

Investigations of Aerodynamics and Flight Dynamics for Micro-UAVs at Low Airspeeds and Reynolds Number Values

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Abstract

Some special features are discussed for aerodynamics and flight dynamics of very small unmanned aerial vehicles (micro-UAV) as well as evaluation problems for aerodynamic and dynamic characteristics associated with these features. Some experimental results are presented for micro-UAV obtained by using wind tunnel experiments and flight tests as well as mathematical modeling results to estimate micro-UAV transient processes caused with some disturbances.

Keywords: unmanned aerial vehicle (UAV), micro-UAV, aerodynamics, hysteresis, flight dynamics, transition processes

Nomenclature

m	– mass of UAV
ρ	– mass air density
S	– wing area of UAV
c	– mean aerodynamic chord
U	– flow velocity within a wind tunnel; airspeed
H	– altitude
q	– dynamic head
Re	– Reynolds number
α	– angle of attack
C_L	– lift coefficient
C_D	– drag coefficient
C_N	– general force coefficient
C_m	– pitching moment coefficient
μ	– relative density
$\bar{\tau}$	– time ratio
p	– angular velocity about X-axis
q	– angular velocity about Y-axis
r	– angular velocity about Z-axis
I_Y	– pitching-moment inertia
σ_U	– speed stability index

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Specific features of aerodynamics and flight dynamics for micro-UAV

A class of very-small unmanned aerial vehicles (micro-UAVs) including UAVs with a mass in the range from several dozen grams up to 1 kg (or up to 5 kg according to other appraisals) was emerged in the 90s due to formation of new technological possibilities to implement such kind of vehicles. UAVs with flight mass approximately between 5 kg and 150–200 kg are classified usually as mini-UAVs.

However micro-UAV design is a very difficult problem due to lack of appropriate theory of flight for such kind of objects. The point is that the micro-UAVs are much more similar to birds and insects than to conventional aircraft including larger UAVs (see Table 1 and Fig. 1) in terms of mass, dimensions, relative density, airspeed, Reynolds number values. We have no adequate analytical or numerical techniques to describe micro-UAV motion taking into account peculiarities mentioned above. This complicated problem remains still unsolved for modern aerodynamics and flight dynamics. On the other hand conventional theory of flight based mainly on empirical-type relationships reproducing long-term experience in design of 'large' aircraft does not specify flight of living beings as well as very small UAVs.

Table 1. Some features for various kinds of flying objects

Object kind	Mass m , kg	Re	Relative density, μ	Specific pitch moment, $M_{\text{spec}}, 1/\text{sec}^2$	Time ratio, sec
Sporting airplanes and gliders	500-1200	$6 \cdot 10^5 - 10^7$	70-200	8-20	1.0-5.0
Middle-sized UAV	50-150	$3 \cdot 10^5 - 10^6$	100-300	20-40	0.5-3.0
Micro-UAV	0.15 – 0.35	$5 \cdot 10^4 - 2 \cdot 10^5$	20-40	200-1000	0.2-0.5
Albatross	8-12	$2 \cdot 10^5 - 4 \cdot 10^5$	80-100	25-50	0.5-2.0
Sea-gull	0.8-2.0	10^5	60-80	60-120	0.5-2.0
Butterfly	0.0005-0.01	$2 \cdot 10^3 - 8 \cdot 10^3$	2-6	2000-10000	0.01-0.06

Airspeed values for micro-UAVs are usually in the range from 8 m/sec to 25 m/sec. Micro-UAVs reach at low airspeeds the area of critical Reynolds numbers (see Fig. 2), where almost all UAV aerodynamic characteristics change very rapidly, practically in the stepwise manner. The micro-UAV characteristics become better at increasing of Reynolds number and become worse at its decreasing.

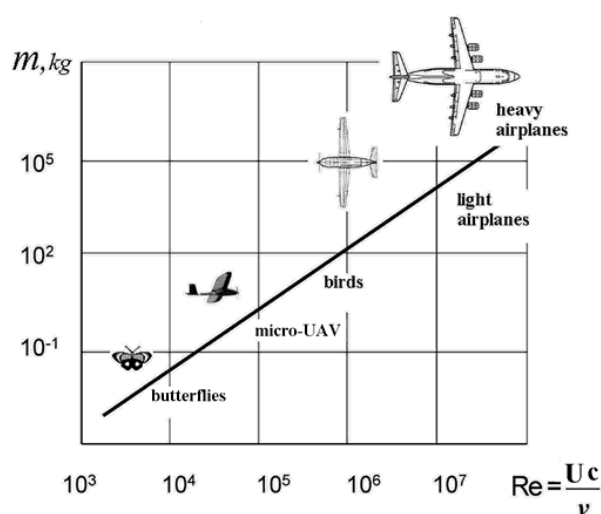


Fig.1. Typical Reynolds number values for flying objects with various masses and airspeeds

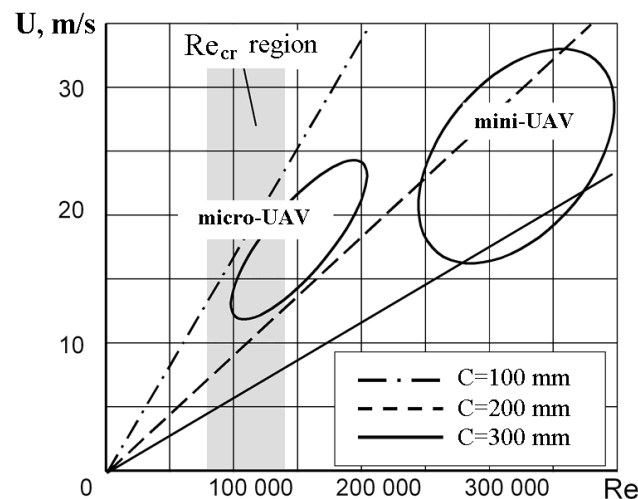


Fig. 2. Typical airspeeds for mini-UAVs and micro-UAVs as well as area of critical Reynolds numbers

Problems which are picked out usually in contemporary scientific publications dedicated to the micro-UAV flight aeromechanics associate mainly with steady-state aerodynamics for low Reynolds numbers [1–3]. There is no doubt that steady-state aerodynamic characteristics are very important because they are needed to calculate such significant UAV performances as its airspeed and flight range.

Some experimental results are presented below for micro-UAVs within the bounds of steady-state aerodynamics. These recently obtained results relate to full-scale micro-UAV specimens. They were acquired using the T-1 wind tunnel at the MAI.

However it is very important to investigate too micro-UAV unsteady aerodynamic characteristics because of some features which are typical for vehicles of such class.

