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CONCEPTUAL AND AERODYNAMIC STUDY OF A HIGHLY MANOEUVRABLE JET TRAINER

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Abstract

The article discusses the initial study of the two-seat jet trainer with high manoeuvrability. The study included the concept of structural layout of the aircraft, as well as the development of its aerodynamics. The mail aim was to ensure the correct airplane characteristics (in particular control efficiency and dynamic properties) in the wide range of angles of attack. Another challenge was to ensure adequate aerodynamic characteristics at high transonic speed range. The geometry of the aircraft has been developed using CAD system (Simens NX). Initial aerodynamic study and aerodynamic design of the plane were performed using both: the low speed wind tunnel tests performed at Warsaw University of Technology using six-component internal balance and computational work performed using ANSYS CFX computer system. The first was used mainly to check characteristics at high angles of attack. Modifications of the wind tunnel model geometry at this stage were performed using the plastic mass (plasticine), or replacing some components of the model. An important problem with such approach was the lack of a precise definition of the revised geometry in the CAD system. Computational study was performed mainly to check high-speed characteristics. The final geometry of the modified wind tunnel model generally meets the requirements.

Keywords: *aerodynamics, aerodynamic project, high angles of attack, manoeuvrability, aircraft design*

1. Introduction

Since the dawn of military aviation, great role was paid to the class of aircraft used for pilot training. This kind of aircraft should meet very specific requirements. As a standard was adopted two-seater aircraft, which allowed faster and safer to enter into the secrets of the military pilot profession. On the one hand they had to meet the economic requirements (low cost of production and operation), on the other ensure the safety of young flying students - should therefore be properly piloted and forgiving the initial mistakes. At the same time, especially with respect to more advanced training, such aircraft should have properties as close as possible to the target combat aircraft, on which will fly trained pilot. These requirements stand in partial contradiction. With the introduction of jet-powered military aircraft, it was necessary to enter trainers with the same propulsion and similar flying characteristics. In the case of military pilots training, it is also important to use avionics equipment, compatible with that used in combat aircraft, and even the compatibility of the cockpit, its ergonomics and indicators (analogue or digital). The rate of exchange of training aircraft in military aviation is much slower than exchange of combat aircraft; a very important issue is the opportunity of modernization and customizing aircraft of this class to the current requirements. The ability to modify the structure of the aircraft, its equipment and change the arrangement of the cockpit, exist only in cases of using aircraft owned design and production. In the case of foreign aircraft, any process of adaptation requirements changes is not only difficult, but also expensive. An example of this problem is the aircraft TS-11 Iskra. Although it remains in operation for more than half a century and differs significantly from contemporary design, its subsequent adaptation to the current needs of training and introduced (unfortunately quite shallow) modernization, caused that it was (and still is) very positively perceived by users. Other highlighted features of training planes are (compare with the combat aircraft) much longer and more intense exploitation, much more frequent take-offs and landings, and higher possible undercarriage load during the landing (due to possible higher vertical speeds at approaching by novice pilot). Finally, it is necessary to provide longer service life of the aircraft structure. Additionally currently fundamentally has changed the requirements for jet trainer designed for present military adepts. This is due to the revolution, which had (and still has) a place in military aviation, in particular with regard to fighter and multi-purpose aircraft. Currently come into operation new generation of aircraft that allows for manoeuvres inaccessible for older aircraft, both in terms of manoeuvrability, as well as with regard to the avionic equipment and the new class of weapons. Particularly important is the ability to operate (while providing full control) in the wide range of angles of attack. Examples include Eurofighter Typhoon, Saab Gripen, F-35 (having a limit of operational angles of attack 50°), or fighter F-22, which could operate up to 60° angles of attack. This allows to use in combat operations (especially in air combat), a new type of manoeuvres, inaccessible to older types of aircraft, making the latter opponents little effective in the case of a clash in the air.

Until now, there exist only a few aircraft that meet the requirements for training of pilots in such conditions. Practically only Russian Yak-130, the Italian Aeromacchi M-346, and the Chinese Hongdu L-15, was introduced into operation, provide similar features to the latest combat aircraft. The aircraft M-346 allows operating up to 40° angles of attack. These aircraft are however, twin-engine design, quite heavy; the cost of production and operation is much higher compared to the relatively simple jet trainers used previously.

