Evaluation of structural parameters on linear/non-linear design spaces of the Joined Wing Sensorcraft

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Abstract

The United States Air Force requested an aircraft capable of transporting sets of advanced sensor over very large distances and at extreme altitudes. To achieve these objectives, an unconventional aircraft is required. The Joined Wing Sensorcraft, from Boeing^{TM}, may be the solution to this problem. Although this new design could have instabilities due to geometric nonlinearity, not normally investigated in preliminary designs. In this paper, different structural parameters were explored in order to understand the behavior of this type of configuration. The parameters that will be focus on are the joints and the stiffness of the members that compose the aircraft. Sensitivity analyses and carpet plots were generated on linear and non-linear analysis. During the development of this study, it was found three different types of geometric nonlinearity that can occur with this type of structure. To carry out this study, matching a high fidelity model with a simplified beam model is needed, in order to decrease the time to generate the design space. Furthermore, a few static test on the airplane and also material tests were made to identify how accurate the high fidelity model is when compared with the actual UAV already produced.
Keywords: Joined Wing, Sensorcraft, UAV, structural parameters, sensitivity analysis

1. Introduction

SensorCraft is the name given to a high altitude and long endurance (HALE) unmanned aerial vehicle (UAV), capable of carrying out revolutionary intelligence, surveillance, and reconnaissance (ISR) in military and civil sectors when equipped with advanced sensor packages [1].

Nowadays, constant surveillance over vast geographical areas is a vital point in military missions. Due to this fact, the Air Force Research Laboratory (AFRL) is developing the SensorCraft concept to have a solution for constant battle space awareness [2]. In order to do so, the SensorCraft should be able to stay in missions for more than 30 hours plus has the capability of covering a maximum range of 2000 nautical miles [3].

To respond to these objectives, different companies presented different concepts. Boeing^{TM} brought back to study a Joined-Wing configuration, which is made of a wing pair, forward and aft wings connect each other forming a diamond shape (Figure 1).

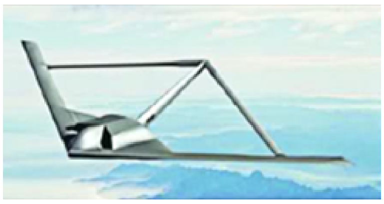

Figure 1: Boeing Concept [4].

It has discovered from computational studies that Joined Wing SensorCraft (JWSC) has the possibility of presenting a nonlinear structural response, due to large deflections on the wings, which can cause a collapse of the structure [2] [5] [3] [4].

This work aims to expanding these computational studies by evaluating different types of nonlinearities that my occur with JWSC. First of all, the results from the experimental static tests in the GSRPV made in Quaternion Aerospace are presented. These results will be used to match a High Fidelity Finite Element Model (HF FEM) [4]. With the results of the HF FEM, a simplified beam model was created in order to perform sensitivity studies to assess the influence of the different body part stiffness, such as forward and aft wings, fuse and boom.

Here it is presented and discussed the main outcomes of this study. In the end the conclusions of this work are drwn and future development is suggested.

2. Static tests

In the beginning of this work, several static tests were performed to investigate the response of a prototyped JWSC aircraft. The first analysis will be to discover which are the deflections of the forwards wings and boom. To do that, the aft wings will be detached from the aircraft. A symmetry load will be applied on the forward wings. To prevent the airplane from lifting sand bags were stack above the fuselage (Figure 2 and Figure 3).

Figure 2: Static Test Forward Wings Load.

Figure 3: Static Test Boom Load.

After testing forward wing and boom, the aft wing is included to create the characteristic diamond shape (Figure 4).

Figure 4: Static Test with Aft Wings, Wing Load.

These tests show a linear behavior of the aircraft structure.

2.1. Comparisons of HF model

To check the accuracy of the High Fidelity Model (HFM) a comparison with experimental results was made. To have the realistic displacement two load steps were simulated. In the load step1 (LS1) just the gravity was taken into account, in load step2 (LS2) the gravity and the load were implemented. The difference for the displacement in zz direction between these load steps was the value to consider in comparison with realistic test. Next a comparison of the experimental results and the HF FEM is presented, without the aft wings (Table 1) and with the aft wings (Table 2).

No Rear Wings				
Load on	Load *[Kg]*	FEA def. *[mm]*	exp. def. *[mm]*	relative error to exp.
wing	33.24	53.08	77	-31.1%
boom	23.06	5.42	29	-81.3%

Table 1: Comparison without the Aft Wings.

