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Model Update of a Micro Air Vehicle (MAV) Flexible Wing Frame with Uncertainty Quantification

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ABSTRACT

This paper describes a procedure to update parameters in the finite element model of a Micro Air Vehicle (MAV) to improve displacement predictions under aerodynamics loads. Because of fabrication, materials, and geometric uncertainties, a statistical approach combined with Multidisciplinary Design Optimization (MDO) is used to modify key model parameters. Static test data collected using photogrammetry are used to correlate with model predictions. Results show significant improvements in model predictions after parameters are updated; however, computed probabilities values indicate low confidence in updated values and/or model structure errors. Lessons learned in the areas of wing design, test procedures, modeling approaches with geometric nonlinearities, and uncertainties quantification are all documented.

INTRODUCTION

Micro air vehicles (MAV), because of their small size, weight and flexibility, can provide unprecedented new capabilities to many sectors in our community. For example, firefighters can deploy an MAV in a burning building to search for survivors. Another example is surveillance of urban areas using cameras on-board the MAV. To develop these systems for commercial use, government, industry, and several universities partners are joining forces to mature the technology. By combining biologically inspired concepts with modern composite materials new innovative vehicles are emerging. For example, the University of Florida has a vehicle design using a truss-like structure constructed of graphite/epoxy material covered with a thin transparent monofilm membrane. In this case, flexible wings allow the vehicle to naturally adapt to aerodynamic changes. This adaptability results in smooth flight characteristics and unprecedented agility even under gusty conditions.

Although this class of new vehicles is quite different from conventional vehicles, flight controls, will likely be developed using traditional methods. This involves wind tunnel test and model validation under aerodynamic loads to predict the vehicle behavior. Unfortunately, because of the low cost associated with these vehicles, analytical models are rarely pursued. This is the area this work is focused on.

In structural modeling and validation, a significant part of this effort deals with the problem of parameter updates to reconcile differences between test and analysis. This area has been investigated thoroughly by researchers in the US and abroad. However, no single approach is universally accepted and used. Often sensitivity information is computed to assess the relative importance of parameters and to assist in making model changes. These tools, in the hands of experienced engineers, provide heuristic approaches to model updating that work very well for problems with a small number of parameters. Other more general approaches have been reported by Hasselman et al., 1994, Herendeen et al., 1998; Alvin, 1997; Farhat and Hemez, 1993). Hasselman et al., (1994) discussed propagation of parameter uncertainty in frequency response calculations and presented various approaches to handle variability of response values near dynamic resonant conditions. Herendeen et al., (1998) discussed a mathematical procedure using optimization to conduct analysis/test correlation studies of frequency response data. Alvin (1997) extended a procedure developed by Farhat and Hemez, (1993) to improve convergence of Farhat's approach and to incorporate uncertainty information into the estimation process.

The approach used in this paper draws from the aforementioned work but the update process is set up as a two-step process; statistical information of the output space is computed first, followed by nonlinear optimization. Statistical information is used to evaluate the output space range as a function of input variable range and probability distribution. A question answered in the first step is; what is the probability that the predicted output range contains the output observed in the test? If the probability is greater than zero, then the nonlinear optimization provides parameters to reconcile differences between tests with analysis.

MICRO AIR VEHICLE WING

The University of Florida Micro Air Vehicle (UFMAV), shown in figure 1, has been under investigation at the NASA Langley Research Center for the last few years (Waszak and Ifju, 2001; Ifju et al., 2001; Waszak et al. 2002). Built with a truss-like skeleton and membrane wings the vehicle can be configured with many different batten/membrane arrangements. A qualitative assessment of flight behavior was used to select an initial wing configuration, but quantitative data is needed to address vehicle performance as a function of wing design. To this end, UF provided Langley with several two-batten wing frames for use in this investigation.

A schematic of the wing frame is shown in figure 2 with labels to indicate key components. The total wing-span is 6.25 inches, root cord 4.25 inches, and batten width and thickness of 0.0938 inches and 0.017 inches, respectively. All components are fabricated using hand laid carbon fiber, which results in non-uniform cross-sectional areas throughout the structure. Because fabrication procedures are not repeatable and/or well controlled, all wing frames specimens built are slightly different. To get the wing geometry for modeling purposes, measurements from six wing specimens are averaged and then curve-fitted using 3D b-splines to approximate the outer shape of the rib frames. It is this configuration with average geometry what is referred to as the baseline configuration in discussions to follow. Also, to simplify the analysis, the wing frame structure is analyzed without the membrane material.

Since our goal is to develop an analytical model to predict wing deformation under aerodynamic loads, data with the wing loaded under similar conditions is needed. In order to control the loading and boundary conditions for model validation, an independent set of static tests is required.

STATIC TESTS

All static tests are designed to provide data consistent with wind tunnel test data; i.e., the displacement ranges and loads are based on maximum deformations observed in wind tunnel test. Also, to simplify the boundary conditions, the wing frame is rigidly attached at the center with point loads applied at four locations, (see figure 3a). Displacement measurements are taken at pre-selected target locations using a commercially available photogrammetry system known V-Stars (www.geodetic.com).

