall Interference in 2-D Ventilated Wind Tunnels, AGARD-CP-174, March 1976, Paper No. 14.

16) B.S. Baldwin Jr. et.al., Wall Interference in Wind Tunnels with Slotted and Porous Boundaries at Subsonic Speeds, NASA TN 3716, 1954.

17) R.E. Hansford, The Removal of Wind Tunnel Panels to Prevent Flow Breakdown at Low Speeds, AGARD-CP-174, March 1976, Paper No. 41.

18) B. Gmelin, A Model for Wind Tunnel Rotorcraft Research, Model Design and Test Objectives, 2nd European Rotorcraft and Powered Lift Aircraft Forum, September 1976, Paper No. 32.

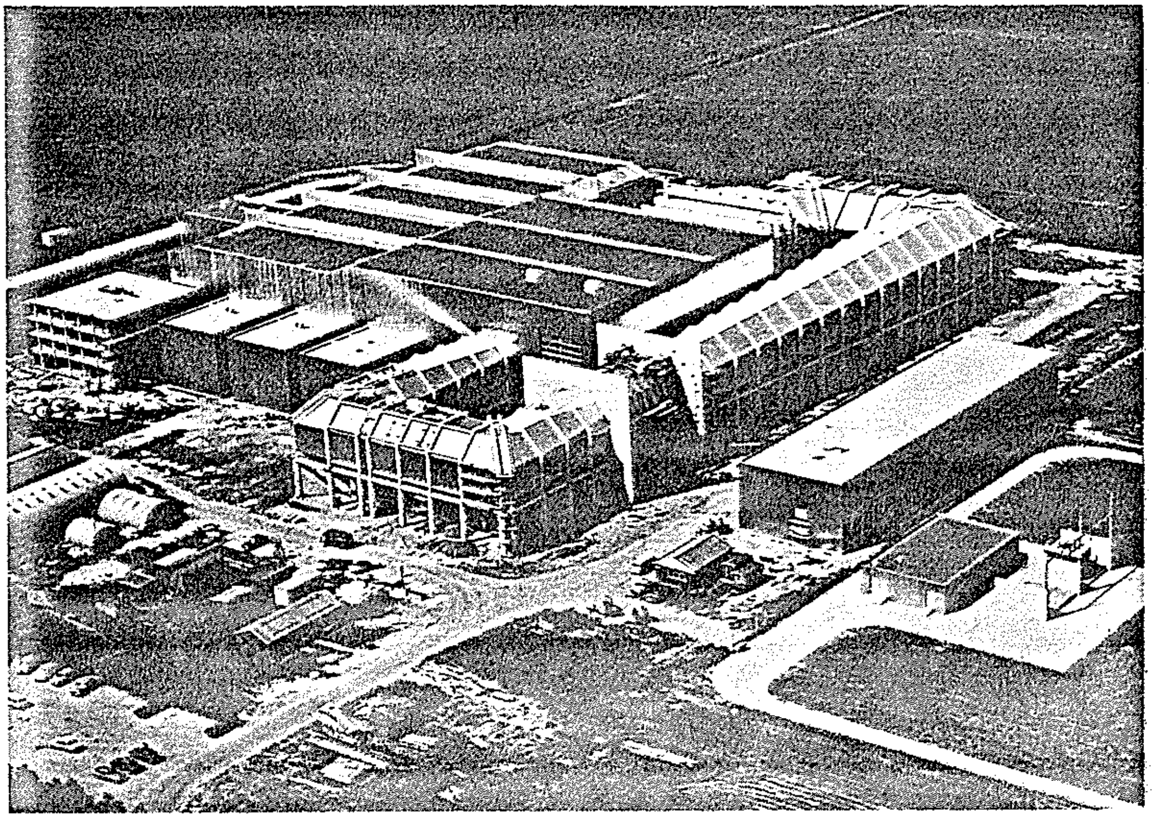


FIG. 1 AERIAL VIEW OF THE DNW (KLM-Aerocarto)