As can be seen from Table 1 mass m , longitudinal relative density $\mu = 2m/\rho S c$ and time ratio $\bar{\tau} = 2m/\rho S U$ for micro-UAV are much smaller than for manned aircraft and for larger UAVs. Here following designations are accepted: ρ is mass air density, S is wing area of UAV, c is mean aerodynamic chord, U is airspeed. On the contrary, specific pitch moment values $M_{spec} = q S b / I_Y$ are dozens times more for micro-UAVs in comparison with larger aircraft [2]. From this it follows some specific features of motion nature for micro-UAVs:

1. Atmospheric disturbances are not only comparable with baseline in-flight forces influencing on the UAV but often exceed these forces.
2. Damping forces and moments are often similar in magnitude with baseline ones that provides rather fast attenuation of arising oscillations.
3. Angular velocities and angular accelerations of UAVs can reach very large values. This circumstance limits (though does not excludes completely) usage of stationary aerodynamic characteristics in flight dynamics problems for such vehicles.
4. Low-air-speed operating micro-UAVs are in the region of so-called critical Reynolds number values. Fast, practically stepwise variations of UAV aerodynamic characteristics are typical for this region. These variations influence immediately on the UAV motion, its stability and controllability.

All of these features dictate a need to improve baseline hypothesis, assumptions and models of motion as applies to micro-UAV. In turn, such improvements will be impossible

without appropriate experiments basing on modern techniques and tools because of significance of the practice both as the basis for theoretical models and as validation criterion for used techniques. Certainly, this statement is fair for the UAV motion case as well.

Some results of experimental and theoretical research carried out by the authors in the recent years are discussed in the subsequent sections of the paper.

Experimental investigation of steady-state aerodynamic characteristics for micro-UAV

Experimental investigation results are presented in this section as applies to aerodynamic characteristics for some prototype micro-UAVs. These investigations were carried out by using the T-1 wind tunnel (see Fig. 13) installed in the Aerodynamic Laboratory at the Moscow Aviation Institute (MAI).

The subsonic T-1 closed-layout wind tunnel has an open working section with such main parameters as: output diameter of the contractor is 2.25 m, length of the working section is 3.4 m, range of operational flow velocities is from 5 m/sec to 50 m/sec, critical Reynolds number $Re = 3.5 \times 10^5$, initial turbulence degree is 0.35%.

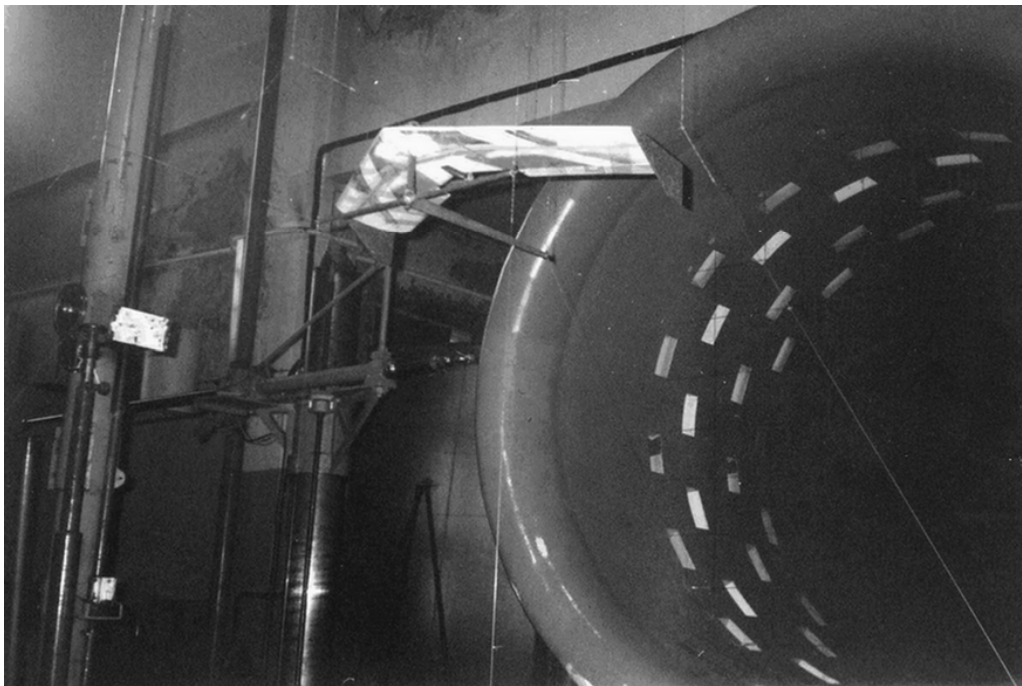


Fig. 3. Real micro-UAV «002» within working section of the T-1 wind tunnel at the MAI

Several real micro-UAVs were tested in the T-1 wind tunnel including “Model No. 1”, “Model No. 2” and “Model 002” micro-UAVs. Schemes of these micro-UAVs are presented on Figs. 4, 5 and 6.

Some results obtained in these experiments are presented on Figs. 7 through 11.

Experiments were performed at values of Reynolds number which are typical for micro-UAVs including study with operating engines and propellers as well as with autorotating propeller and without propellers.

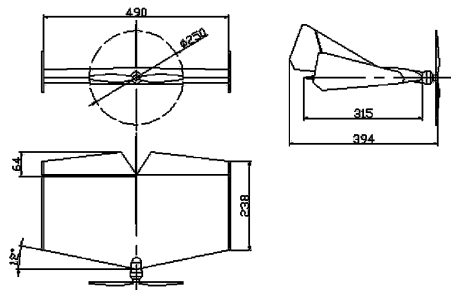


Fig. 4. Scheme of the "Model No. 1" micro-UAV

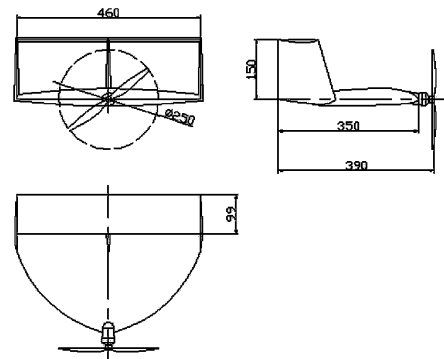


Fig. 5. Scheme of the "Model No. 2" micro-UAV

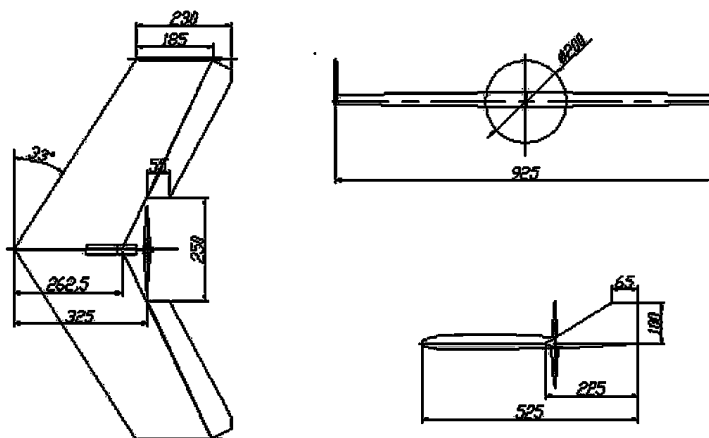


Fig. 6. Scheme of the "002" micro-UAV

It was revealed a strong influence of rotating propeller on lift coefficient C_L for the micro-UAV (see Fig. 7). A value of this coefficient multiplies by 1.5 as compared to the case without propeller. Autorotating propeller is "aerodynamic brake" and in consequence of which micro-UAV drag coefficient C_D increases significantly (see Fig. 8).