Photogrammetry set-up

The photogrammetry optical measurement technique is chosen primarily to minimize impact of sensor weights on test article. Perhaps its most attractive feature is that the test article is never physically touched. In addition, processing time is adequate, it is extremely accurate, and the equipment is readily available. Photogrammetry uses the principle of triangulation to calculate three-dimensional coordinates for points observed in two-dimensional images (pictures). The photogrammetry process starts by collecting digital images from different orientations and then processing the images to recover 3D coordinates. Image processing is conducted using the V-Stars photogrammetry software.

Figure 3b shows the test article with bonded targets and several fix-coded targets (white border frame off the test article) for reference. Fix targets in the image are processed and used to determine the accuracy of each particular data set. By knowing that a certain feature in an image is fixed, the software is able to gage the amount of motion against these references. Other devices (shown in figure 3b) like the scale bar, as its name suggests, is used to set the scale of the photograph. The autobar is used to set a coordinate system. In order to achieve the desired accuracy, approximately 20 pictures are taken and processed for each loading configuration. To assure proper coverage, camera angles are changed for each of the 20 pictures.

The accuracy of photogrammetry measurements is a function of area coverage and photo resolution. Because the MAV wing is perhaps the smallest structure to which photogrammetry has been successfully applied to, it is necessary to look closely at the accuracy of this setup. To address this issue data from the unloaded wing is collected at different times to determine target coordinates. It was determined that the z-direction is accurate to approximately 0.003”, while the x- and y-coordinates are consistently accurate to 0.0003”. The mean value of the standard deviation across all of the data sets for each individual point is 1.73E-4 inches. This accuracy is adequate for the update problem.

FINITE ELEMENT MODEL

A finite element model is created from the baseline wing rib geometry using EDS-IDEAS and then translated to MSC/NASTRAN format for batch execution. The FEM, shown in figure 4, has 820 grid points with 4920 degrees of freedom, and 609 quadrilateral elements (CQUAD4). PCOMP cards in MSC/NASTRAN are used to specify the composite lay-up, which consists of 3 graphite/epoxy plies 0.006” thick for the mid and outer battens; six to seven 0.009” thick plies through the spar, wing box aft spar and inner battens (shown in figure 4); and 3 plies 0.006” thick for the wing box. Furthermore, nine 0.009” plies are used in regions where the ribs overlap. The choice of ply thickness and number is based on the estimated number of plies used during fabrication, measurements taken from the spar and ribs, and engineering judgment. Isotropic graphite epoxy material properties for the plies included in MAT8 cards are listed in Table 1. Finally, new grid points are defined to map the measurement locations to the FEM.

ANALYSIS APPROACH/PROCEDURE

For a preliminary assessment of the baseline wing rib frame under loads, a linear static and a nonlinear static analysis are conducted using MSC/NASTRAN. Displacement results from the static analysis show considerable differences, in some cases up to 15%, between the linear and nonlinear results. Results show an overly stiff structure (50% stiffer) when comparing measured displacements to NASTRAN predictions. Hence, a full nonlinear analysis is warranted.

Design Sensitivity Analysis

Sensitivity analysis is used to understand and identify critical model parameters. In fact, model update cannot proceed until a subset of all possible parameters is selected for update. To reduce the number of parameters, a linear sensitivity analysis is conducted and only those parameters showing the greatest impact on the resulting static deformation are retained. Initially laminate ply thickness, material properties, and ply orientation are all considered. However, laminate ply thickness has the greatest impact on the response. Consequently, eighteen ply thickness values are used as the candidate set of design variables for model update.

Figure 5 shows the wing rib frame with the ply thickness variable location circled and labeled “X” where X is an integer from 1 to 18. Thickness variables 1 thru 10 define the ply thickness of the plate elements (CQUAD4) for the leading edge spar excluding the overlaps or joints. Ply thickness for areas where there is material overlap or joints are defined in variables 11 thru 15. Thickness variables 16 through 18 define the ply thickness for the outer, mid, and inner battens, respectively. To allow the freedom to adjust the torsion stiffness, the laminate lay-out of the forward and rear sections of the mid and outer leading edge spars, each have their own thickness parameter defined.

Model Update Objective Function

For parameter updates, a goodness criterion (objective function) consistent with the end goal needs to be defined. One such criterion is

$$F(\nu,u)=(\nu_0-\nu)^T S_{\nu\nu}^{-1}(\nu_0-\nu) + (u_t-u)^T S_{uu}^{-1}(u_t-u) \qquad (1)$$

where u is a vector of predicted responses corresponding to the parameter vector ν; ν_0 is a vector containing the initial parameter values; u_t is a vector with the measured response; and $S_{\nu\nu}$ and S_{uu} are the weighting matrices. This form of the objective function, used extensively by Herendeen et al., (1998) and others, penalizes both prediction errors and parameter changes.

Algorithm Implementation

To undertake the task of updating models generated using commercial codes like MSC/NASTRAN, the most general approach is to work directly with the NASTRAN bulk data file structure. In order to do this, MATLAB Script files are written to modify the NASTRAN bulk data and also to read NASTRAN output files. Since all results are now within the MATLAB environment, all the MATLAB toolboxes are available for use. In this particular case the MATLAB optimization Toolbox is used.

