Invited paper

TURBULENCE INVESTIGATION IN THE VTI'S EXPERIMENTAL AERODYNAMICS LABORATORY

by

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Wind tunnels are the aerodynamic laboratories which task is to enable high quality and stabile airflow in controlled volume, a test section, during run time, in order to study the effects of streaming around various aeronautical or non-aeronautical models (airfoils and bluff bodies with complex motorized or robotic constructions). The main requirement that leads to quality and reliable measurement results is a high flow quality in the test section: uniformity of the velocity and pressure fields along and across the test section, low turbulence level and low flow direction angularities or swirling. The knowledge of low parameters enables the exchange of the scientific and technical information, comparison of the experimental results from different wind tunnels and data scaling of the model to the real scale. The turbulence intensity TI significantly affects the wind tunnel results and reduction of turbulence is of the highest importance for the quality measurements. This paper presents the Experimental Aerodynamics Laboratory of the VTI in Belgrade, the equipment and methods of turbulence measurements in the test section stream and around different test models. Wind tunnel facilities maintain equipment and devices for sampling, acquisition and data reduction for various test types, from forces and moment measurements, over the pressure distribution measurements to the advanced measurements, followed with the appropriate flow visualization techniques. The modern instrumentation enables determine flow quality and its influence on tests and measurement results of static and dynamic model characteristics.

Key words: *wind tunnels, turbulence, aerodynamics, measurement, flow visualization*

Introduction

Implementation of the wind tunnels, for research and engineering, demands increasing aerodynamic characteristic accuracy to achieve better energy efficiency and transportation costs. An accuracy of the measured data in first depends on: testing flow quality, a test model design and precision of the measuring equipment.

Successful aircraft design needs very precise behavior prediction. Experimental aerodynamics gives the most accurate prediction or confirmation of the calculated aerodynamic parameters for the models in various sizes and in different flow conditions.

This paper presents the Experimental Aerodynamics Laboratory (EAL) of the Military Technical Institute (VTI) in Belgrade, the equipment and methods of turbulence investi-

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gation in the test section stream and around different test models. The special attention is paid on description of flow quality and its influences on aerodynamic characteristic determination, sources of flow perturbations in the test section, turbulence characteristics of wind tunnels, modern equipment, and methods used in EAL for turbulent flow measurement and visualization. The results obtained in a number of turbulence experimental tests in the EAL are presented and illustrated with numerous diagrams and photographs.

Turbulence in the wind tunnel

Wind tunnels (WT) and water tunnels are the experimental facilities for research on the aerodynamic nature of scaled objects surrounded/submerged within an artificial free stream flow of desirable characteristics and low level of turbulence, to simulate atmosphere and obtain realistic results. Many factors influence measurements of the model aerodynamic characteristics, still turbulence is a major unknown and most influential factor.

The flow quality parameter describing turbulence is the turbulence intensity (TI), $Tu[\%] = u_{rms}/\overline{u}$, correlation between rms of stream longitudinal velocity fluctuations and mean velocity.

The turbulence in WT is disturbing the boundary layer – deforming a shape, stability, place of the transition and separation points, pressure distribution, and shock wave-boundary layer interactions [3]. The reported turbulence levels [1-3] increased with the increase of the WT Mach number (M) and unit Reynolds number (Re). The presence of turbulence, under certain conditions, is even capable to impact the tunnel operation [2].

The turbulence of free stream impact may be longitudinal and normal to the stream. In streamline direction, turbulence produces fluctuations of the dynamic pressure around the model, while in normal direction produces fluctuations of the model position. Furthermore, flow disturbance is composed from turbulence and noise [2]. Both velocity and pressures, as time dependent variables, are present with a difference in dominancy of effects: the unsteadiness of velocity is predominant in low speed WT and, in the contrary; pressure unsteadiness is dominant at supersonic and hypersonic range [1]. Large closed circuit and continuous type wind tunnels, like large subsonic WT of VTI produce a flow of small amplitude and low-frequency fluctuations. Empirically obtained requirements for the flow quality [4] pointed out that longitudinal fluctuations of velocity of 0.1% are considered as good flow property, even for basic tests of boundary layer transition. About '70s, several WT achieved very low TI levels, just about 0.02% to 0.05% [5].

The most sensitive aerodynamic characteristics under turbulence have a blunt body [6-8], especially sphere, thus it is used as a calibration standard for flow quality characterization in a range of M up to 0.4 [8]. The influence of local initiation of turbulence over the model with imperfections or roughness leads to a requirement of high quality model production [8].

Sources of turbulence in the wind tunnels

Requirements of basic characteristics of the WT tests, Mrkalj [9], together with WT type selection, Zotovic [10], in first defines the model, test section size and required flow characteristics, while all parts have the goal to support and prepare flow and measurement accuracy. Successful WT construction is a product of many compromises meeting acceptable costs.

For overcoming of the aerodynamic problems caused by free stream turbulence, of the major importance is the quality of WT design and details of calculations [11], in addition with numerical simulations nowadays, which have to give the optimal dimensions and power supply that will produce the best flow quality and energy efficient facility. Afterwards, scaled the pilot WT building and testing are following, and finally building of the WT with special care and skills.

It may be resumed that main parts, that produce free stream turbulence are all the parts at which the pressure difference or sudden cross-section changes occur. Sisojev [2, 12] and Zotovic recommended the original calculation methods and applied it on the VTI wind tunnels. Major sources of turbulence in subsonic tunnels are: collector, settling chamber, propeller, corners and other devices.

At supersonic wind tunnels the turbulence intensity TI is decreased at the beginning, because of downstream chocking, but with the increase of Mach number, for high Reynolds numbers, turbulence intensity TI returns the path of increase [1]. Inside intermittent wind tunnels [1], the diffuser is producing intermittent flow separation, and further on transport complex flow along the tunnel. Therefore, construction of the transonic WT [1] has to be made with attention to sonic choke device design, screens, honeycomb, corners and acoustic baffles, *etc*. The boundary layer transition and separation, as other flow phenomenon in the vicinity of a mode, are in major induced by noise. Pope [13] summarized that in transonic regimes WT produces a very high level of turbulence mainly because of the influence of reflected shock waves from the walls, diffusion pulsations shocks inside the pressure regulator of the intermittent wind tunnels.

Devices that intentionally create turbulence are used in testing with some of the purposes: aerodynamic characteristics of model under different free turbulence, testing of a model with fixed roughness for comparison of results, testing of a motorized model, ground effect testing, *etc.*

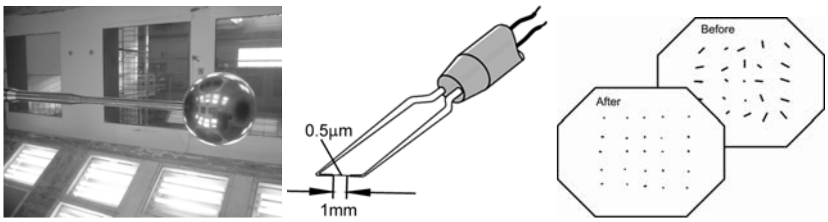
Turbulence measurements

Measurement techniques are selected according to the test velocity mainly. The imperative is to know the characteristics of the WT flow quality and the effects on measuring errors [1, 9, 10].

Measurements of TI at low speeds are made by sphere models (force and pressure type) [14], fig. 1(a), while with a velocity increase (over $M = 0.4$) the dominancy is taken by a cone model, hot-wire/hot-film, fig. 1(b), and optical non-destructive techniques. For the aim of validation, for different velocity ranges, tests in different techniques are overlapped. Hot-wire anemometer or direct measurement transducers are disturbing the flow and measures collected high frequency fluctuations of velocity, temperature, and static pressure (noise). Devices that do not disturb the flow, with or without introducing particles are: Laser Doppler anemometry (LDA) (supersonic), Particle image velocimetry (PIV) (subsonic/supersonic). Especial contribution to revealing and understanding of turbulence phenomenon, both; large- and small-scale gives flow visualization, example: large-scale turbulence by mesh, fig. 1(c).

