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Preparation of Computer Model of the Aircraft for Numerical Aeroelasticity Tests – Flutter

M. Rychlik, R. Roszak, M. Morzynski, M. Nowak, H. Hausa, K. Kotecki

Abstract**—**Article presents the geometry and structure reconstruction procedure of the aircraft model for flatter research (based on the I22-IRYDA aircraft). For reconstruction the Reverse Engineering techniques and advanced surface modeling CAD tools are used. Authors discuss all stages of data acquisition process, computation and analysis of measured data. For acquisition the three dimensional structured light scanner was used. In the further sections, details of reconstruction process are present. Geometry reconstruction procedure transform measured input data (points cloud) into the three dimensional parametric computer model (NURBS solid model) which is compatible with CAD systems. Parallel to the geometry of the aircraft, the internal structure (structural model) are extracted and modeled. In last chapter the evaluation of obtained models are discussed.

Keywords**—**computer modeling, numerical simulation, Reverse Engineering, structural model

I. Introduction

IF computer methods are increasingly replacing traditional research methods based on the experiments. This is due to the growing demands of customers for a low cost of the constructed elements, and shortening the entire process of creating the final product. For this reason, virtual models are created based on the technical documentation, or reconstruction of geometry from existing elements based on computer-aided design software (CAD systems) and Reverse Engineering techniques [1], [3]. Capabilities of these devices, combined with the advantages of CAD / CAM systems are creating new opportunities previously unattainable by other techniques. Furthermore, these technologies significantly reduce the time of a new product design process and simultaneously improve the quality

M.R. Author is with the Institute of Combustion Engines and Transportation, Poznan University of Technology, Poznan, Poland (phone: +48-61-6652167; fax:+48-61-6652204; e-mail: rychlik.michal@poczta.fm).

R. R. Author is with the Institute of Combustion Engines and Transportation, Poznan University of Technology, Poznan, Poland (phone: +48-61-6652167; fax:+48-61-6652204; e-mail: robert.roszak@put.poznan.pl).

M. M. Author is with the Institute of Combustion Engines and Transportation, Poznan University of Technology, Poznan, Poland (phone: +48-61-6652778; fax:+48-61-6652204; e-mail: marek.morzynski.@put.poznan.pl).

M. N. Author is with the Institute of Combustion Engines and Transportation, Poznan University of Technology, Poznan, Poland (phone: +48-61-6652104; fax:+48-61-6652204; e-mail: michal.nowak@poczta.fm).

H. H., K. K. Authors are with the Institute of Combustion Engines and Transportation, Poznan University of Technology, Poznan, Poland (phone: +48-61-66521; fax:+48-61-6652204).

To support design processes of machines, commonly the computer methods are used – so called: Computational Structure Mechanics - CSM [4], [6]). When design of new aircraft is testing, particularly in the prototype stage, important roles have the tests in the wind tunnel and tests carried out on the fly. These experiments are very expensive and require the preparation of scale models of the behavior of similarity, and for aeroelastic models additionally faithfully imitating the behavior of the real object. Therefore, as an alternative to the experimental methods, the numerical support is often used, allowing carrying out research in a virtual environment which are much cheaper and no risk of damaging the test model.

In the presented work, these advanced computer technology have been applied to develop a virtual model (geometry and structure) which is equivalent to the real aircraft model to flutter tests (model airframe IRYDA I-22).

II. Object Of The Analysis

Presented in the paper research work, was done basis on the real model of the airplane IRYDA I-22 (Fig. 1). Airplane was prepared according to the design of the Institute of Aviation in Warsaw.

Fig. 1 The I-22 IRYDA airplane

One of the constructed model is a model designed to study of the flutter phenomenon in the wind tunnel. Due to limitations in dimensions of the wind tunnel, the airframe was made in smaller scale. The geometric scale of the model was 1:4, according to this the dimensions of aircraft model are 3.3x2,4x1m (length, span, height), while the other scales were as follows (Fig. 2):

– K_v – speed scale 1:10;
– K_f – frequency scale 1:2,5;
– K_m – mass scale 1:64;
– K_ρ – density scale 1:1.