PARAMETER SELECTION APPROACH

Selection of parameters for model update is perhaps the most important step in the update process. Although researchers have proposed localization approaches to pinpoint problem areas in the model, often times engineering judgment, knowledge of parameter uncertainties, and sensitivity information seems to work best. Parameter uncertainties in the MAV finite element model are associated with the fabrication irregularities. In particular laminate thickness variation along the wing ribs, irregular cross-sectional areas, uncertainties in the type of graphite/epoxy used for construction, and the geometry. All these uncertainty sources must be considered and evaluated in the selection process.

Parameter Sensitivity

As mentioned earlier, eighteen ply-thickness parameters are selected and considered for use in the update process. Figure 6 shows the sensitivity analysis, number of plies corresponding to each thickness parameter, and the probability distribution function for ply thickness (nominal values indicated by dash). Sensitivity values are computed by numerical differentiation of the objective function F in Eq. (1) with respect to a specific thickness variable (v).

Parameter Uncertainty Quantification

Sensitivity alone does not provide enough information to proceed with the parameter selection process. Suppose that after selecting a set of parameters for update, the model predictions are unable to match test observations. This is the case when the model structure is incorrect, nonlinear effects are not accounted for, and/or one is dealing with erroneous experimental data. Of course this is not known a priori, but the point here is that the update process must provide some guidance.

Statistical information about the predicted output as a function of parameter uncertainty must also guide the selection of parameters and parameter ranges. In this study, a probabilistic approach is used first to compute the output probability that the measured test values are within the predicted output range. Output range probabilities are obtained using the parameter distribution shown in figure 6 and Monte Carlo like simulations of the structure under load. Unlike standard Monte Carlo simulations seeking low probability values, this problem seeks high probability values when selecting the parameters and their ranges. In other words, pick the parameters and their ranges such that the output probability is high. Since probability values are computed by counting the number of occurrences of a particular event (number of times predictions agreed with test), high probability estimates require a small number of function evaluations to get reasonable estimates. In fact, 200 to 300 function evaluations are used to generate the results shown in Figs. 7a-7b for both linear and nonlinear NASTRAN solutions. Figures 7a and 7b show the probability that the measured displacement is predicted by the linear and nonlinear solutions. For example results in figure 7a show the probability that the measured output for output 1 is predicted by the linear solution is less than 0.5 %. For the nonlinear case (figure 7b), it is less than 1.0 %. However, note that all the outputs have non-zero output probabilities therefore a solution that reconciles the model with test exists. Using engineering judgment, output probabilities, and sensitivity values, thickness parameter variables: 4, 5, 9, 10, 11, 14, 15, 16, 17, 18 are retained for model update

MODEL UPDATE RESULTS

After selecting a set of parameters for update, nonlinear optimization is used to find a set of parameters to reconcile test data with analysis. Figure 8 shows results from the nonlinear optimization. Darkened rectangles correspond to parameters whose values decreased from the nominal whereas empty rectangles correspond to parameter increases. Five out of seven updated parameters (4,9,10,14,15 corresponding to the leading edge spar) show reductions from their nominal values ranging from 17% to 43 %, while parameters 5 and 11 show an increase up to 15%. Batten thickness, parameters number 16 and 17, are reduced by

14 and 20% for the outer and mid battens respectively, and 30 % for the inner batten, parameter 18.

Figure 9 shows a comparison of displacements from test, predictions from the baseline model, and updated model. Displacement prediction errors of the leading edge spar vary from 1.0% to 40%, 1.2 to 3.0 % for the outer batten, 0.2 to 28 % for the mid batten, and 7 % for the inner batten. Since the leading edge spar displacements are close to the ± 0.003” photogrammetry measurement accuracy, several data points exhibited poor measurement resolution. Nonetheless, when comparing the updated results with the baseline values, the finite element model has been improved dramatically.

CONCLUDING REMARKS

A procedure for nonlinear model update with uncertainty quantification of a Micro Air Vehicle (MAV) flexible wing frame has been demonstrated. A two-step approach was developed and used where statistical information of the output space is generated prior to performing nonlinear optimization. In step 1, the statistical analysis answers the question, what is the probability that the model predicts test observations? If the probability is greater than zero, nonlinear optimization provides the parameter values.

Static test data of the MAV model was used and ten thickness parameters updated in the process. Prediction errors, over 200% initially, were reduced to under 43%, worst case. Although this represents a dramatic improvement in the model prediction error, output probabilities indicating confidence in the parameter values was low. This is an indication of model structure errors, system nonlinearities, and geometry uncertainties.

