Design and Analysis of a Foldable Wing Mechanism

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Abstract: Rocket and missile systems are often kept in launch tubes until they are fired. Dimensions of the tubes are determined by the munitions inside them. In some cases, due to space and weight limitations, launch tubes must match certain dimensions other than imposed by the system. Inner diameter of the launch tube is mainly determined by control surface span. Thus folding the control surfaces decreases space occupied in the tube. In foldable wing mechanisms, wings are held in folded position in the tube. After munitions leave the tube, wings erect and are locked secure in unfolded position. These mechanisms contain a spring like element that stores necessary energy to unfold the wing and a locking pin that secures the wing in desired position. In this study a foldable wing mechanism has been designed and analyzed under dynamic working conditions. Models were built using ABAQUS/CAE and dynamic implicit solutions were obtained. In the analysis models impact loads on the structure when the wing hits held piece, were determined. Opening time of the wing from folded position to fully erected position was also examined. A series of iterations has been performed to optimize the spring parameters and fold positions. At the end of design study, optimized model was manufactured. To conclude the study, a test program was conducted. Test equipment that measures dynamic loads and opening time was manufactured. Following the tests, verification of the model was performed.

Keywords: Aerospace, Design Optimization, Dynamics

1. Introduction

Control surfaces such as wings, tails, and fins generate necessary lift and maneuverability for rocket and missiles. (Figure 1) These surfaces extend from outer diameter of the munitions. The space occupied by the munitions increases because of these extensions from main diameter. Folding the control surfaces, effectively improves storage capacity. In order to achieve this goal a mechanism that keeps wings in folded position and locks at unfolded position after launch must be designed. The mechanism must also withstand aerodynamic loads acting on the control surface and impact loads upon unfolding. Small space available and weight constraints make the design of such mechanism more challenging. The mechanism consists of a spring that stores necessary energy to unfold the wing and locking pin that holds wing unfolded position. Increasing the stiffness of spring, wings can be unfolded in less time. However this greatly increases stress on the structure. Design of the mechanism is optimized by iterations in such a way that it meets system requirements and design constraints.

2. Finite element analysis model

Finite element model of the mechanism is created using ABAQUS/CAE. All geometric modifications and simplifications are handled in the same environment. Model is built using quadratic solid elements (C3D10 and C3D20R). Spring is modeled by connectors and stiffness is defined in connector section as seen in Figure 2.

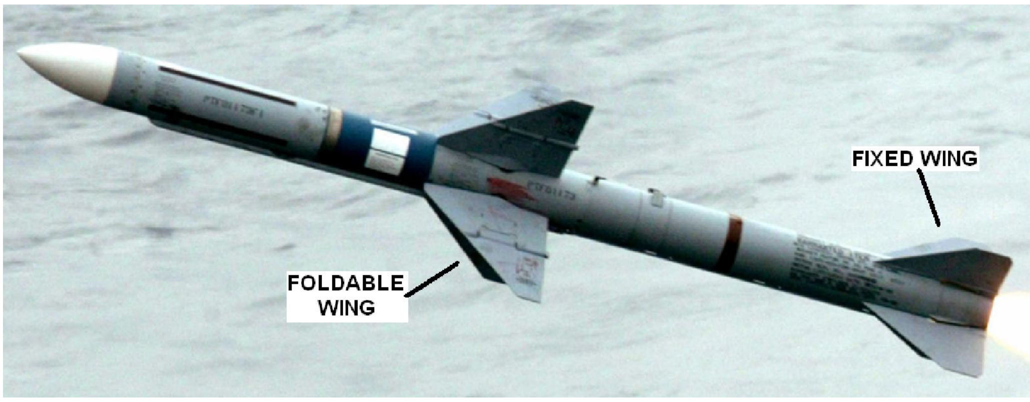

Figure 1. Representation of a missile (courtesy of US Navy).