Some turbulence reduction measures

Selection of type [10] and characteristics of future WT [9] and implementation of a detailed WT design calculation for specific needs are major pre-building turbulence reduction measures as well as development of a pilot wind tunnel. However, as possibly large test section is favorable, also the optimal elongated design for cones, radial corners, composition of the settling chamber items. Turbulence reduction measures might elongate the gross dimensions of a WT so necessary field area, much more constructional materials and building time or power are needed. Again, costs led to compromises between construction and flow quality. For instance, screens of meshes may multiply in several different design stages of reduce turbulence gradually while producing decreased gross power loss in comparison to single screen of dense strings, or the plates have replaced the screens since a quite similar effect [5]. The wall perforation has double task – to prevent shock reflection and wall boundary layer suction. After building, turbulence reduction measures may be an addition, after existing settling chamber, if such an assessment reduces turbulence yet unaffordable.



(a) (b) (c)

Figure 1. Small-scale turbulence measuring devices (a) sphere model in VTI T-35 WT (b) hot-wire and (c) sketch of a screen with tufts in the test section
(for color image see journal website)

The walls, model support and model finishing treatment and cleanliness of the WT tube in operation are also imperatives, both for preventing turbulence and for the test safety. The overall WT walls should have aerodynamically smooth surfaces, connections without significant convex details, covered concave or gap details, repaired small imperfections of tube surfaces, in one – all details and configuration/measuring support devices (pressure tubes, model part carriers and positioners etc.) that are not purposed for measurement should be immersed into wall/support/model contours.

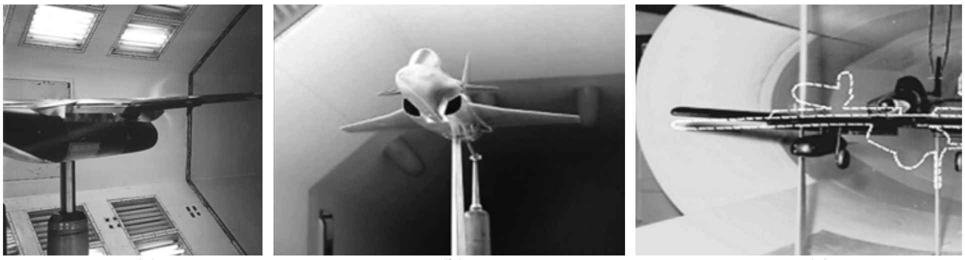
Unfortunately, the ones made an unrecoverable construction mistake, causing unacceptable TI, cannot be repaired just moderate to a lower level or even leads to re-building. In cases that specific required turbulence level is not reachable in a facility, it is sometimes better even to change the facility.

Calibration and correction of the WT results

The WT measuring equipment (fig. 1) required for turbulence measurements is of the highest level of accuracy, WT calibration tests are wide and times consuming, furthermore, some of the effects are still a subject of research. All this leads to increased costs. In the practice, each WT has to be calibrated before putting into operation, as well after constructional changes. Test section calibration is presenting the flow field quality, characteristics, and parameters of flow along the test section over cross sections and providing the flow correction factors for the aerodynamic measurements. The basic WT calibration data are as follows: distribution and fluctuations of static, stagnation pressure and temperature; magnitude, distribution, fluctuation and direction of flow velocity and turbulence and noise, by means of intensity, length and time scale, at different positions over the cross section of a test section. Comparison of the available standard models [13, 16] from different institutions leads to verification and measures for adjustments and final validation of model aerodynamic characteristics are obtained in flight test.

Corrections due to turbulence are incorporated in two segments of the test. Measurements of flow parameters, in operating range, are corrected with data of all calibrated influences for the empty test section, as are angularity, turbulent intensity, *etc*. [17]. A test is usually compounded of a number of separated tares with the goal of subtraction of a number of influences, for example of support system, with/without model propellers running, fig. 2(a) [18], open/closed inlet model, fig. 2(b) [19], *etc.* Tests may be run in schemes with involved mirrored configurations, fig. 2(c), use of the magnetic levitation, vertical free flight and similar, for mitigation of secondary effects.

Application of various test and correction techniques provide in high reliability of the WT results for a number of verifications, especially for theoretical calculations and numerical simulations because the flow quality at the research wind tunnels provides excellent flow quality. Furthermore, the WT are used as a secondary calibration standard, for example, testing of: a flow cell [20], an anemometer [21], a Pitot tube, *etc*.



(a) (b) (c)

Figure 2. Examples of model configurations and support systems

A good estimation of aerodynamic coefficients and stability and control derivatives are of fundamental importance in the design and development process of an aircraft. Stability derivatives have a strong influence on aircraft and missile response to maneuver conditions. Generally, these coefficients and derivatives are obtained using theoretical methods and WT testing. Turbulence causes variations, of random nature, in the angle of attack (α), in the airspeed (V), and in all other variables of the dynamic model [22-25].

Experimental Aerodynamics Laboratory in the VTI

The Military Technical Institute (VTI) in Žarkovo is the largest national institution dedicated to the scientific and technical research. Since the establishment in 1946. it is continually developing. The Aeronautical Department employs state-of-the art installations for designing and testing of the aeronautical and non-aeronautical models and devices [24]. Four divisions provide a task of scientific and technical support to the industry and the organizations on a national and international level: Aircraft Design, Avionics, Experimental Aerodynamics Laboratories and Structure Testing.

Significant clients of the VTI are: the Military of the Republic of Serbia, LAGG, IPTN, UTVA, Serbian Railways, and Central Hydrodynamic Institute CAGI in Moscow, *etc*. Wind tunnels are equipped with modern instrumentation, making possible various WT tests and measurements of static and dynamic model characteristics. Workshop facilities are equipped with CAD/CAM systems and CNC lathe and milling machines. VTI can also provide the complete design and building of wind tunnels, WT systems, and instrumentation for various types of tests.

The growth of VTI as a design center in the field of experimental aerodynamics was backed up by the development of WT facilities. The first WT was built in 1952. and the latest one was the T-38 Trisonic WT in 1986. The VTI facilities were used to support Galeb G-2, Jastreb, Kraguj, Orao, Super Galeb G-4, Lasta and Super Galeb G-4M aircraft programs.

Wind tunnel facilities of the VTI

T-32 WT. Small low-speed wind tunnel is the oldest WT in use. It has a closed-circuit with semi-open, elliptic, test section (1.8 m × 1.2 m, length 2.0 m). Driven by a DC motor of 91 kW, with manual control and continuous regime, it is running up to speeds of 72 m/s, while unit length Reynolds number is up to 5 million/m. The main equipment consists of external six-component balance, pressure and temperature transducers for flow and pressure distribution measurements, smoke generator. Data acquisition and data reduction system are available.

T-33 water tunnel. It is continuous close circuit tunnel, driven by DC motor of 91 kW and controlled manually. Maximal water velocity is up to 11 m/s and unit length Reynolds number up to 10 million/m. Test section is octagonal, dimensions are 0.5 m × 0.35 m, length of 0.5 m. It is equipped with pressure transducers, thermometers, 2-D LDA system, TV system and other flow visualization devices.

