DESIGN OF A FLEXIBLE NOZZLE FOR PROBE CALIBRATION PURPOSES

by

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LIST OF SYMBOLS

d	thickness of flexible plate
H	height
L	length of flexible plate
M	Mach number
x	coordinate along nozzle axis
y	coordinate along nozzle height

Subscripts

1	throat
2	nozzle exit

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1. INTRODUCTION

The development of appropriate blade profiles for transonic stages in both gas and steam turbines relies still to a great deal on the experimental verification of the blade performance in high speed cascade wind tunnels. In some cases the requests for performance measurements span the whole Mach number range from M = 0.5 to 1.8.

Reference 1 reviews a great variety of probes with their basic characteristics which may be used for this type of testing. Most of the probes require extensive calibrations since their aerodynamic characteristics depend strongly on Mach number and flow angle. It is our experience that probe calibration presents a significant proportion of the total work of a high speed cascade test program and every effort should be made to reduce this necessary but unproductive part of the test program.

2. VARIOUS NOZZLE DESIGN CONCEPTS

The testing of probes at subsonic Mach numbers is usually done by placing the probe in the free jet at the exit of a fixed convergent nozzle. Such nozzles can also be used to produce low supersonic Mach numbers at the nozzle exit by expanding the outlet flow through a Prandtl-Meyer expansion around the corners of the nozzle blocks. The inconvenience of such a procedure is that it creates a considerable velocity gradient along the nozzle axis. The maximum allowable gradient depends on the size of the probe and in particular on the distances between the various sensing holes. This limits the Mach numbers in general to values $M < 1.1$.

A better way of producing low supersonic Mach numbers is given with slotted nozzles of constant geometry. The increase in Mach number is obtained by blowing off an increasing amount of the main flow through slots in the side walls. Such a nozzle type is used, for example, at the RAE for Mach numbers up to $M = 1.4$.

The most widely used method to produce uniform supersonic flow fields is the convergent-divergent nozzle. The variation of the Mach number is obtained either by different nozzle blocks or by a continuous change of the nozzle end walls through a system of jacks. The last method allows to adopt any arbitrary shape for the end walls. Both methods have, however, some drawbacks. Exchanging the nozzle blocks is simple but time consuming and the Mach number variation is limited. Varying the nozzle shape by a system of jacks requires a complicated mechanism which does not seem to be justified for a nozzle used solely for calibration purposes.

3. SINGLE JACK FLEXIBLE NOZZLE

The single jack flexible nozzle combines the capability of a continuous variation of the end wall contour with a great simplicity of the wall displacement system. Such a nozzle was developed first for use with the Ames 1- by 3- 1/2- foot high speed wind tunnel (Ref. 2). This flexible supersonic nozzle employs a single jack on each of the two identical oppositely facing walls as shown in figure 1. A similar nozzle was designed and fabricated at VKI. But contrary to the Ames nozzle type the end walls of the VKI nozzle are activated by jacks at the exit of the nozzle instead of in the throat region. Full details of the nozzle design are given in figure 2. A photograph of the nozzle in the test section of the C-3 high speed cascade tunnel is shown in figure 3. Calibrating the probes in the same tunnel in which the cascade tests are carried out has the advantage that Reynolds numbers and turbulence levels are roughly the same for both the probe calibration and the cascade tests.

The contour of the end wall is a function of

(a) the wall angle β in the throat and at nozzle exit;

(b) the vertical displacement Δh of the end wall at nozzle exit; $M = f(\Delta h/H_1)$ where H_1 represents the throat height;

(c) the end wall thickness distribution; $d = f(L)$ where L represents the length of the flexible plate.

The wall angle is imposed to be zero in the throat and at nozzle exit. The downstream ends of the flexible plates are free to move in axial direction. The axial shift is dependent on the amount of the vertical displacement. The thickness of the flexible plates varies linearly from the throat to the nozzle exit. The material of the plates is a chrome-nickel steel with maximum allowable stresses $\sigma = 1.1 \times 10^3$ N/mm^2.