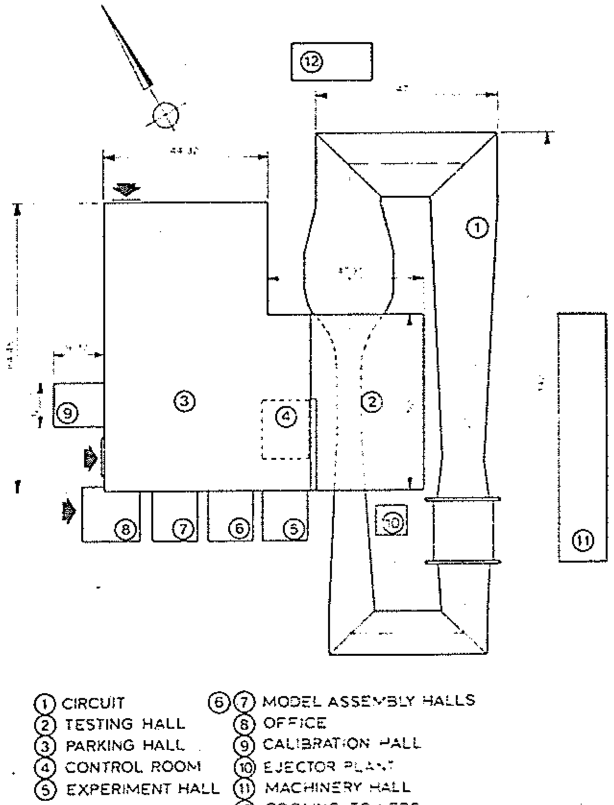


FIG. 2 ARRANGEMENT OF BUILDINGS

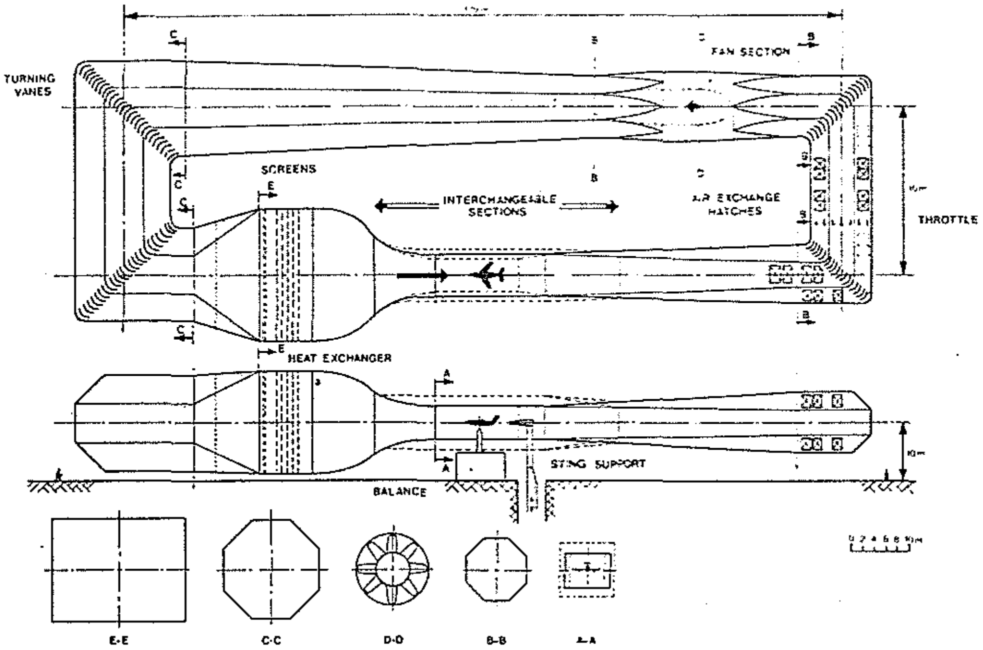


FIG. 3 CIRCUIT AIRLINE VIEW

