11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
E. Oñate, J. Oliver and A. Huerta (Eds)

THE GENERATION OF HIGHER LEVELS OF TURBULENCE IN A LOW-SPEED CASCADE WIND TUNNEL BY PRESSURIZED TUBES

Thorben Aufderheide[†]**, Christoph Bode**[†]**, Jens Friedrichs**[†] **and Dragan Kožulović**[‡]

[†] Institute of Jet Propulsion and Turbomachinery
Technische Universität Braunschweig
Hermann-Blenk-Str. 37, 38108 Braunschweig, Germany
e-mail: t.aufderheide@ifas.tu-braunschweig.de, web page: www.ifas.tu-bs.de

[‡] Department of Automotive and Aeronautical Engineering
University of Applied Sciences Hamburg
Berliner Tor 9, 20099 Hamburg, Germany
e-mail: dragan.kozulovic@haw-hamburg.de, web page: www.haw-hamburg.de

Key words: Turbulence Generation, Grid, Turbulence Intensity, Integral Length Scale, Cascade Wind Tunnel

Abstract. This paper deals with the generation of higher levels of turbulence intensity Tu in a Low-Speed Cascade Wind Tunnel by an active turbulence grid. The grid consists of pressurized tubes with evenly distributed jet injections. The mass flow injection for each rod is continuously adjustable to produce homogeneous turbulence distributions. In this way, a turbulence intensity range of $Tu = 4 - 10$ % can be obtained in the test section. Care has also been taken to the flow homogeneity, which proved to be as challenging as the production of high turbulence intensity levels. Construction details and results for different turbulence intensities as well as decay rates and integral length scales are presented in this paper.

1 INTRODUCTION

Many flow conditions are characterized by very high levels of turbulence intensity. For example, turbulence intensity of up to 20 % is achieved in turbomachinery flows, due to periodic rotor-stator interaction and wake convection. Corresponding wind tunnel investigations have to simulate similar turbulence intensities, in order to reproduce the flow phenomena in a realistic manner. In particular, the laminar-turbulent transition and heat transfer are highly dependent on the free stream turbulence level. The combination of high turbulence intensity and relatively low Reynolds number ($Re_{2th} < 500,000$), as typical of turbomachinery flow, leads to highly pronounced transition effects, which considerably determine the boundary layer development and aerodynamic performance parameters, cf. Mayle [1] and Hourmouziadis [2]. Hence, the reproduction of characteristic turbulence levels is of great importance for corresponding wind tunnel investigations. Typically, well designed wind tunnels show low turbulence intensity in the free stream. Therefore, turbulence generators are used to change the characteristic of downstream turbulence and modify the time-mean velocity distribution. Turbulence generators may be grouped into two main categories depending on the function:

Passive Turbulence Generator Usually, passive turbulence grids or screens are used for elevating the turbulence level in cascade wind tunnels. Applying a proper combination of grid parameters (grid element shape, element width, element pitch, etc.) turbulence levels up to 4 or 6 % can be achieved, as frequently reported in the literature, cf. Kiock et al. [3], Kotlarski [4], Roach [5], Ortmanns [6]. Passive turbulence generators are the simplest method to produce turbulence downstream in wind tunnels. Parts of the generator products wakes and the wake effect contributes turbulent energy to the downstream flow field. The wake induced energy is relatively high frequent and decrease the scale of the upstream turbulence eddies. The energy decay downstream the grid is rapidly. Long distance downstream the grid, the flow is characterized by fairly good homogeneity and isotropy, cf. Hinze [7].

Active Turbulence Generator Active turbulence generators change the turbulence intensity in the flow by adding momentum either by moving parts (cf. Kiock [8]) or jet injections. For example, periodic oscillating rods in front of the cascade are used to simulate the rotor-stator interaction, cf. Pfeil and Eifler [9]. An other common method to influence the turbulence intensity in the test section are jet injections. The level of turbulence intensity depends on the injection ratio and direction. Downstream jets with weak strength can lead to smaller turbulence levels at a prescribed distance downstream, due to reducing the rod wake width through entrainment effects. Strong downstream injection counteract the effect of the width decrease in the rod wakes because of the additional turbulence and shear in the jets themselves. At higher injection ratios, the jets become unstable. Hence, the turbulence intensity increase. For upstream injection, relatively small injection ratios cause unstability and elevate the turbulence intensity. In the literature, injection ratios up to $J = 8$ % are used to influence the turbulence intensity in the flow. Active turbulence generator can achieved turbulence levels up to 11 %, cf. Gad-el-Hak and Corrsin [10], Tassa and Kamotani [11], Dörr [12]. A mesh of an active turbulence grid with downstream injection is shown in figure 1. With the aid of figure 1, the principle of an active jet grid is described and the change of the flow conditions by adding momentum through the jet injection is visualized.