4. NOZZLE FLOW CHARACTERISTICS

The nozzle design was strongly influenced by the following items :

(a) maximum available mass flow;

(b) relatively long testing times;

(c) wide range of Mach numbers (up to M = 1.8);

(d) uniformity of outlet flow;

(e) flexibility, stiffness and maximum allowable stresses of plates.

Points a and b fixed the throat height to H_1 = 60 mm; the test section width being 100 mm.

As far as the uniformity of the outlet flow field is concerned, the plates with variable thickness proved to be by far superior to the end wall plates of constant thickness. This behaviour was of course expected. The difference between both types of plates is clearly demonstrated in figure 4 for the following case :

- throat height H_1 = 60 mm
- exit height H_2 = 66 mm
- length of plate L = 150 mm
- thickness of plate

  (a) constant d = 2 mm

  (b) linear variation d = 1 → 3 mm

The same figure shows that the velocity gradient at nozzle exit tends gradually towards zero with increasing plate length (plate thickness variation d = 1 → 3 mm). Similar tendencies are observed when varying the nozzle height (and therewith the exit Mach number) at constant nozzle length : the velocity gradient at the nozzle exit decreases with decreasing Mach number and vice versa (Fig. 5).

The final choice for the nozzle geometry was as follows :

- throat height H_1 = 60 mm
- length of flexible plate L = 165 mm
- thickness of plate : linear variation d = 1.6 → 4.0 mm

Figure 6 shows the velocity distributions along the axis and the end wall for M ≈ 1.4. The curves indicate that this nozzle should provide outlet flow conditions which meet the requirements for accurate probe calibration.

5. PRELIMINARY RESULTS

Figure 7 presents, for two exit Mach numbers, the measured Mach number distribution alõng the nozzle axis, M = f(x), and across the nozzle height at nozzle exit, M = f(y). The degree of non-uniformity is unfortunately considerably higher than expected. This result is, however, not inherent to the nozzle design concept, but due to some weaknesses of the present mechanical layout :

(a) there is not enough provision to keep the end wall plates in place during running conditions. The shape of the nozzle changes considerably under the effect of the aerodynamic load;

(b) the transition from the flexible part of the plate to the rigid end piece which serves for fixation in the jack is not smooth enough.

Modifications are made to overcome these problems. Besides that, the single jack flexible nozzle proved to be very easy to use and allows indeed to reduce considerably the calibration time.

REFERENCES

1. SIEVERDING, C.H.; STARKEN, H.: LICHTFUSS, H.J.; SCHIMMING, P.: Aerodynamic measurements in cascades, in Modern Methods of Testing Rotating Components of Turbomachines.
AGARDograph-207, 1975, pp 1-76.

2. ALLAN, H.J.: Transonic wind tunnel development of the National Advisory Committee for Aeronautics.
Sixth Meeting of the Wind Tunnel and Model Testing Panel, Paris, France, November 1954.
AGARD Memorandum AG 17/P7, pp 198-217.

