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Flow visualization and aerodynamical coefficients determination for the *LASTA-95* model in the wind tunnel T-35

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Flow visualization in the vicinity of the model in subsonic flow, is frequently performed using tufts. Bending of tufts following every change in local vector velocity is observed or recorded using still camera.
In this paper, model of LASTA-95 airplane, wind tunnel, criteria for choice of tufts and glue, complete procedure of preparation of the model for investigation, as well as results obtained by flow visualization with tufts, are shown.

Key words: **airplane, wind tunnel, flow visualisation, visualization with tufts, glue.**

Labels

mark – definition, unit
C_x – drag coefficient
C_y – side force coefficient
C_z – lift coefficient
C_l – rolling moment coefficient
C_m – pitching moment coefficient
C_n – yawing moment coefficient
L – length of model [m]
l_{sat} – referent length of model [m]
S_{ref} – referent area of model [m^2]
M – Mach number
p_{st} – static pressure [MPa]
p_0 – total pressure [MPa]
q – dynamic pressure [MPa]
Re – Reynolds number
T_0 – total temperature [K]
α – angle of attack [°]
β – sideslip angle [°]
V – velocity [m/s]
X_r – distance between the point of reduction and front of model [m]
X_{ref} – distance between the point of reduction and virtual center of balance [m]
F.S. – full scale
VTI – Military Technical Institute
NACA– National Advisory Committee for Aeronautics

Introduction

THIS paper presents the testing of the airplane model for basic training, *LASTA-95* in the test section of subsonic wind tunnel T-35 of the Military Technical Institute in Belgrade.

Along with the *LASTA-95* model, the wind tunnel T-35, instrumentation, methods of data acquisition and reduction, criteria for choice of tufts and glue, complete procedure of preparation of the model for testing, as well as results obtained by flow visualization with tufts and the course of experiment, are described.

The experiment included the testing of the *LASTA-95* model at $M = 0.3$, in the subsonic wind tunnel *T-35* test section “A”, for the range of angle of attack $-3.5 < \alpha < +26^\circ$, and with the sideslip angle of $\beta = 0^\circ$.

The basic goal of investigation was recording flow field figure around *LASTA-95* model by flow visualization with tufts and comparing characteristic values with the data obtained in previous experiments.

Testing results are shown in the form of figures and diagrams.

Flow visualization

Aerodynamics studies the law of interaction of fluid and objects moving through it and can be divided into theoretical and experimental part. Theoretical aerodynamics exposes and solves complex problems by mathematical apparatus, while experimental aerodynamics studies interactions between the fluid and objects in free motion or those in laboratory conditions. Numerous attempts to develop and use new methods for qualitative and quantitative investigations of the flow around a model in aerodynamic tunnel, in the past two decades, were made possible by interdisciplinary approach , i.e. using new results from different scientific and technical areas. The multidisciplinary principle made possible the development and application of methods, which can be gathered in separate scientific disciplines to be used within experimental aerodynamics i.e. in flow visualization. New methods of visualization enabled an "insight into the physical processes", studied in basic fluid mechanics, thermodynamics, aerodynamic projecting, thermal

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machines, production process testing, car industry, medicine, architecture and other areas.

Moving of water and air, i.e. basic fluids which are used in experimental aerodynamics, around airplanes and their models, can not be observed or recorded, because the mentioned fluids are colourless. Flow visualization methods can transform invisible picture of flow field into visible without a disturbance of fluid flow [1-6].

Although visualization methods can be divided according to different criteria, only five groups of methods will be mentioned here:

- flow visualization by tufts,
- flow visualization by indicators (markers),
- flow visualization by coatings,
- special methods of flow visualization and
- optical methods of flow visualization.

Flow visualization by tufts is often used for flow field investigation in the test section of the wind tunnel and complete area of the test section. The method is frequently used for subsonic flow, but very effective results can also be obtained for the supersonic flow [2]. This method is of special importance for rotational flow and is also used in free flight airplane tests [2].

