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Aeroelastic Analysis for the CH601XL and the CH601 with a maximum take off mass of 600kg

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Figure 1: Ground Vibration Test CH601XL

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1. Task description

In this paper, linear aeroelastic investigations on the flutter stability of the aircraft CH601XL are documented in order to show compliance with the requirements of JAR-23. With a complete Ground Vibration Test (GVT) and flutter calculations based on the modal values found in the GVT, linear flutter stability has to be shown up to a true airspeed (TAS) of as much as 120% of the design speed (1.2*VD).

The method used here to calculate the flutter speed of an aircraft based on Finite Element Analysis (FEA) has been verified and validated with several wind tunnel tests [1].

The method used for the evaluation of the time series resulting from ground vibration tests have been verified and validated with both FEA results and experiments[2].

The flutter calculation initially is worked out for the airplane with minimum take off mass (Empty: No luggage, no fuel, one pilot), free controls and fixed controls at sea level.

After this, flutter calculations with maximum take off weight (pilot and copilot, maximum amount of fuel and maximum luggage), blocked and freed controls at sea level are performed.

To show aeroelastic effects of manufacturing tolerances in the ailerons, additional mass points are added to the trailing edge of the aileron and all previous calculations are repeated.

For some of the different mass configurations of the CH601XL flutter calculations are repeated also for flights in high altitude (5000m).

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[1] Uwe Weltin, Berechnung und Überprüfung der Flattergeschwindigkeit eines Flügelstreifens im Winkanal des DLR_School_Labs der TUHH, Interne Berichte des Institutes für Zuverlässigkeitstechnik an der TUHH, 2004 .

[2] Swantje Johnson, Dynamische Strukturanalyse einer Aluminiumplatte, Institut für Zuverlässigkeitstechnik an der Technischen Universität Hamburg, August 2007.

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2. Ground Vibration Test

To implement the vibration test, the CH601XL is equipped with as much as 78 accelerometers (see Figure 2) and hooked up at the ceiling of the hangar.

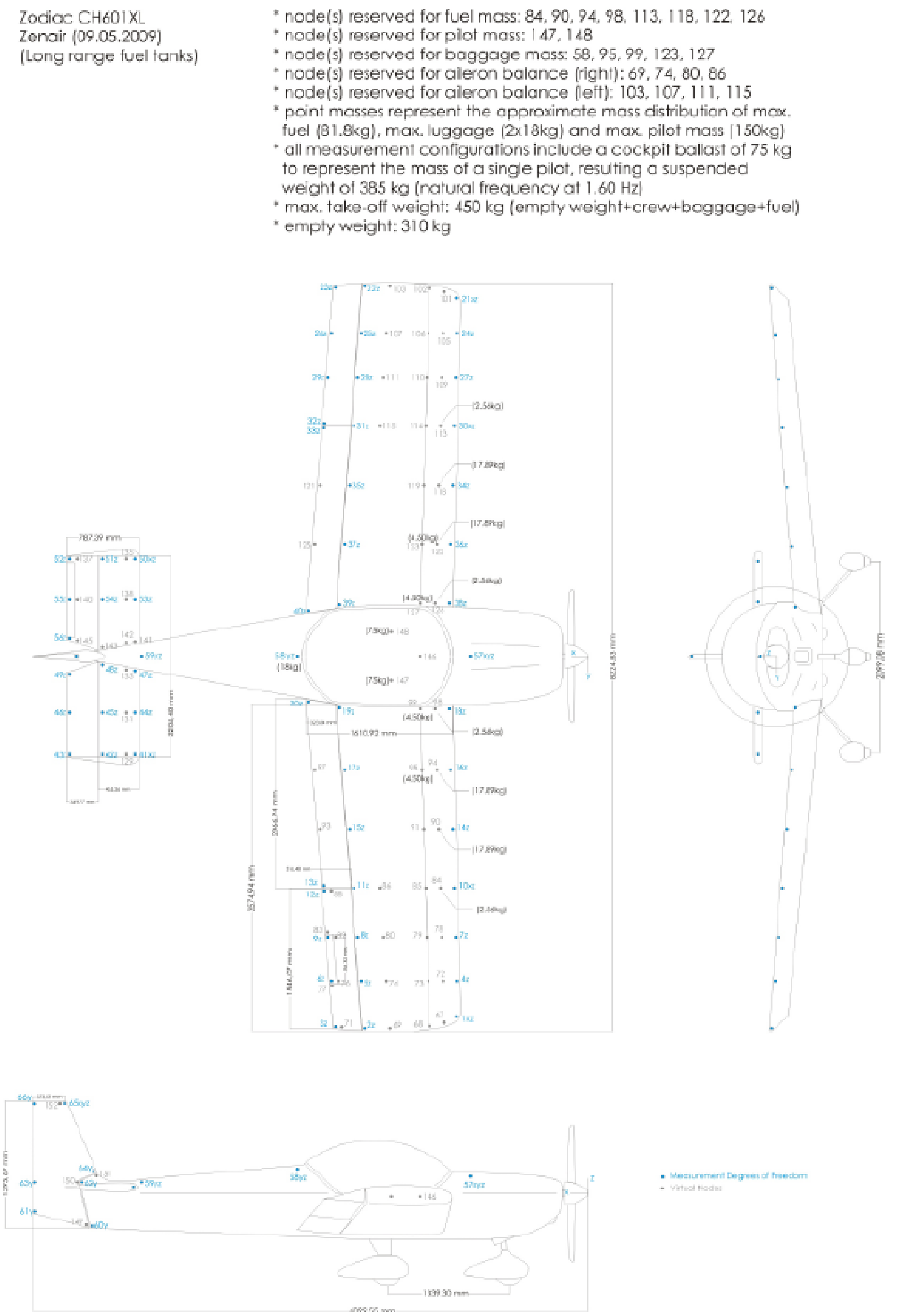

Figure 2: Node numbers for accelerometers and synthetic mass perturbation

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The springs of the suspension have an effective stiffness of Cs = 39 kN/m. The CH601XL in its minimal mass configuration loads 385 kg. The highest rigid body resonance frequency (vertical movement of the total airplane) in its elastic suspension therefore is

- F_{R1} = 1.6 Hz.

The other rigid body Eigen frequencies of the aircraft are all at considerably lower values. Because the lowest structural mode shapes of the aircraft need to be captured accurately enough, all rigid body natural frequencies have to lie significantly below the first structural Eigen frequency. The first wing bending Eigen frequency is determined at

- F_{S1} = 10.1 Hz

so that the required frequency spacing is fulfilled. For a complete GVT multiple multi shaker configurations have to be used in order to be able to identify all relevant natural modes. Figure 3 shows the shaker configurations for the identification of the control modes of the CH601XL.

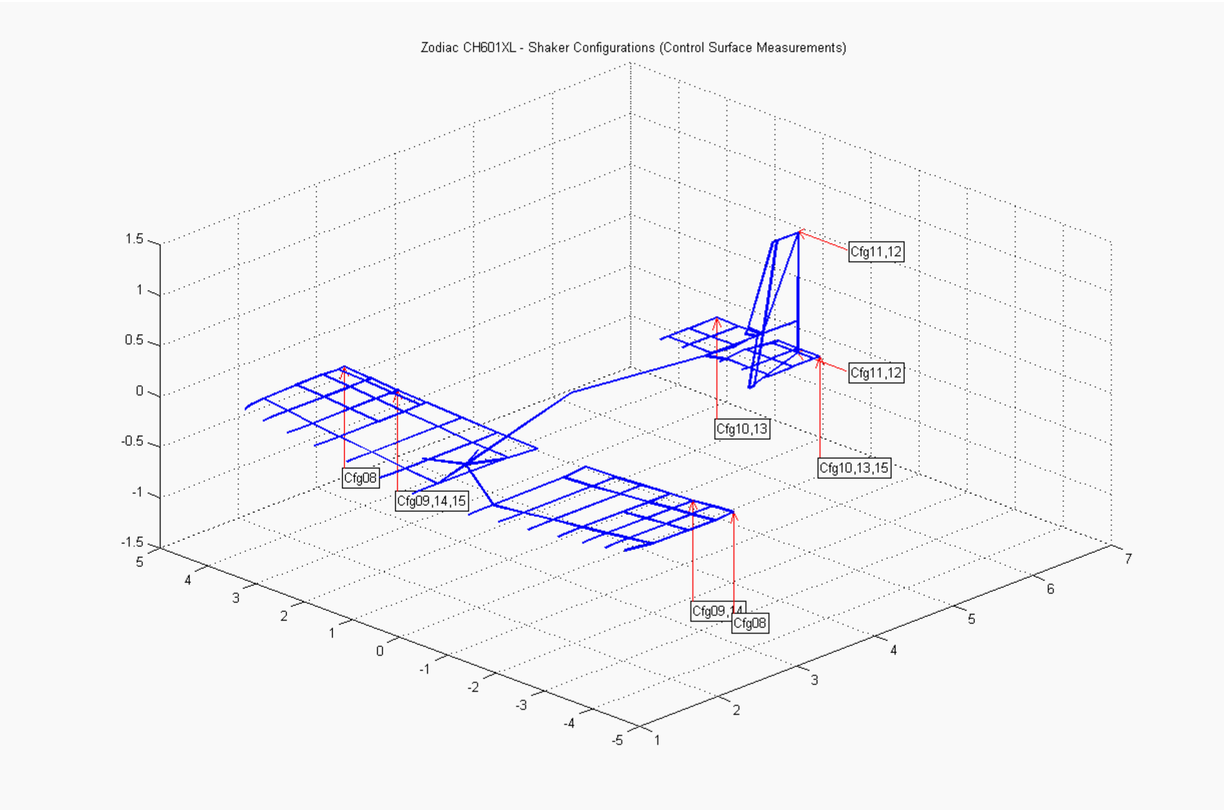

Figure 3: Shaker configurations for the identification of the control modes of the CH601XL

Figure 4 shows the shaker configurations for the identification of the structural modes of the CH601XL.

