

DIFFERENCE BETWEEN CONTINUOUS TRAVERSING AND STEP BY STEP MEASUREMENT AT THE LINEAR BLADE CASCADE OUTLET

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Abstract

Outlet measurements of linear blade cascades are often performed using pressure probes and traversing techniques that affect both accuracy and experimental efficiency. This paper compares continuous traversing and step-by-step traversing applied to steady pressure measurements at a linear blade cascade outlet. Experiments were conducted in a low-pressure wind tunnel using a needle pressure probe connected to differential pressure transducers. The comparison addresses local pressure distributions, outlet flow angle, axial velocity density ratio, and kinetic energy dissipation over a range of Mach numbers. Continuous traversing introduces deviations in static and stagnation pressure distributions, particularly at lower Mach numbers, due to the finite dynamic response of the measurement system, while global performance parameters remain in good agreement. The results indicate that, although continuous traversing significantly affects the local distributions of flow parameters, it can still provide reliable integral cascade characteristics with substantially reduced measurement time under appropriate conditions.

Keywords: Linear blade cascade, pressure measurement, experimental research.

1 Introduction and aim of the work

Measurement at the outlet of a linear blade cascade using multi-hole pressure probes is an essential experimental approach for investigating outlet flow parameters and, consequently, evaluating cascade quality through the assessment of outlet kinetic energy dissipation coefficients. The pressure probe measurement technique has been described in detail in several books and papers, such as those by [1], [2], and [3].

There are various types of pressure probes that can be used for such measurements. One classification is based on their construction, see [4]. For example, pressure taps on classical multi-hole probes are typically located on a single probe head, while needle probes have pressure taps positioned apart from each other. Each type of probe has its own advantages and disadvantages.

Another classification can be made based on the pressure transducers used. Steady pressure measurements are typically performed with probe pressure taps connected to pressure transducers via silicone tubes (or other tubing). This set-up allows only the investigation of stationary flow behaviour, as the air volume in the system attenuates higher frequencies. The limiting frequency is determined by the tube length, along with the air volume contained within the tubing. This technique is frequently used to investigate the flow through linear blade cascades, see e.g. [5]–[8] and many others.

Symbols

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i	Incidence angle	π	Pressure ratio
M	Mach number	ϱ	Density
p	Pressure	<i>Indexes</i>	
q	Dynamic pressure	01	Stagnation at the inlet
Re	Reynolds number	02	Stagnation at the outlet
u	Flow speed	2	Static at the outlet
α	Flow angle	2,is	Isentropic at the outlet
ζ	Kinetic energy dissipation	201	Pressure ratio p_2/p_{01}
κ	Ratio of specific heats	0201	Pressure ratio p_{02}/p_{01}
λ	Dimensionless velocity	$\langle \bullet \rangle$	Reduced variable

For measurements requiring higher frequency responses, fast response pressure probes (FRAPs) are developed and frequently used, see e.g. [9]–[12]. These probes integrate the pressure transducer directly into the probe head, allowing for a theoretically infinite frequency response (though, in practice, the response is typically on the order of tens of thousands of Hz).

Based on the information above, two traversing approaches can be employed for measurements at the cascade outlet. The first approach relies on the probe having a sufficiently high frequency response; in this case, data are acquired during so-called continuous traversing, in which measurements are recorded while the probe is in motion.

The second approach involves moving the probe to a predefined measurement point, allowing a certain relaxation time for the measurement system to reach steady conditions, and only then acquiring the data. This raises an important question: What is the appropriate relaxation time, and can a slow-response probe be used for continuous traversing?

The latter question implies that higher-frequency components will be attenuated in the measured signal. However, if the measurement system is able to relax sufficiently quickly, it may still be possible to obtain reliable steady-flow data using the continuous traversing approach.

1.1 Aim of the work

The main objective of this work is to compare the two traversing approaches described above. The continuous traversing approach is employed in the Laboratory of Internal Flows at IT CAS, which uses intermittent high-speed wind tunnel and thus requires shorter measurement times, whereas the step-by-step traversing method is used in the VZLU Laboratory of High-Speed Aerodynamics which has at its disposal continuous high-speed wind tunnel.