Fig. 2 airplane model for flutter testing (from top): external geometry of the airframe, the internal structure of the airframe

The entire model of the plane, have sheathing made of laminate, which corresponded to the external geometry. This geometry was used for create of the virtual model of the airplane shape. Internal structure of the model was simplified in comparison to the original but with keeping appropriate properties of mass, elasticity and damping. The hull consisted of primary aluminum girder cross-section, which was divided into sections differing mechanical properties. In addition, the burden of lead placed in locations that correspond to items such as aircraft landing gear, engines, fuel tanks, cockpit equipment, etc. Similarly, the wings were built and rudders: horizontal and vertical. It received a cross I-beams and U-beams.

The process of reconstruction and development of computer models (shape geometry and structure) has been presented in the further paragraphs.

III. The Measurement Process – 3D Scanning

Reverse engineering (RE) is a branch of knowledge, dealing with the whole issue of three-dimensional scanning. It covers areas related to data acquisition (all of the spatial scan methods), technology (construction of measuring devices) process of reconstruction of the geometry of the measured objects, and data processing to formats, acceptable by the various CAD systems. The most common RE devices are based on optical methods: laser or structured light scanners.

In the present study for measuring the optical scanner - structured light (Fig. 3) were used. The measuring resolution of scanner is 0.05 mm with the volume of the measuring 450x450x120mm.

Fig. 3 Three-dimensional structured light scanner; example of the measuring process (projection of the raster)

Because of the size of the measured model, which greatly exceeds the measuring range scanner, it was necessary to make several measurements from different directions. To facilitate identification of individual measurements of the whole plane, he is divided into areas by special reference stripes with a constant pitch. Addition, the entire hull was covered with a special powder in order to minimize light reflections on the surface of the paint.

Such prepared aircraft underwent a process of 3D scanning, which took place according to the following pattern (Fig. 4). The plane along length was divided into 14 sections measuring (assigned numbers from 1-14), while the cross section of the hull separated 7 (numbered from the A to E) and one additional section F for vertical rudder. Due to the symmetry of the object, the scan was performed for only one half of the aircraft

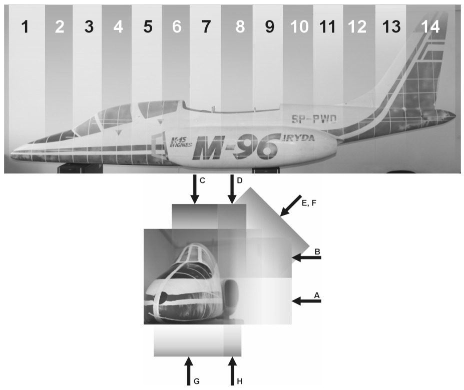

Fig. 4 Distribution of the measuring sections for the plane fuselage (from left): along the hull 1-14, cross sections to the hull A-F

In each of the measurements, were received set of points (called a points cloud) along with the data in the form of surface texture (RGB color palette). The total number of measurements of the hull was nearly 100 measurements.

In the next steps, each measuring point clouds were pre processed: remove error points (the noise), smoothing, removing discontinuities and simplification (reducing the number of points). The subsequent step was the merging of each points cloud (registration process) so that they form an integral whole (Fig. 5).

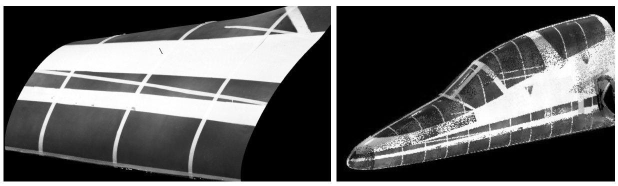

Fig. 5 Pre processing of the point clouds (from left) : prepared point set, the result of the registration process of several clouds of points

Due to the very specific shape (thin profile), for the wings the different measuring methodology were adopted. On each element - wing or rudder surface - the additional markers (in the shape of spheres) were installed (Fig. 6).

