THE MODERNIZATION PROGRAM OF THE TRANSONIC WINDTUNNEL HST OF NLR: LESSONS FROM THE PAST, PROSPECTS FOR THE FUTURE

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Abstract

The first part of the paper summarizes the experience build up during 35 years of windtunnel testing in the NLR High Speed Tunnel HST. More specifically the Reynolds number problem is discussed together with the need for higher accuracy and more detailed flow field information. The primary goals of the phase 1 modification of the HST, executed in 1992, have been partly derived from this experience: increased test section length, new model supports and modernized tunnel control systems to improve upon accuracy and productivity. Results from validation experiments demonstrate that the HST has retained or improved its good standard of quality. The basic elements of the phase 2 modification, a further increase in Reynolds number, flexibility and productivity following a necessary power plant replacement, are presented. These improvements are essential to maintain and strengthen the complementary role of the HST for aerodynamic research and pre-development relative to other large european facilities like ETW and DNW that are and will be used in the future for final design verification.

1 Introduction

The High Speed Tunnel HST of NLR (Fig.0, 1) is in operation since 1959. The tunnel is characterized by test section dimensions of 2x1.6/1.8 (variable) m^2, a Mach number range up to 1.3 and the ability to evacuate and to pressurise the wind tunnel till 4 bar (Fig.2).

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Although primarily built for the national industry it has played, since its opening, a major role in the aerodynamic development of many flying vehicles in Europe. The larger part of the windtunnel models for the Fokker F-28, the Fokker-100 and the Fokker-70 programs have been tested in the HST. Also several national technology programs were executed. Examples of some european projects involving HST tests are the Concorde, the (early) Airbus development, various Ariane launcher configurations together with numerous projects for customers like Dassault, Aerospatiale, Saab, IAI, DA, Alenia and many others.
The facility has been improved continuously over the years and subsystems have been added or replaced. The basic layout and hardware, however, was still essentially based on technologies of the fifties. Since the early days of the HST, windtunnel test technology has advanced drastically through improved hardware and the introduction of computer aided measuring and control systems. Also new requirements of the aircraft industry asked for new capabilities that could only partly be met. Moreover, international cooperation altered the windtunnel scene in Europe as exemplied by the large subsonic windtunnel DNW operated jointly by DLR and NLR and the construction of the German/French/English/Dutch ETW in Cologne that has become operational this year.
In the eighties, discussions started within NLR how to respond to the new environment. This resulted in the formulation of a modification plan that, because of budget restrictions, had to be realized in 2 phases. Work on the first phase, that was mainly concerned with a test section

modification and new tunnel controls, started May 1992. At the end of the same year the tunnel was operational again. The year of 1993 was extensively used to calibrate and validate the modified HST, together with development work for customers that had to continue.
This paper recalls in chapter 2 some of the lessons learned from over 30 years of windtunnel testing in the HST, notably as far as wing design verification is concerned. These arguments contributed to the definition of the HST modification plan that will be discussed in section 3 together with some typical results of the validation experiments. In section 4 finally an outlook is given of the future role of the HST within the european scene of windtunnel testing.

2 Windtunnel testing in the HST: lessons from the past

2.1 Wing development

In the early days of the HST the major national program was the development of the Fokker F-28 "Fellowship". Extensive windtunnel tests in the NLR facilities supported the wing design. A large number of basic airfoil sections were tested in the NLR transonic pilot facility (PT) using .18 m chord models with a Reynolds number at cruise condition (around Mach=.72) of about 2.2 million. Out of these the most promising candidates were selected for the wing design. A range of full models, half models and partial models were constructed and tested in the HST. Although the larger part of the low speed development was done in the 3x2 m^2 low speed tunnel LST, tests in the HST were essential for the higher Reynolds number that could be realized. A half model was constructed to further increase the Reynolds number, since it was well known that Reynolds number effects had a significant effect on the low speed characteristics. Reynolds number effects at cruise conditions were at that time less of a worry.
In the late sixties Nieuwland[1] at NLR succeeded in designing by theoretical means a shock free supercritical airfoil. The small pilot facility was again used to verify the design experimentally. In a large technology program to investigate the application of supercritical wing technology many more airfoils were designed and tested. To further improve the aerodynamic performance, rear loading was introduced. The high velocity levels connected with locally supersonic flow and the rear loading resulted in strong pressure gradients over the rear of the airfoil with a real risk of separation, either at the shock, terminating the supersonic region or at the trailing edge. Haines, Holder and Pearcy[2] noted already in 1954 the problem of scale effects at transonic conditions. The experience with the C-141 reported by Loving[3] in 1966 dramatically illustrated the problem that separation effects can completely undermine the tunnel-flight comparison.
The early supercritical airfoil tests at NLR were done with free transition to reduce the severity of the viscous effects at the relatively low Reynolds numbers of 2.2 million that could be achieved in the PT. Also measurements were initiated for one of the first supercritical designs (the airfoil NLR 7301) in the Compressible Flow Facility of Lockheed Georgia. Tests could be made up to 30 million in Reynolds number representing the first NLR experience with Reynolds number effects in the transonic regime. This study reconfirmed the notion that tests with free transition give spurious results especially due to laminar shock wave interactions and large variations in transition location. However, the remedy of fixing the boundary layer is only of use when the Reynolds number is high enough to prevent separation near the cruise condition at low tunnel Reynolds numbers. This is similar to saying that a certain critical Reynolds number should be passed for the windtunnel test to be useful. At a much later date the argument has been carried even further by Haines[4] in 1976 stating that Reynolds number duplication is essential for a proper optimization of a wing design. Similar thoughts resulted in the early seventies in the decision to develop cryogenic facilities that could duplicate flight Reynolds number. The aircraft industry could not wait that long and intermediate solutions had to be found either by upgrading existing facilities and test techniques or by developing special methodologies to assess the Reynolds number effects (see section 2.3).

2.2 Reynolds number testing in the HST

The increase in Reynolds number for windtunnel testing was realized in the HST by various means. In 1979 the second stage and half of the fan blades of the third and fourth stage of the originally four stage fan were removed. This increased the fan efficiency and hence the Reynolds number at high subsonic conditions by about 20% at the expense of the maximum achievable Mach number due to blade stall

(Fig.2). This increase, though not insignificant, was not considered sufficient. A further increase was only possible using larger models.
Provisions were made in the tunnel side walls to mount large two dimensional models of .5 m chord and 2 m span resulting in a more than five fold increase in chord Reynolds number relative to the Pilot Tunnel. The high aspect ratio of 4 strongly reduces the side wall effects.
Additionally, blowing is applied at the model/wall junction for the development of high lift devices in the low speed regime to assure two-dimensionality of the flow near maximum lift.
For 3-D wing development half models were used to achieve the highest possible Reynolds number for the HST operating envelope. Much effort was spent on the development of the half model test technique[5]. Half model sizes, typically of 1.2 to 1.4 m span in a 2m wide and 1.6 m high test section, were pushed close to the limit of what seemed to be acceptable. This was only possible by adopting an empirical procedure to correct for wall interference effects based on a comparison with a similar full span model. Since the pressure can be varied in the HST, such a comparison can always be made at the same Reynolds number, an essential condition for such a correction procedure. In this perspective, half model tests are specifically made to supplement the data obtained from full model tests as far as Reynolds number effects are concerned.
In addition to these test set-ups also an inlet test rig was designed to study the inlet flow of turbofan engines at sufficiently high Reynolds number. Since this flow has some similarity to subsonic or transonic flow on wings, Reynolds number effects are equally important both at low and high speed conditions.
In the figures 3 and 4 the Reynolds numbers for the various test set-ups as can be realized at present in the HST are given. These new test set-up's have been commissioned and validated around 1981 during the development period of the MDF-100 (a cooperation between McDonnell Douglas and Fokker to launch a 100 seater that lasted till 1982). In the subsequent development of the Fokker 100 the half model technique proved to be essential for the prediction of the low speed and cruise characteristics[6,7].
These new possibilities have triggered a concentrated research effort leading to an improved understanding of Reynolds number effects. Part of this experience is reflected in reference [8] and will be discussed shortly in the next section.

2.3 Reynolds number duplication, simulation or extrapolation

On an AGARD conference in 1971[9] the conclusion was reached that it was essential to duplicate the flight Reynolds number in the wind tunnel in order to eliminate the risk of a design failure. Soon after that occasion the cryogenic technology appeared to be the most promising to realise the required Reynolds numbers and this resulted in the development of the NTF in America and some time later the ETW in Europe. In the mean time, there was an urgent need to refine the usual test procedures in the existing facilities for a better prediction of the flight characteristics.
To this end the Fluid Dynamics Panel of AGARD established in 1984 working group WG-09 on "Wind Tunnel Boundary Layer Simulation and Control". It was the aim of this working group to define a methodology to derive the aerodynamic characteristics at flight Reynolds numbers from wind tunnel tests at lower tunnel Reynolds numbers. When duplication of the flight Reynolds number is not possible because of limitations in the windtunnel, two different approaches can be followed in an attempt to close the Reynolds number gap: extrapolation through Reynolds number variation and simulation using the aft fixation technique (Fig.5). In the final report of this working group[10] different scenario's are described depending on the severity of the Reynolds number effects for a particular configuration. In the methodology a mix of different approaches is suggested: simulation followed by extrapolation and guided by CFD methods.
Two important notions should be recalled here. First, in the scenario's a "critical Reynolds number" (R_{crit}) is introduced (Fig.6). Below this Reynolds number significant "premature" separation occurs that effects the flow in a non-correctable way. Beyond R_{crit} the Reynolds number trends are believed to be gradual, (normally) monotonic and correctable. There is not such a thing as a critical Reynolds number beyond which the flow does not change anymore (for ideal smooth surfaces).
Of course, duplication of the flight Reynolds number in the wind tunnel would eliminate the need for such a methodology. When this is not possible, testing beyond the critical Reynolds number would be the next alternative (Fig.7). The results would still be meaningful though they have to be corrected to flight conditions. In the aft-fixation technique the effective tunnel Reynolds number can (within certain limits) be

shifted beyond R_{crit}. In other cases, depending on the design, the maximum tunnel Reynolds number that can be realized on a large half model may already exceed $R_{crit.}$ In that case one can do without the more expensive and complicated aft fixation technique or restrict its use only to the verification of the extrapolation procedure for some isolated points. R_{crit} will depend on the severity of the Reynolds number effect of a particular configuration in relation with its aerodynamic characteristic. In a practical design one would like to have some margin between R_{crit} and R_{flight} for the growth potential of the aircraft and to reduce the design risk. A factor of 2 can be regarded as an absolute minimum. A factor of 10 would probably make the design too conservative. These rather loose arguments suggest that a factor of the order of 5 between R_{tunnel} and R_{flight} might still be acceptable for useful aerodynamic data, even for a critical design, resulting in a *minimum acceptable* Reynolds number of 6 to 10 million in the tunnel.
It is to be expected that in the near future results from the cryogenic facilities will shade some more light on the nature of Reynolds number effects and this will certainly influence the use of conventional windtunnels.
The second notion is the application of CFD methods to supplement the experimental information. The use of CFD codes to assist the extrapolation between between R_{crit} and R_{flight} is a good example how CFD and the wind tunnel can be complementary.
This of course is only possible with well validated CFD methods. For this purpose experiments are needed that show the change of characteristics over a range of Reynolds numbers. The NLR airfoil 7301, tested in 1985 in the HST, is an example of such a validation experiment[11].
Finally the importance of the Reynolds number problem for take-off and landing configurations should be emphasized. At transonic conditions the Reynolds number problem (for fixed transition) results from complicated interactions between separation at the foot of the shock and at the trailing edge. For multi-element wings at take-off or landing conditions, many more phenomena like transition, laminar separation, bubble formation and bubble burst to name a few, are interacting with each other. As a result of this the Reynolds number trends appear to be less predictable and less monotomic as for *transonic flow conditions*[12]. The use of the aft-fixation technique is almost impossible for these conditions. Reynolds number sweeps are still important to assess the sensitivity of the flow to a Reynolds number variation but extrapolation based on these results requires a very careful interpretation of the flow itself. The separation of Reynolds number and Mach number effects is essential for such an analysis.

