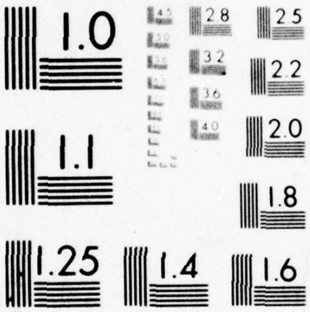
AD-A035 308 AERONAUTICAL RESEARCH INST OF SWEDEN STOCKHOLM AEROD--ETC F/G 20/4
TRANSONIC FLOW AT A SLOTTED TEST SECTION WALL.(U)
NOV 76 S B BERNDT AF-AFOSR-2184-72
UNCLASSIFIED AFOSR-TR-77-0035 NL

1 OF 1
AD
A035308

END
DATE
FILMED
3-77



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AFOSR - TR - 77 - 0035

ADA035308

(12)

Grant No. AFOSR 72-2184

TRANSONIC FLOW AT A SLOTTED TEST SECTION WALL

Sune B. Berndt
Principal Investigator

The Aeronautical Research Institute of Sweden (FFA)
Stockholm, Sweden

29 November 1976

Final Scientific Report, 1 March 1974 — 30 September 1976

Approved for public release; distribution unlimited

Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFSC)
Bolling AFB, USA

and

EUROPEAN OFFICE OF AEROSPACE RESEARCH AND DEVELOPMENT (EOARD)
London, England

by

THE AERONAUTICAL RESEARCH INSTITUTE OF SWEDEN (FFA)

This research has been sponsored in part by the AFSC and, to matched amount, by the FFA.

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFSC)
NOTICE OF TRANSMITTAL TO DDC
This technical report has been reviewed and is
approved for public release IAW AFR 190-12 (7b).
Distribution is unlimited.
A. D. BLOSE
Technical Information Officer

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

⑲ **REPORT DOCUMENTATION PAGE**	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ⑱ AFOSR - TR-77-0035 2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER ⑨
4. TITLE (and Subtitle) ⑥ TRANSONIC FLOW AT A SLOTTED TEST SECTION WALL.	5. TYPE OF REPORT & PERIOD COVERED FINAL rept. 1 Oct 71 — 30 Sep 76,
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) ⑩ SUNE B./BERNDT	8. CONTRACT OR GRANT NUMBER(s) ⑮ ✓AF-AFOSR [illegible]-2184-72
9. PERFORMING ORGANIZATION NAME AND ADDRESS THE AERONAUTICAL RESEARCH INST OF SWEDEN/FFA AERODYNAMICS DEPARTMENT PO BOX 11021, S-161 11 BROMMA, SWEDEN	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS ~~601307~~ ⑯ 9781-01 ⑰ 01 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA BODG 410 BOLLING AIR FORCE BASE, D C 20332	12. REPORT DATE ⑪ 29 Nov 76 13. NUMBER OF PAGES 14
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) ⑫ 16p.	15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

TRANSONIC WIND TUNNEL WALL INTERFERENCE
SLOTTED WALLS
TEST FACILITIES

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of the now concluded research (Oct 71-Sep 76) has been to make possible the accurate computation of slotted walls interference in transonic wind-tunnels. This has been achieved through studying experimentally the flow at and through slotted walls and through developing theoretical models for such flows. The final result is a homogeneous wall boundary condition to be used when computing numerically the three-dimensional transonic flow around a wind-tunnel model, be it to determine the interference from the test-section walls or to adjust the wall parameters for zero interference. The boundary condition is of rather → next page

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED 407 117

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

mt

general applicability, admitting great freedom in the choice of slot geometry and facilitating the inclusion of corrections for viscous effects, such as disclosed by the experiments.

TABLE OF CONTENTS

Grant No. AFOSR 72-2184
Final Scientific Report, 71 Oct 01 – 76 Sept 30

TRANSONIC FLOW AT A SLOTTED TEST SECTION WALL

by Sune B. Berndt

1. Objective and Achievements

The objective of the now concluded research (Oct. 1971 - Sept. 1976) has been to make possible the accurate computation of slotted wall interference in transonic wind tunnels. This has been achieved through studying experimentally the flow at and through slotted walls and through developing theoretical models for such flows. The final result is a homogeneous wall boundary condition to be used when computing numerically the three-dimensional transonic flow around a wind-tunnel model, be it to determine the interference from the test-section walls, or to adjust the wall parameters for zero interference. The boundary condition is of rather general applicability, admitting great freedom in the choice of slot geometry and facilitating the inclusion of corrections for viscous effects, such as disclosed by the experiments.