Rotating propeller have an influence upon micro-UAV moment characteristics too increasing values of its pitching moment coefficient C_m (see Fig. 9). Propeller blowing of UAV elevator or elevons increases effectiveness of longitudinal control (see Fig. 10). Maximum values of micro-UAVs lift to drag ratio obtained by means of wind tunnel tests are $L/D_{max} = 7.4$ for Model No. 1 and $L/D_{max} = 6.2$ for Model No. 2. These maximum L/D values correspond airspeeds U from 8.5 m/sec to 10 m/sec. Increasing of airspeed causes a sharp decreasing of the L/D ratio.

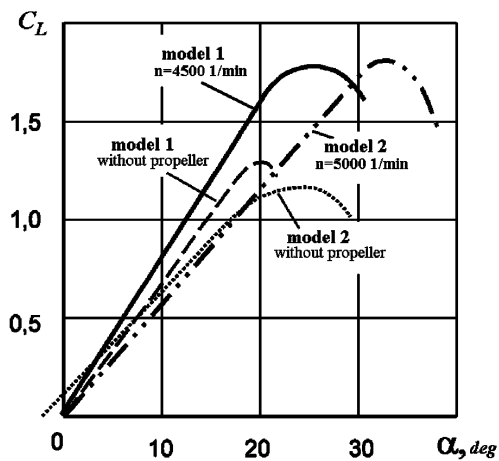


Fig. 7. Relationship $C_L(\alpha)$ for micro-UAV models No. 1 and 2

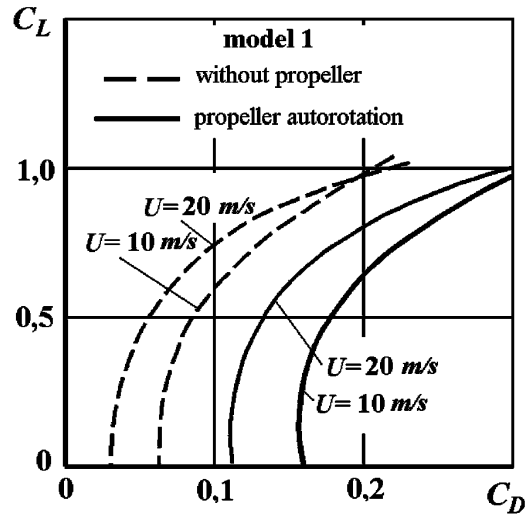


Fig. 8. Aerodynamic polars $C_L(C_D)$ for micro-UAV model No. 1

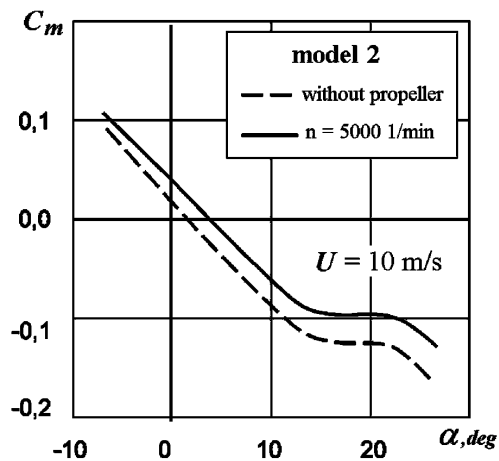


Fig. 9. Pitching moment coefficient $C_m(\alpha)$ for micro-UAV with and without operating propeller

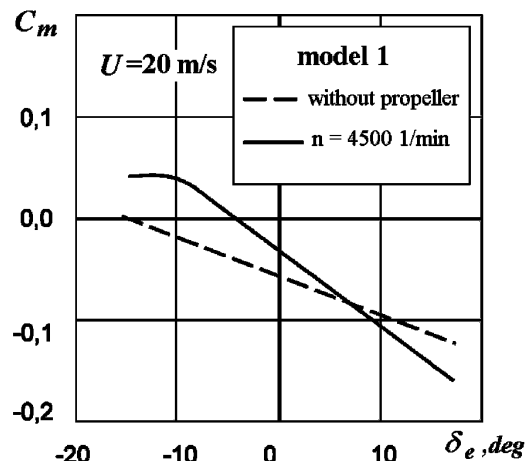


Fig. 10. Propeller blowing influence on longitudinal control efficiency for micro-UAV model No. 1

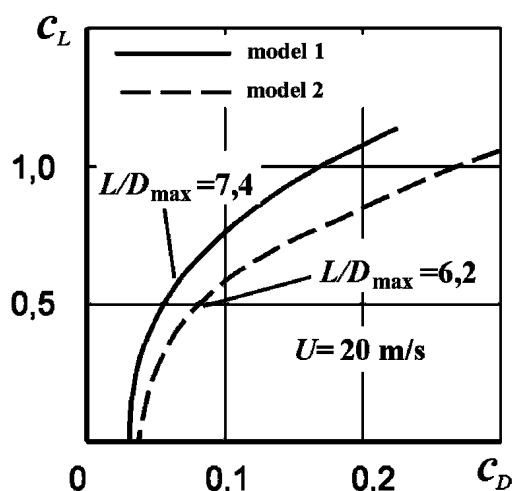


Fig. 11. Aerodynamic polars C_L (C_D) for micro-UAV models No. 1 and No. 2

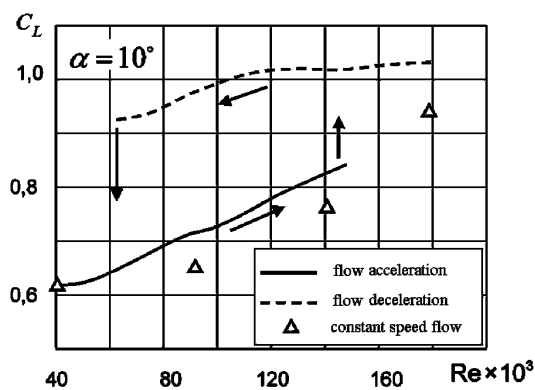
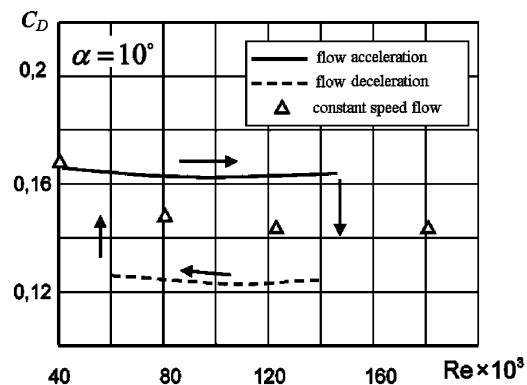
Experimental investigation of unsteady aerodynamic characteristics for micro-UAV

Concerning unsteady aerodynamic characteristics some results are presented basing on wind tunnel tests to demonstrate Reynolds number influence on aerodynamic characteristics of a rectangular micro-UAV wing with the NACA-60 airfoil. Wing span was 500 mm and chord value was 80 mm in these experiments. A specific measurement technique (it was the Schmitz measurement technique [7]) has been used in the wind tunnel investigations. According to the technique wind tunnel flow velocity values (and Reynolds number values as a consequence) are changed at appropriate fixed values for angle of attack. The hysteresis phenomenon is revealed for micro-UAV aerodynamic characteristics depending on the Reynolds number while its values vary in 'forward' and 'backward' direction through the region of critical Reynolds number values.