With Rear Wings							
Load on	Load *[Kg]*	FEA def. *[mm]*		exp. def. *[mm]*		relative error to exp.	
		boom	wing	boom	wing	boom	wing
wing	33.24	0.62	15.12	6.5	24	-90.5%	-37.5%
boom	23.06	5.44	6.58	28	5	-80.6%	31.6%

Table 2: Comparison with the Aft Wings.

These experiences reveal that the FEA model is stiffer than the real model. There are many factors that can lead to this result as the material properties, the manufacture constraints and even the joints, without mentioning mistakes that can happen in experience and in finite element modulation.

2.2. Match Experimental Results

In order to match the experimental results with the joints as variables, a project was created in ModelCenter™ as illustrated in Figure 5. The optimization algorithm used was the Darwin Algorithm.

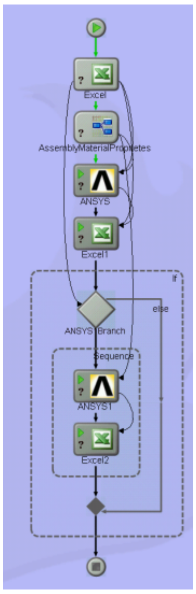

Figure 5: High Fidelity project in ModelCenter^{TM}.

Figure 6 summarizes the first idea to match the results.

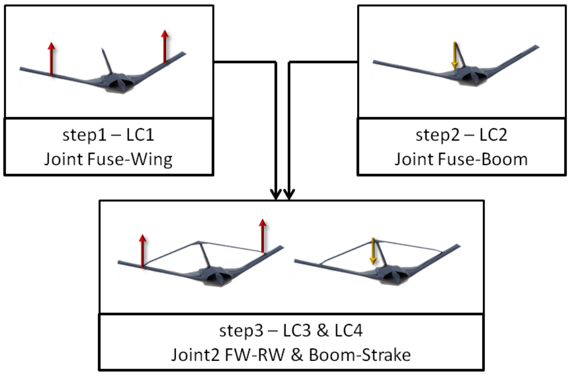

Figure 6: Steps for the optimization of the Joints on the Sensorcraft.

After the optimization processes was completed, the joints came up with the values represented in Table 3. In this table, the error are presented relatively to experimental results.

Joint	Joint [Nmm/rad]	Loadcase	relative error to experimental	
			boom	wing
Fuse-Wing	166000	1	N/A	0.4%
Fuse-Boom	6400	2	0.0%	N/A
FW-RW	1000	3	84.8%	12.2%
Boom-Strake	10000	4	61.5%	81.3%

Table 3: Values of the first optimization of the Joints for the HF FEM.

The result for the step1 of the optimization was an error value of 0.4%, with this deviation of the results of both wing tips due to the asymmetry of the model. Step2 shows that it is possible to get an error of 0% and get the perfect solution. In other hand, for step3 the optimization shows a huge error In order to improve the results, another optimization process was performed. This time, all joints were used in a single optimization for load case 3 and 4. After that, the results for load case 1 and 2 were checked. Table 4 shows the relative error to the experimental results for this optimization using only the step 3 on the first process

Joint	Joint [Nmm/rad]	Load case	relative error to experimental	
			boom	wing
Fuse-Wing	170000	1	N/A	-13.8%
Fuse-Boom	200000	2	71.0%	N/A
FW-RW	185000	3	17.1%	-39.7%
Boom-Strake	185000	4	39.5%	-15.8%

Table 4: Values of the second optimization of Joints for the HF FEM.

3. Simplified Beam model

The geometry of the Joined Wing aircraft has been converted into a simplified beam model. Figure 7 shows a 3D sketch of it where the blue lines are beams, which their points are in 50% of the chord along the span. The red lines are the rigid elements (MPC184), and they just transfer forces between nodes that are connected to it, creating moments that will be transferred to beams. These rigid elements are connecting the fuselage with joint on the boom.

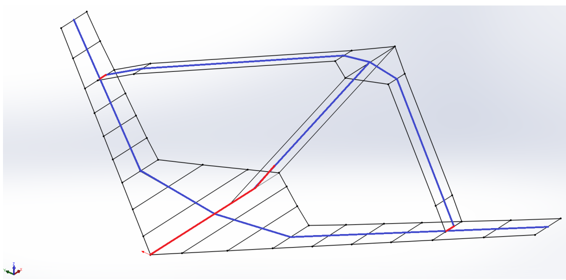

Figure 7: Geometry of Simplified Beam model.

