THE INFLUENCE OF TAILBOARDS WITH VARIOUS WALL POROSITY ON TRANSONIC TURBINE CASCADE FLOW

by

J. M. Henne* and H. E. Gallus

Institute for Jet Propulsion and Turbomachinery, RWTH Aachen

Abstract

This paper describes a recently developed transonic cascade wind tunnel with a VKI-2 steam turbine tip section cascade installed, and discusses some aspects of its performance.

Special reference is made to:

- the exit flow periodicity with various slotted and perforated tailboards evaluated by static wall pressure measurement and schlieren visualization

- the problem of a correct setting of tailboard angle at subsonic and low supersonic exit Mach number

- comparative measurement of shock wave and pressure fluctuations in the cascade with and without tailboards.

It is shown that the structure and porosity of the tailboards strongly influences the exit flow and its periodicity. A quite reasonable flow periodicity was achieved with a perforated tailboard with inclined holes. The tailboards were applied for supersonic as well as for subsonic exit Mach numbers. The unsteadiness of the flow in the cascade largely depends upon whether tailboards are used or not. Without tailboards, the shock waves exhibited large, random fluctuations, which were greatly reduced when tailboards were applied.

* present address: MTU München, Dept. EWV
Dachauer Str. 665, 8000 München 50

1 Introduction

In testing plane transonic turbine cascades, one main concern of the experimentalist is to achieve a good quality of the cascade exit flow. Firstly, the time mean flow is adversely affected by reflection of shocks and expansion waves from the flow boundaries, which might interfere with the flow inside the cascade and/or cause a poor periodicity of the exit flow. Secondly, oscillations of the cascade flow are likely to occur caused by instabilities of the free shear layers at the flow boundaries and pressure fluctuations arising from the outlet duct.

As a means to cope with these problems, tailboards are applied in several installations to guide the exit flow and thus avoid the free shear layer instability. The reflection of waves can be partly suppressed by tailboards of controlled porosity, as recommended by Gostelow /1/. The wave cancellation is due to the fact, that a shock wave is reflected as a shock wave from a solid boundary and reflected as an expansion wave from a free shear layer. Perforated walls, for instance, are routinely applied in windtunnels for testing supersonic compressor cascades in order to reduce the reflection of bow shocks at the cascade inlet.

On the contrary, the use of tailboards in transonic turbine cascades might pose difficulties at near sonic outlet conditions in achieving a repeatable flow field. Furthermore, blockage effects due to probes and probe supports might become severe. In previous experiments therefore tailboards were mainly applied at supersonic exit flows above a certain Mach number value /2/.

In the present experimental program a steam turbine rotor tip section cascade, known as VKI-2 cascade /2/, is investigated. Of major concern is the time mean and unsteady interaction of shock waves with boundary layers at steady and periodically varying outlet conditions. Thus, the experiments should give some insight into flow effects related to self-excited and forced oscillations of blades in the transonic flow regime.

For these specific measurements, it was decided to apply tailboards throughout the range from subsonic to supersonic outlet flows. In the first part of this paper, the usefulness of tailboards with respect to investigations of the unsteady flow is demonstrated. Secondly, the empirical method of relating the cascade pressure ratio and the angular setting of the tailboards is discussed and compared to published measurement data of the VKI-2 cascade. Finally, this paper reports on the design of three tailboards with different wall porosity and their performance with regard to the exit flow periodicity.

2 Description of the Cascade Windtunnel

The test section of the cascade windtunnel in its original design is shown in Fig. 1. It was built especially for the investigations on the VKI-2 steam turbine tip section cascade (Fig. 2), but might also accomodate similar, low deflection cascades. The windtunnel is continously supplied with air by a compressor at a maximum mass flow of 5.5 kg/s and operates in a partly closed loop. The geometric data of the test section and the cascade are summarized in Table 1. A bleed system at the cascade inlet allows for boundary layer suction at the upper and lower endwalls. The slotted endwalls later were replaced by solid plates, as test results revealed, that boundary layer suction at the cascade inlet was not necessary with respect to the exit flow periodicity. The tailboards are hinged at the trailing edges of the upper and lower end blade and can be moved to a prescribed angular setting by means of screws.

3 Comparision: with/without Tailboards

Some test runs were conducted in order to evaluate the effect of tailboards on the unsteady flow characteristic. The measurement of wall pressure fluctuations about one chord length axially downstream of the cascade clearly demonstrates the high level of flow instability when the tailboards were removed, Fig. 3. The pressure fluctuations are most severe at near sonic outlet conditions and reach values approximately ten times higher than measured with tailboards. The unsteady pressure measurement corresponds well with measured shock oscillations by the laser - density gradient - technique, as shown in Fig. 4.

Large oscillations of the reflected shock were observed without tailboards, while the use of tailboards almost completely stabilized the shock wave. The shock wave fluctuations are mainly of a random nature. Depending on the exit mach number, single weak frequency peaks appear, which might be related to oscillation mechanisms of the free jet forming at the cascade exit.

These test results clearly underline the necessity of applying tailboards for unsteady flow measurements in this cascade facility.

4 Setting of Tailboard Angle

It is typical for a transonic turbine cascade, that the exit flow angle varies largely with the pressure ratio or the exit Mach number of the cascade respectively. This poses an obvious problem to the experimentalist when tailboards are used as one has to relate correctly the angular setting of the tailboards to the exit Mach number.

The following simple considerations lead to the method, that we applied to define the correct setting of the tailboard.