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Table 1. Material properties of graphite/epoxy composite

	Generic graphite/epoxy
Modulus of elasticity (lb_f/in^2)	
E_1	1.94E+7
E_2	1.29E+6
Poisson's ratio	
ν	0.28
Shear Modulus ($lb_f/in^{2)}$	
G_{12}	0.74E+6
G_{1Z}	0.74E+6
G_{2Z}	0.74E+6
Density, (lb_f - $sec^2/in^{4)}$	
ρ	1.5E-4

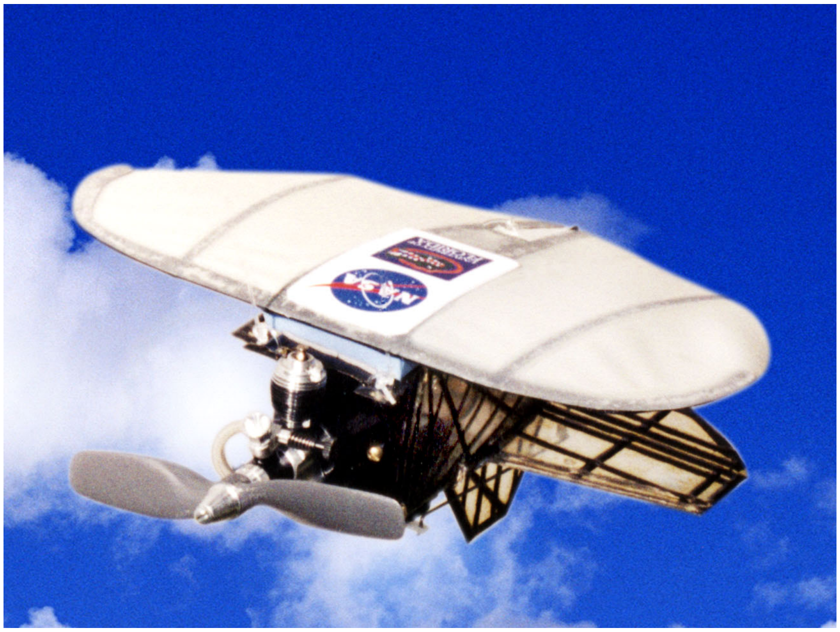