To join the parts of the model: fuselage, front wing, rear wing and boom a few joints were needed. Figure 8 shows the axis where the joints are allowed to rotate, like a torsion spring.

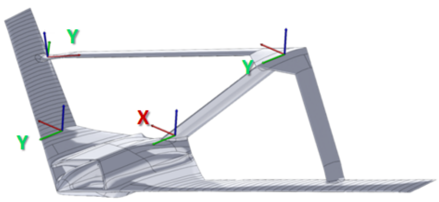

Figure 8: Original CAD model with joints rotations.

Beams were model with hollow sections which, as a start point. The base and height were set equal to 60% of chord and thicknesses, respectively, of the airfoil. The webs and the caps will be two variables (Figure 9).

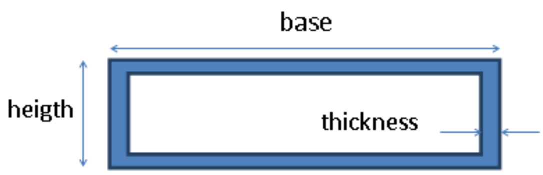

Figure 9: Hallow Cross Section.

Another variable was the TAPER which is defined below.

$$a = thickness_{root} \tag{1}$$
$$b = thickness_{tip} = TAPER \times a \tag{2}$$

In order not to have so many variables, an isotropic material was chosen for the entire model. All beams are model as aluminium alloy. The finite element beam model is shown in Figure 10.

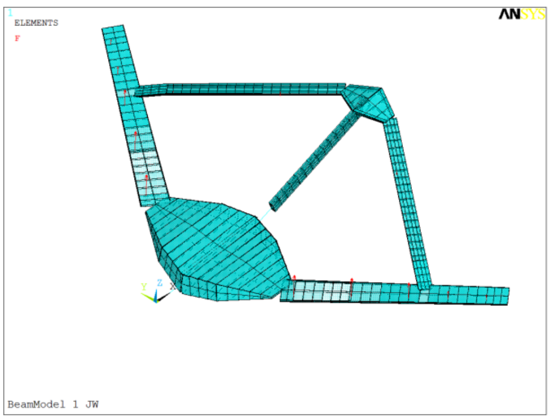

Figure 10: Simplified Beam Model.

3.1. Description of the project

Figure 11 shows the overview of this project built in ModelCenter^{TM}. This software provides the users with a unique way of wrapping other computational softwares in a single optimization problem. Wrap is the termed used when program codes, originally conceived to be operated in a stand alone manner, can communicate with each other directly. It uses a unique architecture to wrap and integrate legacy programs, data, and geometry features. With this program it is possible to perform different studies as the performance of parametric and optimization studies Design of Experiments (DoE), Response Surface Methodology (RSM) and the ability to save, track and compare design histories [6].

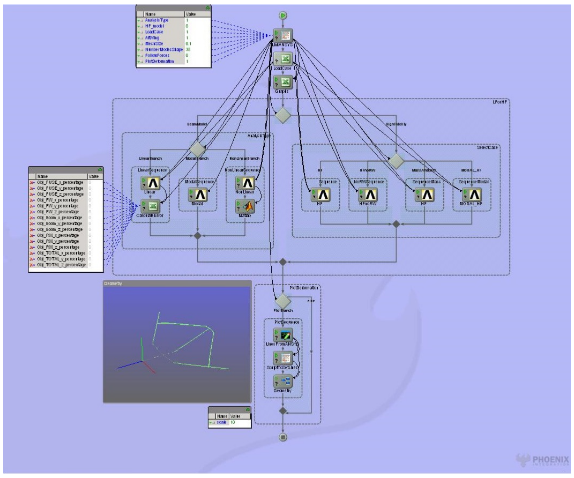

Figure 11: Overview of the Project.

This software is used here to perform an optimization for matching HF FEM and simplified beam model responses. The objective functions are set as the minimization of the sum of all the relative error to the power of two. In this way, the error will never be negative. Each node has one objective function, so the optimization is multi-objective.

$$obj.\ func. = \left(\frac{value\ from\ FEM - target\ value}{target\ value}\right)^2 \tag{3}$$

The output of interest is the percentage error, which is simply the square of objective function times 100.

$$percentage\ error = \sqrt{objective\ function} \times 100 \tag{4}$$

The average error of each part of the Sensorcraft, is the sum of all errors divided by the number of nodes to match. Table 5 shows the number of nodes to match.