Tufts are glued onto the model surface or a special grid, which is positioned in front or behind the model (Fig.1) [1]. Bending the tufts is observed or recorded because it is predicted that they are thin enough, without inertia and able to follow all changes of local vector velocity. While choosing tuft characteristics via technique of gluing and spreading them onto the model surface, disturbance to the flow should be kept to the minimum so the most authentic record is made.

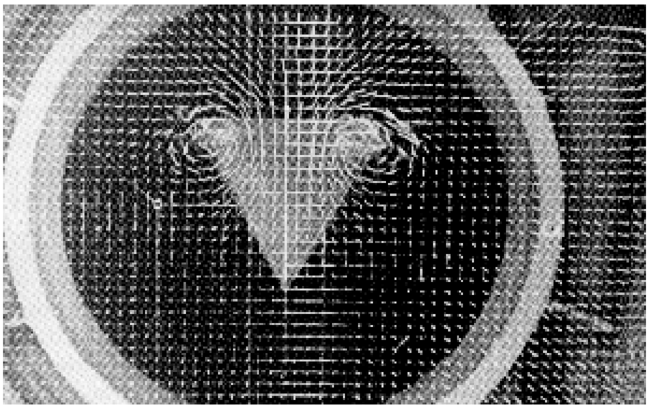

Figure 1. Flow visualization by tufts grid behind delta wing [1]

Tufts, glued to the surface of the model, are subjected to the influence of strong centrifugal forces, which interfere with the flow field and their resultant determines the tuft orientation. It is advisable to minimize the influence of the centrifugal forces, so that aerodynamic forces became dominant in tuft orientation. Experiments proved that aerodynamic forces are proportional to tuft diameter, while centrifugal forces are proportional to cross section, i.e. square of tuft diameter [4].

Depending on the current problem, it is necessary to choose a tuft diameter, which will ensure centrifugal forces and can be neglected in comparison with the aerodynamic forces. If tufts have too small a diameter, the problem of quality recording occurs due to the small quantity of the reflected light and long time of exposition.

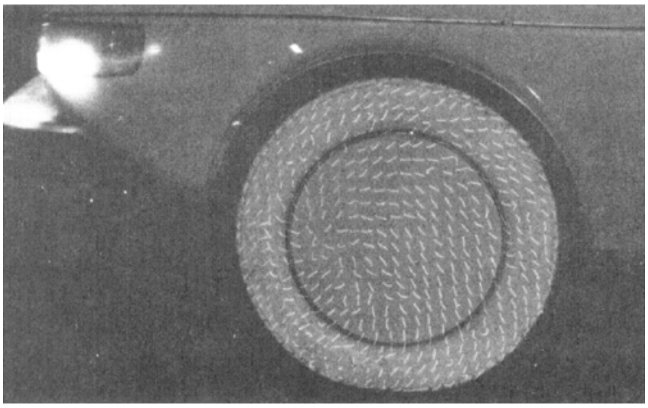

Figure 2. Mini-tufts on a rotating wheel [3]

In choosing tufts, a compromise between two opposite demands must be made: on one hand, tufts must be thin and of stiffness as small as possible; on the other hand, tufts must reflect enough light [1]. Basic surface of the model should be prepared in such a way to have minimum light reflection and maximum possible contrast. The angle of the light and recording of visualization effects is very important. Lighting with stroboscope during recording allows determining the local angle of flow and frequency of flow pulsation. Flow visualization by tufts on a car wheel is shown on Fig.2 [3].

Flow visualization by tufts around the *LASTA-1* model, is shown on Fig.3.

Figure 3. Flow visualization by tufts around the *LASTA-1* model [7]

Model

VTI has designed family of the *LASTA* models for the purpose of testing them in its own wind tunnels.

Wing span of the *LASTA-95* model is 1.803 m. This model has extremely high accuracy of manufacture; maximum error does not exceed 0.03 mm.