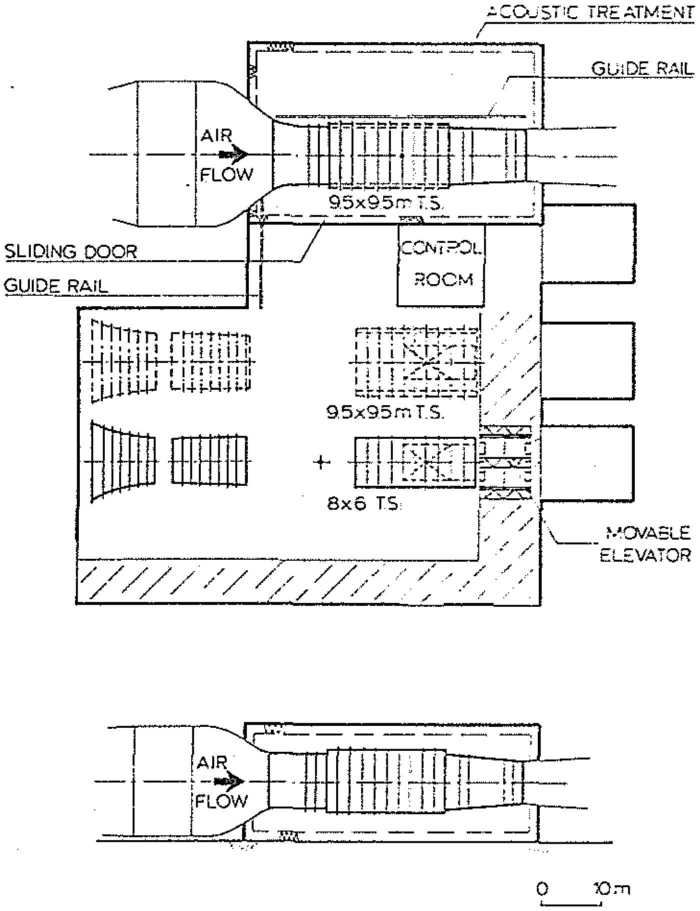


FIG. 4 INTERCHANGEABLE TEST SECTIONS

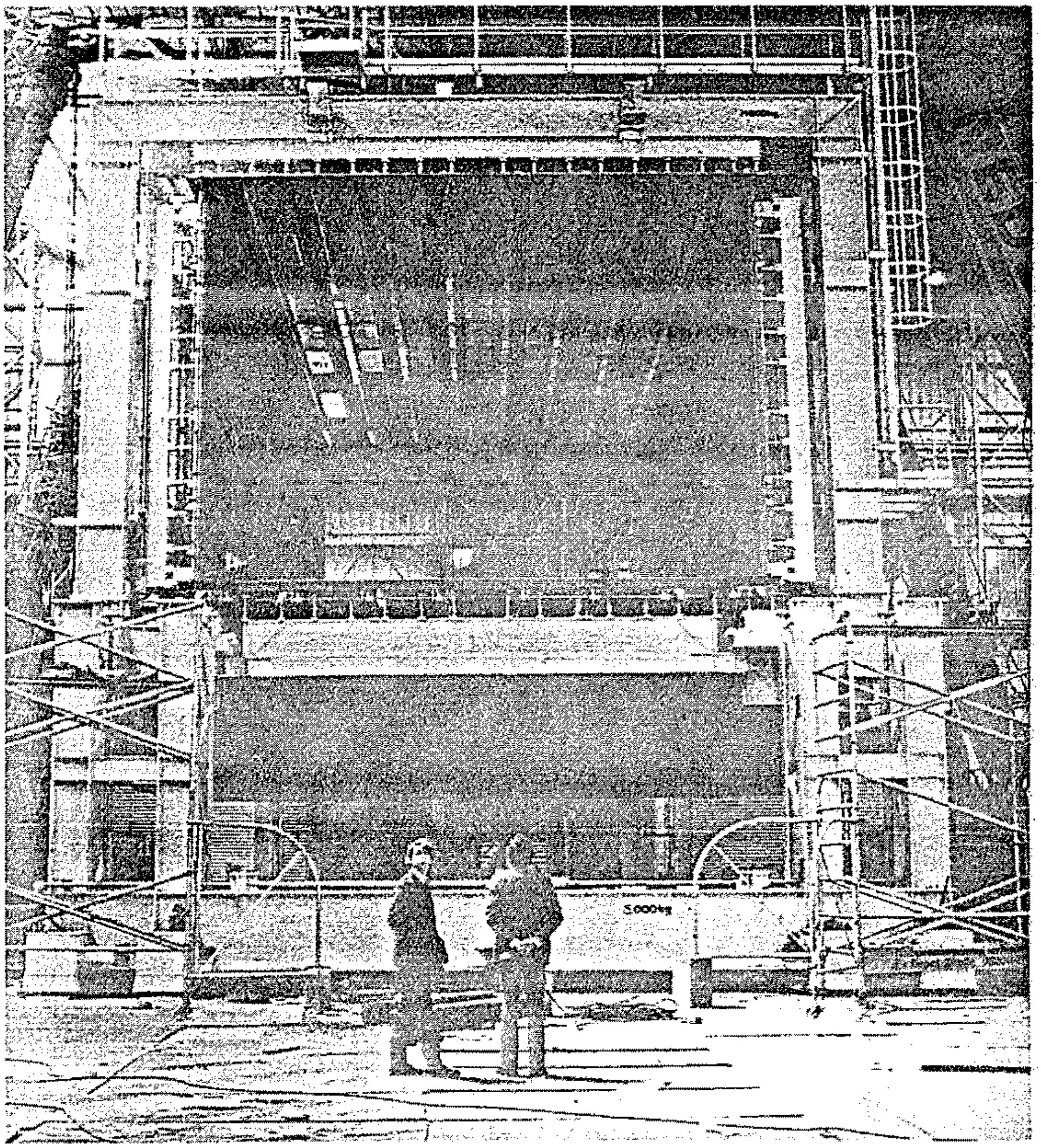
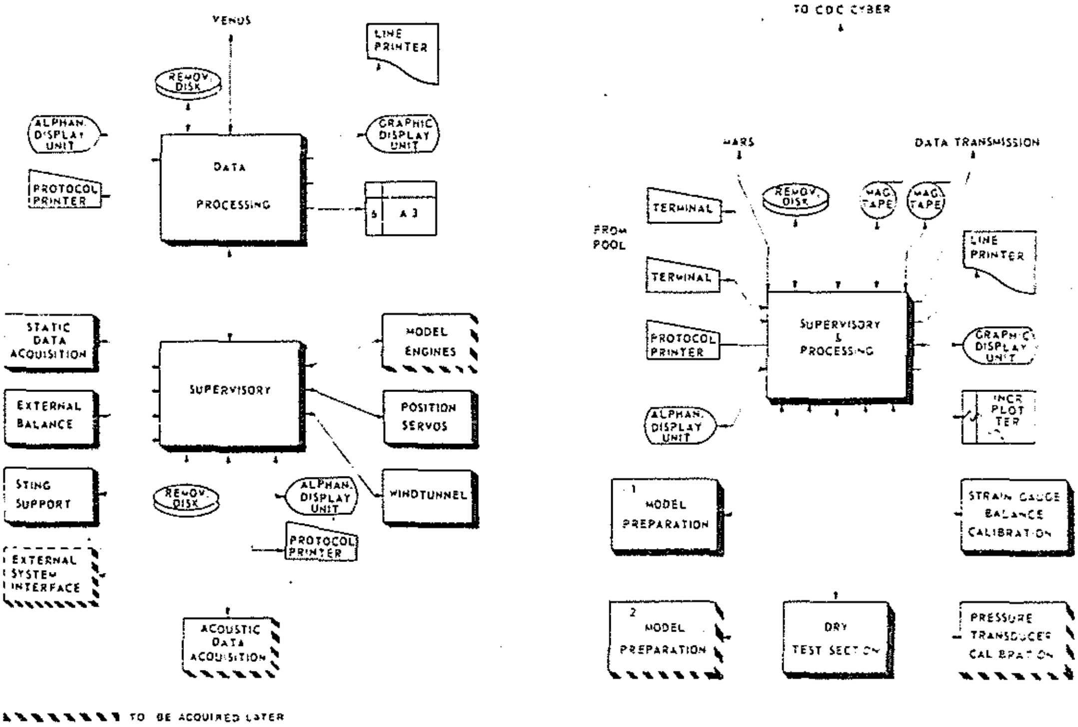


