Performance of Slotted End Wall Linear Cascade Tunnels at Off-design Conditions

Aldo Rona* and J. P. Gostelow†

*Address correspondence to: Aldo Rona, Department of Engineering, University of Leicester, UK

University of Leicester, Leicester, LE1 7RH, UK

Linear cascade transonic wind tunnels with an open jet test section can suffer from pitchwise end-wall interference. This causes a loss of pitchwise periodicity in the cascade, increasing the uncertainty in the measurements and producing less accurate estimates of turbine stage performance, flow exit angle and loss coefficient. To reduce the end-wall interference, a slotted tailboard is tested in a transonic cascade run off-design, in a regime at which the profile trailing edge shocks produce substantial reflections in the absence of a suitable end-wall treatment. The tailboard is optimised by numerical modelling for an isentropic discharge Mach number of 1.27. Tests over the wider isentropic Mach number range $1.20 \leq M_i \leq 1.32$ quantify the restored periodicity gained by the use of this tailboard. When the tailboard is used away from its design point of $M_i = 1.27$, the discharge remains more periodic than with an open jet test section. The tailboard performance varies non-monotonically away from its design point, driven by complex changes in the discharge wave pattern. Some of these changes are identified by schlieren flow visualisation.

Nomenclature

<table>
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<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>$\bar{c}$</td>
<td>Blade chord, m</td>
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<td>$h$</td>
<td>Cascade pitch, m</td>
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<td>$M$</td>
<td>Mach number</td>
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<td>$p$</td>
<td>Pressure, $N/m^2$</td>
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Subscripts

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<tr>
<td>0</td>
<td>Settling chamber condition</td>
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<td>a</td>
<td>Ambient laboratory condition</td>
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<td>i</td>
<td>Isentropic condition</td>
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Conventions

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<tr>
<td>$\bar{p}$</td>
<td>Pitch average of $p$</td>
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<td>$\check{M}_i$</td>
<td>Zero mean unit variance of $M_i$</td>
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Symbols

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<th>Symbol</th>
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<tr>
<td>$\alpha$</td>
<td>Tailboard angle to the cascade inflow, deg</td>
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<tr>
<td>$\Delta \bar{p}$</td>
<td>Pitch-averaged pressure scatter, $N/m^2$</td>
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<tr>
<td>$\Delta p$</td>
<td>Periodicity pressure scatter, $N/m^2$</td>
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*Lecturer, Department of Engineering, University of Leicester, UK, AIAA Member;
†Professor of Engineering, University of Leicester. UK, AIAA Member
I. Introduction

Transonic wind tunnel techniques have been the backbone of more than fifty years of advances in turbomachinery aerodynamics, supporting and validating empirical, analytical and numerical design tools for gas and steam turbine stages. While computational fluid dynamics has become the method of choice for many turbine stage designers, linear cascade tunnels remain a valuable tool to verify the numerical predictions with regard to key performance parameters, such as pressure distribution, flow exit angle and losses, of a transonic axial turbine stage mid-section. In academia, linear cascade tunnels continue to provide valuable insights into the flow physics of turbine stages, pushing the envelope of the numerical methods available for axial turbine blade design.

Nowadays, a significant proportion of wind tunnel tests for turbine stages is carried out in annular cascades, where the annulus geometry more readily reflects that of an axial turbine stage. These tests are comparatively more expensive than those on a linear cascade, as a full rim of blades is required, together with often more complex, rotary instrumentation. In a linear cascade, a smaller set of blades is stacked in pitch, to simulate the azimuthal periodicity around a turbine stage annulus. These tests can use more economical static instrumentation but, at certain inflow conditions, can display a lack of pitchwise periodicity, due to the discharge flow interfering with the wind tunnel boundaries. This can result in variations in loss coefficient of up to a factor of two between blade passages. This effect is particularly severe when the linear cascade discharge is supersonic, as shock reflections at the wind tunnel pitchwise boundary propagate towards more interior passages, affecting the flow throughout the discharge test section.

