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METHODS OF MODERN AIRCRAFT AEROELASTIC ANALYSES IN THE INSTITUTE OF AVIATION

Wojciech Chajec

Institute of Aviation
Materials and Structures Research Centre
Krakowska Av. 110/114, 02-256 Warsaw, Poland
tel.: +48 22 8460011 ext. 251
e-mail: wojciech.chajec@ilot.edu.pl

Abstract

The aeroelastic phenomena analysis methods used in the Institute of Aviation for aircraft, excluding helicopters, are presented in the article. In industrial practice, a typical approach to those analyses is a linear approach and flutter computation in the frequency domain based on normal modes, including rigid body modes and control system modes. They are determined by means of the finite element method (FEM) model of structure or a result of ground vibration test (GVT). In the GVT case, relatively great vibration amplitudes are applied for a good examination of a not truly linear structure. Instead or apart from the measure of generalized masses, a very theoretical model is used for mode shapes cross orthogonality inspection and improvement. The computed or measured normal mode sets are the basis for flutter analysis by means of several tools and methods, like MSC.Nastran and ZONA commercial software as well as our own low-cost software named JG2 for the flutter analysis of low speed aeroplanes and for a preliminary analyses of other aircraft. The differences between the methods lie in determining normal mode set, unsteady aerodynamic model, flutter equation formulation, time of analysis, costs, etc. Examples with results comparison obtained by means of distinguished methods are presented. Some works in the field of aeroelastic analysis with nonlinear unsteady aerodynamic in the time domain using Tau-code and ANSYS Fluent software were also performed. Aeroelastic properties of deformed structures, like a sailplane with deflected wings, can be also analysed. The simplest way of this analysis is the semi-linear approach in which the deflections modify the aircraft geometry for normal modes determination.

Keywords: *flutter, normal modes, ground vibration test, unsteady aerodynamic models*

1. Introduction

A modern, environment friendly aircraft usually contains aerodynamic surfaces with high aspect ratio and high flexibility of structure. Additionally, the aircraft design can be unconventional. These reasons promote a disadvantageous aeroelastic phenomena like aerodynamic flutter, divergence, control surfaces reversal, pilot induced oscillations or others. However, the certified aircraft should be free from any dangerous aeroelastic effects, so they should be predicted and removed during a design process or latest at the stage of flight tests before certification.

The basis for analysis is the normal mode set that contains all significant modes of aircraft in selected configuration, up to a high frequency of practically possible aeroelastic vibration. This upper frequency value can be determined according to [13] or [21]. It depends on the possible flutter kind, on the never exceed true airspeed and on the chord of the aerodynamic surface inducing the vibration.

The normal mode set can be determined by ground vibration test (GVT) or on the basis of FEM model of structure. The first method can be applied for existing structures, even for old structures without detailed technical documentation. It is difficult in the case of several structure variants, excluding small mass alterations. The second method of the normal modes determination needs detailed knowledge about structure, so the detailed FEM model of structure should be made by their designer. However, some simple, beam-like models are also useful.

The standard for aeroelastic applications are linear, inviscid methods of unsteady aerodynamic forces determination and frequency-domain flutter analysis. This approach is applied by the most popular commercial software MSC.Nastran [16, 17, 23], ZONA ZAERO [26, 27] and SAF [11]. The MSC.Nastran includes several methods of aerodynamic forces determination and solution of the flutter equation.

The ZONA TECHNOLOGY offers the ZEUS Euler nonlinear unsteady inviscid aerodynamic solver [29], for both time domain and frequency domain aeroelastic analysis in sub-sonic, trans-sonic, and super-sonic flow ranges. Several works exist concerning fluid/structure interaction (FSI) using nonlinear, viscous CFD solvers, like Tau-code or ANSYS Fluent, but they are great computational time consuming, so are not popular for industrial purpose.

In the article, aeroelastic analysis methods used in the Institute of Aviation are presented. The article focuses on dynamic phenomena, like aerodynamic flutter.