If the tailboard angle does not coincide with the true exit flow angle, the streamlines close to the tailboard will be different from streamlines in the central flow passage. This would be equivalent to a non-periodic exit flow which can be recognized by measurements of the wall pressure distribution across several pitches. During the test runs, the tailboards were set at a specific angle and the cascade pressure ratio was varied until an optimum periodicity of the exit Mach number distribution was achieved. The periodicity was judged by plotting the distribution of the isentropic exit Mach number as well as by calculating values of the non-periodicity factor ε_i, expressed according to Sieverding /2/ as:

$$\varepsilon_i = \frac{\overline{M}_2\ (\text{pitch } i) - \overline{M}_2\ (3\ \text{pitches})}{\overline{M}_2\ (3\ \text{pitches})}$$

based on the wall pressure tappings No. 4 to No. 28, see Fig. 5. Several Mach number distributions from subsonic to high supersonic exit Mach numbers are also presented in Fig. 5. In terms of ε_i, the non periodicity amounted to

$$\varepsilon_i < 0,01 \text{ for } M_2 < 0,9$$
$$\varepsilon_i < 0,02 \text{ for } M_2 < 1,2$$
$$\varepsilon_i < 0,03 \text{ for } M_2 > 1,2$$

which was considered satisfactory for this cascade.

The exit flow angle itself was not measured in this test series. In Fig. 6, a comparison is shown of the tailboard angle, determined by the procedure described before, with exit flow angle measurements of the DFVLR-AVA /4/. The agreement is quite good up to M_{2is} = 1,25. At higher Mach numbers our values are significantly higher than those of the DFVLR. Part of the difference is due to deviations of the blade contours, increasing the throat height and thus the inlet Mach number.The higher inlet Mach number also means a greater exit flow angle for a specific exit Mach number, illustrated by the theoretical curves in Fig. 6. The remaining difference finally could be related to leakage flows, caused by an incomplete sealing of the blades at the perspex sidewalls. The leakage only occured at high Mach numbers, because of the rising inlet pressure of the tunnel.

Therefore it can be stated, that the use of tailboards is possible throughout the range from subsonic to high supersonic exit Mach numbers and reproducible results can be obtained.

5 Variation of Tailboard Wall Porosity

Three tailboard configurations with different wall porosity were tested in order to find out the one which minimizes reflections of shock and expansion waves and gives the best exit flow periodicity. The investigations were confined to the upper tailboard, as in supersonic flow reflections from the lower tailboard would not affect the considered flow area close to the cascade exit, Fig. 1.

Tailboard A contains a perforated wall with an open area ratio of 6 %. The holes of diameter 1 mm are inclined by 60° as indicated in Fig. 7. The inclination of the holes increases the resistance to flow into the test section compared to vertical holes. The thickness of the perforated wall is 1 mm. The wall was machined from a single piece of aluminium alloy. For stability reasons the perforated wall is glued to a solid steel plate, forming 7 mm high, small chambers between the rows of holes and the steel plate, Fig. 7. The perforated wall was designed according to recommendations from Goethert /5/. Similar perforated walls are installed in supersonic windtunnels.

Tailboard B also consists of a perforated wall, but with an open area ratio of 30 % and vertical holes of diameter 1 mm, Fig. 8. The perforated plate is a commercially available material from stainless steel. It is screwed onto a constant pressure chamber with dimensions of 25 mm x 180 mm (height x length). Over a length of 40 mm the perforated plate is partly covered inside the chamber by solid strips, which leads to a linear increase of the open area ratio in the forward position of the tailboard from 0 % to 30 % (not shown in Fig. 8). This is a typical feature of perforated windtunnel walls /5/.

Tailboard C is of the same overall design as tailboard B, but with a slotted wall of 37 % open area ratio instead, Fig. 9. The slot width is 3 mm. This tailboard configuration meets quite closely the design recommendations of Bölcs, Suter /6/.

The comparision of the three tailboard configurations was performed at supersonic exit Mach numbers, as only in this flow regime a significant difference might be expected. For each of the four selected tailboard angles (24°, 26°, 28°, 30°) the wall pressure distribution was measured and the flow was recorded by schlieren photos.

Fig. 10 shows the results for an angle of 26°. The schlieren photo and the Mach number distribution have equal scales to allow for a direct comparison.

Disturbances of the cascade exit flow periodicity are mainly caused by right running waves, for instance the right running trailing edge shocks. Reflections of these shock waves from the tailboards are more or less visible in every schlieren image, but the accompanying pressure disturbance can barely be deduced. The wall pressure distributions reveal, that shock reflections from tailboard A only give rise to a slightly reduced expansion of the flow in pitch 1 and 3. With tailboards B and C on the contrary, the non-periodicity of the exit flow is more severe. In both cases, the average

Mach number in pitch 2 is much lower than in pitch 1 and 3. From inspection of the schlieren images it seems unlikely, that this effect is solely caused by shock wave reflections.

A further comparision of exit Mach number distributions for the selected tailboard angles also leads to the conclusion, that the best exit flow periodicity was achieved with tailboard A, the perforated wall with inclined holes, Fig. 11. This becomes obvious from a continuous increase of the Mach number level in every pitch with increasing exit flow angle, compared to a discontinuous development of the exit flow with tailboards B and C.

A thorough discussion of the local flow effects at perforated and slotted walls was given nearly thirty years ago by Goethert /5/, who summarized experiences from transonic windtunnel tests. According to /5/, a complete shock cancellation can be achieved, if the pressure loss of flow through the porous wall is equal to the shock pressure rise. That means, the pressure inside the chamber is equal to the static pressure upstream of the shock. This condition is met, disregarding wall boundary layer effects, by a perforated wall with 50 % open area ratio and vertical holes. For a slotted wall, the optimum open area ratio depends on the deviation angle and the upstream Mach number of the shock.

