Effects of atmospheric turbulence on UAV

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Abstract: Nowadays the UAV (Unmanned Arial Vehicles) are investigated, developed in very large number. Because the size and relatively smaller operational velocities, the UAV, especially the small UAV , are more sensitive to air turbulences, and effects of winds then the small aircraft, generally. The lecture analyzes the effects of air turbulences and winds on the UAV performance. The goal of this work is the identification of the major effects required further investigations, solutions and/or regulations. The lecture has two main chapters. The first one defines the air turbulences and winds effecting on UAV. The second major chapter gives a review of the tools for aerodynamic researches into the influence of the atmospheric turbulence and coherent vortex structures on the UAV flight situations.

Keywords: UAV, atmospheric factors, air turbulence, flight dynamics

1. INTRODUCTION

The atmospheric turbulence has significant safety, economic and capacity impact on the air transport. According to the technical report (Aviation, 2004) of the OFCM (Federal Coordinator for Meteorological Services and Supporting Research), in US the weather causes the 75 % of accident related to the FAR (Federal Aviation regulation) Part 121. "Operating Requirements: Domestic, Flag, and Supplemental Operations" (Sharman, 2010). Fortunately, this data related to the accident statistics for period 2003 - 2207 had been reduced below 34 % (Weather-related, 2012). The cost of

The weather is second leading factor effecting on the US NAS (National Airspace System) (Sharman, 2010).

Nowadays the UAV (Unmanned Arial Vehicles) are investigated, developed in very large number. The civilian UAV may open a new business in aviation including the freight transport, recognition, surveillance, etc. *Because the size and relatively smaller operational velocities, the UAV, especially the small UAV are more sensitive to air turbulences, and effects of winds then the small aircraft, generally.*

The lecture analyzes the effects of air turbulences and winds on the UAV performance. The goal of this work is the identification of the major effects required further investigations and/or regulations.

The lecture has two main chapters. The first one defines the air turbulences and winds effecting on UAV as gust, air turbulence model, wind, wind-shear models, and complex model combining the wind, and air turbulence depending on the 3D environment as buildings, mountains, etc. It classifies the UAV into several groups depending on their size, goal of usage and operational environmental conditions. Finally it discusses the effect of the air turbulence and winds on the aerodynamics, flight performance, flight dynamics and control and size effects.

The second major chapter gives a review of the tools for aerodynamic researches into the influence of the atmospheric turbulence and coherent vortex structures on the UAV flight situations. In particular, such approaches and methodologies are considered with some examples of their applications: simplified methods (engineering, panel, discrete vortex), boundary-value problems of CFD (EULER, RANS), experimental facilities (wind tunnels with flow angularity/gust/vortices simulators and free flying models).

The paper is supported by Moscow Institute of Physics and Technology (MIPT) developing a special laboratory Aviation Factors of Risk dedicated for investigation of the Atmospheric hazards. The laboratory will working in close cooperation with TsAGI (Central Aerohydrodynamic Institute named after Prof. N.E. Zhukovsky (*TsAGI*)).

The Faculty of Aeromechanics and Flight Engineering leaded by professor Vyshinsky had a long period investigation on atmospheric hazards (Vyshinsky, 1996; 2001, Bobylev et al. 2010) and very active in developing and using the UAV (Ageev, 2011; Kolchev, Sviridenko and Vyshinsky, 2013), too. The MIPT is organizing a series of International Scientific Workshop "Extremal and Record Breaking Flights of the UAVs and the Aircraft with Electrical Power Plant"

The department of Aeronautics, Naval Architecture and Railway Vehicles at Budapest University of Technology has a large activities in investigation of the UAV/UAS including developing new theoretical models (Gati and Somos, 2008; Nagy et al., 2013) application of the well developed control systems (Gati and Drouin, 2013) developing a series of systems (D. Rohacs and Jankovics, 2010) and measurement technologies (Nagy and J. Rohacs, 2012; 2013) as well as developing and using of the simulation technologies (Nagy and Jankovics, 2012).

2. THE PROBLEMS IDENTIFIED

2.1. Atmospheric phenomena

The Aircraft fly in lower part of atmosphere. There are many atmospheric hazards are defined (Table 1.).

Table 1. NTBS (US National Transportation Safety Board) factors and weather categories (Stailey, 2008)

Restricted visibility and ceiling: • Below approach/landing mins • Clouds • Fog • Haze/smoke • Low ceiling • Obscuration • Whiteout *Precipitation (non-icing):* • Rain • Snow • Drizzle/mist *Icing conditions:* • Icing conditions • Ice fog • Freezing rain • Carburetor icing	*Turbulence and convection:* • Turbulence (thunderstorm) • Thunderstorm • Thunderstorm outflow • Microburst (dry) • Microburst (wet) • Updraft • Downdraft • Gusts • Wind shear • Dust Devil/Whirlwind • Variable wind • Sudden wind shift • Mountain Wave • Turbulence • Turbulence, clear air • Turbulence in clouds • Turbulence (terrain induced)	*Temperature and lift:* • Temperature inversion • High density altitude • Temperature, high • Temperature, low • Thermal lift • No thermal lift *En route and terminal winds:* • Unfavorable wind • Crosswind • Tail wind • High wind *Electrical:* • Lightning • Static discharge *Airborne solids:* • Sand/dust storm • Hail

There are many articles explain the listed weather phenomena. For example the Figure 2 taken from the well known book o Lester (1994) is widely used for showing the different air turbulence factors.