Darwin algorithm was the chosen algorithm to run this optimization. The Darwin algorithm ensures that the optimization procedure continually progresses towards an optimal solution by allowing

Part	Nº of nodes to match
Fuse	1
Boom	5
FW	10
RW	7
Total	23

Table 5: Number of nodes to match.

the best designs in each generation to survive for the next generation with the cost of an enormous amount of runs [6].

4. Results of the project

After a long travel on this optimization process, there are the results of the matching the High Fidelity Model with a simplified Beam Model. The displacements in zz are matched in different points of the structure. After the 15000 runs, the best value found was in iteration 9701. The error are described in Table 6 for the different parts oj JWSC.

Average Error on:	%
Fuse	7.95
FW	7.79
BOOM	5.78
RW	3.96

Table 6: Results for matching both models.

Overall, the error stays always below 8%. The discrepancy could be because the HF model has not symmetry results, and also due to very small number displacements in order of 10^{-5} of some nodes. Nevertheless the results are acceptable, all errors are below 10%. Finally, the results of the variables for this optimized point are represented in Table 7.

	Thickness (mm)		Tapper	Young Modulus (GPa)
	webs	caps		
FUSE	256.7	40.2	0.26	N/A
FW	69.2	1.1	0.77	N/A
RW	29.6	3.6	N/A	N/A
BOOM	17.8	40.5	N/A	480

Table 7: Results of the variables obtained after the matching both models.

4.1. Sensitivity study

A series of sensitivity studies were performed on the joints and on the stiffness of the structural members in order to understand which parameters affect most the structural response. The load case chosen is with the point loads applied at the joints with a magnitude chosen to yield equivalent forward wing root bending moments of those of a 3.5g pull-up manoeuvre. The variables can change within 10% from their initial value, which are the optimized point. The sensitivity graph of all joints' variables with their respective colors are presented in Figure 12. The bigger the bar is the more influence has that variable on the response, which is the ratio between z direction of the boom and the wing tip deflections.

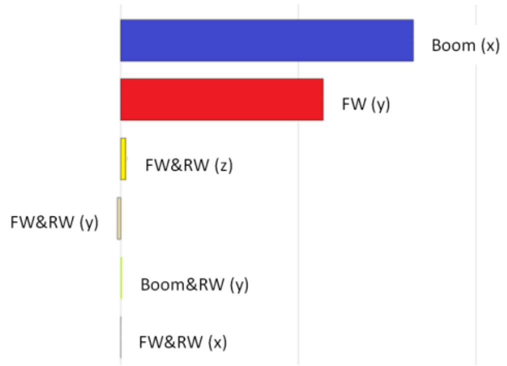

Figure 12: Sensitivity Study for joints.

The boom joint reveals to be the parameter that most influence the results. Also, the wing deflection has an impact on the response. Similarly, an investigation into the effects of the running stiffness of the main structural components was performed. The results can be seen in Figure 13.

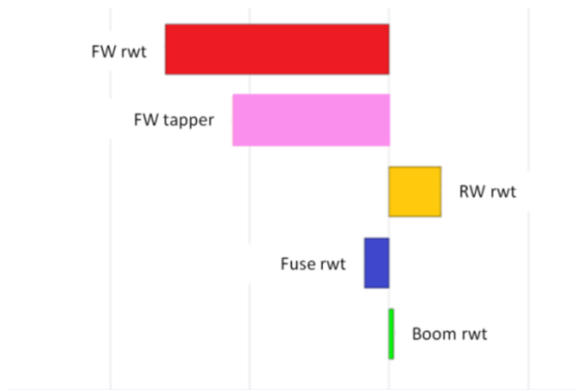

Figure 13: Sensitivity Study for stiffness.

The thickness of the boom reveals to have a very small influence on the results. As expected the forward and rear wings are the parts of the structure that have the most influence on the results.

4.2. Design Space Exploration

With the DOE, it is possible to draw some carpet plots where each intersection between lines is one FEM run. As before, the response for the DOE is the ratio boom and wing displacements. The variables can vary to the double or half of their initial value. The arrows in the next series of images represent an increase of the corresponding variable in that direction. The FW(y) and Boom(x) joints variables are analyzed in Figure 14.