The *LASTA-95* model (Figures 4 and 5) has receiving adaptors on external six-component wind tunnel balance/support. Geometric characteristics of the model are shown in Table 1. Airfoils in the root and on the end of the wing are *NACA* 63_2415. Airfoils of the horizontal and vertical tails are symmetrical. Airfoils in the root of the horizontal and vertical tails are *NACA* 64_A012. Airfoils on the end of the horizontal and vertical tails are *NACA* 64_A008. The angle between the leading edge of the swept wing and the fuselage axis is 2.82°, aspect ratio of the wing is 6.3 and its installation angle is 2° in relation to the fuselage axis. The angles between the leading edge of the horizontal and the vertical tail, and the fuselage axis are 11.07° and 53.0°, respectively. The wing has dihedral angle of 4° and it is non-linearity geometry warped with –3.5°.

The *LASTA-95* model is scaled 1:5, and it is of modular type. The main part is the fuselage, which is made of iron grid. The fuselage is designed for the installation on the external six-component wind tunnel balance/support with strictly defined geometry. The distance between the main and rear strut is 560 mm. The chains make possible interval angle of attack from -20° up to +30°. The chain of rear connection is 54 mm above the main chain, when the model occupies zero position. The wing of the model is made of duralumin as one part. Elements for measuring hinge moments are installed in chains of flaps and all control surfaces.

Table 1. The basic geometric characteristics of the *LASTA-95* model

LASTA model	Wing area [m²]	Wing span [m]	l_{sat} [m]	Fuselage length [m]	X_r [m]	X_{ref} [m]
95	0,516	1,803	0,2922	1,581	0,4946	0,1482

Figure 4. The *LASTA-95* model on the model support system in the wind tunnel *T-35* test section (front view)

Figure 5. The *LASTA-95* model on the model support system in the wind tunnel *T-35* test section (side view)

Wind tunnel T-35

Subsonic wind tunnel *T-35* of *VTI* is located in Žarkovo. The wind tunnel is of continual type. The test section has octagonal cross-section, with width of 4.4 m and height 3.23 m. The test section cross-section area is 11.93 m^2. The length of the test section is 5.5 m.

The range of the Mach number, which can be achieved by fan only is from 0.1 to 0.52 and with the combination of the fan and injector from 0.52 to 0.8.

The test section "A" with external six components balance *TEM T-35* is used in this test. Model support system enables step-by-step movement of the model and continual movement of the model ("sweep") for two axes, i.e. change of the angle of attack and sideslip angle.

Mach number regulation is achieved by changing fan rotation rate and the angle of fan blades.

The value of Reynolds number is up to 12 million/m with fan only and up to 23 million/m with the combination of fan and injector.

The value of total pressure in the test section is 0.1 MPa with fan only and up to 0.152 MPa with the combination of fan and injector.

Theoretically, duration of the test with fan only is unlimited and with the combination of fan and injector is up to 120 s.

Instrumentation and data acquisition

Absolute pressure transducer with Bourdon quartz pipe and manufactured by Mensor is used for the measurement of total pressure P_0 in the test section. The transducer is pneumatically connected with Pitot probe, located in the upper part of the collector. The range of the transducer is 0.165 MPa. Non-linearity and hysteresis of these transducers are 0.02% F.S. The transducer is calibrated along with the system for data acquisition.

Static and total pressure difference, $P_{st} - P_0$, is measured by differential pressure transducer, manufactured by Druck, with the range of 0.007 MPa. Measurement points are the openings on the wind tunnel wall, at the exit of the collector. Non-linearity and hysteresis of these transducers are 0.02% F.S. The calibration procedure for this transducer is the same as the procedure for the total pressure transducer.

Total temperature T_0 is measured by RTD probe, which is placed on the same support as the probe for total pressure. The transducer accuracy is ± 0.5 K.

Resolvers, located in the mechanism for model movement measure the angle of attack, sideslip angle and rolling angle of the model.

Output of accurate digital watch is used as time base for data segmentation and it is sampled along with other transducer signals.

Data acquisition system is 64-channel system Neff 620/600, under control of VAX 8250 computer. Control of model support system movement is implemented onto a PC using software. The software on PDP 11/84 computer is used for controlling the wind tunnel operation.

Input signals of flow parameter transducers (i.e. P_0, $P_{st} - P_0$ and T_0) are adequately amplified and filtered, with low pass fourth order Butherworth filters, which have cut off frequency of 1 Hz.

