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Wall-Interference Assessment in Three-Dimensional Slotted-Wall Wind Tunnels

FINAL TECHNICAL REPORT

by
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1. INTRODUCTION

The subject cooperative agreement provides for the principal investigator to work interactively with NASA/Langley Research Center personnel in the development of procedures for assessing wall interference in wind tunnels having slotted-wall test sections with particular emphasis on the National Transonic Facility (NTF). The major thrust of this effort has been the development by the principal investigator of an interference assessment computer program which will combine refined modeling of the test section walls with the data from limited wall pressure measurements to form an accurate outer boundary for computing the wind tunnel flow from which wall interference is to be extracted. A computer code to accomplish the test section modeling has been developed within the context of a wind tunnel flow simulator, that is, all boundary conditions are specified without recourse to measured pressures. Section 2 of this report summarizes the simulator code development in broad terms and refers the reader to formal publications which give a comprehensive description of the development and use of the simulator code.

Application of the test section modeling to an interference assessment procedure is discussed in Section 3. This work, applied to a sample test case in the Langley Diffuser Flow Apparatus (DFA), was carried to the point where limited interference assessment results have been produced and certain problems related to the limited extent of wall pressure measurements have been identified.

Section 4 describes other activities performed under the cooperative agreement including publication of prior work on wall interference assessment in two-dimensional tunnels, a brief conceptual investigation of the two-variable interface approach to interference assessment, and a short study of a candidate diffuser choke design for the NTF.

Major results of the work performed under this cooperative agreement have been disseminated through both formal publications and meeting presentations. A list of the formal reports and articles and of conference and meeting presentations is included as Section 5 of this report.

2. SLOTTED TUNNEL FLOW SIMULATION

The development of the slotted tunnel simulator code and lessons learned from its use are summarized only briefly herein. The reader is referred to items 2, 3, and 4 of the Reports and Articles list in Section 5 for details.

The high order panel method was selected as the basic procedure for aerodynamic computations. The panel singularities are supplemented by line sources to represent discrete wall slots. Methods using Fourier series or fast Fourier transforms were rejected because of the difficulty in imposing mixed or special local boundary conditions. Although a finite difference formulation would be more directly extendable to transonic flows, it was believed that the direct control of singularity types offered by a panel method would assist the development of appropriate modeling of the slotted tunnel details. It is not clear at this point whether future extension to transonic speeds should be accomplished by complete reformulation into a finite difference procedure or by supplementing the panel method with field integration of nonlinear terms in the governing equation.

In addition to modeling discrete wall slots of finite length, the simulation accounts for most features of the tunnel test environment which can affect the pressure distribution on the test section walls. These features include slot reentry flaps, wall contours, the test model and its sting support system. The process of developing and evaluating the simulation code was effective in clarifying certain phenomena of slotted tunnel flows. It is possible with the discrete slot simulation to demonstrate that the log cosecant term appearing in theoretically derived slotted wall boundary conditions such as that by Davis and Moore (ref. 1) quantifies the streamline curvature effects occurring in only the tunnel interior flow approaching the slots and should, therefore, be omitted from the discrete slot boundary condition. Studies of finite slot length effects showed that a static pressure difference between the upstream and downstream ends of the slotted section causes a characteristic mode of velocity distribution along the tunnel length to appear. An analysis with simplifying assumptions showed that this mode has an exponential shape. Finally, accounting for the predominant nonlinear slot flow phenomena resulted in a difference between the slotted wall resistance to outflow and that to inflow which could have significant effects on wall interference. In particular, the nonlinear effects produced a wall-induced longitudinal velocity perturbation due to model lift of significant magnitude relative to the more familiar blockage interference.

3. INTERFERENCE ASSESSMENT PROCEDURE

The identifying feature of a wall interference assessment process is the measurement during a tunnel test of the distribution of some flow property on a surface at or near the tunnel walls for subsequent use in forming boundary conditions for a flow computation capable of identifying the wall influence on the flow at the test model. The concept of the present approach is to reduce the required number of measurements to a convenient level by using a numerical model of the slotted-wall test section as an intelligent interpolator between coarsely resolved wall pressure measurements. Under the present cooperative agreement, the amount of effort directed to applying the numerical model in an interference assessment mode was much less than that used in developing, evaluating and documenting the numerical model as a test section flow simulator. As a result, the assessment code is not complete but, in the present form, it will produce wall interference results if certain requirements on the location of wall pressure measurements are met.