The end-wall interference in a transonic cascade wind tunnel is mainly due to the non-periodic pressure field that the tunnel pitchwise boundaries impose on the discharge. A more periodic end-wall pressure distribution can be obtained in a transonic wind tunnel by the use of slotted boundaries, which can reduce impinging shock reflections. Such technique can be applied to linear cascade tunnels, where a slotted wall or tailboard, of appropriate void ratio, is placed downstream of the outer-most blade, as diagrammatically shown in Fig. 1. Empirical correlations for the design of tailboards for a linear cascade wind tunnel are given in Davis based on wind-tunnel data. More recently, Paciorri et al. have developed a new design tool for tailboards, based on computational fluid dynamics. This numerical approach enables the assessment and optimisation of the performance of a transonic linear cascade tunnel end-wall with respect to its interference on the discharge, by predicting an optimal void ratio and tailboard pitch angle for a given cascade inflow condition and blade geometry.

Linear cascade wind tunnel tests that implement a slotted tailboard designed by the Paciorri et al. method produced a transonic flow discharge with an improved periodicity with respect to a benchmark discharge with either no tailboard or with a tailboard of more conventional design. This demonstrated the effectiveness of the optimised tailboard geometry in enhancing the wind tunnel discharge pitchwise periodicity, at the design inflow conditions, with respect to more conventional end wall designs. In practice, wind tunnel tests of turbomachinery blades often cover a range of inflow conditions that depart from the blade profile design operating point. These tests aim to predict and assess the off-design performance of a turbine stage, reflecting the use of a turbomachine at part load conditions.

The aim of this paper is to explore, by wind tunnel measurements, the performance of a linear cascade tunnel tailboard, optimised by computational fluid dynamics at given inflow conditions, when used to test a cascade away from its design point. The practical purpose of this work is to estimate what range of inflow conditions can be tested experimentally on a linear cascade without changing the tailboard. Specifically, what range of isentropic discharge Mach numbers can be tested, with the optimised tailboard, over which the discharge periodicity remains better than from tests with a more conventional end wall design. These results have practical implications on the cost of linear cascade tests, as they give the experimentalist a pointer to estimate the number of optimised tailboards the test campaign may require to survey a certain isentropic discharge Mach number range.
II. Experimental Facility

Tests have been conducted on the University of Leicester linear cascade wind tunnel. This blow-down cascade is supplied by a 60 bar 6m³ compressed air reservoir via a Fisher valve with pneumatic feed-back. The valve controls the air supply to the cascade settling chamber, which is pressurised during testing at a typical working pressure below six bar gage. Flow straighteners inside the settling chamber help to quieten the flow before this accelerates through a contraction into the test chamber. The test chamber discharges into the laboratory ambient air without a diffuser. Six blades of Rolls Royce T2 profile are tested in a linear assembly, as shown in Fig. 1. These nozzle (stator) blades operate with an axial inflow. The blade chord \( c = 45.37 \) mm, the cascade pitch is 0.67\( c \) and the trailing edge metal angle is 63.4° to the axial inflow direction, as determined from the profile geometry. The blades are cantilevered from the wind tunnel side wall, which has been mirror-polished, as indicated in Fig. 1. The mirror-polished area is 127mm × 217.62mm. This surface finish and blade installation allows the use of a double-pass spark schlieren technique to visualise the transonic flow in the test section. An Argon flash spark light source with a flash duration of approximately 200\( \mu \)s is sufficiently rapid to ‘freeze’ the flow, visualising any unsteady flow structure down to the size of the blade trailing edge thickness. The optical set-up of the schlieren image visualisation is documented in previous work.

Synchronous to the schlieren flow visualisation, wall pressure measurements are obtained from 0.5 mm diameter pressure taps drilled into the mirror polished back wall, along the cascade trailing edge line. These taps are marked with numbers 6 to 17 in Fig. 1. Tap number one is connected to the settling chamber and taps 2 to 4 record the test section inflow static pressure, downstream of the contraction and upstream of the cascade. A 16 port DSA3017 digital Scanivalve is connected via small diameter manometer tubing to the pressure taps, to obtain a wall pressure record that is stored on a Pentium 1 PC. The DSA3017 pressure range is from \( -101.3 \) kN/m² to 206.7 kN/m². The pressure transducer is triggered from the Argon flash solenoid circuit, via a Stamford Research Systems 535 signal generator, which delays the pressure acquisition to account for the spark solenoid activation time. This improves the synchronisation between the light flash and the DSA3017 pressure scan.