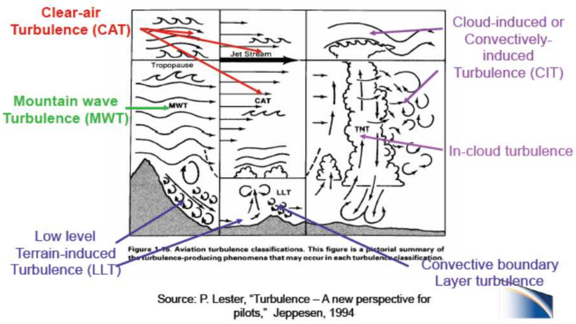

Figure 1. Explanation the different air turbulence phenomena (Sharman, 2010)

According to the US statistics, in case of commercial aircraft (FAA FAR part 121) accidents the leading weather factor is a turbulence ((Fig. 2.), while in weather related accidents of the general aviation (FAA FAR Part 91.) mostly is caused by wind (Fig. 3.).

The investigations in NTSB records has shown that, in lot of cases there are two or even more weather factor is listed between the causes resulted to accidents.

Another interesting feature: in generally (because the number of aircraft and therefore the number of accidents of aircraft of General aviation (Part 91) about 10 times greater) the wind plays role in nearly 52 % of accidents (Weather-related (2010). it must be underlined, the gusts are listed by NTSB to the wind effects.

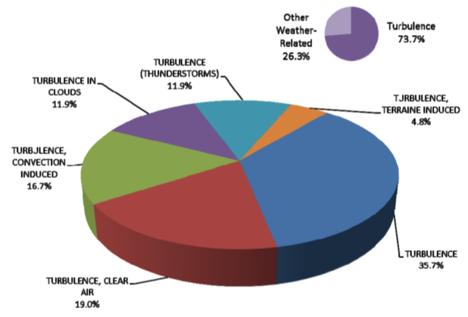

Figure 2. Breakdown of the Part 121 turbulence citations for period 2003 - 2007 (Source NTBS, used from Weather-related, 2010)

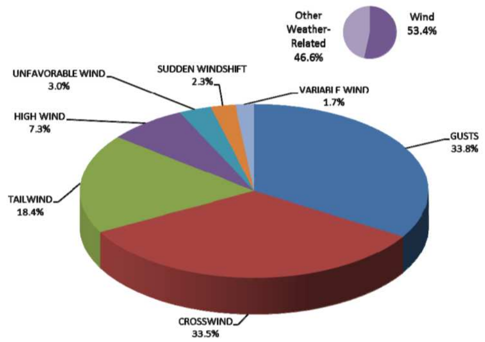

Figure 3. Breakdown of the Part 91 wind citations for period 2003 - 2007 (Source NTBS, used from Weather-related, 2010)

Unfortunately, there are not controlled statistics about the UAV/UAS, however, according to the press information about every second week there is a crash of military drones (Drone, 2014). The Figure 4. shows that the military UAV accident rate (according to the flight hours) about 5000 - 10 00 times is greater than the accident rate of general aviation.

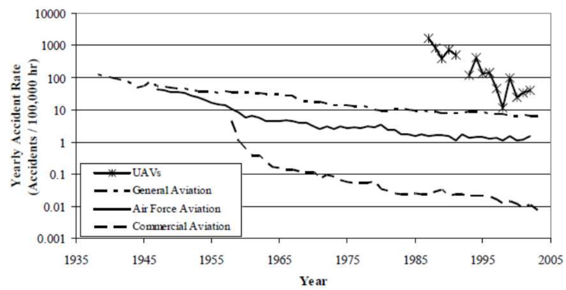

Figure 4. Comparison of the accident rate trends (Weibel and Hasman, 2005a)

On the other hand, it seems, the human factor is a most important factor in UAV accidents, too (Asim, Ehsam and Rafique, 2010), while the weather plays role in several per cent of UAV accidents, only. This unique fact can be explained by use of UAV in relatively good weather conditions and in well predefined situations. Another feature of this fact is that, the accidents are classified on their main causes and the weather effecting on the accident realization process appearing as common factor in accident causes are not listed.

2.2. UAV classification

The civilian UAVs are using in many different applications (Table 2.).