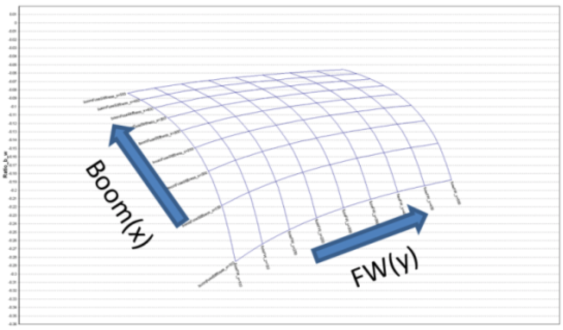

Figure 14: DOE - FW(y) and Boom(x) joints.

From the previous carpet plot (Figure 14), it is possible to see that the gradient of the variable Boom(x) decreases when the FW(y) increases its value. The ratio wall thickness variables, for the FW, RW and Boom were also analyzed (Figure 15). The blue line is for no boom deflection, so below the blue line the boom has a negative deflection in z direction, and above the blue line the boom has the positive deflection in z direction, the same positive direction as the forward wing.

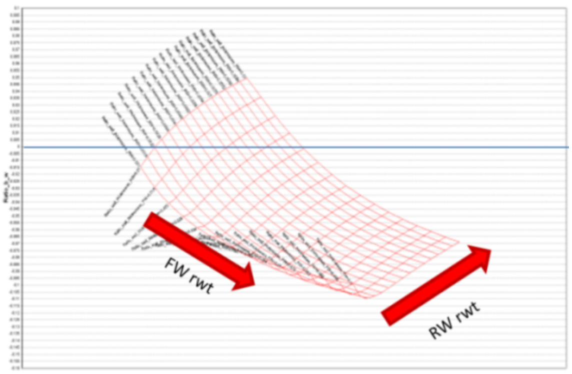

Figure 15: DOE - FW and RW ratio wall thickness.

It can be said that the combination of the stiffness of the FW and RW can made the boom goes up, instead of going down when the load is equivalent to a 3.5g manoeuvre. This can be possible with a lower stiffness on the FW and a higher value on the RW. Another combination possible is the FW and boom ratio wall thickness (Figure 16).

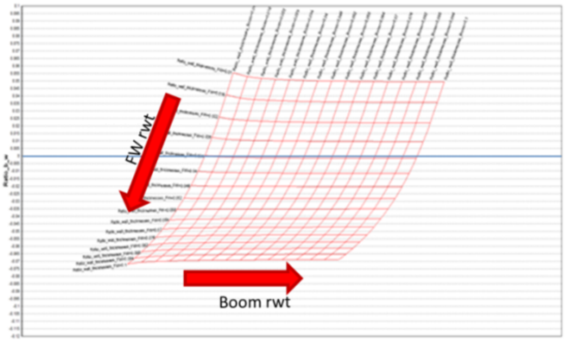

Figure 16: DOE - FW and Boom ratio wall thickness.

From the previous image, it can be concluded that if the FW stiffness decreases 125% the boom will go up. The variation of the boom is not so relevant for this response. The very low value corresponds exactly what was seen in the sensitivity studies.

4.3. Non linear design space

A subset of the parameters with the largest effect on the nonlinear response was chosen to further investigate the design space. The parameters chosen were the FW and RW ratio wall thickness. A regular grid was used to build the Design of Experiments in order to explore the design space. Figure 17 shows the projection of the design space in 3D. With RW and FW stiffness on the plane, where the arrow shows the increase direction. The vertical axis represents a measure of the Non-Linear Factor, which measures how the boom response diverge from the linear analyses.

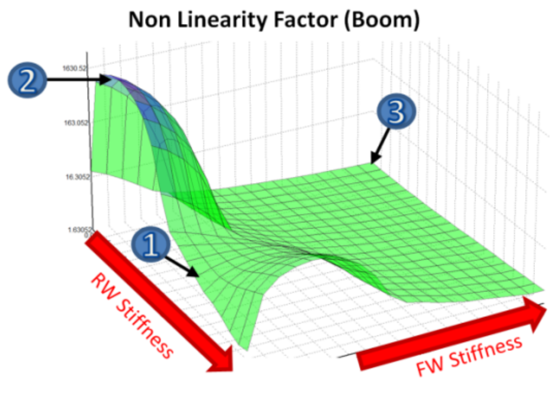

Figure 17: Non linear Factor - FW and RW rwt.