The wind tunnel tests are conducted without a tailboard and with two different tailboard configurations. In the tests without a tailboard, the cascade flow is allowed to develop as a free jet from the blade 0 trailing edge. This flow is the benchmark against which the benefits of using a tailboard are evaluated. The remaining tests use a 15% void ratio tailboard, fitted downstream of the outermost blade trailing edge, as shown in Fig. 1. The tailboard is mounted to stand at an angle \( \alpha \) to the cascade inflow direction. Two configurations are tested, with \( \alpha = 62° \pm 0.083° \) and \( \alpha = 64° \pm 0.083° \) respectively.

The 15% tailboard void ratio and the 64° pitch angle were identified by the Paciorri et al. method as the optimal configuration to conduct tests at a laboratory ambient to settling chamber pressure ratio.
of $p_a/p_0 = 0.3728$ on this cascade. This regime corresponds to a cascade exit isentropic discharge Mach number $M_i = 1.276$, which is higher than the T2 profile design exit Mach number of $M_i = 0.955$. Under these conditions, the supersonic discharge creates a complex wave pattern, making a challenging case to test the tailboard effectiveness in preserving the pitchwise periodicity across the discharge. Further geometrical details of the tailboard are given in Rona et al.

III. Flow Periodicity

In an ideal cascade wind tunnel, each blade is subject to an identical flow regime. In the cascade, each flow passage is delimited by the pressure side of one blade and by the suction side of the blade above. Under ideal test conditions, the flow pattern across successive passages repeats itself in pitch, giving a pitchwise periodic discharge. For instance, the end-wall pressure $p$ at corresponding pitchwise locations $y$ should be so that $p(1.50h) = p(2.50h) = p(3.50h)$, where $h$ is one blade pitch.

In practice, linear cascade tests exhibit some degree of passage to passage variation, so that, for instance, the flow through passage 0-1, delimited by blades 0 and 1, is either under-expanded or over-expanded with respect to discharge through passage 1-2, between blades 1 and 2. This degree of pitchwise non-periodicity gives passage to passage variations in cascade performance measurements, resulting in a significant statistical uncertainty on these measurements.

The loss of pitchwise periodicity in a cascade wind tunnel can be determined from the scatter of time-synchronous in-flow measurements taken at corresponding positions among the passages. Figure 1 shows that the T2 cascade is instrumented with four pressure taps at each passage exit, along the trailing edge line. These taps are spaced 25% pitch apart. Following Rona et al. the scatter in static pressure at 25% pitch is determined from the DSA scanivalve measurements as

$$\Delta p_{25\%} = (|p(1.25h) - p(2.25h)| + |p(1.25h) - p(3.25h)| + |p(2.25h) - p(3.25h)|)/3$$

Similar expressions are obtained for $\Delta p_{50\%}$ and $\Delta p_{75\%}$. The pitch-averaged pressure scatter $\Delta \bar{p}$ is obtained by integrating the periodicity pressure scatter using Simpson’s rule and dividing the result by $h$. This gives

$$\Delta \bar{p} = \frac{1}{2} \left( \frac{1}{3} \Delta p_{25\%} + \frac{4}{3} \Delta p_{50\%} + \frac{1}{3} \Delta p_{75\%} \right)$$