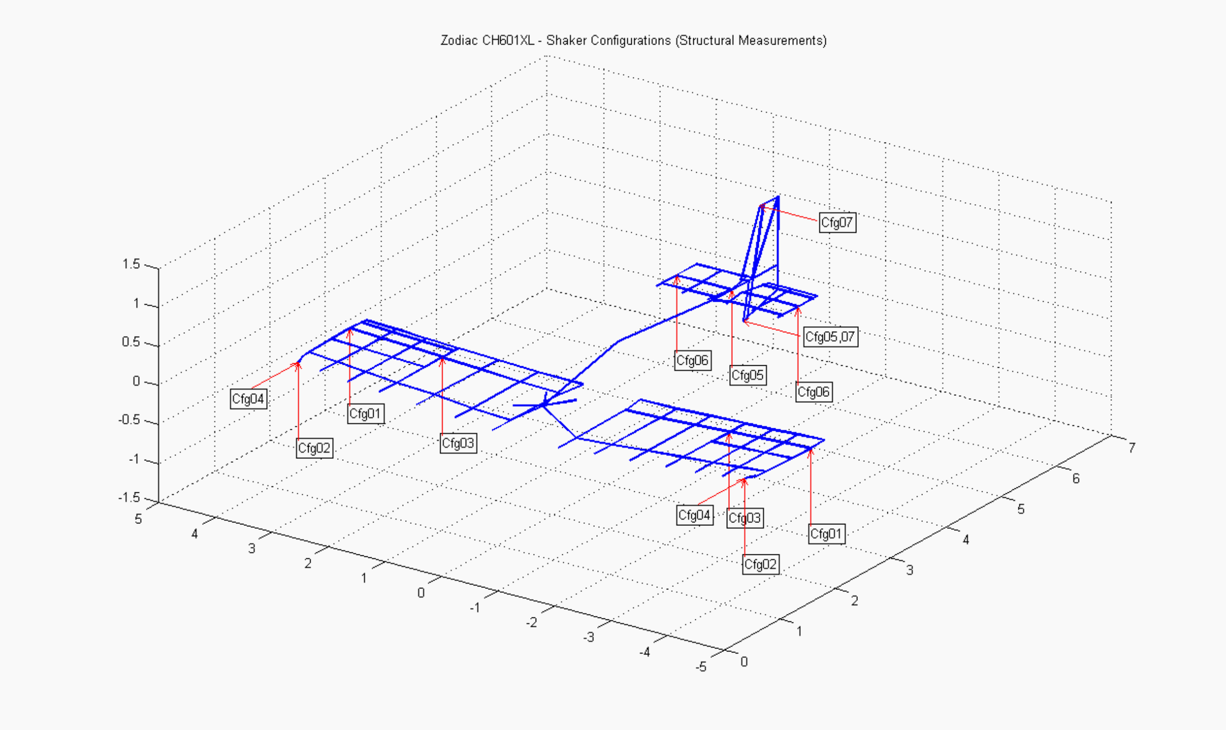

Figure 4: Shaker configurations for the identification of the structural modes of the CH601XL

2.1 Modal data from GVT for CH601XL with minimum take off mass and fixed controls

After evaluating the measurements of the ground vibration test for the CH601XL with minimum take off mass and fixed controls the values for the Eigen frequencies, the generalized masses and modal damping are obtained. The value PRC (Phase Resonance Criterion) is one of the two quality indicators used in this report. If the value PRC is better than 95% the excitation of the corresponding Eigen modes was successful. For PRC values smaller the 80% another measurement with shaker positions in the antinodes of an actual mode is advised.

In order to work out robust flutter margins with respect to the possible variances of control cable tension of the airplane in service, a total of three modal measurements are performed for the CH601XL (see Tables 1 to 3).

A second indication for the quality of the GVT- evaluation is the Modal Assurance Criterion which shows the result of the orthogonality of the Eigen modes found with the ground vibration test (see Figures 5 to 7).

Table 1: Modal data from GVT for CH601XL with minimum take off weight and fixed controls, control cables adjusted to 5 lbs

Datafile: CH601XL_basic_5lbs_fixed_v2.unv								
#	Symbol	Definition	Section	Freq. (Hz)	Damping (%)	Gen. Mass (kgm^2)	Config	PRC (%)
001	AQ1	1st rotation	ailerons (fixed)	9,67	2,42	43,56	90,06	100
002	S1	1st bending	wings	10,10	1,30	23,28	1,01	99
003	SQ1	1st rotation	ailerons (fixed)	14,41	1,74	13,36	90,10	92
004	AHZ1	1st swing	horizontal fin	15,26	1,79	64,40	4,02	97
005	SHR1	1st rotation	elevator (fixed)	17,81	3,73	2,17	10,06	100
006	AS1	1st rotation	rudder (fixed)	20,06	1,34	21,70	11,11	97
007	AZ1	1st swing	wings and body	22,08	2,05	25,56	4,09	98
008	AHR1	1st torsion	elevator	26,10	2,40	4,95	10,12	96
009	A1	1st bending	wings	28,22	1,92	37,01	2,06	96
010	ATS1	1st torsion	rudder	29,32	2,21	21,75	11,08	95
011	SQT1	1st torsion	ailerons	29,78	2,29	4,58	92,10	96
012	AQT1	1st torsion	ailerons	29,97	1,05	11,74	92,22	96
013	SZ1	1st swing	wings	31,40	2,48	62,86	4,13	86
014	AH1	1st bending	horizontal fin	45,09	1,28	59,54	2,13	92
015	AS2	2nd rotation	rudder (fixed)	45,43	0,69	2,78	11,28	99
016	SHRT1	1st torsion	elevator	57,28	0,52	33,63	13,27	96
017	AT1	1st torsion	wings	58,75	1,94	47,18	1,31	93
018	SH1	1st bending	horizontal fin	62,76	2,05	5,85	6,12	89
019	ST1	1st torsion	wings	64,28	1,49	28,19	1,27	94
020	SHRT2	2nd torsion	elevator	67,26	2,43	4,85	10,18	93
021	S2	2nd bending	wings	80,76	0,90	56,70	1,42	88
							Ave.:	95

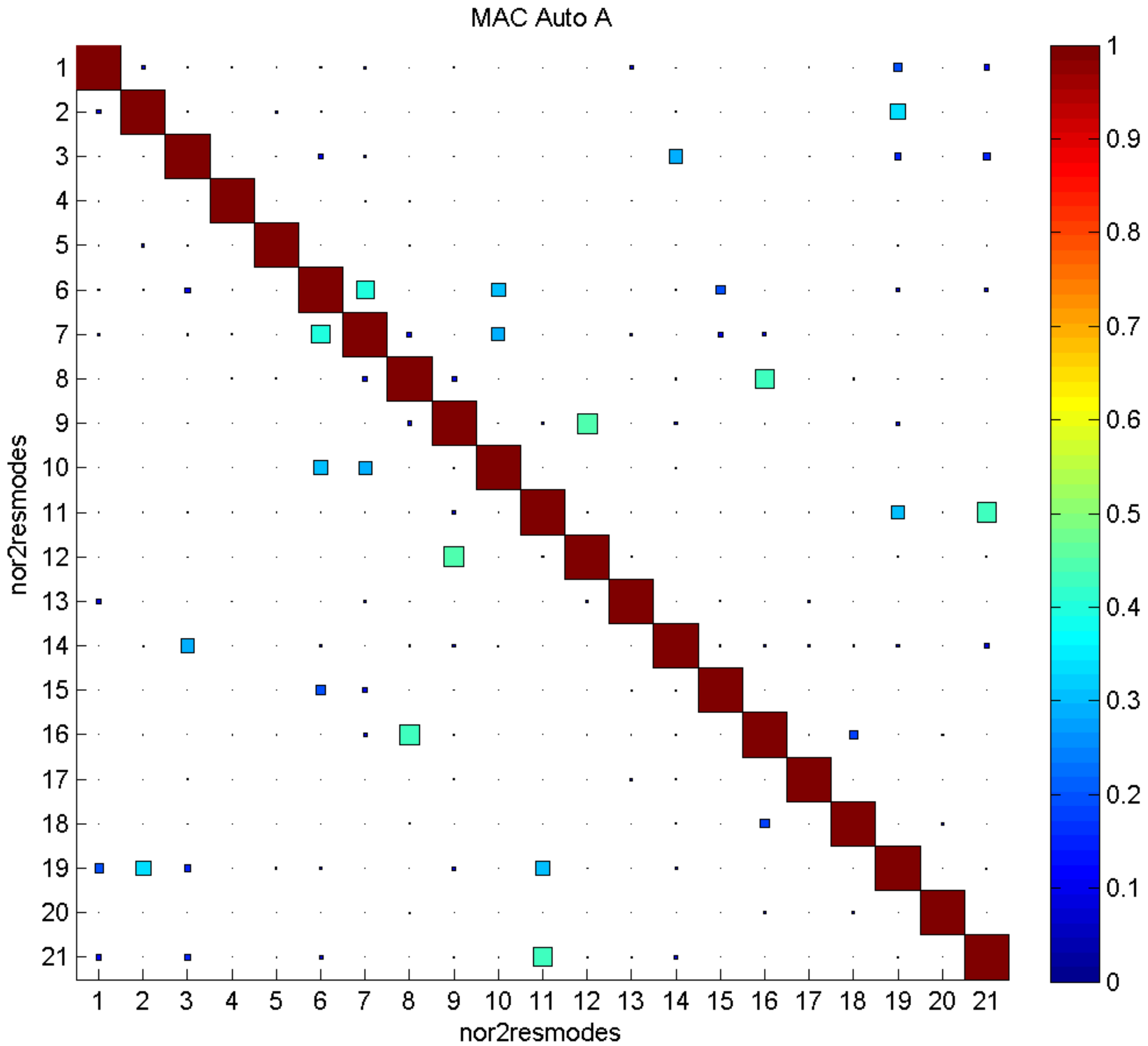

Figure 5: Modal assurance criterion matrix (MAC) for the Eigen vectors evaluated from the time series of the ground vibration test for the CH601XL with minimum take off weight and fixed controls, control cables adjusted to 5 lbs.