2. Tools for flutter analysis in Institute of Aviation

The aeroelastic analysis in our institute can be performed using the rapid, low-cost software named JG2 [19, 20] based on incompressible strip theory in aerodynamics and V-g method of flutter equation solution with reduced frequency as a parameter of computation. It was verified in [7] by comparison with ZONA ZAERO I [26, 27] commercial software results and is particularly efficient for flutter calculation based on GVT results. This method was used for several low-speed aeroplanes and sailplanes, like I-23 [2] and EM-11 Orka four seats GA-aircraft, Pipistrel Virus SW 121 and Aero-Kros MP-02 Czajka [7], Aeroprakt A32L, Funk FK-9 ELA ultralight aircraft, AOS-71 and Icare II [22], electric powered sailplanes, SZD-55, SZD-56 Diana, SZD-54-2 Perkoz, Swift S-1, MDM-1 Fox [1], PW-5 sailplanes and others.

The MSC.Nastran commercial software [16, 17, 23] is used for flutter calculation, including the whirl-flutter of propeller power plants, based on an FEM model of structure. In particular, it offers the panel Doublet Lattice method for sub-sonic flow and the ZONA51 method for super-sonic flow. The PK method (with modifications named PKNL, PKS) of flutter equation solution is most popular. In this method, the speed is a parameter of computation. The examples of flutter computation by this method are PZL-M28 Skytruck [7], EM-12 Małgosia II [4], I-23 [3]. New results of computation by means of this method are presented in the 4th and 5th chapter of this article.

Nowadays we have active license for the ZONA ZAERO I use for subsonic flutter analysis. This software offers G-method of flutter equation solution and slightly better aerodynamic models than the ones in the MSC.Nastran that was confirmed in [6], where the flutter computation results using both software were compared with wind tunnel test results. The ZAERO I software is convenient for flutter analysis based on both measured and computed normal modes of aircraft.

In flutter analyses, we pay attention to precise modelling (FEM) or identifying (GVT) manually operated aircraft control systems.

Some works were made in field of time-domain flutter analysis using modern CFD solvers, like ANSYS Fluent [6, 7] or Tau-code in cooperation with Poznan University of Technology [24].

3. Flutter analysis based on ground vibration test results

The GVT are conducted in the Institute of Aviation using the MIMO method, for the airplane as ready to fly, but usually without fuel and with pilots' dummy masses, usually steel weights [25]. To simulate free flight conditions, the aircraft is supported using flexible rubber cables, Fig. 1.

Before the tests, Institute of Aviation in Warsaw prepares the short plan of the test. For this purpose the aircraft geometry, the designed dive speed, V_D and celling are needed. The main control devices in the cockpit are set in neutral position by means of thin rubber, if necessary. Some resonant modes are measured twice after dummy pilot's hand/foot mass addition to stick/ /control wheel and pedals.

Fig. 1. GVT of the I-31T turboprop aircraft (I-23 after the power plant change), 2015

Nowadays for a results presentation the LMS TEST LAB ver. 13A software as well as home software is used.

The excitation system consists of the generator LMS DAC4, the steering unit PRODERA CG 511/512, the power amplifiers PRODERA A-436 and the electrodynamics exciters PRODERA EX303. The exciters allow the implementation of a large amplitude of excitation, which is important for test results credibility of real, not ideally linear structures [9].

The vibration acquisition system contains uni-axial as well as 3-axial PCB accelerometers (up to 150 channels); mechanical impedance sensors type PCB 288D01, the LMS SCADAS LAB III with V8 input modules and the LMS SCADAS MOBILE with V8-E input modules.

Frequencies, mode shapes, generalized masses and damping coefficients of each resonant mode are measured.

The flutter calculations are performed based on the GVT results and mass model of the aircraft. In the flutter analysis, the measured modes as well as the numerically determined rigid body and control mechanism modes are taken into account. The measured resonant modes can be orthogonalized. Suspension elements' masses will be eliminated in flutter analysis. The procedure of GVT results preparation for flutter analysis has been described in detail in [2, 5].

Apart from the base mass configuration, alternate mass models can be considered – for optimal control surfaces mass balancing or fuel and payload change, for example. For this purpose, the customer should deliver the mass distribution of the aircraft: masses and e.g. position of the main assemblies, especially for control surfaces. For control surfaces, the actual location of balance masses is needed as well as the kinematics and masses of the main elements of the control system.

The flutter computation is performed using the low-cost JG2 flutter computation software and/or Zona ZAERO I commercial software. The flutter calculation results are presented in form of $g(V)$ and $f(V)$ graphs for a few values of flight altitude up to celling and animation of the most important complex vibrating modes. If the critical flutter speed is too low, we propose changes of structure.