As the cascade discharges into the laboratory ambient air with no diffuser, the average static exit pressure in the discharge is expected to be similar to the laboratory ambient $p_a$. It seems therefore appropriate to normalise the pitch-averaged pressure scatter $\Delta \bar{p}$ by $p_a$ to obtain the non-periodicity index $E$ as

$$E = \Delta \bar{p}/p_a$$

IV. Results

A. Overview

Figure 2 shows an overview of the non-periodicity index $E$, with and without a tailboard, over a range of isentropic exit Mach numbers. The continuous line reports the results from tests with the $s = 15\%$ tailboard set at the optimal pitch of $\alpha = 64^\circ$, the dashed line refers to the tests with the same tailboard angled at $\alpha = 64^\circ$ and the dashed-dotted line refers to the open jet cascade tests. The dotted lines around each curve indicate the 50% confidence interval for $E$, determined from the least squares residuals of the wind tunnel data interpolation.
The results for tests without a tailboard focus around $M_i = 1.27$, which is a test condition at which non-periodic flow features were identified by schlieren flow visualisation in previous work. Without a tailboard, a significant lack of flow periodicity affects the cascade discharge throughout the isentropic discharge Mach number range $1.20 \leq M_i \leq 1.32$. The non-periodicity index $E$ peaks at $M_i = 1.275 \pm 0.0025$ and $E_{max} = 9.6\% \pm 0.3\%$

Introducing a tailboard with a void ratio of $s = 15\%$, which is designed to suppress end-wall reflections at Mach 1.27, reduces the non-periodicity index across the range $1.20 \leq M_i \leq 1.32$. The tailboard angle is set ad-hoc to align approximately with the passage 0-1 outflow at $\alpha = 62^\circ$. From this configuration, $E$ is maximum at $M_i = 1.23 \pm 0.0025$ and $E_{max} = 7.9\% \pm 0.4\%$. The lowest non-periodicity index is at $M_i = 1.295 \pm 0.0025$ and is $E_{min} = 3.9\% \pm 0.4\%$. While this tailboard configuration gives a non-periodicity index that is consistently below the open jet cascade one, operating the cascade with tailboard away from $M_i = 1.295 \pm 0.0025$ doubles the non-periodicity index with a change in $M_i$ of 0.065.

A further reduction in the non-periodicity index is obtained by setting the tailboard angle to $\alpha = 64^\circ$. This incidence was identified by numerical modelling as the optimal tailboard pitch for this cascade configuration at $M_i = 1.72$, to minimise the non-periodicity. The lowest non-periodicity index $E_{min} = 1.76\% \pm 0.38\%$ is obtained at the slightly higher Mach number of $M_i = 1.300 \pm 0.0025$ in experiment and $E$ remains below 5.2% over the range $0.9 \leq M_i \leq 1.32$.

From Fig. 2 it is concluded that it is advantageous to use a tailboard of optimised void ratio and pitch when testing in the T2 linear cascade tunnel at supersonic discharge speeds in the range $1.2 \leq M_i \leq 1.32$. At the tailboard design point of $M_i = 1.27$, the non-periodicity index is reduced by a factor of 3.5 with respect to the open jet configuration. The lowest non-periodicity index is achieved at the slightly higher outflow Mach number of $M_i = 1.3$ and the average periodicity performance degradation from this optimum, $dE/dM_i \sim 0.209$. These parameters quantify the off-design performance of the slotted tailboard for this configuration.

B. Flow periodicity in a cascade with open jet boundaries

The overview of the performance of different end-wall configurations at design and off-design presented in the previous section may suffice as guideline for the wind tunnel practitioner to select appropriate test conditions that minimise the measurement uncertainty due to the flow non-periodicity. Still, it is interesting to further explore why the three different end-wall configurations give significantly different non-periodicity index trends.

Figure 3 shows the variation of the non-periodicity index $E$ for the open jet test case in isolation. The scattered dots in Fig. 3 each represent one evaluation of $E$ from a single time-synchronous survey of the test section wall static pressure. The $M_i$ associated to each $E$ is determined from the settling chamber stagnation pressure that is measured synchronous to the wall static pressure by the DSA digital pressure transducer. 102 estimates of $E$ are plotted in Fig. 3, most of them covering the range $1.25 \leq M_i \leq 1.32$. A cubic polynomial least squares fit of the form $E = \sum_{n=0}^{3} a_n M_i^n$ gives a good fit to the experimental data, as indicated by the narrow $50\%$ confidence band, which is plotted as two dashed lines siding the continuous line of the polynomial in Fig. 3. The polynomial coefficients $(a_0, \cdots, a_3)$ are $(215.9, -552.6, 421.6, -113.3)$.
The 50% confidence band is derived from the $L^2$ norm of the data regression residuals. Statistically, the band includes at least 50% of all $E$ data points.