Nevertheless, the cross-flow characteristic of those perforated or slotted walls is not ideal, as their resistance to flow into the test section is too low, meaning that expansion waves can not be adequately cancelled. A better compromise is obtained by perforated walls with inclined holes, as sketched in Fig. 7. The increased resistance to flow into the test section is demonstrated in Fig. 12 (Fig. 11.20 in /5/) for a perforated wall with 6 % open area ratio and 60° inclined holes. The nearly linear cross-flow characteristic of such a wall is the reason for the capability to cancel compression - and expansion waves equally. This might serve as an explanation for the better exit flow periodicity obtained with tailboard A.

6 Conclusions

A transonic turbine cascade facility is described which is utilized to investigate shock and boundary layer effects at the VKI-2 steam turbine tip section cascade. Comparative measurements with and without tailboards demonstrated, that tailboards are a useful and necessary tool to suppress time dependent flow disturbances. The correct angular setting of the tailboards for a specific pressure ratio can be obtained by evaluating the respective exit flow periodicity.

To further improve the flow periodicity and avoid wave reflections from the tailboards, three different perforated and slotted tailboards were tested.

The best results were achieved with a perforated tailboard with 6 % open area ratio and 60° inclined holes. This type of wall porosity offers the best compromise for cancellation of compression und expansion waves, according to the cited reference of Goethert /5/.

References

/1/ Gostelow, J. P.:
"Cascade Aerodynamics", Pergamon Press

/2/ Sieverding, C. H.:
"Base Pressure Measurements in Transonic Turbine Cascades" VKI LS-84, Transonic Flows in Axial Turbomachinery, Febr. 1976

/3/ Sieverding, C. H., Decuypere, R., Hautot, G.:
"Investigation of Transonic Steam Turbine Tip Sections With Various Suction Side Blade Curvatures"
Design Conference on "Steam Turbines for the 1980's", Inst. Mech. Engrs. 1979-12

/4/ Swamy, K. M. M., Heinemann, H. J.:
"Some Experimental Investigations of the Steam Turbine Rotor Tip Section Profile VKI-2 at the Rectilinear Cascade Tunnel (EGG) of DFVLR-AVA"
DFVLR-Interner Bericht IB 222-88 A 06, 1988

/5/ Goethert, B. H.:
"Transonic Wind-Tunnel Testing"
Pergamon Press, 1961, AGARDograph Nr. 49

/6/ Bölcs, A., Suter, P.:
"Transsonische Turbomaschinen",
Verlag G. Braun, 1986

Test section width (b) * heigth (h)	79 * 100 mm^2
length of upstream straight end wall	250 mm
area ratio settling chamber: test section	36 : 1
number of blades	3 + 2 end blades
chord c	68.3 mm
aspect ratio b/c	1.16
pitch/chord ratio	0.9
stagger angle (chord to circumferential direction)	24°
inlet Mach number M_1	0.6
outlet Mach number M_2 (design)	1.7
inlet flow angle β_1	24°
outlet flow angle β_2 (design)	29°

Table 1 Data of test section and cascade; aerodynamic design data according to /3/