4. Flutter analysis of the ILR-33 Amber rocket stabilizer

This chapter presents a simple example of sub-sonic and super-sonic flutter analysis based on an FEM computational model of structure. The ILR-33 Bursztyn (Amber) [18] rocket fin was considered. The fin is stiffly mounted to rocket fuselage that is treated as stiff and heavy. The flutter analysis was performed by MSC.Nastran based on the FEM model [10] prepared by D. Cieśliński, Fig. 2, left. The model contains of 3,626 CHEXA parabolic solid elements.

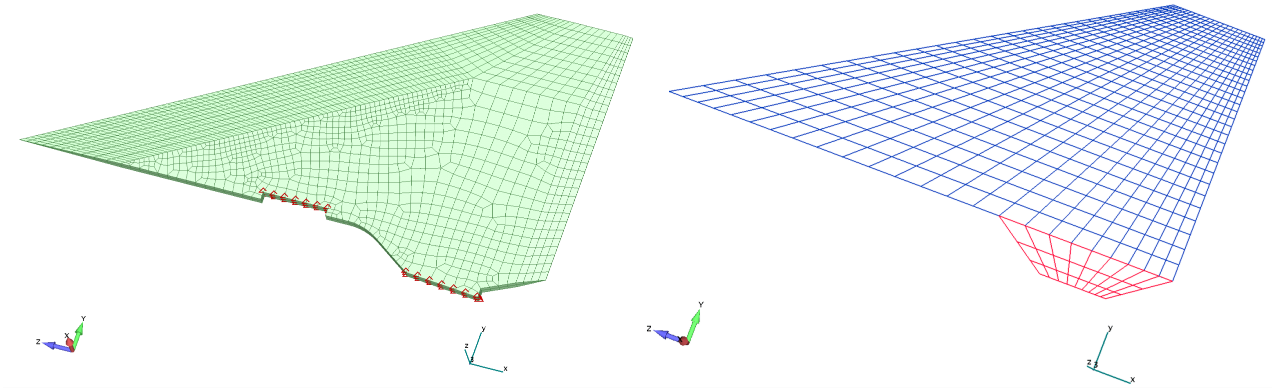

Fig. 2. The FEM and aerodynamic models of the ILR-33 Amber rocket fin

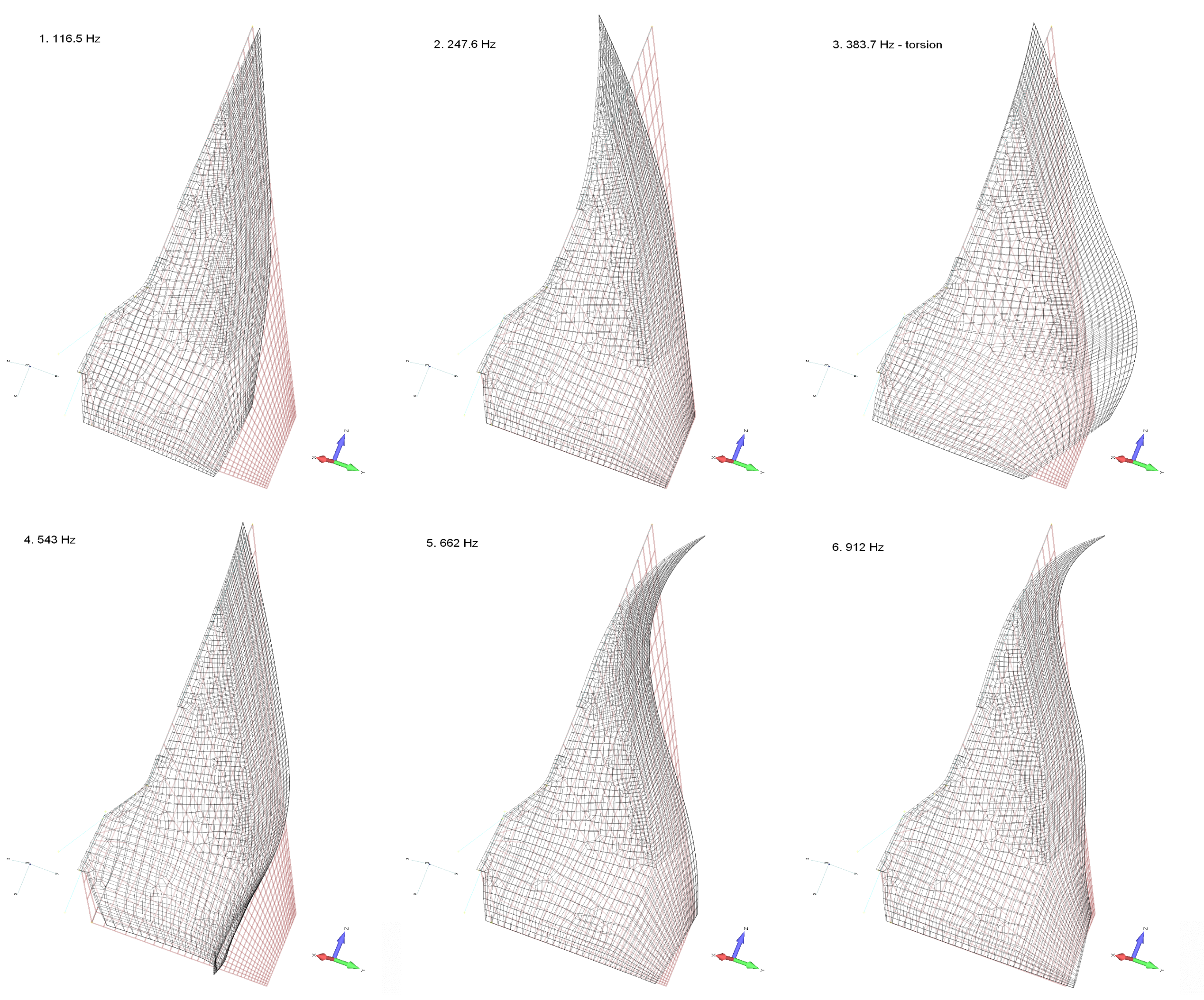

Fig. 3. The first six normal modes of the ILR-33 Amber rocket fin

Based on the FEM model geometry, an aerodynamic model was defined, Fig. 2, right. It contains two CAERO1 panels divided into 24×30 + 9×3 = 747 aerodynamic boxes.

According to [13], an aerodynamic flutter of the cantilever wing of small aspect ratio can practically appear at reduced frequency *k* lower than 1.1. For fin chord length at 0.7 span equal to 0.244 m, 1.2 speed safety margin and maximal speed of 1,268.8 m/s from Tab. 1. upper real flutter frequency of fin is 2,185 Hz. The frequency of the 15-th mode is 2,398 Hz, so it is sufficient to make the flutter analysis using 15 first normal modes only.