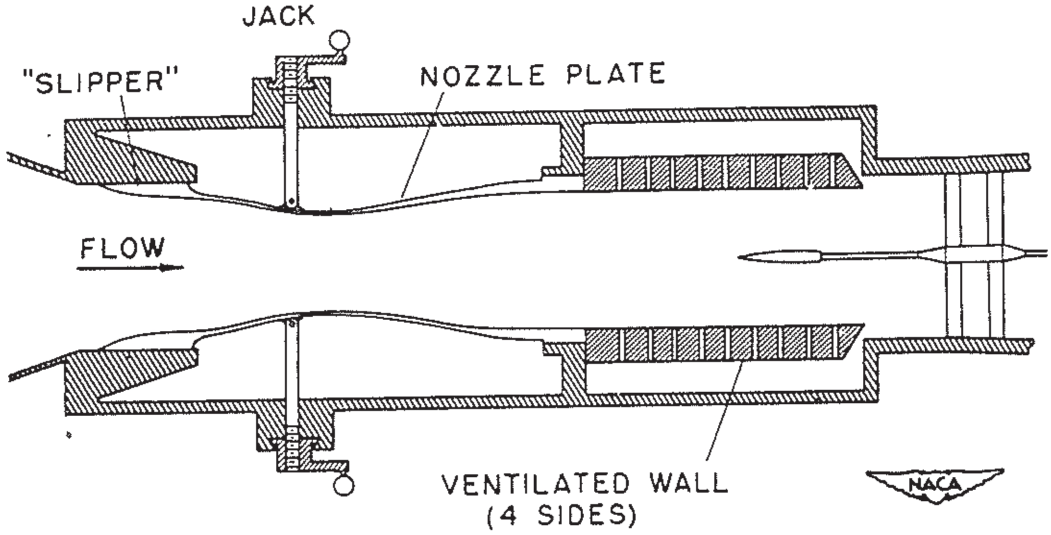

Fig. 1- NACA SINGLE JACK FLEXIBLE NOZZLE

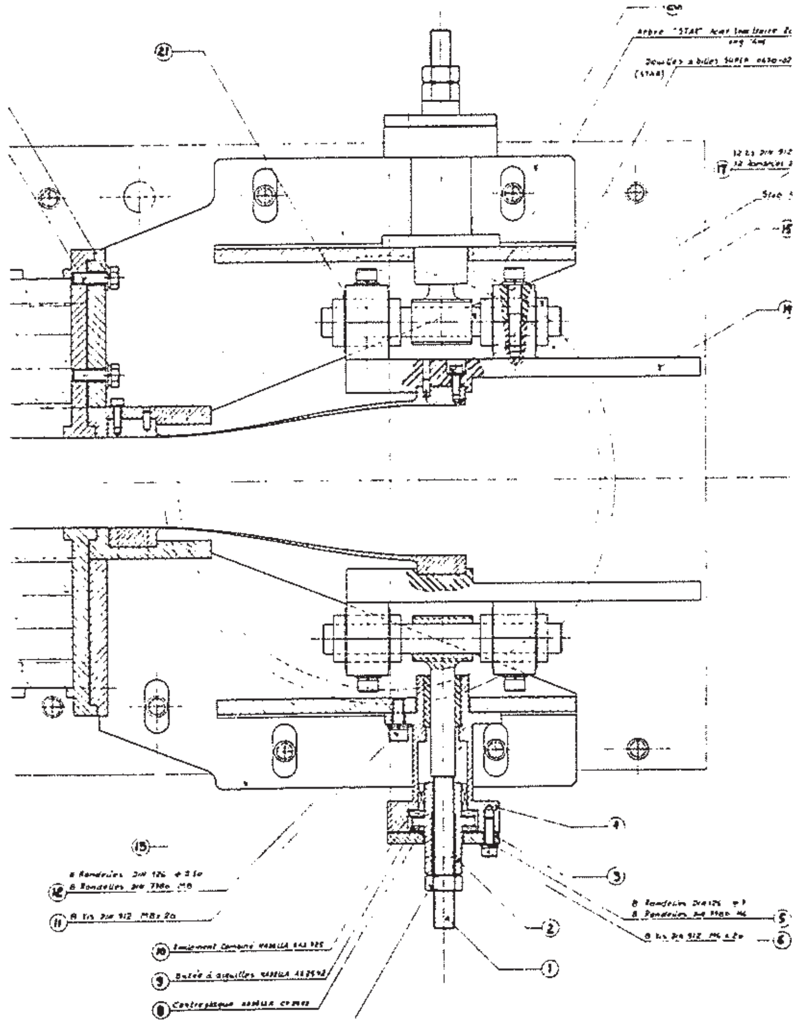

Fig. 2 - DESIGN OF VKI SINGLE JACK FLEXIBLE CALIBRATION NOZZLE.

