18th International Conference
ENGINEERING MECHANICS 2012
Svratka, Czech Republic, May 14 – 17, 2012

pp. 169–176
Paper **#15**

AEROELASTIC CERTIFICATION OF LIGHT SPORT AIRCRAFT ACCORDING "LTF" REGULATION

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Abstract: *Submitted paper deals with the aeroelastic certification of a light sport aircraft according the German regulation standard "LTF-UL". The procedure is simple, fast and low-cost, however it keeps the high standard regarding the quality and reliability of the obtained results. The procedure is based on the ground vibration test of the aircraft and flutter analyses based on the measured mode shapes. Paper is focused to the used experimental and analytical tools and methodologies. Whole process is demonstrated on the example of the FM-250 "Vampire II" light sport aircraft certification.*

Keywords: ***aeroelasticity, ground vibration testing, light sport aircraft, LTF regulation***

1. Introduction

In the Czech Republic, there have been a considerable growth in development and production of the light sport aircraft recently. New generation aircraft are lighter, aerodynamically refined and equipped by more powerful engines. It allows installation of advanced equipment, also flight performances are increasing. In many aspects, they expand to the higher aircraft category. However the design of such aircraft is ordinarily made with no regard to the aeroelasticity (e.g. under-balanced controls), also home-made alteration of the structure with possible negative influence to the aeroelastic stability (see Čečrdle (2010)) is a typical practice. Aeroelastic certification of these aircraft is based on the formal flight flutter tests, however due to the mentioned factors, there are additional requirements regarding aeroelasticity in some regulation standards. The typical example is the German national regulation standard "LTF-UL". It requires the ground vibration test and flutter analyses prior the flight flutter test for the aircraft with the design velocity over ***200 km.h^{-1}*** (section 629(3)). It is obvious, that the aeroelastic certification of the light sport aircraft must be fast, simple and low-cost. On the other side, the high standard of the results quality and reliability must be kept. The paper describes the certification procedure used at the VZLU. It is based on the ground vibration test of the aircraft and the flutter analysis using the measured modal characteristics. The procedure is demonstrated on the ***FM-250*** "Vampire II" aircraft example (fig.1). The duration of the whole procedure was about 20 workdays from the aircraft delivery to the analytical results available.

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Fig. 1: FM-250 Vampire II aircraft (source: Flying Machines s.r.o.)

2. Ground Vibration Test

The purpose of the ground vibration test (***GVT***) is to get the modal parameters of the structure. These parameters, it means natural frequencies, mode shapes and modal masses are the input parameters for the follow-on flutter analyses. The ***FM-250*** aircraft test was performed on the completely equipped and weighted aircraft. The empty weight was ***280.5 kg***, plus ***2*** pilots of ***75 kg*** each and ***26 lt.*** of fuel representing ***50%*** of loading. The aircraft total mass was ***450 kg***. The control system (rolling, pitching, yawing) was free, there was used only soft rubber spring to fix a stick with no significant influence to the measured system. Due to the unstable vibrations, the elevator tab was fixed excluding the measurement of the tab flapping mode. Flaps were at the zero position excluding the skin modes and flap 2nd modes measurements.

The aircraft was suspended in the flight position by means of the rubber springs. The front belt was placed on the front fuselage and the rear belt was behind the wing. The natural frequencies of the aircraft on the suspension were ***1.1 Hz*** vertical, ***0.6 Hz*** lateral and ***0.5 Hz*** longitudinal.

Fig. 2: GVT test arrangement (source: VZLU)

