Unmanned aerial vehicle “Tsimlyanin” for studying turbulent structure of atmospheric boundary layer

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Abstract. A fixed-wing unmanned aerial vehicle “Tsimlyanin” having a hybrid vertical take-off and landing (VTOL) scheme with a compact meteorological payload is designed for an application to the atmospheric boundary layer (ABL) studies. The main purpose of such an observational platform is to supplement traditional mast observations by sampling horizontal and vertical inhomogeneities of mean variables and turbulent statistics. Such observations are needed to advance turbulence theory especially for the ABL over inhomogeneous landscapes and also in non-stationary conditions. The VTOL scheme is chosen as it provides a safer take-off and landing and is less demanding to the landing conditions. The designed turbulence payload consists of a seven-hole probe, inertial navigation system and a fast-response platinum-wire temperature sensor. It is complemented with the static pressure sensor, a slow-response temperature and humidity sensor and an infrared surface temperature sensor. The data acquisition and logging is performed by an on-board computer. The designed system has been successfully tested in the summer campaign in 2020 in Tsimlyansk, Russia.

1. Introduction

A theoretical description of the atmospheric turbulence is well established for rather idealized, horizontally-homogeneous and stationary conditions. In nature, however, such conditions are rare. Most of the natural surfaces are heterogeneous with respect to roughness, temperature and humidity and are characterized by a multiscale character of heterogeneities. The effect of such inhomogeneities on the atmospheric boundary layer remains an open challenge [1]. Moreover, even over a flat surface, the atmospheric boundary-layer (ABL) turbulence experiences the effect of non-stationarities of various scales, such as rapid transitions during the diurnal cycle, effects of clouds and mesoscale motions [2].
From the observational point of view, traditional eddy-covariance systems installed on a mast are not sufficient to resolve the turbulent structure of the ABL over inhomogeneities [1]. They need to be supplemented with aircraft and multiphase observations. UAVs offer a much more affordable and flexible solution as compared to the pilot flying laboratories.

Meteorological application of the unmanned-aerial vehicles (UAV) has been experiencing a rapid growth. This is associated with the fact that the components of the UAVs are becoming lighter and cheaper and are commercially available. An increased number of observational campaigns involve the usage of meteorological UAVs [3, 4].

UAVs are also more frequently applied for turbulence research. Typically they are using the fixed-wing scheme [5]. It has several advantages over the multi-rotor platforms, such as a longer endurance and a smaller distortion of the air flow. Recently, the vertical take-off and landing (VTOL) scheme have started to be used on such UAVs [6, 7]. It allows for a safer landing and provides more universality with respect to take-off and landing conditions.

This paper presents the VTOL UAV “Tsimlyanin” and its turbulence payload developed for the atmospheric boundary layer studies. The results of the first test flights are demonstrated.

2. Unmanned aerial vehicle “Tsimlyanin”

2.1. The UAV scheme

The UAV “Tsimlyanin” is shown in Figure 1a. It was designed in the Moscow Aviation Institute specially for the application to the atmospheric boundary-layer studies. The chosen scheme meets the following requirements: payload mass up to 1.2 kg, mission endurance up to 60-90 min, cruising altitude up to 2000 m, the near-surface wind speed limit not less than 8 ms\(^{-1}\), the possibility to locate sensors in the undisturbed flow and safe landing.

The two schemes were tested and compared: the VTOL fixed-wing scheme and the flying-wing scheme. The latter was based on the commercially available Skywalker-X8 model. During test flights it was found that the steadiness and the level of control of the flying-wing scheme strongly depends on the location of the payload which limits the flexibility of the whole system design. The VTOL fixed-wing scheme proved to provide wider limits for the payload placement. Thus, although both schemes meet the listed requirements, the VTOL fixed-wing scheme was chosen as optimal.

The developed aircraft has the frame design in which the central section and the twin-boom tail are tied. On the latter, the propeller-engine systems of the vertical take-off and landing are located. The truss structure fuselage is attached to the frame. The sensors of the payload are located in the nose of the fuselage. Inside the fuselage there is also an automatic control system and a power battery. The UAV is using the electric propulsion engine.

2.2. Meteorological payload

The turbulence payload (Figure 1b) consists of the seven-hole probe designed in the Khristianovich Institute of Theoretical and Applied Mechanics SB RAS (Novosibirsk, Russia) [8], a fast-response platinum-wire temperature sensor designed in the Central Aerological Observatory (Dolgoprudniy, Russia) and of the inertial navigation system (INS) Ellipse-2N (SBG Systems). The meteorological payload also includes the slow-response temperature and humidity sensor HMP110 (Vaisala), the infrared surface temperature sensor (Melexis) and the relative humidity sensor P14 Rapid (IST AG) which has a relatively fast response (about 1 s in still air according to the manufacturer). The data acquisition and logging is performed by a Linux-based single-board computer RaspberryPi4 at 100 Hz sampling rate.