2.4 The quality of information: accuracy aspects

The extensive technology program on supercritical wings in the 70'ies made it very clear that the achievable accuracy of test results on the HST was not sufficient. Aircraft design modifications are typically assessed on the basis of differences in the order of one drag count[13] ($\Delta C_D = .0001$). This corresponds to a required accuracy in incidence of $\Delta\alpha = .01°$ and in an allowable static pressure variation along the fuselage of less than $\Delta C_p = .001$.
To increase the repeatability of the test results, improvements in three area's were necessary: the measurement of the model incidence, the balance and Mach number control during an α-sweep. At that time the incidence was derived from the angular position and deformation (derived from the balance loads) of the model support. The existing support boom/sting/balance combination showed some mechanical deficiencies. This resulted in poor repeatability. For that reason it was decided to measure the model position directly with an optical system that uses two light sources in the fuselage[14]. In order not to rely exclusively on the optical system for incidence measurements, it was still essential to make the model support systems more rigid.
Secondly, a new type of monoblock balance was designed to replace the existing balances. Finally, the Mach number control was optimized such that Mach variations during an incidence sweep were of the order of .001 at most. The results of measurements on a reference model made over a period of 2 years (Fig.8) indicated that the repeatability improvement was actually achieved. It should be noted here that this result was achieved for routine testing, using the standard sweep rate of .25 °/sec.
In aircraft development the study of derivatives of existing configurations has become more and more important. This very often involves an increase in wing area and fuselage length. In some cases model dimensions were pushed very close to the limit in order to use as much as *possible existing model elements*. Analysis of the test results with an increased fuselage length showed unexpected drag variations, both in

fuselage drag and drag creep. The problem appeared to be related to the fact that for these larger models the fuselage nose actually penetrated the transition from the closed to the slotted part of the test section (upstream of the model). This introduced a Mach number dependent static presure gradient over the model nose, giving spurious drag results.
This example illustrates a more general feeling that for the HST an increase in test section length would be beneficial. This is particular true for half model testing where Mach number dependent static pressure variations at the nose and tail of the fuselage necessitate large corrections.
A typical hierarchy in the experimental uncertainty is resolution, instrumental error and bias error. Of these uncertainty sources, resolution and instrumental error can be quantified (see e.g. reference [14]). However, the bias errors are by far the most difficult to assess. For the aircraft industry the tunnel-to-flight comparison is of course highly relevant. However, such a comparison involves a number of extra uncertainties e.g. configuration differences, deformation of aircraft and windtunnel model, the engine characteristics and Reynolds number differences. In-house methods are used by the aircraft industry to assess the relevance of the experimental data obtained in the wind tunnel. Very often differences between wind tunnel and flight are carried over from one aircraft configuration to the other (the "delta-method"). The justification of this procedure goes back to the necessity to reduce or eliminate possible bias errors. Although this procedure provides insight in some typical problem area's, it is less suited from the point of view of windtunnel test techniques to assess possible bias errors in a systematic way.
The dominant sources of bias errors are wall and support interference, flow quality and the Reynolds number deficiency (including transition strip effects). Some indication of bias error is derived from tunnel-to-tunnel comparisons on one and the same model (see e.g. for the HST reference [16] and [17] for high and low speed configurations respectively). However an independent assessment of the origin and magnitude of possible bias errors should follow from specific research into these problem area's.
For ventilated wall windtunnels, wall interference correction methods have not yet been advanced to a state where corrections are possible with the required accuracy. The most promising developments are based on the so called "measured boundary conditions" and require pressure information on all tunnel walls to derive the wall interference flow field. NLR has been active in this field for many years now. For the two-dimensional test set-up in the HST, wall interference corrections are derived routinely on the basis of measured wall pressures[18]. Before the HST modification the application of this technique to half models was impossible due to the limited test section length.
Support interference effects are next in importance to wall interference effects. They are closely related to the tunnel calibration itself as will be illustrated in section 3.5. In the eighties a study was initiated in collaboration with MBB-Bremen (now DA) to derive a methodology to correct for support interference effects based on a mix of contributions derived from the tunnel calibration (for various model supports), some limited additional experiments and CFD-calculations. This study[19] resulted in reliable corrections for the lift and pitching moment but needed improvement as far as drag was concerned. The inclusion of wall interference effects and a better understanding of the tunnel calibration itself were considered key elements in a further study. Especially in view of the importance of the tunnel calibration itself, it was decided by NLR to continue the study of support interference effects after the HST modification, as will be reported in the next section.
Accuracy assessment, notably in an absolute sense (what is equivalent to estimating a possible bias effect), is expected to be more and more important in the future. Firstly, within the framework of "Quality Assessment" industry will ask not only for the measurand but also for the related uncertainty. This is a rational and essential step in "Quality Assessment" from the suppliers up till the customers.
The validation of CFD methods to be used in the design process calls for an uncertainty estimate. Giving the rapid advancements in CFD methods, the point is reached where a possible discrepancy between a windtunnel test result and the results of a CFD calculation can only be resolved by having both parties investigating in detail the possible error sources. This will result in the future in more experiments that are specifically designed for and in close co-operation with CFD specialists for validation purposes[11].

2.5 The extent of information: more flow detail

Improvements in aerodynamic design within the small margins still available require a good knowledge of the flow. The ever increasing role of CFD methods in the design process allows a detailed analysis and understanding of particular flow phenomena. These developments strongly contribute to an increasing demand for detailed flow field information. However, as a result of the high operating costs of large windtunnels, this can only be done in a cost effective way with high productivity techniques. Typical examples of developments in the last decade that meet this requirements and have been implemented in the HST are the infrared technique for transition detection, combined and continuous sweep force and pressure measurements using EPS modules, the laser screen technique, computer controlled probing of the velocity field using 5-hole probes (Fig.9) and fast moving total pressure rakes for wake drag analysis (Fig.10). Some of these methods are described in more detail[20]. Others, like pressure sensitive paint and PIV are presently being developed. The wake drag measurements are particularly helpful in the evaluation of Reynolds number effects on large half models. With the traversing wake rake a complete scan of the total pressure losses behind the wing, as typically illustrated in Fig.10, can be made in 90 seconds. This technique will be further developed to map complete flow velocity vectors to derive drag components. It is to be expected that high productivity methods that yield surface or flow field information will become increasingly important.

2.6 The rate of information: productivity

Since the beginning of testing in the HST a tremendous increase in "overall productivity" has been realized. An important step was the ability to perform continuous force measurements (before the HST modification typically executed at rate of .08°/sec or .25°/sec depending on the Mach number). This was only possible with adequate filtering techniques (that preserved signal synchronization) and automated Mach number control.
A further limitation to increase the sweep rate was imposed by the mechanical design and drive of the model support booms. Note that the results shown in Fig.8 have been obtained in the continuous sweep mode at a rate of 0.25°/sec.

The rapid developments in data acquisition and data reduction techniques contributed most significantly to the productivity increase.
Before the HST modification of 1992 the tunnel control constituted a basic limitation to a further increase in data rate. The original tunnel control system of the HST was essentially based on relay technology from the time of the construction of the HST in the fifties. Although parts of the system were improved (e.g. Mach number control) a new integrated approach was considered essential for a further productivity increase.
Another important limitation in a further productivity increase is the power plant that drives the HST fan. This steam power plant consists of six boilers. By the control of steam to the turbines the fan speed is held more or less constant. Most of the elements of the power plant were bought in the late fourties out of American war surplus escort vessels (destroyers) and later integrated in the drive system. It takes considerable time to start and cool down the power plant. When energy is available, the rate of increase of the drive power is limited by the thermal lag of the boiler/turbine combination. Improvements in this area would significantly reduce the starting and stopping times of a tunnel run.

3 The HST Modernization program: present status

3.1 Basic goals

The primary goals at the outset of the HST modification program follow from the previous section:

- An increase in test section length meant to reduce the effect of flow non-uniformities at the slotted/solid wall transition (for long models and half models). This also allows a better application of wall interference correction methods based on measured wall pressures and/or installation of flexible walls to eliminate wall interference almost completely.
- New model support systems to provide larger attitude ranges for improved productivity and more repeatable results. They are also laid-out for higher loads to cope with higher dynamic pressures when the power level will be increased in the second phase.

- A complete modernization of the tunnel control system, including a new control desk and improved control of the power plant. This is meant to open the way to a further increase in tunnel productivity through automation.

All these goals have been realized in the first phase of the HST modernization program. The second phase modification will be primarily related to the power plant and tunnel drive system with the aim to increase the Reynolds number, the productivity and the flexibility in operating the HST at lower costs. The inclusion of flexible walls in this phase is still a matter of study. This will further be discussed in section 4.

3.2 Test section

The test section length was increased by 1.15 meter in downstream direction, limited by the bulkhead of the plenum (9 m diameter) surrounding the test section. The strut for the model support mechanisme was moved downstream over the same distance. This also allowed the use of a high incidence support mechanism (the "articulated boom") that differed essentially from the existing "yaw-boom" in its kinematics, significantly increasing the possible attitude range. Figure 11 shows the essential differences due to the test section modification.

The increase in test section length causes an equal decrease in diffuser length and a corresponding increase in diffuser entry area. It is clear that a higher test section would reduce the problem of matching the diffuser to the test section. A higher test section is also attractive to allow larger incidence ranges without compromising on model length. This however would reduce the maximum Reynolds numbers whereas it was uncertain how the supersonic characteristics would be effected when the original nozzle shape was maintained. Therefore it was decided to have the opportunity to select between two test section heights, namely 1.6 and 1.8 m. With the existing structure of the test section this can easily be done because the parallel side walls already extended over more than .5 m below the floor and above the ceiling. By providing the first 2 meters of the diffuser with movable flaps in the ceiling and floor, the diffuser can be tuned in an optimal way for both test section heights. The side walls between test section and diffuser were newly shaped to compensate for the strut blockage. Extensive test in a 1:4.16 scale pilot tunnel (the PHST, the modified pilot tunnel PT as mentioned in section 2.1) had indicated that the angle of the slat extensions and the flaps are crucial for the energy losses and the static pressure gradient in the test section. Therefore it was decided to adjust these angles during a tuning process when commissioning the new tunnel. The first tests in the modified HST confirmed that the static pressure gradient over the test section length is extremely sensitive to small geometry changes in the transition region from slotted walls to diffuser.