FIG. 5 UPSTREAM VIEW OF THE CONVERTIBLE 8m x 6m TEST SECTION WITH SLOTTED WALLS



On-line branch "MARS" Off-line branch "VENUS"

FIG. 6 WIND TUNNEL DATA ACQUISITION, REDUCTION, AND PRESENTATION SYSTEM

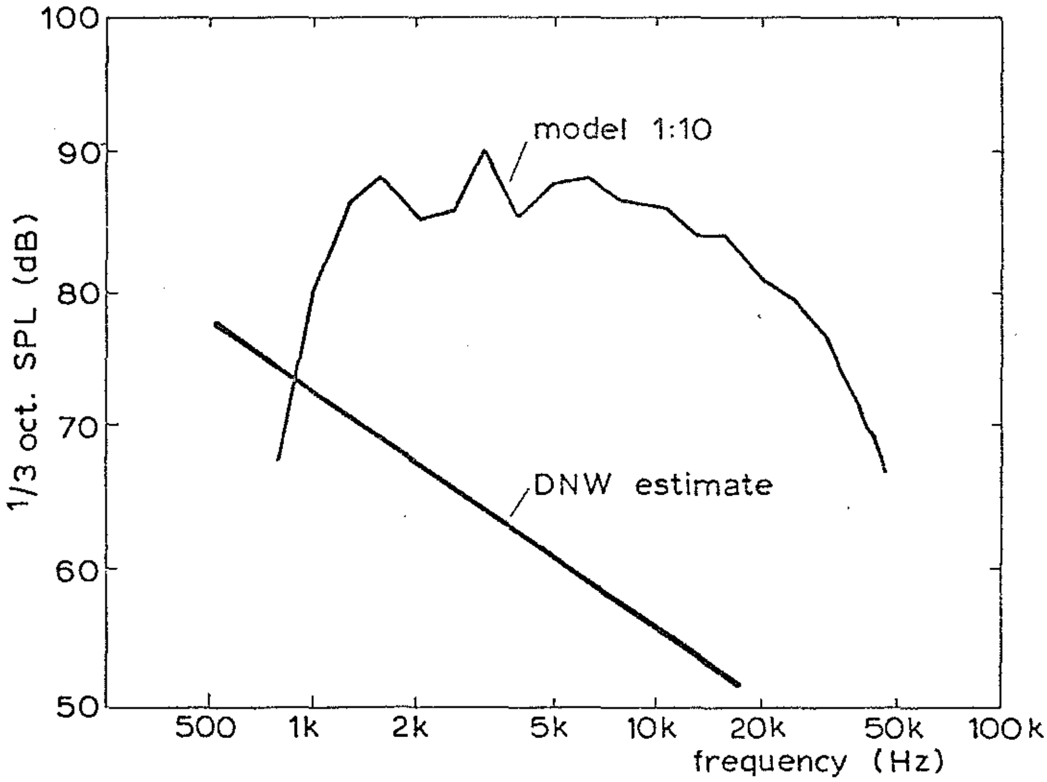


FIG. 7 TYPICAL TAKE-OFF SPECTRUM OF AIRLINER 95 PNdB AT 150m (FAR-36-10 dB)