Hysteresis appearance description in the form of ambiguous relationships for such static aerodynamic characteristics as experimentally defined general aerodynamic force and moment is presented in [4–7]. However these articles contain only qualitative discussion of rate of change for various kinematic parameters but they do not specify quantitatively the rates.

Therefore it is necessary to carry out specific research which allows us to make more exact physical understanding of aerodynamic phenomena caused with change of kinematic motion parameters such as velocity, angle of attack, angle of sideslip for a broad range of their values. Besides we need to study an influence of the phenomena on micro-UAVs aerodynamic characteristics as well as on their stability and control. Such extension of understanding is required to derive efficient supervision and control techniques for rapid and unstable processes relating to micro-UAV motion.

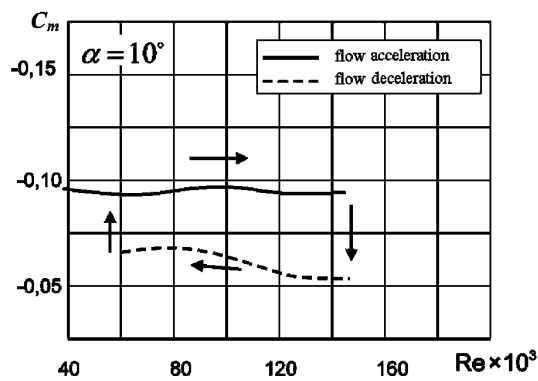
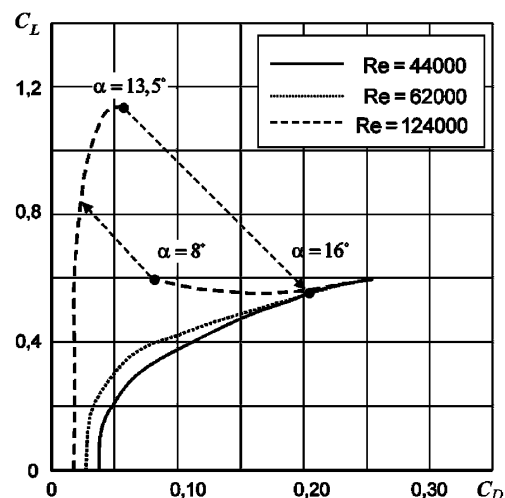
Relationships between C_L , C_D , C_m and Re obtained experimentally for angle of attack value $\alpha = 10^\circ$ are presented on Figs. 12, 13 and 14. For all of these experiments carried out for angle of attack values from -10° to 20° flow velocity within wind tunnel increases initially with acceleration $\dot{V} = 1.18 \text{ m/sec}^2$ and then decreases with the same rate. Arrows on Figs. 12, 13 and 14 indicate direction changes for Reynolds number values with respect to a specified rate of velocity change.

Fig. 12. Relationship $C_L(Re)$ for $\alpha = 10^\circ$ Fig. 13. Relationship $C_D(Re)$ for $\alpha = 10^\circ$

We can see from relationship $C_L(Re)$ shown on Fig. 12 that the lift coefficient increases gradually when airspeed value enhances up to $Re \approx 146000$. After that the lift coefficient C_L jumps from $C_L \approx 0.84$ to $C_L \approx 1.04$. Following-up airspeed increasing leads only to a slight growth of the lift coefficient.

Decreasing of the airspeed causes a jump change of the lift coefficient to its original value but it happens for $Re \approx 60000$ rather than $Re \approx 146000$. So-called hysteresis loop arises.

Relationships $C_D(Re)$ and $C_m(Re)$ have hysteresis loops too (see Figs. 13 and 14). It should be noticed that such hysteresis-like behavior of the $C_L(Re)$, $C_D(Re)$ and $C_m(Re)$ relationships needs additional investigations both in the unsteady aerodynamics area and in micro-UAV stability and control for low airspeeds.

Fig. 14. Relationship $C_m(Re)$ for $\alpha = 10^\circ$ Fig. 15. Wing polars for $Re = 44000$, 62000 and 124000

Aerodynamic wing polars and relationships $C_L(\alpha)$ are presented on Figs. 15 and 16 for three Reynolds number values $Re = 44000$, 62000, 124000, which were obtained by processing relationships $C_L(Re)$ и $C_D(Re)$ for angle of attack values from -10° to 20° . Behavior of polars and two hysteresis loops is demonstrated on Fig. 17 depending on values

of Re , C_L and C_D parameters. The a,b,c,d loop arises here as velocity increases due to inertia of flow structure alteration within area of critical Reynolds number values.

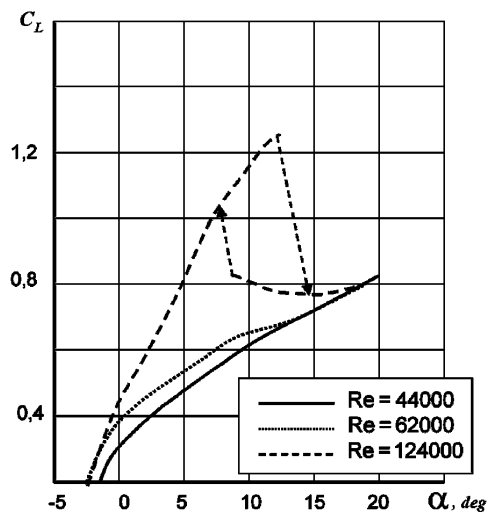


Fig. 16. Relationships $C_L(\alpha)$ for $Re = 44000$, 62000 and 124000

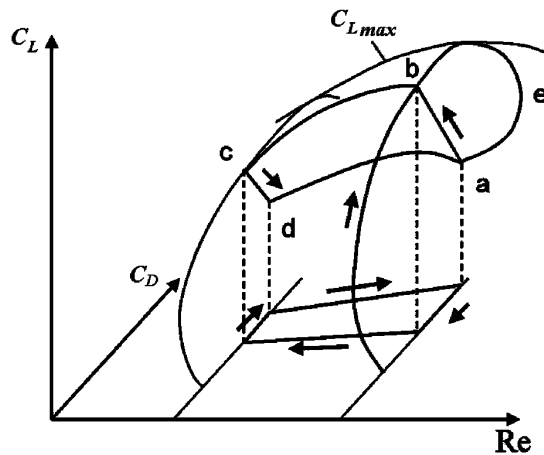


Fig. 17. Polars in space with Re , C_L , C_D coordinates and two hysteresis loops

Wind tunnel investigations of non-steady wing aerodynamic characteristics with respect to angle of attack changing values were carried out using a special mounting (see Fig. 18). A distinctive feature of the mounting consists in modeling support for rotational wing movements with respect to various instantaneous centers of rotation. A six-component strain gage balance with torque sensor was used to measure wing aerodynamic characteristics.