In the late 90' s in Poland was taken up a program of light jet aircraft EM-10 Bielik [1], which was an attempt to build (for realized stage) experimental aircraft with straked wing, able to operate at high angles of attack (in the intentions of the order 35°) . The plane did not gain interest of the customer and practically a program has been deleted (the prototype had performed only two flights), but it seems that the experience gained that time can provide an impulse to the new approach to such a topic.

The paper describes the initial stage of the study of the light, single engine jet-trainer concept, which could operate at such angles of attack, which are typical for modern, today introduced into service fighter aircraft. At the same time, it would be a much smaller and lighter plane, with a significantly reduced cost of the design, production and operation.

2. Scale effect on the aircraft properties

We can consider two aircraft that have the same shape and structure but different size – Fig. 1. The second aircraft has all dimensions smaller, and the linear scale factor is ***n***. Scale factors for other quantities can be easily found and are presented in Table 1. In the case of figure 1 scale, factor ***n*** is equal 1/2. It is seen that scale factor for surface area is 1/4, volume 1/8. Assuming the same material the mass of the second plane will be also much smaller: 8 times. Inertia moment is 32 times smaller. Assuming the same aerodynamic properties of both aircraft, the characteristic speed (for the same angle of attack) will be smaller $2^{1/2}$ times. The same for characteristic time (e.g. time of specific manoeuvre). The characteristic angular speeds will be higher $2^{1/2}$ times. It may be shown that for the same load factor stresses in the structure will be smaller 2 times, structure linear deflections 4 times smaller, bending angles 2 times and structure vibrations frequency 2 times higher. Summarizing up we can find that smaller aircraft is much more manoeuvrable, has reduced stress level (and longer structure lifetime) and causes fewer aeroelastic problems (e.g. flutter). As a result, we can find that overall problems related to development of smaller aircraft are much smaller. In addition, the production cost and final price (related to the aircraft empty mass) is much smaller in a case of smaller aircraft. Finally we could find, that pure military jet trainer (with no, or only very limited capabilities of carrying weapons) should be designed as small one. This reduces cost and technical problems. Difficulties rising with such solution are smaller range (not important in a case of trainer), larger movement of the plane centre of gravity and general difficulties with aircraft arrangement (crew, ejected seats cannot be scaled; cockpit and avionics cannot be equally scaled).

Fig. 1. The scale factor for the plane

Tab. 1. Scale factors

SCALE FACTORS	
Linear dimensions	n
Area	n^2
Volume	n^3
Density	1
Mass	n^3
Linear acceleration	1
Moment of inertia	n^5
Linear velocity (α = const)	$n^{1/2}$
Time	$n^{1/2}$
Angular speeds, roll rate, …	$n^{-1/2}$
Stresses (σ, τ – same load factor)	n
Linear structure deflections	n^2
Bending and torque angles	n
Structure vibrations frequency	n

3. Problems of high angles of attack aerodynamics

High angles of attack are inherently related to the flow separation and generation (intentionally or unintentionally) the strong vortical flow. As a result, we have a highly non-linear dependence between the aerodynamic forces and moments vs angles of attack, sideslip and control surface deflections [2, 3, 4, 5]. In order to increase the lift force at manoeuvres, vortical flows are generated using specifically shaped elements, that enforce (at high angles of attack) flow separation and generate strong and stable vortices. One of such solution is the use of strakes (typically sharp surfaces having small aspect ratio and large sweep angle, located in front of wing root).

Aerodynamics dealing with high angles of attack and vortical flows is called *nonlinear aerodynamics*, where the laws of classical aerodynamics and flight mechanics do not apply. Among other things, modern fighter aircraft are equipped usually with a system of indirect control ("fly-by-wire") and are generally longitudinally statically unstable. Desirable properties of the flying characteristics are provided through customized aircraft flight control system and control laws. It must be, however, guaranteed the required "controllability" of the aircraft. In other words, the ability to produce certain moments, necessary to enforce an appropriate aircraft response due to control system input. Lateral and directional stability are usually provided in a natural way, through proper composition of the aerodynamic layout of the aircraft. At high angles of attack there is usually difficult to enforce efficiency of aerodynamic controls due to strong flow separation. Dependences of forces and moments on the angle of attack, angle of sideslip and control surfaces deflections are also strongly nonlinear. Typically, at high angles of attack we have problems with generating required negative longitudinal moment, required to reduce angle of attack in order to restore level flight. Also aerodynamic derivative of directional stability due to sideslip Cn_β is incorrect (due to hiding tail by separated wing and fuselage wakes. The lateral derivative Cl_β becomes incorrect at moderate angles of attack (~30^O-35^O) due to flow separation and nonsymmetry of vortex core corruption (vortex break down).