Figure 1 . University of Florida Micro Air Vehicle

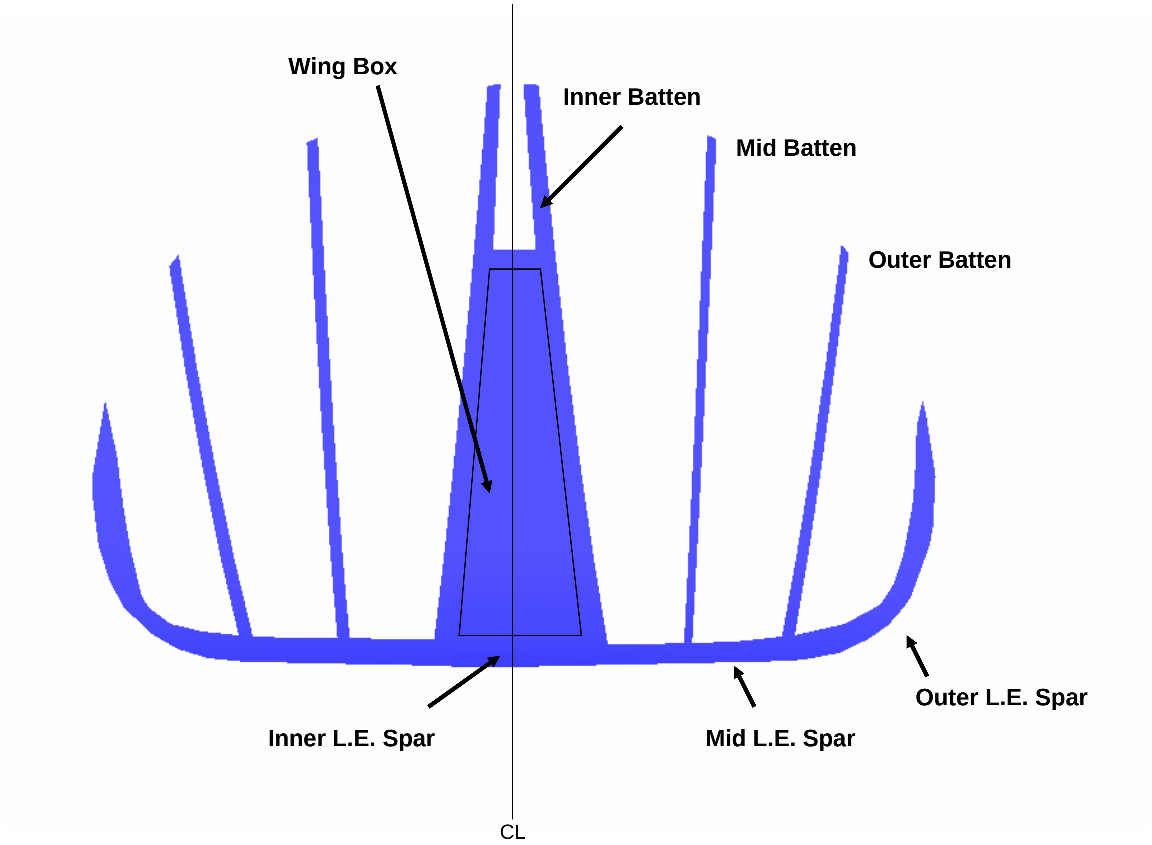

Figure 2. MAV wing rib frame schematic

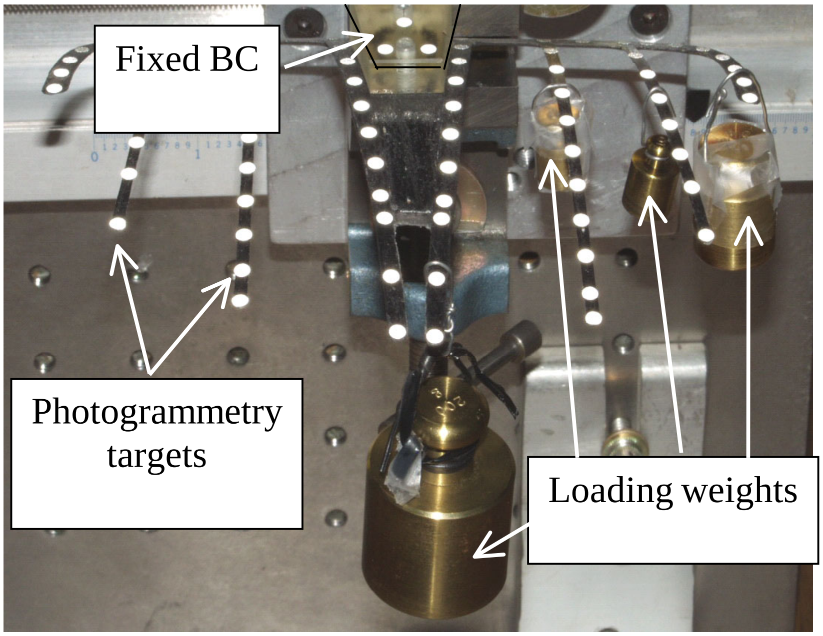

Figure 3a. Wing rib frame test setup

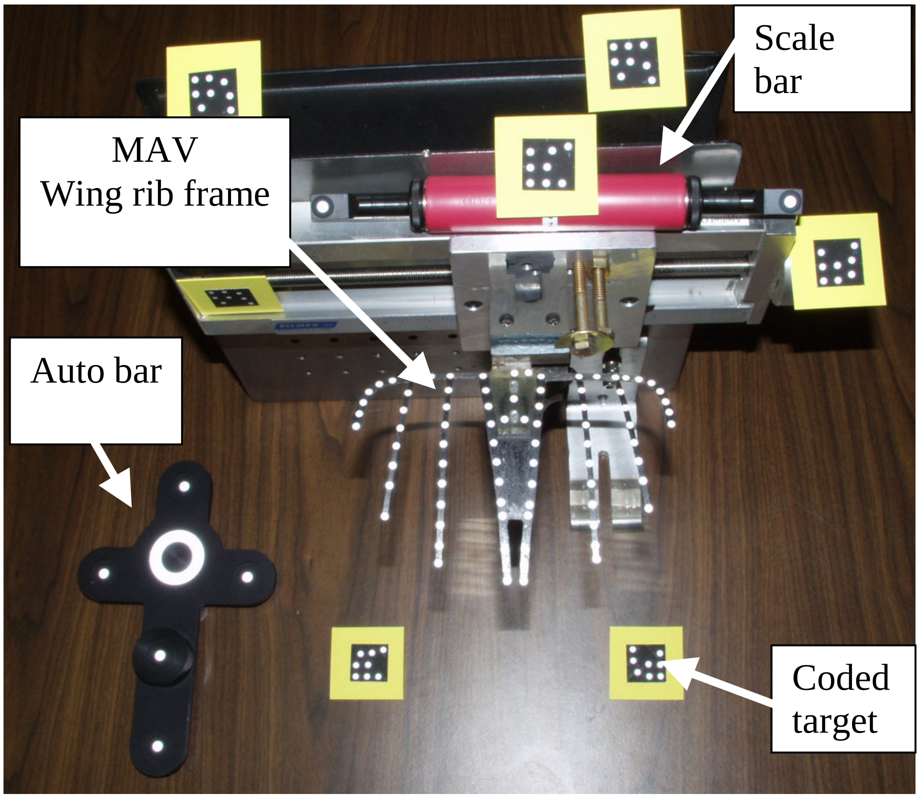

Figure 3b. Photogrammetry test setup

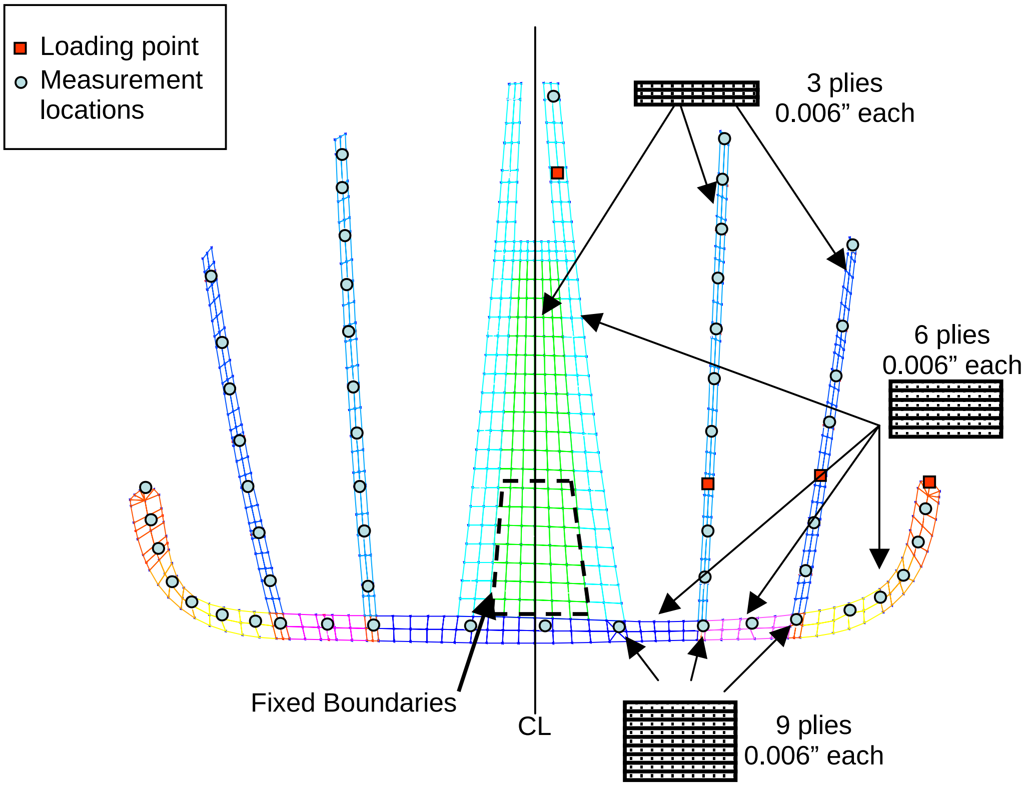

Figure 4. MAV wing rib frame FEM with mapped test measurement and loading locations