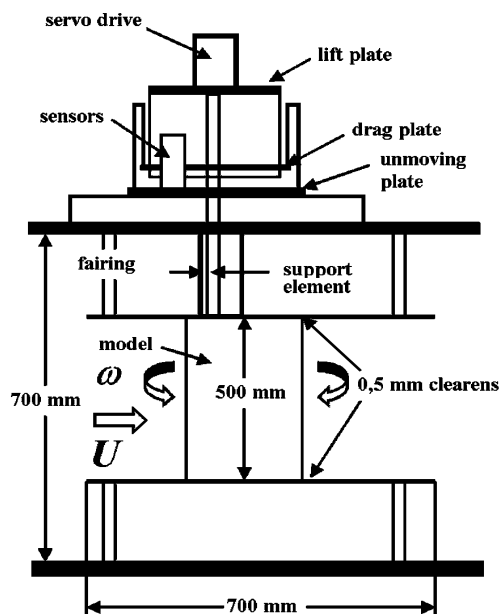


Fig. 18. Mounting scheme providing rotational freedom degrees for a wing model in wind tunnel

An essence of the experiment implemented using the test bench shown on Fig. 7 consists in measurement of general aerodynamic force represented with C_N coefficient values with respect to angle of attack changed continuously. The angle of attack values was varied in these experiments by means of constant-speed rotation for the wing model with respect to some instantaneous center of rotation.

Experimental results demonstrating influence of angular velocities and a location of instantaneous center of rotation on wing aerodynamic characteristics are presented on Figs. 8 –12. Here $\bar{\omega} = \frac{\omega \cdot c}{2U}$ designates dimensionless angular velocity with respect to some arbitrary center of rotation, ω is angular velocity with respect to some arbitrary center of rotation, c is wing chord and U is airflow velocity.

Experimental investigation results are presented on Figs. 19 through 23 to evaluate influence of angular speed values and instantaneous center of rotation locations on aerodynamic characteristics for lifting surfaces.

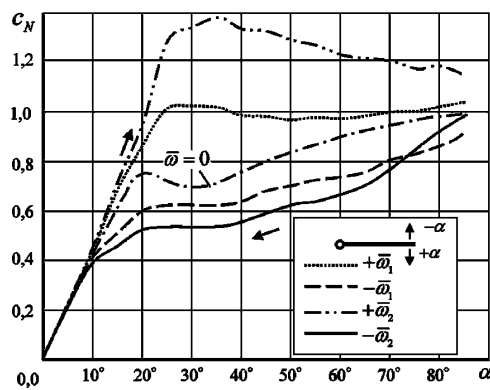


Fig. 19. Relationships $C_N(\alpha)$ for angular velocities $\bar{\omega}_1 = \pm 0.0131$ and $\bar{\omega}_2 = \pm 0.0393$ with respect to leading edge

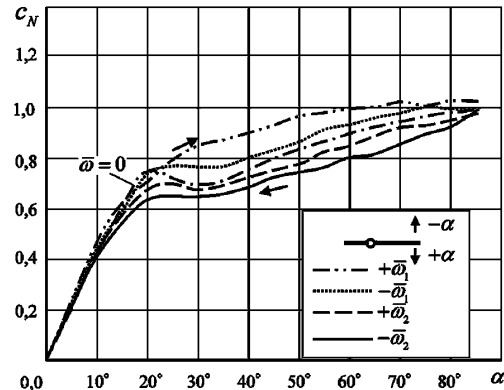


Fig. 20. Relationships $C_N(\alpha)$ for angular velocities $\bar{\omega}_1 = \pm 0.0131$ and $\bar{\omega}_2 = \pm 0.0393$ with respect to 0.25 of chord

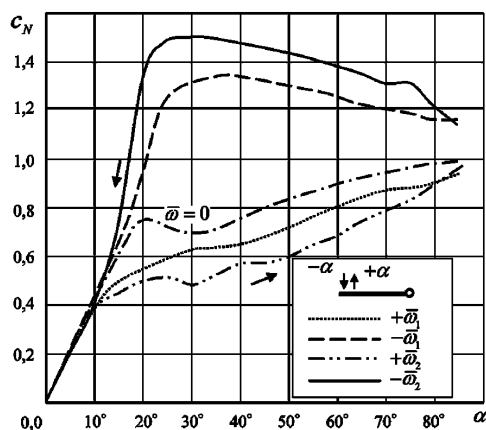


Fig. 21. Relationships $C_D(\alpha)$ for angular velocities $\bar{\omega}_1 = \pm 0.0131$ and $\bar{\omega}_2 = \pm 0.0393$ with respect to 0.25 of chord

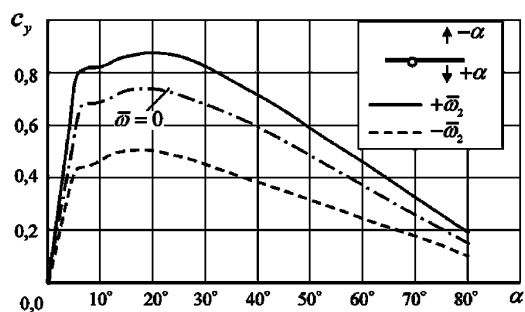


Fig. 22. Relationships $C_N(\alpha)$ for angular velocities $\bar{\omega}_1 = \pm 0.0131$ and $\bar{\omega}_2 = \pm 0.0393$ with respect to trailing edge

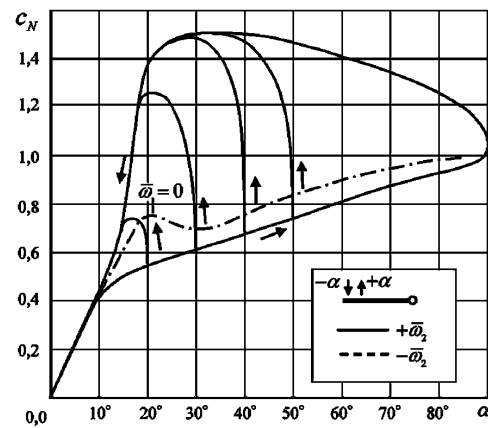


Fig. 23. Relationships $C_N(\alpha)$ for angular velocities $\bar{\omega}_1 = \pm 0.0131$ and $\bar{\omega}_2 = \pm 0.0393$ with respect to trailing edge depending on the switch point for direction of rotation

These experimental results demonstrate significant influence of angular velocities and instantaneous center of rotation coordinates on aerodynamic characteristics for lifting surfaces. Such relationships need to be studied by means of elaborate investigation of theoretical and experimental aspects related to this research area.

Features of longitudinal balance for micro-UAV at critical Reynolds number values

Longitudinal balance for micro-UAV flying within area of critical Reynolds numbers has some special features. As it has been demonstrated above aerodynamic characteristics of micro-UAV at critical Reynolds numbers change considerably. Lift coefficient C_L increases and drag coefficient C_D decreases without angle of attack α changing. Since angle of attack value is left unchanged these variations of C_L and C_D are equivalent enhancing of C_{L_α} value and reducing of C_{D_α} one.