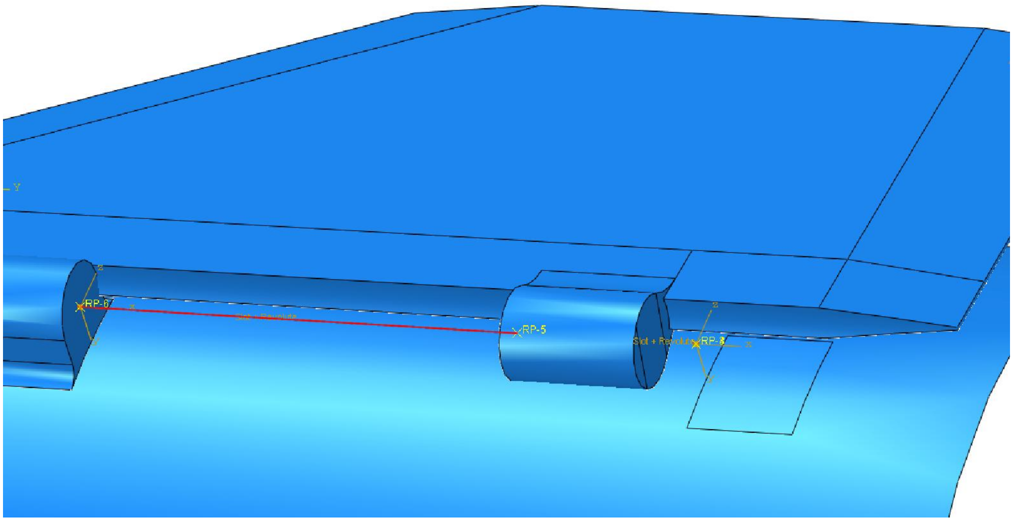

Figure 2. Connector representing spring.

Different modeling strategies are implemented in order to decrease iteration time. Regions of folding wing that are not interested in are meshed with coarse element density. Another modeling methods implemented are that using rigid elements on those regions and substituting those regions with point mass representing mass and inertia. In Figure 3, wings modeled with different modeling methods can be seen.

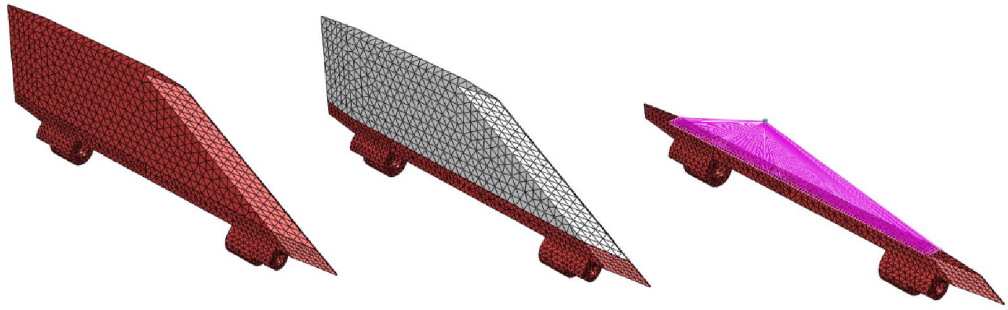

Figure 3. Wings modeled with different methods ((a) all deformable, (b) white section rigid, (c) point mass).

After iterations on different parameters of the model, mesh sensitivity study was conducted. Total opening time of the wing and reaction forces and moments when the wing unfolds are determined. Reference point where reaction moment upon impact of the wing during unfolding requested is shown in Figure 4.