They were used as markers for the registration process. By this way, the effect of deformation of the shape of the leading and trailing edges, which occurred in the case of measurements without markers, was eliminated.

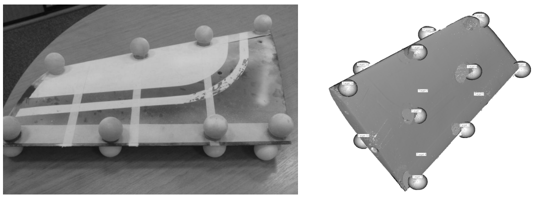

Fig. 6 The measuring procedure for wings and rudders (from left): a system of markers on the test object, the result of the data registration process using markers

Further processing of the point clouds of the wings and horizontal rudder was the same as in the case of the hull. The end result was obtaining three global point clouds, one for the fuselage, wings and horizontal rudder (Fig. 7.)

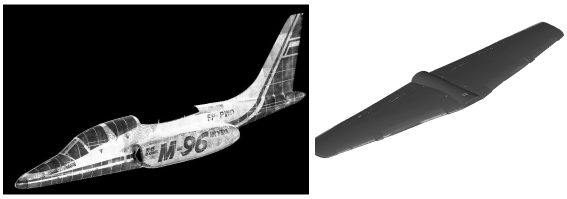

Fig. 7 The result of the scan process: the global points clouds of fuselage and wings

IV. The Geometry reconstruction process – NURBS modeling

The Geometry reconstruction of the object based on data from 3D scanners is complex and time consuming process. Quality of the model is dependent not only on the quality of data obtained from the scanner, but also the proper data processing at each stage. Therefore, it is necessary to permanently control the process parameters as well as points of reference and characteristic, of the created geometry.

Due to the above conditions have been developed, algorithm of process of building NURBS model (Fig. 8):

1) First phase – preparation of input data.
2) Second phase – creating a triangular surface mesh and computation of skeletal curves.
3) Third phase – create NURBS surfaces from skeletal curves and guide curves.
4) Fourth phase – analysis of curvatures and merging of the surfaces into a single compact model

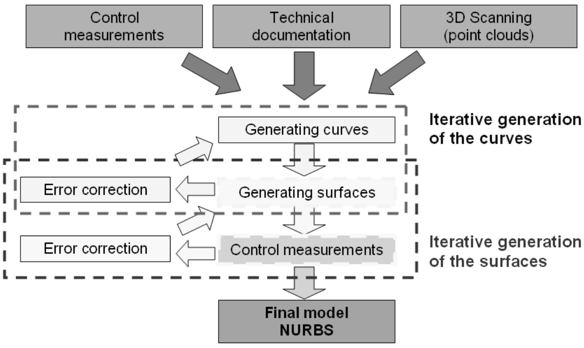

Fig. 8 Geometry reconstruction algorithm

In order to properly reconstruct of the geometry and to its control in the first phase, the data from three primary sources were collected (Fig. 9): manual measurements of selected reference points (such as length, wingspan, etc.), technical documentation data, measurements of the 3D scanner.

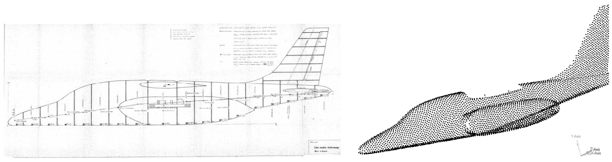

Fig. 9 The input data to the geometry reconstruction process (from left): technical drawings, a point cloud of the plane hull

In the second phase the point clouds were subjected to a triangulation process (Fig. 10). In this case, the result was the triangular mesh consisting of approximately 4.5 million triangles describing the hull of the plane. A similar process has been made for the wings and horizontal rudder.