Tab. 1: GVT results summary

#	mode title	f_0 [Hz]
1	Rudder Flapping (Fixed Pedals)	6.941
2	1st Symmetric Wing Bending	8.575
3	Tailplane Rolling	9.697
4	1st Fuselage Lateral Bending	10.57
5	1st Fuselage Vertical Bending	11.17
6	Antisymmetric Aileron Flapping (Fixed Sticks)	14.63
7	1st Antisymmetric Wing Bending	15.03
8	Symmetric Elevator Flapping (Fixed Sticks)	15.06
9	Symmetric Elevator Flapping (Free sticks)	15.21
10	1st Antisymmetric Wing In-plane Bending + Lateral Engine Vibrations	15.22
11	1st Symmetric Wing In-plane Bending	16.97
12	Symmetric Aileron Flapping	23.51
13	Antisymmetric Tailplane In-plane Vibration	24.39
14	Elevator Balance Tab Flapping	24.50
15	1st Symmetric Tailplane Bending	24.92
16	1st Engine Vertical Vibration	27.48
17	1st Fin Bending	28.93
18	1st Antisymmetric Wing Torsion	31.61
19	1st Symmetric Wing Torsion	32.33
20	2nd Symmetric Wing Bending	37.57
21	Antisymmetric Elevator Flapping	42.57
22	2nd Fuselage Vertical Bending	47.71
23	2nd Antisymmetric Wing Torsion	54.09
24	2nd Symmetric Wing Torsion	54.26
25	2nd Fuselage Lateral Bending	55.89
26	2nd Antisymmetric Wing Bending	62.97
27	2nd Symmetric Tailplane Bending	63.22
28	1st Symmetric Tailplane Torsion	68.42
29	1st Antisymmetric Tailplane Torsion	71.97
30	3rd Symmetric Wing Torsion	73.39
31	2nd Engine Vertical Vibration	75.46
32	1st Fin Torsion	86.98

The test arrangement is shown in fig.2. The measurements were performed by means of the ***PRODERA 2008*** test system. It includes circuits for the excitation, measurements and data acquisition as well as the algorithms for the vibration evaluation and the test control. There were used ***50 N*** exciters, the elevator tab flapping mode was excited by means of ***4 N*** exciter. The acquisition points grid contained ***139*** uni-axial accelerometers with the mass of ***0.001 kg*** each. The rigid chord of surfaces was assumed. The rough estimation of the natural modes distribution was measured by means of the swept sine excitation. Then the particular modes were investigated by means of the phase resonance method. Each mode was characterized by the natural frequency, mode shape, modal mass and damping ratio. The modal masses and damping ratios were obtained by means of the complex power method and by supplied energy method respectively. The exception was the elevator tab flapping mode for which the modal mass was set analytically due to the large play inside the actuation mechanism. Quality of the measured parameters were assessed by criteria functions (***Δ*** and ***MIF***) characterizing the quality of the particular mode excitation. Natural frequencies and modal masses were corrected with respect to the additional mass and stiffness of the test device. Also the nonlinearities were evaluated by means of dependence of the natural frequency on the reference point displacement and as mechanical impedance respectively.

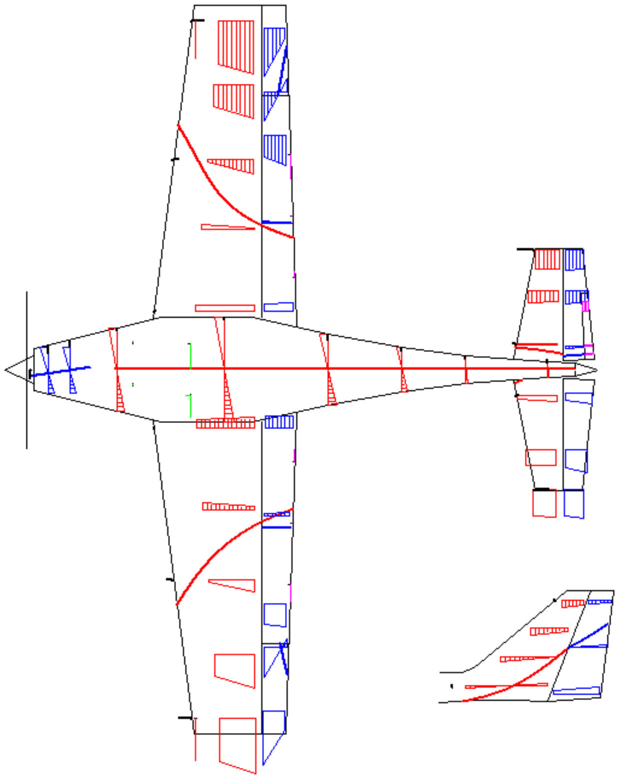

Fig. 3: GVT Example of mode shape visualization

The measured modes were divided into two sets: 1) significant modes of the main aerodynamic surfaces, controls and tabs and: 2) modes of auxiliary parts as flaps, landing gear, propeller blades etc. The former modes were used for the flutter calculations. These modes are summarized in tab.1. Fig.3 demonstrates the specific graphic format for the visualization of the mode shapes showing node lines and phase relations.