The advantage of the continuous traversing method is evident: the overall measurement time is significantly reduced, which in turn leads to substantially lower experimental costs compared to the step-by-step approach. However, this benefit is accompanied by an important concern—can this approach be reliably applied when using a steady pressure probe?

This paper aims to address this question by presenting a comparative analysis of results obtained using both measurement methods.

2 Experimental apparatus, methods, set-up and uncertainty

2.1 Apparatus

The experiments were conducted in 2023 in a circular low-pressure aerodynamic wind tunnel (WT) at the VZLU Laboratory of High-Speed Aerodynamics in Palmovka. The flow was generated by a twelve-stage radial compressor, with the Mach number controlled by the compressor rotational speed. The wind tunnel pressure was regulated using vacuum pumps, enabling independent adjustment of the Mach and Reynolds numbers. A schematic of the WT is shown in Figure 1.

In this case, the traversing was performed using a needle probe equipped with three closely grouped pressure taps to measure the stagnation pressure and the pressures required for flow-angle evaluation. An additional pressure tap, separated from the group, was used for static pressure measurement. This probe configuration is suitable for measurements at the cascade mid-span, where the flow can be assumed to be two-dimensional, as the second flow angle cannot be evaluated.

The probe was connected to UNIK5000 pressure transducers via silicone tubes with an inner diameter of 1.5 mm and a length of approximately 2.5 m, resulting in an air volume in the system of $V \approx 4.42 \times 10^{-6} \text{ m}^3$. On the other hand IT CAS laboratory uses traversing device with integrated pressure transducers. This allows for significantly shorter pressure tubes (their length is below 0.5 m), therefore the effect of continuous traversing on the resulting data is less pronounced as compared to the current study.

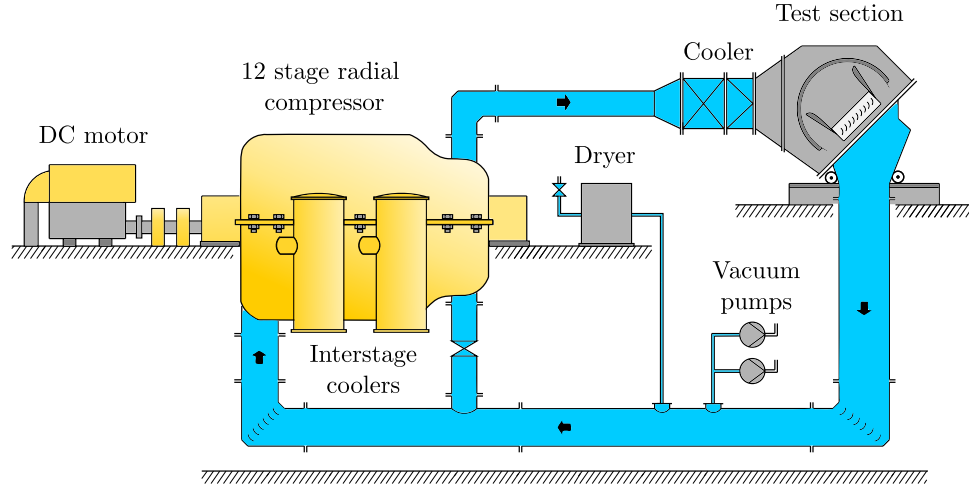


Figure 1: Wind tunnel scheme.

2.2 Methods and set-up

The probe traversing was performed at several Mach number levels to capture the effect of pressure drop across the cascade using both approaches, as all measured pressures (except the pressure differences used for flow-angle evaluation) were connected differentially to the inlet reference pressure.

The measurements were performed over a range of isentropic outlet Mach numbers $M_{2,is} \in \langle 0.4, 1.0 \rangle$, while maintaining a constant isentropic Reynolds number of $Re_{2,is} = 5 \times 10^5$ and a nominal incidence angle of $i = 25^\circ$, defined with respect to the cascade axial direction.