Let us imagine a situation when micro-UAV flying horizontally with some acceleration. It begins the flight from a small velocity value which belongs for certain to the area of subcritical Reynolds number values. In this case, aerodynamic characteristics of the micro-UAV such as C_{L_α} and C_{D_α} correspond subcritical Reynolds numbers and the flight is balanced with respect to UAV aerodynamic forces and pitch moment. At some moment of time airspeed reaches the value corresponding to critical Reynolds number value. Aerodynamic characteristics are change fast, almost stepwise. At the same time lift coefficient C_L increases (see Fig. 24) and drag coefficient C_D decreases. Angle of attack value remains unchanged corresponding one of its subcritical characteristics values and considered micro-UAV will be out of balance. Here enhanced lift L exceeds micro-UAV weight W , propeller thrust P exceeds decreasing drag D , pitching moment M_A is not equal to zero. =

The micro-UAV has to decrease angle of attack value (see Fig. 25) to reset the balance, i.e. to ensure fulfillment of equality condition for the current value of the micro-UAV lift coefficient and the lift coefficient value needed for the level flight.

It is assumed originally that an additional elevator deflection will be needed to put the micro-UAV to a smaller angle of attack. The elevator should be deflected on some nonnegative angle $\Delta\delta_e > 0$ to generate some negative pitching moment increment $\Delta M_A < 0$. A

suggestion was arised afterwards that unbalanced pitching moment $\Delta M_A(\Delta C_L)$ appearing as a result of the UAV lift increasing for supercritical Reynolds numbers can have a stabilizing influence without elevator deflections. Simulation results for the micro-UAV "003" confirm this suggestion.

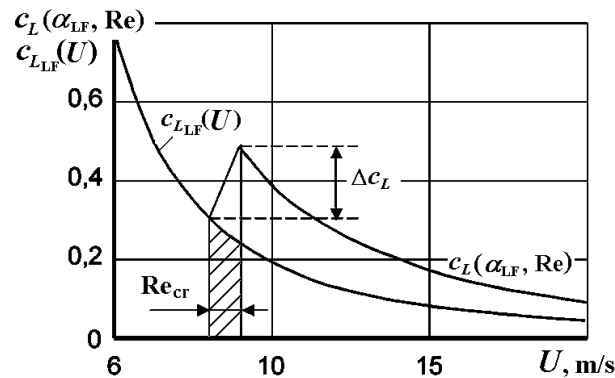


Fig. 24. Increasing of ΔC_L for micro-UAV at critical Reynolds numbers

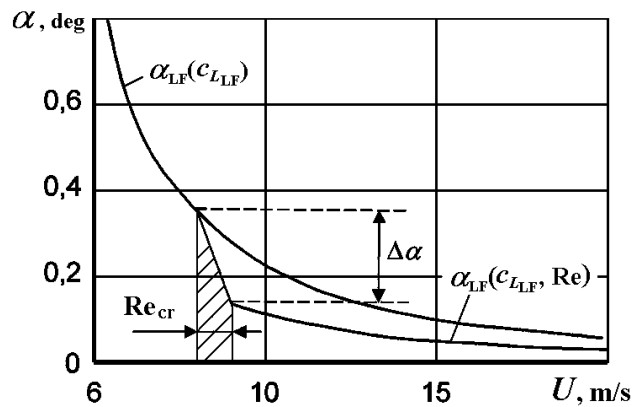


Fig. 25. Decreasing necessity for angle of attack α_{LF} needed to provide level flight in supercritical Reynolds numbers

A level flight of micro-UAV was simulated with its acceleration from initial velocity $V = 8$ m/sec up to maximum speed of steady level flight which is provided with available thrust of propeller. Values of the C_{L_α} derivative was enhanced within the area of Reynolds numbers critical for this micro-UAV. A decreasing of drag coefficient C_D did not take into account because its influence on the micro-UAV pitching balance is too slight.

Simulation results for the case are presented on Figs. 26 and 27. Acceleration dynamics of the micro-UAV through its velocity $V(t)$ chaging are shown on Fig. 26. Changing of pitching angular velocity $q(t)$ is demonstrated on Fig. 26 too.

As it can be seen from Figs. 26 and 27, an intensive rotation with negative pitching angular velocity arises for the micro-UAV at airspeed value which is about 10 m/sec. Such intensive appearance of the micro-UAV rotation, which is almost stepwise virtually, can be explained if we consider an influence of very small inertia moment I_Y .

This intensive micro-UAV rotation decreases rapidly a pitching angle value for the UAV and its angle of attack α accordingly (see Fig. 27).

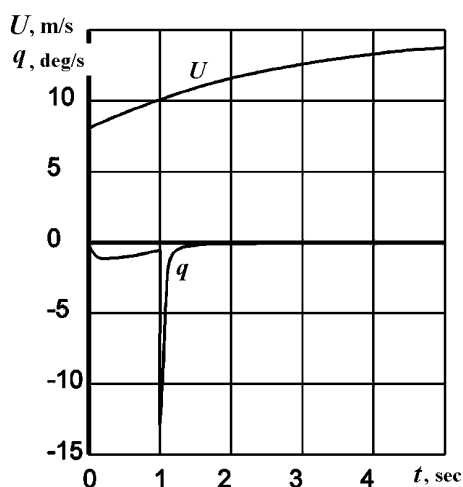


Fig. 26. Relationships $U(t)$ and $q(t)$ for “003” micro-UAV at accelerated level flight

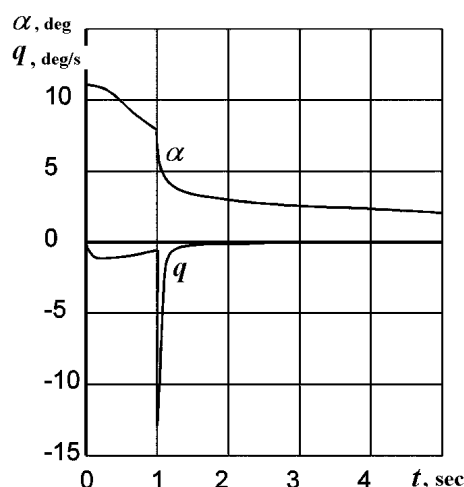


Fig. 27. Relationships $q(t)$ and $\alpha(t)$ for “003” micro-UAV at accelerated level flight

An angle of attack decreasing for the micro-UAV caused with its pitching rotation reduces the UAV lift coefficient down to values corresponding the current level flight velocity. Consequently the micro-UAV will be balanced again with respect to forces and moments acting on the UAV but this time the vehicle will be within the supercritical area of Reynolds numbers.