A/D converter, with resolution of 16 bits, digitalizes data from analogous channels. Accuracy of A/D conversion is 0.1% F.S. of the respective channel. The sampling rate for all channels is the same, 200 samples per second.

Digitalized data are sent via fast receiver to the AlphaServer DS20E computer, where they are saved for the purpose of consequent reduction.

Preparation for testing

Criteria for tuft choice

Tufts with different diameters and various lengths are chosen for flow visualization of the local field. It is imperative to use polyamide, cotton or silk tufts because they are flexible and indicate the actual states of local vector velocity [1, 2, 3].

Tufts lengths from 0.5 m to 5 m are used in investigation of flow in the test section of wind tunnel. Tufts are fixed on special carriers in the centre of wind tunnel or on a wall. When flow is laminar and steady, the tuft is placed in the direction of the flow element and still. When flow is unsteady and turbulent, tufts follow the changes in the flow during the wind tunnel test. It is important that tufts follow the changes of turbulent flow in every moment, and at rotational flow to minimize the influence of centrifugal forces.

Tufts, which are to be glued onto the surface provided for visualization, must be flexible, of low density and adequate strength.

As surface of the *LASTA-95* model has great light reflection since it is not covered with dark paint, in order to ensure maximum contrast, black colour cotton tuft 30 mm long and 0.5 mm diameter was chosen.

Criteria for glue choice

In order to fix tufts for more or less twisted wing surfaces and also to keep tufts fixed to the surfaces during the whole period of visualization experiment, the glue must meet certain requirements [5].

Firstly, it must belong to a group of glues which are able to join duralumin and cotton.

Secondly, it must perform a joint of such strength, that tufts are glued in one spot, i.e. at a surface as small as possible on the model and to withstand all forces during the visualization test.

Thirdly, the glue must have such viscosity to spread over the surface of the model and along the tufts in a minimum amount, so that the realized joint is as small as possible disturbance on the model surface and that tufts maintain their flexibility, so more realistic flow picture can be obtained.

Then, the glue should cure as fast as possible for purely practical reasons.

And finally, the glue should be transparent to impart minimum disturbance at lighting and recording of tufts during testing.

Based on the given criteria, the choice of glue was narrowed. The two given glues meet the mentioned demands:

1. Loctite IS 454
2. Loctite LT 5366

Glue *Loctite IS 454* is cyanoacrylate gel adhesive, capable of joining cotton and duralumin and belongs to the so called moment (IS) group of adhesives i.e. the glued joint cures in 20 seconds. It is not coloured i.e. it is transparent. It is recommended for use on vertical and opposite surfaces.

Glue *Loctite LT 5366* is elastic paste adhesive, capable of joining cotton and duralumin and belongs to the group of adhesives which cure in the presence of air and the glued joints cure in 5 minutes. For this purpose, a transparent type was chosen. It is recommended for gluing and sealing of joints, which are exposed to vibrations.

Using both above-mentioned adhesives, a preliminary bonding of tufts and duralumin and determining of shear strength was done. Joint of tufts and duralumin, realized with adhesive *Loctite IS 454* has bigger shear strength than the joint of tufts and duralumin made with *Loctite LT 5366* glue. Based on this, the first adhesive was chosen for joining tufts to the model used in flow visualization. The *Loctite IS 454* glue was used for the first time for bonding of tufts for flow visualization in *VTI*.

Preparation of the model of LASTA-95 airplane

After final polishing, the surface of the *LASTA-95* model was cleaned and degreased using acetone, but it was not painted with dark colour. In this way, the surface was prepared for tufts bonding phase and visualization of the local field flow. On the surface, planned for visualization, i.e. on the upper surface of the wing, fuselage, horizontal tail, and both sides of the vertical tail, a net with 35 mm mash was drawn, in order to maintain proper distance between tufts and to prevent their entanglement.

The model of *LASTA-95* airplane for basic training, prepared for flow visualization in the test section of the wind tunnel *T-35*, is shown in Fig. 6.

Recording of changes in the boundary layer i.e. flow visualization effect was done using digital photos and camera.

