Experimental investigation on flow quality in MF-TA1 Wind Tunnel

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Abstract. This paper presents the results of the first calibration stage of the MF-TA1 wind tunnel: measurement of velocity distributions in the median plane of the test section using 3D Laser Doppler Anemometer. Are presented the main functional and technical features of MF-TA1 wind tunnel and 3D Laser-Doppler Anemometer. For this experiment a 3D Laser Doppler Anemometer was positioned at 90 degrees from test section and lenses with focal length at 800 mm was used. The measurement domain is a matrix of 273 points on 500x300 mm. The laser probe movement in each point was performed with a 3D traverse system. The results are presented through graphics for velocity distributions, while for mean of velocity components, dynamic pressure and mean turbulence in the median plane of test section the results are presented through numerical values.

1. Introduction
In the wind tunnel section is must to obtain high standards for the flow quality in order to accomplish accurate and reliable measurement data. Flow quality in the test section of wind tunnels relates mainly to spatial aspects of the flow. For aeronautical applications is required a spatial uniformity in the entire empty test section of the wind tunnel. Spatial flow uniformity can be documented by contour plots of velocity magnitude in one or more cross-sectional planes of the wind tunnel. The flow in test section of wind tunnel must meet high standards of spatial uniformity. A set of indicators for evaluation the flow quality in test section is developed by Moonen [1].

Measurements in empty test section of wind tunnel are required that could be used for the identification and means for suppression of suspected sources of flow disturbances in the test section and around the wind tunnel circuit, [2].
In order to make accurate measurement on a model in a wind tunnel is necessary to determine the flow parameters. The main flow parameters are: pressure, temperature, Mach number and Reynolds number. These parameters can be determined from calibration relationships, calculated or measured.

Dynamic pressure can be determinate with a Pitôt-static probe or a high-quality pressure transducer connected to a pressure taps in the nozzle before test section of wind tunnel, and from dynamic pressure, the velocity can be further calculated [3].
On the other hand, velocity is a fundamental parameter in fluid mechanics. One of the most advanced method for velocity measurement in fluid mechanics is laser velocimetry, that used an optical technique based on light scattering by tiny particles used as flow tracers, [4], the laser velocimetry being the preferred technique used to measure instantaneous velocity.
In this paper is presented the measurement of velocity distribution in the median plane of the test section of the MF TA-1 wind tunnel using 3D Laser-Doppler Anemometer. Also, four quality indicators related to the longitudinal component of the flow and four indicators for turbulence are presented.

2. MF-TA1 Wind Tunnel description

The MF-TA1 wind tunnel is part of the Aerodynamics and Hydrodynamics Laboratory of the Department of Fluid Mechanics, Fluid Machinery and Fluid Power Systems. The full modernization of the MF-TA1a wind tunnel took place in 2014-2016 through the project POSCCE-A2-O2.1-2009, ID 911, No. 430 / 21.12.2012, SMIS code 13987, "Development of the research platform for efficient and sustainable energy - ENERED". The aerodynamic and constructive conception and design of the wind tunnel belongs entirely to the Department of Fluid Mechanics, Fluid Machinery and Fluid Power Systems. The main features of MF-TA1 wind tunnel are: low-turbulence, closed-circulation, controlled cooling, continuously adjustable velocity in the range of 0 ÷ 80 m/s, octagonal work area of 0.48 m², shape factor $\sqrt{2}$, and contraction ratio 9. Installed power on the wind tunnel is 90 kW. The tunnel is used for testing aerodynamic profiles, testing experimental body models and experimental validation of numerical models in aerodynamics.
The main elements of the MF-TA1 wind tunnel are shown in figure 1, (a) 3D general view; (b) 3D test section view; (c) turbofan; (d) heat exchanger; (e) 2D section view. The components of the wind tunnel are presented in figure 1, (e): T1- settling chamber; T2 nozzle; T3-test section; T4a, T4b-diffuser number 1; T5-elastic connection; T6, T7 corner number 1 and corner number 2; T8-upstream connection; T9 (V) - turbofan; T10 - downstream connection; T11 diffuser number 2; T12-heat exchanger with elliptical tubes; T13, T14 - corner number 3 and number 4.