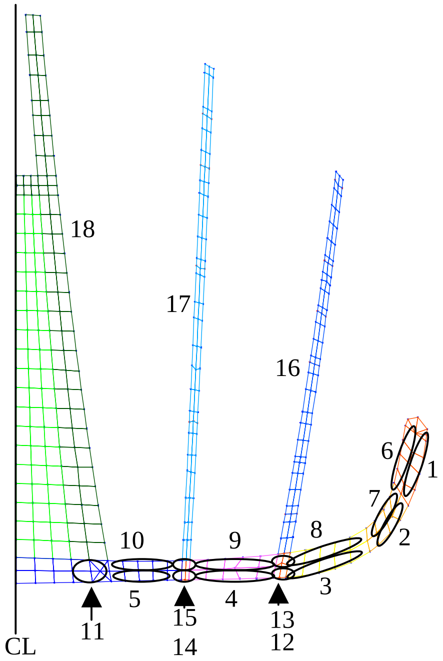

Figure 5. Design variable distribution

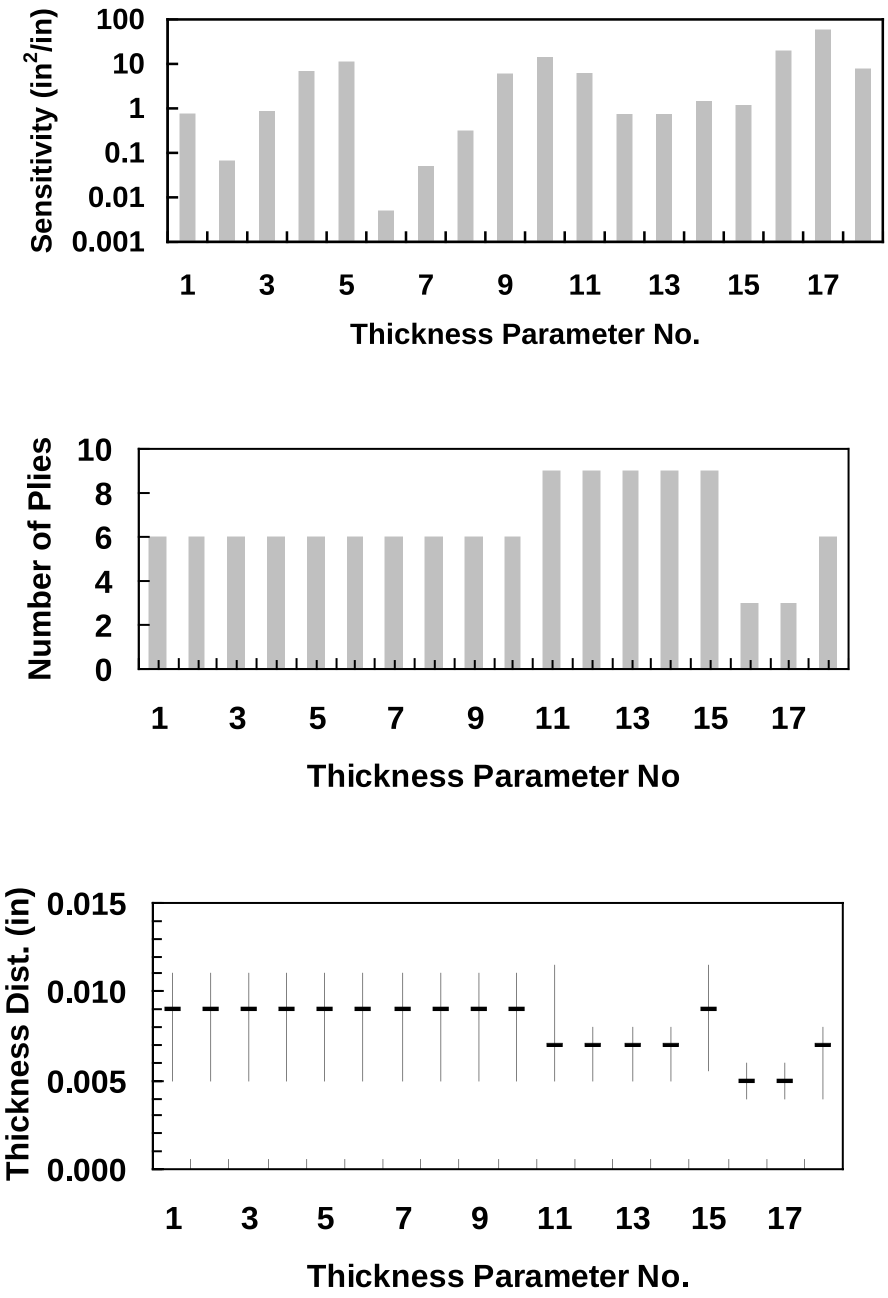

Figure. 6. Parameter sensitivity, number of plies, and assumed uniform thickness distribution (dashed mark is nominal value) for parameter considered.