Table 2: Modal data from GVT for CH601XL with minimum take off weight and fixed controls, control cables adjusted to 30 lbs

Datafile: CH601XL_basic_30lbs_fixed_v2.unv

#	Symbol	Definition	Section	Freq. (Hz)	Damping (%)	Gen. Mass (kgm^2)	Config	PRC (%)
001	S1	1st bending	wings	10,10	1,30	23,28	1,01	99
002	AHZ1	1st swing	horizontal fin	15,26	1,79	64,40	4,02	97
003	AQ1	1st rotation	ailerons (fixed)	15,38	0,12	50,56	93,10	98
004	SHR1	1st rotation	elevator (fixed)	17,81	3,73	2,17	10,06	100
005	SQ1	1st rotation	ailerons (fixed)	17,89	0,45	31,92	93,13	98
006	AS1	1st rotation	rudder (fixed)	20,06	1,34	21,70	11,11	97
007	AZ1	1st swing	wings and body	22,08	2,05	25,56	4,09	98
008	AHR1	1st torsion	elevator	26,10	2,40	4,95	10,12	96
009	A1	1st bending	wings	28,22	1,92	37,01	2,06	96
010	ATS1	1st torsion	rudder	29,32	2,21	21,75	11,08	95
011	SQT1	1st torsion	ailerons	29,78	2,29	4,58	92,10	96
012	AQT1	1st torsion	ailerons	29,97	1,05	11,74	92,22	96
013	SZ1	1st swing	wings	31,40	2,48	62,86	4,13	86
014	AH1	1st bending	horizontal fin	45,09	1,28	59,54	2,13	92
015	AS2	2nd rotation	rudder (fixed)	45,43	0,69	2,78	11,28	99
016	SHRT1	1st torsion	elevator	57,28	0,52	33,63	13,27	96
017	AT1	1st torsion	wings	58,75	1,94	47,18	1,31	93
018	SH1	1st bending	horizontal fin	62,76	2,05	5,85	6,12	89
019	ST1	1st torsion	wings	64,28	1,49	28,19	1,27	94
020	SHRT2	2nd torsion	elevator	67,26	2,43	4,85	10,18	93
021	S2	2nd bending	wings	80,76	0,90	56,70	1,42	88
							Ave.	95

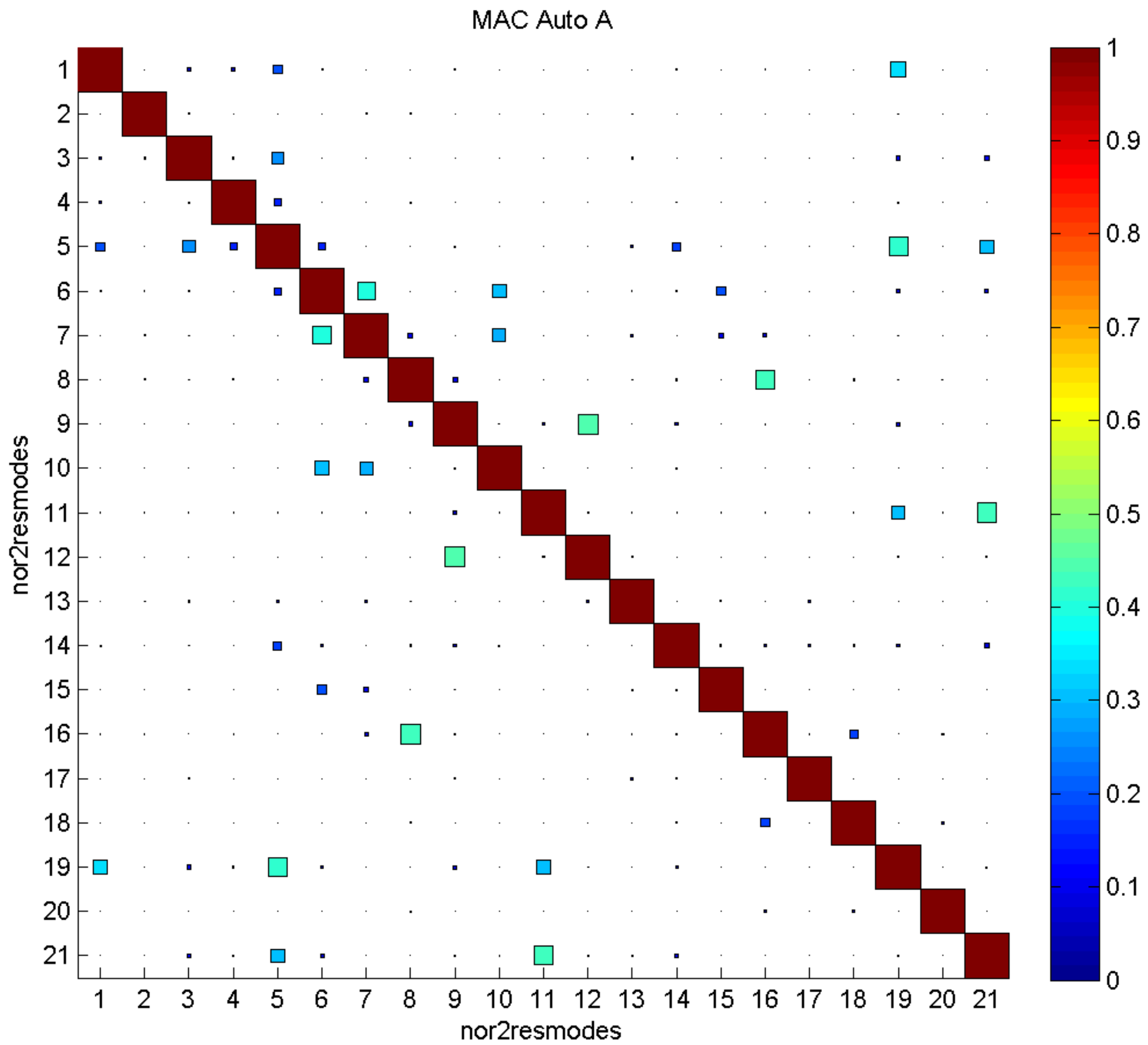

Figure 6: Modal assurance criterion matrix for the Eigen vectors evaluated from the time series of the ground vibration test for the CH601XL with minimum take off weight and fixed controls, control cables adjusted to 30 lbs (nominal value).

Table 3: Modal data from GVT for CH601XL with minimum take off weight and fixed controls, control cables adjusted to 45 lbs

Datafile: CH601XL_basic_45lbs_fixed_v2.unv

#	Symbol	Definition	Section	Freq. (Hz)	Damping (%)	Gen. Mass (kgm^2)	Config	PRC (%)
001	S1	1st bending	wings	10,10	1,30	23,28	1,01	99
002	AHZ1	1st swing	horizontal fin	15,26	1,79	64,40	4,02	97
003	AQ1	1st rotation	ailerons (fixed)	15,63	2,15	26,10	92,06	91
004	SHR1	1st rotation	elevator (fixed)	17,81	3,73	2,17	10,06	100
005	SQ1	1st rotation	ailerons (fixed)	18,42	3,27	3,83	92,09	90
006	AS1	1st rotation	rudder (fixed)	20,06	1,34	21,70	11,11	97
007	AZ1	1st swing	wings and body	22,08	2,05	25,56	4,09	98
008	AHR1	1st torsion	elevator	26,10	2,40	4,95	10,12	96
009	A1	1st bending	wings	28,22	1,92	37,01	2,06	96
010	ATS1	1st torsion	rudder	29,32	2,21	21,75	11,08	95
011	SQT1	1st torsion	ailerons	29,78	2,29	4,58	92,10	96
012	AQT1	1st torsion	ailerons	29,97	1,05	11,74	92,22	96
013	SZ1	1st swing	wings	31,40	2,48	62,86	4,13	86
014	AH1	1st bending	horizontal fin	45,09	1,28	59,54	2,13	92
015	AS2	2nd rotation	rudder (fixed)	45,43	0,69	2,78	11,28	99
016	SHRT1	1st torsion	elevator	57,28	0,52	33,63	13,27	96
017	AT1	1st torsion	wings	58,75	1,94	47,18	1,31	93
018	SH1	1st bending	horizontal fin	62,76	2,05	5,85	6,12	89
019	ST1	1st torsion	wings	64,28	1,49	28,19	1,27	94
020	SHRT2	2nd torsion	elevator	67,26	2,43	4,85	10,18	93
021	S2	2nd bending	wings	80,76	0,90	56,70	1,42	88
							Ave:	94