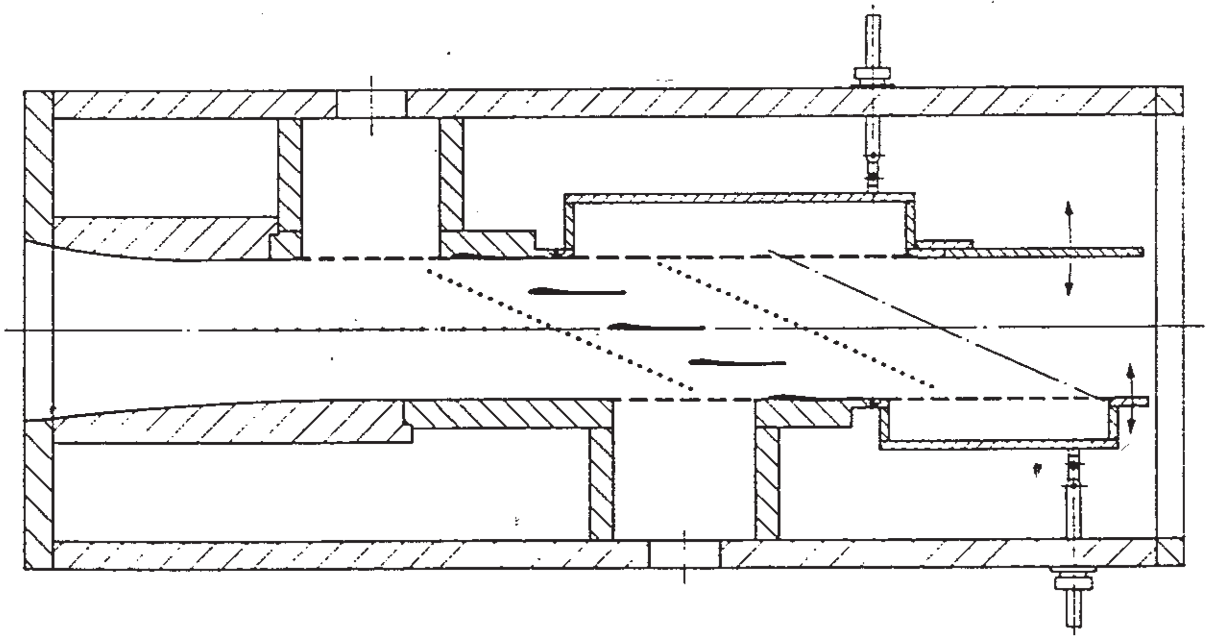


Fig. 1: Sketch of the transonic turbine cascade windtunnel

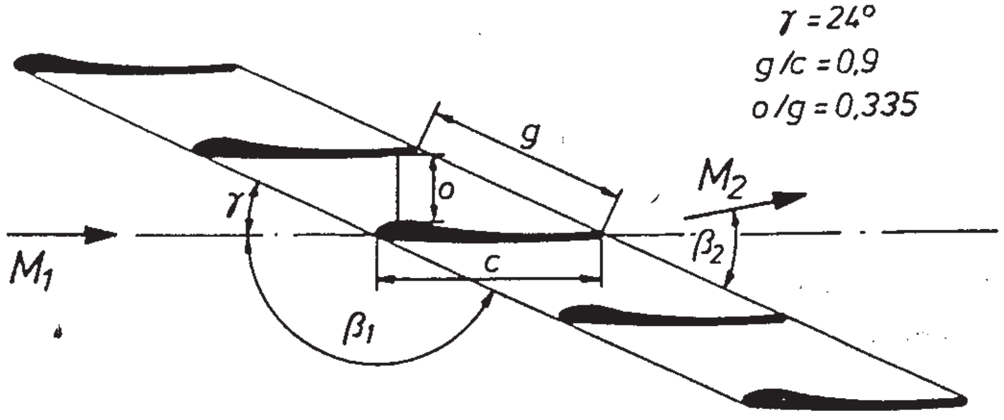


Fig. 2: The VKI-2 steam turbine rotor tip section cascade

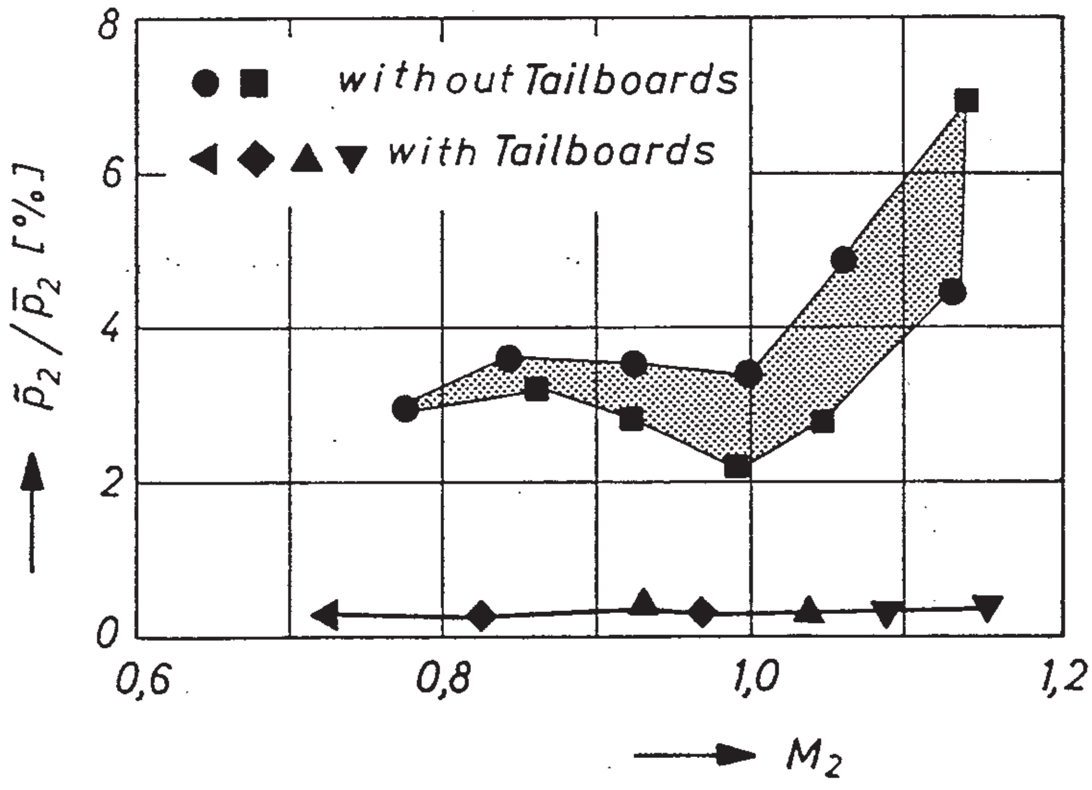
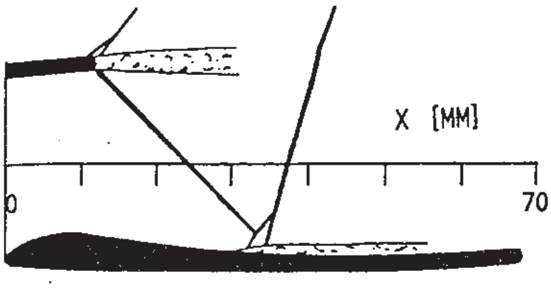
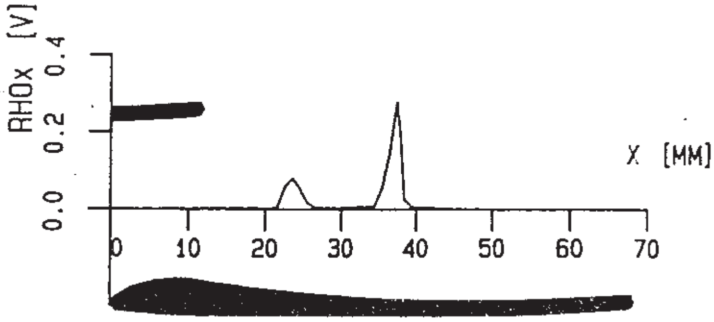