The polynomial fit to $E$ gives $E \geq 8\%$ over the range $1.20 \leq M_i \leq 1.30$ and indicates a trend towards a reduction in $E$ at $M_i > 1.30$.

Some understanding of the causes of this relatively high non-periodicity index is gained by analysing a selected schlieren flow visualisation of the cascade discharge at $M_i = 1.27$. In this experiment, the pitchwise flow boundaries develop free shear layers. Figure 4(a) shows one of such boundaries downstream of blade 0. The cascade boundary shear layer is considerably thicker than the shear layers from the more central blades 2, 3 and 4. Close to the blade 0 trailing edge, this shear layer bows outwards, away from the cascade, where indicated by arrow number 1. This expands the supersonic discharge through the first passage, between blades 0 and 1, with respect to the more interior passages projecting a flow-normal pressure gradient across the entire cascade. This results in a pattern of alternating under-expanded and over-expanded flow passages across the cascade that compromises the flow pitchwise periodicity.

At the selected test condition of $M_i = 1.27$, strong fish tail shocks stem from the blade trailing edges. These waves are marked by arrows number 2 in Fig. 4(a). The suction side branch of these shocks propagates towards the blade 0 shear layer. The pressure side branch reflects off the neighbouring blade, where indicated by arrows number 3, and then runs also towards the cascade free jet boundary. The suction side branch of the blade 2 trailing edge shock experiences a strong refraction, where indicated by arrow number 4, as it crosses the blade 1 trailing edge shear layer. The shocks from blades three and four do not experience such strong refractions when crossing the shear layers from the more interior blades 2 and 3.

Upon impinging against the blade 0 shear layer, indicated by two white number 5’s in Fig. 4(a), these shocks reflect back towards the interior of the cascade as expansion fans. These expansions are highlighted by dashed lines in Fig. 4(a). These flow features are spurious flow-boundary interferences of the open jet wind tunnel arrangement. Their propagation across the more interior passages propagate this boundary interference across the cascade, over-expanding the discharge.

At the higher isentropic Mach number of 1.30, Fig. 4(b) the non-periodic shear layer downstream of blade 0 still causes a significant flow non-periodicity. However, the higher exit Mach number produces fish tail shocks that are more oblique to the flow. This shifts the shock impingement point on the blade 0 shear layer further downstream. The impingement points are marked by two white number 5’s in Fig. 4(b). Spurious wave reflections are generated by shock-shear layer interaction, more oblique to the flow than at $M_i = 1.27$, mirroring the shallower angle of the impinging waves. The path of these spurious reflections is further downstream than the path of the corresponding features at $M_i = 1.27$, either missing the cascade exit plane or affecting it to a lower extent. This reduces the over-expansion in selected flow passages and reduces the non-periodicity index $E$ over the range $1.30 \leq M_i \leq 1.32$.

C. Flow periodicity in the cascade with tailboard at 62°

99 tests were conducted with a 15% void ratio tailboard set at $\alpha = 62°$ and the estimated non-periodicity index for each test is shown in a scattered plot in Fig. 5(a). Most of the data covers the range $1.25 \leq M_i \leq 1.32$. A fourth power polynomial fit of the form $E = \sum_{n=0}^{4} a_n M_i^n$ regresses the experimental data in the
Figure 4. Experimental schlieren visualisation of the cascade flow discharge without a slotted wall.

(a) $M_i = 1.27$.

(b) $M_i = 1.30$. 
range $1.20 \leq M_i \leq 1.31$, resulting in acceptably narrow 50% confidence bands. The polynomial coefficients $a_n = (445.8, -1457.1, 1784.1, -969.8, 1975)$. The raw data distribution around the $E$ maximum is rather sparse, as highlighted by the widening of the confidence interval band, and the range $1.10 \leq M_i \leq 1.20$ is characterised by just two $E$ data points. Inferences from Fig. 5(a) below $M_i = 1.25$, including the location and value of the $E$ maximum, should therefore be treated with some caution.