T-35 WT. Large low-speed wind tunnel has a closed circuit of length 72 m and width 30.6 m, from the top, three changeable octagonal test sections of dimensions 4.4 m × 3.2 m, length 5.5 m, with a cross-section area of 11.93 m^2, forming a flow of excellent quality. Mach number range: from 0.1 to 0.6 with fan only and atmospheric conditions, 0.6 to 0.8 with fan and injector running simultaneously while pressurized up to 1.52 bar. The unit length Reynolds number is up to 2.3 million/m. In continuous regime the WT is driven only by a fan, and if the injectors are added as a power supply running time is bounded to 120 s at M = 0.8. Fan drive is consisted of four AC motors of maximum continuous power of 7.2 MW, propeller of 23 variable pitch blades, rotating at 400 RPM. Injector system is fed with pressure up to 20 bars, through 8 nozzles in the tube. It is equipped with: six-component external TEM balance, multi-component internal balances, Scanivalves for pressure distribution measurements, stability derivatives apparatuses for pitch/yaw/roll and translation measurements, air intake testing rig, *etc*. Data acquisition and reduction systems are supported all the tests.

T-36 WT. The small trisonic wind tunnel is of an indraft type with square test section, dimensions of 0.25 m × 0.25 m, length 0.6 m, with changeable walls - solid or fixed porosity perforated. It is driven by vacuum level of 0.1 bar. It is driven by vacuum tanks, MPR pumping unit and air dryer. Operational M is from 0.2 to 1.1, and over at 1.56, 1.86, 2.48, and 3.24. The maximal unit Reynolds number is up to 15 million/m. Single test run duration is up to 60 s. T-36 is equipped with: multi-component internal balances, side wall strain gauge balance, Scanivalves for pressure distribution measurements, Schlieren system, 2-D LDA system, data acquisition and reduction system, too.

T-38 WT. The large trisonic is the youngest (1986.), and the only one that was not designed and manufactured by national WT experts. The T-38 is of intermittent, blow-down tunnel type. Drive consists of two five-stage compressors, compressor drive of 3.8 MW AC motors, storage tanks of capacity 2600 m^3 and pressurization up to 20 bars. Operational range is from Mach number 0.2 to 4.0 (controlled by the flexible nozzle) while the unit Reynolds number is: up to 140 million/m when 3D test section is in use and up to 62 million/m at M = 1 with the 2-D test section. The stagnation pressure range is from 1.8 to 16 bars. Run time is from 6 s to over 50 s depending on the test conditions. The three test sections are available for different operational ranges as follows: a) subsonic/supersonic with closed, solid walls, dimensions of 1.5 m × 1.5 m square, length 4.5 m; b) transonic 3-D closed test section with variable porosity perforated walls, dimensions 1.5 m × 1.5 m square, length 4.5 m, and c) subsonic/ transonic 2-D closed test section with variable porosity perforated walls, dimensions of 1.5 m × 0.38 m, length 1 m. Flow quality/ regulation over Mach number is 0.5% and for stagnation pressure: 0.3%, while noise is treated by LEHRT requirements. Equipment is capable of 3-D and 2-D force and moment measurements, pressure distribution, model dynamic derivative measurements [22-24] and flow visualization, consisting of: multi-component internal balances, Scanivalves and electronically scanned integrated transducers for pressure distribution measurements, wake traverse system for accurate 2-D drag measurements, stability derivatives apparatuses for pitch/yaw and roll measurements, air intake testing rig. The high-speed system for data acquisition and data reduction is in use.

Equipment, methods, and some results of turbulence investigations in EAL

Hot-film anemometer

The hot film anemometer with constant temperature (CTA) is a modular type produced by TSI, consists of: linearized anemometer, model 1054B, monitor and power supply modules, model 1051, RMS (DC) voltmeter, model 1076, hot-film and hot-wire probes; model 1232 wedge hot-film, model 1238 wedge hot-film 450 sensor edge, probe supports and accessories and FFT Analyzer. It is used for turbulence measurements in all WT in VTI.

The intensity of the longitudinal turbulence (*Tu*) in the T-38 wind tunnel, in a 3D test section with flat walls, in the range of M from 0.2 to 0.8, is presented in fig. 3. [26].

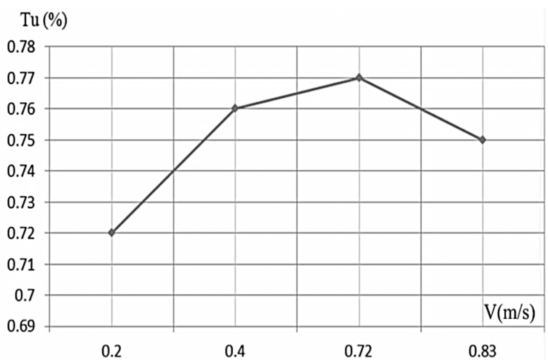
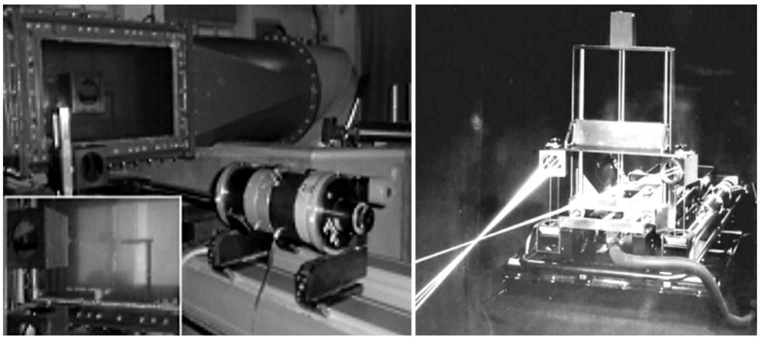


Figure 3. Longitudinal *Tu* in FN 3D test section in T-38 (1984)

LDA measurements of turbulence

Laser Doppler Anemometry (LDA) is an optical technique for measurements of velocity and turbulence in gas, liquid, and mixing fluids, flame, rotating machinery, in combustion, channels, chemically reacting flows, wave tanks, and wind or water tunnels. LDA systems are designed as compact or modular ones, with fiber optics or classical, for large distance and large area measurements or for micro applications [27-32]. The basic idea underlying LDA is to measure the velocity of tiny particles transported by the flow. If these particles are small enough, their velocity is assumed that of the stream and LDA provides a measure of the local instantaneous velocity, the mean velocity as well as the turbulent quantities.

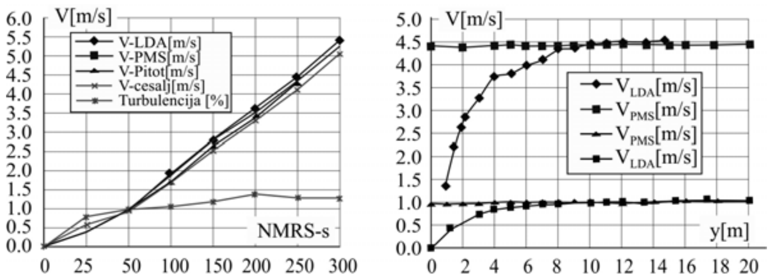
Three LDA systems are used in the VTI laboratories, the first is one component, the second is two components LDA (separation of two components of velocity is achieved by polarization of He-Ne laser light). It can be used in a velocity range up to 300 m/s, measuring point up 0.6 m from the front lens, fig. 4(a). The third system is 3D LDA, designed for VTI WT T-38 [33]. It is based on three colors of the Ar-Ion laser with 5 W power. The mirrors and prisms direct the beams leaving the transmitters to a common probe volume, fig. 4(b), at a suitable angle to resolve three simultaneous velocity components. This system is used for velocity measurement up to 750 m/s at distance up 2.7 m.