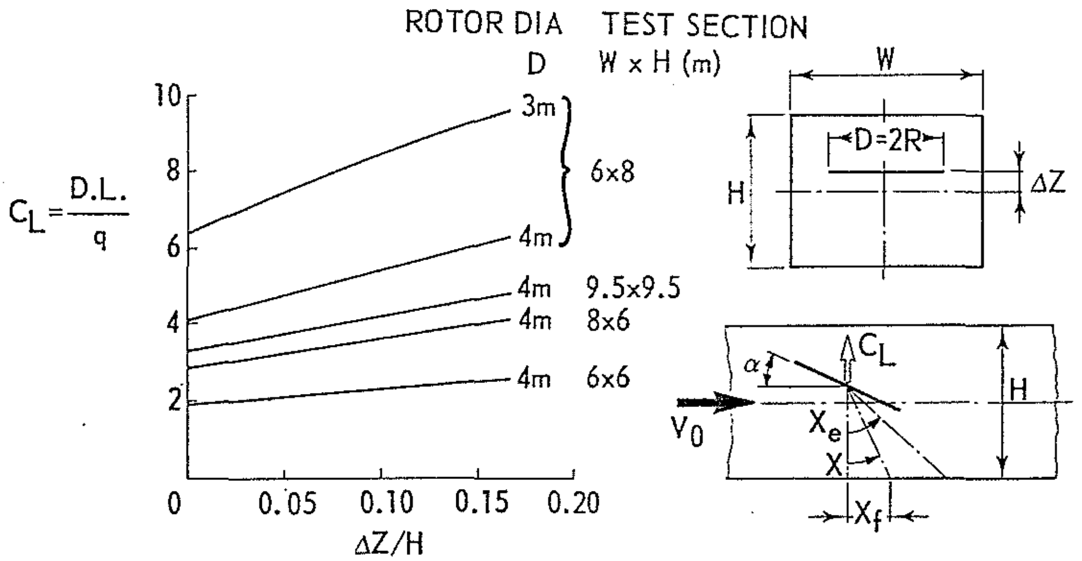


FIG. 8 MAXIMUM ALLOWABLE ROTOR LIFT COEFFICIENTS ACCORDING TO HEYSON's FLOW BREAKDOWN CRITERIA

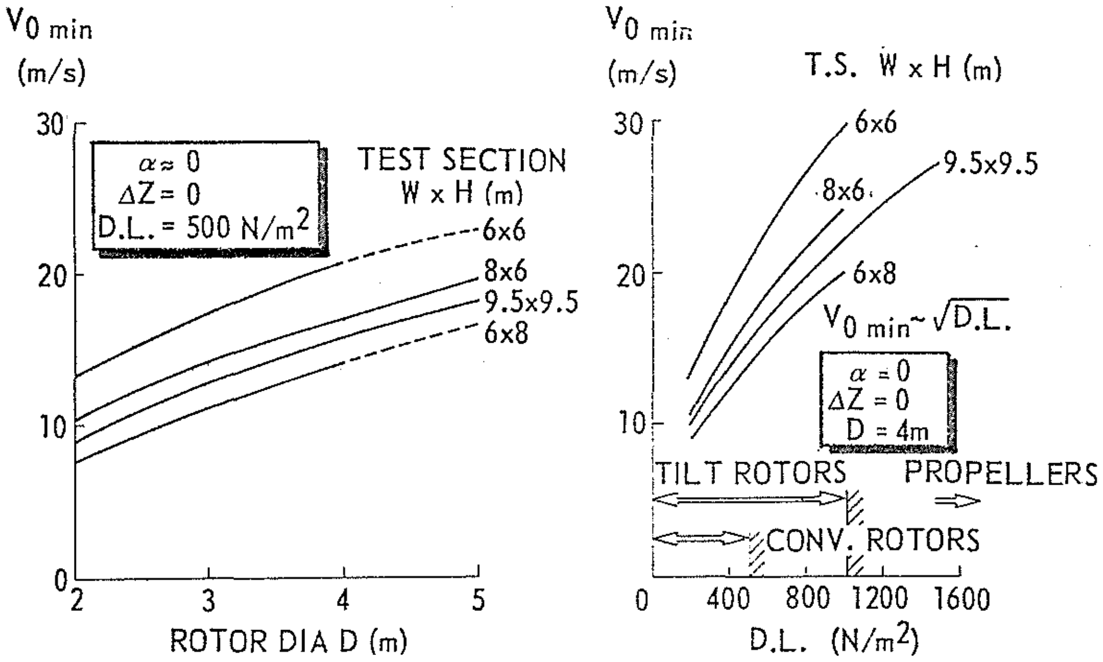


FIG. 9 MINIMUM ALLOWABLE WIND SPEED AT FLOW BREAKDOWN ONSET