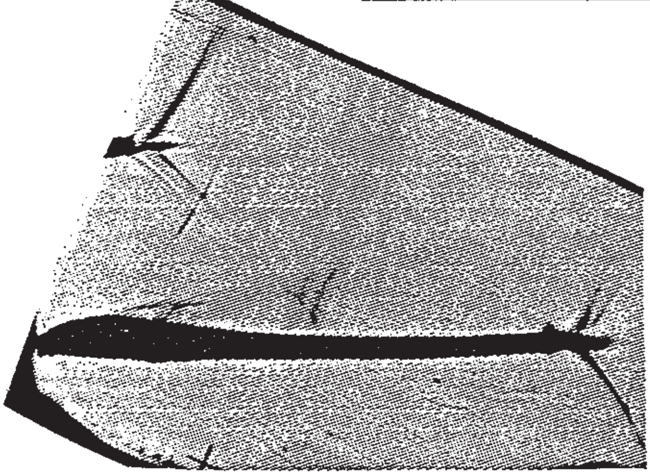
Fig. 3: RMS-value of pressure fluctuations at the cascade exit

WITH TB (M_2 = 1,08)





WITHOUT TB (M_2 = 1,06)



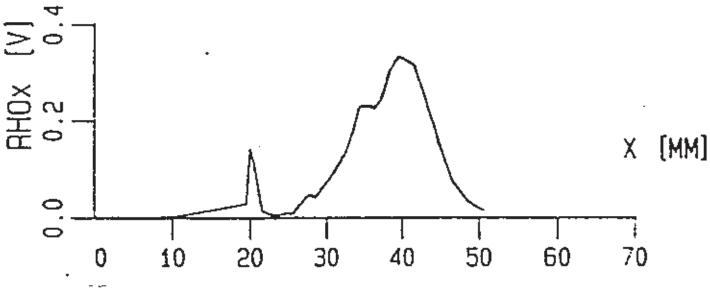


Fig. 4: Comparison of shock oscillations with/without tailboards

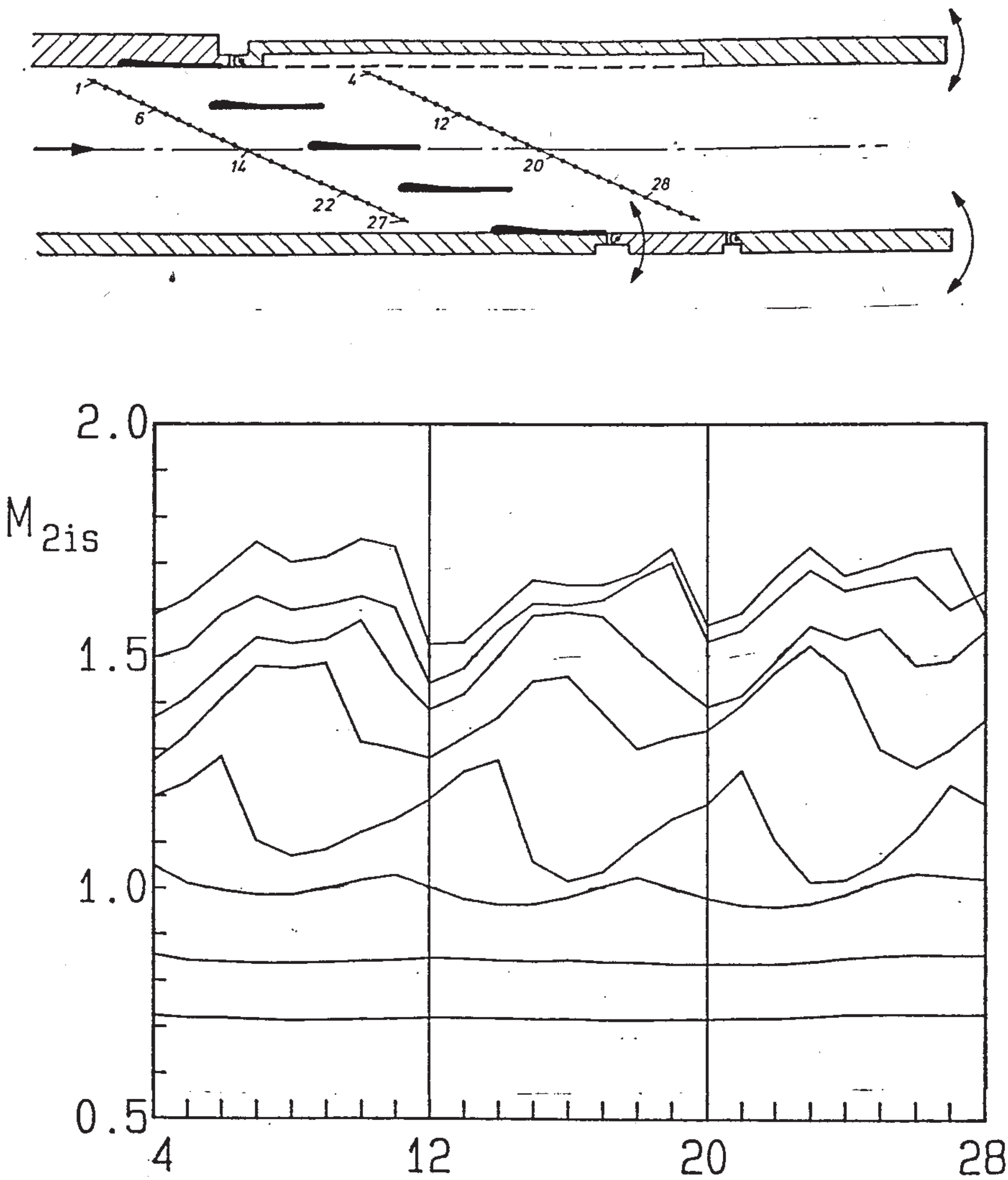


Fig. 5: Location of wall pressure tappings and measured exit Mach number distributions (with tailboard A)