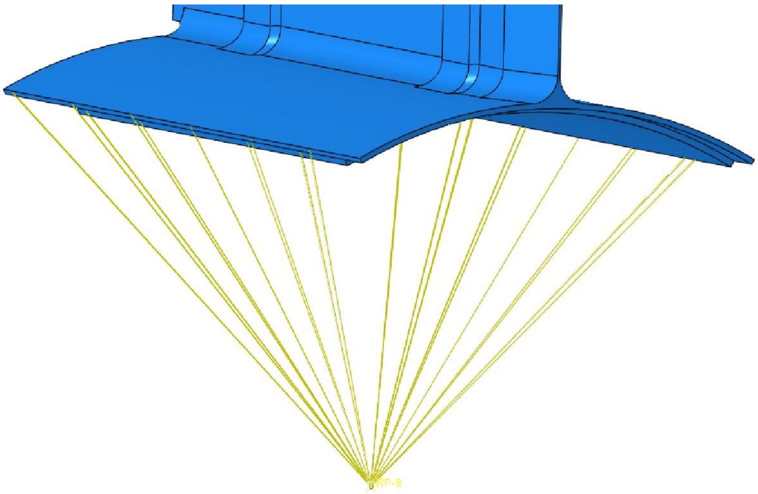

Figure 4. Point where reactions of impact during unfold is requested.

3. Results

Solutions were obtained from dynamic implicit solution step. First models were created at unfolded position and wing was folded in a static step by imposing connector rotation in order to see interaction of the mating surfaces during folding process. Then, the wing was released from that position in dynamic implicit solution step. In subsequent iterations, this first static step was omitted and initial compression of the spring was imposed by defining proper reference length in connector section. Models were prepared using ABAQUS 6.11 and run on 8 core cpu workstation. For full detailed fine meshed model solution was obtained in 20 hours. In Figure 5, unfolding sequence of the wing in finite element solution can be seen.

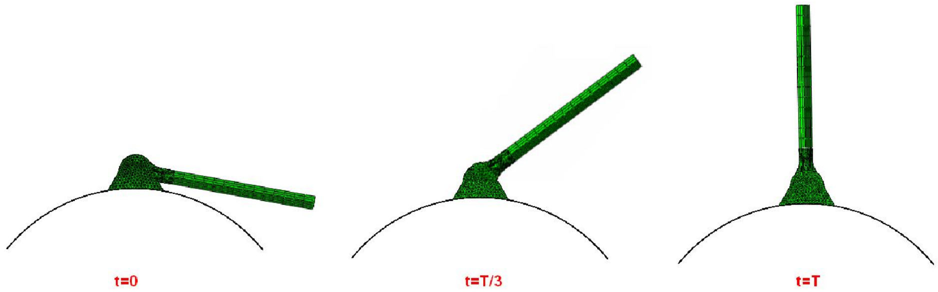

Figure 5. Positions of the wing during unfolding.

The highest load on the structure occurs at the first impact of the wing during unfolding. Equivalent stress contours at the time of initial impact is given in Figure 6. Stress levels that exceed yield strength of material are seen on the regions of interaction. After series of design iterations structure is loaded above yield strength and just below UTS limit of material.

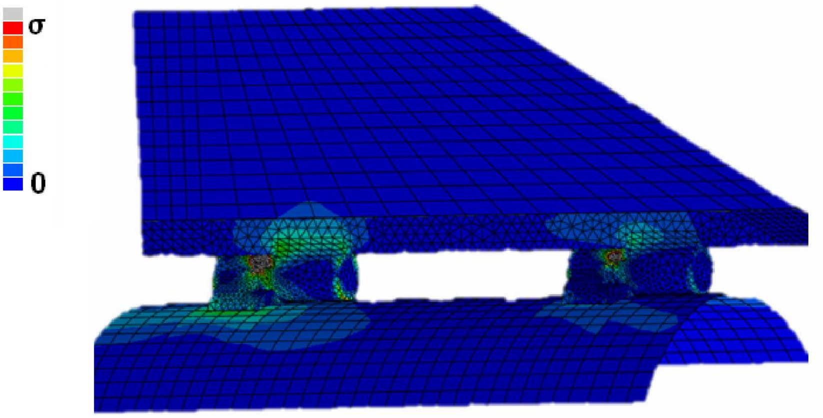

Figure 6. Equivalent stress contours at impact.