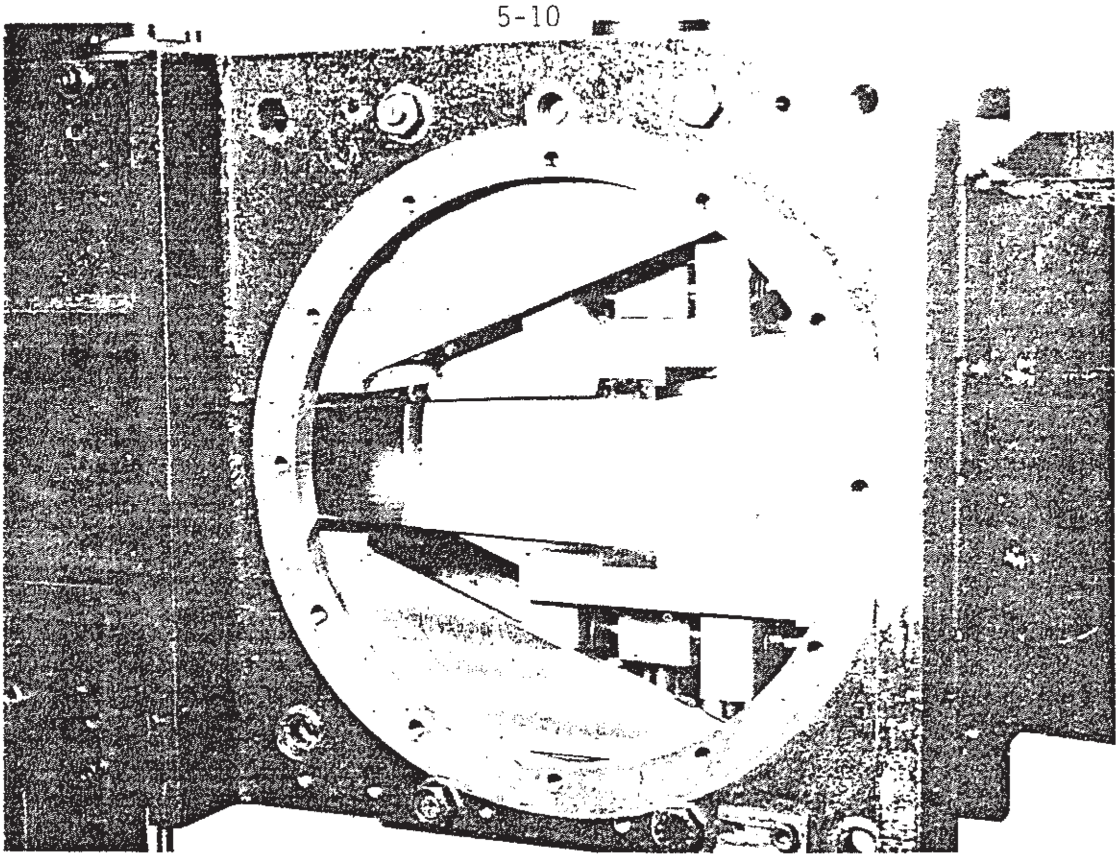

Fig. 3 - PHOTOGRAPH OF FLEXIBLE NOZZLE IN TEST SECTION OF VKI HIGH SPEED CASCADE TUNNEL.