Dynamic properties of the aircraft at high angles of attack due to sideslip, however, do not depend directly on the above derivatives and must be analysed in a different way [6]. This can be illustrated as follows. In a case of sideslip at high angle of attack, there should be tendency for reduction of departure from the flight path direction. This depends on both **Cn** and **Cl**, and the angular acceleration of restoring the initial direction is proportional to the term:

$$Cn_{\beta dyn} = Cn_\beta \cdot \sin\alpha - \left(I_z / I_x\right) \cdot Cl_\beta \cdot \cos\alpha . \tag{1}$$

It is required positive value of this term, in which case an aircraft should have no departure and pro-spin tendency. It should be noted that modern aircraft have, due to its small wingspan, a small moment of inertia with respect to the longitudinal axis (Jxx) compared to the moment of inertia around the vertical axis (Jzz). A typical ratio Jzz / Jxx of modern combat aircraft is 6-7, and as a result, a derivative of the lateral moment due to sideslip (Cl_β) at high angles of attack is critical to the characteristics of stability and dynamic behaviour of the aircraft. It should also be noted that any underwing weapons have significant influence on the moment of inertia Jxx, typically limiting value of $Cn_{\beta\, dyn}$ and reducing the maximum permissible angles of attack.

Other term that describes aircraft property at high angle of attack is LCDP (Lateral Control Departure Coefficient):

$$LCDP = Cn_\beta - Cl_\beta \cdot \frac{Cn_{\delta a} + ARI \cdot Cn_{\delta r}}{Cl_{\delta a} + ARI \cdot Cl_{\delta r}} , \tag{2}$$

where: $Cn_{\delta a}$ and $Cl_{\delta a}$ are directional and lateral moment derivatives due to ailerons deflection,
$Cn_{\delta r}$ and $Cl_{\delta r}$ are directional and lateral moment derivatives due to rudder deflection,
ARI is ailer-rudder interconnection factor

This coefficient describes aircraft response on correct pilot's ailerons deflection in a case of sideslip. It should be positive.

Flight tests and aircraft dynamics simulations allowed to define the parameter ranges $Cn_{\beta dyn}$ and ***LCDP*** in which the aircraft has desirable or undesirable dynamic behaviours. This represents the so-called integrated Bihrle-Weizmann chart - Fig. 2. In the area A an aircraft properties are entirely correct, it has no departure, pro-spin and aileron reverse tendencies and is fully controllable. Area D is typical for classical aircraft that have spin tendencies at high angles of attack.

4. Basic concept and design objectives of the jet trainer

Presented conceptual study of the high manoeuvrable jet trainer refers to light, single-engine aircraft with straked wing, with "fly by wire" control system and digital avionics ("glass-cockpit").

The main additional criterion to be fulfilled is the low cost of production and operation. The aircraft should meet all modern requirements for the two-seater trainer, including the performance and ergonomics. One of the requirements of the standard presently is the elevation of the rear pilot to meet the visibility requirements. It was assumed that the dimensions of the aircraft under consideration should be close to the size of the TS-11 Iskra aircraft. This also applies to the weight.