Relative to the original situation a slight deterioration in maximum Reynolds number capability was found (Fig.2b). This relatively small loss in Reynolds number can easily be compensated in the the next phase of the modification.

3.3 Transonic model supports

The new model support was required to be stronger (anticipating an increase in Reynolds number in phase 2), more rigid (to improve the repeatability of the angle of incidence), more movable (to increase the attitude range), possibly combined with a smaller upstream influence. It is clear that compromises had to be made. In order to meet these conflicting requirements it was decided to use exchangeable booms on a vertically movable strut that had a fixed incidence mechanism at the strut/boom junction. Three boom types were selected: a straight boom, a double roll boom and an articulated boom (Fig.12). The operating ranges of the various booms are depicted in Fig.13. The straight boom (SB) was especially designed for accurate drag performance tests at transonic cruise conditions. This boom could be kept slender at the expense of yaw capability for an incidence variation of $\pm$ 15°. The double roll boom (RB) provides a combined yaw ($\pm$ 10°) and incidence (-5° to 25°) range. Also the strut movements, including the incidence mechanism on the strut, remain active, such that in total four degrees of freedom are in operation during a movement.

The movement of the strut is, like the booms, computer controlled. Usually an incidence sweep at constant yaw angle, wing level yawing (impossible with the old "yaw boom") or a rolling motion will be selected. Both the straight boom and the double roll boom can be extended upstream by inserting a .6 m respectively .45 m filler block just in front of the strut incidence

mechanism (named E(xtended)SB and ERB respectively). The articulated boom (AB) is less slender than the others but provides maximum attitude variation. Yaw and incidence ranges are ±30° and from -5° to +45° respectively. In total 5 degrees of freedom might be in operation during the movement of the boom.
Each motion of the sting support mechanisme is achieved by an electric motor that drives a mechanical screw spindle or rolling mechanisme through a harmonic drive. All support booms can be operated at a maximum incidence rate of 1°/sec. The (rotation) position is measured by a pair of resolvers (the two automatically checking each other) with an accuracy of .005°. Also each electric motor has an internal resolver for inner loop control. At the end of a specific motion, i.e. close to the set point, an outer loop control becomes effective using the data from the position resolvers on the axis to control the motion exactly to the set point. This control system is part of the tunnel control system that will be discussed below.

3.4 Control system

The introduction of a new control system based on an entirely new control policy required the complete renewal of all control hardware including all cabling, actuators and sensors. The new control system allows full automatic tunnel operation with graceful degradation to lower control levels if wanted or needed. The lowest level of control is the manual level from the central desk at which the operator is directly responsable for the movements of the actuators. This level is similar to the situation before the modification process.
The next level is (stand alone) computer control where the computer calculates the required set-point or control path during a sweep for a complex movement (like a beta-sweep at constant incidence for the double roll boom). It is also possible to hold a specific tunnel flow condition constant (e.g. Mach number, Reynolds number, speed, dynamic pressure, total pressure) at a preset value during a model sweep.
In the integrated control level the different sub-systems (e.g. tunnel control, model support control, probe control, model engine control, data acquisition, data processing) may use data from anywhere in the control system. This level makes it possible to do dedicated measurements, e.g. the determination of drag creep at constant lift and/or controling to corrected control parameters (e.g. incidence or Mach number) so that online data presentation and data consistency is highly improved.
Integrated control also allows combined model and probe control in a predetermined sense.
In the automated control mode the sequence of commanding the control computers of the various subsystems is defined by the test automated system. This system is not yet in full use but will ultimately increase the productivity by an estimated 30%.

3.5 Some results from calibration experiments

The tunnel calibration was derived from long static pipe measurements. The pipe was supported far upstream with wires in the settling chamber and at the downstream end in one of the support booms. By mounting the long static pipe directly into the strut an "empty" test section calibration (no support booms present) could be obtained. A number of calibrations have been obtained with wire suspension also at the downstream end to better simulate the effect of a deflected support boom as e.g. used for a Z-sting model support (see Fig.14). The empty test section calibration is Mach number dependent (see Fig.15a), as was also the case in the old HST. The average Mach number gradient appears to be related to the detailed geometry at the transition from slotted test section to diffuser. Due to the direct effect of the model support itself, the final Mach number gradient along the test section center line depends also on the actual model support (Fig.15b).
In Fig.16 the buoyancy effect on drag for a particular reference model measured before the tunnel modification on the so called "slender support boom" is compared with the "straight boom" (SB) and the "double roll boom" (DR) after the HST modification. The old and new low drag supports show a comparable buoyancy effect whereas the "double roll boom" shows much higher values due to the larger volume. The figure suggests that buoyancy effects are largely due to the model support boom.
Further evidence for this is obtained from an additional study on model support effects. In this study a model of a transport-type configuration was mounted on the so-called subsonic model support (Fig.17). With an internal balance the overall forces and moments on the model could be measured. Next the transonic model support boom was moved from a position far away to a representative location close to the model. The resulting drag variation experienced by the model

represents a "far field" effect of the support interference. It can can be compared with a buoyancy contribution derived from the long static pipe calibration. The agreement, as shown in Fig.18 is acceptable and confirms the validity of the calibration procedure. (Note: this excercise was part of a much larger investigation to derive support interference effects by splitting up the interference field in a "near" and "far" field contributions (see Ref.[19] for a discussion of the basic method); as a further illustration the effect of interference corrections for the same model for a FIN and Z sting mounting respectively is shown in Fig.19). Since the buoyancy effect is mainly due to the model support boom, a further reduction in buoyancy can be realized by moving the model upstream on a longer sting. The new model support booms have been prepared for this and a special mechanism has been designed to rigidly mount the sting to the booms instead of the existing cone connection. However, the formerly used stings with cone ends can still be used with sting adapters. For this short and long (slender) adapters are available (named SCA and LCA respectively).
A selection of calibration results in the supersonic flow regime is presented in Fig.15c. The results are comparable with what has been obtained before the tunnel modification. There is still room for improvement, notably by better contouring the transition from the adjustable nozzle block to the fixed part of the test section.
Finally some results are presented of noise measurements executed in the new HST (Fig.25). The measurements have been made with Kulite pressure transducers (filtered between 10 and 10.000 Hz) mounted on the NLR cone (similar to the standard AEDC cone). The results indicate a slight decrease in noise level that most likely can be contributed to reduction of downstream noise due to the more downstream position and better shaped strut.

3.6 Some results from validation experiments

Tests on different configurations have been made during 1993 to validate the modified HST. The aim of these tests was twofold: to show that the results were consistent in itself and to show the relation with tests made before the modification of the HST. These tests were either made with customer supplied models or with the HST reference model. The latter is representative of a transport type configuration. To obtain the most accurate results possible the model was equipped with the optical incidence measurement system and the newly developed high accuracy balance (see section 2.4).
As discussed in section 2.4 inconsistent variations in drag level were obtained in the HST before the modification when the fuselage length was increased and/or when the model was moved upstream in the test section. This situation has been drastically improved in the new test section. By mounting the model with the long (LCA) or short (SCA) cone adapter on the straight boom with (ESB) and without (SB) the filler piece, various model positions can be realized in the test section (Fig.20). In Fig. 21 a comparison is shown of the lift, drag and pitching moment characteristics for the three tested model positions (the SB+SCA configuration was not measured since this was considered to be too far downstream). (Note that only two Mach numbers are presented for clarity; C_{DNT} is the drag with the ideal induced drag subtracted). Other measurements, not shown here, showed no appreciable differences when the test section height was increased from 1.6 to 1.8 m.
All these results indicate that wall interference effects are probably absent or at least identical for all tested model positions and tunnel configurations. Only the drag shows some increase when the model is moved to the most forward model position (ESB+LCA). The model is then at the same location relative to the beginning of the slots, as it used to be before the HST modification. It is believed that blockage induced static pressure variations over the model nose are responsable for the difference. This was one of the reasons to increase the test section length. On the basis of this and similar comparisons, the optimum support configuration is chosen to be the straight boom with long cone adapter (SB+LCA).
In Fig.22 a comparison is shown of test results on the same model before and after the HST modification. The model was again (as above) mounted on a Z-sting, on the "slender support" before the HST modification and on the "straight boom" (SB+LCA) after the modification. The comparison is favourable, suggesting that the modification of the test section has not altered the wall interference (free?) effect. This result is reassuring, though expected. Extensive tests in the PHST had already indicated that the slot geometry should be retained for minimum wall interference.
Two sets of drag comparisons have been presented. They correspond to buoyancy correction obtained with the support boom in the

mid-position (Fig.14a) and in the Z-position (Fig.14b) respectively as measured before and after the HST modification. The comparison shows some discrepancy in drag level. The calibrations in the modified HST have been made more extensively and more detailed than before. They appear to be consistent in themselves. For that reason it is believed that the most recent results are more reliable. The observed discrepancies illustrate the problem of absolute accuracy as discussed in section 2.4. Small static pressure variations along the tunnel axis will have a large effect on drag. This necessitates a careful calibration process in combination with wall- and support interference studies. Fortunately, the results indicate that transonic drag creep does not appear to be effected.

Finally some validation results are presented for the double roll boom mounting. Fig.23 compares the same reference model, this time including the tailplanes, mounted on the straight boom and the double roll boom (RB). The comparison is quite acceptable and illustrates that the buoyancy drag corrections (e.g. compare with Fig.16) are adequate. A comparison for the a-symmetric components before and after the HST modification shows very good agreement as Fig.24 indicates. Some small a-symmetries that could be observed before the HST modification are eliminated or reduced.

From these and other calibration and validation tests one can conclude that the modernized HST has retained or improved the good aerodynamic characteristics from the past. In addition the modernization has opened new possibilities for more accurate and more advanced measurements in the years to follow.

4 The HST: Prospects for the future

4.1 The phase 2 modernization program

The phase 1 modernization of the HST concentrated on the test section and the control room. The phase 2 modification, that is discussed now, will be mainly concerned with the power plant and the drive system.

The steam boiler plant will require in the near future a further updating in order to meet the forthcoming environmental rules set forward at the end of this decade in The Netherlands. An alternative is to hook-up to the public power grid being feasible now since a nearby power-substation has recently been upgraded. From a cost point of view the last alternative seems to be attractive but the pro's should be weighted against the con's of power extraction limitations during peak hours.

Hook-up to the public grid will easily allow a power increase since the fan design allows 25% higher power supply. This will improve the Reynolds number capability to the same extent. Furthermore, the starting and stopping times will be highly reduced yielding a much more flexible tunnel operation. Of course, the capacity of the cooling system must be improved with the increase in power level.

Since the fan has been aerodynamically designed for supersonic conditions in the test section a re-design is being considered to yield higher efficiency at high subsonic speeds, possibly penalizing the performance at supersonic speeds. The fan pressure ratio should not be further diminished. Fig.26 gives an estimate of the tunnel performance after the modification phase 2 has been completed.