Table 2. Attractive civilian UAV application (Weibel and Hasman 2005a)

Remote Sensing	Surveillance	Delivery
• Pipeline Spotting	• Law Enforcement	• Firefighting
• Powerline Monitoring	• Traffic Monitoring	• Crop Dusting
• Volcanic Sampling	• Coastal/ Maritime Patrol	• Package Delivery
• Mapping	• Border Patrol	
• Meteorology		Entertainment
• Geology	Search and Rescue	• Cinematography
• Agriculture		• Advertising
	Transport	
Disaster Response	• Cargo Transport	Broadcast
• Chemical Sensing		• Television/ Radio
• Flood Monitoring	Comm Relay	
• Wildfire Management	• Internet	
	• Cellular Phone	

From safety point of view, these applications have a considerable influence on the UAV operation, but not deterministic. So, the UAVs must be classified depending on their mass (Figure 5.) and performance (Figure 6.).

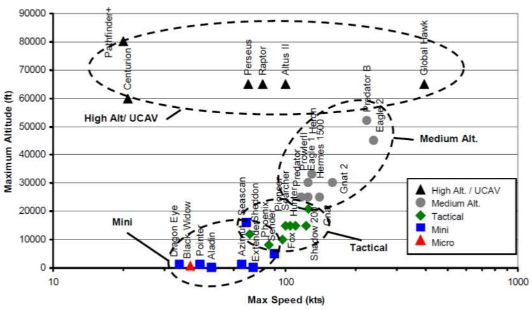

Figure 6. The classes of the UAV depending on their performances (Weibel and Hasman 2005a)

Following to the Weibel and Hasman (2005a; 2005b) recommendation, we had accepted the classification of UAV:

(i) micro - with TOM (take-off mass) less than 1 kg and flying at altitude up to 150 m,
(ii) mini - TOM between the 1 - 15 kg, and flying locally up to 3 km,
(iii) tactical - TOM = 15 - 450 kg, regionally used at flight levels from 500 up to 5500 m,
(iv) MALE (Medium Altitude Long Endurance) - TOM equals from 450 kg up to 15 t, flying regionally and nationally at flight levels from 5500 m (FL 180) up to FL 600,
(v) HALE (High Altitude Long Endurance) - the same as MALE, but flying internationally,
(vi) heavy - TOM is greater than 15 t and flying at FL 180 up to FL450.

Because the mass of UAVs is in a good correlation with size, this classification is acceptable for investigation of the atmospheric effects on the UAVs, too.

2.3 Models of atmospheric phenomena

Principally there are many models, simulation and design methods for calculating the effects of the atmospheric phenomena on the aircraft. For example the classic (stable) wind must be taking into account as vector summ of wind and aircraft velocity. It is a good technique even in case of study or controlling the effects of wind-shear on the aircraft dynamics (Mulgund and Stengel, 1996). Another important phenomena, the wind turbulence is even standardized. The most used gust models are the Drynden and the von Karman models (see for example the military standard: MIL-STD-1797A (Flying, 2014). The effect of simple gust on aircraft load must be determined by using the recommended formulas and methodologies described by airworthiness and requirements. For example, the FAA FAR Part 23 - as it well know - had defined how to calculate the gust effect on the load factor.

Unfortunately these methods had been developed for the manned aircraft and they are not usable to small UAVs. There are many works on developing the UAV certification and operational standards, but still the weaher effects are not defined well. Especially such problems like icing of small UAV, or flying and landing of UAV in urban areas have not studied on the required levels, yet. However, there are many interesting results like are shown in Figures 7 - 9. Figure 7. demonstrates how the discrete vortex method can be used for investigation of the flow separating from montains.

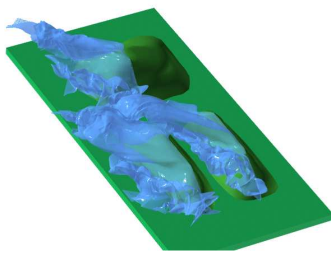

Figure 7. Flow over the mountainous terrain

The enother example shows how complex problems how the UAV may rerecovers on ship (Wong et al. 2008). In this situation the UAV must move from the relatively stable (steady) air into the turbulence air around the ships. There weas used PowerFlow and the Lattice-Boltzman approach in Very Large Eddy simulation (VLES) turbulence model and modified wall functions at high Reynolds number. The simulated flow around the frigate in side wind is shown in Figure 8. The possible accuracy of landing of the UAV eqiuipped by MP2028 autopilot system on frigate (into the 6m x 6m area). The hardware-in-the-loop simulation was run.

Finally, the Figure 9. demonstrates how air turbulence born in urban area (Par Avenue canyon, Oklahoma City) on the flying objects (Klipp and Measure, 2011). The figure shows the number of accelerations greater than 1G in each 10-min block of data (6000 data points) at the 1.5 m level of the mid-canyon tower for different aircraft types. There are two small birds (humming bird and wren) having reader similar mass/area ratios and therefore similar responses to turbulence. The simulated responses of a fix-wing micro UAV WASP II on the urban air turbulence is shown in Figure, too. As it can be seen the smaller mass/area ration, generally smaller size increases the reaction on the air turbulence.