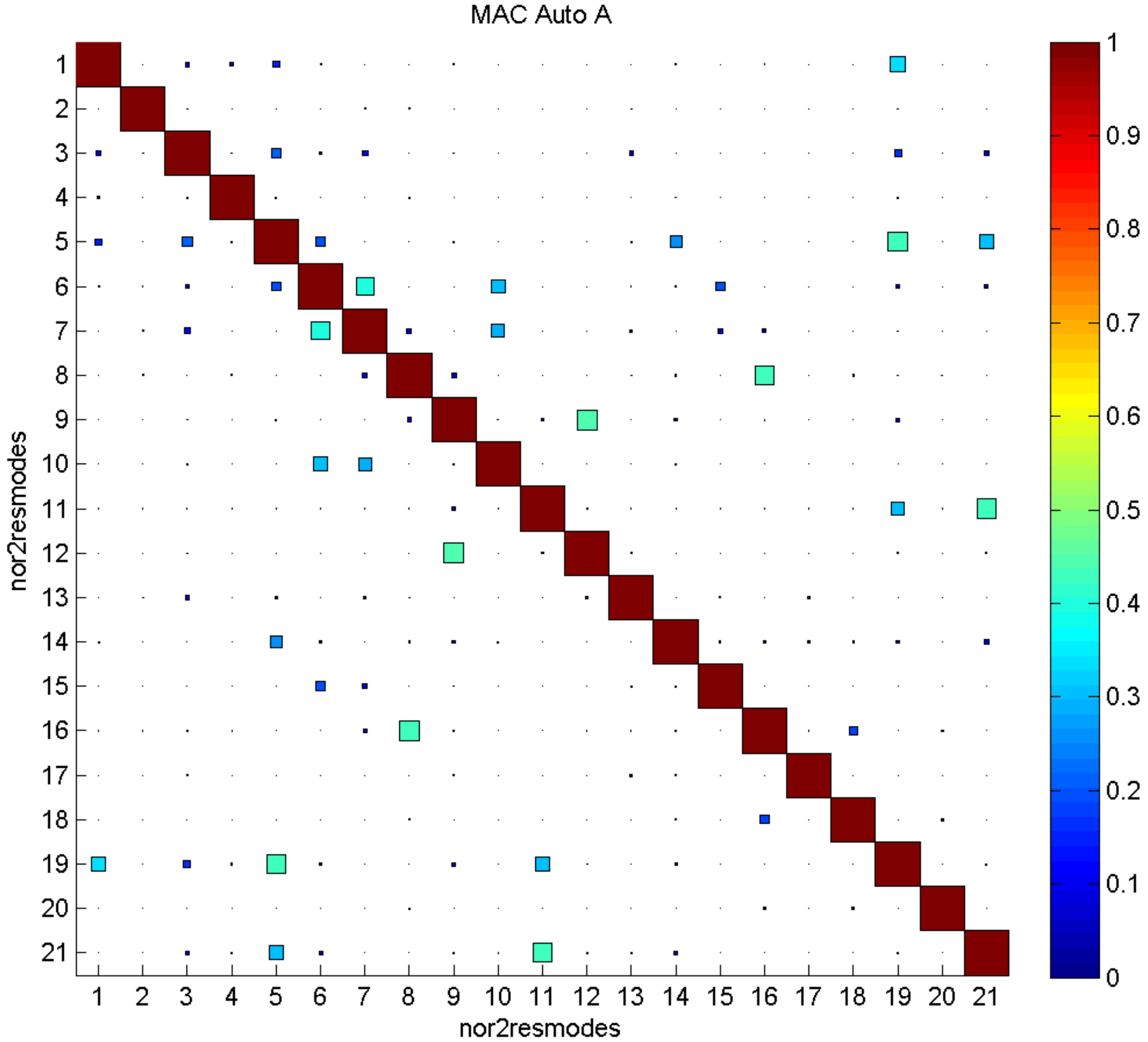

Figure 7: Modal assurance criterion matrix for the Eigen vectors evaluated from the time series of the GVT for the CH601XL with minimum take off weight and fixed controls, control cables adjusted to 45 lbs.

2.2 Modal data from GVT for CH601XL with minimum take off mass and free controls

After evaluating the measurements of the ground vibration test for the CH601XL with minimum take off mass and free controls the values for the Eigen frequencies, the generalized masses and modal damping are obtained. The value PRC (Phase Resonance Criterion) is one of the two quality indicators used in this report. If the value PRC is better than 95% the excitation of the corresponding Eigen mode was successful. For PRC values smaller the 80% another measurement with shaker positions in the antinodes of an actual mode is advised.

In order to work out robust flutter margins with respect to the possible variances of control cable tension of the airplane in service, a total of four modal measurements are performed for the CH601XL. Nevertheless if the controls are left free the modal values remain unchanged.

Table 4: Modal data from GVT for CH601XL with minimum take off weight and free controls

Datafile: CH601XL_basic_30lbs_free_v2.unv

#	Symbol	Definition	Section	Freq. (Hz)	Damping (%)	Gen. Mass (kgm^2)	Config	PRC (%)
003	QR1	1st rotation	ailerons (free)	15,59	3,25	4,51	14,05	98
004	QS1	1st rotation	ailerons (free)	17,46	3,59	2,53	14,06	96
005	HR1	1st rotation	elevator (free)	18,51	1,77	18,01	13,06	94
006	ASR1	1st rotation	rudder (free)	20,24	1,11	49,22	12,19	98
007	AZ1	1st swing	wings and body	22,08	2,05	25,56	4,09	98
008	AHR1	1st torsion	elevator	26,10	2,40	4,95	10,12	96
009	A1	1st bending	wings	28,22	1,92	37,01	2,06	96
010	ATS1	1st torsion	rudder	29,32	2,21	21,75	11,08	95
011	SQT1	1st torsion	ailerons	29,78	2,29	4,58	92,10	96
012	AQT1	1st torsion	ailerons	29,97	1,05	11,74	92,22	96
013	SZ1	1st swing	wings	31,40	2,48	62,86	4,13	86
014	HR2	2nd rotation	elevator (free)	42,81	2,12	16,64	13,11	99
015	AH1	1st bending	horizontal fin	45,09	1,28	59,54	2,13	92
016	SHRT1	1st torsion	elevator	57,28	0,52	33,63	13,27	96
017	AT1	1st torsion	wings	58,75	1,94	47,18	1,31	93
018	SH1	1st bending	horizontal fin	62,76	2,05	5,85	6,12	89
019	ST1	1st torsion	wings	64,28	1,49	28,19	1,27	94
02	SHRT2	2nd torsion	elevator	67,26	2,43	4,85	10,18	93

0								
02 1	S2	2nd bending	wings	80,76	0,90	56,70	1,42	88
							Ave.	95

A second indication for the quality of the modal data is the Modal assurance criterion matrix (MAC) which shows the result of the orthogonality test of the Eigen modes found with the ground vibration test (see Figure 8).

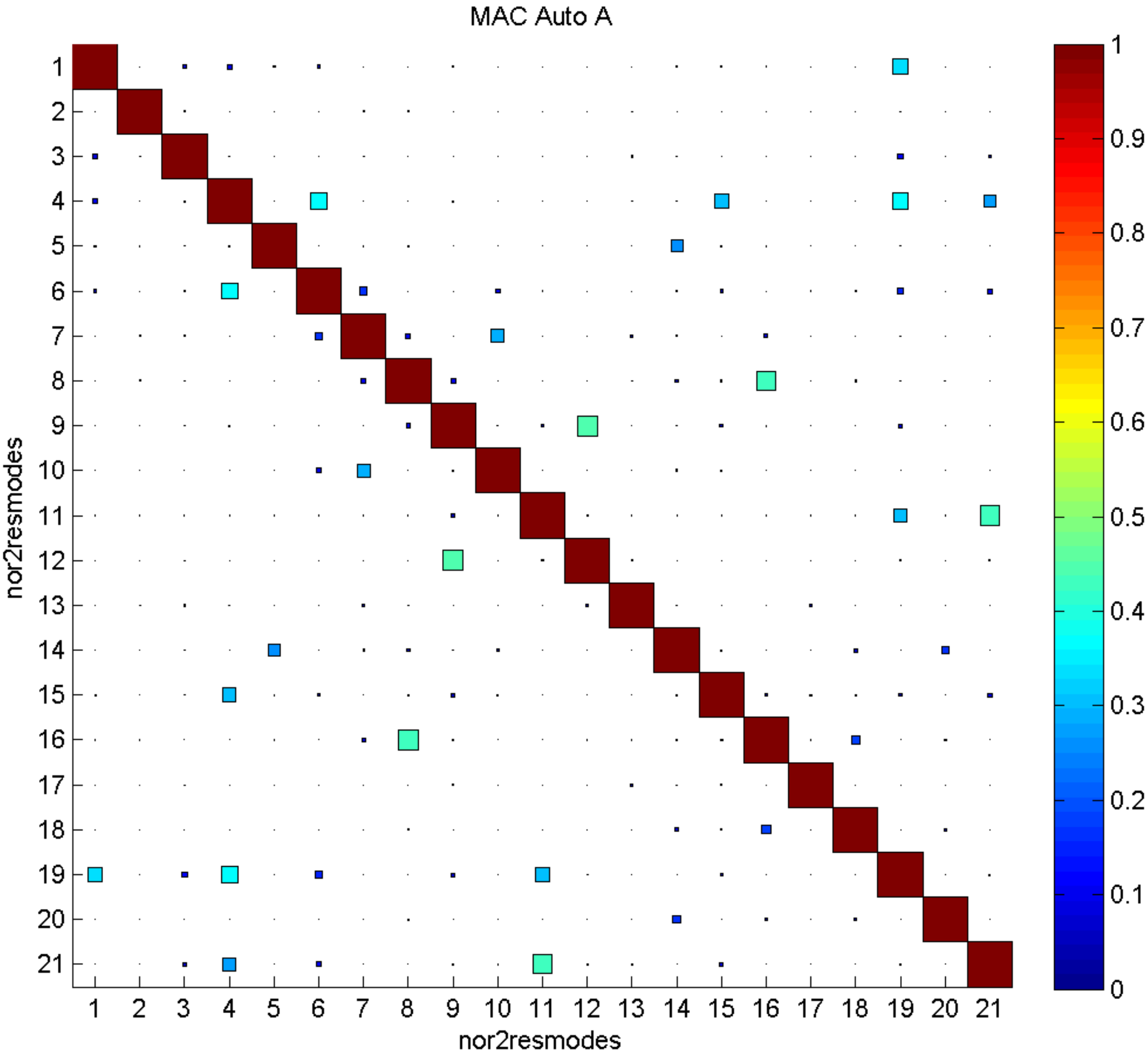

Figure 8: Modal assurance criterion matrix for the Eigen vectors evaluated from the time series of the GVT for the CH601XL with minimum take off mass and free controls.