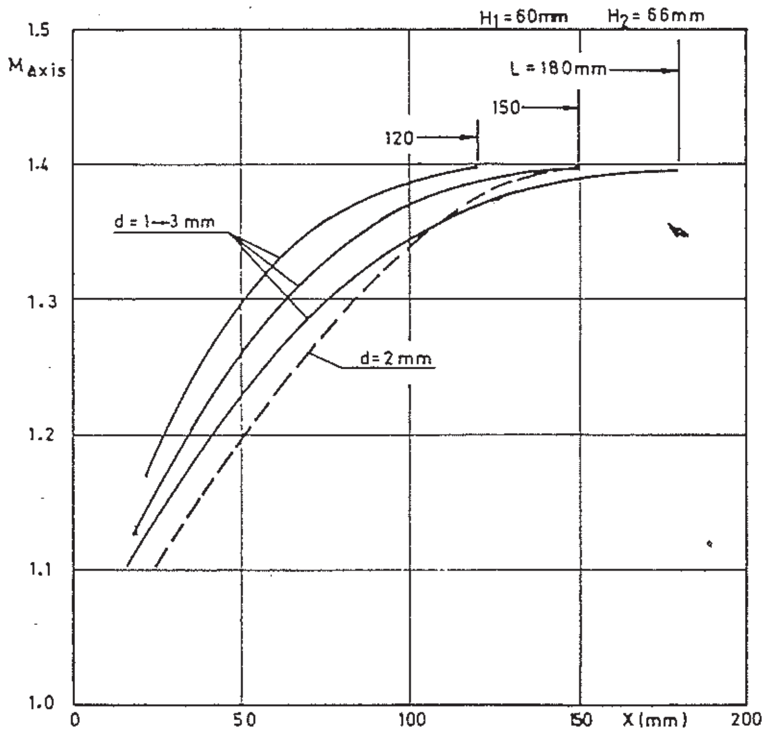

Fig. 4 - THEORETICAL MACH NUMBER DISTRIBUTION ALONG NOZZLE AXIS - INFLUENCE OF NOZZLE LENGTH AND THICKNESS DISTRIBUTION OF FLEXIBLE NOZZLE END WALL.

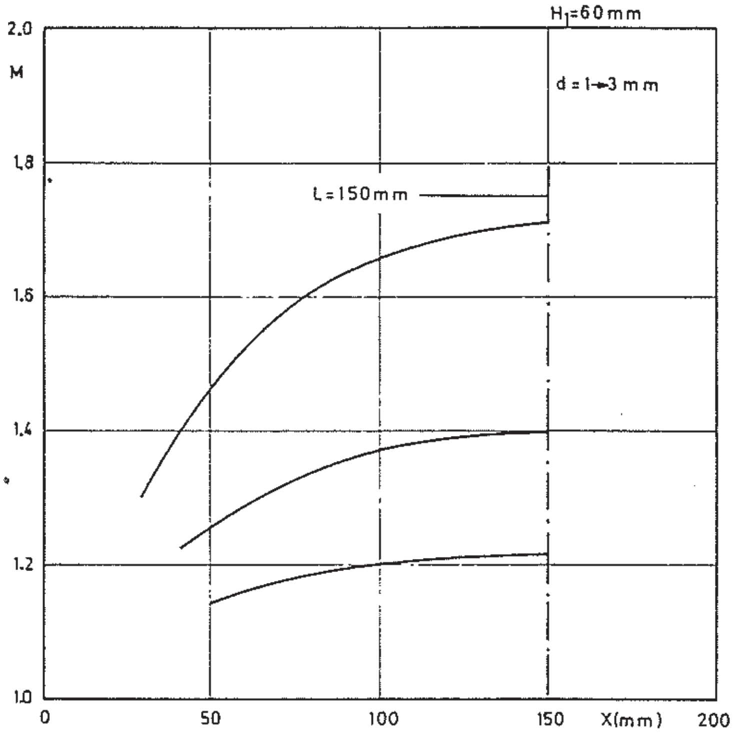

Fig. 5 - THEORETICAL VELOCITY DISTRIBUTIONS ALONG NOZZLE AXIS FOR DIFFERENT EXIT FLOW CONDITIONS.