The cross section of the wind tunnel is octagonal, with three exceptions: sections T8, T9 (V) and T10. The useful overall dimensions of the wind tunnel are: length 13120 mm, variable height 4140/3330 mm and maximum width 2500 mm. For the vibrations not to be transmitted to the test section, the following measures have been taken: the turbofan and the heat exchanger is framed by elastic connections, the turbofan is supported and fixed by six vibration dampers. The VAN 1400-0 / 50-4-90 turbofan (made by Howden Turbowerke GmbH) is powered by VEM IE3 W41F 280 M4 capacity motor, with 1487 rpm nominal speed, and 90 kW installed power. The motor is powered by a frequency converter of the type SINAMICS G120 (Siemens). Accuracy of engine speed modification (real speed deviation from prescribed speed) is 0.015 rpm.

3. Laser Doppler Anemometer description and components
The Laser Doppler Anemometer uses the non-intrusive principle in the measurement procedure. This equipment is recommended for reversible flow applications, chemical reactive or high temperature media, where the physical sensors are difficult or impossible to be used. For measurements, the fluid flow should be filled with tracer particle. The main advantages of the laser velocimetry method are: non-intrusive measurement, spatial and temporal resolution, no calibration is required at each use and reverse flow measurement ability, [5].

The main component of Laser Doppler Anemometer is Flow Lite System. This system allows several measurement configurations to be carried out: measurement of a single velocity component - module 1D, figure 2, (a); measurement of two velocity components - module 2D, figure 2, (b), and measuring the three components of the velocity by combining 1D and 2D modules aligned under a certain angle so that the volume of measurement coincides. For this experiment the Flow Lite 2D system was used, [6].

The Flow Lite system is the continuous laser beam generation equipment, including beam splitter, optical receiver, interference filter, photodetector, and focusing lenses. The laser probe is part of the Flow Lite system structure and represents the element that comes in direct contact with the test section. The laser probe is mounted on the 3D Traverse System and is moved to each measurement point. For signal processing and analysis of experimental data, the Flow Lite system is connected to the BSA-F60 signal processor.

Figure 2. Laser Doppler Anemometer components.
The signal processor, receives information from the photo-detector which converts the fluctuating light intensity received to the laser probe to an electrical signal. Information are filtered and amplified in the signal processor, by frequency analysis using the robust Fast Fourier Transform algorithm, [5,6].

The laser probe is moved in each measurement point by a computerized 3D traverse system. All 3 working axis of the traverse system have a length of 1010 mm and a pitch of 0.1 mm, being moved by stepper motors, figure 2, (c). The control equipment of traverse system, figure 2, (d), is connected to the process computer by a RS 232 port, [7].

4. Experiment setup
To perform the measurements, the Flow Lite 2D module with two laser beams with wavelengths of 532 and respectively 561 nm was used. The laser probe is equipped with a lens with a focal length of 800 mm. The laser beam is oriented perpendicular to the wind tunnel test section axis. An array of measurement points has been created in the median plane of the test section.

The area covered by the array is 500x300 mm and the pitch on both axes is 25 mm, resulting 21 points on the y axis and 13 in the z axis; the reporting being made to the xyz system of the traverse system, figure 3. In front of the test section, the significance of the axes is: x-longitudinal axis, y-transverse axis, z-vertical axis.

In this experiment, only two components of velocity are determined: \( u \) (longitudinal velocity) and \( w \) (transversal velocity), which represent the mean of each particle velocity on the measurement volume for every point.

The laser beam remains positioned at each measuring point until one of these two conditions is accomplished: a measuring time of 60 seconds, or 10000 particles passing through the measurement volume. The results obtained for each point are mediated by the signal processor.

![Figure 3. Measurement points.](image)

5. Experimental results
The variation of longitudinal velocity component, and transversal velocity component in the median plane of test section are presented in figure 4, respectively in figure 5 by surface plots 3D.