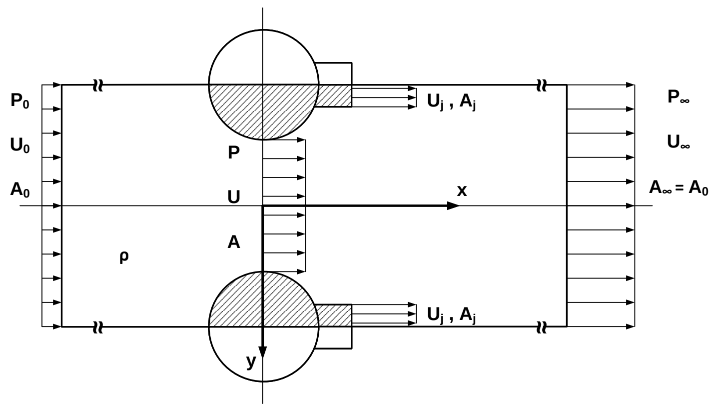


Figure 1: Model for the flow through a grid, Gad-el-Hak [10]

2 TURBULENCE GENERATING GRID

The aim of this work is the design of an turbulence grid which generates a homogeneous turbulence intensity up to $Tu = 10$ % in the test section of a wind tunnel. At first, a passive turbulence grid is developed with middle high turbulence intensity. Subsequently, the turbulence intensity is increased by supplying momentum to the free stream due to jet injection. The level of grid generated turbulence depends on diverse factors and is hard to predict. Laws and Livesey [13] presented a theoretical treatment for the design of passive turbulence grids

$$Tu = 100\sqrt{\frac{M \cdot \zeta}{b(x - x_0)}} \cdot K \tag{1}$$

where Tu is the streamwise turbulence intensity, M is the mesh-size, ζ is the loss coefficient of the grid and x is the distance downstream of the grid. The distance downstream the grid where the turbulent energy can be assumed as isotropic is $x_0 = 10M$ and for parallel arrays of round rods or wires is $b = 50$, cf. Laws and Livesey [13]. Typically, the diameter of the rods is a ration of the mesh-size and determined as $M/d \approx 5$. The definition of the grid parameters M and d for square-mesh and parallel-mesh grids is shown in figure 2. If necessary, the effect of the wind tunnel contraction downstream the grid is characterized by the parameter K, cf. Dunham [14]:

$$K = \sqrt{\frac{1}{2k}\left(1 + \frac{ln(k^{\frac{3}{2}}(1 + \sqrt{1 - k^{-3}})}{k^3\sqrt{1 - k^{-3}}}\right)} \qquad \text{with} \qquad k = \frac{A_{Grid}}{A_x} > 1 \tag{2}$$

where A_{Grid} is the cross sectional area of the grid and A_x the cross sectional area downstream the grid. A transformation of equation 1 yields the mesh-size for a desired turbu-

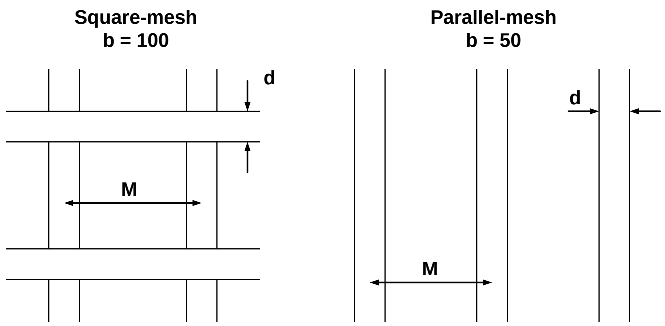


Figure 2: Parameter definition of square-mesh and parallel-mesh grids

lence intensity:

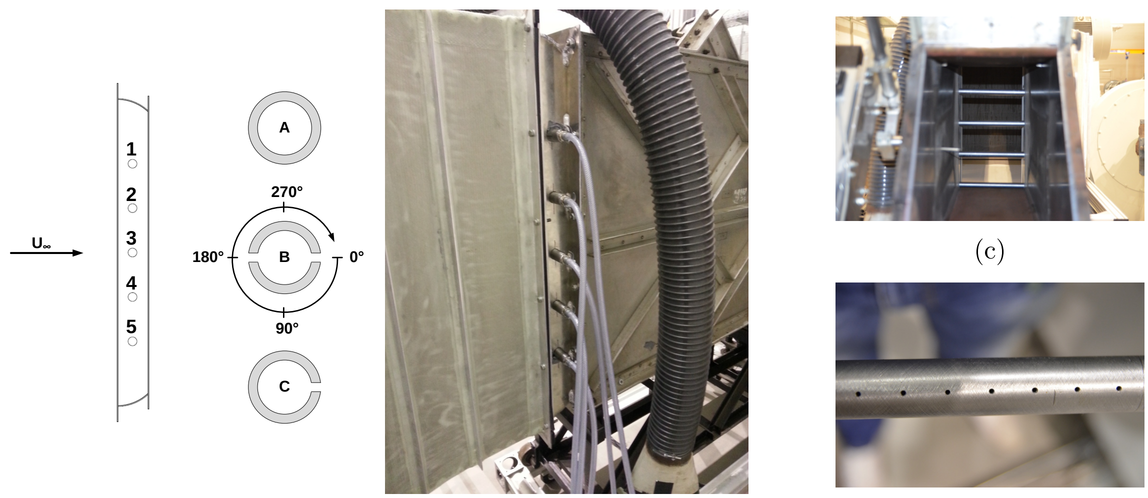
$$M = \frac{Tu^2 \cdot b \cdot x}{\zeta \cdot 100^2 \cdot K^2 + Tu^2 \cdot 10b} \tag{3}$$