(a) (b)

Figure 4. (a) 2-D LDA in T-33 and (b) 3-D LDA for T-38

The LDA velocity and turbulence measurement in the T-33 water tunnel. The calibration of water tunnel was made by the 1-D LDA system and compared with data obtain from Primary Measuring System (PMS), Pitot tube and rake. The velocity and TI distribution along horizontal and vertical line, crossing in tunnel axis, was measured. Special attention is considered to measurements in the boundary layer. The results for two velocities 1 m/s and 4.5 m/s are represented in figs. 5(a) and 5(b) [34, 35], comparative calibration diagrams V (m/s) and Tu (%) as the functions of numbers of motor rotation per minutes, and boundary thickness measured by LDA in the water tunnel.



(a) (b)

Figure 5. Calibration of the water tunnel by LDA measurement around a hydrofoil
(for color image see journal website)

The velocity and turbulence distribution around the central profile has been measured by 2-D LDA. The results of measurements have been used as data for making the velocity vector diagrams shown in figs. 6a and 6b, together with diagrams of velocities and turbulence intensities. The hydrofoil angle was and $\alpha = 25°$, the free stream velocity $V_\infty = 5.32$ m/s. These results are used for definition of boundary conditions in CFD [34-36].

The LDA measurements in the T-38. The calibrating results of the T-38 trisonic WT test section with 3-D LDA system are shown in fig. 7. Application of LDA in calibration of

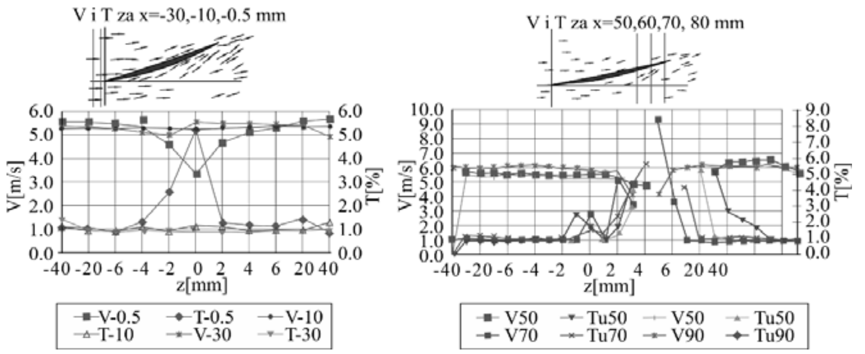


Figure 6. LDA velocity and turbulence measurements around hydrofoil in T-33, V_∞ =5.3 m/s, α=25° *(for color image see journal website)*

the large test section has some advantages, but has disadvantages (expensive running time of a large WT, a large measuring distance, decreasing light intensity with the 4th power of the distance, vibrations either of the wind tunnel, the tested model or the LDA system), too.

The operational application of the LDA instrumentation requires a fully automatic measuring run, which includes a computer controlled traversing mechanism with high speed and short time of data acquisition. To optimize that, the laser intensity as well as the aperture of the receiving optics has to be increased. However, laser with a large power are non-stable in Gaussian mode and optics with large apertures are very expensive. To avoid this disadvantage, achieve the necessary improvement in sensitivity, and reduce the amount of unwanted scattered light, the forward arrangement can be used. Very often off-axis setups are preferred as long as measuring distance is not too large [37, 38]

Calibration of T-38 WT test section with 3-D LDA system, velocity and turbulence data are presented in fig. 7. The dashed line is expecting value of the velocity and the plane line is measurement values.

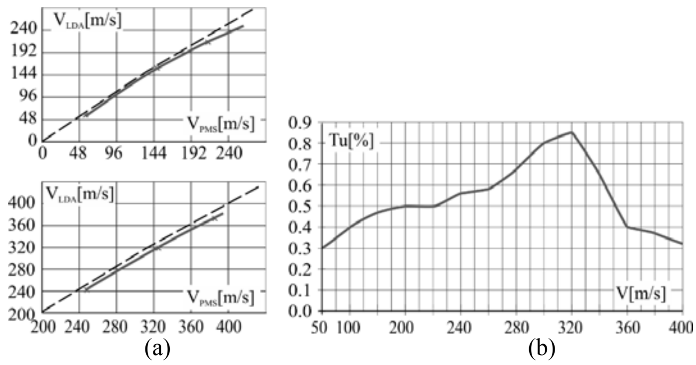
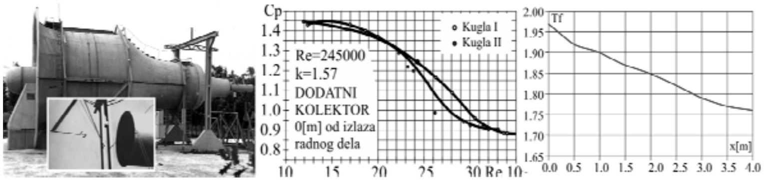


Figure 7. (a) Calibration of T-38 test section with 3-D LDA system, (b) longitudinal TI in T-38 WT determined by LDA measurements
(for color image see journal website)

Investigation of turbulence by pressure and force measurement

The turbulence factor, TF, for low speed wind tunnels, is a free flow correction parameter of Reynolds number, for obtaining an effective Reynolds number, and commonly spheres are used as standard test models. For the aim of validation of results, two types of spheres are used: a drag sphere and a pressure sphere. Models of standard dimensions, glossy finished [7, 14, 39, 40], made of wood, metal or plastic, are mounted in the test section, by sting support preferably. Glossy finish and accuracy of shape are oblique for turbulence influence measurements because roughness or shape deviations are causing unknown errors in readings and thus errors of turbulence factor. Drag sphere is subjected to force and moment measurements, with interest in drag component, while the pressure-sphere model is subjected to measurements of pressure coefficient, calculated from measured values of stagnation (by one front orifice) and average base pressure (by four centered orifices).

Turbulence factor in T-31 WT (1957). Blower from the 1951. year was the very first WT at the VTI (fig. 8) [39, 40]. Regardless, it was an open circuit wind tunnel; turbulence factor was estimated by two pressure spheres. Results of calibration tests are shown in figs. 8(b) and 8(c) for the cross section of the T-31 and 10 m downstream, and were TF = 1.57 and 1.9, respectively.



(a) (b) (c)

Figure 8. (a) T-31 WT, (b) Pressure coefficient *vs.* Reynolds number of the T-31 test section entrance, (c) turbulence factor along distance from the test section

Turbulence measurement in T-32. Turbulence measurements were made of a metal high polished pressure-sphere, diameter of 110 mm. The sphere was mounted on a one-leg support and positioned for one cross section in five places in order to centre line of a test section and similar over a three cross sections: at 550 mm, 460 mm from test section entrance and at the test section centre line. The estimated turbulence factor for the WT is TF = 1.14.

Turbulence measurement in T-35. Measurements of the drag and pressure coefficient for estimation of the turbulence factor of the T-35 test section were done by a metal glossy sphere. The sphere model was supported with a sting on model strut support system (fig. 9) [14]. Drag coefficient *vs.* the unit Reynolds number is plotted in fig. 9(b), from where the critical Reynolds number was found and used for obtaining the turbulence factor of the T-35 wind tunnel, TF = 1.03.

The turbulence factor, $TF = 385000/\text{Re}_{\text{critical}}$ represents the ratio of the critical Reynolds number of a sphere in free flight and a critical Reynolds number obtained for the wind tunnel. $\text{Re}_{\text{critical}}$ was agreed to be defined as Reynolds number under which drag coefficient of the sphere takes the value $C_d = 0.3$. An effective Reynolds number, $\text{Re}_{\text{effective}} = TF\cdot\text{Re}$, used in testing of different other models, is the corrected value that bridged the flow condition in the test section to free flight. TI could not be obtained by the sphere test and for its determination a hot-wire measurements have to be added. Force and hot-wire measurements are determining a function of TI with the critical Reynolds number for sphere. TI is increased while Reynolds number is decreased.