2. Chronicle

A complete chronological bibliography of publications, Scientific Reports and papers resulting from the work is appended (Refs. B1-B13). As far as final research results are concerned the following three reports give an essentially complete coverage:

B7: P. Löfgren, Simplifications of the boundary condition at a slotted wind-tunnel wall with a boundary layer. Scientific Report No. 1 (March 1975).

B11: S.B. Berndt and H. Sörensén, Flow properties of slotted walls for transonic test sections. AGARD Conf. Proc. No. 174, Paper No. 17 (Oct. 1975).

B13: S.B. Berndt, Inviscid theory of wall interference in slotted test sections. Scientific Report No. 2 (Oct. 1976).

The Final Scientific Report is therefore restricted to a review of the research performed under the Grant.

Throughout the work it has been deemed important, in view of the urgency and high level of activity of research on transonic wall interference, to keep in contact with other groups active in the field and to give a wide and early distribution of results obtained. Thus the Principal Investigator has been participating in the AGARD Fluid Dynamics Panel working group on design of transonic working sections and supplying information on the present research for inclusion in the reports of the group (Refs. B9 and B12). Progress reports were given to the Euromech Symposium 40 on Transonic Aerodynamics in Sept. 1973 (Ref. B2) and to the Supersonic Tunnel Association in March, 1974. On the latter occasion the Principal Investigator travelled in the USA and Canada, visiting most of the laboratories engaged in research on transonic wall interference. The AGARD Flight Mechanics Panel Symposium on "Flight/Ground Testing Facilities Correlation" in France in June 1975 gave an opportunity to present some of the experimental data (Ref. B10). The report B11 mentioned above was presented to the AGARD Fluid Dynamics Panel Symposium on "Windtunnel Design and Testing Techniques" in London in Oct. 1975 (see also Ref. 1), while the report B13 was presented to the 10th ICAS Congress in Ottawa in Oct. 1976.

3. Basic Problems

The classical inviscid linear small perturbation theory of slotted wall flow, developed in the fifties, has not been successful in correlating experimental wall interference data. At the start of the project it was not clear in what respects the theory would need to be amended, although a number of suggestions were found in the literature. The following basic problems, in particular, stood out as requiring investigation (see Sec. 2 of Ref. B11 for details):

(i) The effect of low-momentum air from the wall boundary layer going into the slot;

(ii) The presence or absence of flow separation at the slot edges, and the related problem of designating a section across the slot at which plenum pressure prevails;

(iii) The slot flow inducing a secondary flow in the plenum chamber, thus effectively changing the local plenum pressure at the slot;

(iv) Other viscous effects (a linear cross-flow pressure drop is often mentioned in the literature);

(v) The effect of low-momentum air from the plenum chamber going into the slots and the test section;

(vi) Interference from the wall boundary layer changing its displacement thickness in response to the pressure variation induced by the model.

(vii) Cross-flow velocity in slot too large for linearization.

The main tool for finding out about these various aspects has been a detailed experimental investigation of typical slot flows, as reported in Ref. B11. The comprehensive theoretical analysis of Ref. B7, backed up by an experimental survey (not reported) of the over-all mass flux balance in the test section, demonstrated at an early stage that the effect of (vi) is small and can be handled with sufficient accuracy by available theory; it was therefore not considered in the main part of the investigation.

4. The Slot Flow Model

From the experimental observations, largely oil-flow pictures, has been abstracted an inviscid flow model to serve as a first approximation and as a datum for defining viscous effects. Adapting this model, which is considerably more complicated than the classical one, implies tentative answers to a number of the basic problems just enumerated.