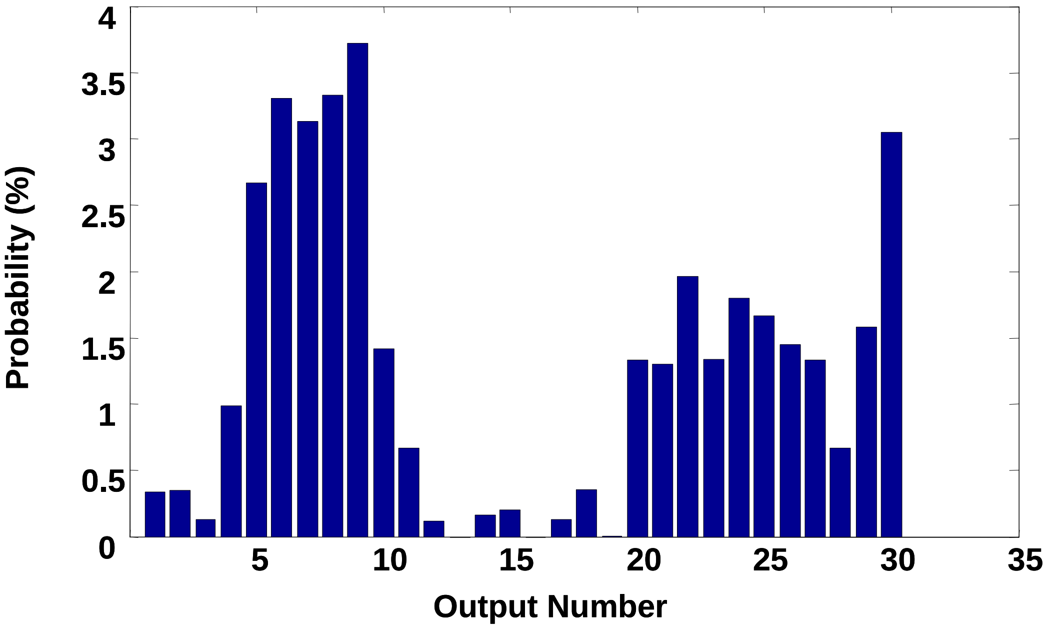

Figure 7a. Linear model statistics

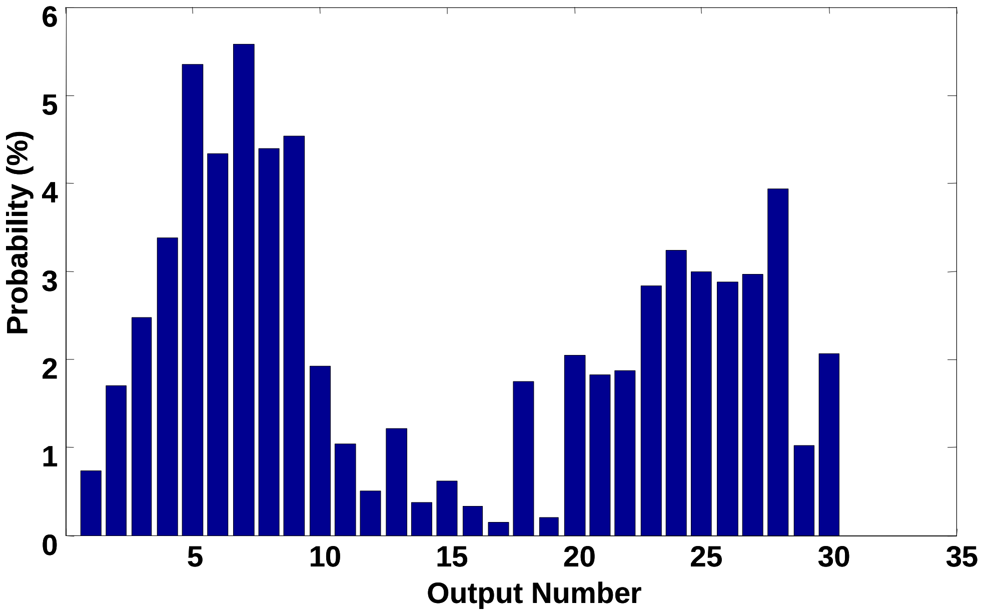

Figure 7b. Nonlinear model statistics

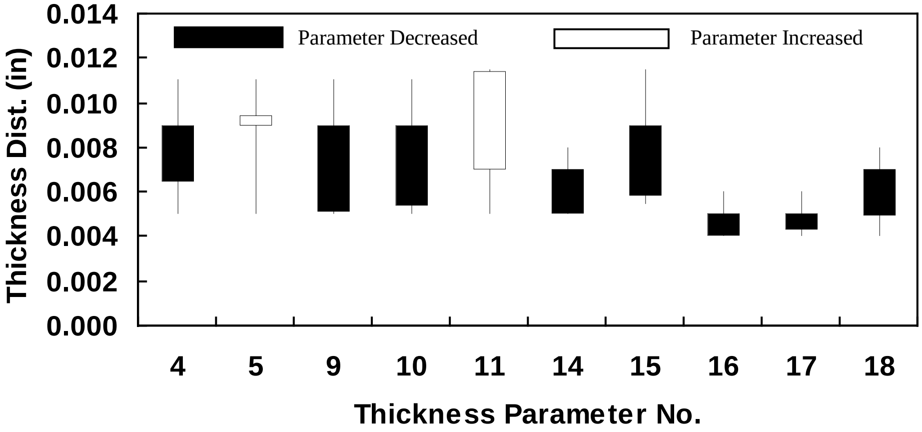

Figure 8. Parameter update results from nonlinear optimization solution.