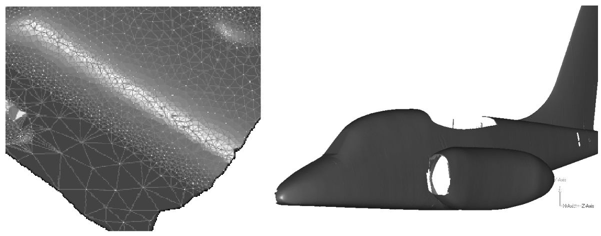

Fig. 10 The processing of point cloud (from left): the triangulation process, triangular mesh of the plane hull (4.5 million triangles)

During generation a surface mesh, appear a numerous errors such as (Fig. 11): ambiguity errors in the areas of edges of the object, the local errors of concavity or convexity, surface discontinuities (gaps in the measurement data), areas of intersecting points. All defects must be removed by smoothing, correcting errors and also by filling cavities (called "patching holes") in the grid surface. For this purpose special algorithms that are supplied with special Reverse Engineering software.The final result of this stage is cleared triangular surface mesh.

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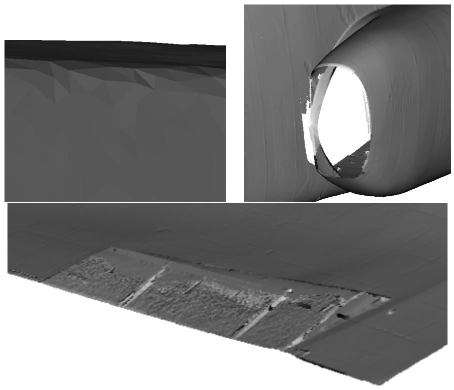

Fig. 11 Examples of errors of process generate surface mesh (from top-left): edge errors, the surface of discontinuity (the missed input data), areas of intersecting points

Based on the prepared surface mesh, on airframe the cross sectional profiles, in three main directions, were determined (Fig. 12): transverse, horizontal and vertical sets of curves.

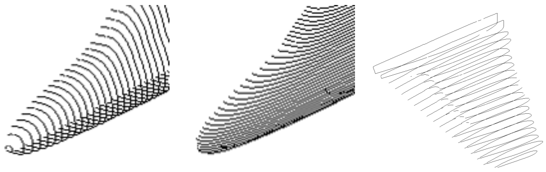

Fig. 12 Cross-sectional profiles of the airframe (sets of curves): transverse, horizontal and vertical direction

The individual curves were smoothing (with curvature analysis) in order to eliminate future concave or convex surface. The following steps are carried out activities related to the elaboration of optimal curves describing the various parts of the reconstructed surface of the object (Fig. 13). To maintain consistency between future NURBS surfaces is necessary to connect to the common nodes of curves from different directions (e.g. cross-sections of vertical and horizontal). During this process the guided curves are created that are elements leading and controlling the shape of the surface area between the curves in profiles. On the end the NURBS surfaces is created on curve network.

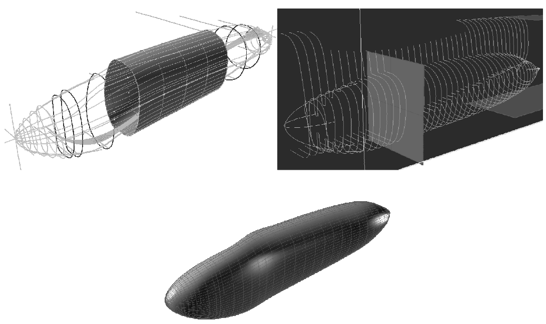

Fig. 13 The processing of curves and NURBS surface creation (from top-left): smoothing and curvature analysis of individual curves, the curves connectivity the common node, final NURBS model of engine nacelle

For the wings and rudders (horizontal and vertical) used a different technique of reconstruction. Difference stems from the need to behave in accordance with the original aerodynamic profile of the wings. Based on technical data plane cross sections were determined geometries of the wing (NACA-64A010 and NACA-64A210), and based on data from a 3D scanner create the outline curves adjusted for the size of the wings in the documentation. Individual profiles were subjected to cross-connect at nodes of the outer contour curves (Fig. 14). The prepared data were used to determine the NURBS surfaces describing the geometry of the wing.

