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Multi-phase Design Optimization of a Long Range Aerial Lift Boom Structure

Henry Panganiban, In-Gyu Ahn, Tae-Jin Chung

Abstract—**Topology, size and shape optimization methods are carried out on a long range aerial lift truck. The first phase involves the determination of the optimum cross-section dimension, overlaps and wall thickness of the telescopic boom segments. The optimization problem is formulated as mass minimization under various structural performance constraints and solved using the metamodel-based optimization method. Optimal-space filling design, Kriging algorithm, and screening methods are used for the design of experiment (DOE) sampling, response surface generation and optimization steps, respectively. The second phase consists of 2 steps that deal with the search for optimum frame reinforcement layout using topology optimization in the first step and frame plate thickness optimization in the second step. The ultimate goal of design optimization in the second phase is to obtain a lightweight frame that is structurally stiff and with improved torsional natural frequency. The design optimization is done using ANSYS Workbench in the first phase while HyperWorks in the second phase. Optimized boom is about 250-kg (2.2%) lighter with significantly lower stresses than the reference design. The stiffness and torsional natural frequency of the frame increase by 33% and 59%, respectively with the weight reduce by 35-kg.**

Index Terms—**Aerial boom, topology, shape, optimization**

I. Introduction

EXISTING boom and outrigger frame design of a certain aerial lift device is claimed to have been based on designer and engineer's experience and intuition. A systematic approach is needed to ensure optimal design that meets all prescribed constraints and eventually rise above the competition in the industry. Computer aided engineering (CAE) tools are widely proven economical and time-saving when used in addressing such need. CAE-based design optimization method for one, have been used to provide information that help designer and engineers in their decision making and solve a wide variety of engineering problems ([1-4] among others).

Topology, size and shape optimization methods are kinds of structural optimization technique that can be efficiently carried-out to obtain quick design solutions. These methods had been proven useful in many industrial applications. In topology optimization procedure, it finds the optimal layout of the limited amount of material in the design space that will result to the stiffest structure. Hence, topology optimization is widely used for obtaining conceptual and preliminary structural designs with high performance and lightweight features (see [5-7] among others). Size and shape optimization enable the selection of the best geometric properties such as size of holes, thickness, width or length of plate components of the structure that will reduce the weight or add a limited amount of material while maintaining or improving performance. To deal with large models that require expensive analysis, metamodel-based method can be employed for size and shape optimization [8, 9].

In this paper, optimal design of a long-range aerial lift boom truck utilizing CAE-based tools implemented in a 2-phase design optimization framework is presented. Firstly, metamodel-based method is employed to determine the optimal values of the design parameters for the lightweight design of the boom system based on structural performance constraints. Secondly, the optimal design of the frame structure supporting the boom system is searched. Subsequent topology and size optimization is carried out to obtain the optimal design of the frame.

II. Initial Design

Figure 1 shows the aerial lift boom and frame structure considered in this paper. At maximum range, the work platform (not shown) connected at the tip of the end boom can reach a maximum elevation of 75 meters above the ground where the four outriggers seat. The boom is of telescopic type consisting 9 overlapping segments that can be extended or retracted. Each segment is over 9 m in length with wall thickness ranging from 3 to 8 mm. Henceforth, for ease of discussion, boom segment closest to the support post will be referred to as boom 1 and to the end boom as boom 9. The booms in between are referred to accordingly. Low friction guide pads are situated in each boom segment not only to enhance extension or retraction but also to provide support, fix and secure the booms through the overlap of any two succeeding segments.

III. Design Optimization

Design optimization is carried out in two subsequent phases. The model structure shown in Fig. 1 is split into two sub-assemblies: boom system and frame as shown in Fig. 2. The boom system design optimization is treated in the first phase. After the optimal design in the first phase is found, reaction forces and moments are imposed as loads to the frame and the second phase of design optimization is performed.

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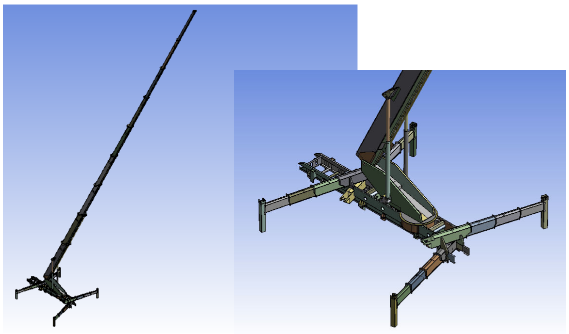