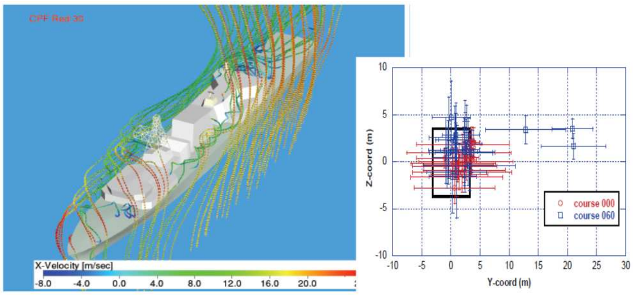

Figure 8. Flow around the firgate in side wing in which the UAV landing accurace is studied (Wrong et al., 2008)

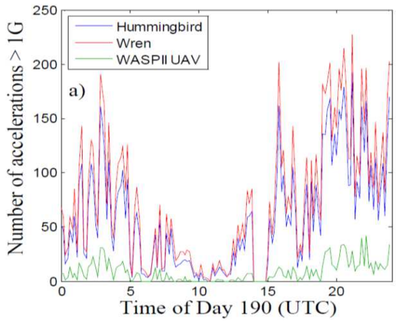

Figure 9. Influence of the urban air turbulence on the load factor (Klipp and Measure, 2011)

2.4. Some thoughts about the problems

The major problems to be solved for understanding the effects on the atmospheric hazards on the small UAVs as air, model and UAV related problems.

At first the air related problems are associated with not well understanding the flow atmospheric phenomena as flow separation, icing, appearing the microburst, etc. The problems of model formation and using the models are determined by lack in understanding the atmosphere phenomena.

At second, all the UAV related problems depend on the size and flight performance. There are two major parameters, aircraft characteristics length (l) and aircraft velocity (V) equals to the airspeed. They together define the Reynolds number as important similarity number.

In very simplified case, when the aircraft is in horizontal flight with constant velocity, then the lift (L) equals to the aircraft mass (M). The lift depends on angle of attack (α) through the non-dimensional lift coefficient (c_L), air density (ρ), aircraft velocity (V) and characteristics surface, as wing surface (S) that is a function of size ($S = f(l^2)$. In this case, the fluctuation in air velocity (ΔV) has influence on the aircraft load factor (n_z) as follows:

$$L = c_L \frac{\rho V^2}{2} S = c_L^\alpha \alpha \frac{\rho V^2}{2} S, \quad where\ c_L^\alpha = \frac{\partial c_L}{\partial \alpha},$$

$$dL \approx \Delta L = c_L^\alpha \Delta\alpha \frac{\rho V^2}{2} S + c_L^\alpha \alpha \rho V \Delta V S,$$

$$\Delta n_z = \frac{\Delta L}{W(=L)} = \frac{c_L^\alpha \Delta\alpha \frac{\rho V^2}{2} S + c_L^\alpha \alpha \rho V \Delta V S}{c_L^\alpha \alpha \frac{\rho V^2}{2} S},$$

$$\Delta n_z = \frac{\Delta\alpha}{\alpha} + \frac{2\Delta V}{V},$$

$$\Delta\alpha = \frac{|(\mathbf{V} + \Delta V) \times \mathbf{V}|}{(|\mathbf{V} + \Delta V||\mathbf{V}|)}, \quad \Delta\alpha_{max} = \Delta\alpha \cong \frac{|\Delta V|}{|\mathbf{V}|},$$

$$\Delta n_z = \frac{1 + 2\alpha}{\alpha} \frac{\Delta V}{V}.$$

Because, the angle of attack as usually in cruise part equals to 4 - 6 degree, therefore changes in load factor equals to $(11 \div 16)\Delta V/V$.

As it can be understood, with increases in velocity fluctuation (gust) and decreases in aircraft velocity the load factor is increasing. For example, if the aircraft speed equals to 5 m/s and the maximum fluctuation in velocity (perpendicular to the aircraft speed - gust) equals to 0.2 m/S then the load factor increases for 0,44. In case of load factor equal to 1g, during 0.1 sec, the aircraft moves (up) for 4.9 cm.

It should be underlined, the maximum changes in angle of attack cannot be greater than 0.22 - 0.33 because the stall (separation of flow from the wing surfaces).

It is well understandable, the aerodynamic force depends on the wing area, namely on scale factor, characteristics length (l) square and the aerodynamic moment (M) is a function of l^3. At the same time the moment of inertia (I) equals to mass (m) x l^2, that means $I = f \propto l^5$. From here, angular acceleration is $\dot{q} = \frac{M}{I} = f \propto l^{-2}$. So, with decreases in scale, the angular acceleration is increasing very rapidly. For example, following to (Klipp and Measure, 2011) let assume the uncompensated force equal to ma generates moment ($M = mac^2/5$) on a small object with aerodynamic chord (l=c), while $I = mc^2/10$ (comparing with solid cylinder of diameter d at $md^2/8$). It means, the angular acceleration can be determined as $\dot{q} = \frac{M}{I} = 2a/c$. So, if the aerodynamic chord equals to 20 cm and the acceleration (a) equals to 1g then during 0.1 sec the flying object will rotate for 28 degree.

This very simplified calculation has shown that, the safe operation of small UAV (especially in urban area or in all weather condition) needs new and original solution for elimination of the weather hazards.