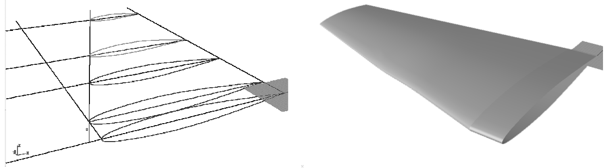

Fig. 14 The stages of reconstruction of the wing: the transverse profiles of NACA and the outlines of the wings, ready NURBS model of the wing

The last stage of the creation of a NURBS model, was to combine into one unit different airframe components: fuselage, engine nacelle, wings, vertical stabilizer, horizontal stabilizer (Figure 15). Ultimately resulting is a three-dimensional model fully compatible with CAD systems.

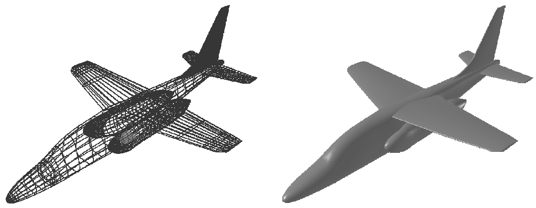

Fig. 15 The reconstructed geometry of the airplane model for flutter tests: main grid of the curves, final computer model (CAD)

In order to determine the quality of the resulting model was a two-step evaluation by using the control measurements (Fig. 16). In the first stage were measured characteristic geometrical dimensions, such as: total length aircraft wing span, span horizontal stabilizer, vertical fin height, the width of the wing at the fuselage. Then they were compared with data contained in the technical documentation of the aircraft. The average size of the reconstruction error did not exceed 0.17 mm.

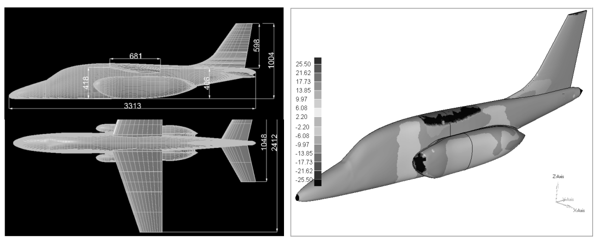

Fig. 16 Evaluation of a computer model of geometry (from left): measurement of the characteristic dimensions, comparative measurement of deviation between the NURBS model and triangular surface mesh

In the second step was to check the surface measurements by verifying the NURBS surface deviation from the data source, a triangular surface mesh (3D scanning). The measurements showed that the mean distance between the surfaces did not exceed 0.33 mm. Analyzing these data we can say that the aircraft geometry reconstruction error is + / - 0.5 mm

V. The process of Creating A Computational Structural Model Of Aircraft

Since there wasn't all of the necessary information's (relevant dimensions and information about the material properties of individual elements) that are needed to create a precise model of the structure, was developed auxiliary solid model - so-called transition model. The purpose of this procedure was to obtain the coordinates of gravity and the size of the moments of inertia of all elements included in the test object. Solid model was created in CAD system, based on: the technical documentation, and direct measurements on the elements of a real airplane model for flutter testing (Fig. 17).

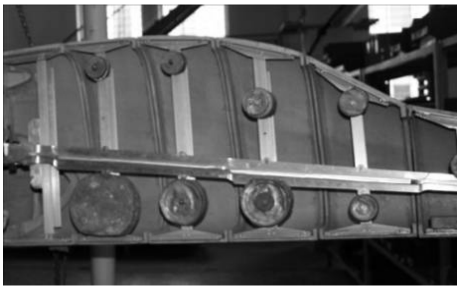

Fig. 17 View of the internal structure of a real airplane model for flutter testing

The real object for flutter testing consisted of:

– hull divided into 18 sections,
– wings divided into 13 sections,
– rudders: horizontal and vertical, divided into 6 sections.