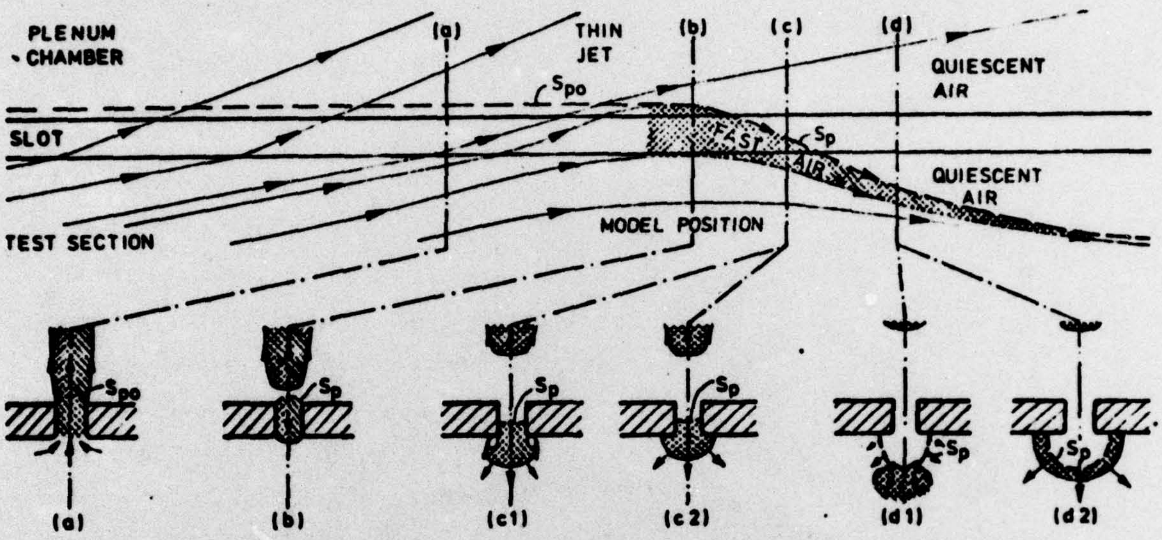


Fig. 1. Inviscid model for slot flow (not to scale)
▓ = fast air from slot.

The flow model is presented in Fig. 1. Upstream of the wind tunnel model the flow is going outwards through the slot into the plenum chamber, where it forms a thin jet. The flow inside the slot is attached as indicated in cross-section (a). Above the model the slot flow turns back, leaving the jet to continue on its own into the interior of the plenum chamber. This 'splitting' of the fast air into two separate streams is shown beginning at section (b). At (c) the fast air in the slot, having entered farther upstream, is returning to the test section. At (d) the fast air has left the slot and behind it appears a 'bubble' of quiescent air at plenum pressure, the boundary of which is expanding into the test section flow. Typically, the bubble is narrow and extends along the slot (Fig. 2).

Fig. 2. Bubbles of slow air from the plenum chamber. The oil flow on a thin sheet in the plane of symmetry of the central slot shows the penetration into the test section flow (two-dimensional test at $M_\infty = 0.91$, $\alpha = 3^o$).

This description leaves undecided whether the fast air returning from the slot to the test section is a vorticity-carrying slug, as in (c1) and (d1), or whether it expands around the slot edges without separation, as in (c2) and (d2). The evidence, although not quite conclusive, points to the first alternative; perhaps both occur. For simplicity, the second alternative has been adopted in the analytical work.

In the analytical specification of the model further simplifications have been introduced. They serve to define in as simple terms as possible the surfaces S_{po} and S_p which form together the surface on which to prescribe plenum pressure.

5. The Homogeneous Wall Boundary Condition

A homogeneous boundary condition in the present sense applies to an 'average' potential $\bar{\varphi}$ which has been substituted for the original velocity perturbation potential φ, $\bar{\varphi}$ being defined in such a way as to agree closely with φ in the central part of the test section and to have smooth and weak variation over the test section wall (whereas φ is strongly varying at the slots). The present homogeneous wall boundary condition has the form $\bar{\varphi} = \mathcal{F}[\bar{\varphi}_n]$, where $\bar{\varphi}_n$ is the normal derivative of $\bar{\varphi}$ at the wall and $\mathcal{F}[\ \ ]$ is a functional over the wall. In other words, $\mathcal{F}$ determines the pressure distribution at the wall corresponding to a given 'average' cross-flow.