Optical methods for turbulent flow investigation

The three principal optical methods for turbulent flow investigations are: shadow, Schlieren, and interferometry. Optical methods are contactless and very sensitive to little cha-

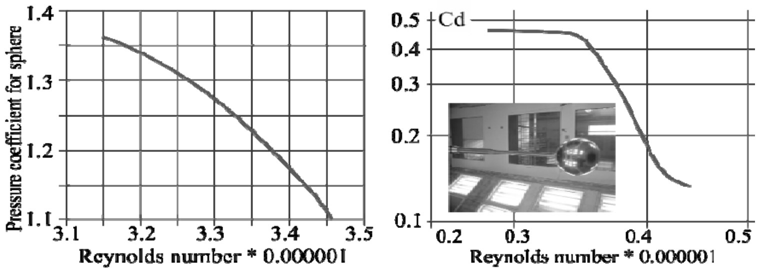


Figure 9. (a) *Cp* at T-32 test section, (b) C_d sphere in the T-35 test section *(for color image see journal website)*

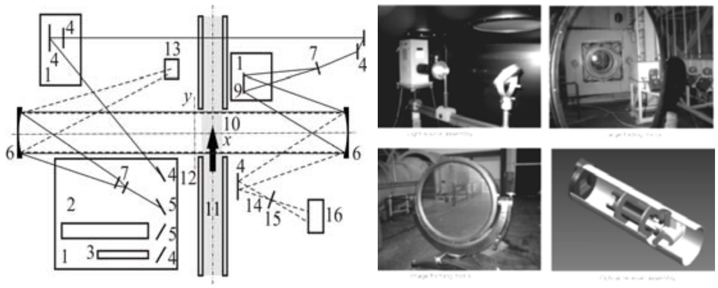
nges of flow properties. Optical methods make possible to visualize and determine aerodynamically flow parameters in total volume of the test section (density, pressure, flow velocity, M, show location of shock and expansion waves, nature and transformation of a boundary layer, an interaction of different effects in complex flow fields and so on) [41-44].

The base arrangement of all optical methods consists of a light beam which passes through such a set of windows and through the flow field. Each ray of the light beam is disturbed somehow depending on the inhomogeneous distribution of refractive index in the fluid. The simultaneously alterations occur: the ray can be deflected from its original direction and the phase of the disturbed ray can be shifted with respect to that of the undisturbed ray. The first phenomenon is related to shadow and Schlieren methods, and the second with interferometry. The shadow method visualizes only fields in which the second derivative of refractive index (density) is not uniform and is not zero. The Schlieren method visualizes the field with non-uniform light propagation direction, *i. e.* the field with constant density gradient. Interferometry is capable to visualize the changes in refractive index, *i. e.* the changes of density. This method makes possible to evaluate quantitative density measurements.

The possibilities of optical methods, for turbulent flow visualization, have been expanded within a wide range due to the innovation of the optical laser. Laser light is highly monochromatic and coherent with high-energy concentration. The laser light sources have successfully been able to conventional optical visualization systems, but they have led to the development of completely new methods, *e. g.* holography and holographic interferometry.

Optical devices

The WT in EAL have optical devices for flow visualization. (Holographic interferometer with parallel beams is at the same time a Schlieren and a shadow device. The schematic diagram of the experimental setup is shown in fig. 10. The ruby laser (Apollo model 22, E = 3 J, t = 30 ns, l_c = 1 m) (2) is used as a recording light source, while 6 mW He-Ne laser (3) is used for interferometer setting and reconstruction of holograms (9). The Hg lamp (13), small mirror (14), horizontal knife-edge (15) and still camera (16) are the different parts belong to Schlieren device with Z-shape. The large concave mirrors (D = 300mm, F = 2750 mm) (6) are for both systems. The shadow effects are recorded without second large mirror (6). Instead of it, there is the still or video camera. Laser and Hg lamp are both used as light sources for shadow technique. Some mirrors, beam splitters and lenses are used for laser beams directed, enlarged, collimated and focusing (4, 5, 7). The lasers, and all other mechanical and optical components, are fixed on the adjusting platform (1) with height equal to the height of the WT axis (11). It passes next to knife-edge, causing a bright patch at screen (16).



(a) (b)

Figure 10. (a) Scheme of optical device, (b) elements of Schlieren system in T-38 *(for color image see journal website)*

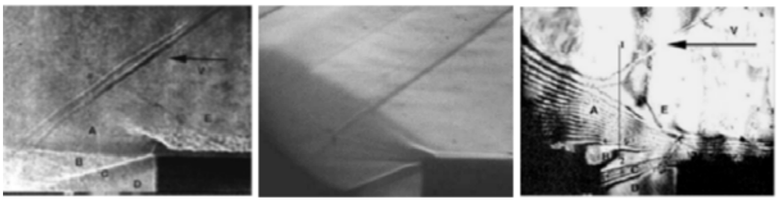
The intensity of it may be used to determine the magnitude of the refractive index or density gradient, which produced the light deflection.

The main holographic interferometer performances are: detection range of refractive index is 10^{-7} to 10^{-4}, accuracy of refractive index measurement is 10^{-7} and optical field diameter is Φ = 900 mm.

Visualization of turbulent flow

Optical methods

The following photos show visualization images of local turbulent flows, with different optical methods [41, 42, 45-47]. Figure 11 shows a visualization of supersonic flow around 2-D, 90° edge nozzle, Prandtl-Meyer expansion fan at the sharp end of the nozzle at M_∞ = 1.56: a) shadow, b) Schlieren, and c) holographic interferogram. The turbulent boundary layer and turbulent area in expansion fan are more visible in shadogram and on interferogram than in the Schlieren image.



(a) (b) (c)

Figure 11. Visualization of Prandtl-Meyer expansion fan *(for color image see journal website)*

Very interesting example of flow visualization is made in the vicinity of tunnel wall perforations. Many transonic tunnels are operated with performed walls in the test section. A number of investigations have been performed to determine how the flow in the test section is affected by the presence of the perforation.

The figs. 12(a)-12(c) report on test performed in T-36, with a single slanted slot in the bottom plate of the test section, for M_∞ = 0.83. Flow direction is from right to left. The slanted slot was used because it had been reported that such geometry would considerably reduce the perturbation of free flow. The disturbances originating from the slot are expressed by distortions of the parallel fringe system. A concentration of fringes indicated the formation of a pressure wave. The interferogram however, shows that the disturbance from the slot is not at all negligible and reaches even beyond the axis of the test section (to about 60% of the test section height).

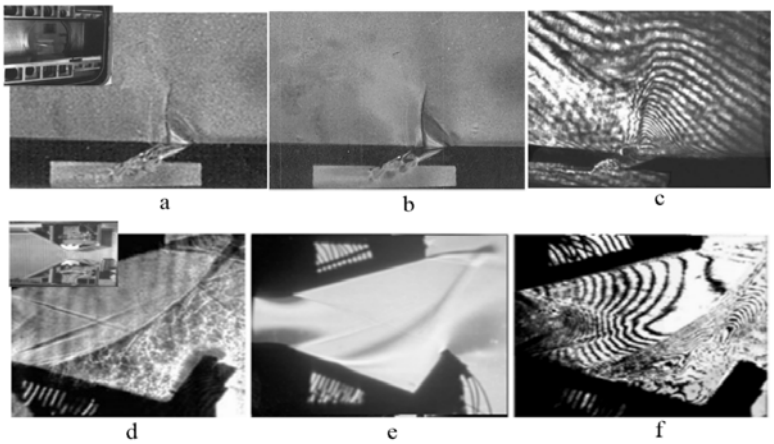


Figure 12. (a-c) The flow in the WT test section with wall perforation (slanted slot), (d-f) Two dimensional model of rocket nozzle with barrier in T-36
(for color image see journal website)

The prediction of the flow separation in supersonic nozzle is important for designing an efficient nozzle–deflector configuration. Test of the complex flow in the two-dimensional supersonic nozzle with the deflector by three optical methods, performed in T-36 WT, shows again the significant advantages of these ones in comparison with classical methods.