3. Flutter calculation CH601XL

To calculate the critical flight speed, which indicates the beginning of a possible flutter phenomenon the aeroelastic model of CH601XL must be established. The entire surface of the airplane is discretized with Doublet Lattice Elements (DLE) with the corresponding module of the software package ZAERO[3]. Figure 9 shows the results of this modeling.

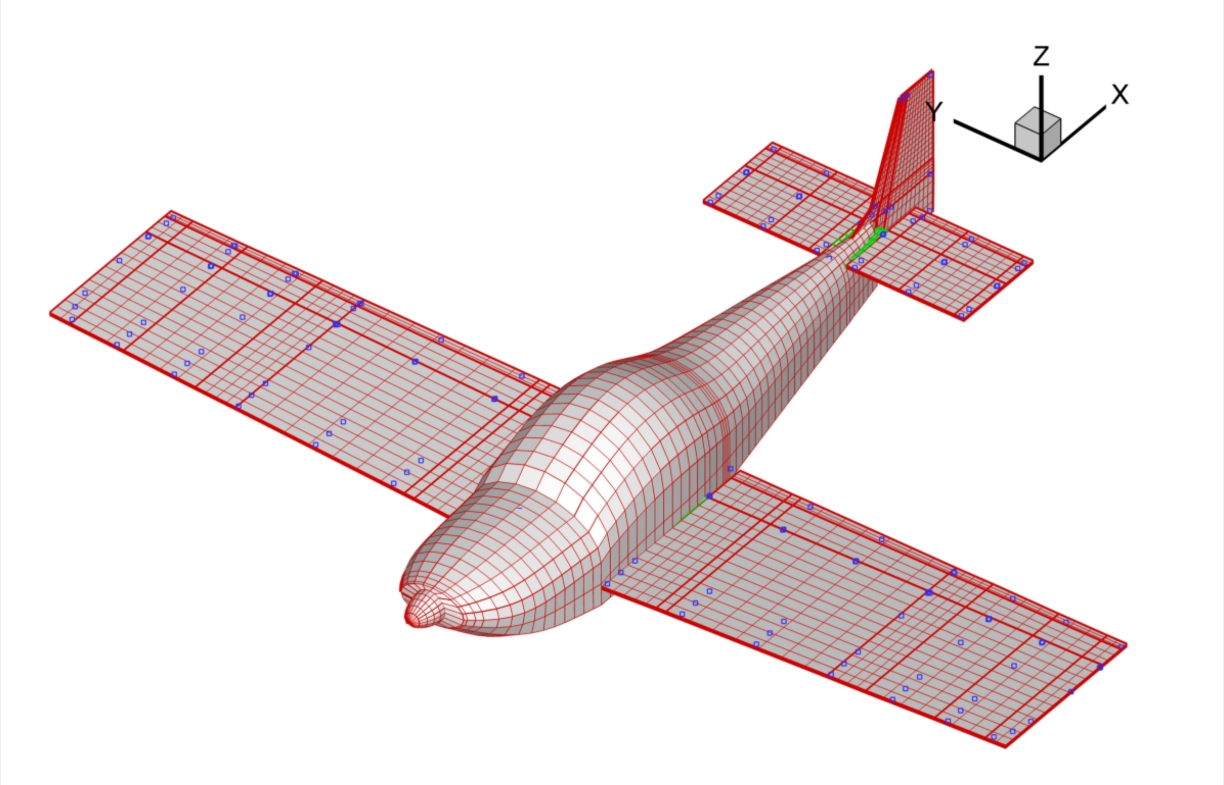

Figure 9: Aeroelastic Model of the CH601XL

After modeling the skin of the airplane the natural vibration modes identified in the time series evaluation from the ground vibration test are imported into the ZAERO program. Each vibration mode is connected to the DLE elements of the aircrafts surface by three dimensional splining methods. The result of this procedure is exported from ZAERO for each mode using standard data sets to allow the printing or animation of these modes. In this work the IDEAS standard universal file format is used. The animation and the images of the modes are produced with the MATLAB toolbox SDTools[4]. The structural dynamic toolbox SDTools allows both, FEA calculations and time series analysis. The first three splined natural modes out of 18 for the CH601XL with controls fixed and cable tension adjusted to the nominal value are shown in Figures 10 through 12. The first three splined natural modes out of 18 for the CH601XL with controls fixed and cable tension adjusted to a value al low as 5 lbs are shown in Figures 13 through 15.The rest of the natural modes for nominal control cable tension as well as for low cable tensions (5 lbs and 15 lbs) and higher cable tension (45 lbs) can be found on the project- DVD as JPG- files and UNV- Files together with the corresponding MATLAB animation source codes.

[3] ZAERO, Users manual, Version 8.2, March 2008, www.zonatech.com, downloadable PDF
4 SDTools, Users manual , Version 6.0, 2008, www.sdtools.com, downloadable PDF

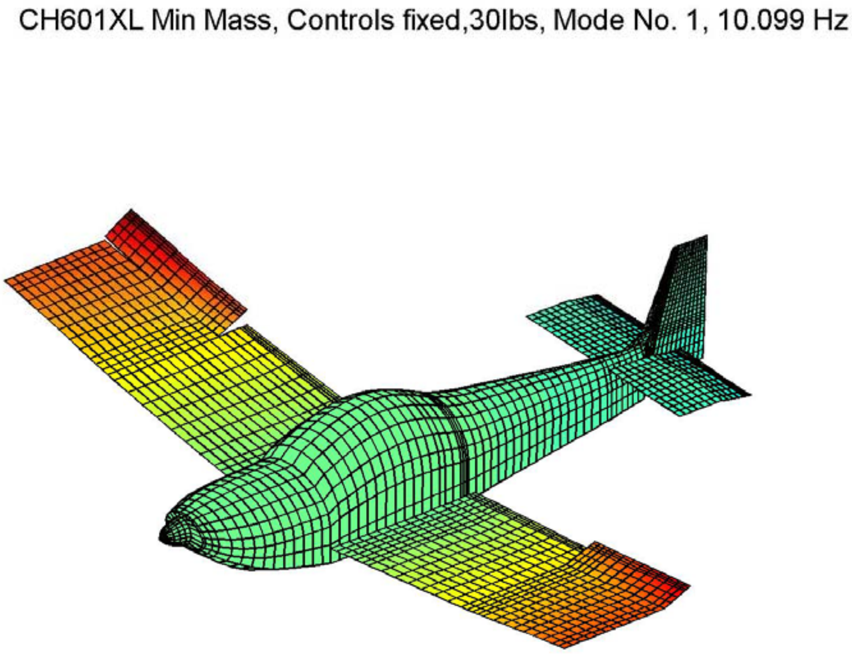

Figure 10: First natural mode of the CH601XL with minimum take off weight, controls fixed and cable tension adjusted to the nominal value 30lbs

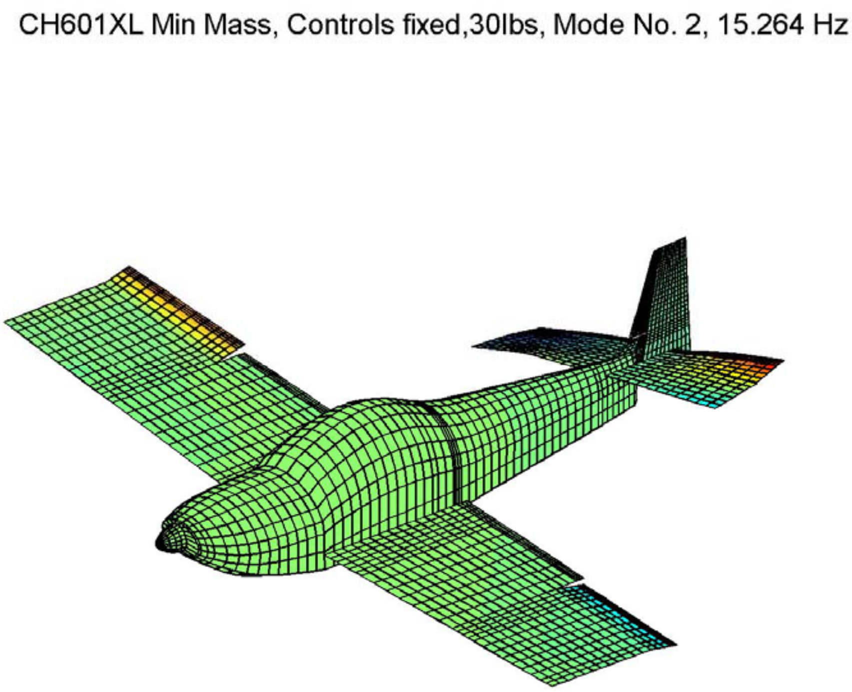

Figure 11: Second natural mode of the CH601XL with minimum take off weight, controls fixed and cable tension adjusted to the nominal value 30lbs