In this work, a parallel-mesh grid is developed. The distance between the grid and the measuring plane is $x = 1.5\ m$. The loss coefficient of a grid is hard to predict by theoretical treatments and is estimated by experimental investigations with $\zeta = 0.2$. The dimensions of the wind tunnel and test section ($k = 2$, $b = 0.3\ m$, $h = 0.5\ m$) and a desired turbulence intensity of about $Tu \approx 6\ \%$ yields to a mesh-size $M = 0.145\ m$ and a rod diameter $d = 0.028\ m$. In order to further increase the turbulence level, the passive design is changed into an active grid. It consists of pressurized tubes with evenly distributed jet injections. The mass flow injection for each rod is continuously adjustable to produce homogeneous turbulence distributions. However, there is no appropriate theoretical approach for the design of active turbulence grids. The resulting turbulence intensity need to be figured out by experimental investigations. The geometrical solidity σ and the injection ration J are introduced to compare different grids. The parameters σ and J can be derived by figure 1.

$$\sigma = (A_0 - A)/A_0 \tag{4}$$

$$J = Q_j/Q_0 = U_j A_j / U_0 A_0 \tag{5}$$

Each tube of the grid can be separately pressured by an air pressure system. Figure 3a shows a model of the designed turbulence grid. The grid consists of five tubes $(1 - 5)$ which can be separately pressurized. Different types of tubes $(A - C)$ can be integrated in the grid position 1 to 5. The types of tubes distinguish themselves in the number of injections holes and injection direction. For example, type A is used for the passive application. Type B injected flow in two opposite directions and type C in one direction. Also, the rods are rotatable and the injection direction can be changed stepless. Figure 3b-c depict the active turbulence grid integrated in front of the test section of the wind tunnel. A tube with injection holes (type C) is shown in figure 3d.



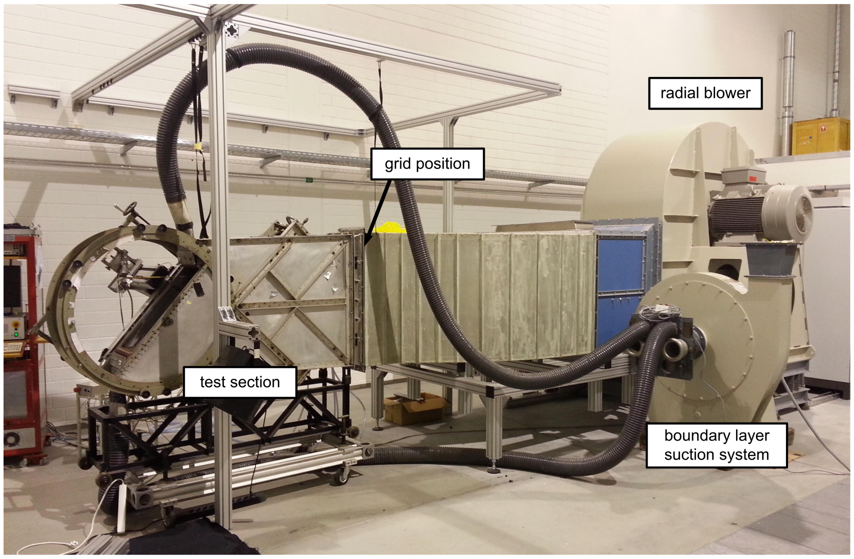
(a) (b) (c) (d)

Figure 3: a) Model of the active turbulence grid. b) Pressurized tubes integrated in front of the test section. c) Front view into the test section. d) Tube with jet injection holes