In finite element solutions, position of the wing during unfolding is plotted against time and compared between design iterations. Increasing spring stiffness obviously decreases unfolding time whereas this situation damages structural integrity of the overall structure due to high impact forces (Figure 7).

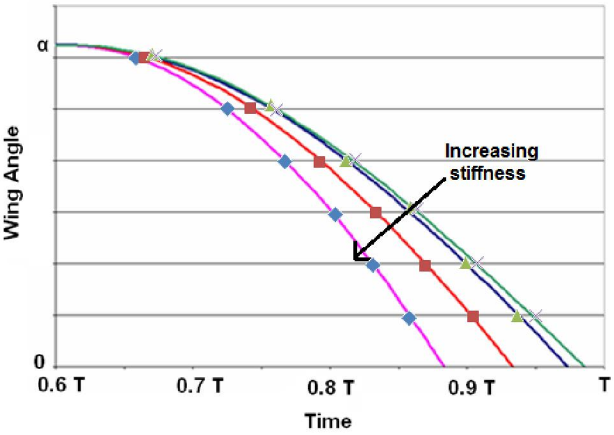

Figure 7. Wing angle versus time plot for different iterations.

Reaction moment occurred at center of rotation of the wing assembly is another investigated parameter during iterations. In Figure 8, iteration 1 shows baseline for design of the mechanism. After series of iterations opening time of the wing was decreased whereas reaction moment impacted on the structure was increased. There was a tradeoff between reaction moment and opening time. In the optimum solution, structure is pushed to the strength limits of the material so the fastest opening time can be achieved.

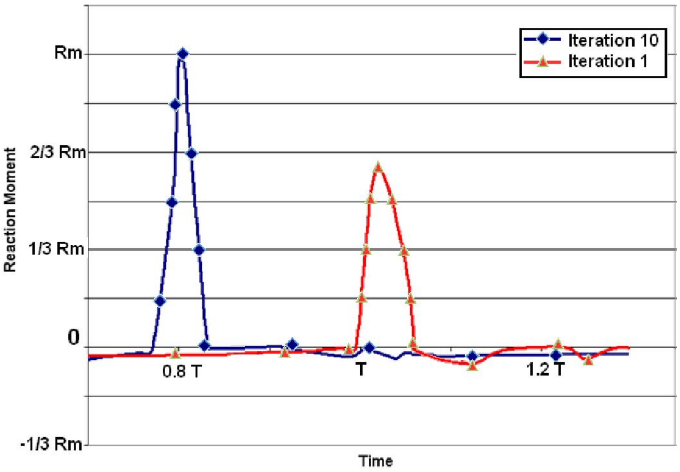

Figure 8. Reaction moment versus time plot for different iterations.

4. Test studies

Design and manufacturing of a test setup that will allow measurement of reaction moment and opening time of the wing was done. Different wing mechanism configurations to be tested were manufactured. A test program including different design and spring configurations was conducted. One quarter of the tail section of the rocket was manufactured for testing. This section includes wing, unfolding mechanism and connection interface for the test equipment. The effect of spring stiffness and folding angle on the performance of mechanism was investigated. The results of reaction moment and opening time were compared with finite element model results. Hence verification of the method was performed.

In Figure 9 the effect of spring stiffness and folding angle on the reaction moment is shown. It is clear that stored energy in the spring directly relates to reaction moment. Folding angle affects reaction moment in an almost linear relation.

Finite element solution of the reaction moment is compared to test results in Figure 10. Amplitude and duration of the first impact during unfolding is estimated quite accurately in the finite element model. While oscillation due to subsequent impacts on the reaction moment is seen on finite element model, the test results quickly damps. Since the highest load occurs on the first impact, model is sufficient to evaluate structural integrity of the mechanism. Also it is difficult to predict damping of the real system and energy loss upon impact.