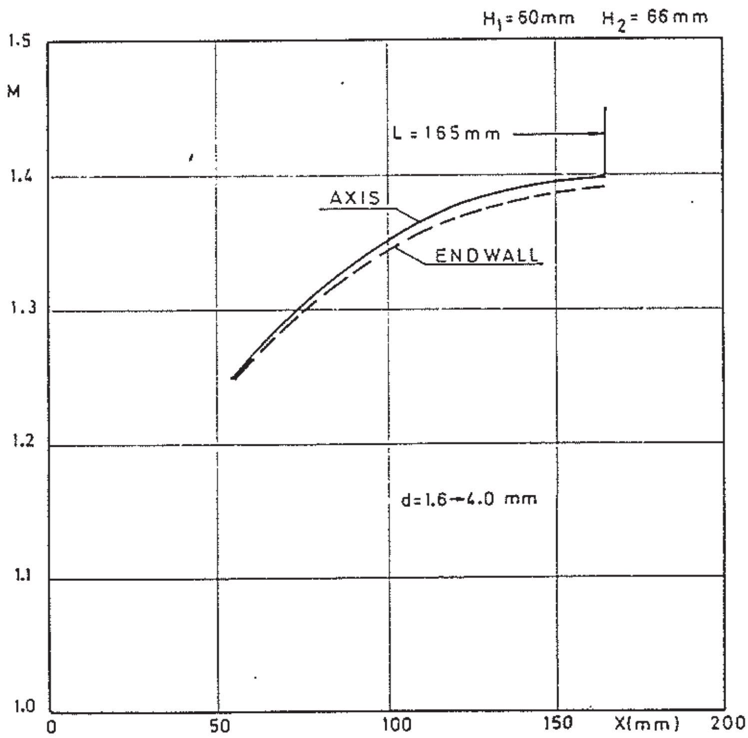

Fig. 6 - THE COMPARISON OF PREDICTED VELOCITY DISTRIBUTION ALONG NOZZLE AXIS AND END WALL FOR MANUFACTURED CALIBRATION NOZZLE.

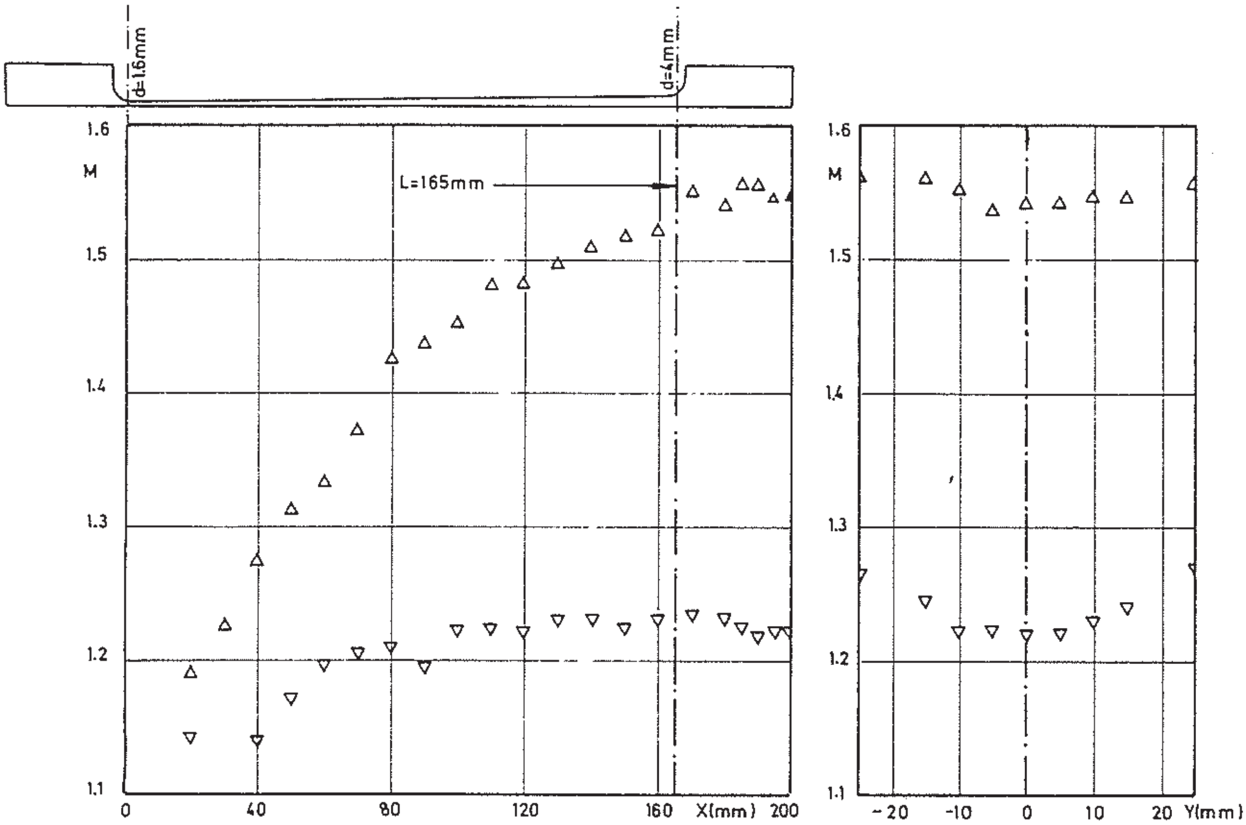

Fig. 7 - PRELIMINARY EXPERIMENTAL RESULTS.