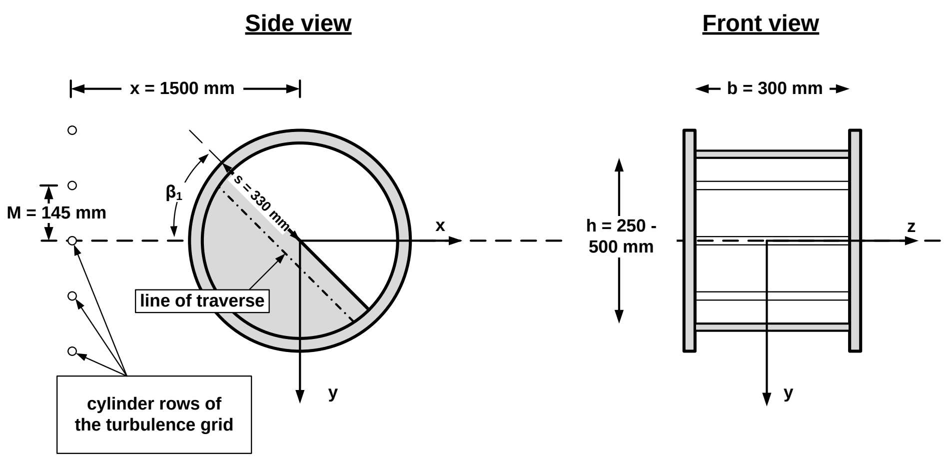
3 EXPERIMENTAL EQUIPMENT AND PROCEDURE

Low-Speed Cascade Wind Tunnel The Low-Speed Cascade Wind Tunnel of the Institute of Jet Propulsion and Turbomachinery at Technische Universität Braunschweig is used for compressor and turbine cascade investigations with and without gaps at the endwall. The cascade wind tunnel is powered by a radial blower with a driving power of 58 kW. The maximum free stream velocity is about $U_\infty \approx 60\ m/s$. The test section is 300 mm width and determines the maximum height of the blades. The height of the test section is variable and between 250 mm and 500 mm. The cascade is fixed on rotatable sidewalls whereby the inlet angle β_1 is continuously adjustable. The stagger angle and the pitch of the cascade held constant. The periodicity of the inlet flow can be controlled by a boundary layer suction system at the top and the bottom of the test section. The background turbulence intensity of the wind tunnel is measured to $Tu \approx 0.75\,\%$. Figure 4a shows the cascade wind tunnel in the test facility of the Institute of Jet Propulsion and Turbomachinery. Figure 4b depict a model of the test section and shows the position of the grid tubes.

Measurement Technique The mean and fluctuating velocity components were measured with a Dantec Streamline $90C10$ hotwire system. A Dantec single-sensor miniature hotwire probe ($55P14$) operated in a constant temperature anemometry mode with an overheat ration of 250 °C. The platinum-plated tungsten wire sensors has 5 μm diameter and the sensitive part is 1.25 mm long. The data was captured by a transient recorder with a sample rate of $t_s = 10^{-4}\ s$ and a cut-off-frequency of $f = 10\ kHz$.



(a) Low-Speed Cascade Wind Tunnel



(b) Model of the test section

Figure 4: Low-Speed Cascade Wind Tunnel of the Institute of Jet Propulsion and Turbomachinery

4 EXPERIMENTAL RESULTS

Turbulence Intensity Turbulence can be characterizes as a three-dimensional, irregular motion whereby eddies of a wide range of size cause strong diffusion. The momentary value of the velocity consist of an average value $\overline{u}$ and a fluctuation value u'. The turbulence intensity is determined by the fluctuation of the velocity. The turbulence intensity in the streamwise directions is defined as:

$$Tu = 100 \frac{\sqrt{u'^2}}{\overline{u}} \tag{6}$$

The turbulence intensity Tu in the test section of the wind tunnel for different free stream velocities with and without turbulence grid is shown in figure 5 - 7. Without turbulence grid (cf. Fig. 5), the turbulence intensity is measured to $Tu \approx 0.75$ %. The measuring plane shows a homogenous turbulence distribution in the free stream. Towards the side-walls of the test section, the turbulence level increase due to the boundary layer. The passive turbulence grid ($J = 0$, cf. Fig. 6) elevate the turbulence intensity and generate turbulence levels between $Tu = 5.0 - 6.5$ %. Hence, the design approach for a passive grid by Laws and Livesey provides an appropriate result. However, the turbulence intensity depends on the free stream velocity U_∞. The turbulence distribution is nearly homogenous but in the corner of the test section is a drop of the turbulence intensity. The active turbulence grid ($J > 0$, cf. Fig. 7) increase the turbulence level up to $Tu = 8$ %. This result is achieved with upstream injection, whereby just tubes 1 and 5 are pressurized. Here, the turbulence intensity is almost independent of U_∞. Considering the large flow distortion, which is an inherent side effect of large turbulence generation, the homogeneity of the turbulence distribution can be considered as very good. With the active turbulence grid, a turbulence level range of $Tu = 5 - 10$ % can be achieved, due to regulation the injection ratio.