Conversion of the numerical model from the simulator form to the assessment form is accomplished by altering wall boundary conditions in regions where wall pressure measurements are available. In solid wall regions, the theoretical Neumann condition is replaced by a prescribed pressure condition and the solution defines the corresponding local wall slope. In slotted wall regions, the discrete slot boundary condition is replaced by a prescribed pressure condition at a different but nearby location and the solution defines the local slot flux. Because the prescribed pressure is a nonlinear function of the local perturbation velocity components, the solution must be updated iteratively.

It was found that as the number of prescribed pressures on either kind of wall was increased, the solution stability decreased resulting in the appearance of a spacial oscillation of singularity strengths which diverged slowly in the iterative solution. This problem was cured by incorporating a smoothing algorithm based on that developed by Phillips (see ref. 2) for use in spectral analysis in which the solution is a distribution over the one-dimensional frequency domain. As shown in fig. 1, the algorithm was adapted to the present problem in which the solution is a distribution over each of a group of two-dimensional panel networks. To avoid unnecessary loss of accuracy, the user may specify the amount of smoothing in each direction of each network.

With the smoothing algorithm incorporated, stable wall-interference solutions are easily obtained for the solid-wall case where the solution defines local wall slope. On slotted walls, stable solutions are obtained if pressures are specified in longitudinal rows extending the full length of the slots, and if there is a separate pressure row identifiable with each slot. If the number of slots exceeds the number of pressure rows, the theoretical discrete slot condition may be imposed on those slots in excess of the ones for which pressure rows are available; but the results are, of course, dependent on the slot parameter K specified in the theoretical condition. Attempts to interpret the flux distribution on the pressure-controlled slots in terms of an equivalent longitudinal distribution of K and apply this distribution to the remaining slots in an iterative fashion are as yet unsuccessful.

A test case has been established from one test condition of the experiment described in ref. 3 in which wall pressures were measured in the slotted wall test section of the Langley Diffuser Flow Apparatus (DFA). Unfortunately, pressures were not measured over the full length of the slots. Attempts to use pressure specification for the upstream part of each slot and the theoretical slot condition for the downstream part gave unsatisfactory results. Two approximate methods were used to obtain assessment solutions. In the first method, the solution domain was simply truncated at $x/h = 4.5$ which was the downstream limit of measured wall pressures. Of course, all tunnel features downstream of this location were ignored. In the other approximate method, the slot flux was controlled by the theoretical slot boundary condition and the pressure specifications were satisfied by local variations in wall slope which is the procedure intended for solid walls. Interference velocity components from both assessment approximations are compared in fig. 2 with those from simulation of the same case. The model support sting had a conical flare starting at $x/h = 4.7$ and continuing to a large sting diameter farther downstream, and the sting was inclined at a negative pitch angle. The effects of this sting flare were not represented in the truncated domain assessment but are apparent in the other two solutions. Differences between the two assessment solutions are attributed primarily to the sting effects. In the second method, the presumed equivalence between wall slope and slot flux is subject to some error because of the discrete slot effects on measured wall pressure.

4. OTHER ACTIVITIES

4.1 Two-Variable Assessment Scheme

A requirement of any interference assessment scheme is that the distributions on an interface surface at or near the tunnel walls of two independent potential flow variables be defineable. In the scheme discussed in Section 3, one such distribution is the measured wall pressure and its numerical interpolation. The remaining requirement is satisfied by perturbations from the test model which is represented by prescribed singularity distributions in the tunnel interior. The accuracy of this model representation has been questioned for tests involving significant flow separation. An alternative assessment scheme can be based on prescribing distributions of pressure and flow angle on the interface. For a slotted-wall tunnel, the measured wall pressures could be supplemented by the known wall shape plus measured slot flux distributions.