3. Flutter Analysis

According the **LTF-UL, section 629c** regulation, there must be performed the flutter analysis to prove no flutter appearance up to $\boldsymbol{1.2 * V_D}$ for the aircraft with $\boldsymbol{V_D}$ over $\boldsymbol{200\ km.h^{-1}}$. Note that the $\boldsymbol{V_D}$ is the aircraft design velocity which usually exceeds the $\boldsymbol{200\ km.h^{-1}}$ threshold. The analyses were based on the experimental modal model given by the ***GVT***. It is a common practice, that the usage of the ***GVT*** based modal model is the only possibility due to no structural data (stiffness, inertia) available. For the purpose of analyses, the measured modal deformations were recalculated to the grid of points with 3-directional deformation. Also, the points were moved to the leading and trailing edge respectively in order to avoid the errors due to splining extrapolation. Finally, the data were transformed to the free format. For these purposes, the in-house ***SW*** tool was used. The grid of the measurement points used for the analyses is demonstrated in fig.4. It includes ***70*** points in total.

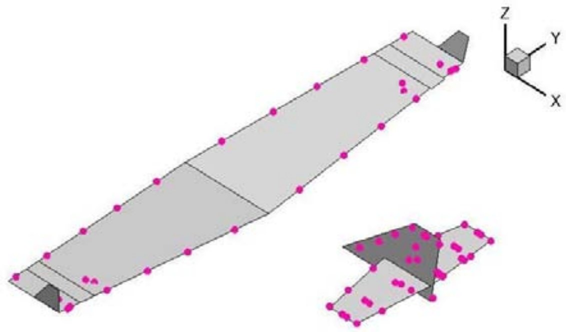

Fig. 4: Points used for analysis

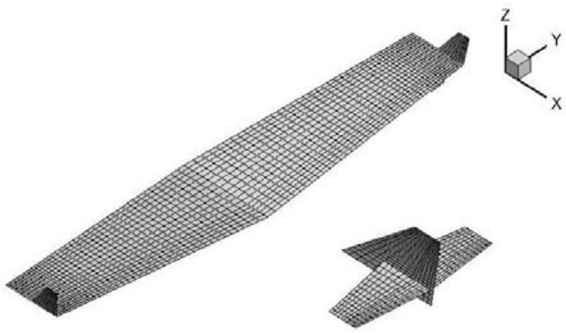

Fig. 5: Aerodynamic model - mesh

For the aeroelastic flutter analysis, the ***ZAERO*** system was used. The aerodynamic unsteady loads were given by the ***ZONA6*** Subsonic Unsteady Aerodynamic Theory. This theory solves the respective unsteady three dimensional linearized small disturbance potential equations of the subsonic aerodynamics. The ***FM-250*** aircraft aerodynamic model included the lifting surfaces only, influence of the fuselage body was neglected. The model includes both left and right hand side respecting the wing and tail unsymmetry (fixed aileron tab and elevator balancing tab on starboard side only). The aerodynamic mesh is shown in fig.5, it consists of ***2405*** aerodynamic elements in total. Aerodynamic matrices were calculated for the selected values of reduced frequency ranging from $k = 0.02$ to $k = 2.0$. Reduced frequency is dimensionless parameter including both flow velocity and frequency of vibrations. Aerodynamic forces are assumed to be dependent on the reduced frequency at a gentle rate, thus aerodynamic matrices are calculated for the selected values of reduced frequency and then interpolated. Considering the velocity range of interest (up to $1.2*V_D$), the Mach number was considered $M = 0.0$ (incompressible flow). This feasible simplification save the analysis effort. For the interpolation between structural grid and aerodynamic model, the "Infinite Plate splines" were used. The wing and fin surfaces were extended also to the fuselage area in order to avoid the unrealistic induced effects, however elements within the fuselage area were splined by means of the "Zero Displacement Splines" which do not transfer the displacements and forces to the structure. The same is applied to the winglets as well, since there was no measurement point there. For the flutter stability solution, the g-method was employed. This method is based on the widely used ***P-K*** method, which includes the aerodynamic matrix into the stiffness matrix (real part) and the damping matrix (imaginary part). In addition, the g-method includes also first order damping term to the solution. Calculations were performed for a several altitudes ranging from $H = 0$ to $H = 3000\ [m]$. The velocities were ranging from $V = 10\ m.s^{-1}$ to $V = 200\ m.s^{-1}$. The Mach number was considered $M = 0.0$ for the whole range of velocities. Thus, the results for high velocities (over $100\ m.s^{-1}$) must be considered as artificial due to incompressible flow aerodynamics used. This is ordinary practice in the aeroelastic analysis, also called non-matched analysis. The artificial results are used to evaluate the rate of reserve in terms of the flutter stability with respect to the certification velocity ($1.2{*}V_D$). The structural damping was included via viscous model. There were considered: 1) no structural damping as a conservative estimation and 2) damping ratio of ***0.02*** as realistic estimation considering the ***GVT*** results. Analyses included those modes listed in tab.1.