The solution of these problems requires new approaches, developing new methodologies, and new technologies.

3. TOOLS FOR INVESTIGATION

Here a short review of the tools for investigation of the UAV aerodynamics in turbulent atmosphere. The description is based on the previous works of authors introducing a series of new methods into study the atmospheric effects on aircraft. Since these or similar methods have used and developed by many authors.

3.1 Experimental and computational modeling of the flows with angularities

The To study the vortex structure effect on an aircraft-type UAV with the deflected control surfaces in the wind tunnel's test section, the flow angularity simulator was created. Numerical simulation of the test conditions allows a mathematical model to be validated. The swirled flow is produced by the deflected at angles $\pm\delta$ two-section tapered wing (Vyshinsky and Mikhailov, 1999).

The tangential velocity distribution over the width of the tunnel's test section, obtained from the measured flow angles allows estimating vortex core radius $r_C \approx 25$ mm and tangential velocity magnitude (Figure 10.). A combined flow-direction probe was used, which was installed on a traversing mechanism providing its automatic translational displacement. Measurement errors for flow parameters are: ±0.25% for speed, ±0.2° for flow angularity at low angles of attack ($\alpha \leq 10°$) and ±0.5° for high angles of attack ($10 < \alpha \leq 20°$).

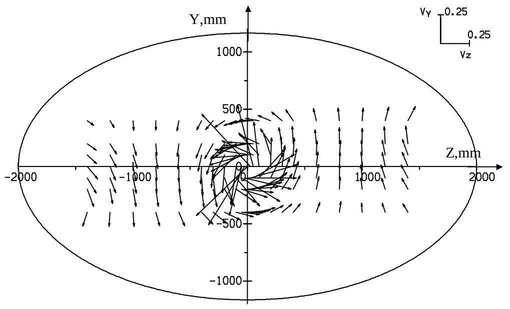

Figure 10. Velocity vector field in the tunnel test section (x = 1500 mm, δ = 10°)

The setup was used for investigating the rotational flow effect on the aircraft-type UAV of different categories with deflected control surfaces and for validating numerical methods for computing flows past full aircraft configurations immersed in nonpotential flow (Mikhailov, 1999).

Taken as the initial data for predicting the effect of a rotational flow on a UAV, were the results of measuring flow angularity. The measurements of the flow field were performed at a free stream speed of V = 50 m/s.

Fig. 2 compares computational results for the lift coefficient, pitching and rolling moment coefficients with experimental data for the model (wingspan b = 2.49 m; average chord of wing MAC = 0.303 m; aspect ratio AR = 8.76; wing area S = 0.71 m^2). The computed and experimental data are in good agreement, except for a range of high angles of attack ($a \geq 20°$) with a developed flow separation from the upper surface of the left wing. The computation reflects the change in the sign of the rolling moment due to equalizing the lift qualities of both, left and right, wings as a result of flow separation.

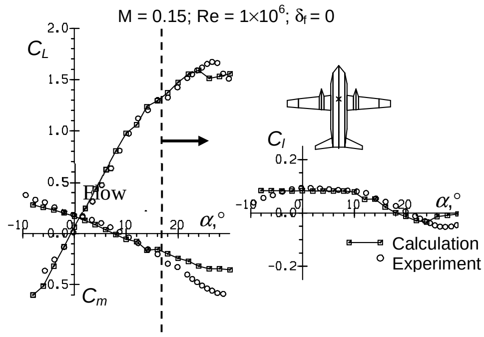

Figure 11. UAV in cruise configuration in rotational flow (δ = 10°)

3.2 Experimental modeling of the gust-laden flows

The experimental setup installed in the low speed wind tunnel with an open test section (Figure 12.).

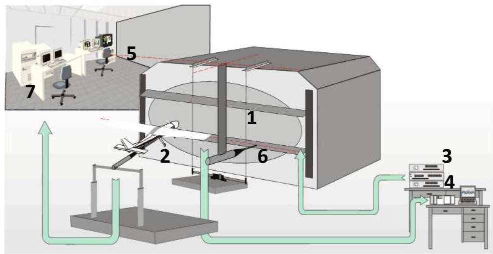

Figure 12. Gust simulator in the wind tunnel
(1.- gust generator, 2.- six-component strain gage balance, 3.- signal generator, 4.- phaser, 5.- the model's control system, 6.- 5-hole pressure probe, 7.-PC controlled test equipments)

The gust generator is located at the wind tunnel nozzle exit and designed in the form of two slotted airfoils capable of symmetrical or differential deflections (the airfoils were controlled by an electro-hydraulic actuator which deflected them to certain angles relative to ongoing flow and changed their angle of attack according to a specific law for providing the formation of asymmetric or symmetric vortex gusts).

Initially, the purpose of the investigation was to obtain experimental data on the quasi steady and unsteady aerodynamics of an aircraft model in cruise and takeoff/landing configurations in testing under the action of vortex gusts (Matveev, Nazarov and Osminin, 1999) and to determine aileron effectiveness in counteracting these disturbances (Vyshinsky and Kuznetsov, 1998). Damping the vortex gusts is a problem of practical importance associated with maintaining passenger comfort especially for general-aviation aircraft flown at low altitudes through rough air (Rohacs and Rohacs, 2012).

