Characterization of the Turbulence Intensity Generated by Passive Grids in Compressible Flows

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Abstract

The generation of representative turbulence intensity levels is mandatory, when it comes to characterize the thermal response of gas turbine cooled components in lab scaled conditions. This is mostly carried out by means of passive grids. A few correlations have been developed during the years, to predict the decay of grid-generated turbulence and are used for the design of these components, but limited amount of experimental studies is available when it comes to assess their reliability in compressible flows. The present work aims at deepening the knowledge of this aspect, carrying out an experimental characterization the turbulence intensity decay generated by means of different kind of grids in incompressible and compressible flows. The experimental results, gathered by means of hot wire anemometry were used to systematically assess the variations induced by Mach and Reynolds numbers on the grids performance, so to assess their effect and eventual inaccuracies induced by not considering their impact during the grid design.

Keyword: *Turbulent intensity, Turbulence decay, Passive Grids, Compressible Flows, Cascade Testing*

1. Introduction

Thermal testing of gas turbine cooled components at low technology readiness level (TRL) is a mandatory step in their design/verification process. In order to achieve representative results, attention must be paid at recreating a relevant turbulence intensity, as it has been shown to significantly influence the components' thermal response, through both heat transfer coefficient [1, 2, 3, 4, 5] and film-cooling behaviour [6, 7].
The most adopted methods to condition the turbulence intensity in laboratory conditions make use of passive static grids [1], active grids with moving parts [8] or jets injection [9]; while the last two approaches may lead to higher intensities, the former is far more frequently adopted, due to quickness and easiness of design, limited pressure drops and negligible thermal field alterations.
Turbulence is generated by passive grids, as high velocity areas are created and then spread and coalesce with each other, so that energy is transferred from the mean flow to turbulent eddies in the zone of intense shear [10]. Turbulence then starts to decay, moving downstream; this decay has been investigated since many years ago through theoretical and experimental studies [11, 12, 13], indicating an exponential decay in the streamwise direction that could be effectively scaled with a grid characteristic dimension. Based on this knowledge, correlations were developed by Baines and Peterson [10] and Roach [14]. Both approaches proposed to scale the turbulence decay using the grid bars diameter and the following type of relation:

$$Tu = A\left(\frac{x}{D}\right)^{-n} \tag{1}$$

with A being a constant characterstic of the grid typology.
Despite these approaches being often adopted for grid design goals, non of them considered the impact of flow parameters like Reynolds and, in particular, Mach number. Regarding this second aspect a limited number of studies have tried to deal with a detailed assessment of compressibility effects on passive grids behaviour [15, 16], despite the adoption of these devices in non-incompressible regimes has shown lower than predicted turbulence levels [17]. From a correlative point of view, Brassulis et al. [18] proposed to scale

the turbulence decay using the grid mesh size P (i.e. bar-to-bar distance) and pointed out to the necessity to introduce a virtual origin, in the following form:

$$Tu = A\left[\frac{x}{P} - \left(\frac{x}{P}\right)_0\right]^{-n} \tag{2}$$

All parameters were found to be sensitive to Mach and Reynolds number.
The present work is aimed at experimentally assess the performance of passive grid, made by parallel square bars, at different flow conditions, in the view of their utilization in transonic cascades with inlet Mach numbers up to the slightly above the incompressible regime. To do so, results from different test cases have been collected and analysed in order to highlight the qualitative effect of different flow parameters.