A very brief conceptual study was made of this alternative assessment scheme applied to a two dimensional tunnel with either closed (zero slope) or open (constant pressure) walls. The two-variable wall data to be used as the assessment scheme input was generated by calculating the tunnel interior flow around a model represented by a point doublet, source or vortex and determining the u- and v-distributions on the tunnel domain boundary. The assessment then consisted of imposing the boundary distribution of one variable as an inner boundary condition on an exterior flow with unbounded far field, calculating the distribution on the tunnel boundary of the other variable in the outer flow, imposing the discontinuity across the tunnel boundary of this second variable as a singularity sheet and calculating its influence at the tunnel axis as the wall interference.

A significant finding of the study was that the accuracy of the final interference result depended strongly on which of the two variables was selected for the inner boundary condition of the exterior flow. Problems arose when the values and trends of this variable at the upstream and/or downstream ends of the tunnel flow were not compatible with the natural asymptotic decay of exterior flow perturbations. When it is recognized that the real flow in a closed circuit tunnel has no far field, it must be concluded that a presumption of asymptotic extension of the tunnel flow (and, therefore, the interference flow) in the upstream and downstream directions is purely artificial. It is the opinion of the principal investigator that assessment schemes requiring an outer flow computation will be more sensitive to errors from inexact representation of the upstream and downstream closure of the tunnel flow domain than will those schemes using direct representation of the test model.

4.2 Documentation of TWINTN4 Code

Prior to the period of this cooperative agreement, the writer developed an interference assessment procedure for airfoil tests in two-dimensional tunnels. The procedure was implemented in a computer code described in ref. 4. Later the procedure and computer code were extended to include the effects of tunnel sidewall boundary layer interaction with the airfoil pressure field. The capabilities of the revised procedure were reported in ref. 5. As a task under the present cooperative agreement, the description and user's guide to the revised computer code was prepared and published as a NASA CR (see item 1 of Reports and Articles in Section 5). In a related activity, a tutorial lecture on this procedure and computer program was prepared and presented as noted in item 3 of Conference and Meeting Presentations in Section 5.

4.3 NTF Diffuser Choke Study

A brief study was made of the flow in the NTF with choke bumps installed in the diffuser entrance. The purpose of the choke bumps is to form a sonic throat to prevent the upstream acoustic propagation of disturbances from the diffuser into the test section. Choked throat operation is desired for a range of test section Mach numbers from 0.7 to 0.9. For best flow quality, the test section slots will be covered to form solid walls. Choke operation with test section slots open is also planned although their effectiveness will be greatly reduced because of acoustic propagation through the thick subsonic mixing region downstream of the slots.

The purpose of the present study was to perform a preliminary review of the tunnel flow characteristics with one or more candidate choke bump installations. The chokes considered were to be installed on the pivoted portion of the top and bottom diffuser walls in the vicinity of the sting support sector so that the existing pivoting wall actuators can be used to vary the choke throat area. The General Electric streamtube curvature computer program (GESTC) was used to calculate the potential flow in the test section and choke region and the boundary layer on the top wall. In this program, the flow between the tunnel axis and top wall was calculated as a two-dimensional duct flow with approximate accounting for duct width variations due to sidewall shape and sting blockage by the principle of one-dimensional flow conservation.

The top wall contours for the low and high test section Mach number settings with test section slots closed and two choke bump shapes are illustrated in fig. 3. Note that the vertical scale is expanded to accentuate contour variations. At the minimum Mach number setting, the reentry flap surface is presumed to be built up to fill the wedge-shaped slot openings to a level flush with the test section top wall. As the choke is retracted for higher Mach numbers, the reentry flaps are pivoted to keep the leading edge flush with the wall. The contour shown in the reentry flap region approximates an average tunnel height across the wedge-shaped slot region but was input with continuous slope to suppress anomalies in the boundary layer calculation. The boundary layer calculation does not model separated flow but does evaluate an approximate separation point criterion. Points of initial exceedance of this criterion are shown by the circle symbols on fig. 3.

At the low Mach number choke settings, no boundary layer separation was indicated. The calculated Mach number, however, continued to increase in the supersonic range downstream of the choke throat. In practice, the flow would be allowed to shock down to subsonic conditions somewhere downstream of the choke throat and separation might well occur, requiring increased tunnel drive power but probably having little effect on the test section and choke flow. At the high Mach number setting with choke shape I, the separation criterion was exceeded over most of the reentry flap region. Although reattachment was indicated on the upstream face of the choke bump, the calculated displacement thickness at the choke throat must be considered unreliable which reflects on the accuracy of the test section Mach number. For choke shape II, the throat location was shifted upstream so that both the pivoted ceiling and the reentry flaps would rotate through smaller angles from the low to high Mach number settings. As a result, the calculated boundary layer remained attached over most of the reentry flap region and the separation criterion was exceeded by a very small amount over a very short region. Note that although a smooth contour was input to the computation, the wedge-shaped slot terminations actually existing in the reentry flap region could produce edge vortices which might delay or suppresss boundary layer separation.