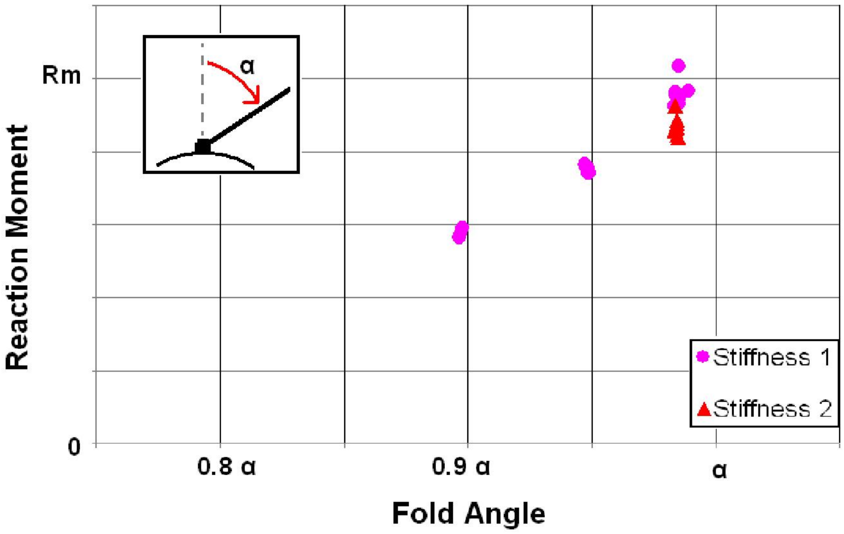

Figure 9. Reaction moment for different fold angle and spring stiffness.

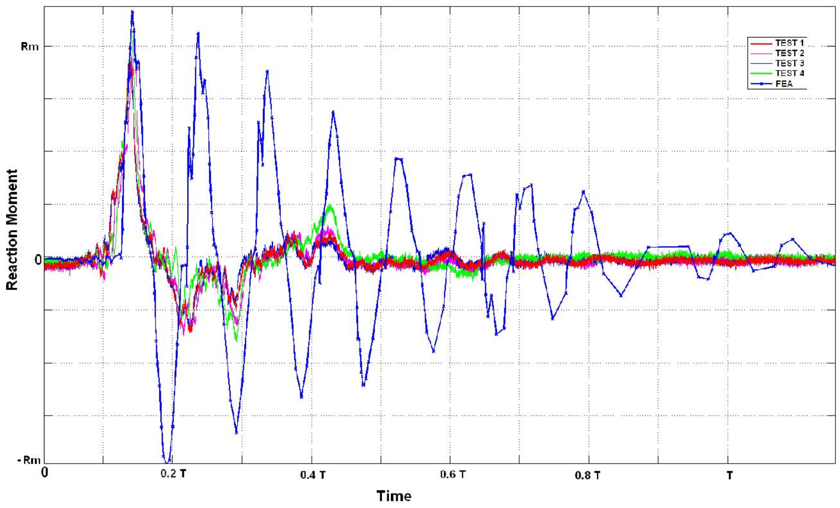

Figure 10. Comparison of reaction moment between test and analysis results.

The other design constraint on the design of a foldable wing mechanism was opening time. During test study, unfolding of the wings were recorded using high speed cameras. It is helpful to investigate these images for fully understanding kinematics of unfolding process. Opening time for different spring stiffness was determined and compared to finite element model results. In Figure 11, it is shown that finite element model results agree well with test results. Small deviations are seen due to manufacturing imperfections and change in stiffness. However they are in acceptable ranges.