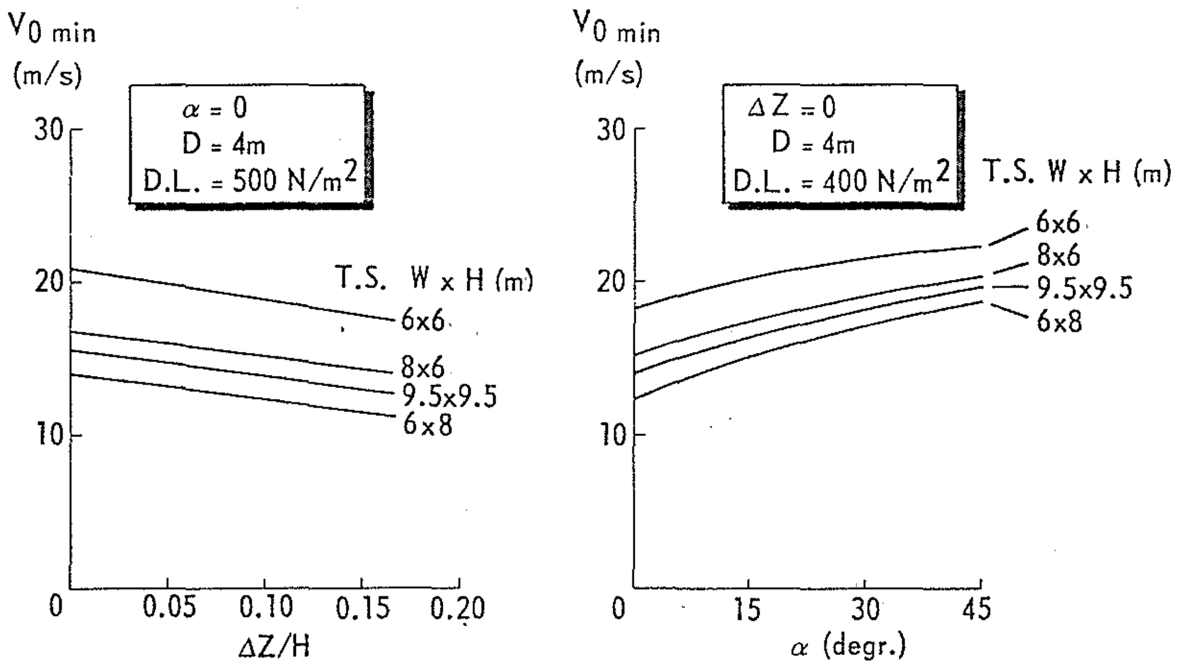


FIG. 10 MINIMUM ALLOWABLE WIND SPEED AT FLOW BREAKDOWN ONSET

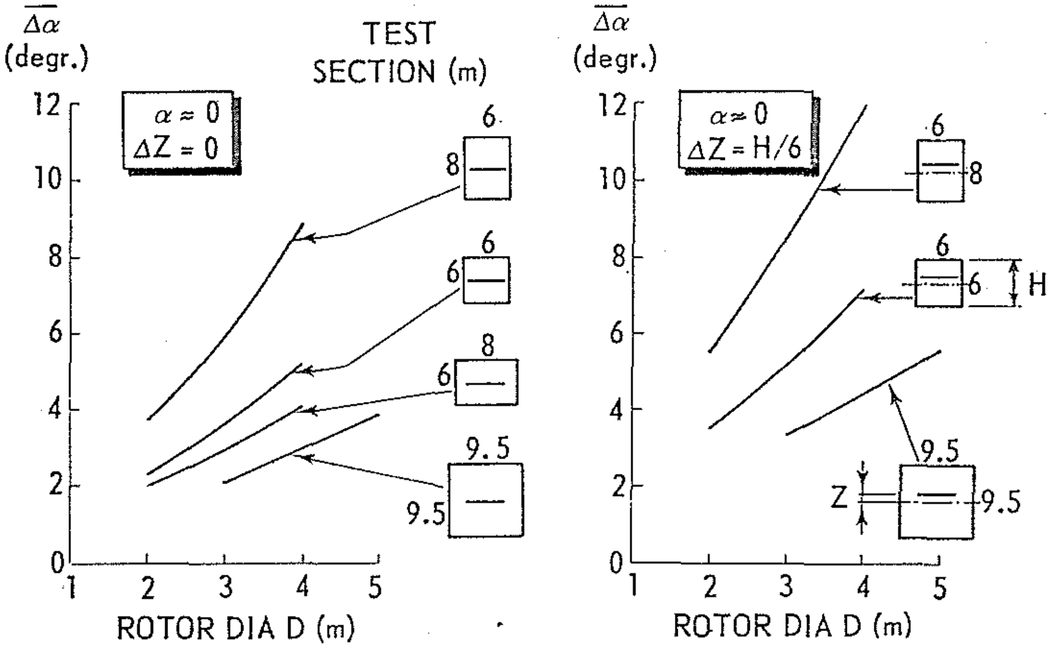


FIG. 11 AVERAGE INCIDENCE CORRECTION $\overline{\Delta\alpha}$ FOR A ROTOR AT FLOW BREAKDOWN ONSET