Figure 6. The model of *LASTA-95*, prepared for flow visualization [4]

Data reduction

After each testing sequence data reduction is done using the standard wind tunnel reduction software *T35-APS*. Data reduction has several phases:

- Reading of raw data, normalization and translating into the standard format;
- Determining the flow parameters;
- Determining the model position;
- Determining the aerodynamic coefficients and hinge moments.

There is a different software module for each reduction phase.

Experimental results

The effects of flow visualization around the *LASTA-95* model at Mach number $M = 0.3$ in the wind tunnel *T-35* are shown in Figures 7 - 12.

Experimental results of testing *LASTA-95* model at Mach number $M = 0.3$ in the wind tunnel T-35 are shown in Tables 2 and 3 and in diagrams (Figures 13 and 14) [6].

The effects of flow visualization are very good. On lower angles of attack, up to $\alpha = 12^\circ$, tufts are still and occupy the flow direction. Fig.7 shows the effects of the flow visualization around the *LASTA-95* model at Mach number $M = 0.3$, angle of attack $\alpha = 4^\circ$ and sideslip angle $\beta = 0^\circ$. The increase of the angle of attack causes changes at the boundary layer and tufts follow these changes during the test. Changes at the boundary layer first occur at the root of the wing. The changes laminar in turbulence boundary layer spread in the direction of the wing end.

These effects cause a drop of lift force, which is shown in non-linearity of the lift coefficient curve and increase of the drag force (Fig.13). The values of the angle of attack which are obtained during testing with measurements of aerodynamic forces and moments with external six-component balance/support *TEM*, coincides with the values obtained in this test when the flow separation starts. The symmetry of flow during the test, as the start of changes at the boundary layer is tracked.

After the testing was done, visual inspection confirmed that only few tufts were missing, as consequence of an excellent preparation for the experiment.

Figure 7. Flow visualization around the *LASTA-95* model at $M - 0.3$, angle of attack α = 4˚ and sideslip angle β = 0˚ [4]

Figure 8. Flow visualization around the *LASTA-95* model at $M - 0.3$, angle of attack α = 12˚ and sideslip angle β = 0˚ [4]

Figure 9. Flow visualization around the *LASTA-95* model at $M - 0.3$, angle of attack α = 16˚ and sideslip angle β = 0˚ [4]

Figure 10. Flow visualization around the *LASTA-95* model at $M - 0.3$, angle of attack α = 20˚ and sideslip angle β = 0˚ [4]

Figure 11. Flow visualization around the *LASTA-95* model at $M - 0.3$, angle of attack α = 24˚ and sideslip angle β = 0˚ [4]

Figure 12. Flow visualization around the *LASTA-95* model at $M - 0.3$, angle of attack α=26˚ and sideslip angle β = 0˚ [4]

Table 2. The basic flow parameters for the testing of the *LASTA-95* model [6]

M	p_0 [MPa]	p_{st} [MPa]	MR_e	T_0 [K]	q [MPa]	V [m/s]
0,299	0.1005	0.0945	1,97	284,1	0.0059	100,074

Table 3. Aerodynamic coefficients for the *LASTA-95* model, obtained during testing at Mach number $M = 0,3$, at sideslip angle $\beta = 0^\circ$ [6]