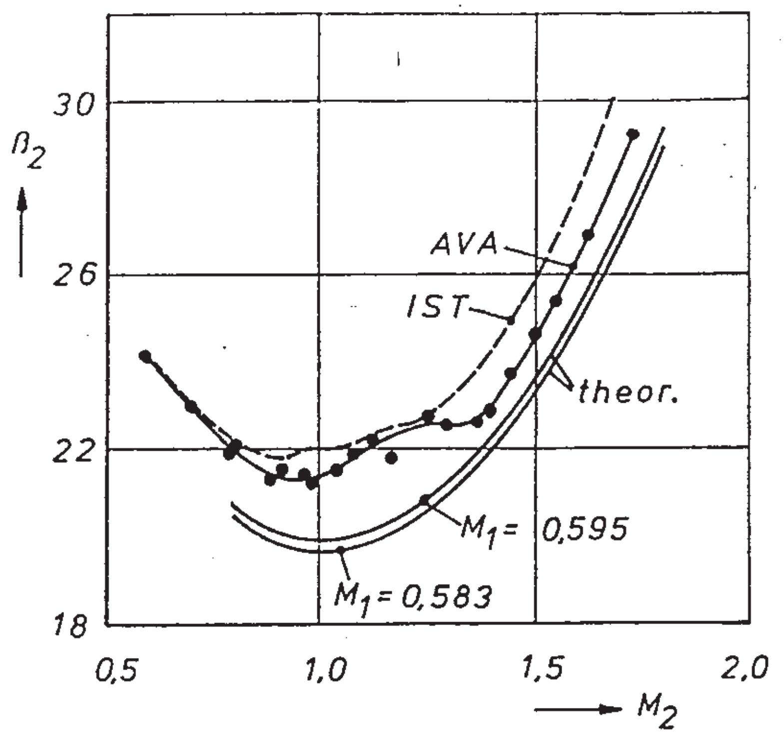


Fig. 6: Comparison of tailboard angle (IST Aachen, tailboard A) with measured exit flow angle data of DFVLR-AVA Göttingen

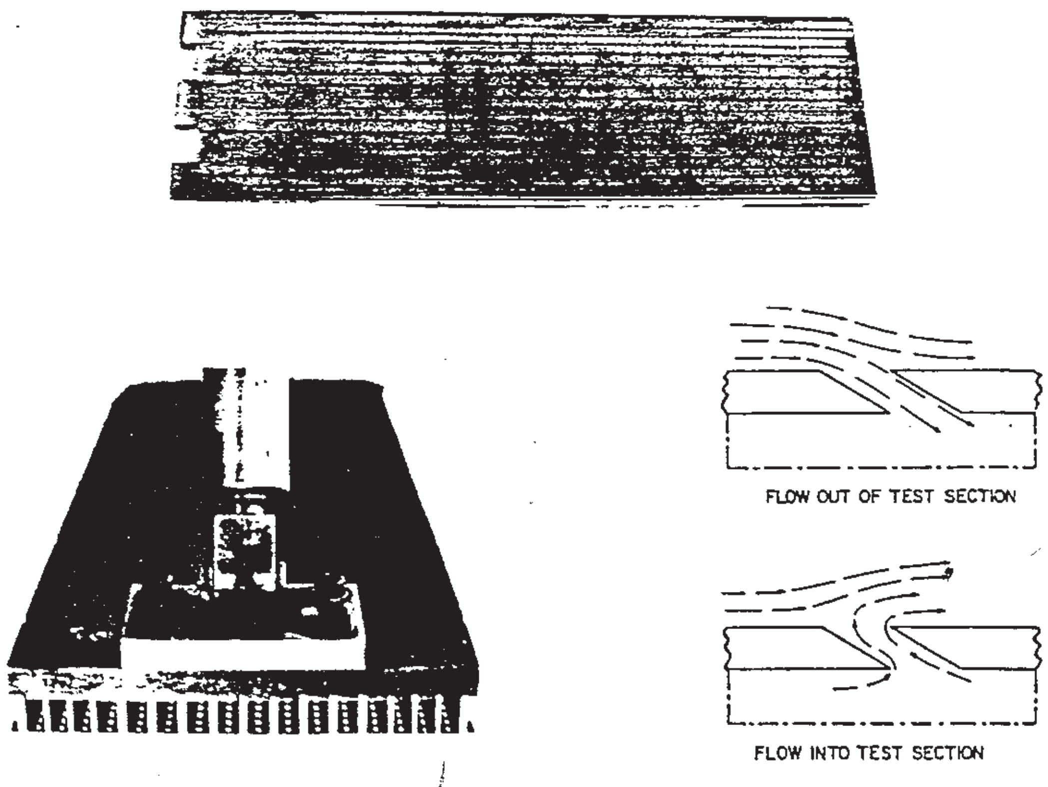


Fig. 7: Tailboard A: perforated, 6 % open area, 60° inclined holes
a) flow surface
b) view looking from downstream
c) sketch of cross-flow according to Goethert /5/