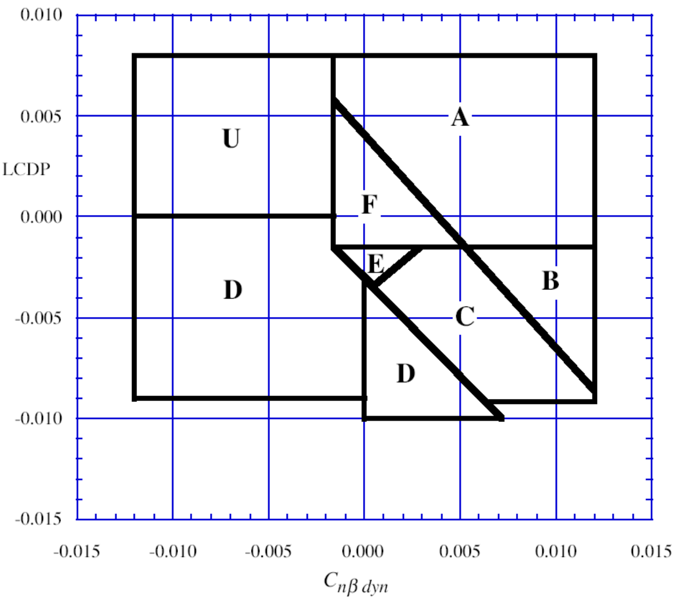

Fig. 2. Integrated Bihrle-Weizmann chart

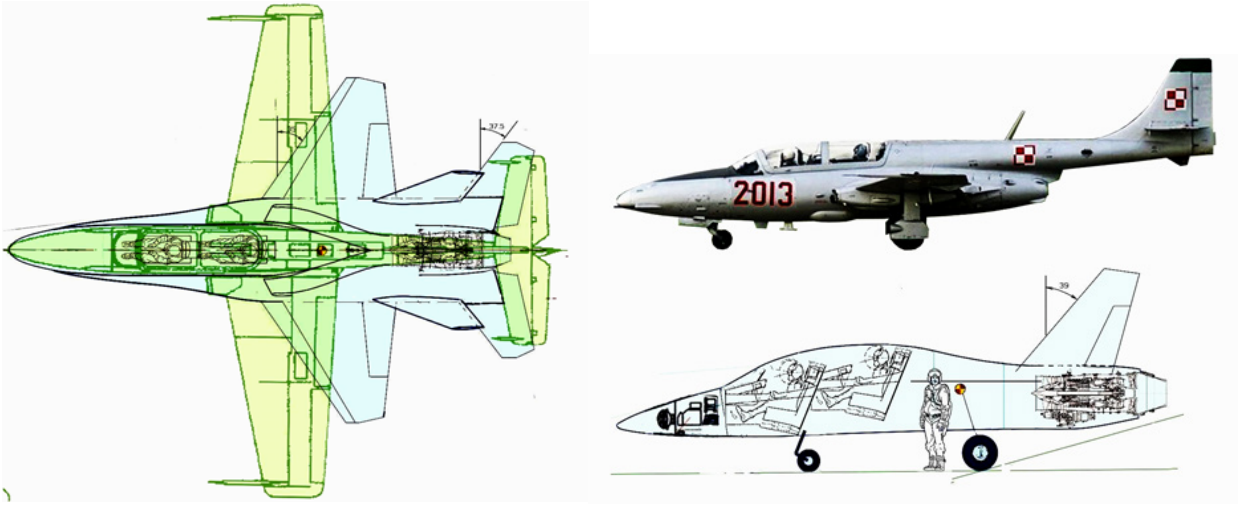

Fig. 3. Conceptual sketch of the considered light jet trainer and older TS-11 Iskra

Fig. 3 shows a rough sketch of the concept and arrangement of the plane along with a comparison to the size and the aircraft TS-11 Iskra. The length of the plane set at less than 11 m, span approx. 7.2 m, and wing surface about 16 m^2.

The analysis predicts the mass of the empty aircraft 2350-2450 kg. Normal take-off weight version for training 3700-3800 kg. Maximum take-off weight with additional under wing weapons (four points, 1200 kg max.) 4800-4900 kg. Proposed propulsion: turbofan engine having max. thrust of the range 2800-3000 [dN]. Anticipated initial estimate of basic airplane performance: top speed at low altitude approx. 1100 km/h, rate of climb, depending on the engine version 80-120 m/s. It is assumed allowable Mach number at high altitude in descent flight 1.2. Planned control surfaces and devices: wing leading edge flaps, flaperons, tailerons, rudder and airbrake. More detailed concept, including internal layout and basic structure is seen on Fig. 4.