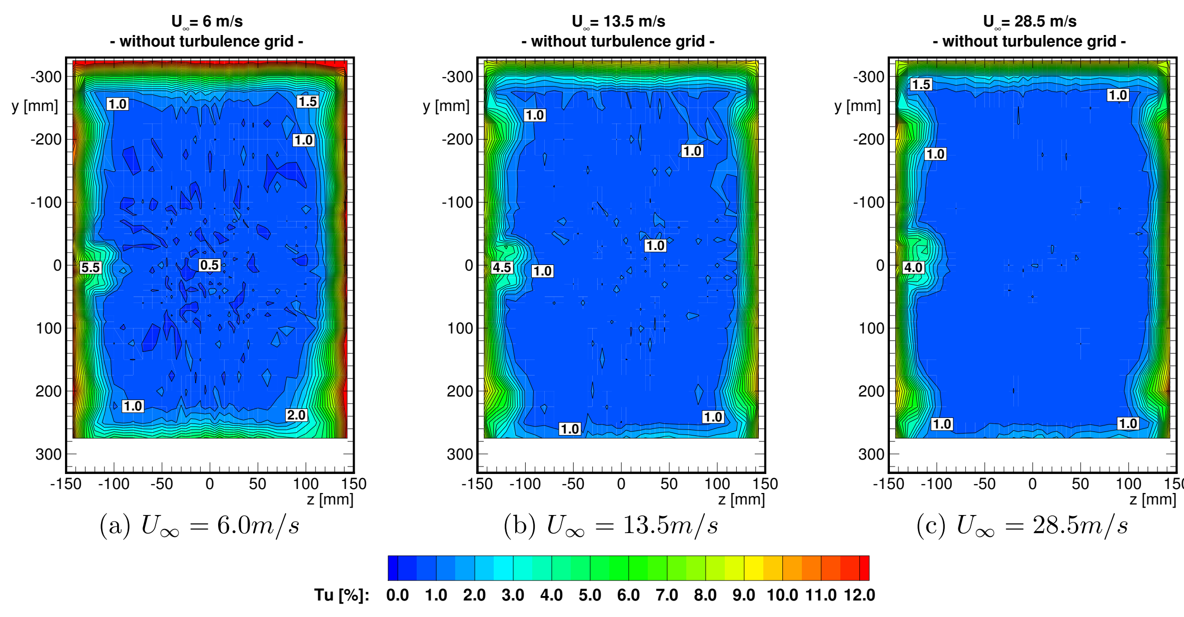
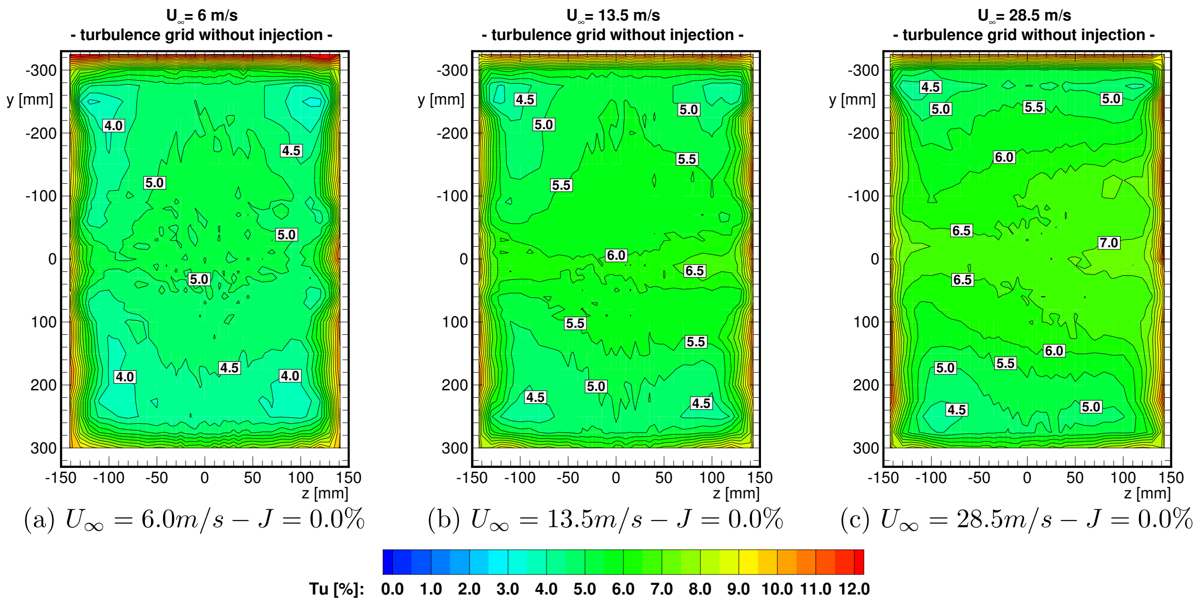
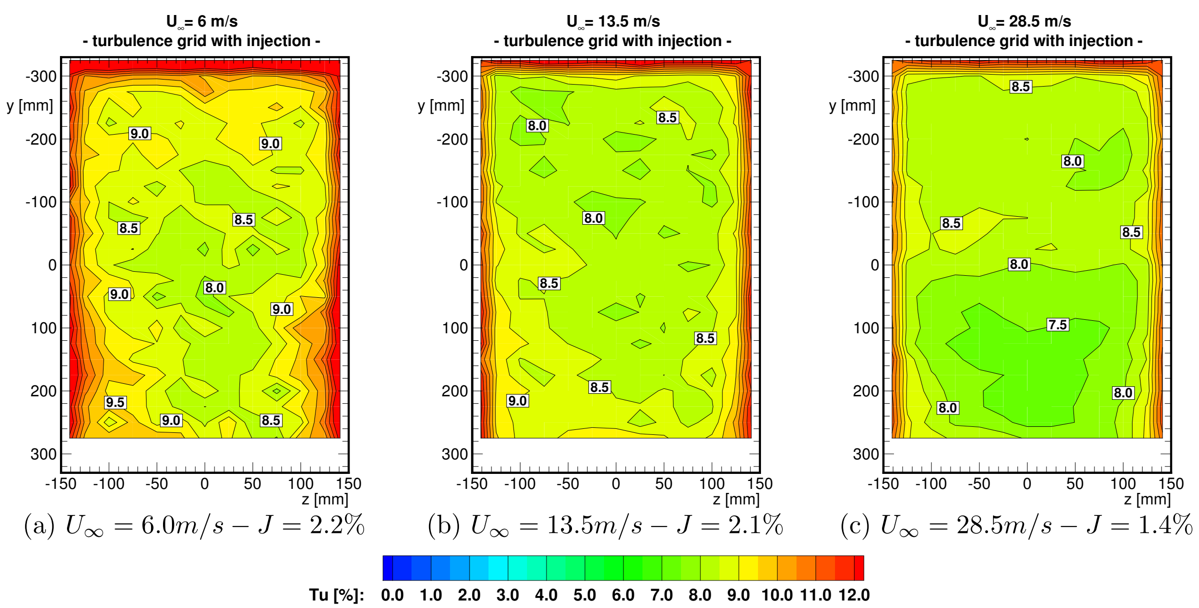