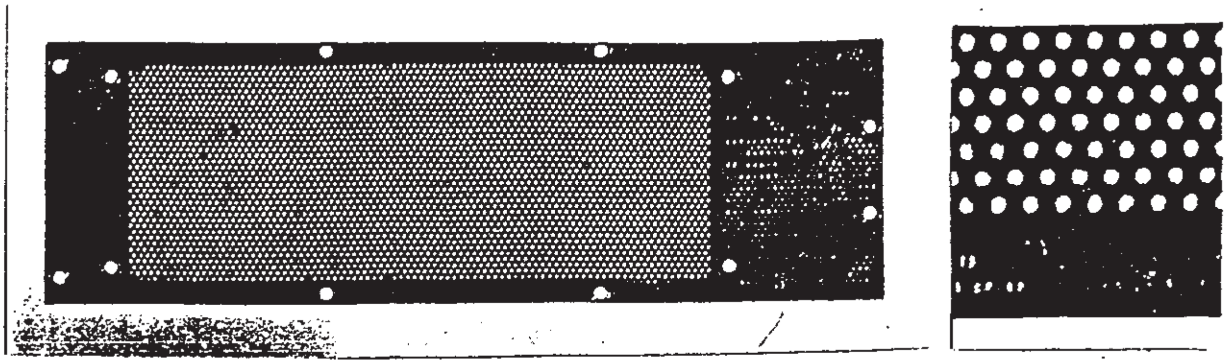


Fig. 8: Tailboard B: 30 % perforated, vertical holes

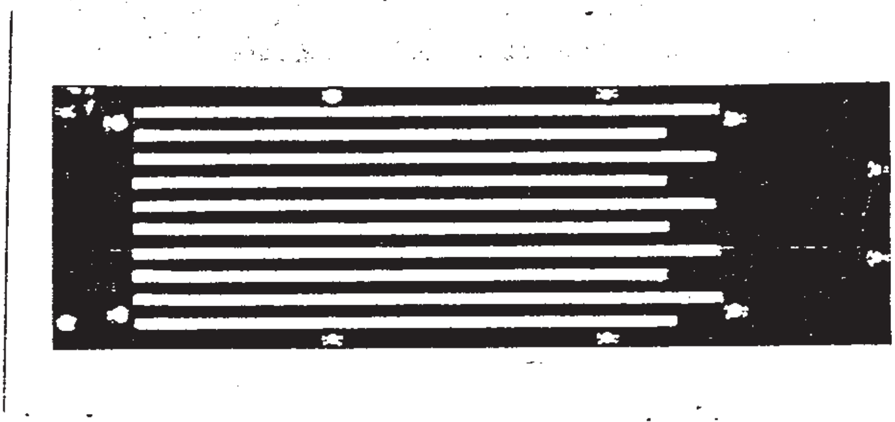
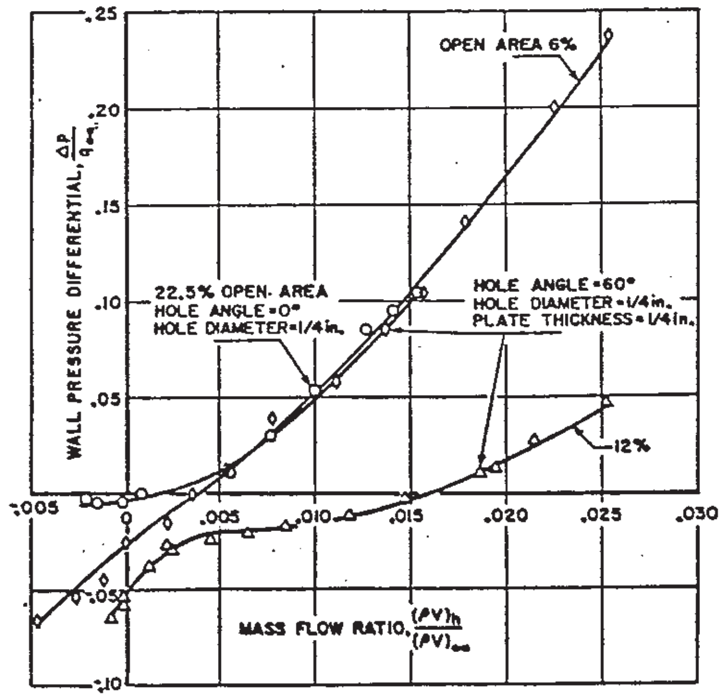


Fig. 9: Tailboard C: 37 % slotted



b. $M = 1.10$.

Fig. 12: Cross-flow characteristic of perforated walls with inclined holes (full symbols) and vertical holes (open symbols); Fig. 11.20 from /5/