The acquisition settings for the step-by-step traversing were defined as follows: the acquisition time was 1 s with a sampling frequency of 1000 Hz and a low-pass filter set to 100 Hz (selected based on prior experience with the system). For continuous traversing, the acquisition time was reduced to 0.2 s while maintaining the same sampling frequency and low-pass filter settings, resulting in 200 samples per measurement point. These samples were instantaneously averaged during the acquisition.

The acquired data were processed using a well-established approach, in which the probe calibration matrices were applied to determine the true values of the static and stagnation pressures, as well as the outlet flow angle α_2 . This procedure involved an iterative process that was terminated when the variation in the dynamic pressure:

$$q = \frac{1}{2} \rho u^2, \quad (1)$$

where ρ stand for the fluid density and u its velocity, fell below 0.1%.

The results are presented in terms of the local distributions of the following pressure ratios and flow angle:

$$\pi_{201} = \frac{p_2}{p_{01}}(x), \quad (2)$$

$$\pi_{0201} = \frac{p_{02}}{p_{01}}(x), \quad (3)$$

$$\alpha_2 = \alpha_2(x), \quad (4)$$

$$(5)$$

where p_2 and p_{02} are the local static, stagnation pressures and flow angle obtained from the probe evaluation, p_{01} is the reference inlet stagnation pressure measured in the settling chamber at the cascade inlet, and α_2 is the local outlet flow angle.

Next, the data reduction method used in the VZLU Laboratory of High-Speed Aerodynamics [13] was applied to both local data sets obtained from the continuous and step-by-step traversing. The methods are then compared using the normalised deviations of $\langle \alpha_2 \rangle$ and $\langle \zeta \rangle$, defined as

$$\Delta\alpha_2 = \alpha_{2,\text{slow}} - \alpha_{2,\text{continuous}}, \quad (6)$$

$$\frac{\Delta\zeta}{\zeta_{\text{slow}}} = \frac{\zeta_{\text{slow}} - \zeta_{\text{continuous}}}{\zeta_{\text{slow}}}, \quad (7)$$

where

$$\langle\zeta\rangle = 1 - \left(\frac{\langle\lambda_2\rangle}{\langle\lambda_{2,\text{is}}\rangle} \right)^2. \quad (8)$$

Here, $\langle\lambda_2\rangle$ and $\langle\lambda_{2,\text{is}}\rangle$ are the dimensionless velocities, calculated as

$$\langle\lambda_2\rangle = \sqrt{\frac{2}{\kappa - 1} \left[\left\langle \frac{p_2}{p_{02}} \right\rangle^{\frac{\kappa-1}{\kappa}} - 1 \right]}, \quad (9)$$

$$\langle\lambda_{2,\text{is}}\rangle = \sqrt{\frac{2}{\kappa - 1} \left[\left\langle \frac{p_2}{p_{01}} \right\rangle^{\frac{\kappa-1}{\kappa}} - 1 \right]}, \quad (10)$$

where $\kappa = 1.4$ is the ratio of specific heats, and $\langle\bullet\rangle$ denotes the variable obtained from the data reduction method.

2.3 Uncertainty evaluation

The flow regimes were defined based on measurements of inlet and outlet pressure (static and stagnation) and temperature. Barometric pressure was measured using a Druck DPI 145 transducer with an uncertainty of 0.013% FS, while individual pressures were obtained using UNIK5000 differential transducers with an uncertainty of 0.1% RDG. Temperature and relative humidity were measured using a Sensorika Humistar HTP-1 hygrometer with accuracies of ± 0.3 K and $\pm 2\%$ RH, respectively. The resulting uncertainties were below 1% for Mach number, 2% for Reynolds number, 6% for flow velocity, and $\pm 2^\circ$ for flow angles. All uncertainties were evaluated at a 95% confidence level ($\pm 2\sigma$). The uncertainties were calculated using the small perturbation method, as described in [14], [15].