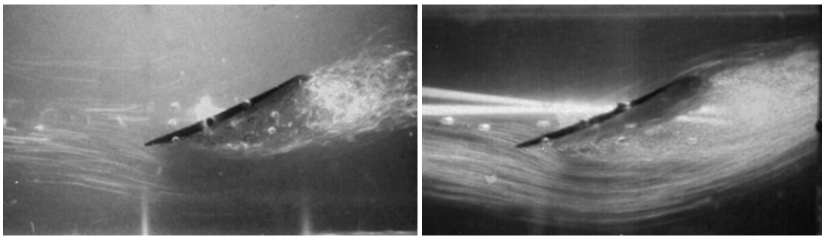
The method of holographic interferometry has special advantages when complex, turbulent flows are tested, *e. g.*, flows around a deflector, in the vicinity of the shock wave. Visualization indicates strong interaction of the turbulent boundary layer with the oblique shock wave in the divergent part of the nozzle, figs. 12(d)-12(f). The area behind shock wave is turbulent. The flow visualization results have served as a base for validation of numerical methods and results. The theoretical and experimental values of Mach number in the expansion area are in good agreement $M_{exp} = 2.15$, $M_{the} = 2.13$.

Non optical methods for turbulent flow investigation

The investigation of the turbulent flow through 2-D straight profile grid (with three profiles), the test carried out in the VTI water tunnel (T-33), include measurements and visualization [45, 47]. The flow visualization was performed using air bubbles. They were injected into the flow at the distance of about 1 m in front of the model, with special device. Figure 13 shows the flow field visualized by different quantity of air bubbles, around the hydrofoil with angle $\alpha = 25°$. Velocity of free stream was $V_\infty = 5.32$ m/s [36].

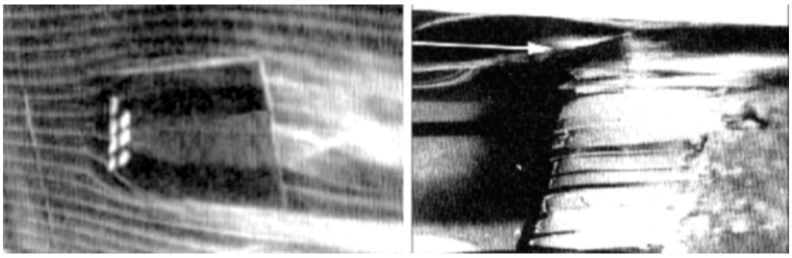
Recent developments indicate that smoke visualization in wind tunnels, one of the oldest flow visualization techniques, will continue as an important experimental tool in the study of complex turbulent flow dynamic phenomena.

Improvements in generation and injection of smoke as well as in lighting (laser as a light source), in image processing (the use of computers) have continued to increase the scientific value of this method. Figure 14(a) shows the smoke line in the small smoke tunnel, generated by the vaporization of paraffin; fig. 14(b) shows the flow around an airplane model visualized by $TiCl_4$ drops in T-32 WT.



(a) (b)

Figure 13. Turbulent flow around hydrofoil visualization in T-33
(*for color image see journal website*)



(a) (b)

Figure 14. Smoke visualization, (a) in a small smoke tunnel, (b) in WT T32

The oil film or dots on the model surface enables to obtain, quickly and easily, a picture of flow pattern on the surface of the model placed in a WT [41]. The especially mixture is prepared of an appropriate oil and a fine pigment (Al_2O_3; TiO_2, powder, fluorescent dye, coloring pigments, graphite). The technique allows observation of the laminar and turbulent lines, or separation and reattachment regions if the flow field at the body surface. Figure 15 shows the visualization with TiO_2 and oil on the surface around three, vertical cylinders fixed on the plate in T-35 for V = 50 m/s, positioned at different angles of attack.

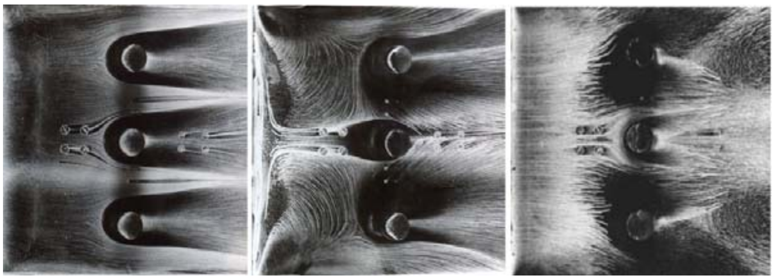


Figure 15. Flow visualization around cylinders fixed on the plate in WT T-35

Results of turbulent flow – numerical simulations validated by measurements

Sphere model in T-35. For the purpose of validation of the applied methodology of numerical simulations of turbulent flow around the sphere model, numerical simulations were done for the rough model of sphere exposed to turbulent free flow. Validation was made by comparison with tests of sphere model prepared for visualization, in the T-35 WT [14]. During flow visualization the emulsion was dried, photographed and the measurements of drag were completed. In the numerical simulations, conditions of the model were assumed while flow conditions from calibration were used and extended. In fig. 16 a sample for comparison of WT visualization with TiO_2 emulsion and flow around a rough sphere from numerical simulations is shown.

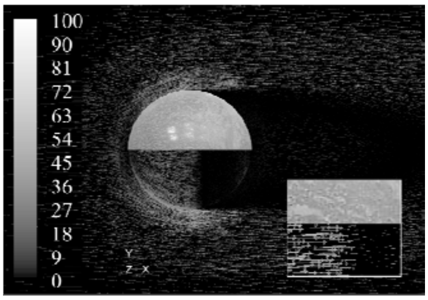


Figure 16. T-35 WT: rough sphere visualization *vs.* CFD
(for color image see journal website)

The 2-D supersonic nozzle. 2-D numerical simulations by solving the Reynolds-Averaged Navier-Stokes equations with standard two-equation turbulence model was used for design of 2-D thrust vectoring nozzles. Three different meshes were used, a coarse mesh (25976 cells), an intermediate mesh (48084 cells) and a fine one (95732 cells). The meshes are structured except in the divergent part of the nozzle, where structured part is next to the wall, otherwise the mesh is unstructured. After making the numerical models of nozzles with different deflectors at the exit, the comparisons of the calculation and experiment were made. The differences of the experimental and numerical visualization occur due to two reasons. The first is the strong interaction of the shock wave and separated boundary layer, and second the flow in the 2-D thrust vectoring nozzle is essentially three-dimensional [45].

The numerical visualization, using Mach number, pressure contours and velocity vectors for two dimensional, supersonic nozzle with deflector can be seen in figs. 17(a)-17(c), deflector has $\alpha_d = 100°$ and $h_d = 43$ mm. The visualization by optical methods of this nozzle is presented in figs. 12(d)-12(f).