Tab. 2: Flutter states list

#	abbr.	title	approx. f_{FL} [Hz]
1	RUDD	Rudder flutter	9.9
2	AILA	Antisymmetric wing aileron flutter	16.7
3	AILS	Symmetric wing aileron flutter	14.5
4	ETAB	Elevator tab flutter	15.2
5	ELEV(1)	Elevator control flutter	24.2
6	ELEV(2)	Elevator control flutter	23.3
7	WHTS	Wing and tail flutter	27.0
8	HTLA	Horizontal tail surface flutter	63.0

The list of the flutter states found is given in tab.2. There were found the flutter of the main lifting surfaces, controls and tabs. The most important ones are rudder, wing aileron and elevator flutter. Other instabilities with a character of low hump mode were suppressed by considering the non-zero structural damping (e.g. elevator tab flutter). The analysis was complex in order to assess the most critical flutter issues and major contributing factors. The lowest flutter speed has the rudder flutter. It was approaching the certification speed, nevertheless the flutter speeds considering the realistic structural damping are all over this threshold. The main contributing factor is low rudder flapping frequency. The next flutter states has a character of the wing bending torsional aileron flutter. The main contributing factor is the aileron static under-balancing as well as the flapping frequency. The elevator flutter appeared as two separated instabilities due to the structural and aerodynamic unsymmetry. The example of the ***V-g-f*** diagram is shown in fig.6.

Flutter speed dependence to the flight altitude is at a gentle rate. The most critical is the altitude of $H = 0$ in the most cases. The influence of the structural damping shows the rate of change in terms of the stability increasing the velocity, the low influence of the structural damping means a high rate of change and vice versa. The summary of the flutter speeds is given in fig.7.