The option to install flexible walls is (still) being studied. Flexible walls would mean a real significant step ahead in absolute accuracy of test results. It would also reduce the aerodynamic losses in the test section and hence lead to a further increase in Reynolds number. This should be weighted against a possible loss in accessability of the test section and the increased complexity, possibly resulting in a loss of repeatability and productivity.

4.2 The mission of the HST in the future

In Fig.27 the Mach-Reynolds number performance of the HST is presented in relation to some other european facilities. The HST "touches" in a performance sence on three other major facilities that have or will be used for "final design verificaton": an almost complete overlap in Reynolds number with the low speed facility DNW (of course for different model sizes), an overlap at the lower Reynolds number end of the ETW (for almost the same model dimensions) and a seemless transition to the supersonic flow regime of the SST (using essentially the same model). The position of the HST between these facilities reflects that the HST has the potential to play a role in the future in basic configuration studies and pre-development work at low costs that proceeds the development and final verification of designs in the large european facilities. There are some necessary conditions that have to be fulfilled however:

1 The Reynolds number should be sufficiently high in order to obtain useful data. In the low speed regime the DNW Reynolds numbers are duplicated. For the high speed regime it has been argued in section 2.3 that the Reynolds number should exceed a critical limit of 6 to 10 million under which significant separation might be present for a critically optimized design. With the additional Reynolds number increase described in section 4.1, this critical value is met, certainly on half models. This will also allow a Reynolds number variation over a sufficiently large range to support and validate the use of CFD for Reynolds extrapolation.

2 The conclusions reached from tests in the HST should be transferable to the other facilities. This necessitates a high and well proven absolute accuracy. Further work in this area is necessary and will be intensified (notably on sting and wall interference effects and half model test technique). The modified HST with its long test section is a good starting point for this development. The already noted overlap in Reynolds number has the advantage that meaningful comparisons can be made with other models in different windtunnels at the same Reynolds number.

3 Testing should give sufficient detail information to assist further developments in the aerodynamic design of aircraft. This implies both a high relative accuracy to measure overall design improvements and test techniques (like surface flow visualizations and flow field probing) to better unveil the flow physics behind the improvements. Also, the tunnel (and infra structure, including staff) should be flexible enough to do special non-standard tests (e.g. different aspects of engine simulation). Developments in this area are continuing.

4 And last but not least: testing should be cost effective, implying low model costs (one model to be used for subsonic, transonic and supersonic conditions), low testing costs (high productivity, low energy costs) and high flexibility (fast and easy access to the test section to make model changes). The first of these points has been acknowledged in the original design of the HST. The latter two will result from the phase 2 modifications.

5 Conclusions

Lessons learned from over 30 years of wing development in the HST have reveiled the importance of a sufficient Reynolds number capability, the necessity to improve on relative and (most·notably) absolute accuracy and a stronger interest in cost effective, high productivity flow field survey's. Partly based on these arguments, a modification program for the HST was proposed. The first phase of this program was executed in 1992 and involved an increase in test section length, three new model supports and a new tunnel control system. Subsequent calibration and validation tests indicated that the goals of the phase 1 modernization have been realized. Test data obtained on various models and model supports were very consistent with each other while a good match was obtained with pre-modification test data. The goals of the phase 2 modification are set and will concentrate on power plant replacement, cost reduction and an increase in productivity and flexibility. These are essential requirements for the HST to maintain and strengthen its role in research and pre-development prior to development and final verification testing in the major new European facilities like ETW and DNW.

Acknowledgement

The authors would like to thank all those that contributed to the success of the HST modification phase 1. The work of mr. F.J.M. Wubben who assisted in preparing this paper is much appreciated.

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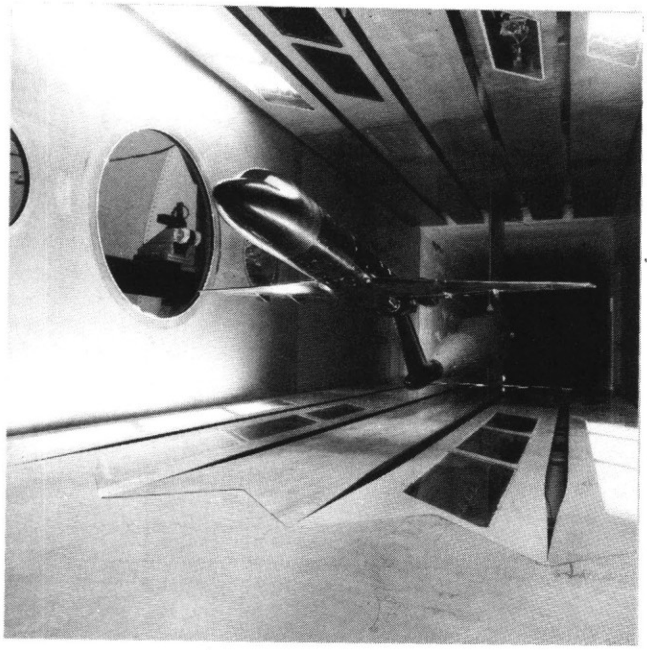


Fig. 0 Fokker-100 model in modified HST

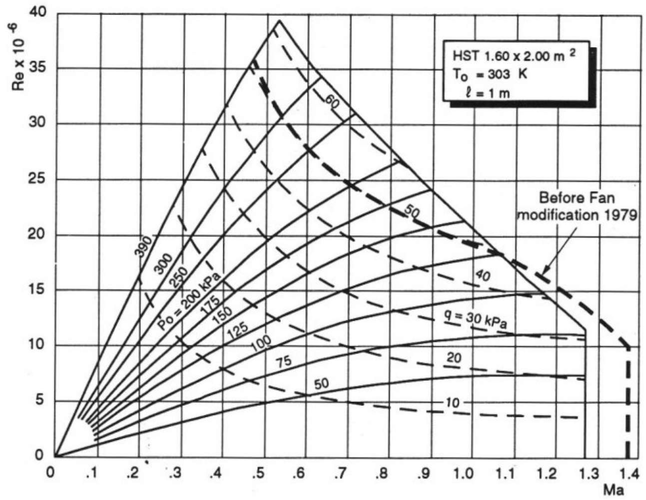


Fig. 2a Operating envelope HST 1979-1992

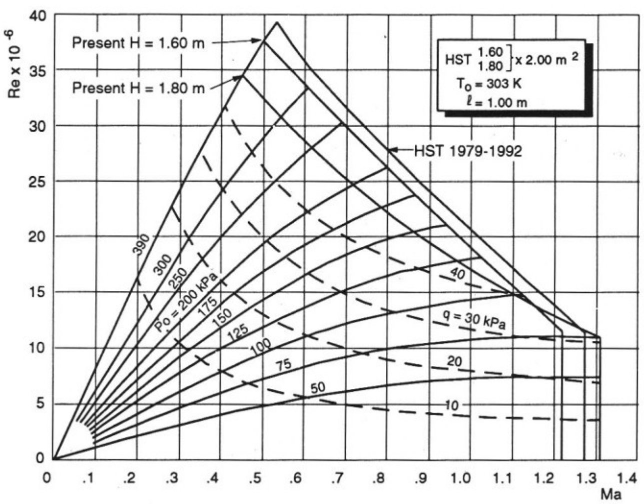


Fig. 2b Operating envelope HST after modification phase 1 (1992)

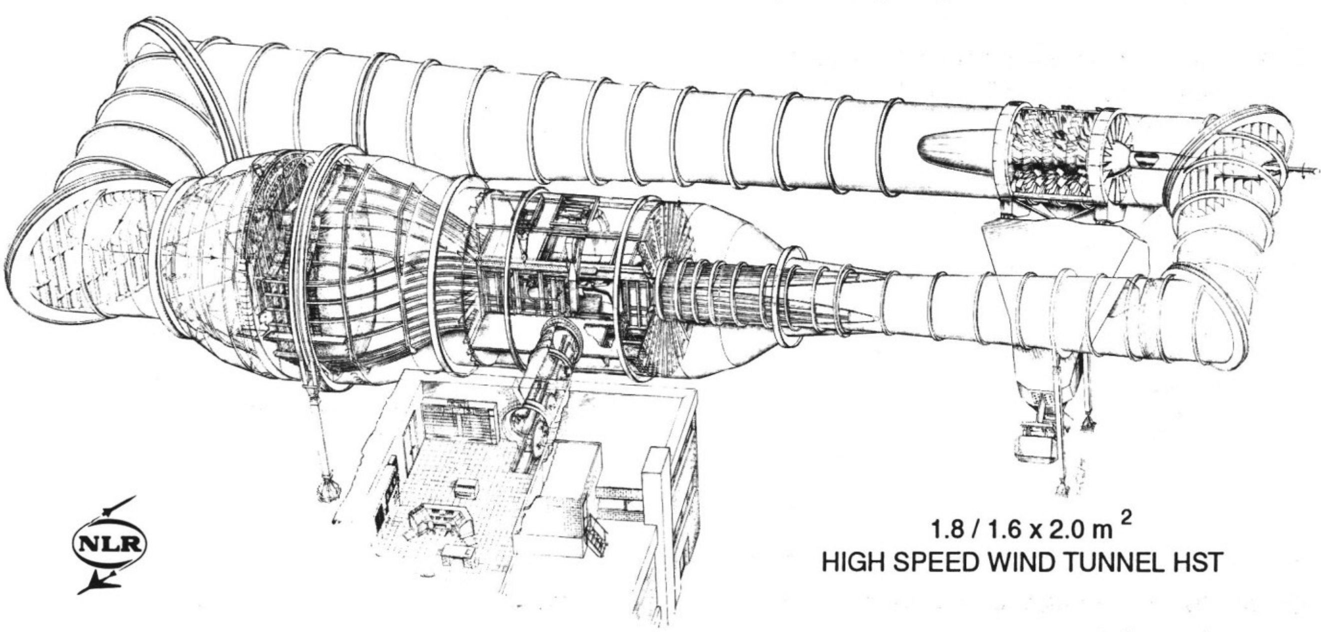


Fig. 1 Isometric view of HST

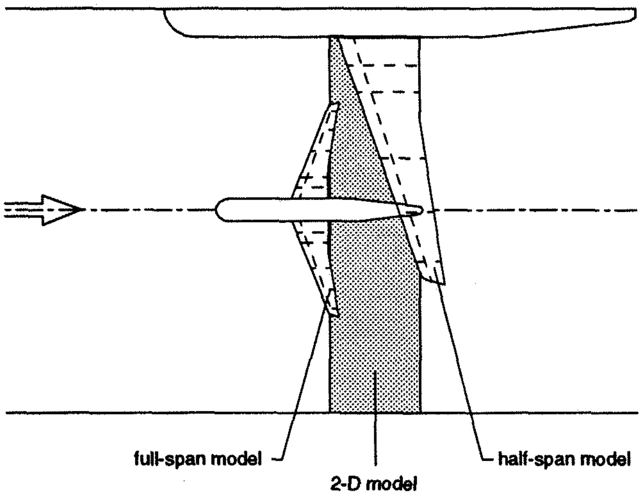


Fig. 3a Different model configurations in the testsection of the HST

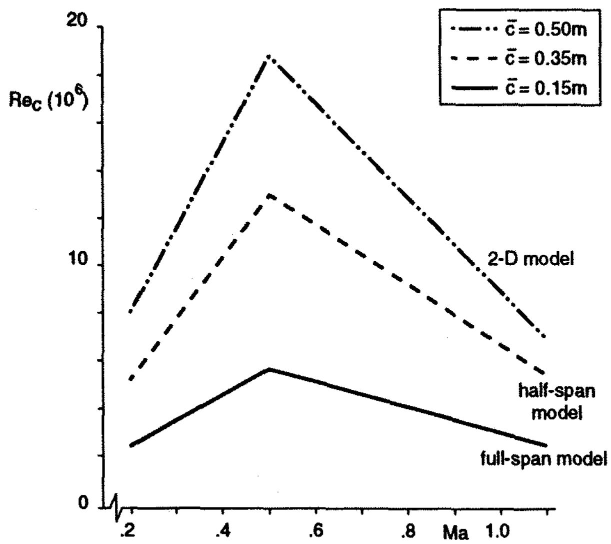


Fig. 3b Max Reynolds numbers for various test set-ups (after phase-1 modification, H = 1.6 m)