Simulation of transient processes for micro-UAV longitudinal perturbed motion

Mathematical modeling and computer simulation were performed basing on experimental results to analyze the micro-UAV transient processes. The analysis was accomplished using linear and nonlinear models of disturbed motion [8]. Obtained numerical results show us that there are some peculiarities in longitudinal stability characteristics of micro-UAVs within region of critical Reynolds number values. It is possible particularly to loose the speed stability ($\sigma_U > 0$) for some value combinations of longitudinal trim parameters, aerodynamic center location and damping coefficient value.

A detailed analysis has been carried out within the framework of the linear model to obtain roots of characteristic equation for some micro-UAVs as well as comparison were made with roots for the Yak-18T light piloted aircraft equipped with a piston engine. The comparison demonstrates that micro-UAVs have several times larger natural oscillation frequencies than larger aircraft due to very small values of inertia moments and large values of specific pitch moment. In addition micro-UAVs have several times larger damping values caused with their small relative density values in longitudinal motion. For the rest, relationships describing changes of the root values remain very similar for micro-UAVs and piloted airplane within their operating ranges of airspeeds, which are certainly different for these classes of vehicles.

Simulation results are presented in the article concerning to transient processes in longitudinal micro-UAV “003” motion. The results obtained for the linear model case indicate that transitions for such angular motion variables as angle of attack α and pitch angular

velocity q include some high-frequency and rapidly damped motion mode as well as a low frequency and relatively slow damped one. There are also transient processes related to changing flight path variables such as airspeed U and flight path angle γ , which have no high-frequency mode (Figs. 28 and 29).

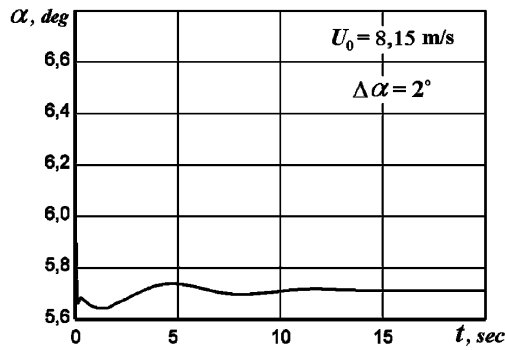


Fig. 28. Transient process for angle of attack $\alpha(t)$ caused with $\Delta\alpha = 2^\circ$ initial disturbance

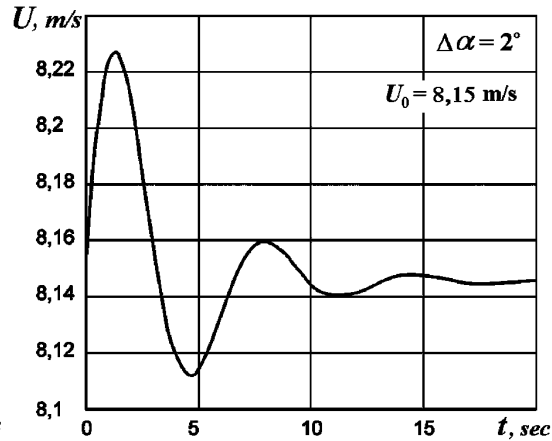


Fig. 29. Transient process for airspeed $U(t)$ caused with $\Delta\alpha = 2^\circ$ initial disturbance for the angle of attack value

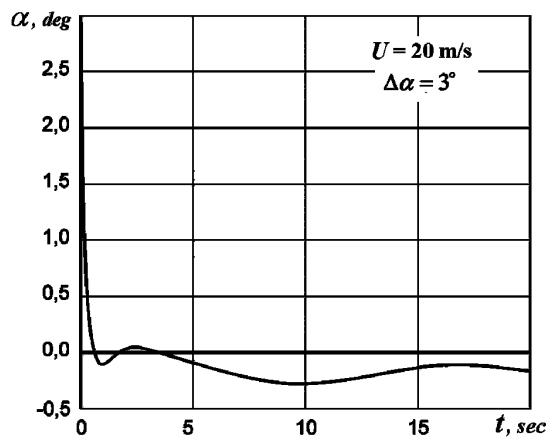


Fig. 30. Transient process for angle of attack $\alpha(t)$ caused with $\Delta\alpha = 3^\circ$ initial disturbance

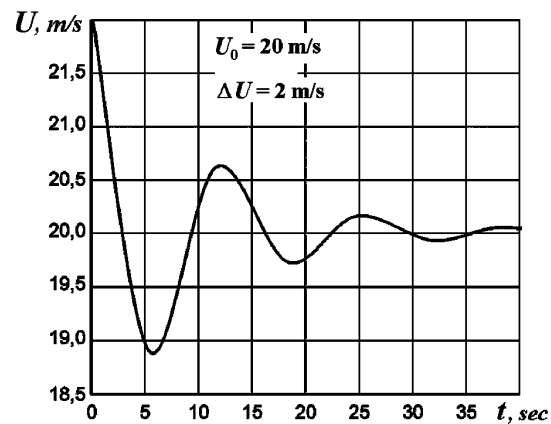


Fig. 31. Transient process for airspeed $U(t)$ caused with $\Delta V = 2$ m/sec initial disturbance

Simulation results are presented on Figs. 30 and 31 to demonstrate transient processes for the X-04 micro-UAV in regard to their angular and flight path movements. These results have been obtained using nonlinear model of aircraft spatial motion.

Comparison of simulation results basing on linear and nonlinear models demonstrates that these models lead to a close agreement in their results if initial disturbances are small. However the linear model (it is inherently analytical) has an important benefit because it allows us to analyze roots of characteristic equation for the investigated system. It is possible using the analysis results to make conclusions about an influence degree of micro-UAV parameters on a kind of transition processes. On the other hand nonlinear model (it is

inherently numerical and simulation-based) of the disturbed motion produces more accurate results and can operate not only for small disturbances but for large ones. It is profitable for practical applications to use these two kinds of models in some joint mutually complementary manner.

Some flight test results for micro-UAVs

Some flight test results are presented in this section (see Figs. 32 and 33) for experimental micro-UAV X-04 equipped with microprocessor-based registration system to record values of UAV flight parameters including airspeed U , barometric altitude H , deflections of control surfaces (angles of aileron ξ , rudder ζ and elevator η deflections), linear acceleration components a_x , a_y , a_z and angular velocity components p , q , r along X, Y, Z coordinate axes.