Figure 5(a) shows an upwards trend for $E$ from $M_i = 1.295 \pm 0.0025$, towards the high $M_i$ end of the experimental data set. Figure 5(b) shows this trend to be driven by a decrement in flow periodicity at 25% pitch. This adversely affects the flow quality in the test section by increasing the pitch-averaged non-periodicity index $E$, according to equation (2). This trend also occurs in the tests with the tailboard set at 64° and it will be discussed further in this context.

D. Flow periodicity in the cascade with tailboard at 64°

Figure 6(a) shows the variation of the non-periodicity index for the configuration with optimised tailboard void ratio and pitch, over the isentropic Mach number range $0.90 \leq M_i \leq 1.35$. As this configuration is the one that yielded the lowest non-periodicity index among the ones tested, a more extensive survey of the off-design tailboard performance has been conducted, resulting in an ensemble of 388 tests covering the isentropic Mach number range $0.90 \leq M_i \leq 1.32$. The experimental data regression suggests a rather complex variation of non-periodicity index though the transonic regime, featuring two distinct $E$ maxima and one $E$ minimum at $M_i = 1.300\pm0.0025$. In this configuration, the cascade operating range is well-sampled in the range $1.00 \leq M_i \leq 1.32$, as shown by the well-populated scatter plot of $E$ estimates in Fig. 6(a). To capture this non-monotonic distribution of $E$, a ninth power least squares polynomial fit is used to regress the non-periodicity index data, in the range $1.12 \leq M_i \leq 1.32$. This polynomial is of the form $E = \sum_{n=0}^{9} a_n M_i^n$, where $M_i$ is the zero mean unit variance isentropic Mach number $\bar{M}_i = (M_i - 1.2718)/0.0362$. The polynomial coefficients $a_0$ to $a_9$ are $(26.899, -15.009, -0.711, -0.709, 5.109, 4.749, 0.184, -0.746, -0.216, -0.018) \times 10^{-3}$. The 50% confidence interval band around the continuous line plot of the polynomial indicates a good fit to the $E$ data scatter.

The non-monotonic variation of the non-periodicity index in the $s = 15\%$, $\alpha = 64^\circ$ cascade configuration is governed by the contributions making up the non-periodicity index from the wall pressure measurements at 25%, 50% and 75% pitch, as shown in Figures 6(b), 6(c) and 6(d). The $E$ maximum at $M_i = 1.135\pm0.0025$ is mainly due to passage to passage flow changes at 50% pitch, whereas the broader $E$ maximum at $M_i =$
(a) Variation of the non-periodicity index $E$ with isentropic exit Mach number.

(b) Variation of the non-periodicity at 25% pitch with isentropic exit Mach number.

(c) Variation of the non-periodicity at 50% pitch with isentropic exit Mach number.

(d) Variation of the non-periodicity at 75% pitch with isentropic exit Mach number.

Figure 6. Tailboard with optimal void ratio $s = 15\%$ and optimal angle ($64^\circ$) to the inflow.
1.205 ± 0.0025 is driven by passage to passage difference throughout the whole exit plane.

The schlieren flow visualisation in Fig. 7 gives a further insight into the non-monotone variation of non-periodicity index when the cascade is tested away from the tailboard design point. At the tailboard design point, corresponding to an ambient to reservoir stagnation pressure ratio $p_a/p_0 = 0.3728$, the cascade generates a discharge that is a visually cleaner from end wall interferences, as shown in Fig. 7(a) with respect to Fig. 4(a). At the trailing edge of blade 0, where indicated by arrow number 1, the tailboard acts as a splitter plate, eliminating the spurious expansion shown by arrow 1 in Fig. 4(a). Further downstream, the trailing edge fish tail shocks, denoted by arrows number 2, run more parallel to one another across successive passages. The points of impingement of the pressure side branch of each shock on the neighbouring blade, marked by arrows number 3, are more pitchwise aligned. The shock refraction when crossing the interior blade shear layers is milder than in the flow without a tailboard, as suggested by the smaller shock refraction angle near arrow number 4. Where the shocks impinge on the tailboard, where marked by two white number 5’s in Fig. 7(a), an arc-shaped reflection is generated that is similar to the reflection from the interaction of the blade 4 pressure side shock with the blade 3 trailing edge shear layer. This indicates that the tailboard is modelling the local pressure field of the more interior blade passages, which is a distinguishing feature of a more pitchwise periodic flow.