Tab. 1. Air density/Mach number/speed parameters for flutter computation

Altitude [m]	Air density [kg/m^3]	Rho/Rho0	Mach number	V [m/s]	a [m/s]	T [K]
0	1.226	1.	0.3	10.0	341	288
0	1.226	1.	0.3	20.0	341	288
0	1.226	1.	0.3	50.0	341	288
0	1.226	1.	0.3	100.0	341	288
0	1.226	1.	0.3	150.0	341	288
0	1.226	1.	0.3	200.0	341	288
0	1.226	1.	0.60	204.6	341	288
0	1.226	1.	0.70	238.7	341	288
0	1.226	1.	0.75	255.8	341	288
0	1.226	1.	0.80	272.8	341	288
0	1.226	1.	0.83	283.0	341	288
0	1.226	1.	0.85	289.9	341	288
0	1.226	1.	0.90	306.9	341	288
0	1.226	1.	1.10	375.1	341	288
2,000	1.007	0.821	1.2	399.6	333	275
0	1.226	1.	1.2	409.2	341	288
4,000	0.819	0.668	1.6	520.0	325	262
2,000	1.007	0.821	1.6	532.8	333	275
6,000	0.66	0.538	2.0	634.0	317	249
4,000	0.819	0.668	2.0	650.0	325	262
8,000	0.525	0.428	2.5	770.0	308	236
6,000	0.66	0.538	2.5	792.5	317	249
10,000	0.413	0.337	3.0	900.0	300	223
8,000	0.525	0.428	3.0	924.0	308	236
12,000	0.31	0.253	3.2	944.2	295.069	217
10,000	0.413	0.337	3.2	960.0	300	223
12,000	0.31	0.253	3.6	1,062.2	295.069	217
15,000	0.194	0.158	4.0	1,180.3	295.069	217
15,000	0.194	0.158	4.3	1,268.8	295.069	217

The flutter analysis was performed by the MSC.Nastran PKNL method for air density/Mach number/speed parameters shown in Tab. 1. The speed/altitude pairs were selected for an oblique trajectory according to [10] and [18].