i	α	C_x	C_y	C_z	C_l	C_m	C_n
1	-3.57	0.0349	0.007	-0.309	-0.0029	0.146	0.0020
2	-2.03	0.0290	0.006	-0.154	-0.0031	0.118	0.0020
3	-0.03	0.0239	0.006	0.044	-0.0032	0.084	0.0018
4	1.97	0.0238	0.004	0.242	-0.0033	0.053	0.0015
5	3.96	0.0267	0.004	0.439	-0.0036	0.023	0.0014
6	5.96	0.0335	0.003	0.634	-0.0036	-0.010	0.0014
7	7.96	0.0446	0.004	0.821	-0.0039	-0.045	0.0015
8	9.96	0.0589	0.003	0.994	-0.0038	-0.076	0.0014
9	11.95	0.0772	0.002	1.155	-0.0036	-0.109	0.0016
10	12.96	0.0880	0.002	1.231	-0.0036	-0.130	0.0016
11	13.95	0.0998	0.002	1.300	-0.0039	-0.156	0.0015
12	14.96	0.1167	0.000	1.329	-0.0047	-0.191	0.0015
13	15.95	0.1358	0.001	1.344	-0.0043	-0.226	0.0016
14	16.96	0.1582	0.001	1.352	-0.0051	-0.250	0.0017
15	17.96	0.1943	-0.002	1.355	-0.0022	-0.253	0.0021
16	18.95	0.2365	-0.009	1.316	-0.0007	-0.281	-0.0003
17	19.96	0.2878	-0.007	1.297	-0.0044	-0.302	-0.0038
18	20.96	0.3217	-0.005	1.256	-0.0033	-0.322	-0.0024
19	21.96	0.3445	-0.004	1.194	0.0027	-0.337	0.0017
20	22.96	0.3671	-0.003	1.158	0.0018	-0.355	0.0060
21	23.96	0.4044	-0.004	1.137	0.0003	-0.375	0.0023
22	24.95	0.4517	-0.007	1.094	0.0120	-0.393	0.0071
23	25.96	0.4850	-0.011	1.043	-0.0128	-0.406	0.0024

Fig.13 shows diagrams of drag and lift coefficients and pitching moment coefficient, obtained during testing at $M = 0.3$, at the angle of attack $\alpha = -3.5\ to + 26^\circ$ and model sideslip angle of $\beta = 0^\circ$.

Fig.14 shows diagrams of side force coefficients, rolling and yawing moment coefficients obtained during testing at $M = 0.3$ at the angle of attack $\alpha = -3.5\ to + 26^\circ$ and model sideslip angle of $\beta = 0^\circ$.

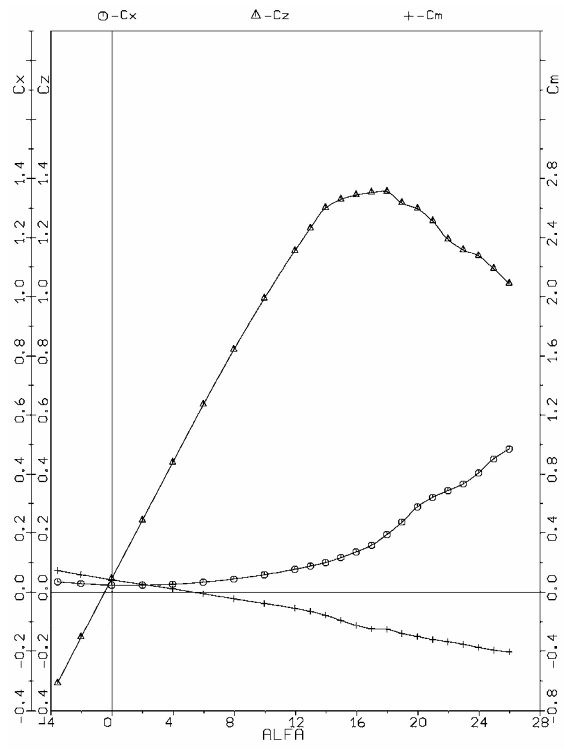

Figure 13. Diagrams C_x, C_z and C_m vs. angle of attack $\alpha = -3,5\ to + 26^\circ$, for the *LASTA-95* model [6]