2. Experimental Apparatus

As partially anticipated, the data reported in this paper have been achieved from testing on two different test rigs. While both of them are transonic cascades they have a different layout: the first one is a sector annular cascade, while the other is a linear one. Since they were developed to test geometry representative of a statoric vane and of a rotor blade (albeit in static conditions), they will be referred to as $stator\ rig$ and $rotor\ rig$ respectively.
For the rotor rig, three different grids can be installed in a rectangular (100 x 53 mm section) inlet duct; all of them were made by parallel square bars, as previous studies showed this configuration to be a good trade-off between maximizing the generated turbulence without creating excessive pressure drops [14]. Different values of bars dimension (d) and pitch (p) were tested, which allows to understand which parameter provides the best scaling capabilities; they are reported in Table 1. The grid porosity (β), defined as the ratio between the grid void area and the total duct area, is reported as well. A traverse system can be installed on the duct, so to autonomously move the adopted probe in streamwise direction on a pre-defined mesh. The rotor rig testing is therefore very useful to achieve an accurate characterization of the turbulence decay downstream of the grids. On the other hand the maximum Mach number that can be achieved is just slightly above compressibility limits, equal to about 0.35.
On the other hand, for the stator rig testing a single grid was adopted and installed in the cascade inlet annular duct (35° span, 80 mm height); its parameters are also reported in Table 1, as defined at midspan of the annular duct. In this test rig only three turbulence measurement positions are available downstream of the grid. A higher Mach number range can be investigated, up to about 0.5, thus allowing to effectively cover all inlet conditions that can be typically found for transonic cascade tetsing. Despite offering less opportunities in terms of turbulence decay characterization and comparison between scaling parameters, results from this test rig provide a useful addition to the previous ones, allowing to have a better understanding of the Mach number quantitative effect. A CAD model of the adopted passive grids is reported in Fig.1.
On both test cases, the flow total pressure is measured downstream of the inlet ducts (i.e. cascade inlet), through a Kiel probe; pressure taps are also spaced across the inlet ducts, in order to measure the static pressure; negligible variations were recorded between the different static pressure measurement positions. The flow total temperature is measured inside the plenum chambers that feed the rigs, through T-thermocouples.

2.1. Measurement Technique

Hot wire anemometry was used in order to measure the turbulence intensity. A $Dantec\ 55P11$ probe was used for the goal. The probe was previously calibrated, using a Nusselt-Reynolds calibration approach, as proposed by Cukurel at al. [19]. Once a certain Reynolds number was imposed, a negligible influence of Mach number on the probe response (i.e. on the HWA output voltage) was evidenced, thus making it impos-

	D [mm]	P [mm]	Beta [-]	Type
Grid 1	5	11	0.55	Parallel Square Bars
Grid 2	2.75	6.05	0.55	Parallel Square Bars
Grid 3	2.75	6.05	0.75	Parallel Square Bars
Stator rig	5	20	0.75	Parallel Square Bars

Tab. 1: Turbulence grids characteristics

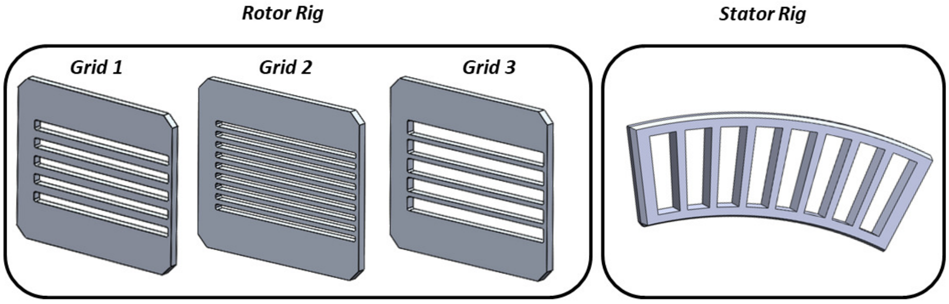

Fig. 1: CAD model of the adopted passive grids

sible to distinguish between independent fluctuation of density and velocity. Therefore mass flux fluctuations were used to calculate the turbulence intensity according to the following relation:

$$T_u = \frac{(\rho V)_{rms}}{\overline{\rho V}} \tag{3}$$

3. Experimental Results

3.1. Stator rig results

As anticipated, results from stator rig investigations can be adopted to achieve a preliminary assessment of the impact of flow compressibility. They are shown in Fig. 2, where turbulence decay trends for different Mach number are reported (left image). A plot of the turbulence intensity at $x/D = 28$, as a function of Mach number, is also shown (right image) to better visualize this effect. It must be pointed out that, since all results being taken from the very same grid, no considerations can be made regarding the proper geometric parameter to be used to scale the results; the bar dimension D has been chosen arbitrarily.