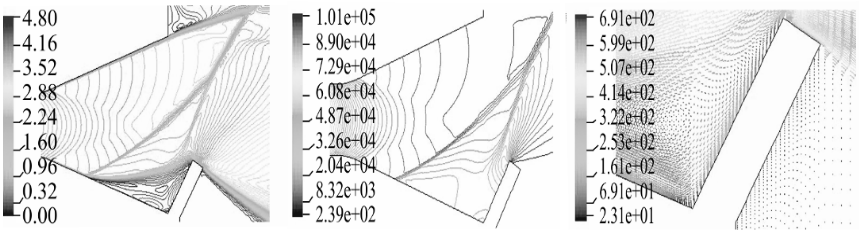
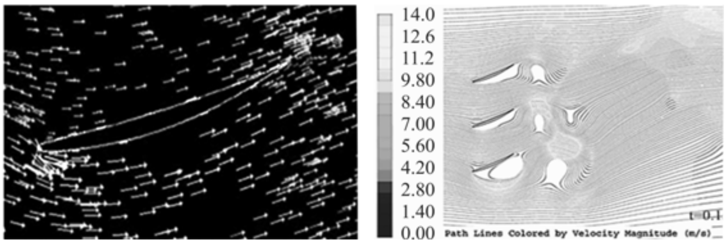


Figure 17. Numerical flow visualization, and contours of (a) iso-Mach number (kg/m^3), (b) iso-pressure, (c) velocity vectors
(*for color image see journal website*)

T-33 water tunnel. Numerical simulation of the flow through straight profile grid is made in Fluent 6.1 program. The results of flow simulation are compared with experimental results. Geometry is modeled (Unigraphics 18.0 program) for grid profile angles of slope, corresponding to the angles in the experiment: 0° and 25° [46]. The boundary conditions are corresponding entirely to the state in water cavitation tunnel during the experiment. For the definition of the boundary conditions, it was very useful the fact that the turbulence level in the area in front of the hydrofoil grid was measured during the experiment.

Number of elements in the generated computational grids varies in the range from 285000 to 386000. The k-ε standard model for turbulent stresses is used for 0°angle of slope, and k-ε realizable model for 25°. Converged solutions for integral quantities of interest were obtained after 550 iterations for 0° angle of attack and mass residuals 10^{-5}. For 25° angle mass residuals are 10^{-4}, and 20 iterations are used for each temporal sequence. The enhanced wall functions are used for turbulent boundary layer. The velocity vectors and path lines around hydrofoil are shown in fig. 18.

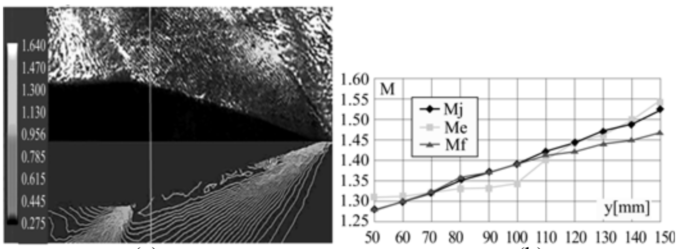


(a) (b)

Figure 18. (a) Velocity vectors for hydrofoil (b) path lines
(*for color image see journal website*)

Cone in supersonic flow at T-38. The experiment was performed with M_∞ = 1.5, 1.7, and 2.0. The calibration model was cone-cylinder, θ_c = 15°, l = 300 mm base Φ = 160 mm, l_c =160 mm. The images of holographic interferograms are the bases for determination of Mach number M_∞ in free stream flow. The maximum difference in the Mach number determination by Primary measuring system and by holography is 5.3% and average 2.4% [47, 48]. Experimentally, the density of flow behind the shock wave is determined with an accuracy of 2.4% in regard to theoretical, and 3.6% in regard to numerical one.

Numerical simulation of flow was performed by ANSYS FLUENT software. Figure 19(a) shows the composite experimental and numerical image of flow iso-density lines around model cone-cylinder for M_∞ = 1.474. Figure 19(b) shows Mach number Θ_u for nominal M_∞ = 1.5. The measured angle of the shock wave from holographic interferograms is between 44.5° and 48.5° that gives M_∞ from 1.4 to 1.49. The average value of $\Theta_{u\ tab}$ = 46.5°.



(a) (b)

Figure 19. The experimental and numerical results in T-3
(*for color image see journal web-site*)

Conclusions

One of the most complicated areas under discussion in many areas of science and engineering is turbulence. Many authors study the unwanted effects of turbulence on the results of WT tests over the world.

The main aim of this paper is to present the EAL of the VTI in Belgrade, the equipment and methods of turbulence investigations in the WT test section stream and around different test models. The role of turbulence in obtaining a spatially and temporary uniform steady stream of air across and along the test section of wind tunnels is considered. The turbulence has a major importance in flow quality of WT and can excite uncorrected results in experimental investigations in WTs. Turbulence causes a variation of pressure, Mach number, density and temperature distribution, the variation of pitch and yaw components of flow angularity, boundary layer change near the walls, noise and the behaviors of vortexes in the test section. The most important sources of turbulence in WT are analyzed, as well as some turbulence reduction measures.

WT in VTI have turbulence intensity below recommendations by international standard for WT good flow quality. The modern instrumentation in VTI, enables determine flow quality and its influence on measurement results of aerodynamic and dynamic stability model characteristics. In this paper, some test results, involving turbulence, performed in VTI WTs are illustrated with diagrams and images.

The VTI WTs were used for testing models for the Ministry of Defence, to support development of aircraft programs: Galeb G-2, Jastreb, Kraguj, Orao, Super Galeb G-4, Lasta and Super Galeb G-4M and missile models: ATM Osa, ATM Zolja, ATM Bumbar, SSM Oganj, SSM Orkan, ASM Grom, marine models of ships and weapons, non-aeronautical models and a number of models for foreign customers.

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Nomenclature

Tu – turbulence intensity, [%]
M – Mach number (= v/a), [–]
Re – Reynolds number (= $\rho vc/\mu$), [–]
V_∞ – velocity, [m/s]
TF – turbulence factor, [–]
D – diameter, [m]
$\mathrm{Re}_{\mathrm{critical}}$ – critical Reynolds num. (= $\rho vc/\mu$), [–]
$\mathrm{Re}_{\mathrm{effective}}$ – effective Reynolds num. (= $\rho vc/\mu$), [–]
C_d – drag coefficient, [–]
Φ – optical field diameter, [m]
t – time, [s]
x – spatial coordinate, [m]
y – spatial coordinate, [m]
E – total energy, [J]

Greek symbols

α – angle of attack, [°]
$\alpha_{\mathrm{deflector}}$ – deflector angle, [°]
Θ_u – angle of the shock wave, [°]

References

[1] Harvey, W. D., *et al.*, An Evaluation and Assessment of Flow Quality in Selected NASA Wind Tunnels, *NASA Technical Memorandum* 85659, USA, 1983
[2] Sisojev, V., Estimation of Losses for the Wind Tunnels (in Serbian), VS-125, VTI, Belgrade, Serbia, 1956
[3] Owen, F. K., *et al.*, An Evaluation of Factors Affecting the Flow Quality in Wind Tunnels, *In AGARD Wind Tunnels and Testing Tech. 22 p*, NASA Langley Research Center; Hampton, Va., USA, 1984
[4] Steinle, F., Stanewsky, E., Wind Tunnel Flow Quality and Data Accuracy Requirements, Advisory report No. 184, AGARD, ISBN 92-835-1440-8, London, 1982
[5] Loehrke, R. I., Nagib, H. M., Experiments on Management of Free-Stream Turbulence, Report No. 598, AGARD, London, 1972
[6] Chang, P. K., *Control of Flow Separation*, Hemisphere, Washington D. C., 1976
[7] Schlichting, H., *Boundary-Layer Theory,* 7th ed., McGraw-Hill, New York, USA, 1979
[8] Achenbach, E., The Effects of Surface Roughness and Tunnel Blockage on the Flow Past Spheres, *Journal of Fluid Mechanics*, *65* (1974), 1, pp 113-125