The \( u \) velocity component values are in range of \( 9.506 \pm 9.605 \text{ m/s} \) and the mean velocity is \( \bar{u} = 9.593 \text{ m/s} \). The mean velocity of \( w \) component velocity is \( \bar{w} = -0.0217 \text{ m/s} \) and range of the \( w \) velocity component is \(-0.142 \pm 0.121 \text{ m/s}\). These values were obtained at 200 rpm nominal speed of the VAN 1400-0 / 50-4-90 turbofan.
The value of standard deviation for both velocity component was calculated with the formula:

$$\sigma_v = \left( \frac{1}{N} \sum_{i=1}^{N} (V_i - \bar{V})^2 \right)^{1/2}$$  \hspace{1cm} (1)

where \(N\) is number of measurement points, \(V_i\) is the \(u_i\) or \(w_i\) values of velocity components in each measurement point while \(\bar{V}\) are the mean value for \(u_i\) velocity component, respectively for \(w_i\) velocity component. The values for standard deviation are \(\sigma_u = 0.0318 \text{ m/s}\) and \(\sigma_w = 0.0409 \text{ m/s}\).

Further, we will calculate four quality indicators related to the longitudinal (streamwise) component of the flow. The indicators related to the residual cross-flow component \(I_{\text{sym-y}}^u(z)\), \(I_{\text{sym-z}}^u(y)\), \(I_{\text{antisym-y}}^u(z)\), \(I_{\text{antisym-z}}^u(y)\) have similar definitions presented hereunder in equations 2-5. The indicators \(I_{\text{sym-y}}^u(z)\) and \(I_{\text{sym-z}}^u(y)\) are describing the lateral flow uniformity of the streamwise component, while indicators \(I_{\text{antisym-y}}^u(z)\) and \(I_{\text{antisym-z}}^u(y)\) are measuring the skewness of the streamwise component of the flow:

$$I_{\text{sym-y}}^u(z) = \frac{\int u_{\text{sym-y}}^2(y,z) dy}{\int \| \bar{v}(y,z) \|^2 dy}$$  \hspace{1cm} (2)
where $u_{\text{sym, } y}(y, z)$ and $u_{\text{sym, } z}(y, z)$ are the symmetric parts of $u$ velocity, while $u_{\text{antisym, } y}(y, z)$ and $u_{\text{antisym, } z}(y, z)$ are the antisymmetric parts of $u$ velocity component along $y$ axis and respectively $z$ axis. Variation of the four quality indicators for streamwise component of the flow are presented in figures 6-9 on longitudinal direction and transversal direction. The uniformity indicators $I_{\text{sym, } y}(z)$ and $I_{\text{sym, } z}(y)$ are near to 1, and skewness indicators $I_{\text{antisym, } y}$ and $I_{\text{antisym, } z}$ are near to 0, what it indicates the very good lateral symmetry velocity distribution in median plane of test section on longitudinal direction, respectively on transversal direction for $u$ velocity component.

**Figure 6.** Index of uniformity along $z$ axis $I_{\text{sym, } y}$.  

**Figure 7.** Skewness index along $z$ axis $I_{\text{antisym, } y}$.  

\[
I_{\text{antisym, } y}(z) = \frac{\int_{y_{\text{min}}}^{y_{\text{max}}} u^2_{\text{antisym, } y}(y, z) \, dy}{\int_{y_{\text{min}}}^{y_{\text{max}}} \left| v(y, z) \right|^2 \, dy}
\]  

(3)

\[
I_{\text{sym, } y}(y) = \frac{\int_{y_{\text{min}}}^{y_{\text{max}}} u^2_{\text{sym, } y}(y, z) \, dy}{\int_{y_{\text{min}}}^{y_{\text{max}}} \left| v(y, z) \right|^2 \, dy}
\]  

(4)

\[
I_{\text{antisym, } z}(y) = \frac{\int_{y_{\text{min}}}^{y_{\text{max}}} u^2_{\text{antisym, } z}(y, z) \, dz}{\int_{z_{\text{min}}}^{z_{\text{max}}} \left| v(y, z) \right|^2 \, dz}
\]  

(4)
Further, statistical analysis on flow quality is developed. In figure 10-13 are presented turbulent stress $\sigma_{xx}$, turbulent stress $\sigma_{zz}$, root mean square velocity $U_{rms}$ and respectively cross moment $\langle u'w' \rangle$ by surface plots 3D.