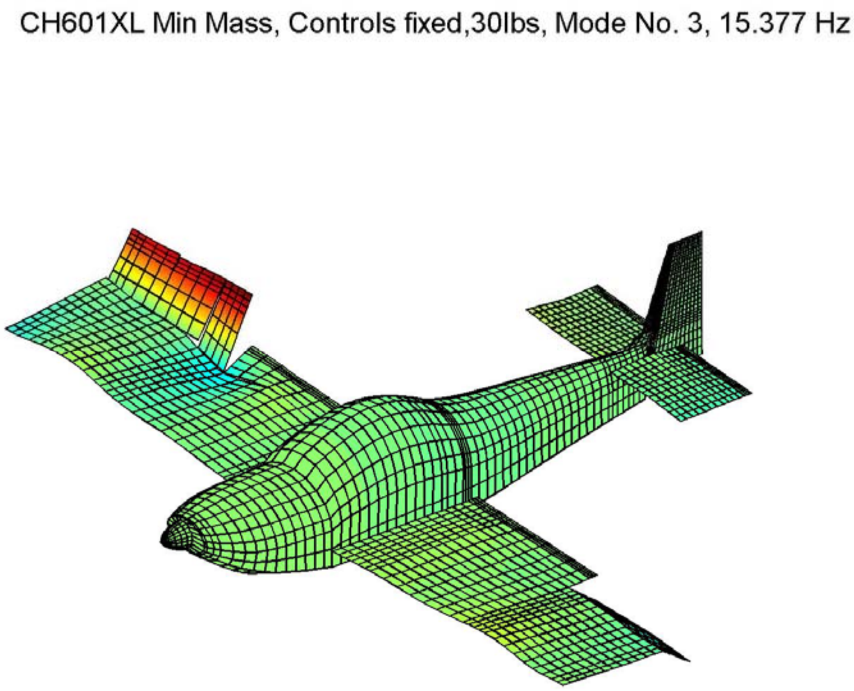

Figure 12: Third natural mode of the CH601XL with minimum take off weight, controls fixed and cable tension adjusted to the nominal value 30lbs

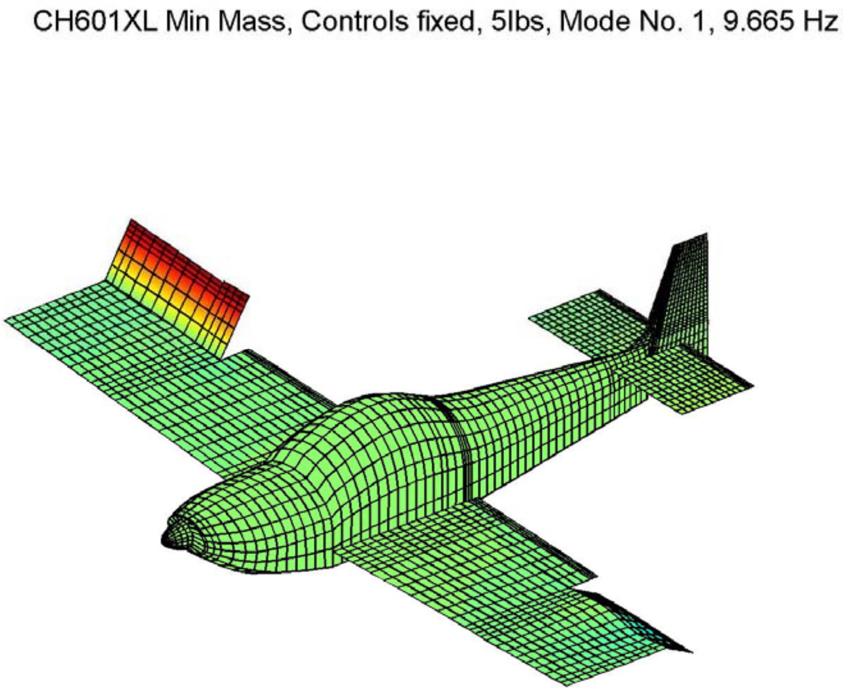

Figure 13: First natural mode of the CH601XL with minimum take off weight, controls fixed and cable tension adjusted to 5lbs

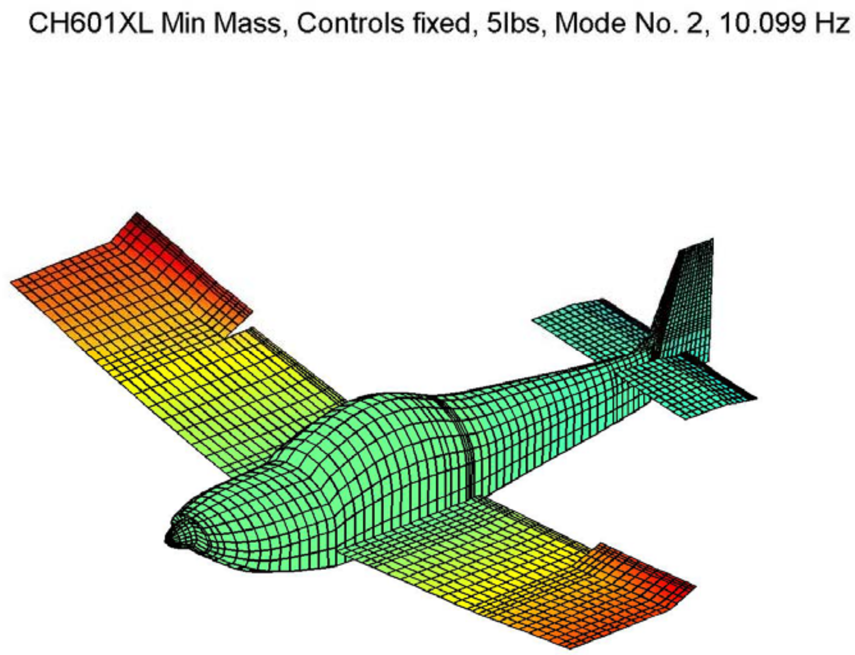

Figure 14: Second natural mode of the CH601XL with minimum take off weight, controls fixed and cable tension adjusted to 5lbs

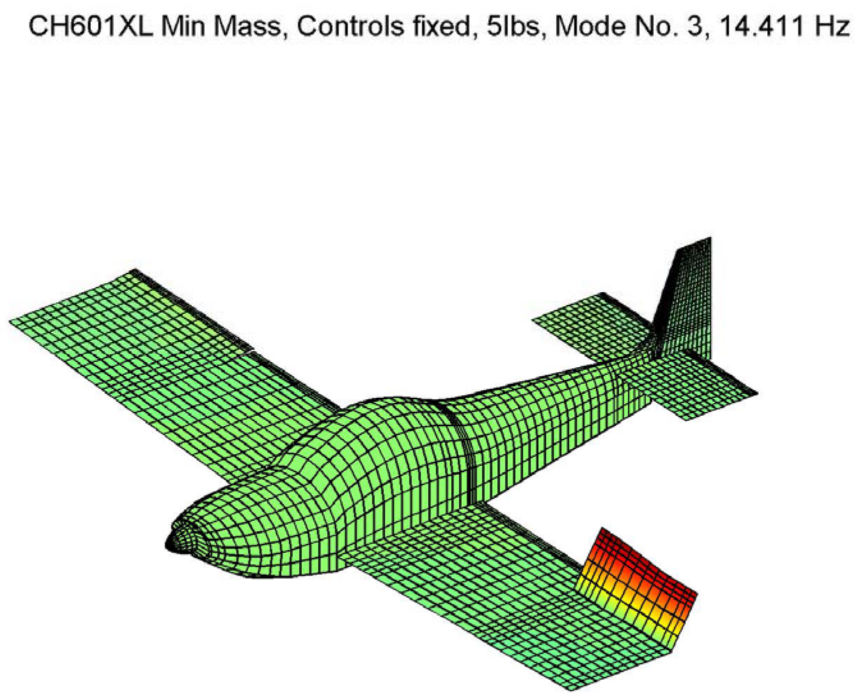

Figure 15: Third natural mode of the CH601XL with minimum take off weight, controls fixed and cable tension adjusted to 5lbs

As can bee seen from Figure 12 and Figure 13 the symmetric aileron mode changes significantly its Eigen frequency if the control cable tension is reduced from the nominal value 30 lbs to 5 lbs.

Nevertheless the airspeed dependent aerodynamic damping of the corresponding flutter calculations remain positive as can be seen from Figure 16 and Figure 17.

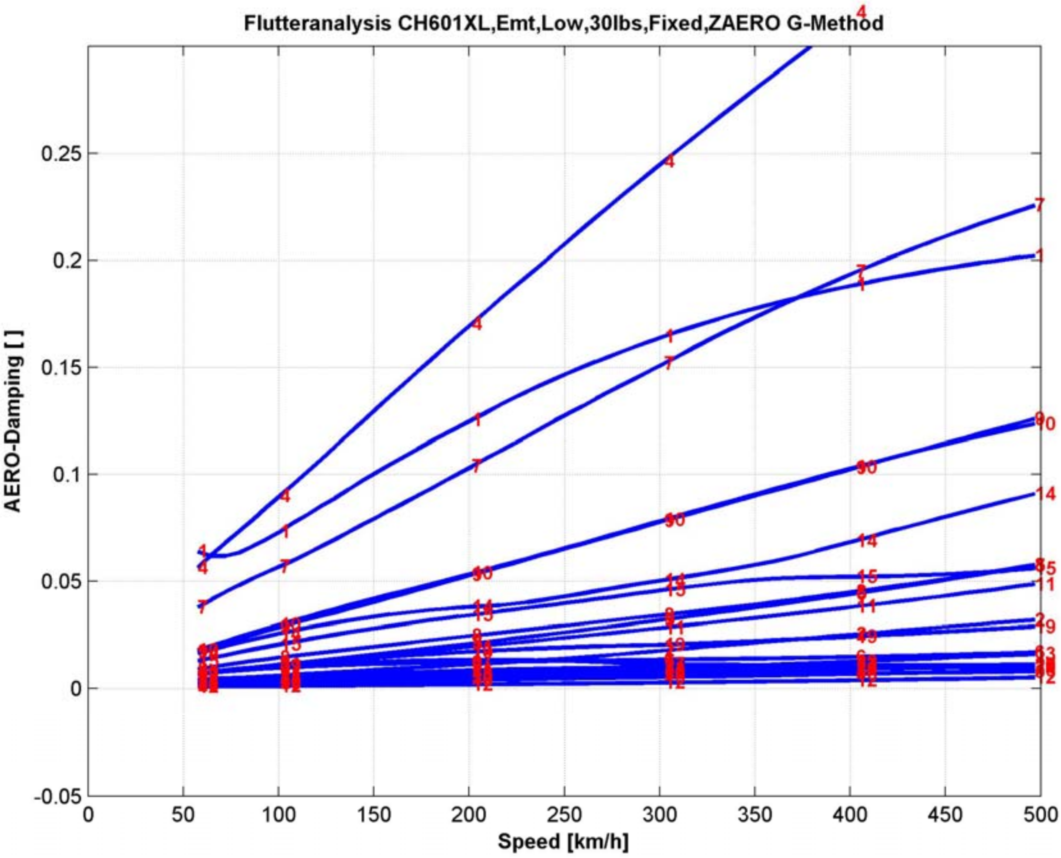

Figure 16: Aerodynamic damping for the CH601XL with minimum take off mass and blocked controls (aileron, elevator and rudder) at low altitude flight from 60 km/h up to 500 km/h. Control cable tension adjusted to the nominal value (30 lbs).