As the ambient to reservoir stagnation pressure ratio is increased to $p_a/p_0 = 0.3814$, the tailboard effectiveness in the preserving pitchwise periodicity in the discharge visibly reduces, as shown in Fig. 7(b). Multiple shock reflections appear across the first passage, between blades 0 and 1. One of such reflections is highlighted by a white arrow number 1. These reflections originate from the blade 0 trailing edge shock reflecting between the blade 1 suction side and the tailboard. Further downstream, the blade 1 suction side trailing edge shock reflects off the tailboard, as indicated by arrow number 2. This reflection turns the blade 1 trailing edge shear layer anti-clockwise upon intercepting it. This turning is more pronounced with respect to the corresponding feature in the shear layers downstream of the more interior blades. This spurious wave then propagates towards the centre of the cascade, crossing the 50% pitch pressure tapping in passage 1-2, at arrow number 4. The local density gradient associated with this wave is significant, as the shadow of the 50% pitch passage 1-2 pressure port in Fig. 7(b) appears higher than where the tap is, due to the locally high air refraction index gradient. The spurious wave stemming from the tailboard at arrow number 2 does not have a corresponding feature in passage 2-3, in which the pressure port at 50% pitch is relatively remote from the shock system. This is one cause for the observed increase in non-periodicity index at $M_i = 1.26$ compared to $M_i = 1.27$. The spurious wave then reflects off the blade 2 suction side, as identified by arrow 6, and crosses over the 75% pitch pressure tapping, near arrow 5. Further downstream, the suction side fish tail shock from blade 2 reflects off the tailboard and propagates towards the blade 4 suction side. In its path, this spurious wave merges with the blade 3 pressure side fish tail shock, affecting the 25% pressure tap in passage 3-4, where indicated by arrow number 3. This feature is absent from Fig. 7(a) and represents an additional source of non-periodicity in this test. Overall, Fig. 7(b) presents a more complex wave pattern with respect to Fig. 7(a) which is indicative of a greater amount of wind tunnel pitchwise boundary interference propagating through the discharge. This reduces the flow pitchwise periodicity.

V. Conclusions

This experimental investigation explored the performance and the limitations of a slotted tailboard, designed and optimised by the numerical method of Paciorri et al., to be used in a transonic linear cascade wind tunnel to test turbine blades at off-design inflow conditions.

The results confirm that using an optimised tailboard at its design flow conditions downstream of a transonic linear cascade with a supersonic discharge reduces the end-wall interferences. This makes the discharge flow more periodic, making measurements from a linear cascade more readily representative of the mid-span flow through the nozzle section of a turbine stage.

Flow visualisation indicates that the ability to suppress end-wall interference is reduced when the cascade with the tailboard assembly is tested at flow conditions away from the ones the tailboard has been optimised.
Figure 7. Experimental schlieren visualisation of cascade flow discharge with a 15% void ratio tailboard.
for. Specifically, the non-periodicity index increases by the rate $dE/dM_i \sim 0.209$. Over the range $1.2 \leq M_i \leq 1.32$ the non-periodicity index with the optimised tailboard remains below the one obtained from open jet cascade tests.

It is concluded that there is a sustained benefit in performance with the use of a tailboard, even at off-design conditions. This coarse guideline is useful to turbomachinery experimentalists on the use of tailboards when linear cascade testing involves assessing the off-design turbine profile characteristics.

However, with a tailboard, the non-periodicity index fluctuates non-monotonically over the range $0.90 \leq M_i \leq 1.32$. The experimentalist has to be aware of this variation when attempting to compare accurate measurements at different operating points. In fact, the uncertainty band in the measurements due to the flow non-periodicity may lead to false conclusions about the off-design performance of a stage, if the variation in the uncertainty band is not correctly accounted for in the data reduction.

VI. Acknowledgements

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