The method used in Ref. B13 to define $\bar{\varphi}$ proceeds in three steps:

a) $\bar{\varphi} - \varphi$, different from zero essentially only at the slots, is approximated there by a two-dimensional harmonic function in each cross-flow section x = constant (the "slender-body approximation");

b) The wall contour in each cross-section is mapped conformally onto a circle, and polar coordinates r, θ are introduced in the transformed plane;

c) $\bar{\varphi}$ is defined to be the sum of the first $(1 + 2\nu)$ terms in the Fourier expansion of φ with respect to θ. The order ν of the highest-order terms kept is such as to make the number of terms at most equal to the number of slots, N. The result of this filtering out of higher-order terms produced by the slot implies that $\bar{\varphi} - \varphi$ vanishes like $r - \nu$ at the origin (where the model is located).

The subsequent construction of $\mathcal{F}[\bar{\varphi}_n]$ in Ref. B13 employs an asymptotic expansion with respect to the slot width as a small parameter (typically it is 4-10 % of the periphery), thus avoiding the very restrictive classical assumption of a large number of equally spaced slots. This leads to a singular perturbation problem where each slot has an inner representation, as isolated in an infinite plane wall, and where in an outer representation the test section wall becomes solid with discrete sinks or sources located at the points into which the slots have contracted (Fig. 3).

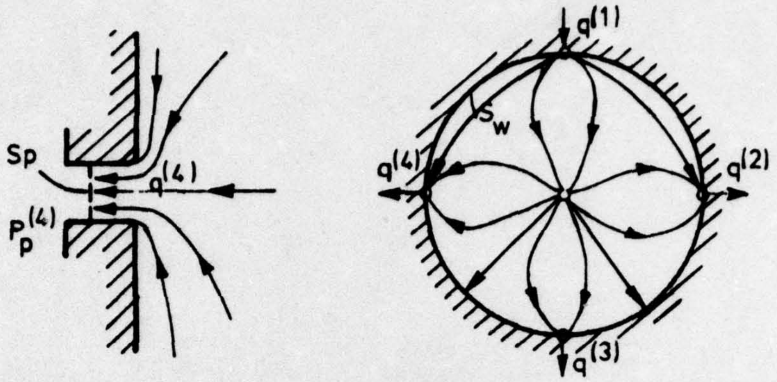


Fig. 3. Inner and outer flows.

The flux densities of these sinks, $q^{(i)}(x)$, $i = 1,2..N$, are natural variables for matching the inner and outer flows.

The first step in the final procedure defining $\mathscr{F}[\bar{\varphi}_n]$ is to compute $q^{(i)}$ from $\bar{\varphi}_n$. This involves a constant matrix determined by the location of the slots but otherwise independent of the slot geometry and other slot flow parameters. Next the local slot flow is determined by integration along each slot separately, keeping track of the free surface S_p (Fig. 1) and satisfying the plenum pressure condition on $S_{po} + S_p$, with quadratic cross-flow terms included (as is consistent with the slender-body approximation). This is where the slot geometry comes in: the width as well as the depth of the slot is allowed to vary. Each slot may also have its own plenum pressure $p_p^{(i)}$. This yields the value of $\bar{\varphi}$ at each slot. In the final step $\bar{\varphi} = \mathscr{F}[\bar{\varphi}_n]$ is obtained by trigonometric interpolation to order ν between the slots. This again requires only the application of a constant matrix determined by the location of the slots.

For slot widths of practical interest the homogeneous boundary condition thus established agrees with the classical one, whenever this is valid, the agreement being to within the inherent uncertainty of the classical approach in not providing a rational and unique choice of S_{po} (Fig. 1) (see e.g. Ref. 2). There is also agreement in the special case of two-dimensional tests as developed previously in Ref. B11 for the purpose of comparison with experiments.

By extensive calculations of axisymmetric near-sonic wind-tunnel flows it has been demonstrated that the new boundary condition admits rapidly convergent numerical schemes to be set up (Ref. B11; the results have not been reproduced as not being of interest per se). In contrast, the inverse boundary condition, $\bar{\varphi}_n = \mathscr{F}^{-1}[\bar{\varphi}]$, leads to consistently slow convergence or even divergence.

6. Viscous Effects

In analysing the local flow at each slot separately the theory of Ref. B13 is such as to facilitate the inclusion of experimentally determined corrections for viscous effects inside the slots and the plenum chamber, such as indicated under points (i) to (v) in Sec. 3. The effect of varying wall boundary layer thickness (vi) is easily handled by applying the wall boundary condition in the form $\bar{\varphi} = \mathscr{F}[\bar{\varphi}_n + \varphi_n^*]$, where φ_n^* is the normal velocity contributed by the boundary layer (determined by conventional boundary layer theory disregarding the slots, or by methods such as explored in Ref. B7).