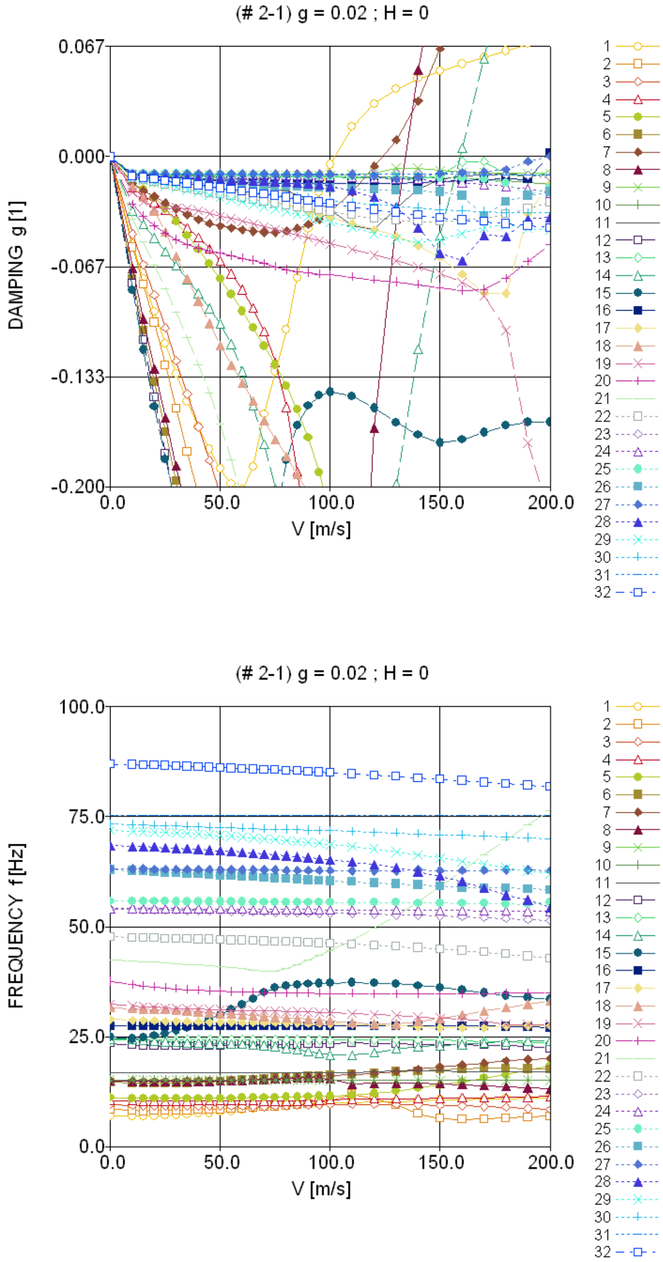

Fig. 6: V-g-f diagram example (g = 0.02; H = 0)

4. Conclusion

The paper deals with the assessment of the flutter stability of the light sport aircraft. It demonstrates the simple and fast certification procedure suitable for this aircraft category based on the ground vibration test of the aircraft and flutter analysis by means of the ***ZAERO*** system. The procedure is simple and fast, however it keeps the high standard with regard to the used experimental and analytical tools and the results reliability. The solution is demonstrated on the ***FM-250*** **"Vampire II"** light sport aircraft certification according German national airworthiness regulations **LTF-UL-2003, section 629**. Doing this, there was evidenced no flutter issue within the aircraft flight envelope.

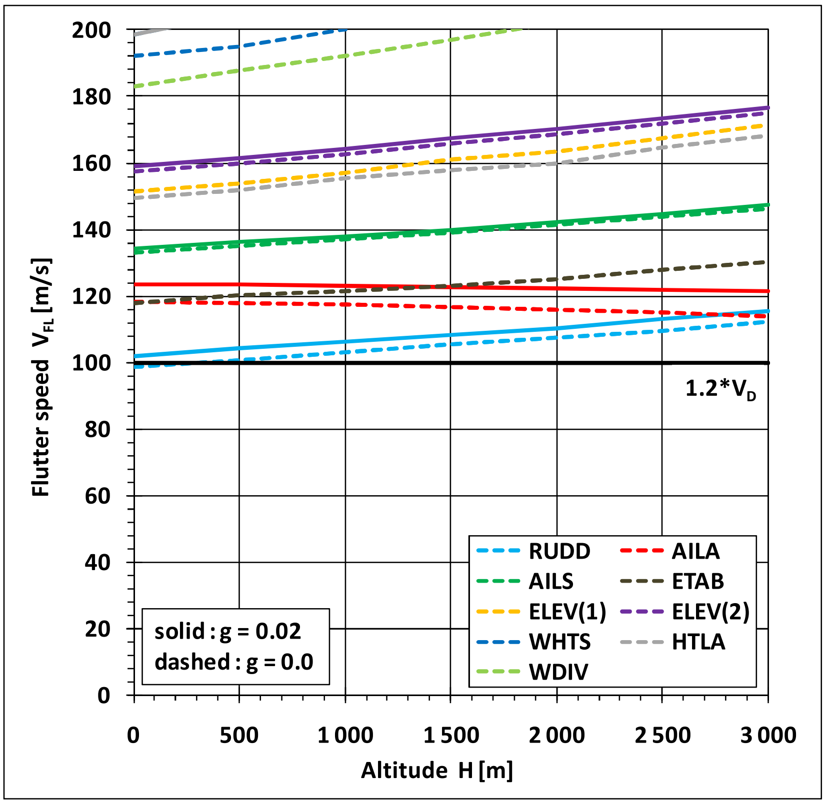

Fig. 7: Flutter speeds summary

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