Each segment contains a portion of the hull girder, two U-beams, two T-beams and sheathing taken into account as a weight-centered (described by a sphere, situated in the center of gravity of the section). This follows from the fact that the hull has a complex external shape with changing its thickness. In front of the fuselage with added weight at the top and bottom sections, reflecting the aircraft elements such as chassis, motors, etc. Each segment of the wing and rudders consisted of a portion of the girder and the shell mass.

As a result of the similarity of components forming each segment, was used parameterization of the model based on a spreadsheet. First, the pattern model was created for each element forming a part of one section (beam, channel bar, I-beam, lead load). Then, the remaining segments of the whole structure were created automatically from entered in a spreadsheet dimension of individual sections (Fig. 18).

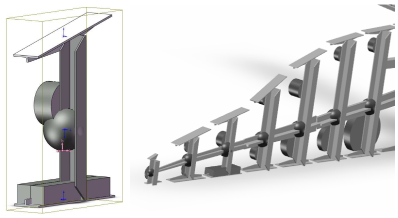

Fig. 18 Creation of segments obtained in the parameterization process (from left): single section, sections of the front of plane

Items not subject to the parameterization are following: the central segment and connections of rudders to the hull. After placing all generated elements the transition model was created (Fig. 19). It consists of 249 parts, including 58 parts by weight mapping mass ticking.

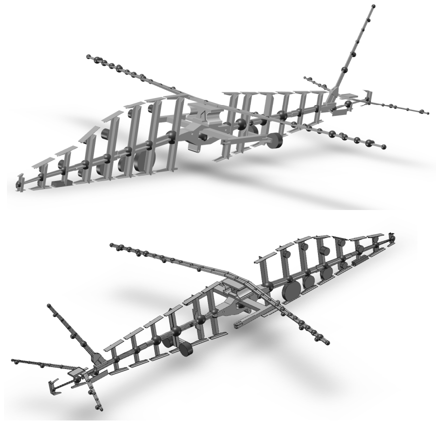

Fig. 19 “Transition model” (solid CAD model) of the structure of a real airplane model for flutter testing

The criterion for the correctness of the design model in CAD software is compatibility of the masses. Actual weight of the model was derived from measurements of 75,6kg, while the mass of a computer solid model was 78kg. Error of the created model was about 3.17%. The discrepancy of the masses resulted from the due to the simplification of the elements connecting the different parts of the model together.

On the basis of the resulting model, prepared statement, this includes all the necessary data to build the final version of the computational structural model. It includes information about the masses of individual elements, the positions of their centers of gravity, moments of inertia and geometric dimensions.

The fluid-structure interaction software, used in the Flutter Laboratory at Virtual Engineering Group, compute the force reactions of the object structure on the fluid flow is calculated based on modal analysis [5]. Loads are introduced based on the pressure distribution, which is interpolated from the results of flow analysis in the structural model nodes. Dynamic properties of the structure are written in the form of modes and eigenvalues.

Ground resonance tests conducted at the Institute of Aviation in Warsaw, helped determine the data using a method of dynamic identification [2].

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Retained the original documentation form allows to reconstruct only the frequency of its own and the general shape of the corresponding modes.

In order to obtain the missing information, modal analysis is performed, which are determined natural frequencies and corresponding eigenvectors for the numerical model. Determined the values and the excitations are used to calculate the displacements of the model during aeroelastic simulations.

In order to perform correct numerical analysis of the structural model is required correspondingly large number of degrees of freedom of which imitate the behavior of the modeled geometry. For numerical calculations, of the modal analysis are important first eigenvectors, corresponding to the eigenvalues of the lowest frequency of vibration. On their basis is formed low-dimensional model that provide good performance at a significantly reduced computational requirements.