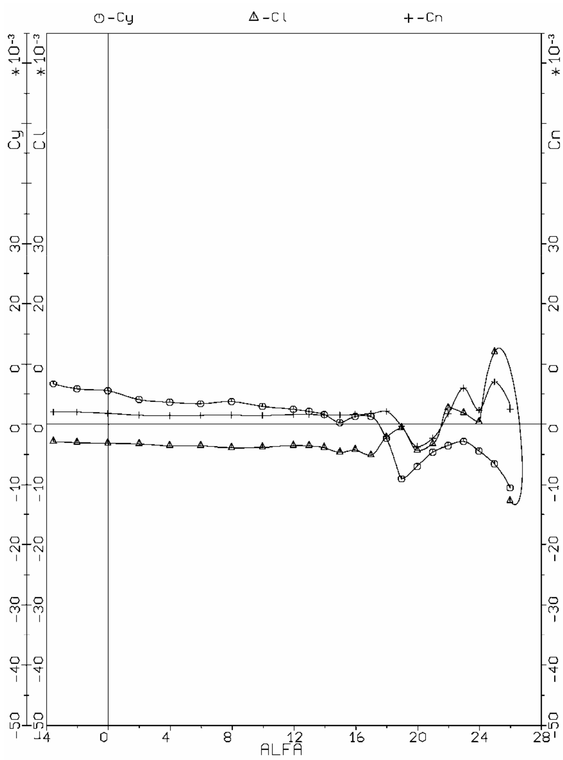

Figure 14. Diagrams C_y, C_l and C_n vs. angle of attack $\alpha = -3,5\ to + 26^\circ$, for the *LASTA-95* model [6]

Conclusion

The basic flow parameters, Mach number and pressure, are within the accuracy limits of measuring devices and equipment, which is the same for all tests. It should be pointed out that the obtained values of the aerodynamic coefficients were expected. The results of the *LASTA-95* model test in the wind tunnel *T-35* can be used for further analysis where they will greatly benefit future tests.

Using visualization with tufts, a good, clear, predicted figure of flow around the *LASTA-95* model was observed. Results, obtained by flow visualization confirmed those obtained from previous experiments without visualization. Effects of visualization test with tufts are clearly visible. To get a clear picture of the flow around the model, the flow visualization method by tufts in the boundary layer was an excellent choice.

Based on this experiment, it can be concluded that the flow visualization method by tufts is very useful for examinations in the aerodynamic tunnels and verification of some numeric methods.

Results of this experiment speak in favour of using a variety of methods to get more reliable results.

The obtained flow visualization results can be accepted on the whole and stated conclusions used for further investigations.

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Vizualizacija strujanja oko modela aviona *LASTA-95* i određivanje aerodinamičkih koeficijenata u aerotunelu T-35

Vizualizacija strujanja pomoću končića se veoma često koristi za ispitivanje strujnog polja u neposrednoj blizini modela. Posmatra se, ili se snima povijanje končića, koji prate svaku promenu lokalnog vektora brzine.
U ovom radu su opisani model aviona LASTA, ispitno postrojenje (aerotunel), kriterijumi za izbor končića i lepka, kompletan postupak pripreme modela za eksperiment, kao i rezultati ispitivanja dobijeni vizualizacijom strujanja pomoću končića.

Ključne reči: **avion, aerodinamički tunel, vizuelizacija strujanja, vizualizacija pomoću končića, strujno polje, lepak.**

Визуализация потока около модели самолёта "ЛасточКа-95" и определение аэродинамических коэффициентов в аэродинамической трубе Т-35

Визуализация потока при помощи ниток очень часто пользуется для испытаний поля потока в непосредственной близости модели. В этом процессе наблюдается или регистрируется каждое сгибание следящее каждое изменение местного вектора скорости.
В настоящей работе описаны: модель самолёта "Ласточка-95", испытательное сооружение (аэродинамическая труба), критерии для выбора ниток и клея, комплектная методика подготовки модели для эксперимента, а в том числе и результаты испытаний, получены визуализацией потока при помощи ниток.

Ключевые слова: самолёт, аэродинамическая труба, визуализация потока, визуализация при помощи ниток, поле потока, клей.

Visualisation de la circulation autour du modèle de l'avion LASTA-95 et détermination des coefficients aérodynamiques dans la soufflerie T-35

La visualisation de la circulation à l'aide d'une touffe est souvent utilisée pour examiner le champ de circulation à la proximité du modèle. On a observé ou filmé les mouvements de la touffe qui accompagnent chaque changement du vecteur local de vitesse. Dans ce travail on a décrit le modèle d'avion LASTA, l'instrument d'essai (soufflerie), critères pour le choix de la touffe et la colle, le procédé complet de préparation du modèle d'essai ainsi que les résultats des recherches obtenus par la visualisation à l'aide d'une touffe.

***Mots clés*: avion, soufflerie aérodynamique, visualisation de circulation, visualisation à l'aide d'une touffe, champ de circulation, colle.**