Figure 5: Turbulence intensity Tu in the test section of the wind tunnel without turbulence grid



(a) $U_\infty = 6.0m/s - J = 0.0\%$ (b) $U_\infty = 13.5m/s - J = 0.0\%$ (c) $U_\infty = 28.5m/s - J = 0.0\%$

Figure 6: Turbulence intensity Tu in the test section of the wind tunnel with turbulence grid without jet injections (passive)



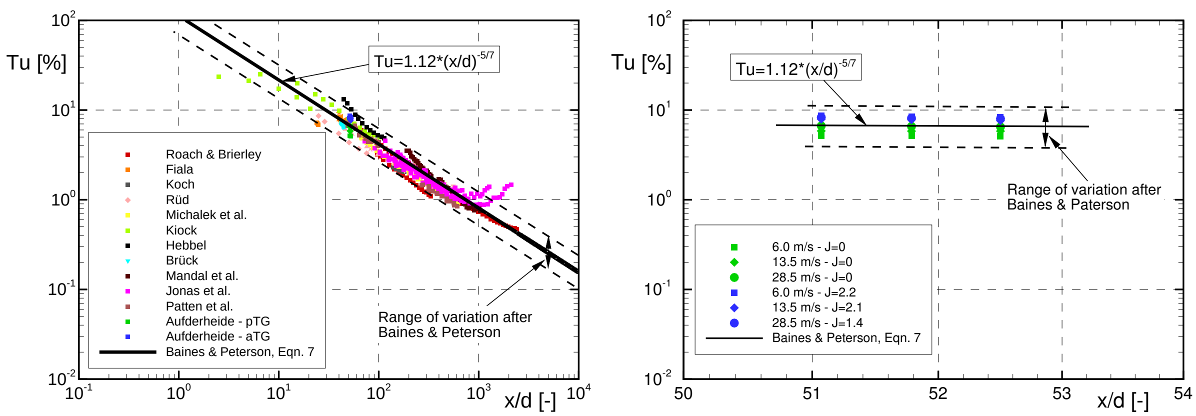
(a) $U_\infty = 6.0m/s - J = 2.2\%$ (b) $U_\infty = 13.5m/s - J = 2.1\%$ (c) $U_\infty = 28.5m/s - J = 1.4\%$

Figure 7: Turbulence intensity Tu in the test section of the wind tunnel with turbulence grid and jet injection (active)