Therefore, the next step of the construction of the low-dimmensional model of structure (in the FEMAP) based on the solid model (in CAD). The process of creating the model began with the designation of the principal axes of the selected nodes defining the location of individual sections of the aircraft (Fig. 20).

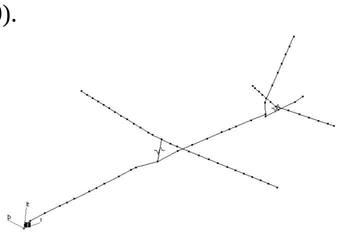

Fig. 20 Visualization of the principal axis for low-dimensional structural model

Then was created: the girders of the hull, wings and rudders, with beam elements. All information on the geometry of the cross sections and material properties were taken from previously prepared spreadsheet (transition model).

All other elements (channels, tees, leaden load, etc.) based on Steiner's theorem is reduced to the point mass (with the appropriate moments of inertia) that are in the geometric centers of each section. This step was performed in a spreadsheet, then the results send to the program FEMAP.

The final model consisted of: 69 beam elements, 96 mass elements and 278 nodes (Fig. 21).

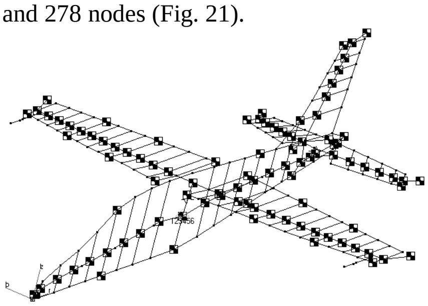

Fig. 21 Preliminary low-dimensional model for the calculation of structure

The criterion for the correctness of the calculation model, which will be used to simulate aeroelasticity, was that the results of modal analysis, i.e. the natural frequencies and modes of their form the corresponding real with the virtual model.

Preliminary model calculations showed most compatibility mode shapes, but differences occurred in the values of frequencies obtained from modal analysis. The accuracy of the results of reduced model was insufficient to conduct aeroelastic numerical simulation. In order to avoid differences between objects made to tune the numerical model. The process was conducted in two stages: Stage 1 - by changing the fixing point of the model and stage 2 - by changing the mechanical properties of materials.

After receiving the preliminary results of modal analysis, new fixing elements, as the two tension springs was used (Fig. 22).

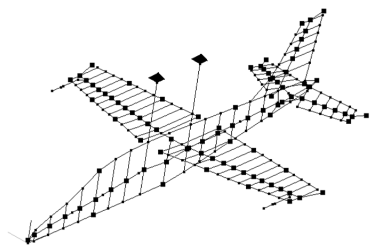

Fig. 22 Low-dimensional numerical model with the revised fixing point

The second modification was to tune the model by changing the material parameters, compensating for differences arising from the simplifications that occur at the stage of creating a solid model. After tuning the model the modal analysis was done and new results were obtained (Table 1, Fig. 23).

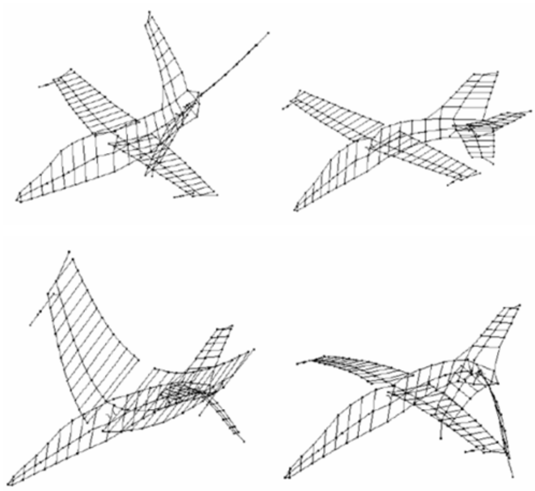

Fig. 23 Examples of 4 first Eigenmodes of I-22 IRYDA (from upper left): 1-st mode, 2-nd mode, 3-rd mode, 4-th mode

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After a calculation of modal analysis and comparing the resulting obtained for numerical model with the results of real model can be stated that the errors are:

– less than 1 Hz for the first five modes and modes No. 8, 10, 11, 13, 14;

– less than 2 Hz for a modes No. 7, 12, 16;

– above the 2Hz for the others.