[9] Mrkalj, N., About Selection of Basic Characteristics of a Wind Tunnel T-35 (in Serbian), VS-116, VTI, Belgrade, 1955
[10] Zotović, S., Selection of Low-Speed Wind Tunnel Type (in Serbian), VS-002. VTI, Belgrade, 1951
[11] Šumonja, S., EA Training: A Low-Speed Wind Tunnel Theory and Design, VTI, Belgrade, 1997
[12] Sisojev, V., *Proračun kolektora* (*Calculation of Collectors* – in Serbian), University of Belgrade, Belgrade, 1948
[13] Pope, A., Wind Tunnel Calibration Techniques, AGARDograph 54, AGARD, London, 1964
[14] Linić, S., *et al*., Experimental and Numerical Study of Super-Critical Flow Around the Rough Sphere, *Scientific Technical Review*, *65* (2015), 2, pp.11-19
[15] Reed, T. D., *et al*., Calibration of Transonic and Supersonic Wind Tunnels, NASA Contractor Report 2920, NASA, 1977
[16] Ocokoljić, G., *et al*., Testing of a Standard Model in the VTI's Large-subsonic Wind-tunnel Facility to Establish Users' Confidence, *FME Transactions*, *42* (2014), 3, pp. 212-218
[17] Šumonja, S., EA Training: Low Speed Wind Tunnel Testing, VTI, Belgrade, 1997
[18] Šumonja, S., Testing of a Motorized Model in Subsonic Wind Tunnel (in Serbian), *Scientific Technical Review*, *48* (1998), 5, pp. 50-63
[19] Mrkalj, N., Šumonja, S., Testing of the Model with Inlet at the Wind Tunnel T-32 (in Serbian), *Scientific Technical Review, 46* (1996), 4-5, pp. 51-59
[20] Mrkalj, N. Šumonja, S., Flow Rate Measurement on the Aircraft Compressor Inlet (in Serbian), *Scientific Technical Review, 49* (1999), 5, pp. 63-68
[21] Ćurčin, M., Šumonja, S., Determination of Balance Rotating Frequency of the Anemometer Turbine Rotor (in Serbian), *Scientific Technical Review, 45* (1995), 4-5, pp. 3-8
[22] Samardžić, M., *et al*., The Sting Plunging Effect on Measured Pitch Damping Derivative, *Proceedings*, 4th International Scientific Conf., OTEH 2011, VTI, Belgrade, Serbia, 2011
[23] Ćurčić, D., *et al*., Model Sting Support with Hard Metal Core for Measurement in the Blowdown Pressurized Wind Tunnel, *Measurement, 79* (2016), Feb., pp. 130-136
[24] Samardžić, M., *et al*., Effects of the Sting Oscillation on the Measurements of Dynamic Stability Derivatives, *Scientific Technical Review, 60* (2010), 2, pp. 22-26
[25] Anastasijevic, Z., Ristic, S., Presentation of Test Capabilities of the Experimental Aerodynamic Laboratories (in Serbian), *Tehnika, Mašinstvo, 55* (2006), pp. 15-24
[26] Vitić, A., Estimation of the Free Flow Turbulence Intensity at Wind Tunnel T-35, in a Velocity Range from 0.2<M<0.8 in a FN3D Test Section by Hot-Film Probes and Constant Temperature Anemometer (CTA) (in Serbian), V3-2385-I-EA, VTI, Belgrade, 1986
[27] Ristić, S., Laser Doppler Anemometry and its Application in Wind Tunnel Tests, *Scientific Technical Review, 57* (2007), 3-4, pp. 64-76
[28] Ristić, S., *et al*., Laser Doppler Anemometry Application in Hydrodynamic Testing, *Atti dela Fondazione Giorgio Ronchi, 62* (2007), pp. 207-218
[29] Ristić, S., Ilić, J., Laser Doppler Anemometry Measurements Inside the Pipes of Various Shapes and Glass Quality, *Scientific Technical Review, 49* (1999), 5, pp. 22-29
[30] Ilić, J. T., *et al*., The Comparison of Air Flow LDA Measurement in Simple and Cylindrical Tube with Flat External Wall, *FME Transactions, 41,* (2013), 4, pp. 333-341
[31] Watrasiewich, B. M., *Laser Doppler Measurement,* Butterworths, London, 1976
[32] Hunter, W. W., Flow Visualization and Laser Velocimetry for wind tunnel, NASA CP 2243, *Proceedings*, Hampton, Va., 1982
[33] Ristić, S., Analysis of the Accuracy of the Third Component of Flow Velocity Measurements for a 3-component, 3-colour Laser Doppler Anemometer., *Proceedings*, Inter. Conference on Laser 97*,* New Orleans, La., 1997, pp. 562-569
[34] Ristić, S., Majstorović, P., Experimental Testing of the Relative Flow Through the Straight Profiled Screen (in Serbian), *Scientific Technical Review, 50*, (2000), 6, pp. 29-36
[35] Ristić, S., *et al*., Experimental and Numerical Determination of the Sr Hydrofoil in Steady and Transient Flow, *Proceedings*, HIPNEF 2006, Vrnjačka Banja, Serbia, 2006, pp. 541-548
[36] Ristic, S., *et al*., Determination of Air and Hydrofoil Cp by Laser Doppler Anemometry, *Theoret. Appl. Mech., 37* (2010), 1, pp. 17-35
[37] Srećković, M., *et al*., The Analysis of Characteristic Materials for Fluid Seeding Particles in Wind Tun-

nels and Their Influence on the LDA System Functions, *Balkan Physics Letters, 7*, (1999), 2, pp. 93-102
[38] Ristić, S., Laser Doppler Anemometry and its Application in Wind Tunnel Tests, *Scientific Technical Review, 57* (2007), 3-4, pp. 64-76
[39] Jovanović, B., *et al*., Factor of Turbulence for the T-31 (in Serbian), V3-138, VTI, Belgrade, 1957, pp. 1-39
[40] Vujić, V., *et al.*, Research of the Turbulence Measurement Methods (in Serbian), V3-796, VTI, Belgrade, 1968, pp. 1-15
[41] Ristić, S., Flow Visualization Techniques in Wind Tunnels, Part I-Non optical Methods, *Scientific Technical Review, 57* (2007), 1, pp. 39-50
[42] Ristić, S., Flow Visualization Techniques in Wind Tunnels, Part II-Optical Methods, *Scientific Technical Review, 57* (2007), 2, pp. 48-49.
[43] Marzkirich, W., *Flow Visualization*, Academic Press, New York, USA, 1977
[44] Settles, G. S., Modern Developments in Flow Visualization, *AIAA Journal*, *24* (1986), 8, pp. 1313-1323
[45] Ristić, S., Capability of Two-Dimensional Reynolds-Averaged Navier-Stokes Simulations for Two--Dimensional Thrust Vectoring Nozzles, *Proceedings*, Institute of Mech. Part G: J. Aerospace Engineering G, 224, (2010) G8, pp. 905-910
[46] Puharić, M., *et al*., Laser Doppler Anemometry in Hydrodynamic Testing, *Journal of Russian Laser Research*, *28* (2007), 6, pp. 619-628
[47] Ristić, S., Investigation of Supersonic Flow in Wind Tunnel T-38 by a Method of Holographic Interferometry, *Scientific Technical Review*, *54* (2004), 2, pp. 3-10
[48] Ristić, S., *et al*., Presentation of the Facilities, Methods and Results of Turbulence Investigation in the VTI's Wind Tunnels, *Proceedings* (eds.: Dj. Čantrak, M. Lečić, A. Ćoćić), Book of Abstracts, Turbulence Workshop International Symposium, University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia, 2015, pp. 14

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