The experiments of Ref. B11 indicate how important the viscous effects are in a flow situation typical of two-dimensional tests. Total pressure surveys inside the slots showed that in regions of continuous outflow from the test section the total pressure in the centre of the slot remains almost unaffected by the wall boundary layers (while artificially doubling the thickness of the boundary layer gave a noticeable effect). Detailed mapping of the flow velocity and direction in the jet emerging from the slot into the plenum chamber - this required the development of a new type of combined total-pressure and flow-direction probe and a machinery for moving it along the slot during tests - permitted determination of the mass flux through the slot and showed that the flow leaving the slot was attached and that the viscous effects in the slot corresponded to a reduction of the effective slot width by some 15 %. It also appeared that the local plenum pressure at the emerging jet was affected by entrainment and secondary flow in the plenum chamber to a noticeable extent. Correcting the theoretical results for these effects led to the kind of agreement between prediction and experiment shown in Fig. 4 (in a region of outflow from the test section).

The pressure difference thus computed and verified consists of two contributions, one being the classical streamline curvature effect

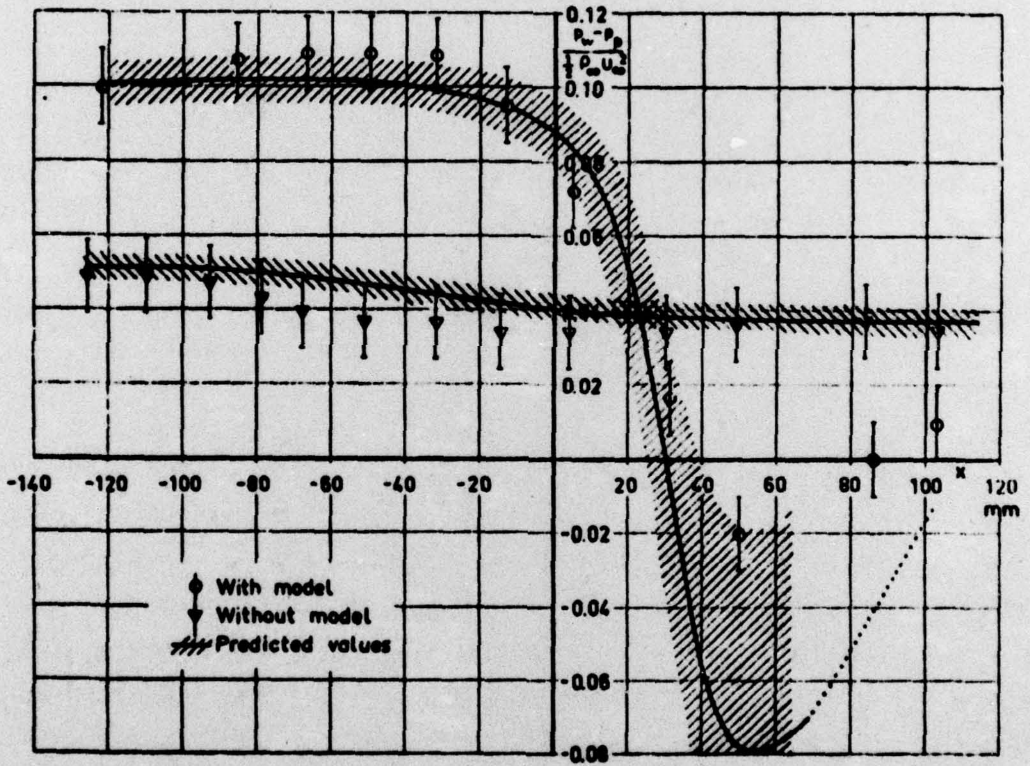


Fig. 4. Comparison of predicted and measured pressure difference across a slotted wall (the model is located between x = 0 and 90 mm).