3 Results and discussion

Local distributions of the pressure ratios p_2/p_{01} and p_{02}/p_{01} , together with the outlet flow deflection angle α_2 (defined as the angle between the probe alignment and the local flow direction), are presented in Figures 2, 3a and 3b for the investigated range of Mach numbers. These distributions allow a detailed comparison of the continuous traversing and step-by-step traversing approaches in terms of both local flow structure and derived performance parameters.

It is evident that, with increasing Mach number, the differences between the p_2/p_{01} distributions obtained using continuous traversing and step-by-step traversing become more pronounced. This behaviour can be attributed to the finite relaxation time of the pressure measurement system, which exceeds the characteristic time scale associated with continuous traversing. Consequently, during continuous traversing the static pressure does not fully reach its equilibrium value at each measurement location, leading to a systematic underestimation of the evaluated flow velocity when compared to the step-by-step approach.

A similar behaviour is observed in the stagnation pressure p_{02} distributions. In this case, the silicone tubing connecting the probe to the pressure transducers is not sufficiently evacuated during continuous traversing, resulting in an underestimation of the stagnation pressure deficit in the wake region. In addition, the dynamic response of the measurement system introduces a noticeable time lag in the stagnation pressure signal, which manifests itself as a spatial shift and smoothing of the measured pressure distributions.

In contrast, the local distribution of the outlet flow angle α_2 appears to be largely unaffected by the selected traversing method. The differences between the two approaches remain small and are generally within the bounds of the measurement uncertainty, indicating that the flow angle evaluation is comparatively insensitive to the dynamic limitations of the pressure measurement system.