In this one slice of the design space we can see different forms of nonlinearity including geometric the stiffening of the boom tip (1), boom up/down reversal (2) and boom softening (3), where the deflections by the load steps can be seen on Figure 18.

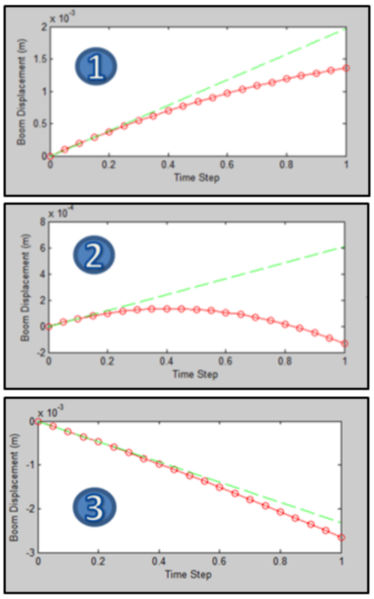

Figure 18: Non linear Factor - three different behaviors.

All three nonlinearities were captured in the design space, with some designs showing boom reversal (up and then down as well as down and then up), nonlinear boom tip deflection and aft wing buckling.

5. Conclusions

This paper shows that the airplane is much stiffer than what FEM calculate from the static test performed.

The matching of the High Fidelity model with a simplified beam model that improves the time of the linear runs in 60 times, not to mention how easier is to run a non-linear analyses. The maximum error of the optimization was less than 8%. With more nodes to match a lower error should be found, although, the time for the optimization should also increase due to the higher number of design variables.

Linear and non-linear design spaces were explored in order to understand the possible behavior that the Joined Wing Configuration can have. Also, these sensitivities studies revealed that for the joint variable, the FW(y) and Boom(x) have the most influence on the structure. Regarding the stiffness variables, the FW ratio wall thickness and also the FW Taper variable were observed to be the ones with the greater impact on the results. However, the combination of the FW and RW, and also FW and Boom stiffness can generate a positive or negative deflection on the boom.

The sensitivity studies showed that several nonlinearities are achievable through the variation of key structural parameters such as joint and wing stiffness. Three distinct nonlinearities were shown which include stress stiffening/softening of the boom tip deflection, a specific form of boom nonlinearity where the boom deflects in one direction in the linear region and then reverses at higher load steps and finally aft wing buckling.

The resulting designs were then proposed as candidates to the US Air Force and Boeing™ as possible starting points for the Aeroelastically Tuned RPV design.

In order to validate the material properties used to build the HF model of the airplane, some tensile tests need to be carried out. Also, the use of a prepag carbon fiber can lead to a better resin content and also a more accurate fiber orientation on the production of the composite structures.

To know the real stiffness of the airplane, for the future it should be done an individual bending test for each part of the airplane. With the results of the FW (forward wing), RW (rear wing), boom and fuselage, it should be possible to match each part individually in a finite element program. After matching each individual part, it is possible to know the real value for the joints.

For the future of the project, there is a possibility to use a non-linear joint with a stop angle, and improve the beam model to be closer to the reality, and so, be able to capture the interaction between the boom and the fuselage skin. The Young modulus of the boom can be a variable in the optimization process in order to capture these interactions.

Also, it will be interesting to understand the effects on the aerodynamic with different types of deflections.

References

[1] http://www.as.northropgrumman.com/products /globalhawk/index.html, [assesed: June 7, 2015].

[2] Canfield R.A. Rasnusseb C.C. and Blair M. Optimization process for configuration of flexible joined-wing. September 2004.

[3] Lucia D. J. The sensorcraft configurations: A non-linear aeroservoelastic challenge for aviation. April 2005.

[4] Richards J. An experimental investigation of a joined wing aircraft configuration using flexible, reduced scale flight test vehicles. PhD Thesis, University of Victoria, Victoria, BC Canada, June 2011.

[5] Garnad-Royo J. Design and evaluation of geometric nonlinearities using joined-wing sensorcraft flight test article. May 2013.

[6] http://www.phoenix-int.com/software/phx-modelcenter.php,[acessed: September 28, 2015].