To address the use of choke bumps with open test section slots, attempts were made to use the multi-channel capability of the GESTC program to impose a reduced velocity stream of reingested plenum air between the high velocity tunnel stream and the choke surface. No successful program runs were accomplished during the limited time addressed to this problem.

5. DISSEMINATION OF RESULTS

Most of the results of work accomplished under this cooperative agreement have been reported both through formally published reports and articles and through presentations at conferences and meetings. The specific items are listed below for both categories. Results from those activities not covered by these items are summarized in Sections 3 and 4 of this report.

5.1 Reports and Articles

1. Kemp, William B., Jr.: TWINTN4: A Program for Transonic Four-Wall Interference Assessment in Two-Dimensional Wind Tunnels. NASA CR-3777, 1984.

2. Kemp, William B., Jr.: A Slotted Test Section Numerical Model for Interference Assessment. J. Airc., vol. 22, no. 3, 1985, pp. 216-222.

3. Kemp, William B., Jr.: User's Guide to STIPPAN: A Panel Method Program for Slotted Tunnel Interference Prediction. NASA CR-178003, 1985.

4. Kemp, William B., Jr.: Computer Simulation of a Wind-Tunnel Test Section with Discrete Finite-Length Wall Slots. NASA CR-3948, 1985.

5.2 Conference and Meeting Presentations

1. Kemp, William B., Jr.: An Interference Assessment Approach for a Three-Dimensional Slotted Tunnel with Sparse Wall Pressure Data. Presented at Wind Tunnel Wall Interference Assessment/Correction Workshop, NASA Langley Research Center, Jan. 25-26, 1983. See NASA CP-2319, 1984.

2. Kemp, William B., Jr.: A Slotted Test Section Numerical Model for Interference Assessment. AIAA Paper no. 84-0627, Aerodynamic Testing Conference, San Diego, CA, March 5-7, 1984. See AIAA CP-841.

3. Kemp, William B., Jr.: Combined four-wall transonic interference assessment theory for airfoil tests and TWINTN4 WIAC code numerics and use. Presented at 0.3-m Transonic Cryogenic Tunnel User Mini Workshop on Airfoil WIAC Procedures, NASA Langley Research Center, Feb. 6, 1985.

4. Kemp, William B., Jr.: Presentations on STIPPAN slotted tunnel simulator code, and TWINTN4 and PANCOR interference assessment codes. Presented at Transonic Wind Tunnel Wall Interference Peer Review, NASA Langley Research Center, Sept. 9-11, 1985.

6. REFERENCES

1. Davis, D. D., Jr.; and Moore, D.: Analytical Studies of Blockage- and Lift-Interference Corrections for Slotted Tunnels Obtained by the Substitution of an Equivalent Homogeneous Boundary for the Discrete Slots. NACA RM-L53E07b, June, 1953.

2. Rust, Burt W.; and Burrus, Walter R.: Mathematical Programming and the Numerical Solution of Linear Equations. Modern Analytical and Computational Methods in Science and Mathematics, Richard Bellman, ed., American Elsevier Publishing Company, Inc., 1972, pp. 22-29.

3. Sewall, William G.: Wall Pressure Measurements for Three-Dimensional Transonic Tests. AIAA Paper no. 84-0599, 1984.

4. Kemp, William B., Jr.: TWINTAN: A Program for Transonic Wall Interference Assessment in Two-Dimensional Wind Tunnels. NASA TM-81819, 1980.

5. Kemp, W. B., Jr.; and Adcock, J. B.: Combined Four-Wall Interference Assessment in Two-Dimensional Airfoil Tests. AIAA Jour., vol. 21, no. 10, 1983, pp. 1353-1359.