Fig. 1. 3D view of the existing long range aerial boom

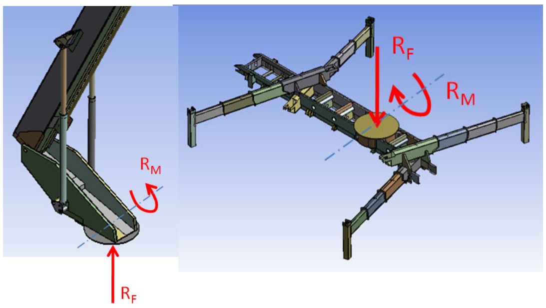

Fig. 2. Boom system and frame sub-assembly

A. *Boom system optimization*

The boom system optimization involves the determination of the optimal cross-section height, overlaps and wall thickness of the 9 telescopic boom segments that will yield a lightweight design without performance degradation when subjected to the given loading conditions. Only one cross-section height design variable is imposed since wall clearances or gaps must remain unchanged. The cross-section width of the smallest boom (end boom) is kept fixed due to predefined design restriction. Each boom segment constitutes 3 thickness design variables. With 8 overlap variables, altogether the boom system has 36 design variables. Due to the size and complexity of the model, metamodel or surrogate-based design optimization method is considered. However, the full boom system design optimization cannot be carried out due to excessive number of design variables or input parameters. To reduce the number of design variables, the optimization of the full boom assembly is done in two steps in accordance with the kinematic functionality of the system. Step 1 only considers booms 4 to 9 with the assumption that the wall thickness of boom 9 is fixed, boom 7 and 8 only have one wall thickness variable for each. These assumptions resulted to a total of 20 design variables. Step 2 considers boom 1 to 3. Figure 3 and 4 illustrates the associated design variables for optimization step 1 and 2, respectively.

In step 1, loads are applied at the tip of boom 9 and the un-extended booms 1-3 are modeled such that they simulate the structural support. The reaction forces at boom 4 in step 1 are imposed as loads via boom 3 in step 2. Figure 5 and 6 show the static load cases considered in the analysis.

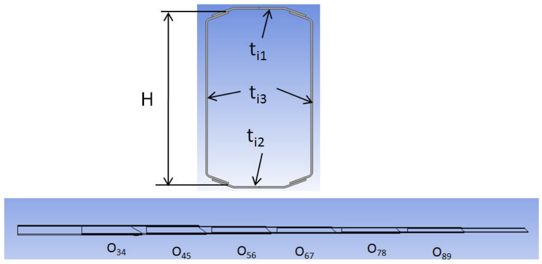

Fig. 3. Optimization step 1 (i = 4, 5,…9): Boom 4-9 fully extended, boom 1-3 un-extended.

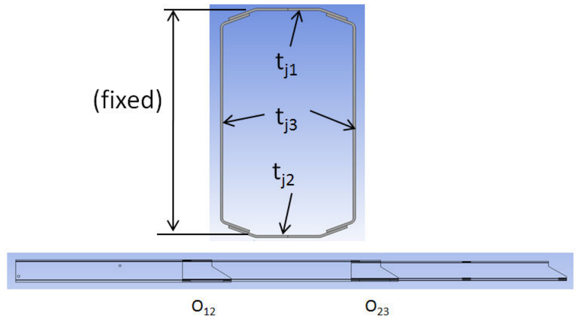

Fig. 4. Optimization step 2 optimization (j = 1, 2, 3): Boom 1-3 fully extended, boom 4-9 removed.

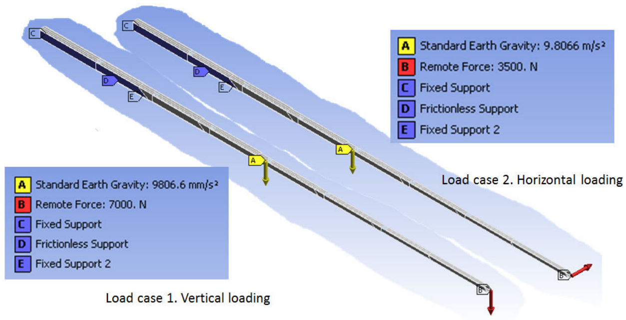

Fig. 5. Step 1 load and support conditions

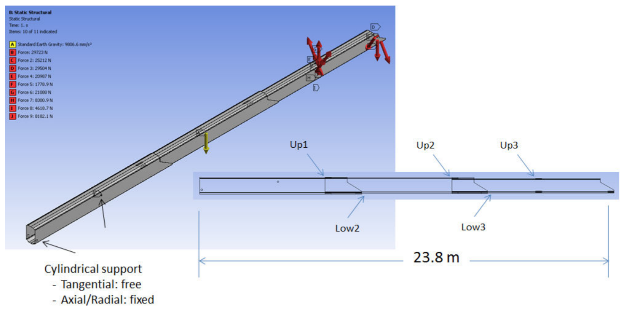

Fig. 6. Optimization step 2 load and support condition with stress regions of interest indicated.