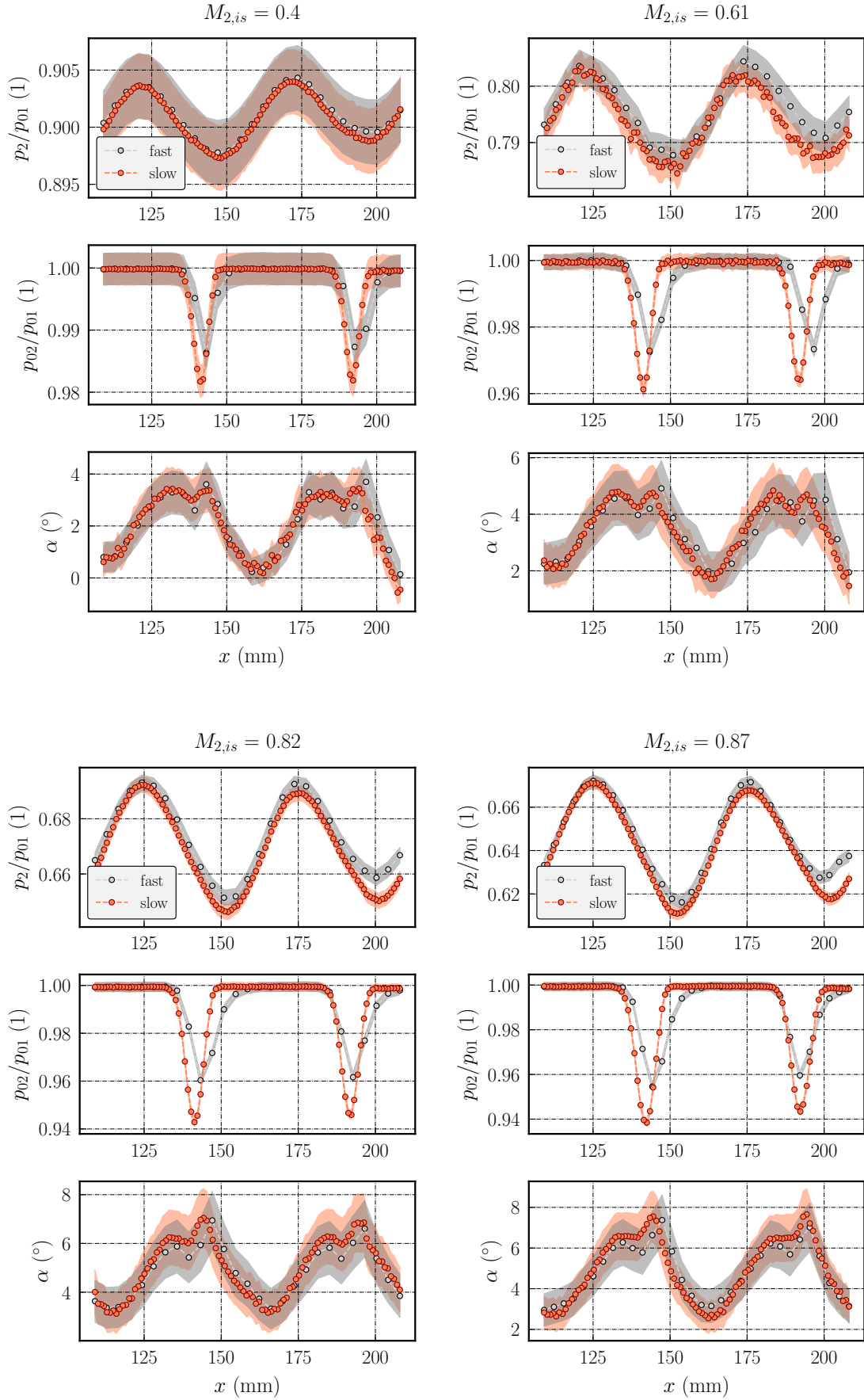


Figure 2: Local distribution of the flow parameters for different Mach numbers.