The aerodynamic matrix was computed for each pair of Mach number from Tab. 1. and the following nodal values of reduced frequency: 9.0, 6.0, 3.0, 2.0, 1.2, 1.1, 1.0, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2. The total normal modes and flutter computation time was below 17 minutes. The flutter computation results are presented in Fig. 4. in the form of $g(V)$ and $f(V)$ graphs for all rows of Tab. 1. For this reason, the lines in Fig. 4. are zigzag lines. In fact, each line has its own width between the *low altitude* and the *high altitude* lines marked in Fig. 4. for the first flutter line.

In Fig. 4. a separate result point (line No. 13) is $g > 0$, but the positive g value is below structural damping, and, additionally, the reduced frequency value in this point is $4.15 > 1.1$, so the flutter is unlikely. According to Fig. 4. a flutter of rocked fin cannot appears.

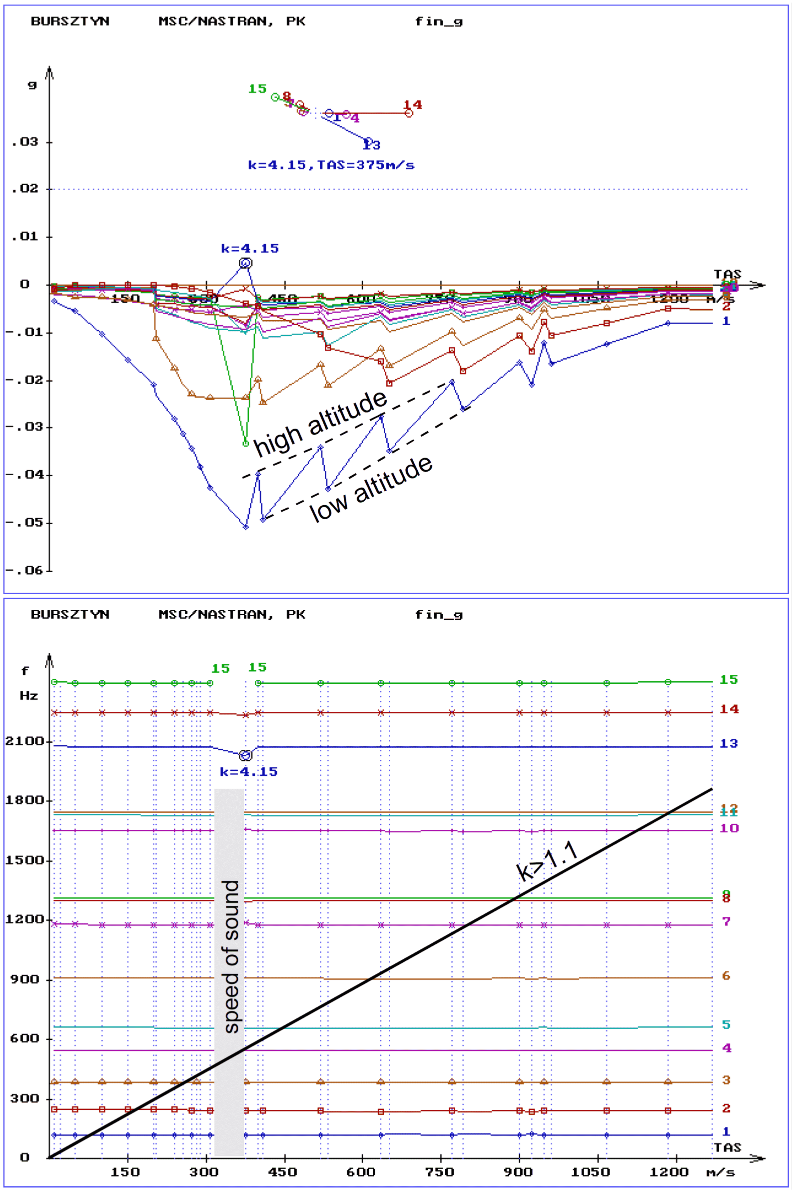

Fig. 4. Flutter calculation results. The k > 1.1 region is marked.

5. Flutter of sailplane with deflected wing

In the case of the wing with flaperon on the whole wingspan, the deflection of the flaperon hinge line can increase the friction during flaperon rotation. Generally, the friction acts positively for critical flutter speed, but in some flight conditions, like at the overload factor n=0, the wing can be not bent, which favours flutter. For this reason, the GVTs of these sailplanes are performed with wings relieved by means of rubber cords. The influence of static wing deflection on the GVT results was tested by Z. Lorenc during GVT of the SZD-56-2 Diana 2 sailplane and in [22].