The Cessna general-aviation aircraft model with a straight strut-braced high-wing and the tail unit with a fixed stabilizer setting were tested in disturbed flow behind the vortex gust simulator (Fig. 13.). The wing features an airfoil section with a thickness-to-chord ratio of 12-13% and a maximum relative camber of 3.8-4.3%. During the investigations, the operating flow speed was V = 15 m/s, which corresponded to the Reynolds number $Re = 0.19\times10^6$ based on mean aerodynamic chord MAC = 0.189 m.

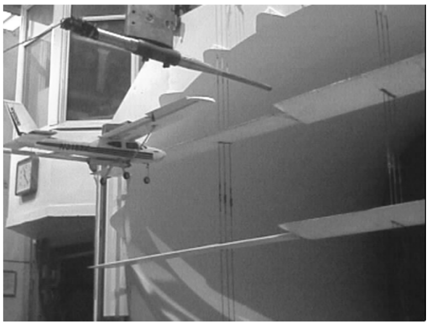

Figure 13. Cessna aircraft model in the wind tunnel

A minimum of lift coefficient (C_l) lies in a range of 0.06-0.08 and is shifted in phase by $\Delta\varphi = 45\text{-}50°$ (Fig. 14.). This indicates that for counteracting a vortex gust a forestalling deflection of the ailerons is needed (for timely restructuring the flow in the area of the ailerons). For the conditions considered at a gust frequency of 1 Hz the lead-time will be 0.125-0.139 s. The effect of the flaps at α = 6° does not result in significant changes in maximum and minimum value of C_l. The value of the phase shift needed to effectively counteract the gust-induced rolling moment, do not change in this case.

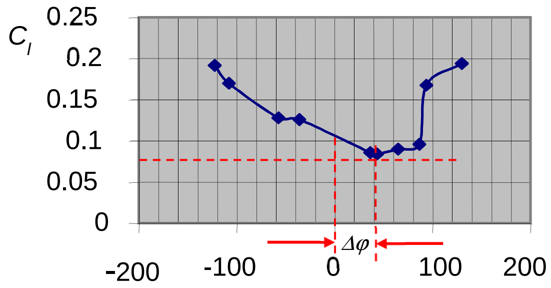

Figure 14. Rolling moment as a function of phase shift $\Delta\varphi$ (in degree), (δ_{flap}= 0)

A more slanting negative derivative of the graph presented is observed in the delay region (negative phase shifts) and a steeper positive derivative corresponds to the lead area (positive phase shifts). This nonlinear effect can be associated with an unfavorable interference between the vortex gust and the aileron whose effectiveness decreases. In the case of forestalling, the aileron operates more effectively.

3.3 Free flying model in wind tunnel tests

Tests of free-flying models in the wind tunnel flow and in catapult setup are promising when designing very small aircraft whose size allows their full-scale models to be tested in a wind tunnel or flown through control region in catapult facility. In this case, the main testing problem is to duplicate actual atmospheric turbulence spectrum in the experiment conditions.

An aircraft flying through a turbulent air execute random displacements under the action of gusts that are also random in nature. Aircraft response: spectral characteristics of vertical displacements of c.g. and wingtips may be determined through transfer functions considered as results of acting sinusoidal gusts on the aircraft.

Fig. 15. represents the experiments which were conducted in low-speed wind tunnel on the free-flying (Froude-number-matched), dynamically scaled model with a flexible wing. Information about a gust and the model response obtained by use of an array of sensors is transmitted to a computer-aided data-acquisition system, where a spectrum analyzer processes it. These experiments were conducted specially for validating the mathematical model developed (Vyshinsky, 2000)].

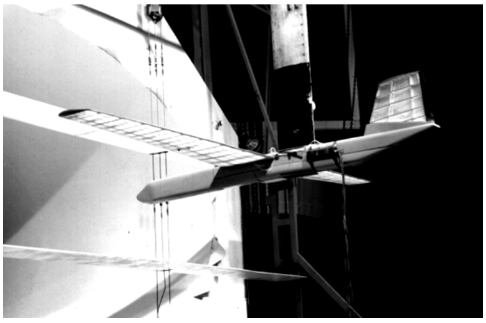

Figure 15. Experiments with free flying model (prediction of the aircraft displacements in turbulent flow)

3.4 Application of the discrete vortex method (DVM) to solving non-linear, unsteady problems

The basis of the method is the idea of Zhukovsky and Prandtl about the substitution of the body and his wake by attached and free vortices (in the ideal fluid approximation). The discrete model of the phenomena is constructed by means of the simplest vortex singularities, which correspond to the types of the solving problem (Aubakirov et al., 1997). This approach is approved when the flow formation and forces acting on the body depend weakly on viscosity and interference between vortices and their action on the streamlined body are more substantial. That is, the turbulent flow at high Reynolds numbers in the DVM approach is modeled by vortices in the framework the Euler equations approximation.