proportional to $\partial\bar{\varphi}_n/\partial x$, the other being a cross-flow effect (vii) proportional to $\bar{\varphi}_n^2$. There is no trace of a linear cross-flow term proportional to $\bar{\varphi}_n$, such as has often been proposed in the literature on the basis of early pressure drop measurements. As stressed by Goethert in Ref. 1, these measurements, the details of which have not been published, were made with a sharp-edged slot of very small depth and a width large compared to the thickness of the wall boundary layer. The linear effect found is therefore not likely to be a viscous effect. We have checked that in our experiments there is no linear effect hidden in the variation with cross-flow velocity of the entrainment influence on the local plenum pressure. Perhaps the linear effect comes from the finite longitudinal extent of the slot, like on a rectangular wing of small aspect ratio, contrary to the slender-body approximation, there is a linear lift distribution spreading from the leading edge over the whole wing.

It remains to get an experimental verification of the theory in regions with inflow to the test section. The need for further experiments seems to be particularly great in cases where shock waves from the model reach the wall.

7. Looking Ahead

It now seems that one can avoid more serious viscous effects by judicious choice of slot geometry. The next step therefore should be to use the inviscid theory for running numerical experiments. These will show how accurately one must describe the action of the slotted wall in different types of application, and what wall adjustment facilities one must provide in order to eliminate the wall interference. They will also help in developing strategies for efficient use of adaptive slotted walls in future wind tunnels. In the end very likely one must obtain more precise data for viscous corrections, but this can perhaps best be done, for any particular wind tunnel design, by tests in a pilot wind tunnel and by final in situ calibration.

CHRONOLOGICAL BIBLIOGRAPHY OF THE RESEARCH PROJECT

B1. Grant No. AFOSR 72-2184, Interim Scientific Report, Oct. 1971 - Sept. 1972 (Oct. 1972).

B2. S. Berndt and H. Sörensén, Transonic flow at a slotted test section wall. Euromech Symposium 40 on Transonic Aerodynamics, Comm. No. 26 (Sept. 1973).

B3. Grant No. AFOSR 72-2184, Annual Inventory of Research, Oct. 1972 - Nov. 1973 (Dec. 1973).

B4. S.B. Berndt and H. Sörensén, Transonic flow at a slotted test section wall. Paper presented at the 41st Semiannual Meeting of the Supersonic Tunnel Association in Los Angeles, Cal. (March 1974).

B5. Grant No. AFOSR 72-2184, Interim Scientific Report, Oct. 1972 - Febr. 1974 (April 1974).

B6. Grant No. AFOSR 72-2184, Annual Inventory of Research, Dec. 1973 - Sept. 1974 (Oct. 1974).

B7. P. Löfgren, Simplifications of the boundary condition at a slotted wind-tunnel wall with a boundary layer. Grant No. AFOSR-72-2184, Scientific Report No. 1 (FFA Technical Note AU-932) (March 1975).

B8. Grant No. AFOSR-72-2184, Interim Scientific Report March 1974 - Febr. 1975 (April 1975).

B9. M. Pindzola, T.W. Binion and J.O. Chevallier, Design of transonic working sections, Appendix 8 of AGARD Adv. Rep. No. 83 (1975).

B10. S.E. Nyberg, Some results from an investigation of the slot flow in a transonic slotted test section wall. AGARD Conf. Proc. No. 187 (June 1975).

B11. S.B. Berndt and H. Sörensén, Flow properties of slotted walls for transonic test sections. AGARD Conf. Proc. No. 174, Paper No. 17 (Oct. 1975).

B12. T.W. Binion, Jr., J.L. Jacocks and J.P. Chevallier, 1976 Meeting Report, AGARD Fluid Dynamics Panel Working Group on Design of Transonic Working Sections (Sept. 1976).

B13. S.B. Berndt, Inviscid theory of wall interference in slotted test sections. Grant No. AFOSR 72-2184 Scientific Report No. 2 (FFA Techn. Note AU-1290). (Presented as Paper No. 76-03 at the 10th ICAS Congress in Ottawa, Oct. 1976).

ADDITIONAL REFERENCES

1. B.H. Goethert, *Technical Evaluation Report on the Fluid Dynamics* Panel Symposium on Windtunnel Design and Testing Techniques (London, Oct. 1975). AGARD Adv. Rep. No. 97 (1976).

2. R.W. Barnwell, Improvements in the slotted-wall boundary condition. Proc. AIAA 9th Aerodynamic Testing Conf., p. 21-30 (1976).