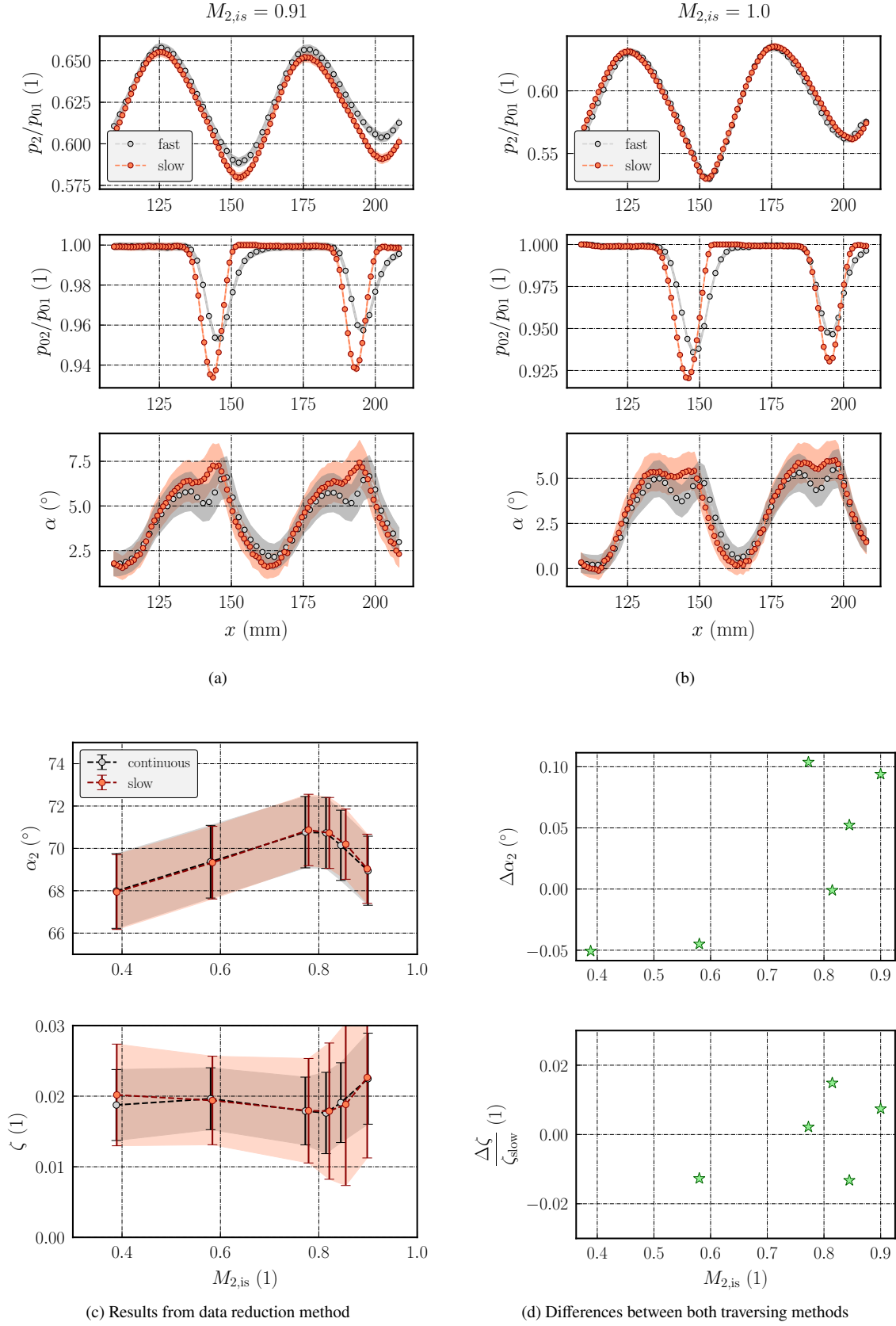


Figure 3: Local flow parameter distributions (top row) and data reduction results (bottom row).

The data reduction analysis further indicates that the largest discrepancies between the two traversing approaches occur at lower Mach numbers in the evaluation of the kinetic energy dissipation coefficient, as demonstrate Figure 3c. In this regime, the deviation reaches approximately 6% when the step-by-step traversing method is taken as the reference. With increasing Mach number, these differences decrease and remain within approximately 2%, see Figure 3d. By contrast, the variations observed in the outlet flow angle are small and can be considered negligible relative to their absolute values.

The dominant source of the observed discrepancies is attributed to the finite dynamic response of the stagnation pressure measurement system. During continuous traversing, the pressure recovery outside the wake requires more time than is available for the system to reach equilibrium, leading to a temporal lag in the measured stagnation pressure. Despite the resulting distortion of the local pressure distributions, the integral quantities derived from the data reduction process remain largely preserved.

Consequently, the areas under the corresponding curves are comparable, which explains the good agreement observed in the global performance parameters. It should be noted, however, that this behavior may also be influenced by the specific data reduction methodology employed.

4 Conclusion

This study compared continuous traversing and step-by-step traversing techniques for steady pressure measurements at the outlet of a linear blade cascade using a needle probe connected to differential pressure transducers. The analysis demonstrates that the choice of traversing method has a noticeable impact on locally resolved static and stagnation pressure distributions, particularly as the Mach number increases. These differences are primarily attributed to the finite relaxation time of the pressure measurement system, which limits its ability to reach equilibrium during continuous traversing.

The largest discrepancies were observed in the kinetic energy dissipation coefficient at lower Mach numbers, where deviations of up to approximately 6% were found when using continuous traversing relative to the step-by-step reference. With increasing Mach number, these differences decreased and remained within approximately 2%. In contrast, the outlet flow angle was largely insensitive to the traversing approach, with differences remaining within the bounds of measurement uncertainty. Current values of discrepancies between continuous and step-by-step traversing are of course depending on the length of pressure hoses connecting the probe head pressure taps with pressure transducers. Apparatus used in this study was equipped with hoses of inner diameter 1.5mm and length 2.5m.

Despite distortions in local pressure distributions caused by time lag effects, the integral quantities derived from the data reduction method showed good agreement between both approaches. This behavior suggests that the global cascade performance parameters are relatively robust to the dynamic limitations of the measurement system. Overall, the results indicate that continuous traversing using steady pressure probes can be an effective and time-efficient alternative to step-by-step traversing for the evaluation of integral cascade characteristics, provided that the limitations associated with system dynamics are properly considered.

Future work will focus on evaluating the present results using an alternative data reduction method (see, e.g., [16]) to assess the extent to which the choice of reduction procedure influences the outcomes.

Acknowledgment

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