It is evident that a limited impact exists as far as the flow stays below compressibility limits ($M = 0.3$), but a non negligible reduction occurs moving to $M = 0.5$; while the presence of only three measurement points does not allow to take precise conclusion regarding the trend shape variation, this decrease in the overall intensity is evident. In the right figure, results collected at $x/D = 28$ are reported as a function of the Mach number, so to better highlight the impact of the latter. In this way, a certain trend can be also recognized in the incompressible regime, with a maximum in Tu achieved between $M = 0.1$ and $M = 0.2$. In order to better understand this aspect, it must be pointed out that all above considerations have been made in terms of Mach number variations, but, being the grid geometry fixed and the operating pressure not regulated, the Reynolds number changes simultaneously. To distinguish the impact of both parameters, results from the rotor rig are analyzed in the next section.

3.2. Rotor rig results

As anticipated, results from rotor rig results allow to have a better visualization of the turbulence decay in streamwise direction, despite being collected up to a lower maximum Mach number (0.35). Turbulence decay plots are reported in Fig. 3

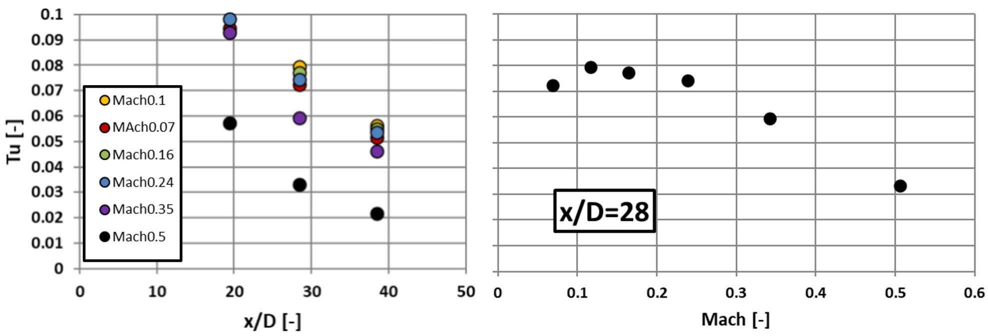

Fig. 2: Mach number effect on stator rig turbulence decay

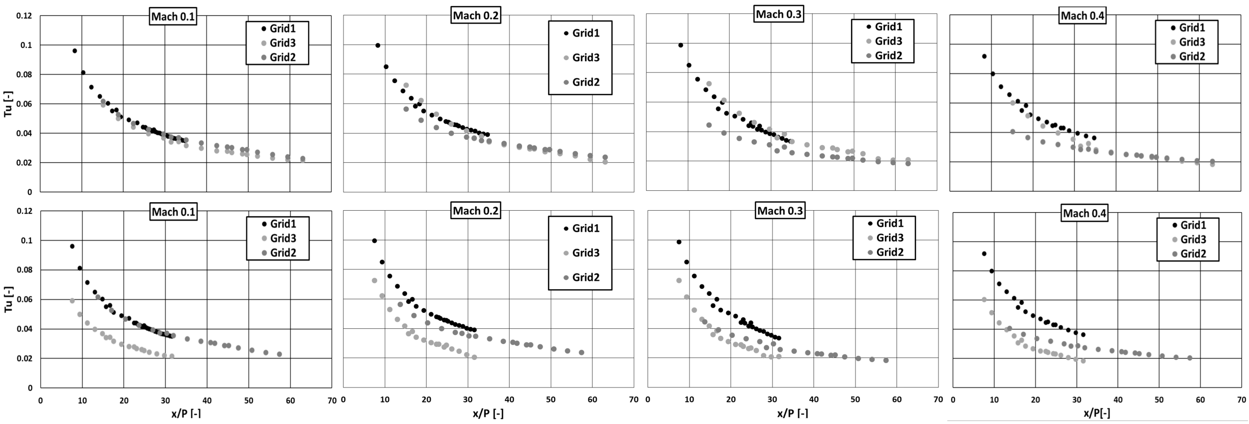

Fig. 3: Turbulence decay from rotor rig testing

Results are reported both in terms of x/D (top images) and x/P (bottom images) on the x-axis, so to assess which parameter allows the better scaling. Focusing on the results at $M = 0.1$ it is clear that the curves for the three different grids collapse on each other only if x/D is used. The adoption of x/P obviously lead to worse scaling (see Grid 3 data). This is in line with Roach [14] and Baines and Peterson [10] studies for incompressible flows. Nevertheless, as soon as the focus moves towards higher Mach numbers, results from Grid 2 start to deviate