Turbulence Decay Over the years, several theoretical treatments have been presented to determine the decay of the turbulence downstream a grid. Baines and Peterson [15] give an experimental correlation for high turbulent flows which fitted fairly good with experimental investigations

$$Tu = 1.12 \left(\frac{x}{d}\right)^{-5/7} \tag{7}$$

where x is the distance downstream the grid and d is the rod diameter. Figure 8 compares several experimental investigations with the correlation by Baines & Peterson [15]. The measured results of the turbulence decay downstream the grid show good agreement with the theoretical approach and lay inside the range of variation given by Baines & Peterson [15]. Information about the experimental investigations used in figure 8a are referenced by Bode et al. [16]. Figure 8b gives a detailed overview for the results of the passive (pTG) and active (aTG) turbulence grid. Furthermore, the result pointed out that the turbulence decay is not just a function of the distance and the rod diameter but depends also on the free stream velocity, cf. Bode et al. [16].



(a) Free stream turbulence intensity decay Tu (b) Turbulence intensity decay Tu (zoom in)

Figure 8: Turbulence decay for several experiments

Integral Length Scale The integral length scale Λ is the physical quantity describing the order of the size of the large energy-containing eddies in the flow. As mentioned before, turbulence short behind a grid is high frequent and contains small-scale eddies. With growing distance the smallest eddies dissipate and the integral length scale growth downstream. The turbulence intensity can be assumed as homogeneous and isotropic at long distance downstream the grid. By using Taylor's hypothesis, cf. Hinze [7], it is possible to determine the integral scale from an autocorrelation. The autocorrelation is a correlation between the streamwise component of the fluctuation velocity at a fixed position in the flow at two different instances in time (i.e. t and $t - T$), cf. Roach [5], and is defined as

$$R(T) = \frac{\overline{u'(t)u'(t+T)}}{\overline{u'^2}} \tag{8}$$

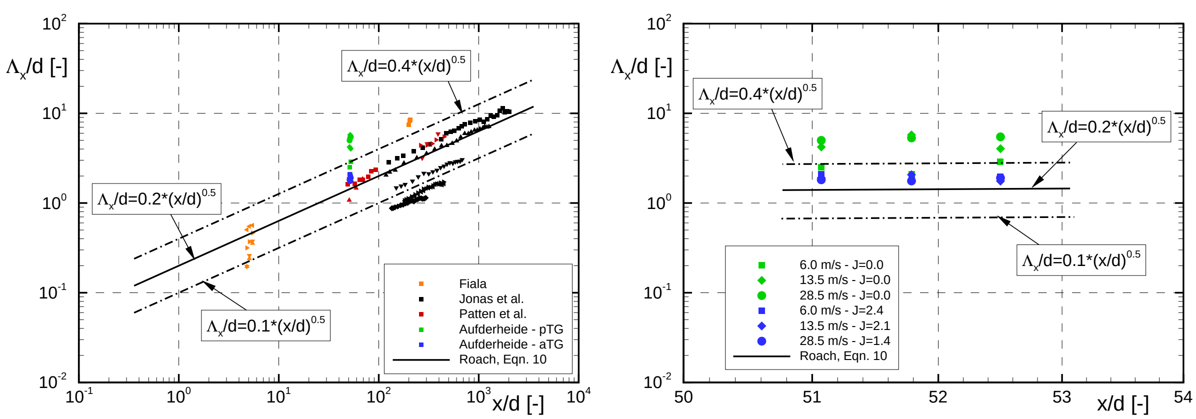
The area below the correlation curve was integrated until $R(T)$ intersected the abscissa. From the autocorrelation, the integral length scale is defined as

$$\Lambda_x = U_\infty \int_0^\infty R(T)dt \tag{9}$$

Roach [5] suggest a theoretical treatment for the integral length scale growth downstream of a grid.

$$\frac{\Lambda_x}{d} = 0.2 \left(\frac{x}{d}\right)^{0.5} \tag{10}$$

Figure 9 compares some measured integral length scales with the approach by Roach [5]. It is shown that some measured integral length scales differ from the correlation by Roach. Roach mentioned that correlation for the integral length scale depends heavily on the design and the flow condition behind the grid. Due to an alteration of the empirical constant, the experimental results show better agreement with the theory. Tables 1 and 2



(a) Integral length scale growth

(b) Integral length scale growth (zoom in)

Figure 9: Integral length scale growth downstream of a grid

outline the average values of the measured turbulence intensity in the test section, as well as the injection ratios for the active grid and the integral length scales.