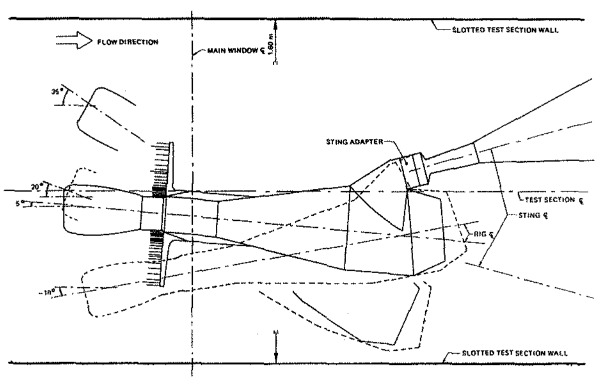


Fig. 4a Side view of inlet/rig combination in HST test section

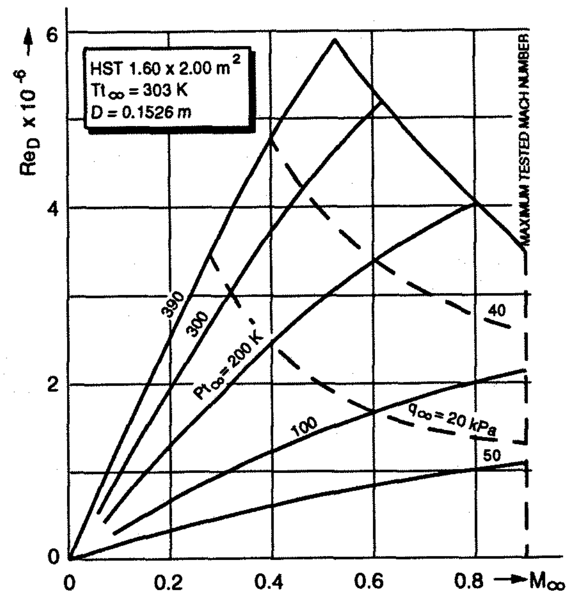


Fig. 4b The Reynolds cabability for inlet tests (H = 1.6 m)

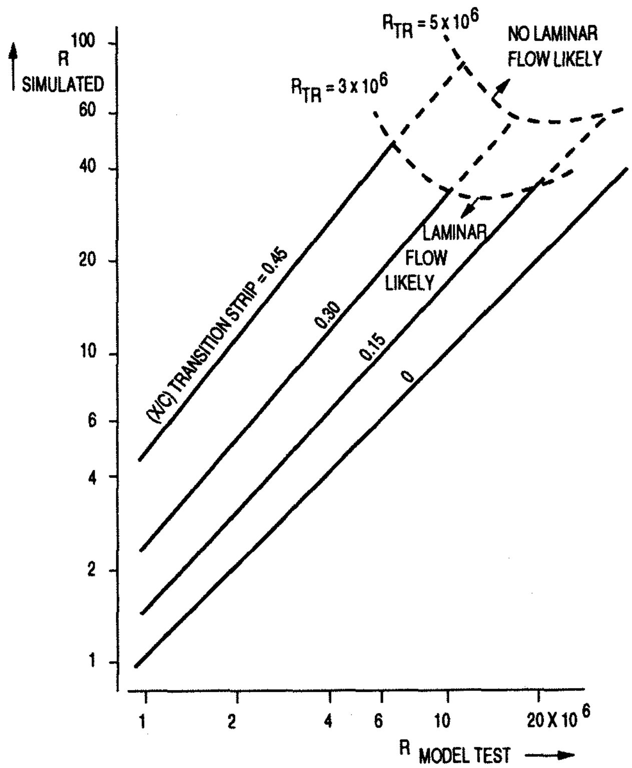


Fig. 5 Reynolds number simulation by aft fixation: Zero level simulation criterion (equivalent momentum thickness at T.E. of flat plate)

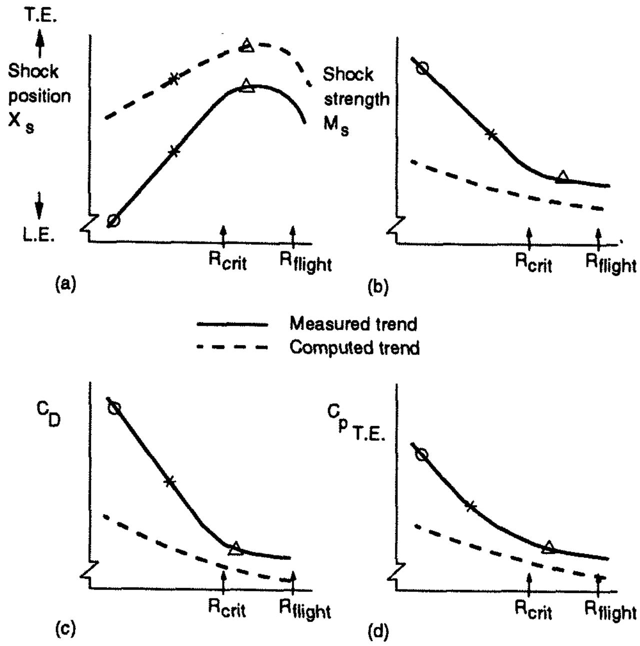


Fig. 6 The concept of $R_{critical}$ (from ref. 10)

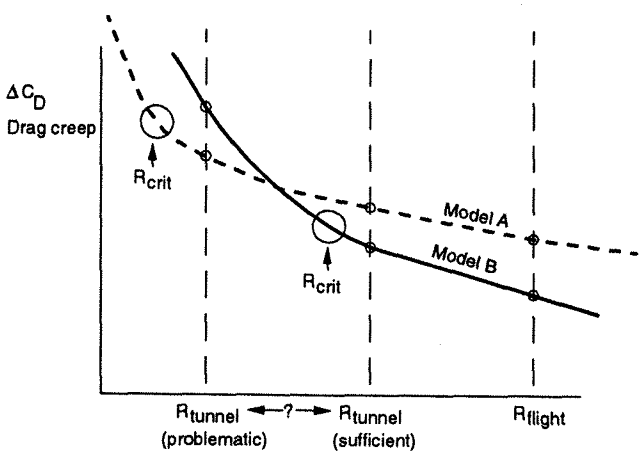


Fig. 7 The problem of design optimization at tunnel Reynolds number

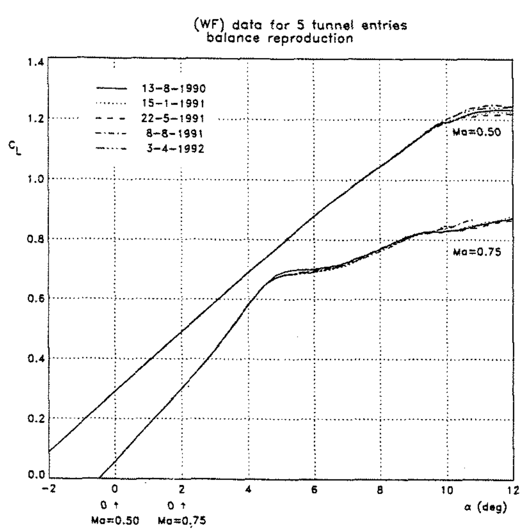


Fig. 8a Example of measurement repeatibility

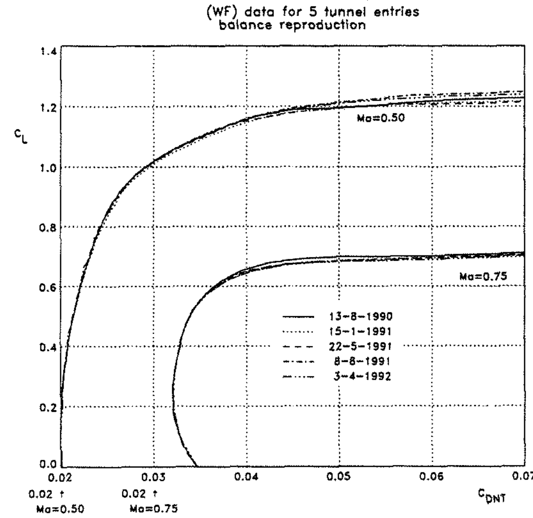


Fig. 8b Example of measurement repeatibility

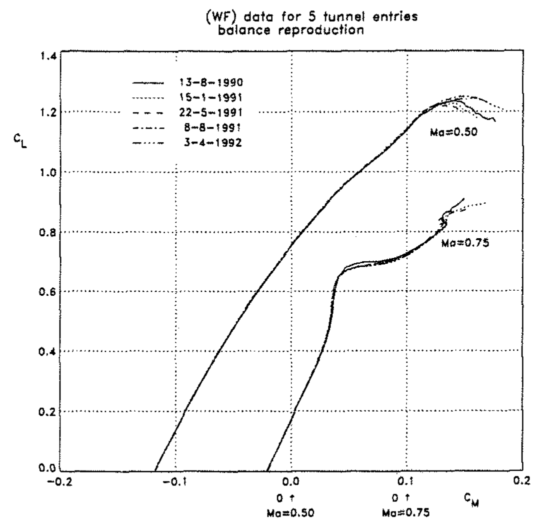
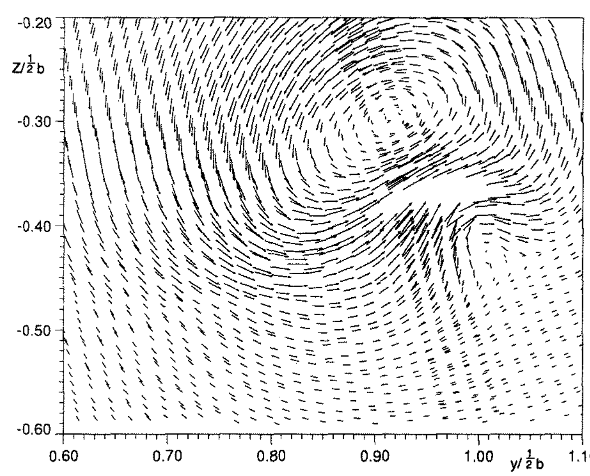