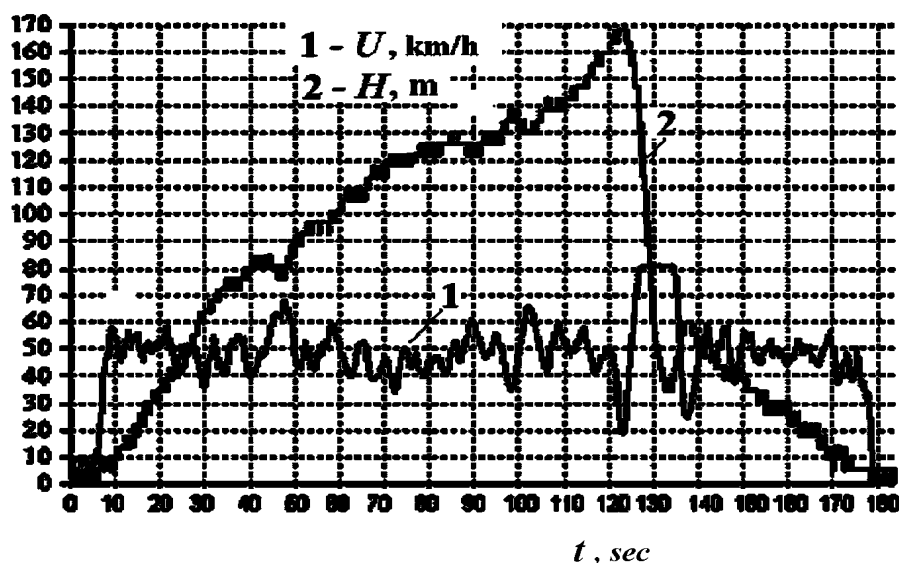


Fig. 32. Micro-UAV angular velocities registered in flight tests

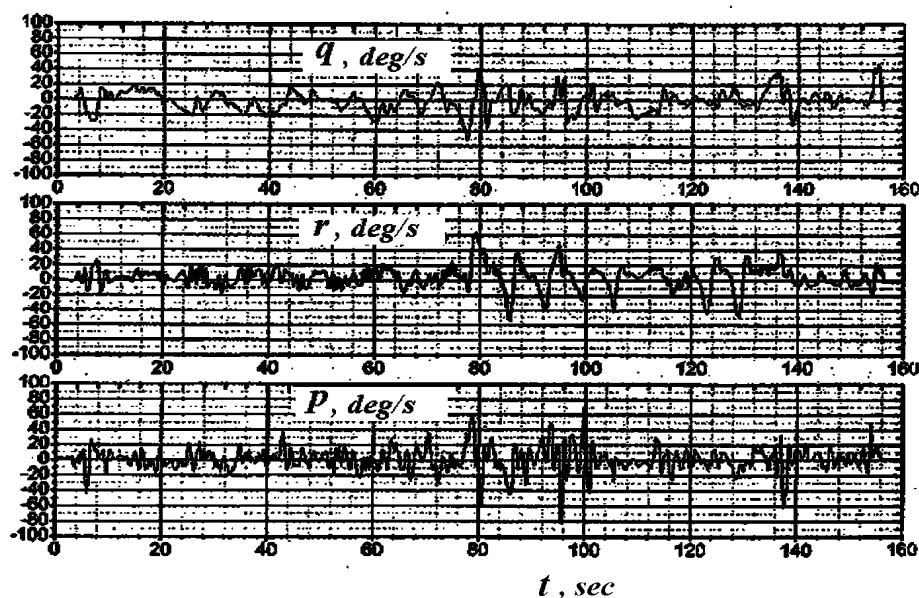


Fig. 33. Micro-UAV altitude and airspeed registered in flight tests

These flight investigation results demonstrate in very convincing manner how fast micro-UAV flight parameters can be changed under atmospheric disturbances or under the action of deflected control surfaces. Especially angular velocities p , q , r vary their values considerably.

A problem of aerodynamic configuration selection for micro-UAVs under uncertainty conditions

A diversity of tasks and flight conditions is typical feature for micro-UAVs as well as the presence of numerous performance criterions to evaluate their effectiveness. One of key features of the UAV to provide the effectiveness is its aerodynamic perfection.

Therefore one of most important problems for the micro-UAVs is the design problem to select an UAV aerodynamic configuration including such its design features as airfoil and planform for its wing. This configuration have to be optimal / universal for some specified area of the UAV flight conditions possibly under some additional requirements.

The aerodynamic design problem under uncertainty conditions was formulated in [9, 10] in terms of the multitask and multiobjective approach. This approach allows us to take into account easily in the course of design process the diversity and uncertainty in the UAV flight regimes and in its performance indexes. The essence of multitask approach consists in some set extraction which includes external conditions of the aerodynamic configuration to solve subsequently a multi-objective optimization problem for the configuration presented as a multi-element design solution which belongs to some set of feasible decisions.

Several problems were solved basing on the multitask approach including selection of appropriate subsonic airfoil selection to minimize reduction of the UAV lift-to-drag ratio for specified Reynolds number region, and selection of appropriate UAV wing to reduce its radar perceptibility for specified Mach number region.

The obtained results demonstrate that application of multitask approach for aerodynamic design of subsonic and transonic UAVs including their airfoil and wing planform selection allows us to enhance significantly the UAV aerodynamic efficiency.

Conclusions

The results of theoretical and experimental investigations described in previous sections indicate clearly that micro-UAVs have some important features which are absent for bigger and faster aircraft. One of these features is presence of hysteresis loop in many aerodynamic characteristics such as lift, drag and pitching moment coefficients for longitudinal motion of micro-UAV. Other special micro-UAV features discussed above relate to non-steady and nonlinear motion nature of these vehicles. Such features impact significantly on micro-UAVs stability and control characteristics and therefore they are needed to take into account while designing micro-UAVs and their control systems.

References

1. Brusov V.S. and Petruchik V.P. Theoretical and experimental investigations of aerodynamic characteristics for micro-UAV. *Proc. 3rd US-European Competition and Workshop on Micro Air Vehicle Systems (MAV07) & European Micro Air Vehicle Conference and Competition (EMAV2007)*, 17-21 September 2007, Toulouse, France.
2. Brusov V.S. and Petruchik V.P. Aerodynamics and flight dynamics for small unmanned aerial vehicles. *Proc. XXI Scientific Conference on Aerodynamics*, TsAGI Publishing Department, 2010 (In Russian).
3. *Aerodynamics stability and handling qualities for supersonic airplanes* / Ed. by Biushgens, Moscow, Fizmatlit, 1998 (In Russian).

4. Kurianov A.I., Stoliarov G.I., Steinberg R.I. About hysteresis of aerodynamic characteristics. *TsAGI Academic Transactions*, vol.10, No. 3, 1979 (In Russian).
5. Begovshits V.N., Kabin V.N., Kolinko K.A. a.o. Free oscillation on elastic joint technique to study non-stationary transonic aerodynamic derivatives. *TsAGI Academic Transactions*, vol.27, No. 3-4, 1996 (In Russian).
6. Kolin I.V., Mamrov V.P., Sviatodukh V.K. a.o. Multiple hysteresis of steady aerodynamic characteristics for aeroplane with a high-aspect-ratio straight wing on low Reynolds number values. *TsAGI Preprint*, No. 87, 1996 (In Russian).
7. Schmiz F.W. *Aerodynamik des Flugmodells*. 2. Aufl., Carl Lange Verlag, Duisburg, 1952.
8. *Aeromechanics of airplane: Flight dynamics* / Ed. by A.F. Bochkariov and V.V. Andreyevsky, 2nd Ed., Moscow, Mashinostroyeniye, 1985 (In Russian).
9. Piyavsky S.A., Brusov V.S., Khvilon E.A. *Multitask optimization of flying vehicles*. Moscow, Mashinostroyeniye, 1974.
10. Brusov V.S., Baranov S.K. *Optimal design of flying vehicles: A multitask approach*. Moscow, Mashinostroyeniye, 1989.