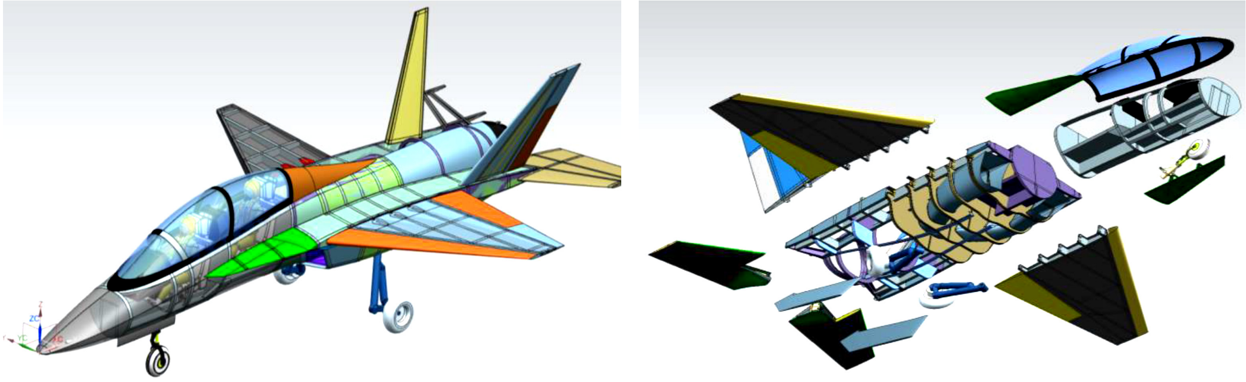

Fig. 4. Basic conceptual layout and structure

5. Aerodynamic analysis

High-speed characteristics were analysed mainly using ANSYS CFX software [7], but additional software was used for two-dimensional calculations and panel method for three-dimensional design. Typical CFX unstructured mesh size (including viscous prism layer) was 7.5 million elements for symmetrical case and 15 million elements for nonsymmetrical one. Basic wing airfoil has slightly peaky type pressure (and very low negative pressure in the middle chord), that allow for high isobars sweep near the leading edge – reducing initial transonic drag rise. Typical picture of a pressure distribution and supersonic flow region and drag rise for two version of the plane at low angle of attack is seen on Fig. 5. Generally, high-speed characteristics are satisfactory at such stage of design. Drag rise is very moderate up to Mach number 0.9.

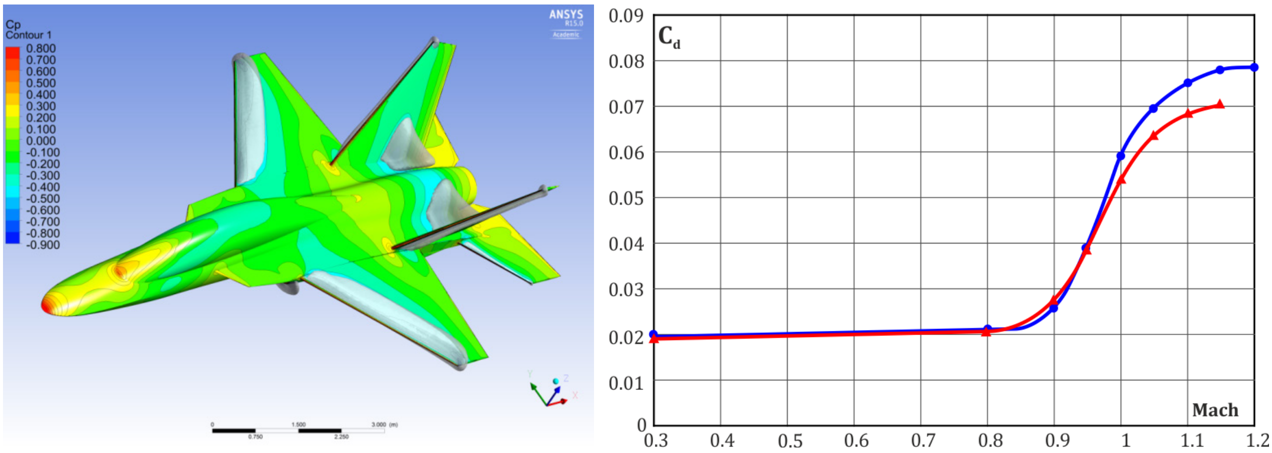

Fig. 5. Pressure distribution and supersonic flow zone at Ma = 0.85 and angle of attack 0.5^{O} (left) and drag rise characteristics at the same angle of attack (right)

Analyses at high angles of attack were performed at low speed open test section wind tunnel at Warsaw University of Technology. Aerodynamic model of size 6% of the full aircraft had composite structure. Six-component internal aerodynamic balance was used. Model support allows reaching angles of attack -2^{O} to $+56^{O}$ and side slip angles +/- 25^{O}. Classical wind tunnel corrections were applied [8]. The aerodynamic model in the test section can be seen on Fig. 6.

Initial results were not satisfactory. Both, the directional and lateral characteristics were incorrect, producing totally improper location of Bihrle-Weizmann chart. The modifications of the geometry included change the vertical tail (planform, size, location and vertical deflection), strake planform, the nose geometry of the fuselage and the inlets. Changes in geometry were made both by exchanging elements (vertical tail) and by manually modifying shapes using plastic mass. In order to obtain satisfied lateral characteristics application of additional elements (vanes) on strakes was necessary. The final characteristics seem to be satisfactory.