The seven-hole probe is using a hemispheric tip with a diameter of 10-mm. At the central hole, the full pressure is measured, while at the six holes located at 60 degree angles relative to the central axis the difference between the local pressure and the pressure at the central
Figure 1. (a): the VTOL UAV “Tsimlyanin” during the Tsimlyansk 2020 campaign. (b): sensors at the nose of the UAV: 1) seven-hole pressure probe, 2) fast-response platinum-wire temperature sensor; 3) slow-response temperature and relative humidity Vaisala HMP110 sensor; 4) P14 Rapid IST AG relative humidity sensor.

hole is measured. Four holes at the sides are connected to a chamber where the static pressure is measured. Honeywell differential and absolute pressure sensors from The TruStability High Accuracy Silicon Ceramic (HSC) Series are used. The pressure transducers were calibrated in a laboratory in order to test and increase their accuracy. The whole probe was further calibrated in a wind tunnel. The seven-hole probe is superior to the frequently used five-hole probes due to an increased accuracy and redundancy of the measured quantities which minimizes potential data loss. The resulting accuracy of the observed wind components using similar systems is in the range 0.1-0.2 m s$^{-1}$ [9, 10].

The fast-response temperature sensor is a resistance thermometer with an open platinum wire placed directly into the air flow. Around the sensor the protective housing is used which does not prevent the airflow through the sensor. The platinum wire has the diameter of 30 $\mu$m and the nominal resistance of 100 Ohm. The small diameter of the wire and a rather intense airflow at a cruising speed of about 20 m s$^{-1}$ ensure a small response time. The sensor was first calibrated in a climate chamber where the resistance-temperature calibration curves were obtained. The wind-tunnel calibration showed that the recovery factor is close to unity and that its dependency on speed and direction of the air flow is small, when the latter vary in a range typical for this type of a UAV. The absolute accuracy of air temperature measurements is of order of 0.1 K, while the accuracy of measuring turbulent fluctuations is better and is reported to be 1.8 mK for similar sensors [11].

The general design of the meteorological payload is, thus, similar to the ones developed earlier for UAV applications, such as the one used on MASC-3 [5].
3. Test flight results

Test flights were carried out over a flat steppe field during the campaign in Tsimlyansk in August 2020 at the field station of the Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences (IAP RAS). During the campaign, multiplatform observations were carried out providing the opportunity to verify the observations obtained by the “Tsimlyanin” UAV. Three sonic anemometers (Gill Instruments) were installed on a mast at 2, 10 and 30 m heights. Gradient observations of wind speed and direction, air temperature and humidity were carried out using the Aanderaa automatic weather station with sensors at 2 and 10 m heights. The Scintec mini-sodar provided wind speed and direction profiles up to 100 m height producing 5-min averaged wind profiles. The vertical profiles of air temperature were obtained using the microwave temperature profiler MTP-5 (RPO Attex).

Figure 2a shows vertical temperature profiles obtained during the flight pattern shown in Figure 2b performed by “Tsimlyanin” between 12:10 and 12:20 UTC on August 13, 2020. The flight pattern consisted of elongated rectangular figures (200 × 1000 m) performed at various heights, namely at 50, 100 and 200 m. A well-mixed convective boundary layer developed by the time of the flight due to a strong heating from the surface. The observed temperature structure of the lower ABL was typical for such conditions and consisted of a quasi-logarithmic profile close to the surface transforming into a dry adiabat at higher altitudes. Clearly, the fast-response sensor temperature, the MTP5 data and the mast observations are in close agreement with each other. Air temperature observed by the HMP110 sensor is also closely following the dry adiabat but has a systematic shift towards higher values. It is likely that this is a calibration issue and it will be investigated in more detail in the future.

The observed wind speed and direction profiles are presented in Figure 3. The three wind components were calculated using the seven-hole probe and the INS measurements using a procedure described in [12]. Observations from sodar and UAV demonstrate a good agreement with respect to wind direction. The latter showed little variation with height being about 320°. The Scintec sodar observed wind speed in close agreement with the sonic anemometers on the mast. The wind speed observed by “Tsimlyanin” also agrees well with that from sonic
Figure 3. Wind speed (a) and direction (b) profiles obtained by the UAV “Tsimlyanin”, the Scintec sodar and three sonic anemometers located at 2, 10 and 30 m heights on a mast.

Anemometers and sodar, but is about 1-1.5 m s\(^{-1}\) weaker. One should keep in mind that wind speed shows large spatio-temporal variations in convective boundary layer and at least part of the difference between the observations from different platforms could be attributed to this.

Only the observations of the mean ABL structure are considered in this study. Further research will be focusing on the derivation of turbulence statistics from the UAV data.

4. Conclusions
The UAV “Tsimlyanin” and its meteorological payload were designed for the application to the atmospheric boundary layer research. The vertical take-off and landing fixed-wing scheme was chosen as it fulfills best the requirements with respect to the mission endurance, flexibility of the payload design, safety and simplicity of operation.

Several sensors and acquisition devices as part of the meteorological payload were custom designed and calibrated. These include the seven-hole probe and the fast-response platinum-wire temperature sensor.

Test flights performed during the summer campaign in Tsimlyansk demonstrated a robust functionality of the designed system. Comparison of the obtained observations of the vertical structure of convective boundary layer with measurements from sonic anemometers, sodar and temperature profiler showed a good agreement between different platforms.

Further research will be focused on deriving turbulence statistics for the UAV data and on their comparison with those from the ground-based instruments.

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