The static deflection of the wing can change the normal modes [14]. It can be important in the case of big masses appearance on the wing tips. To check this suggestion, the symmetric flutter analysis of the MDM-1 Fox aerobatic sailplane with heavy smoke candles at the wing tips is performed. The analysis is carried out twice, once for the original geometry of the glider and again for the glider deformed with the overload factor n = 2.

Performing resonance tests at n = 2 is difficult, so the analysis is performed by means of MSC.Nastran and a simple beam-like FEM model of sailplane. The model was prepared on the base of the sailplane geometry and mass model used in [1], wing stiffness distribution according to

[28]. The control system model from [4] was used. The stiffness distributions of the other sailplane parts were designed to obtain the compliance of the calculated symmetric normal modes with the measured ones, [15] up to 50 Hz, Tab. 2. First pilot mass of 60 kg and 0.5 kg on stick to simulate pilot hand mass were assumed.

Tab. 2. Symmetric normal modes of MDM-1 Fox sailplane

Mode shape description	ζ	Frequency [Hz]				
		Undeflected wing, n = 0			Deflected wing, n=2	
		GVT	s0	s0m	s2	s2m
Rigid body mode TX	0	–	0	0	0	0
Rigid body mode TZ	0	–	0	0	0	0
Rigid body pitch mode RY	0	–	0	0	0	0
Elevator deflection (control system acts as a mechanism)	0.050	2.00	2.00	2.00	2.00	2.00
1st wing bending mode (2 nodes)	0.008	3.00	3.01	2.72	3.04	2.74
1st wing bending in the chord plane	0.015	8.61	8.60	7.92	8.17	7.52
2nd wing bending mode (4 nodes)	0.008	10.05	9.59	7.99	9.67	8.07
Bending of stabilizer	0.011	15.50	15.47	15.11	15.50	15.15
Fuselage bending – stabilizer bending	0.032	19.37	19.98	18.00	20.03	18.06
Elevator deflection (control system acts as a spring)	0.013	21.39	21.41	21.31	21.41	21.35
Wing torsion + aileron deflection and torsion	0.019	21.52	21.45	21.42	21.06	20.96
3rd wing bending mode (6 nodes)	0.046	23.42	24.32	22.89	24.44	22.78
Wing torsion – aileron deflection and torsion	0.027	27.01	27.42	26.65	26.90	28.54
2nd wing bending in the chord plane	0.050	29.56	30.79	26.99	30.49	25.14
Inner aileron part torsion	–	33.60	33.74	33.51	33.87	33.39
4th wing bending mode (8 nodes)	0.013	38.51	39.87	34.71	39.99	34.89
Torsion of elevator	0.018	41.13	45.01	45.00	45.01	45.00
High torsion and bending of elevator	–	41.78	–	–	–	–
High wing torsion		–	49.78	47.34	49.80	46.92

The sailplane is equipped with the Friese-aileron, so the borderline between the wing and aileron in flat aerodynamic model can be selected arbitrarily (Fig. 5). For this reason, two alternate aerodynamic models are used:

g – in which the border line is selected according to upper wing surface, and
d – in which the borderline is selected according to lower wing surface.

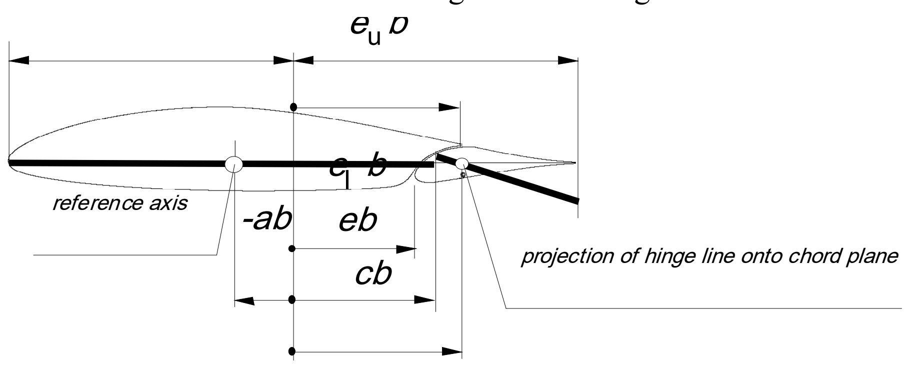

Fig. 5. MDM-1 Fox wing cross-section

The FEM model with aerodynamic *d*-model is presented in Fig. 6.