Linear and nonlinear theories of the wing and the total aircraft configuration were developed on the basis of the method. Different representation levels of the helicopters and airplanes were created for this approach. The nonlinear unsteady theory is most general. The problem statement for aircraft motion and control surfaces deflection under arbitrary laws is presented in Fig. 16. Here σ is the lifting and control surfaces including the pod of the engine; σ_1 is the free vortex sheet trailing from lifting surfaces; σ_2 is the boundary of the jet; L are the lines of the vortex sheet shedding. The direct problem of aerodynamics is solved, that is the 3D aircraft configuration, the cinematic parameters of its motion and deformation are known.

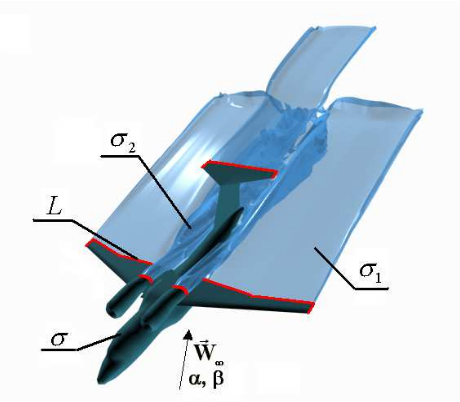

Figure 16. The problem statement

The aircraft is moving with speed W_∞ having the angles of attack α and slip β. The flow is potential outside of the body and wake. Vortex wake is represented by the thin surface shed from given lines L. From the mathematical standpoint the problem consists on finding the unsteady flow and pressure fields, that is the potential of disturbed velocities at any time outside of the body and wake satisfies the Laplas equation with the tangency condition on the body surface σ and the zero pressure difference and tangency conditions on the vortex wake σ_1 and jet σ_2 surfaces (which are the surfaces of the tangential discontinuities). The Zhukovsky-Kutta (limited velocity) condition is satisfied on the separation lines L. The Bernoulli equation is used for describing the velocity-pressure relation. The problem is reduced to finding the unknown intensity of the vortex frames, which model the body and vortex wake, as well as to finding the coordinates of the corner points of the vortex frames.

A nice result of using the discrete vortex method is shown in Figure 7.

3.5 Investigation of the degradation of airfoil characteristics during icing using CFD RANS approach

The urgency of the problem consists in the need for operating UAV in all-weather conditions and possibility of getting aircraft into icing or heavy-shower conditions. In these cases the degradation of the lifting capacity of the aircraft aerodynamic surfaces may lead to emergency situations with grave consequences. The problem is complicated by the fact that the heterogeneous flow is turbulent in nature, which limits the possibilities of using numerical simulation and complicates experimental investigations.

At present, there are three approaches to the numerical simulation of turbulent flows. Most commonly used is an approach based on time averaging the Navier-Stokes equation followed by closing the system of equations with a semi-empirical turbulence model. But such method have a substantial weakness: the averaging is performed over the entire range of turbulent motions whereas the fully developed turbulence contains at least two characteristic scales – large-scale turbulence defined by the structure and nature of the mean flow and the small-scale turbulence which is equilibrium and can be described in a universal manner. Inclusion of the large-scale turbulence in the averaging range makes the model's constants flow-dependent. Generally, they are determined empirically by correlating with simple model flows. On going to actual configurations producing flows of complex structure, these coefficients cease to work well. Thus, the range of applicability of the method is limited by the class of problems, for which the turbulence models are validated and properly "tuned".

Fully free from these drawbacks is the direct numerical simulation (DNS) method, which uses the full system of unsteady Navier-Stokes equations not averaged in time, which do not require to introduce empirical constants. In this case, the grid cell size must be less than that of the least eddy (that is, must have a Kolmogorov scale), which requires enormous computer time and memory thus limiting the range of applicability of the method by small Reynolds numbers where the number of levels of simulated eddies is small.

A third approach is also possible – the large eddy simulation (LES) based on averaging of only those turbulent motions whose linear scale is less than the size of the grid's cells. In this case, large eddies are directly reproduced in computation, whereas subgrid eddies, which can be described in a unified way in the framework of the corresponding closure models, are taken into account by use of additional terms in the set of equations. An advantage of the method lies in the possibility to use less dense grids, not requiring for the cell size to be less than the smallest eddy. Due to a chaotic character of turbulent motion, it may be thought that at the level of such small scales the information about the structure of the mean averaged flow is lost, turbulent fluctuations are isotropic whereas the closure models become universal for a broad class of flows.

It should be remembered that the above-mentioned approaches do not apply to modeling microscopic flows with a characteristic size of $L < 100$ μm (micro- aerohydro-mechanics problems arising in studying flows about micro sensors and micro actuators being created using MEMS technology). At Knudsen numbers within the range $0.01 < Kn < 0.1$ one still can use the continuous medium equations, but corrections for «no-slip / free slip mix» and «temperature jump» must be introduced into boundary condition on solid surface.