from the others, with differences increasing as the Mach number does. Grid 1 and Grid 3 results, on the other hand, remain in a reasonable matching. Moving to x/P does not improve the scaling at high Mach numbers, thus suggesting that the bars width remain the more appropriate characteristic dimension to scale the results, no matter the Mach level. On the other hand, Grid 1 and Grid 2 are geometrically similar to each other, with dimensions of the one simply achieved by scaling the dimensions of the other by a constant factor (see Table 1). Therefore, the fact that their behaviour, at a certain Mach number, can not be scaled by any geometrical parameter suggests that another fluid-dynamic parameter influences their performance. This parameter is thought to be the Reynolds number Re_P, defined using the grids mesh size as the dimensional parameter (note that if D would be used as the dimensional parameter, Grid 2 and Grid 3 would have the same Reynolds number, but still a different behaviour), in agreement with data from Brassulis et al [18]. An attempt to detail the qualitative effect of both Mach and Reynolds number will be made in the next section, considering results from both test rigs.

3.3. Effect of Mach and Reynolds number

Turbulence intensity results at $x/D = 28$ are reported in Fig. 4, as a function of either the Mach number (left) or Reynolds number (right). Both results from stator and rotor rig are reported. From the left plot it can be seen that, for low Mach number $M = 0.1$, rotor rig results show lower values than stator rig ones; on the other hand, looking at the results in terms of Reynolds number, they better align on a common trend, with stator rig having a higher Re_P and slightly higher Tu. At higher Mach number Grid 1 and 3 results collapse fairly well on stator rig ones on the left plot, despite still having a lower Reynolds number (right plot).

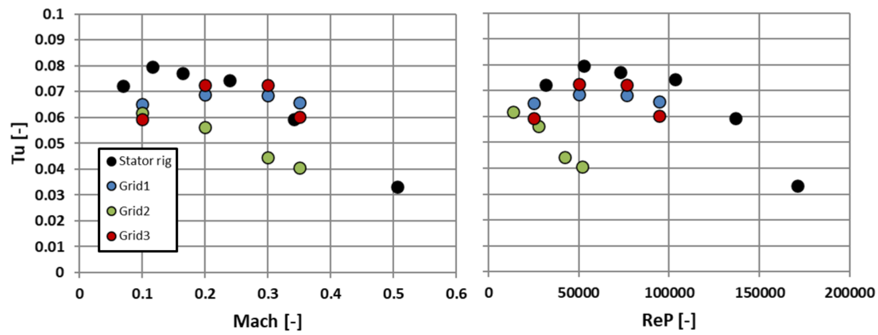

Fig. 4: Effect of Mach (left) and Reynolds (right) numbers on turbulence intensity at $x/D = 28$