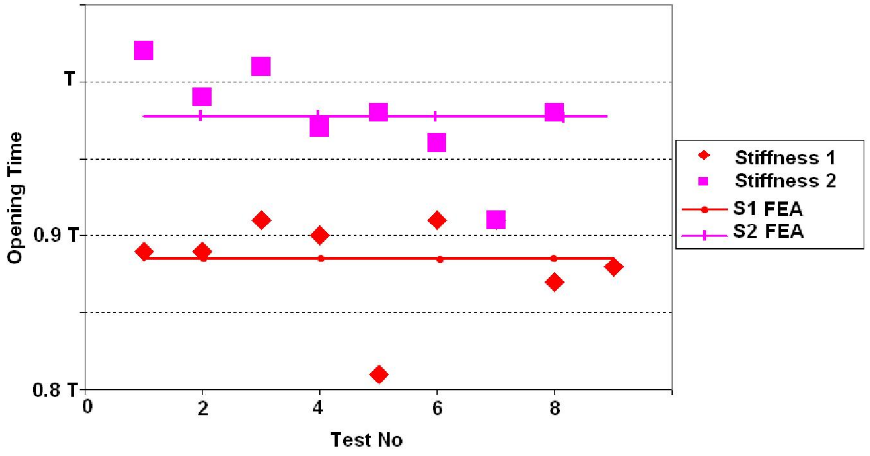

Figure 11. Comparison of opening time for different stiffnesses between test and analysis results.

In Figure 12, images of unfolding sequence of the mechanism are shown. Finite element model solutions are compared with high speed camera images. FEM solution captures well the opening sequence of the mechanism.

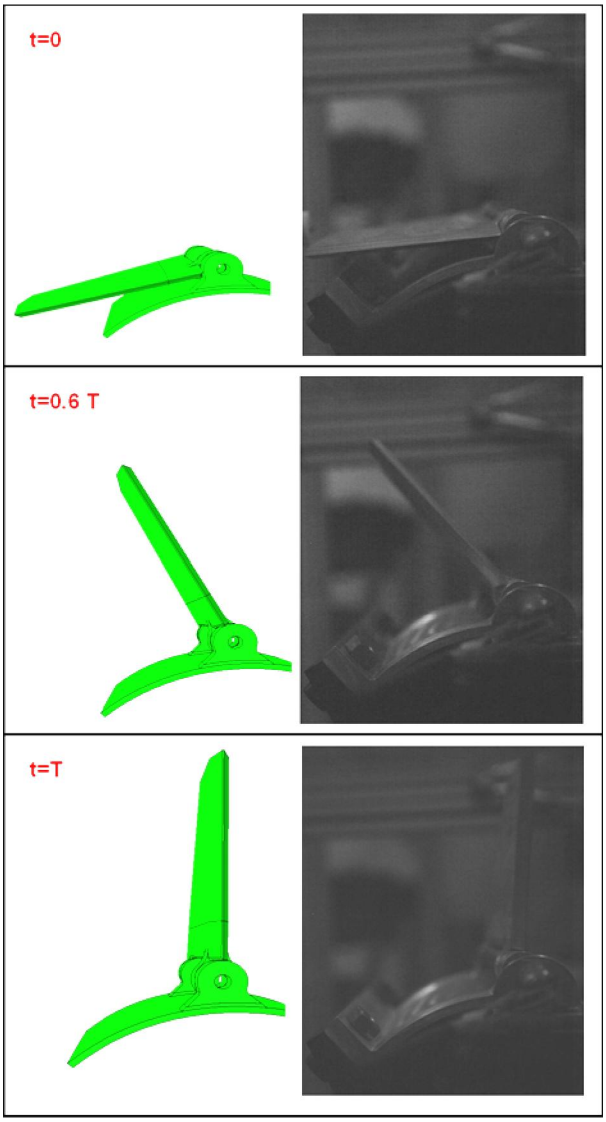

Figure 12. Comparison of reaction moment between test and analysis results.

5. Conclusion

This paper shows different modeling methods implemented during analysis of a foldable wing mechanism. The outputs from analysis models that were examined during design iterations are stated. A test program was conducted for various designed wing mechanisms and the effects of different parameters were studied. Test equipment capable of measuring performance of the mechanism upon design constraint was manufactured. Finite element simulations were compared with test results. In the end FE models were verified against tests and an optimum design was achieved. This newly designed foldable mechanism was adopted in a new generation missile system.