With the defined design variables or input parameters and responses or output parameters, DOE using 10N optimal space-filling design and response surface using Kriging algorithm are generated. Based on the generated response surface or metamodel, the optimization problem (1) is solved using screening method. The optimization problem for each step is formulated in a similar fashion. The objective is to minimize mass with constraints on stresses at regions of interest, transverse and vertical deformation and torsional natural frequency. The optimization is carried in ANSYS Workbench [10].

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B. *Frame optimization*

As pointed out earlier the reaction forces and moments at the base of the boom system support post are imposed as loads on the frame. Five load cases that represent some of the operational loading scenarios (see Fig. 7) are considered to ensure the frame structural integrity.

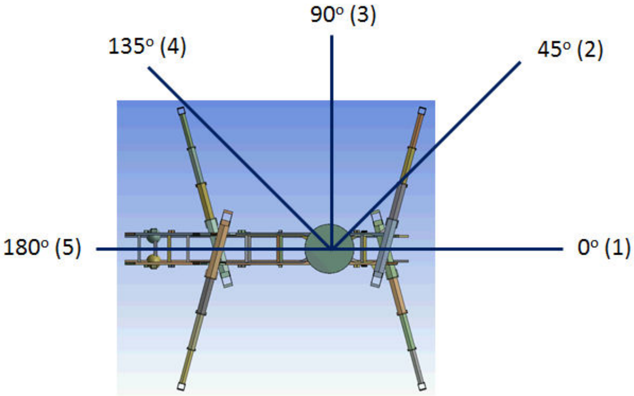

Fig. 7. Load cases according the boom syste orientation.

The goal of frame optimization is to find the optimal layout of the frame reinforcement and component thickness that will yield high stiffness design and particularly torsional natural frequency. To meet such goal, topology optimization is used to find the conceptual design of the frame layout. The cross-beams of the initial frame are removed and the emptied space is filled with solid material which is treated as the design domain. Figure 8 and 9 illustrate one of the load case scenarios and the definition of design domain, respectively.

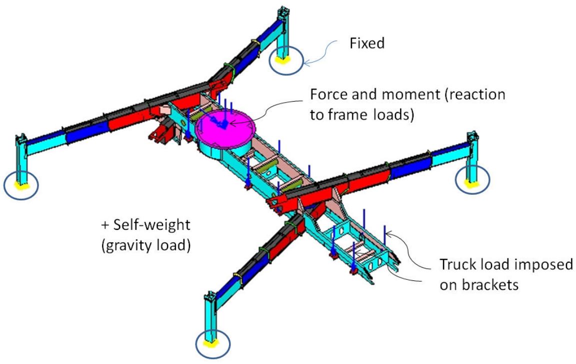

Fig. 8. Example of a load case scenario considered during frame optimization

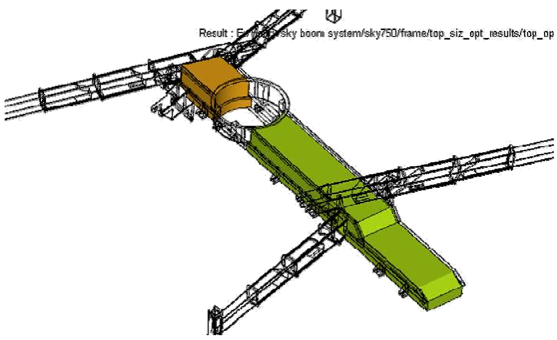

Fig. 9. Design domain for frame reinforcement layout topology optimization

After the topology optimization, post-processing and the subsequent thickness optimization are performed to further reduce the weight of the frame with constraints imposed on static stiffness and torsional natural frequency.

The topology optimization problem considered here can be loosely stated as

$$\begin{aligned} &\text{Maximize}: \textit{torsional natural frequency} \\ &\text{Subject to}: \textit{Mass fraction} \\ &\qquad\qquad \textit{Static compliances of load case } 1-5 \end{aligned} \quad (1)$$

While the thickness optimization after post-processing the topology optimized frame can be described as

$$\begin{aligned} &\text{Minimize}: \textit{Mass} \\ &\text{Subject to}: \textit{Torsional natural frequency} \\ &\qquad\qquad \textit{Static compliances of load case } 1-5 \end{aligned} \quad (2)$$

All frame optimization steps are carried out using HyperMesh and allied tools available in HyperWorks .