As an example Fig. 17. represents turbulent energy calculations for NACA-0012 airfoil at Re=300000 provided using RANS (Reynolds averaged Navier-Stokes equations) computer code on the multigrid with 30000 nodes.

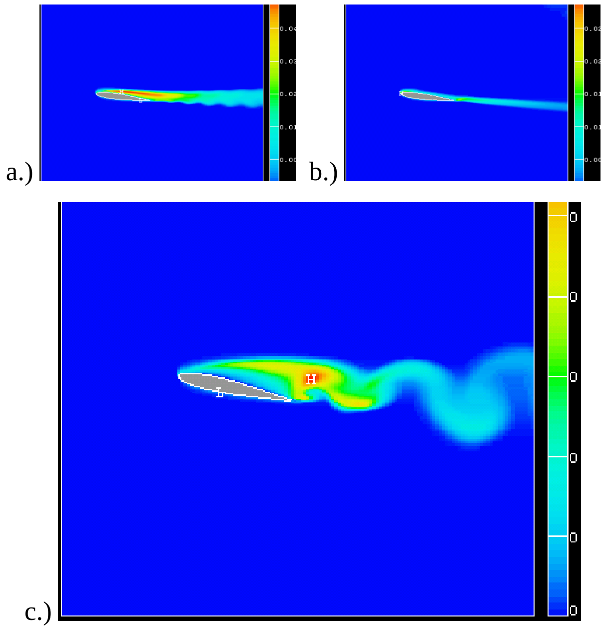

Figure 17. Turbulent energy
a.) $\varepsilon = 0, \alpha = 8^0$, b.) $\varepsilon = 0{,}001, \alpha = 8^0$, c.) $\varepsilon = 0{,}001, \alpha = 12^0$, unsteady flow.

The results of mathematical modeling of the degradation of the airfoil aerodynamic characteristics (C_L, C_{Lmax}) in consequence of increasing the roughness of its surface are presented in Fig. 18. The random distribution of the roughness is used in these calculations.

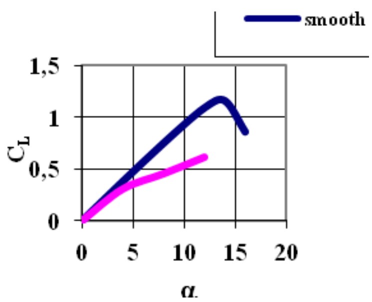

Figure 18. Lift coefficient depending on roughness

Not only quantitative but also qualitative changes in the solutions can be obtained. Besides the degradation of aerodynamic quality, one can see the arising unsteady separated regime of the flow at steady boundary conditions (see Fig. 8).

The form of the boundary (ice formation) may be obtained from flight tests and experiments in cryogenic wind tunnels or from mathematical modeling of ice formation. Studies into physical processes of ice formation in developing mathematical models can be carried out using experiments in high-speed test grounds.

The similar approach may be used in investigating the influence of the heavy rains and insects adhering on the aircraft surface, which result to the degradation of the aircraft aerodynamic characteristics (Vyshinsky, 1994). The role of roughness of a surface in flow and its increase in flight is especially important for small and supersmall aircraft flying at low Reynolds numbers. These aircraft have a significant portion of their external surfaces with laminar flow, and its early turbulization will result in a considerable increase of drag.

Dusts «charges» are also dangerous at takeoff and landing of aircraft. An encounter with a volcanic dust cloud during the cruise flight can disable instruments' sensors, engines, and optical devices. Such cases have been registered by aviation accident/incident statistics. The creation of corresponding engineering models useful for predicting the degradation of aircraft aerodynamic characteristics and propellers efficiency is an absolute necessity.

4. CONCLUSIONS

This paper is a modified version of the lecture presented at the 2nd International Workshop "Extremal and Record-Breaking Flights of the RPAS (UAS) and the Aircraft with Electrical Power Plant", held at Zhukovsky, 1 - 4 July 2014. The purpose of the original lecture was to show the roots of organisation of a new Research Laboratory Aviation Factors of Risk dedicated for investigation of the Atmospheric hazards at the Moscow Institute of Physics and Technology (MIPT). The project is supported by TsAGI (Central Aerohydrodynamic Institute named after Prof. N.E. Zhukovsky (*TsAGI*)), too.

The UAVs are more sensitive to the air turbulence and generally to the atmospheric hazards. There the effects of atmospheric turbulence on UAV is in focus of the forming laboratory.

This paper had two major parts. The first one defines defined the atmospheric hazards causing safety problems in aviation, classified the UAVs into several groups depending on their size, goal of usage and operational environmental conditions. Finally it used a very simplified explanation to show, how the atmosheric hazards may have influence on the small UAVs.

The second major chapters gave a review of the tools for aerodynamic researches into the influence of the atmospheric turbulence and coherent vortex structures on the UAV flight situations.

Not all available tools were presented and briefly discussed here. Their list may be extended. Some of them may needs further developments. However this list of tools has demonstrated that the representatives of forming laboratory had a long period research in the given field.

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