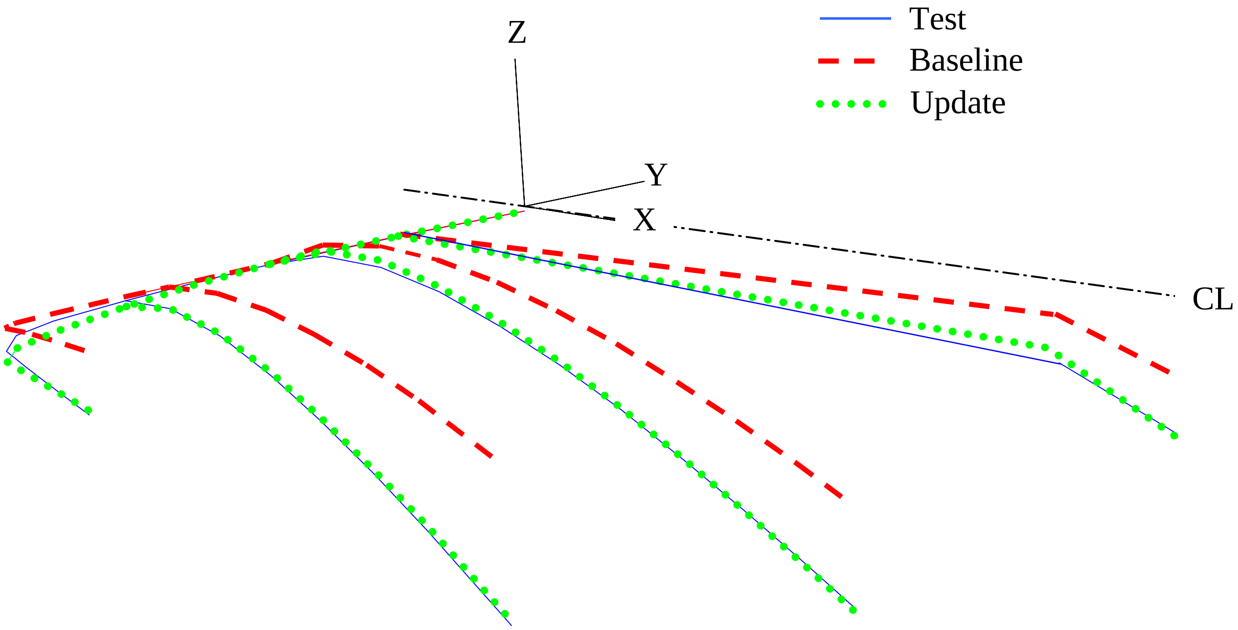

Figure 9. Wing deformation results for test, baseline FEM and updated FEM analyses

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14. ABSTRACT

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