IV. Results and Discussions

A. *Optimal boom system*

Additional post-optimization local parametric study is performed to refine the optimization results. It was observed that the height of the boom cross-section can be increased by 21% in exchange of decreasing wall thickness of few booms. Figure 6 shows corresponding boom wall thicknesses. The completed optimization steps revealed 250 kg reduction in boom system weight with structural performance uncompromised as illustrated in Fig. 7.

Fig. 10. Boom wall thickness comparison

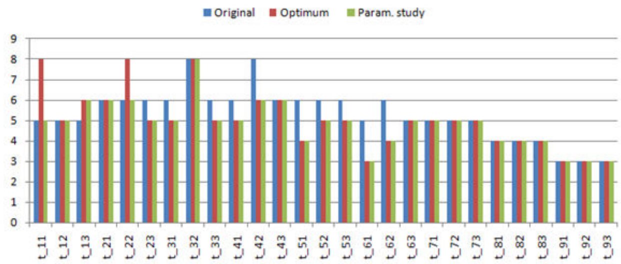

Fig. 11. Static analysis of the fully extended and 64o tilted optimal boom system.

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B. *Optimal frame design*

Figure 12 shows the optimal frame layout resulting from topology optimization. The massive reinforcement on the upper and lower region can be attributed to the optimization problem formulation which was to maximize torsional natural frequency. Since there was no load imposed on the design domain, the resulting reinforcement layout appears to make the structure more dynamically stiff. At this stage, the structure would have increased torsional natural frequency by160% with static significantly lower than the initial design.

As been pointed out, subsequent thickness optimization is performed on the post-processed, topolgy-optimized frame. The thickness design variable assignment is shown in Fig. 13.

The optimal design of the frame using subsequent topology and thickness optimization revealed that the stiffness and torsional natural frequency of the frame increased by 33% and 59%, respectively with the weight reduced by 35-kg. The results of this frame optimization method is summarized in Table 1.

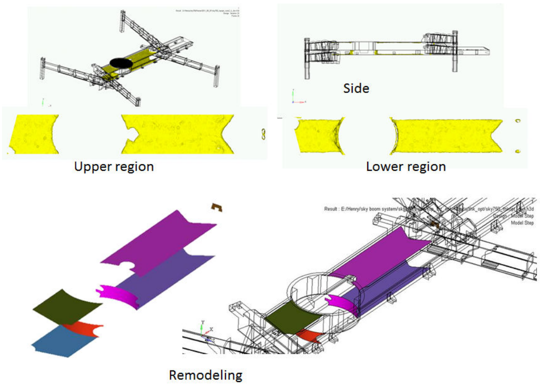

Fig. 12. Frame reinforcement layout resulting from topology optimization.

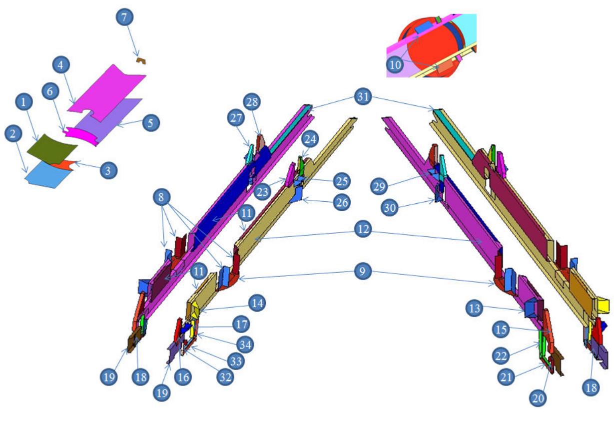

Fig. 13. Frame thickness variable assignment

Table 1. Summary of the frame optimization results

		Initial design	Optimization	
			Topology	Thickness
Mass, kg		5,035.5	5,934.7	4,999.7
Compliance	0°	6.0024E6	3.1938E6	5.9054E6
	45°	7.9134E6	3.3777E6	5.9828E6
	90°	1.0741E7	4.1696E6	7.1971E6
	135°	1.0348E7	4.7619E6	8.1293E6
	180°	9.1232E6	4.9147E6	8.3475E6
f, Hz		5.26	13.23	8.36

V. Conclusion

The multi-stage design optimization utilizing CAE tools has been shown to provide systematic approach for the design of a massive long-range aerial boom structure. The proposed design optimization method enabled the determination of potential design solutions in a time-saving and cost-effective way.

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