Fig. 8c Example of measurement repeatibility



Cross-flow velocity vectors measured in the flow field behind a delta wing

Fig. 9 Example of computer controlled 5-hole probe flow field survey

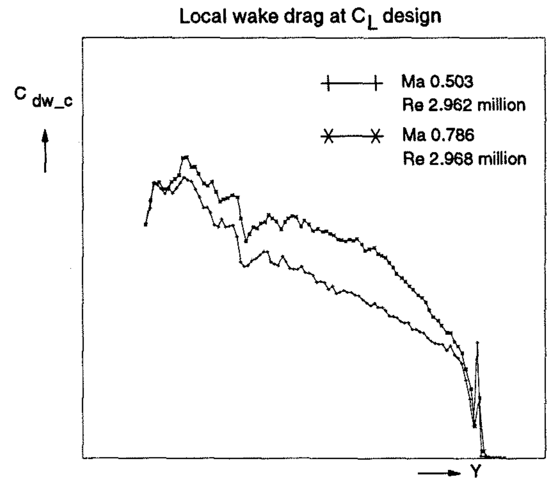


Fig. 10a Example of wake rake traverses to investigate drag creep

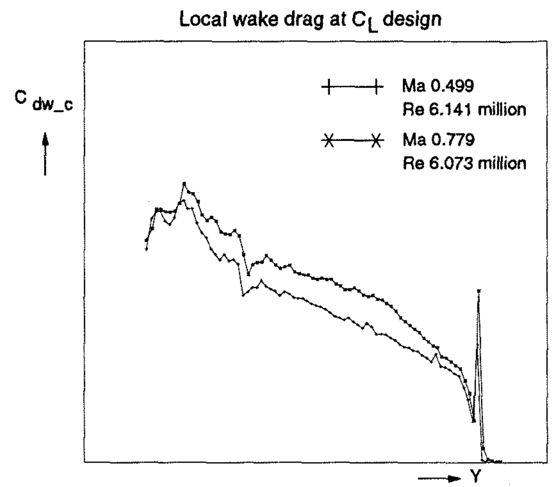


Fig. 10b Example of wake rake traverses to investigate drag creep

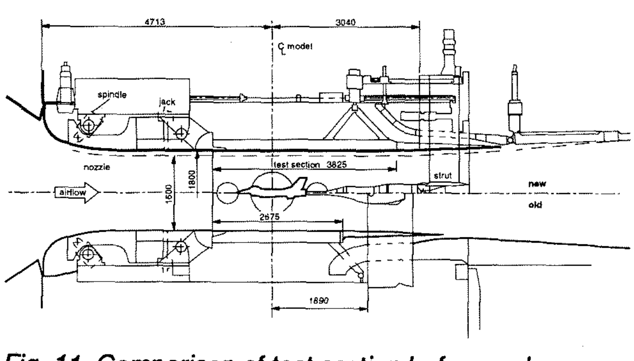


Fig. 11 Comparison of test section before and after phase-1 modification

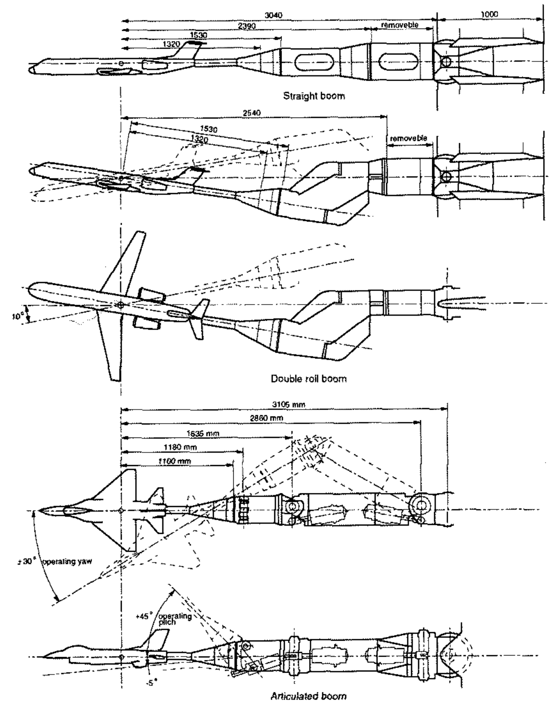


Fig. 12 New model support booms

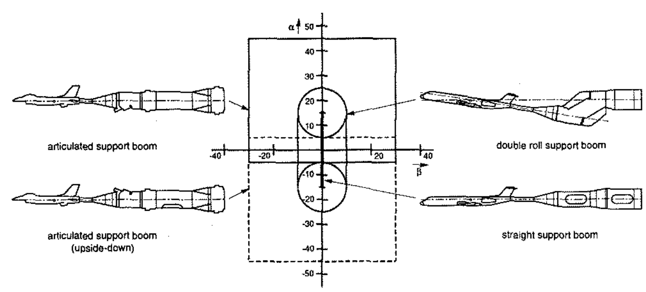
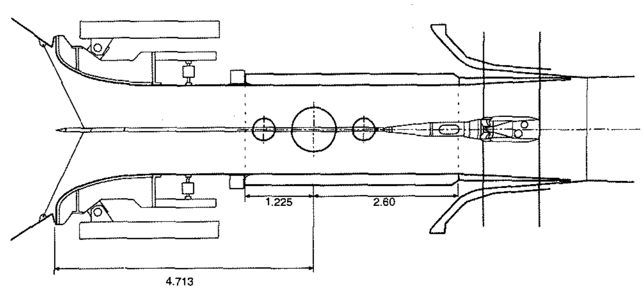
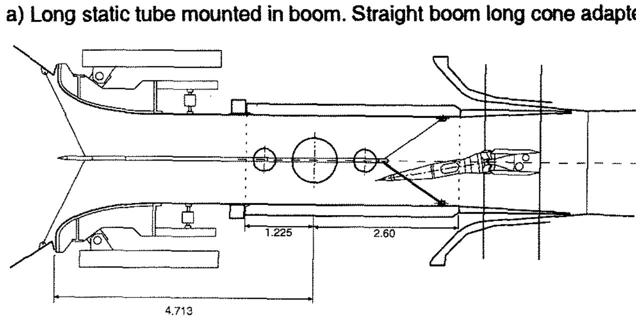


Fig. 13 Operating ranges of new model support booms



a) Long static tube mounted in boom. Straight boom long cone adapter



b) Long static tube fixed with wires. Straight boom long cone adapter, Z3-position

Fig. 14 Set-up for tunnel calibration

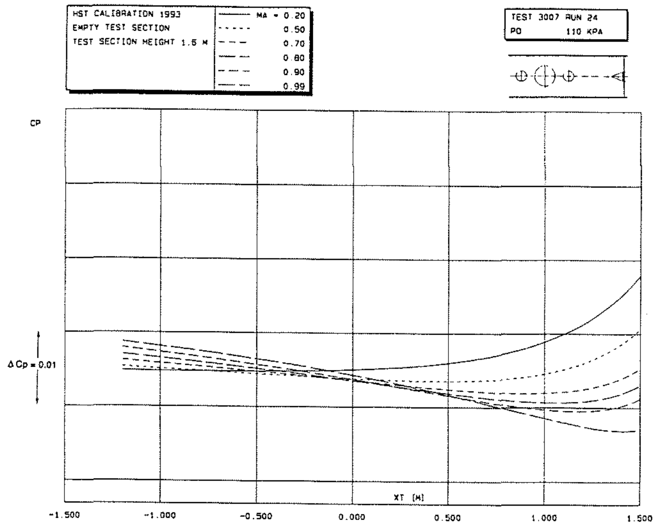


Fig. 15a Tunnel calibration "empty test section"

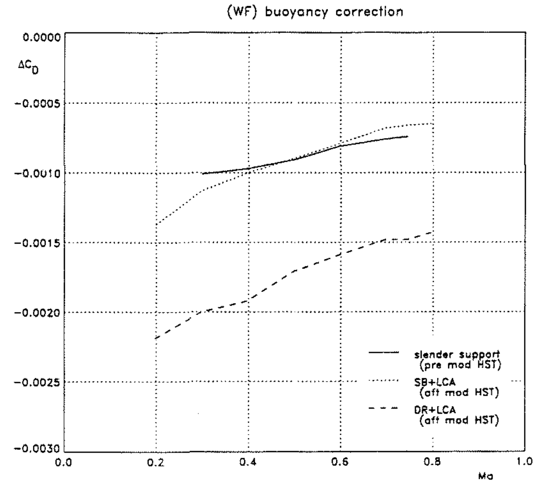


Fig. 16 Comparison of typical buoyancy correction before and after phase-1 modification