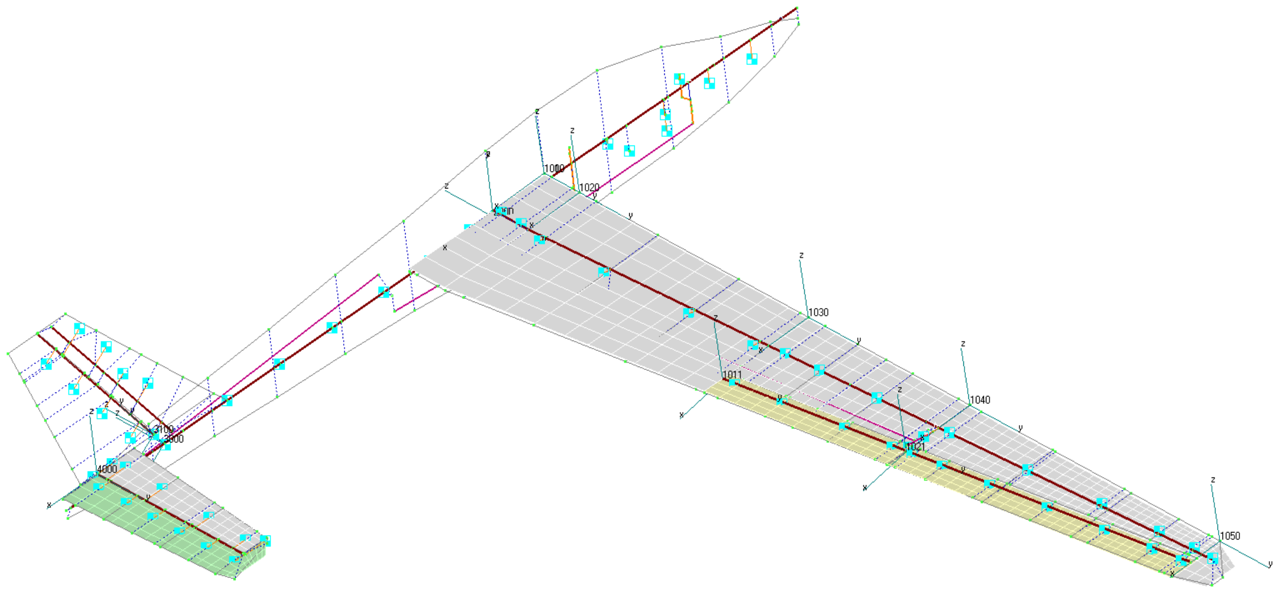

Fig. 6. The FEM and aerodynamic models of the MDM-1 Fox aerobatic sailplane with undeflected wing

As a result of [1] some aileron, elevator and rudder mass balance improvements were introduced. In presented results, the preliminary mass balances are assumed, for simplification. The measured modal damping coefficients are taken into account in flutter calculation.

In the case of the *d*-model, the critical flutter speeds are slightly lower than ones in the case of the *g*-model, so in this article only the results obtained for *d*-model are presented.

The computational FEM model for deflected wing at n = 2 was create by re-defining the local coordinate systems 1011, 1020, 1021, 1030, 1040 and 1050, Fig. 6. according to wing deflection line [28] – 0.5 m at wing tip. The aerodynamic models for n = 2 were defined by coordinate changes of CAERO1 elements.

The mass on wing tip, 1.763 kg is assumed according to [12]. The computational variants with this mass have *m*-letter in variant name for identification. It is assumed that the wing deflection line in the case with additional mass is the same as without this mass.

The normal modes are presented in Tab. 2. The modal damping coefficients ζ are GVT-results. The *s0m* and *s2m* variants are with additional mass on the wing tip.

The flutter calculation results for the *s0dt* (symmetric flutter, without additional mass, not bent wing, *d*-aerodynamic model, damping included) base variant and for the *sm2dt* (mass on the wing tip, deflected wing at n = 2, damping included) variant are presented in Fig. 7. The line g = -0.02 is the safety margin.