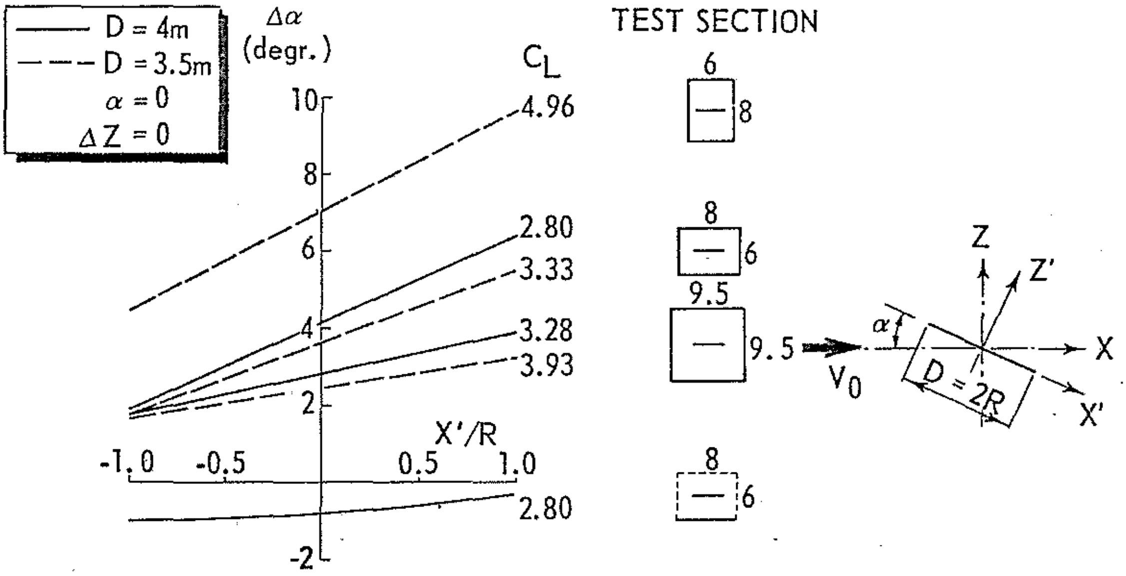


FIG. 12 LONGITUDINAL DISTRIBUTION OF INCIDENCE CORRECTION Δα AT FLOW BREAKDOWN ONSET

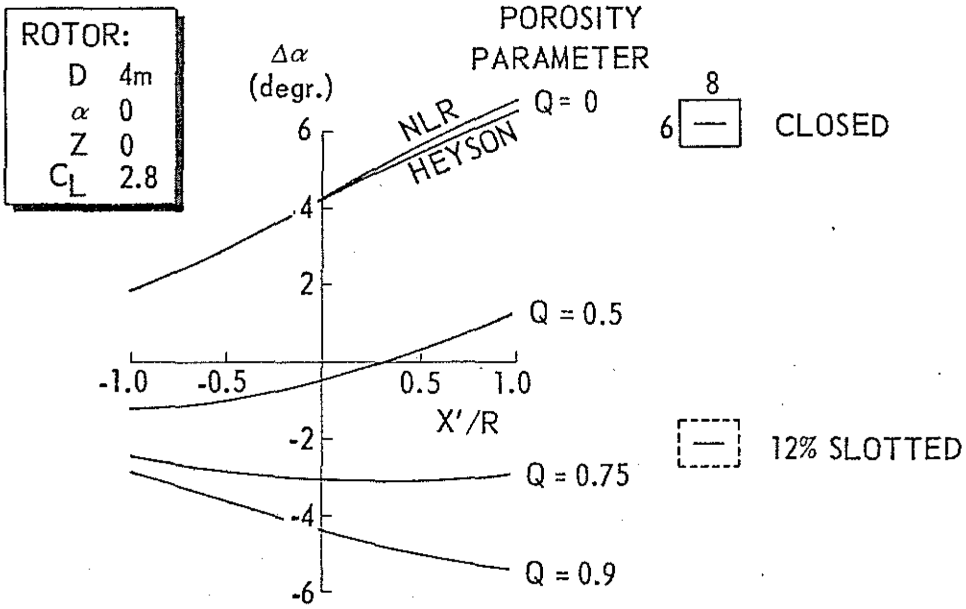
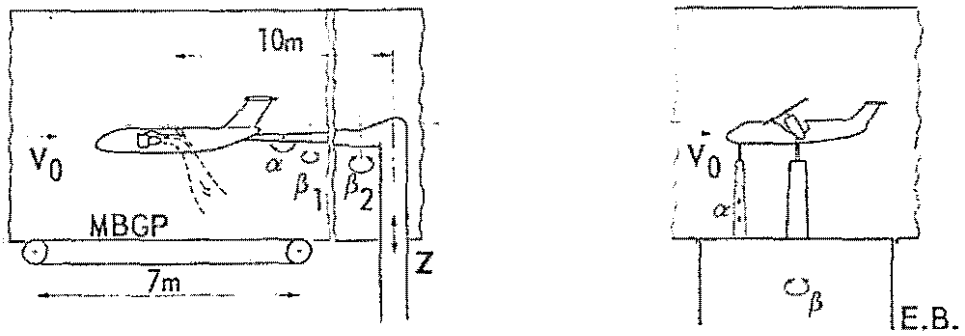


FIG. 13 LONGITUDINAL DISTRIBUTION OF INCIDENCE CORRECTION Δα FOR A ROTOR IN A CLOSED AND SLOTTED TEST SECTION

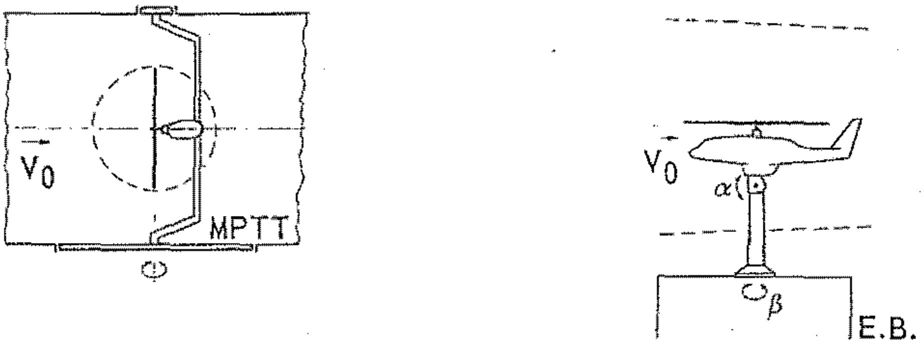


A COMPLETE MODEL ON STING SUPPORT WITH MOVING BELT GROUND PLANE

B COMPLETE MODEL ON EXTERNAL SIX-COMPONENT BALANCE

C HALF-MODEL ON EXTERNAL SIX-COMPONENT BALANCE

D TILT ROTOR TEST RIG ON TEST SECTION FLOOR (MULTI-PURPOSE TURNTABLE)