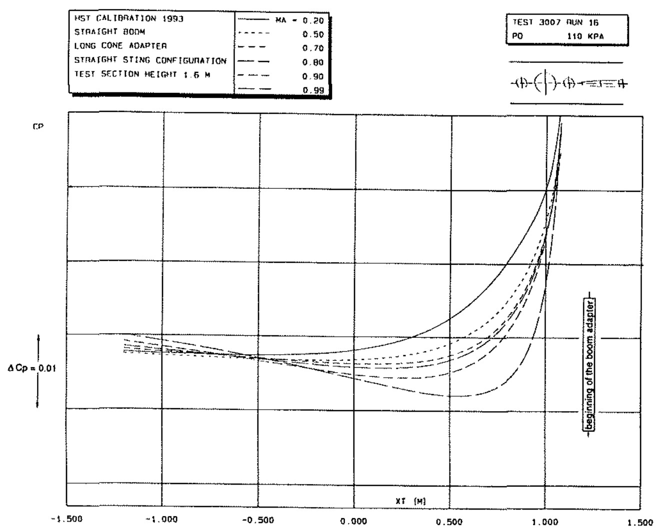


Fig. 15b Tunnel calibration SB + LCA

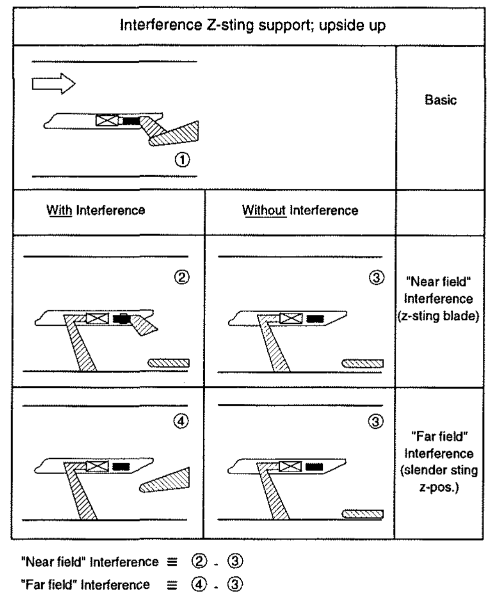


Fig. 17 Set-up sting interference measurements

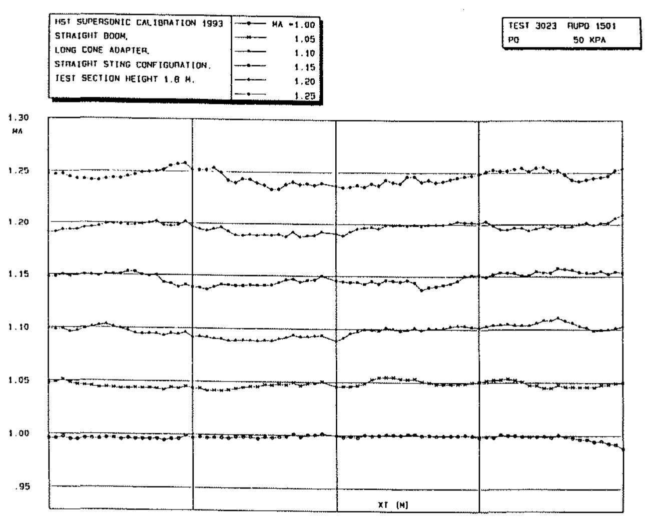


Fig. 15c Tunnel calibration: supersonic regime

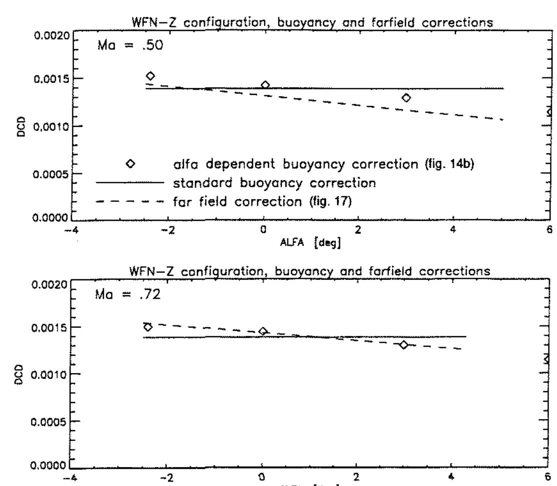


Fig. 18 Comparison of far field and buoyancy correction on drag for WFN on z-sting support

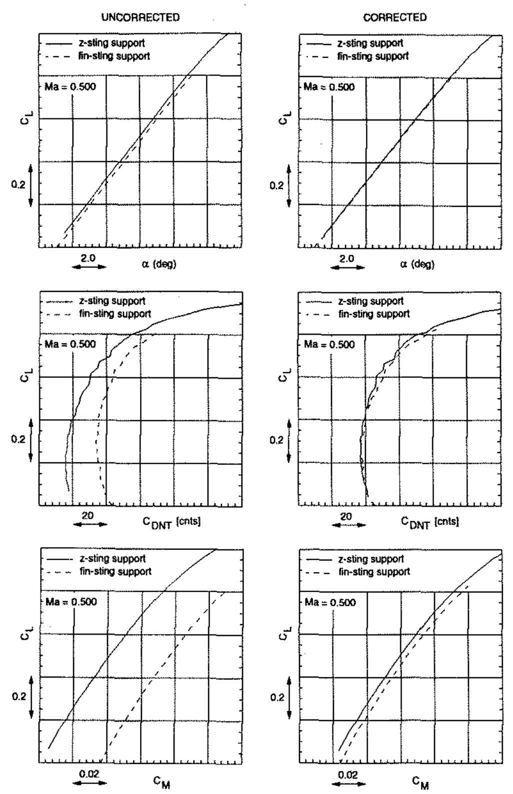


Fig. 19a Effect of corrections for sting interference on comparison of data from tests on z- and fin-support, Ma = 0.50

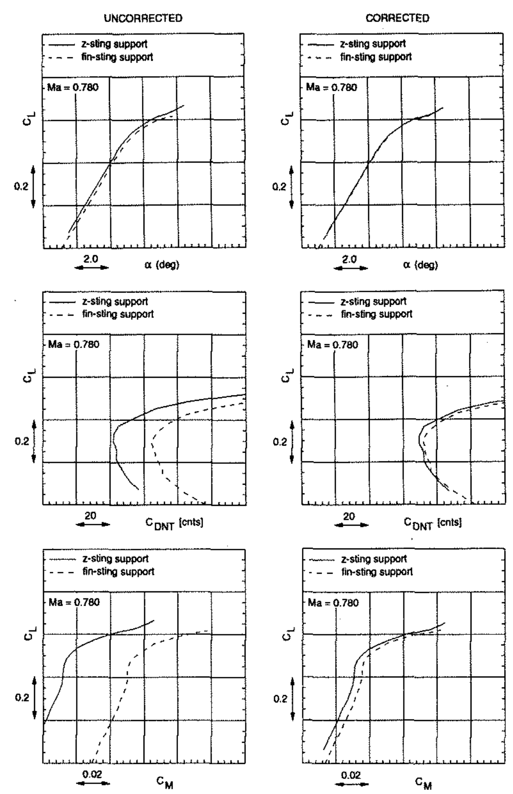


Fig. 19b Effect of corrections for sting interference on comparison of data from tests on z- and fin-support, Ma = 0.780

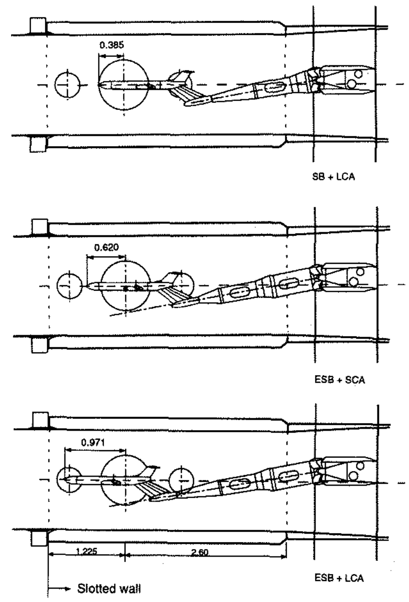


Fig. 20 Reference model at three positions in tunnel

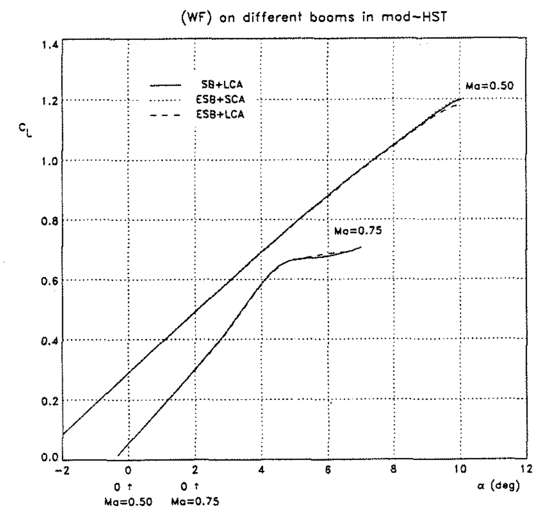


Fig. 21a Reference model: effect of variation model position in test section

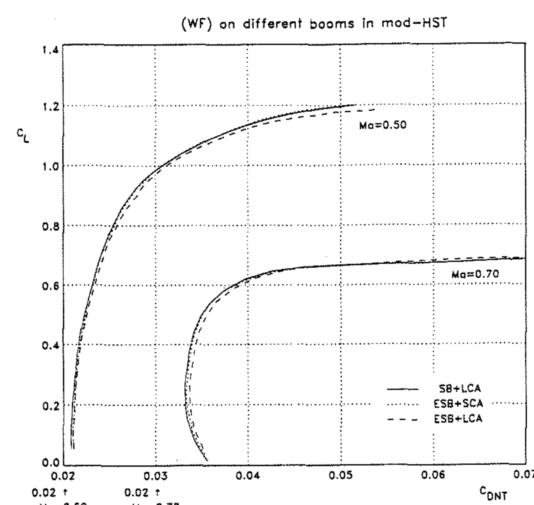


Fig. 21b Reference model: effect of variation model position in test section

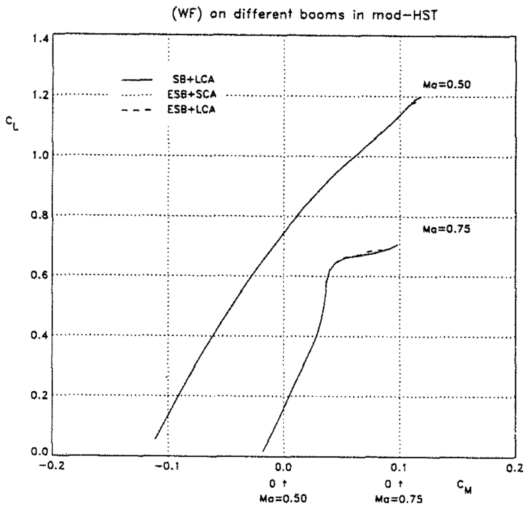


Fig. 21c Reference model: effect of variation model position in test section

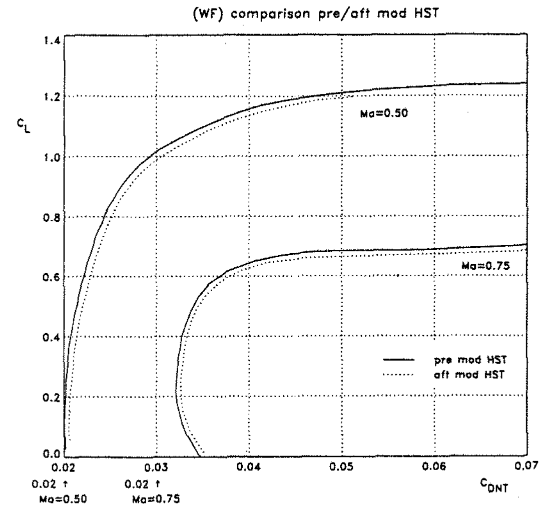


Fig. 22c Reference model: comparison before/after phase 1 modification (buoyancy correction Z-3 position (fig. 14b))