Fig. 6. Aerodynamic model in the test section of the low speed wind tunnel

Basic aerodynamic characteristics of lift and moment coefficients (aft centre of gravity position) for different elevator angles can be seen on Fig. 7 (configuration with leading edge deflection 35^{O}. The plane can be balanced at entire considered range of centre of gravity location and angle of attack up to 50 degree.

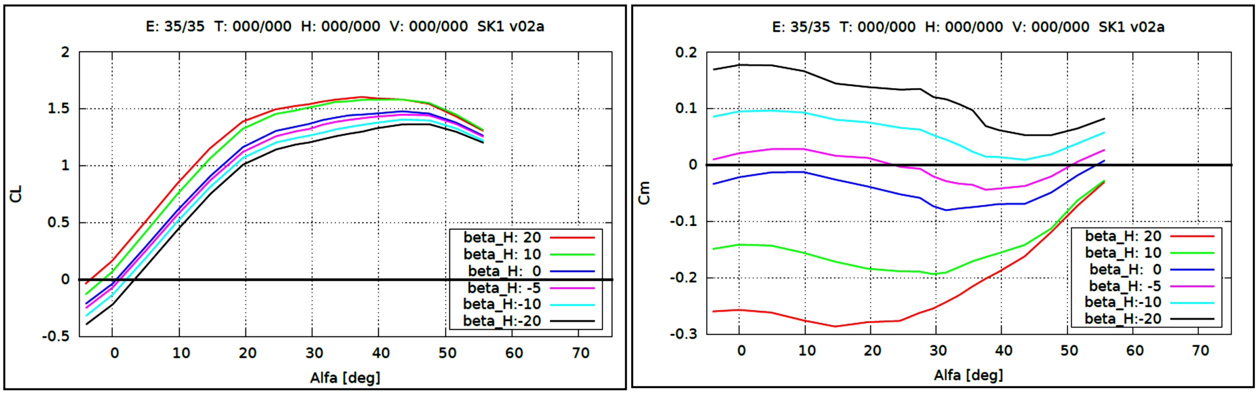

Fig. 7. Lift (left) and longitudinal moment (right) characteristics of the model

The final characteristics indicate also the correct location of the **$Cn_{\beta\ dyn}$** and ***LCDP*** on the integrated Bihrle-Weizmann chart in the entire range of angles of attack (except negative lift) without ARI – Fig. 8.

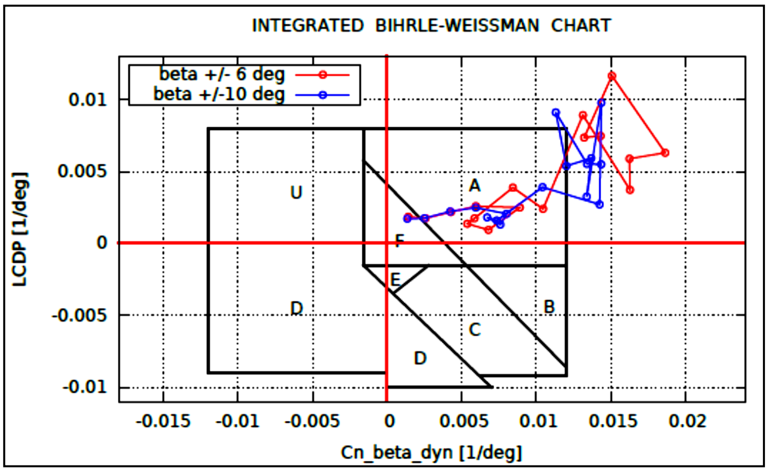

Fig. 8. Integrated Bihrle-Weizmann chart for the final aerodynamic model of the plane

6. Summary

Presented in this paper results were the effect of a fairly comprehensive study of the light jet training aircraft. The work included of both: the conceptual study of the plane, an initial concept of the internal layout and structure, mass and performance analysis and finally the initial aerodynamic development. The main objective of the aerodynamic project at this stage was primarily to ensure the proper dynamic behaviour of the plane at high angles of attack, without departure and pro-spin tendency. The real scope of work was much wider and included different aircraft configurations (combinations of flaps deflection, rudder, air brakes, and additional elements). Final characteristics are satisfactory, fulfilling a number of requirements related to the internal arrangement of the cockpit, undercarriage, propulsion, fuel tanks, etc.

The main drawback of the work carried out was the lack of definition of the final geometry of the aerodynamic model. It was obtained by manual and quite far-reaching changes in the shape of many elements of the model configuration.

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