In the base *s0dt* variant, the flutter calculation results contain the stabilizer/elevator flutter, 11 and wing flutter, 8. The deflection without mass has the smallest influence. After the mass addition without wing, deflection occurs the flutter result 12. Both wing deflection and additional mass on the wing tip acts negative for critical flutter speeds, line 11 and 8. Apart from new flutter line number 12, the new flutter line number 6 appears. This is the wing torsional flutter with both wing-bending modes: the first, perpendicular to the chord plane and the second, in the chord plane.

The mass of the smoke candles at the wing tips of aerobatic sailplanes should be limited.

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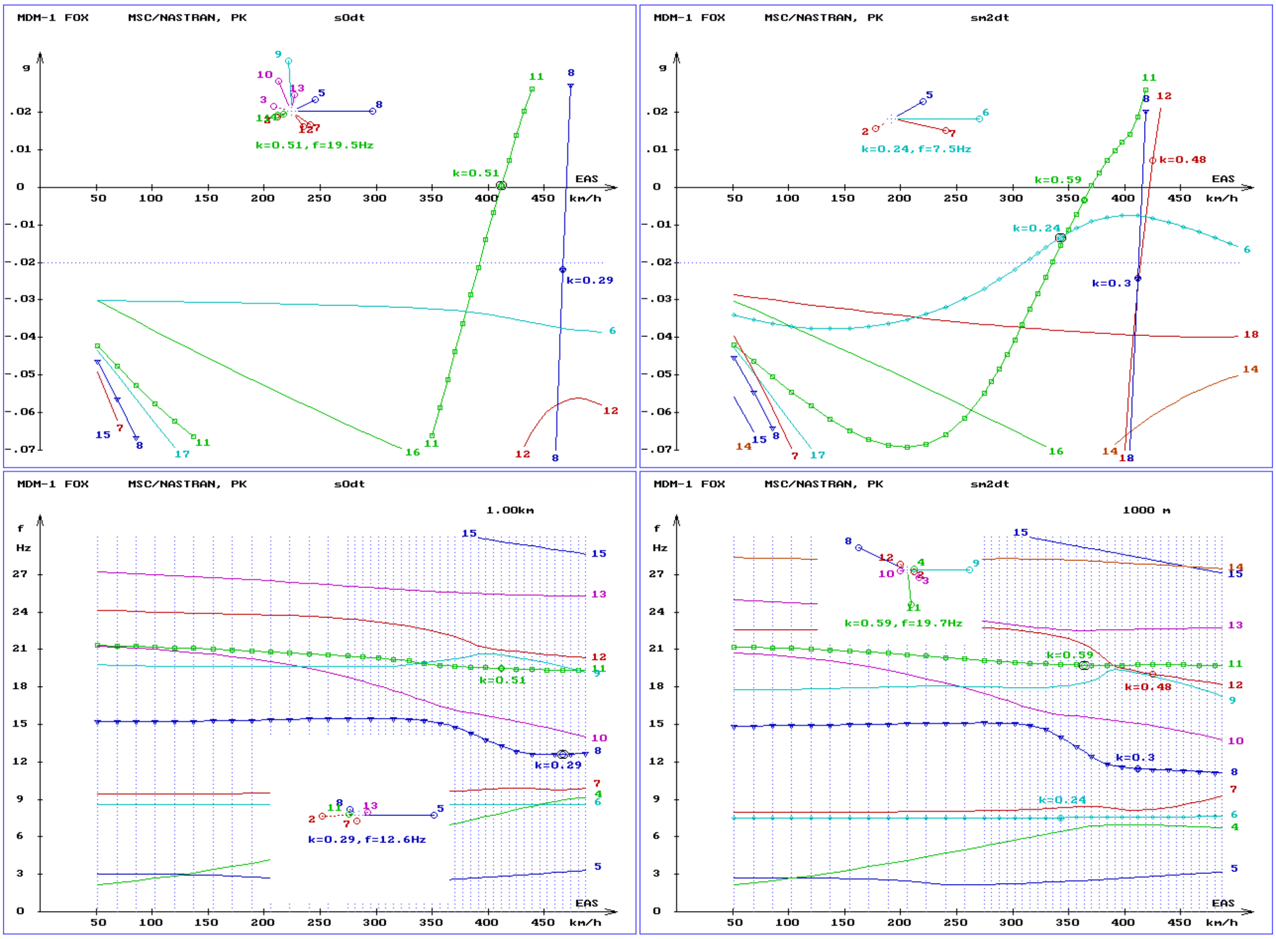

Fig. 7. Flutter calculation results for variants s0dt (left) and sm2dt (right)

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