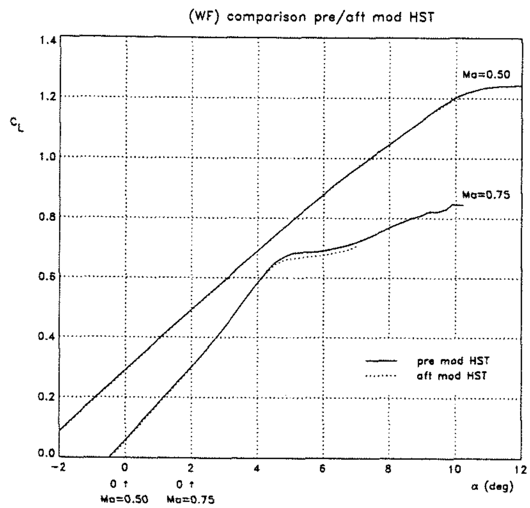


Fig. 22a Reference model: comparison before/after phase 1 modification

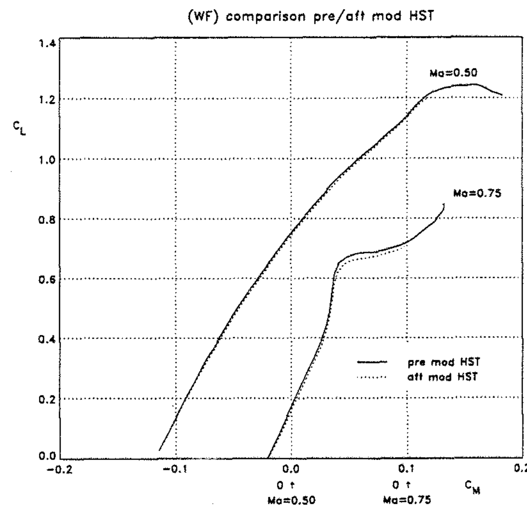


Fig. 22d Reference model: comparison before/after phase 1 modification

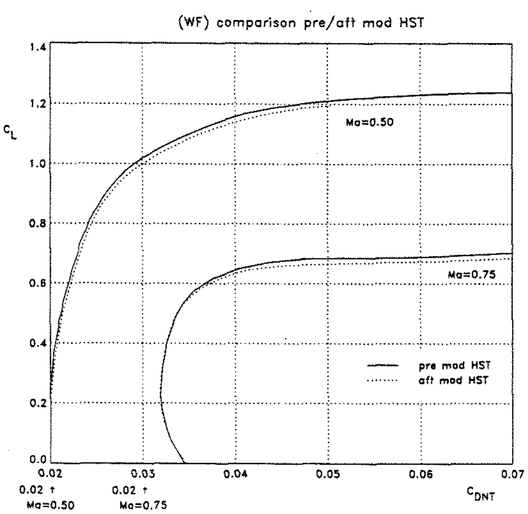


Fig. 22b Reference model: comparison before/after phase 1 modification (buoyancy correction MID position (fig. 14a))

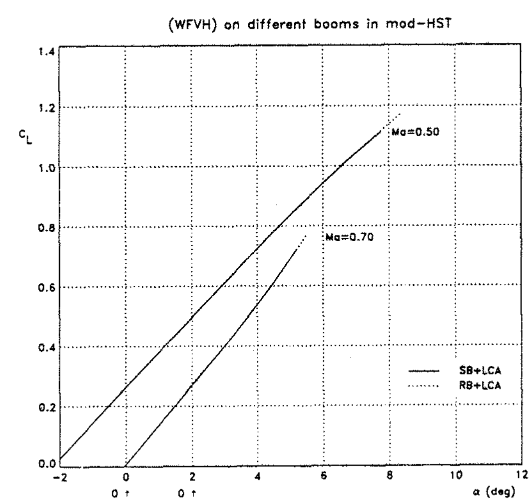


Fig. 23a Reference model: comparison straight- and double roll boom

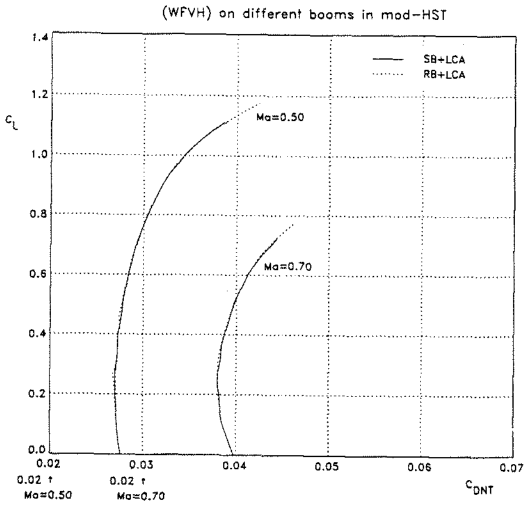


Fig. 23b Reference model: comparison straight- and double roll boom

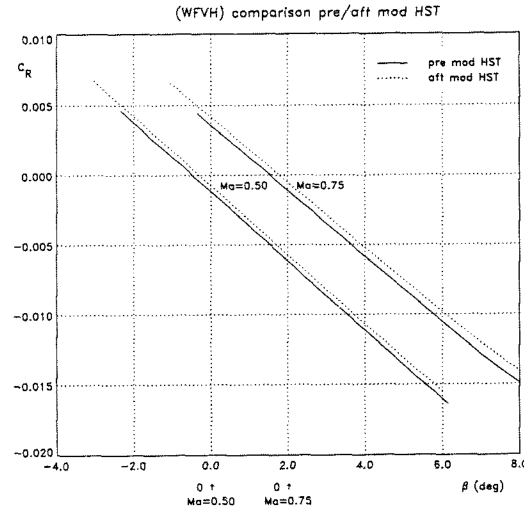


Fig. 24b Reference model: comparison a-symmetric components before and after modification phase 1

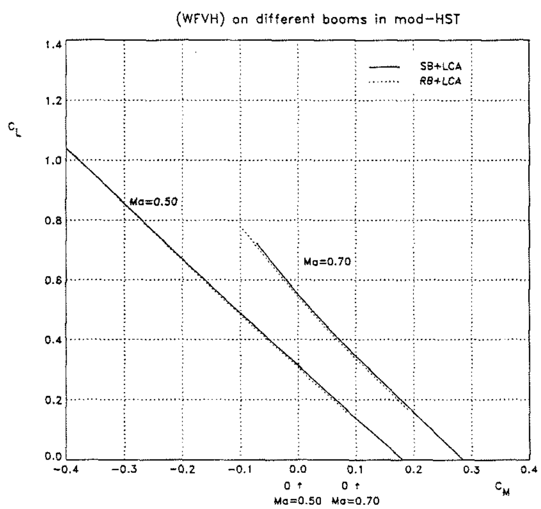


Fig. 23c Reference model: comparison straight- and double roll boom

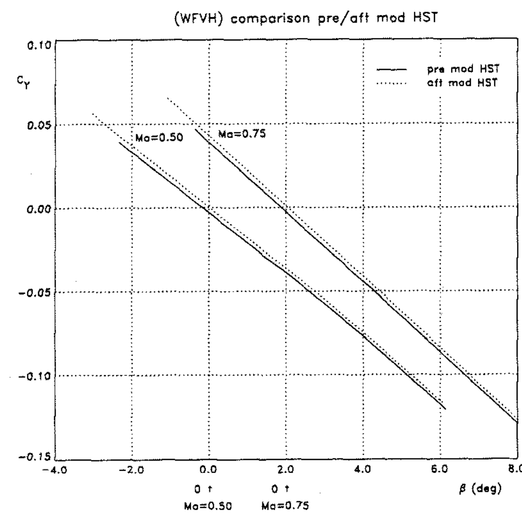


Fig. 24c Reference model: comparison a-symmetric components before and after modification phase 1

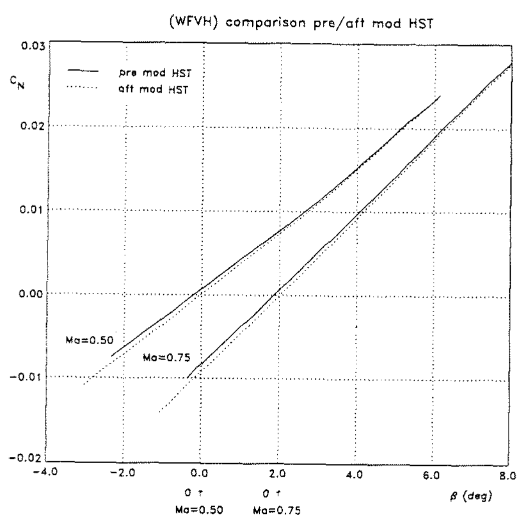


Fig. 24a Reference model: comparison a-symmetric components before and after modification phase 1

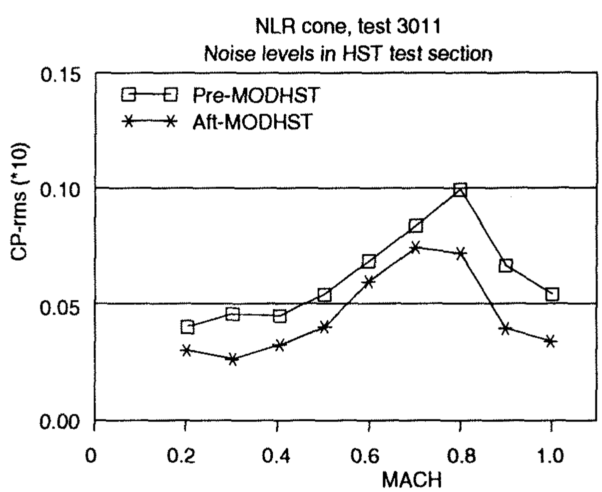


Fig. 25 Noise level before/after modification (10Hz- 10kHz)

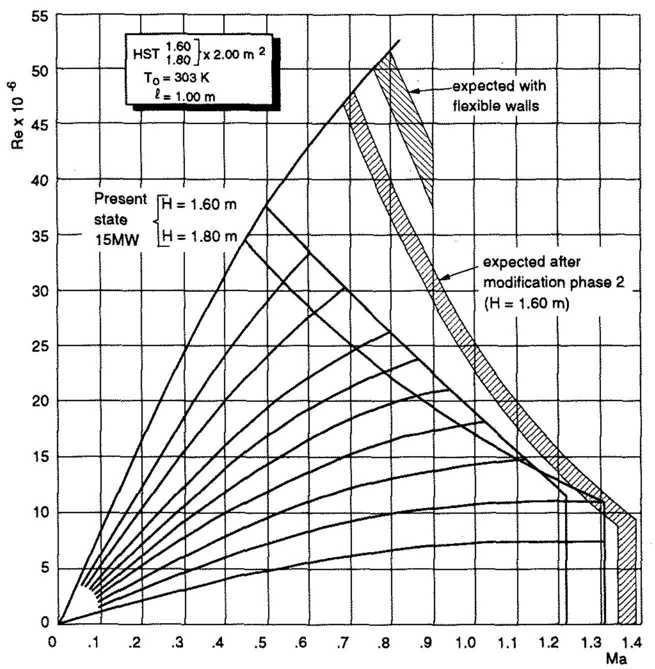


Fig. 26 Projected HST operating envelope after phase 2 modification

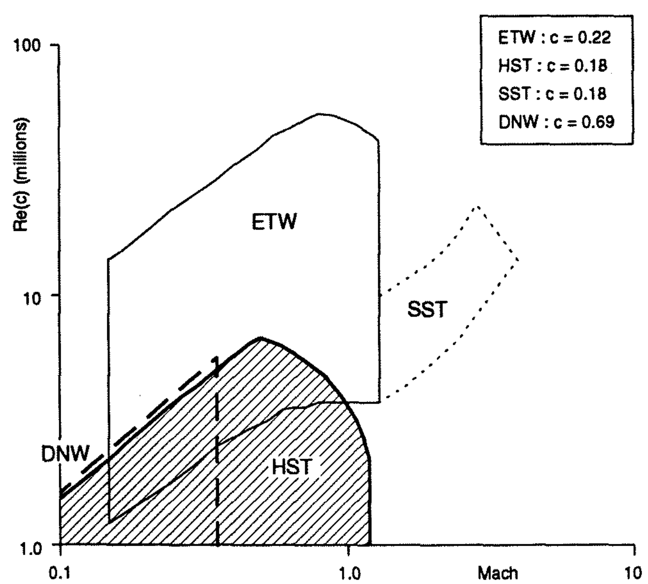


Fig. 27 The HST performance envelope relative to some other major windtunnels