![Figure 8. Index of uniformity along y axis $I^y_{jum, z}$.](image8.png)

![Figure 9. Skewness index along y axis $I^y_{uniwm, z}$.](image9.png)

![Figure 10. Turbulent stress $\sigma_{xx}$.](image10.png)
Minimum and maximum values for all eight quality indicators for streamwise component of the flow are presented in table 1.
6. Discussion and conclusion

The flow quality of MF TA-1 wind tunnel was investigated via Laser Doppler Anemometer measurements. There are presented four uniformity indicators, and four turbulence indicators.

Quality indicators \( I_{\text{sym},y}^u(z) \) and \( I_{\text{sym},z}^u(y) \) shows an excellent transversal symmetry for streamwise component of velocity. For MF TA-1 wind tunnel both indicators have values greater than 0.9999. For the wind tunnel investigated by Moonen [1], the minimum values for uniformity indicators is 0.98 in the best case.

Quality indicators \( I_{\text{antisym},y}^u(z) \) and \( I_{\text{antisym},z}^u(y) \) shows the lack of angularity for MF TA-a wind tunnel. The maximum value for \( I_{\text{antisym},y}^u(z) \) is 1.00808413e-05. The maximum value for \( I_{\text{antisym},z}^u(y) \) is 1.81014937e-05. For the wind tunnel investigated by Moonen [1], the values of angularity indicators are in the range 0.01-0.2 in the best case.

The turbulence indicators show a very good statistical quality. The turbulence stresses \( \sigma_{xx} \) and \( \sigma_{zz} \) have very low values, which indicates low values for rms velocity components. The values streamwise rms component \( U_{\text{rms}} \), are in range 0.006901-0.107973 [m/s]. For comparison, Ghorbanian [8] reported for \( U_{\text{rms}} \) value of 0.24 [m/s] in clean condition and 0.14 [m/s] in trip condition. The range for correlation \( \langle u^i w^j \rangle \) shows actually an isotropic turbulence.

MF TA-1 wind tunnel have an excellent flow quality in the central zone of test section and very good flow quality in the peripheral zone of test section, all proved by the eight considered indicators. There will be performed more detailed measurement in the peripheral flow field in order to improve the quality in this zone.

7. References

[1] Moonen P Blocked B Carmeliet J 2007 Indicators for the evaluation of wind tunnel test section flow quality and application to a numerical closed-circuit wind tunnel Journal of Wind Engineering and Industrial Aerodynamics 95 pp 1289-1314

[2] Owen F K Owen A K 2008 Measurement and assessment of wind tunnel flow quality Progress in Aerospace Sciences 44 pp 315–348

[3] Richard G J 2015 Model test of wind turbine in wind tunnels Technical transactions Civil Engineering 2-B

[4] Boutier A 2012 Laser Velocimetry in Fluid Mechanics London: Wiley–Interscience

[5] https://www.dantecdynamics.com/measurement-principles-of-lda accessed 14.01.2018

[6] DANTEC Dynamics 2010 High Power FlowLite 1D and 2D Installation and User’s Guide Denmark

Table 1. Quality indicators.

| Quality indicator | Minimum value | Maximum value |
|-------------------|---------------|---------------|
| \( I_{\text{sym},y}^u(z) \) | 0.999962151 | 0.999990223 |
| \( I_{\text{antisym},y}^u(z) \) | 2.21826709e-06 | 1.00808413e-05 |
| \( I_{\text{sym},z}^u(y) \) | 0.999992740 | 0.999997456 |
| \( I_{\text{antisym},z}^u(y) \) | 5.21050824e-07 | 1.81014937e-05 |
| \( \sigma_{xx} \) | -5.8339244e-03 | -1.42812634e-02 |
| \( \sigma_{zz} \) | -2.2368217e-03 | -1.22176050e-02 |
| \( U_{\text{rms}} \) | 6.90100520e-02 | 1.079730270e-01 |
| \( \langle u^i w^j \rangle \) | -9.6060000e-04 | 8.3190000e-04 |
[7] DANTEC Dynamics 2011 3D Traversing Mechanism Instalation and User’s Guide Denmark
[8] Ghorbanian K Soltani M R Manshadi M D 2010 Experimental investigation on turbulence intensity reduction in subsonic wind tunnels *Aerospace Science and Technology* 15 pp 137–147

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