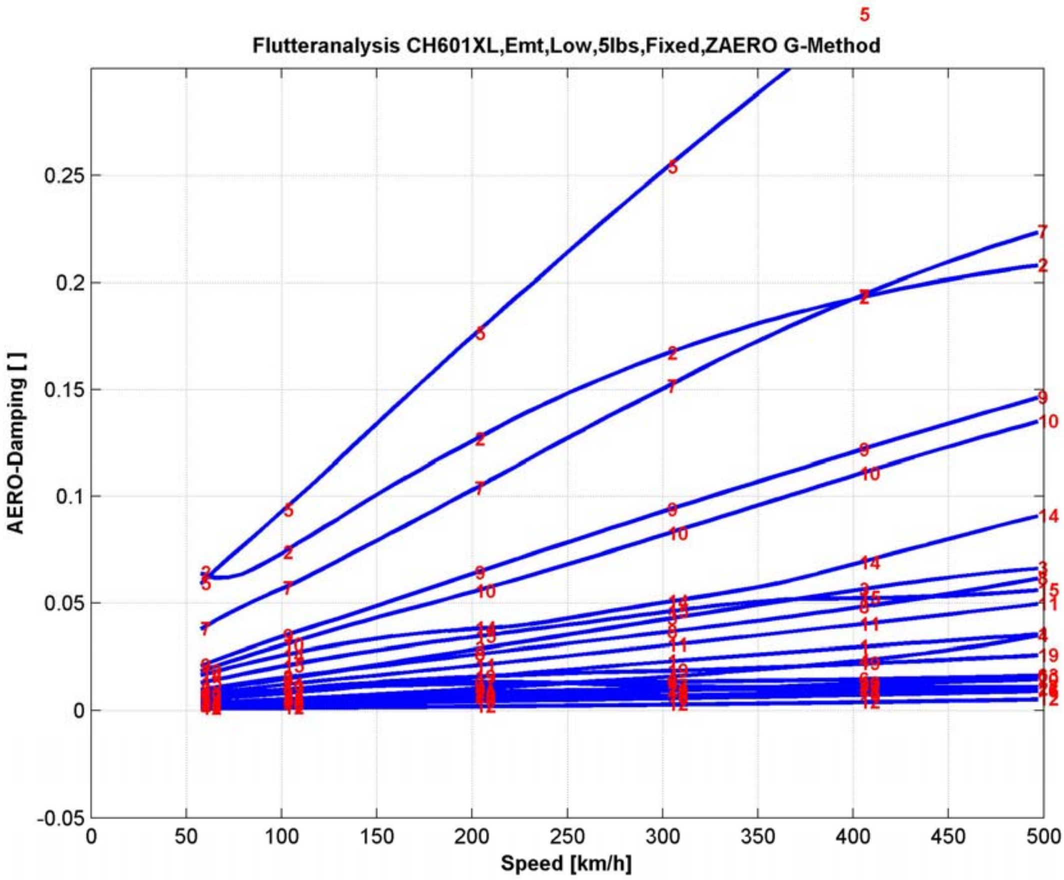

Figure 17: Aerodynamic damping for the CH601XL with minimum take off mass and blocked controls (aileron, elevator and rudder) at low altitude flight from 60 km/h up to 500 km/h. Control cable tension adjusted to a very low value (5 lbs).

As shown in Figure 18 and Figure 19 the airspeed dependent Eigen frequencies of the aileron modes (Mode 2 and Mode 3 in Figure 18, Mode 1 and Mode 3 in Figure 19)[5] are reduced significantly only at low air speed. At higher airspeed the aileron control in both cases appears to become stiffer. This is the usual experience of a pilot in flight.

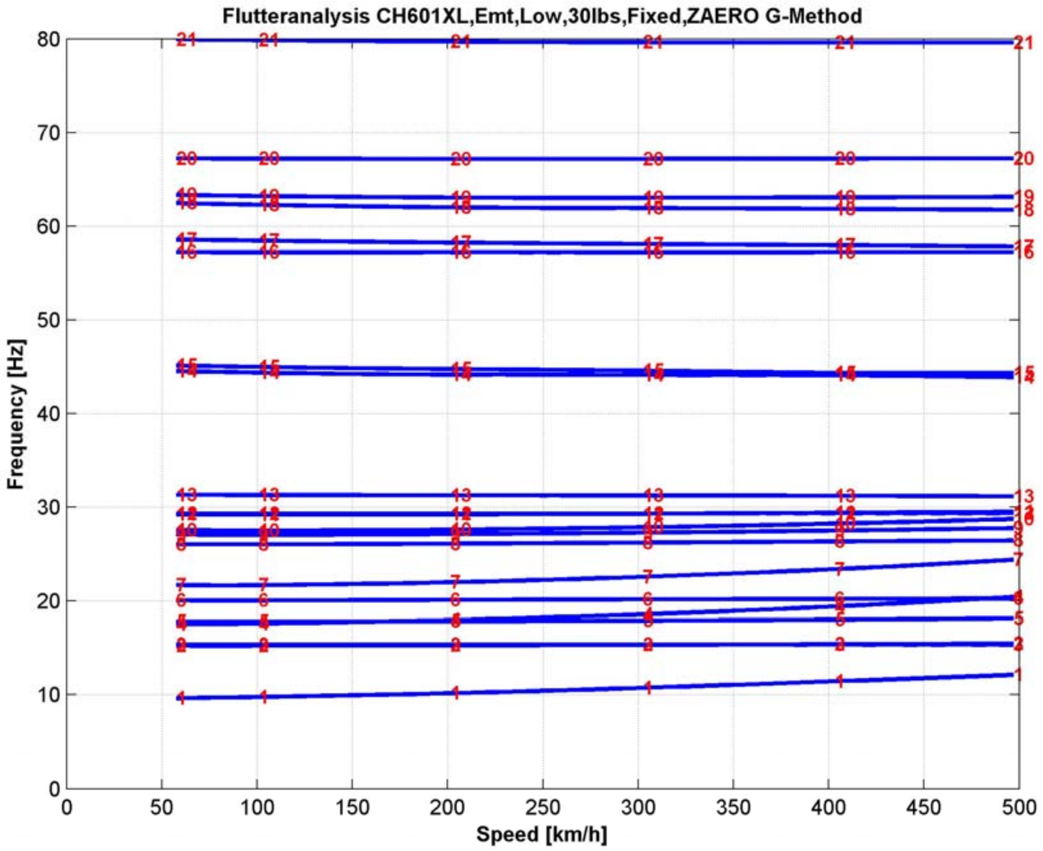

Figure 18: Eigen Frequencies for the CH601XL with minimum take off mass and blocked controls (aileron, elevator and rudder) at low altitude flight from 60 km/h up to 500 km/h. Control cable tension adjusted to nominal value (30 lbs).

[5] The frequencies in ZAERO are sorted with respect to their values in ascending order

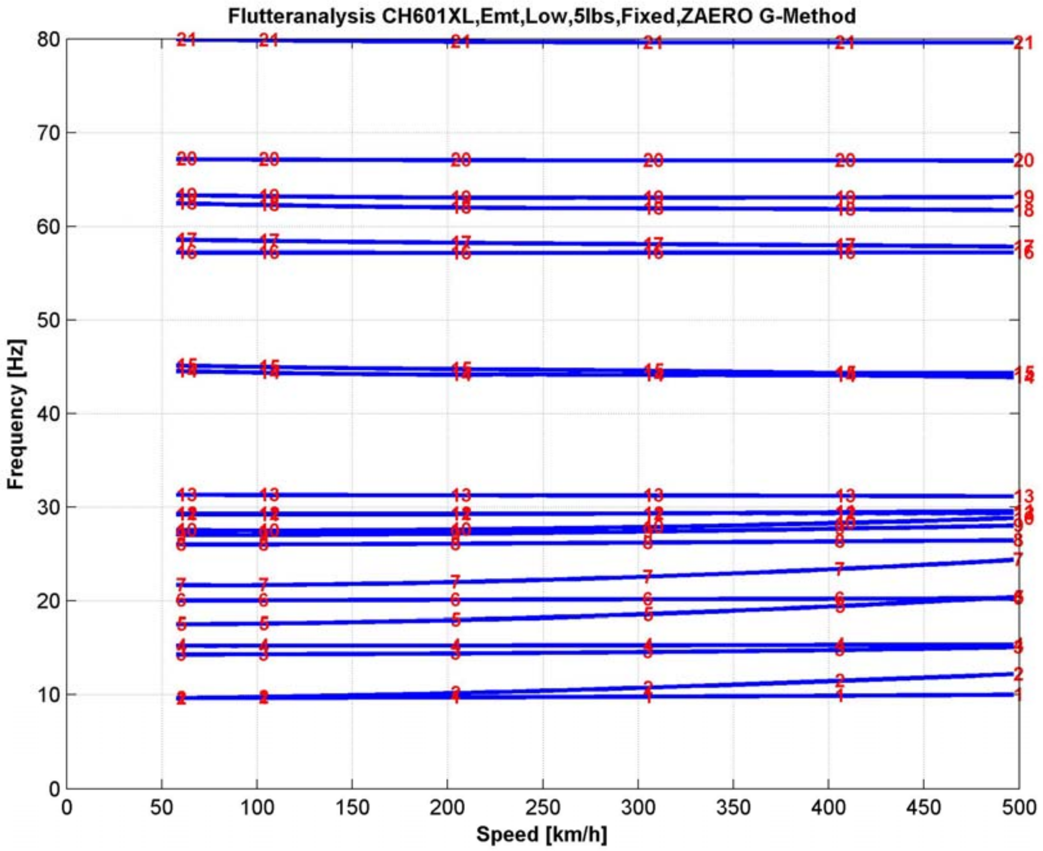

Figure 19: Eigen Frequencies for the CH601XL with minimum take off mass and blocked controls (aileron, elevator and rudder) at low altitude flight from 60 km/h up to 500 km/h. Control cable tension adjusted to a very low value (5 lbs).