E TILT ROTOR "CRANK" RIG ON MULTI-PURPOSE TURNTABLE

F HELICOPTER TEST RIG ON EXT. BALANCE SUPPORT (SHOWN FOR OPEN TEST SECTION)

FIG. 14 PRINCIPLE EXAMPLES OF TYPICAL TEST SET-UPS FOR V/STOL AND ROTOR MODELS

MODEL SUPPORT		TEST SECTION				EQUIPMENT FOR MODEL CHECK-OUT AND STATIC TEST IN EXPERIMENTAL HALL
		CLOSED			OPEN	
		9.5 x 9.5	8 x 6	6 x 6	8 x 6 2)	
TYPE	SUITABLE FOR	1) FLOOR SLOTTED	ALL WALLS SLOTTED			
STING SUPPORT	COMPLETE MODELS WITH INTERNAL BALANCE	● + MBGP 3)	● + MBGP	●	●	DUMMY STING
EXTERNAL 6-COMP. BALANCE	COMPLETE MODELS HALF MODELS	●	●	●	●	TURNTABLE
EXT.BALANCE SUPPORT	AS RIG SUPPORT	●	●	●	●	TEST RIG
MULTI-PURPOSE TURNTABLE	AS RIG SUPPORT	●	●	●		TEST RIG
"CRANK" RIG	SINGLE TILT ROTORS + PROPELLERS (PLANE VERTICAL)	●	●	●		(SPECIAL)

1) EXTENSION TO ALL WALLS AT A LATER STATE
2) FOR FAR FIELD NOISE MEASUREMENTS
3) MBGP = MOVING BELT GROUND PLANE

FIG. 15 SELECTED COMBINATIONS OF MODEL MOUNTING RIGS AND DNW TEST SECTIONS

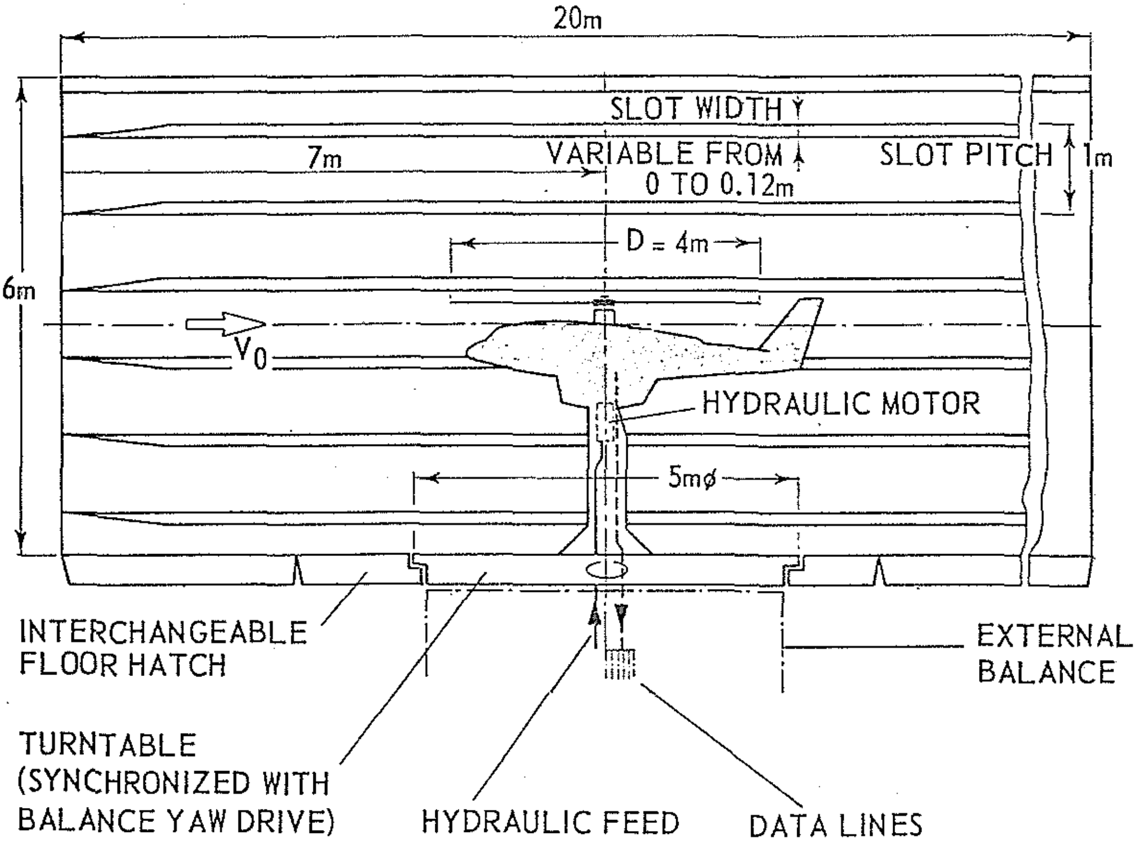


FIG. 16 SET-UP OF THE DFVLR ROTOR AND HELICOPTER TEST STAND IN THE CONVERTIBLE TEST SECTION (LATERAL VIEW)