Not identified numerically 9th and 20 modes shapes, while the 19th form of vibration is far from experimental results.

VI. Conclusion

The paper shows how to create a numerical model of the geometry and structure of the aircraft on the basis of available documentation and measurements of the real model aircraft.

Application of reconstruction techniques in the process of reverse engineering allows for the geometry of an object and putting it into CAD systems. This technology is particularly helpful where there is no technical documentation (no CAD models) describing the object. Final result, three-dimensional model, is fully compatible with CAD systems and can be used for further processing and numerical analysis.

The resulting computational model of a virtual plane I-22 IRYDA, is designed for the analysis of the system used by Flutter Laboratory at the Poznan University of Technology. This model has a relatively small number of nodes, which significantly reduces the computation time.

TABLE I
Comparison of results of ground resonance tests and of the numerical model

	Form of vibration	Results: Experiment f [Hz]	Numerical analysis f [Hz]	Error f [Hz]
1	First	4,11	3,85	-0,26
2	Second	4,61	4,65	0,04
3	Third	4,90	4,06	-0,84
4	Fourth	6,23	5,91	-0,32
5	Fifth	6,70	6,16	-0,54
6	Sixth	7,02	9,68	2,66
7	Seventh	7,81	6,68	-1,14
8	Eighth	10,47	10,15	-0,32
9	Ninth	11,56	-	-
10	Tenth	14,54	14,72	0,18
11	Eleventh	14,47	13,94	-0,53
12	Twelfth	15,10	16,28	1,18
13	Thirteenth	15,58	15,27	-0,31
14	Fourteenth	17,88	17,08	-0,80
15	Fifteenth	17,98	15,12	-2,86
16	Sixteenth	30,80	29,57	-1,23
17	Seventeenth	40,10	37,33	-2,77
18	Eighteenth	39,90	36,74	-3,16
19	Nineteenth	44,60	38,55	-6,05
20	Twenty	48,30	-	-

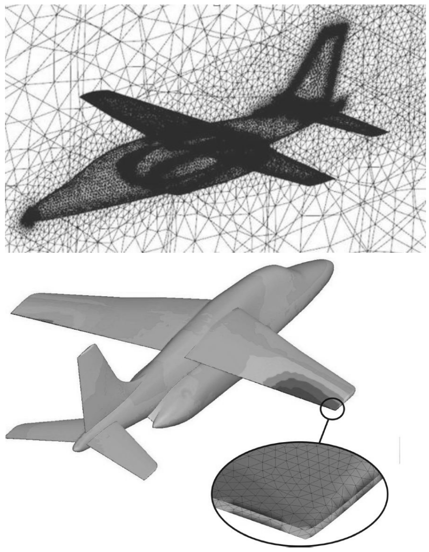

Fig. 24 Example of the results of fluid-structure interaction obtained for I-22 IRYDA aircraft

An example of results (Fig. 24) obtained in the analysis of the flutter phenomenon for aircraft I-22, are outlined in the second part of the work entitled: “COMPUTATIONAL AND EXPERIMENTAL INVESTIGATION OF AERO-ELASTICITY FOR THE FLUTTER AIRCRAFT MODEL” (R. Roszak at all).

The most important criterion for the correctness of reconstruction of the computational model is compatibility the results, of modal analysis with the results derived from ground-based attempts to resonant real model the flutter. Discrepancies between the models are reduced in the process of tuning the model, which consists of independent change of material properties for each item.

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