4. Flutter results for the CH601XL and CH601

Flutter calculations have been performed for the CH601XL based on the results of complete ground vibration tests up to Eigen frequencies of 80 Hz. All results, the input and output files for the software package ZAERO, as well as all pre- and post processing MATLAB program codes are stored on the corresponding project DVD CH601XL. The files on the DVD CH601XL allow complete analysis and reproduction all computed results:

- minimum and maximum take off mass for the CH601XL
- maximum take off mass (600kg) for the CH601
- controls fixed and free
- cable tensions of aileron control system from 5 lbs to 45 lbs
- low altitude flight (MSL) and high altitude flight (5000 m)

No tendency to flutter or divergence was found within the flight envelope. The analysis does not show any reason to install mass balancing weights nor the need for spades.

5. Summary

With the classical linear approach for flutter analysis with ground vibration test and up to date flutter calculations using the software package ZAERO, no aeroelastic instability was found within the flight envelope of the CH601XL and the CH601 with 600 kg take off mass.

If the end stop for the flap according to the manufacturer's specifications is mounted and the cable tensions are in the specified tolerance of the manufacturer, the occurrence of flutter with the CH601XL and the CH601 with 600 kg take of mass is improbable within the well defined flight envelope.

The analysis in this report is based on linear methodology. The analysis of possible nonlinear vibrations due to structural instabilities was not subject of this investigation.

In order to insure that the flutter results worked out in this report are proved to be correct, the following measures have to be implemented:

1. **The control cable tension must never be less than 20 lbs and never exceed 40 lbs (see Figure 20).**

pounds =	kilograms
15	6.804
20	9.072
25	11.34
30	13.608
35	15.876
40	18.144
45	20.412

Adjust tension as necessary by using the appropriate turn-buckles.

Figure 20: Adjusting control cable tension (see XLphotoguide.pdf)

2. **The specified end stops for the retraced landing flaps (see Figure 21) must be installed properly.**

Figure 21: Flap Gap Stop, Part No. 6S3-1

3. The specified speed limitations for flights with extended landing flaps have to be respected by the pilot in order to avoid overloading of the flap suspension.

7.	Wing flaps	- retract when speed of 120 km/h (65 KIAS) is reached, at altitude of 50 m (150 ft)

Figure 22: Speed limit with flaps extended (extraction from the users guide CH601XL)

4. The aileron mobility measured at the hinge axis must be kept within the specified values (+/- 11.5 °). To exclude in principle that the pilot can apply too big control surface deflections, a control stick torque limiter should be installed (see Figure 23).

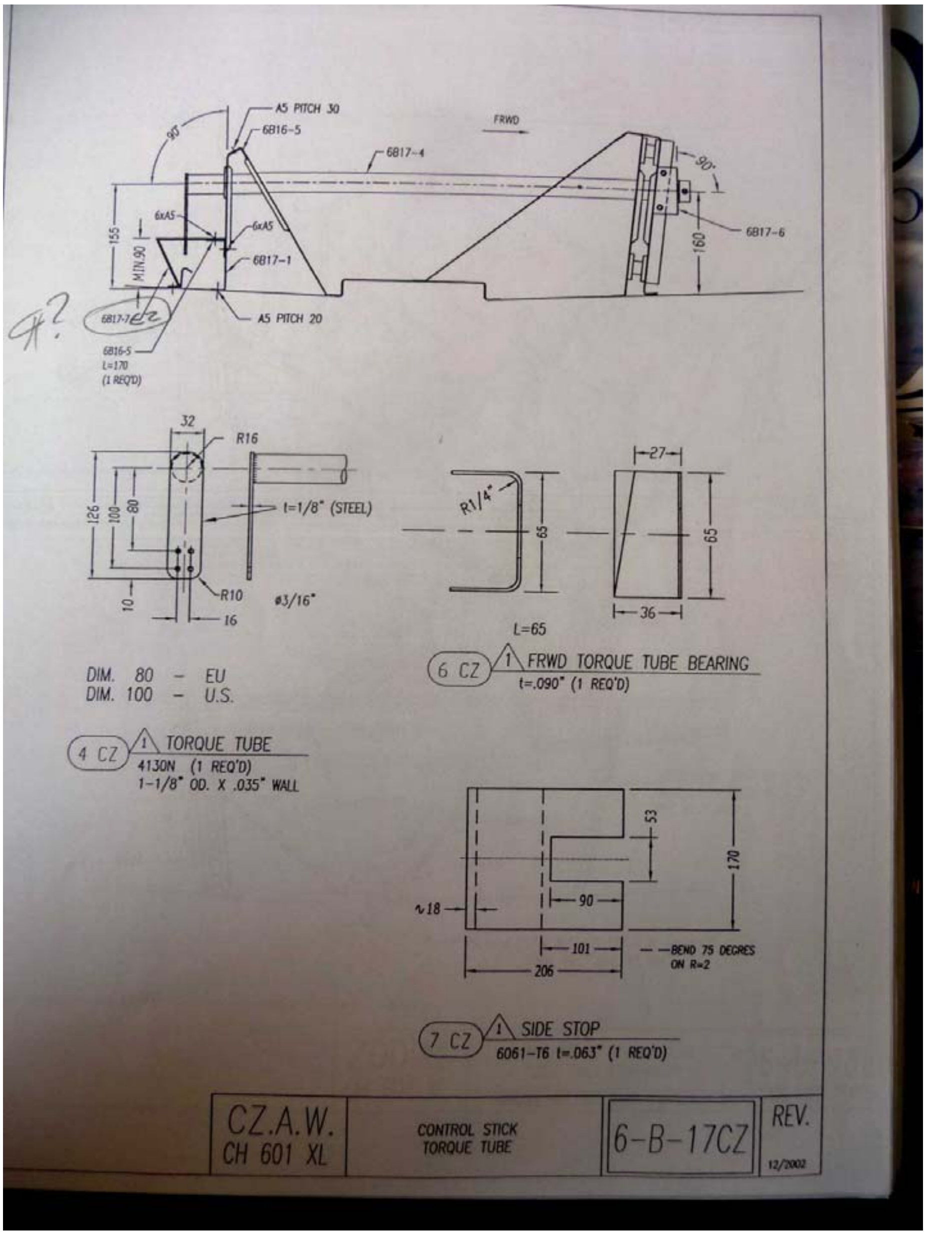

Figure 23: Control Stick Torque Tube

6. Final Remarks and Proposals

The application of mass balancing means for the ailerons of the actual CH601XL (see example Figure 24) or the use of spades (see Figure 25) cannot be reasoned physically from the linear approach of flutter analysis documented in this report.

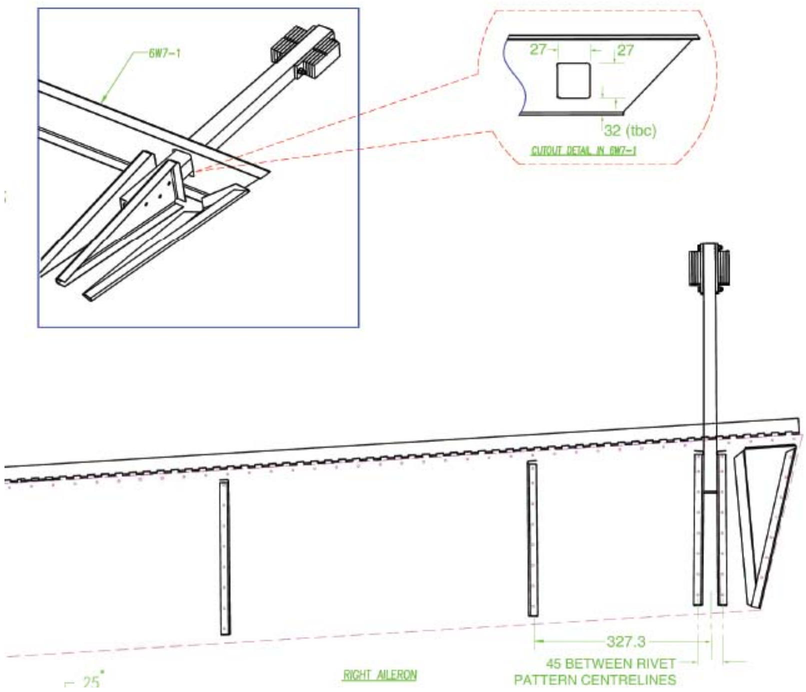

Figure 24: Proposal for Mass Balancing

Figure 25: Proposal for the application of spades

The efficiency of any means to modify the aerodynamics of the CH601XL should first be proved by physical reasoning. Especially in case of potential occurrences of randomly exited nonlinear vibrations one could make matters worse if one does not exactly know what one is doing.

In case of nonlinear structural dynamic instabilities mass balancing of the ailerons may prevent inertia induced nonlinear vibrations. However, the danger of gust induced nonlinear vibrations in principle cannot be eliminated with mass balancing.

Hamburg, May 27, 2009

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