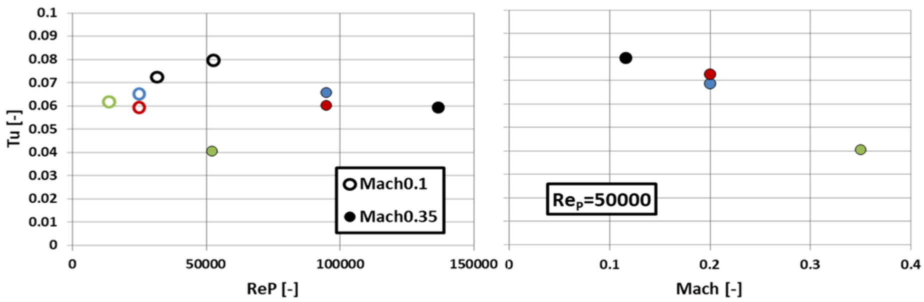

Fig. 5: Separated effects of M and Re_P

Re_P for Grid 2 is always consistently lower than the other configurations and so is the measured turbulence intensity.

These results suggest that the grid generated turbulence intensity is affected by the grid Reynolds number as long as it reach a sufficiently high value to become insensitive to it. In order to better assess this aspect, results at $x/D = 28$ have been grouped in Fig. 5, so to achieve Re_P variations at constant Mach number (left) and Mach variation at constant Re_P. It must be reminded that the tested grids dimensions were chosen for testing goals and not specifically to achieve independent variations of Mach and Reynolds numbers; therefore a limited number of operating points can be used for this goal. In particular a single trend with M is achieved, at $Re_P \approx 50000$, as well as two trends with Re_P at $M = 0.1$ and 0.35. Colors of the data points are in agreement with Fig. 4, so to let the reader understand the corresponding configuration. The left image clearly shows that an increase in turbulence intensity is achieved with increasing Re_P; while the trend is monotonously increasing for $M = 0.1$, since all results are collected at low Re_P, an asymptotic limit seems to be reached, for the series at $M = 0.35$, beyond a certain value of Re_P. Again this points out to a marginal effect of Re_P once a certain threshold is achieved; from the limited available data this threshold seems to stay between $Re_P = 7.5 \cdot 10^4$ and 10^5. On the other hand the measured Tu is always decreasing with increasing Mach number, if Re_P is fixed. In the light of these results, the non-monotonic trend reported in Fig.2 is likely to be due to an initial increase in Tu due to increasing Re_P, as its value is quite limited, and then a significant reduction as the effect of Mach number takes over. It is finally worth pointing out that the only variation of Mach number from 0.1 to 0.35 leads to a relevant reduction in the generated Tu, up to about half of the original value, this pointing out to the necessity to actually consider the actual operating condition when designing a passive grid and in agreement with previous grid testing in high-speed transonic cascade [17].

4. Conclusions

In the present work results from previous passive grids testing in transonic cascades have been collected and analyzed, in order to understand the qualitative effects of different flow and geometric parameters. Results can be summarized as follows:

- Regardless of the flow compressibility, the proper grid dimension to effectively scale the turbulence decay seems to be the grid bar size; mesh size, as suggested by some Authors when dealing with compressible flows, leads to a significant spread of the different curves.
- Both Mach and Reynolds number, with the latter defined using the grid mesh size as characteristic dimension, affect the grid-generated turbulence: geometrically similar grids, tested at the same Mach number, return significantly different turbulence decays.
- Results achieved for independent variation of M and Re_P, from the available data, suggest an increase in Tu, with increasing Re_P until a certain asymptotic value is reached. On the other hand, an increase in Mach number always leads to reduction in Tu, that can be significant even if slightly compressible conditions ($M = 0.35$) are concerned.
- The analysis could benefit from additional testing, in order to achieve detailed turbulence decay trends

for additional $M - Re_P$ independent variation curves, so to precisely address their quantitative effects and tune correction coefficients for the normally adopted design criteria [10, 14].

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