Table 1: Mean velocities, injection ratios and turbulent length scales downstream the turbulence grid for the passive grid

U_∞ $[m/s]$	J [%]	σ $[-]$	d $[m]$	x $[m]$	Tu [%]	Λ_x $[m]$
6.0	0	0.2	0.028	1.45	5.07	0.055
13.5	0	0.2	0.028	1.45	5.93	0.086
28.5	0	0.2	0.028	1.45	6.65	0.095

Table 2: Mean velocities, injection ratios and turbulent length scales downstream the turbulence grid for the active grid

U_∞ $[m/s]$	J [%]	σ $[-]$	d $[m]$	x $[m]$	Tu [%]	Λ_x $[m]$
6.0	2.2	0.2	0.028	1.45	8.42	0.064
13.5	2.1	0.2	0.028	1.45	8.22	0.061
28.5	1.5	0.2	0.028	1.45	8.11	0.055

5 CONCLUSION

An active turbulence grid for the generation of higher levels of turbulence in a Low-Speed Cascade Wind Tunnel is introduced. The jet grid generate a field of nearly homogeneous turbulence in the test section of the wind tunnel. The grid was operated with (active) and without (passive) injection. In the passive mode, turbulence levels up to 6.5 % can be achieved and the turbulence intensity depends on the free stream velocity. In the active mode, the homogeneity was improved by controlled jet injection and the turbulence level elevates to $Tu = 8$ %. Overall, the active turbulence grid show high turbulence levels and an homogeneity of the turbulence distribution which can be considered as very good. Furthermore, the turbulence decay is compared with theoretical treatment by Baines & Peterson [15] and show good agreement. Also, the growth of the integral length scale downstream the grid is compared with a correlation given by Roach [5]. The experimental investigations reveal a similar behavior as the correlation mentioned.

REFERENCES

[1] Mayle, R. E., 1991. *The Role of Laminar-Turbulent Transition in Gas Turbine Engines.* Journal of Turbomachinery, 113, pp. 509-536.

[2] Hourmouziadis, J., 1989. *Aerodynamic Design of Low-Pressure Turbines.* Tech. Report, AGARD Lecture Series 167.

[3] Kiock, R., Laskowski, G. and Hoheisel, H., 1982. *Die Erzeugung höherer Turbulenzgrade in der Messstrecke des Hochgeschwindigkeitsgitterwindkanal Braunschweig zur Simulation turbomaschinenähnlicher Bedingungen*. Tech. Report, DFVLR-FB 82-25.

[4] Kotlarski, T., 1980. *Erzeugung von höheren Turbulenzgraden bei Schaufelgitteruntersuchungen im Windkanal*. Tech. Report, DLR IB 151 - 80/6.

[5] Roach, P.E., 1986. *The Generation of nearly Isotropic Turbulence by Means of Grids*. International Journal of Heat and Fluid Flow, Vol. 8, No. 2., pp. 82-92.

[6] Ortmanns, J., 2001. *Entwurf und Erprobung eines Turbulenzerzeugers für den Gitterwindkanal des Instituts für Strömungsmechanik*. Studienarbeit Technische Universität Braunschweig, Nr. 426.

[7] Hinze, J. O., 1959. *Turbulence*. McGraw-Hill Series in Mechanical Engineering.

[8] Kiock, R., 1973. *Influence of the Degree of Turbulence on the Aerodynamic Coefficients of Cascades*. AGARD-AG-164: Boundary Layer Effects in Turbomachines, Paper No. 1-4.

[9] Pfeil, H. and Eifler, J., 1979. *Turbulenzverhältnisse hinter rotierenden Zylindergittern*. Forschung im Ingenieurwesen, Vol. 42, S. 27-32.

[10] Gad-el-Hak, M. and Corrsin, S., 1974. *Mesurements of the nearly Isotropic Turbulence behind a uniform Jet Grid*. Journal of Fluid Mechanics, Vol. 62, part 1, pp. 115-143.

[11] Tassa, Y. and Kamotani, Y., 1975. *Experiments on Turbulence behind a Grid with Jet Injection in Downstream and Upstream Direction*. The Physics of Fluid, Vol. 4, pp. 411-414

[12] Dörr, T., 1995. *Ein Beitrag zur Reduzierung des Stickoxydausstoes von Gasturbinenkammern*. PhD Thesis, Technische Hochschule Darmstadt.

[13] Laws, E. M. and Livesey, J. L., 1978. *Flow through Screens*. Annual Rev. Fluid Mech., Vol. 10, pp. 247-266.

[14] Dunham, J., 1972. *Prediction of Boundary Layer Transition on Turbomachinery Blades*. Tech. Report, AGARD-AG-164.

[15] Baines, W. D. and Peterson, E. G., 1953. *An Investigation of Flow through Screens*. Transaction of the ASME, Vol. 73, pp. 467-480.

[16] Bode, C., Aufderheide, T., Kožulović, D. and Friedrichs, J., 2014. *The Effects of Turbulence Length Scale on Turbulence an Transition Prediction in Turbomachinery Flows*. ASME Turbo Expo 2014, Paper No. GT2014-27026.