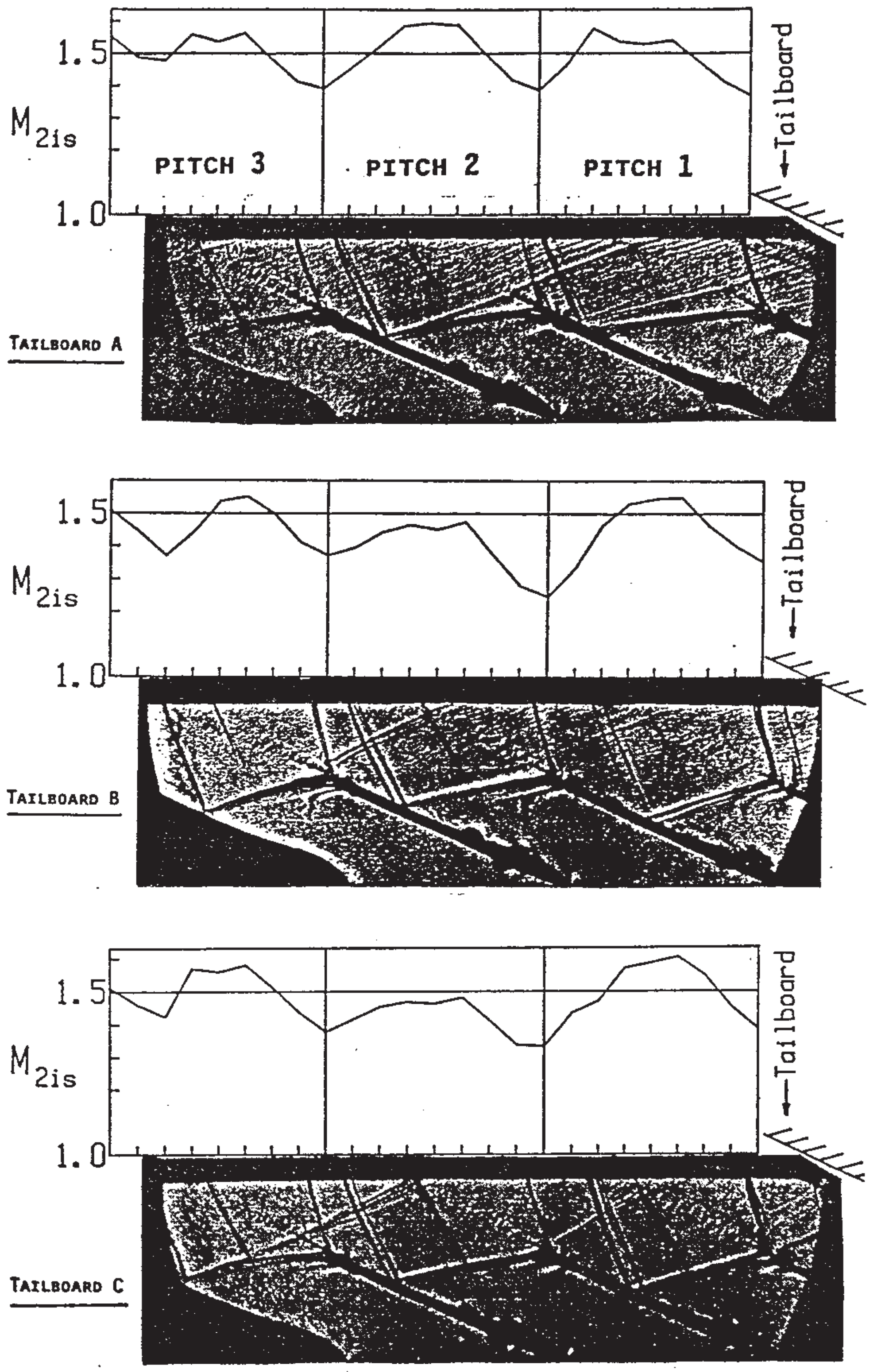


Fig. 10: Influence of tailboard wall porosity on cascade flow and exit Mach number distribution

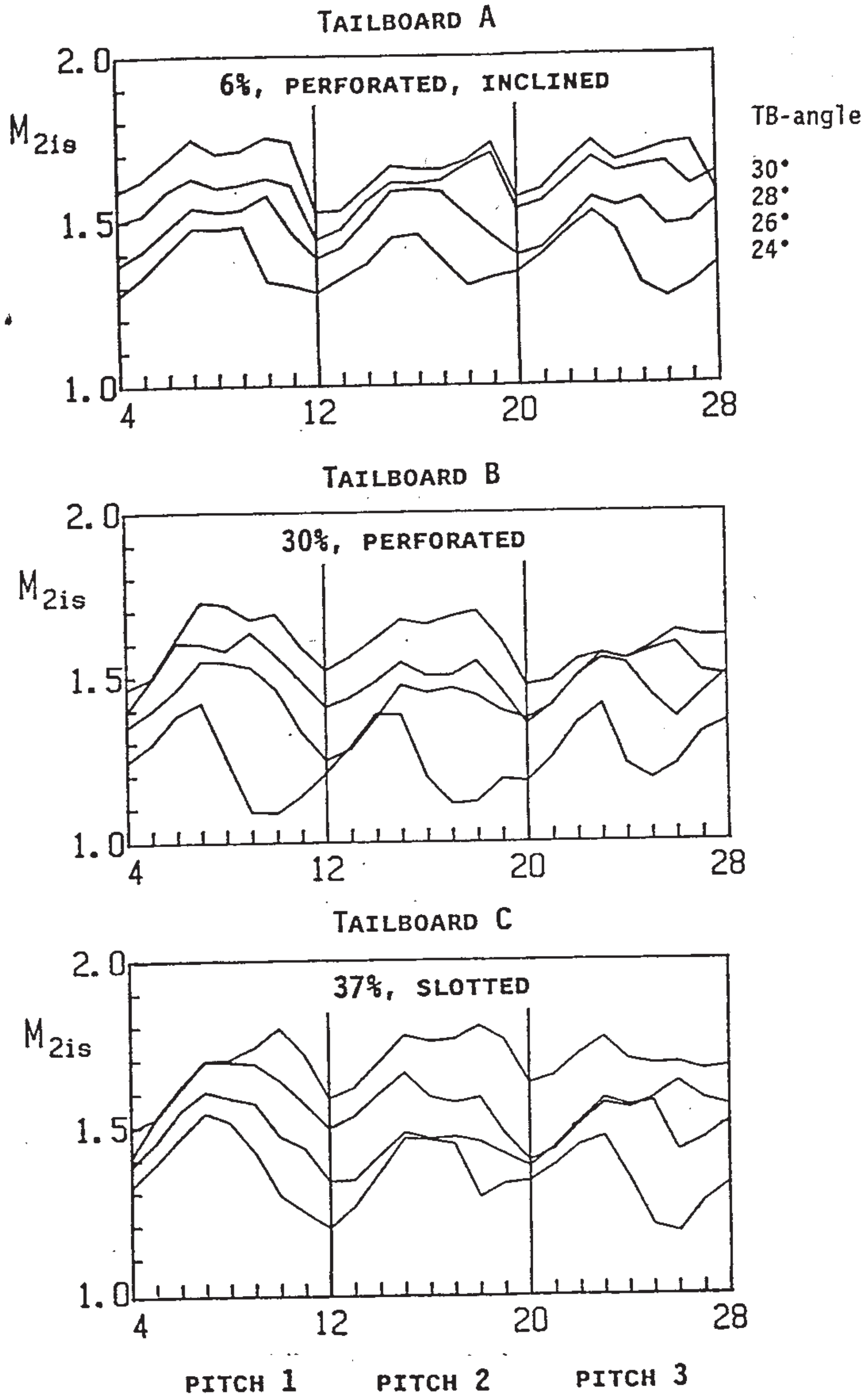


Fig. 11: Influence of tailboard wall porosity on cascade exit flow periodicity