Original unsmoothed system

$$A\,x = b$$

A is coefficient matrix, x is unknown vector, b is RHS

Phillips smoothing developed for spectral analysis - 1D domain

$$[A + k(A^{-1})^T C_1]\, x_s = b$$

k is scalar factor

C_1 is banded smoothing matrix using 2nd differences

For present problem:

C_2 replaces kC_1, generalized for 2D blocks using 1st differences with k specified for each direction in each block

Let $D = (A^{-1})^T C_2 = (A^T)^{-1} C_2$

Then $A^T D = C_2$ solve for D with Gaussian Elimination routine

New smoothed solution:

$$[A + D]\, x_s = b$$

Figure 1.- Application of Phillips smoothing algorithm to present interference assessment procedure.

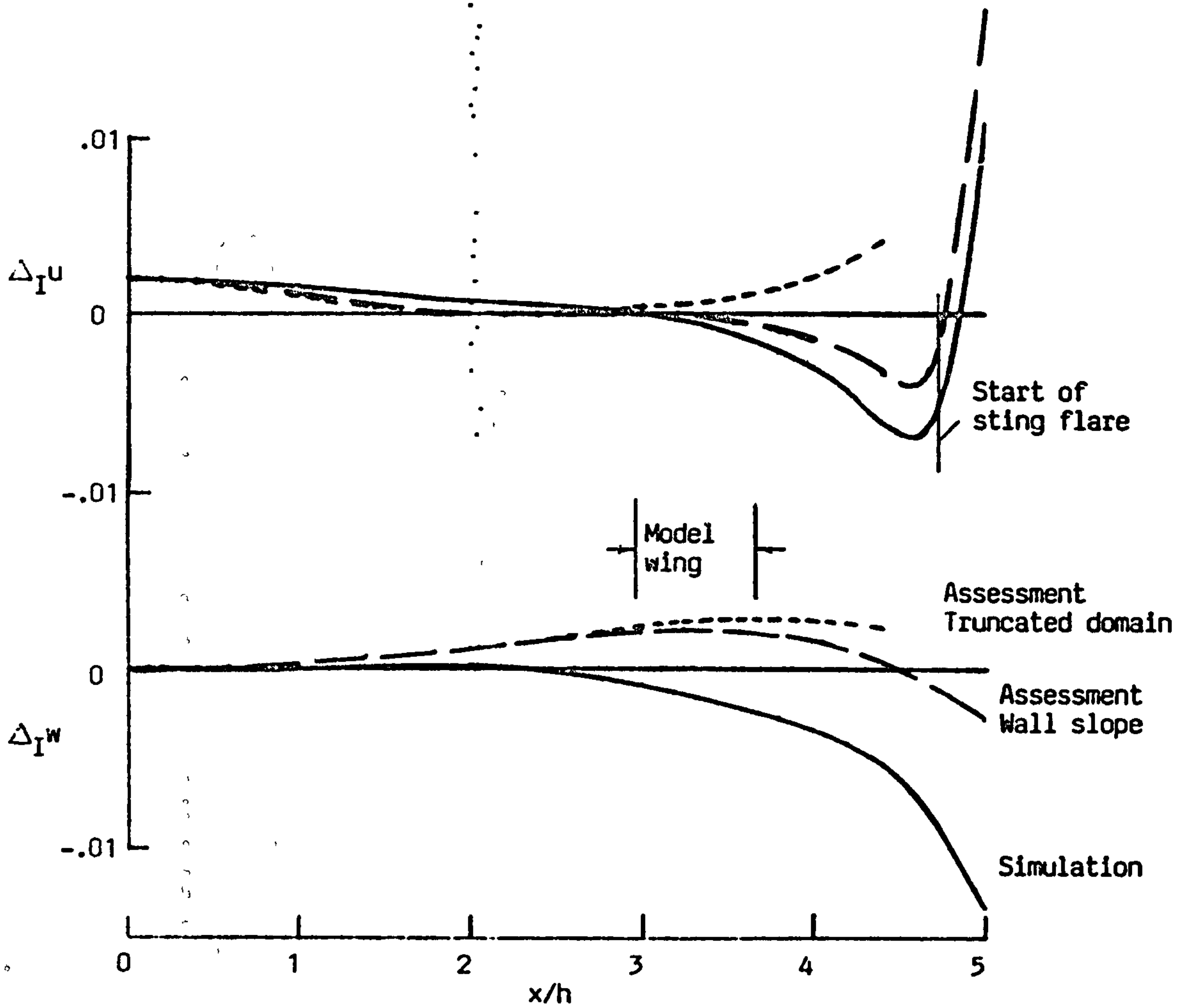
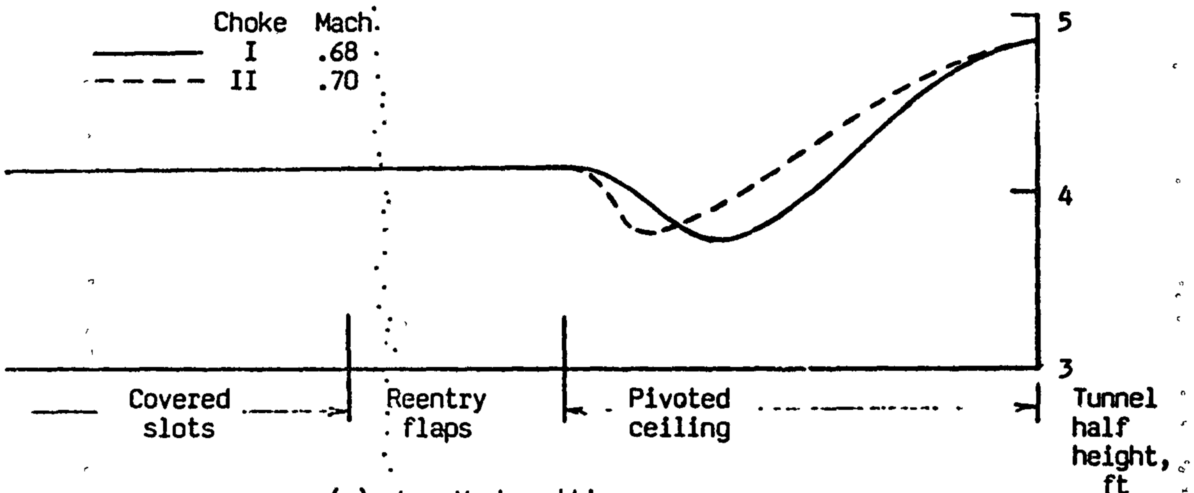
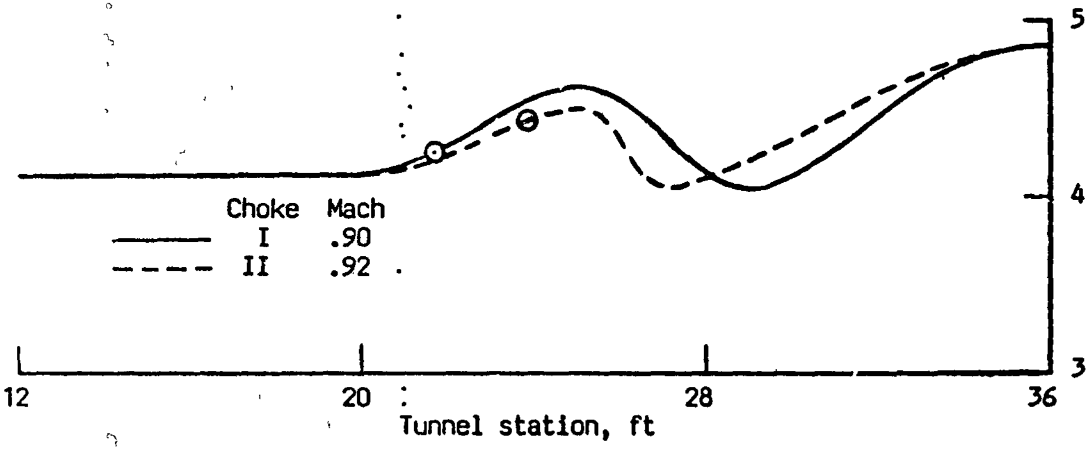


Figure 2.- Simulated and assessed wall-induced velocities on longitudinal line halfway between model center and tunnel sidewall, DFA test case.



(a) Low Mach setting



(b) High Mach setting

Figure 3.- NTF ceiling contours with choke shapes I and II.

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