TOPOLOGY OPTIMIZATION STUDIES FOR A CONTOURED BEAM DEPLOYABLE MICRO-SATELLITE ANTENNA

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ABSTRACT

The increasing capabilities and low cost of micro-satellites makes them ideal tools for new space science missions [1]. Therefore, special attention is being paid to reducing size and weight of satellite antenna as well as its number of components. This is due to the required lower mass and smaller storage volume for the antenna. This serves to minimize overall cost of the project. In recent years there has been a growing research on *design optimization* of deployable satellite antennas [1, 2, 3]. Some of these concepts might suffer from higher risk of having too many mechanical components. Since change in shape and size may not lead the design criterion to the reduction of structural weight, this work proposes use of *topology optimization* to find the minimum weight antenna and its associated mass distribution. The advantage of the current method compared to the conventional force *density method* is its guaranteed weight reduction prior to any shape sizing of the net. This obviously allows easier understanding of the optimized shape and so facilitating its erection.

1. INTRODUCTION

Deployable antennas consisting of cable networks are favored due to their high packing efficiency and low weight [4, 5]. Also, another less obvious benefit is that the structure can better bear the launch loads in the stowed configuration [6]. These structures are capable of large configuration changes. Mostly is that the configuration changes from a packed, compact state to a deployed, large state. A well known example is the umbrella type. Once deployed, the structure is only subjected to the orbital loads, which are considerably low. Major burden in the design of all deployable space structures is to trade between the size of the stowed structure and its precision in the deployed state. Another criticalparameter is the mass and surface density. Low mass is favorable to lessen extremely high launch costs in the order of 10,000 USD/kg. A Lighter and more stiff structure gives a high lowest natural frequency of the structure, which is desirable to separate the structural and attitude control system frequencies [6].

The required smoothness of the reflector surface, significantly affects the choice of structural concept [6]. Typical cable network space antennas consist of surface cables, boundary cables and tie cables [4, 5]. Some of these concepts may suffer from higher risk of having too many mechanical components. These antennas are conventionally numerically simulated by the *force density method* [4, 5]. This method is frequently used in order to control both the geometry and the pre-stress distribution in form-finding of cable and membrane structures [4, 5]. As an example, the *tensegrity* antenna structures [7] are of particular interest of this paper. Usually, more complexity is involved in determination of the equilibrium configuration of these structures. Hence, the self-stressed shape of a *tensegrity* is not identical to that of its corresponding polyhedron and, therefore, proper form-finding methods are needed to find the equilibrium configuration of even the simplest *tensegrity* structure [8].

In layout optimization problems the purpose is to find the distribution of a given amount of material for a structure supported on its boundaries and subjected to a given loading condition, such that an objective function is optimized. Change in shape and size may not lead the design criterion to reduction of structural weight, therefore, this paper proposes using of *topology optimization method* to find the material distribution for the antenna to achieve minimum weight for the structure. This study investigates how small contoured beam space antennas can be shaped out of cable networks or mesh-like reflectors by using *topology optimization* of a parabolic shell model of a micro-satellite antenna. The advantage to the conventional *force density method* is the application of weight reduction prior to any shape sizing of the net which allows for easier understanding of the optimized shape.

2. DESIGN METHODS FOR CABLE NET CONTOURED BEAM ANTENNAS

The *force density method* is widely employed to analyze cable networks [4, 5, 6, 7, 9].The force *density method* analytically linearizes the form finding equations for a tension net. As a result, the method will be independent of the material properties of the membrane. The force density ratios (cable force divided by cable length) need to be specified for each element of the net, and different ratios give different equilibrium shapes. Since the *force density method* cannot be applied directly to continuum elements, the mesh of membrane elements is transformed into a virtual cable network.

The general force density form-finding problem of a *tensegrity* structure is characterized as follows:

1) Members are connected by pin joints.
2) Connectivity between the nodes and members, called topology, of the structure is known, and the geometrical configuration of the structure can be described in terms of nodal coordinates only.
3) No external load is applied and its self-weight is neglected; i.e. the structure is in a self-equilibrium state.
4) Buckling of the strut is not considered.
5) The structure is free-standing without any support.[9]

Consequently, the starting point for the *force density method* is a pin-joint network consisting of cable or bar elements, in which some of the nodes are fixed and the others are free. The final position of the free nodes will be achieved in the equilibrium configuration.

In *topology optimization* the purpose is to find an appropriate distribution of a given amount of material in given geometric 2D or 3D space, in which some constraints is satisfied and an objective function is optimized. No optimization parameters need to be defined and the objective function is either to minimize / maximize the energy of structural compliance or maximize the natural frequency while satisfying the constraints specified. The optimization procedure will determine which points of space are material points and which are voids. To avoid discrete optimization, some techniques are developed in which some intermediate materials are defined and penalized to achieve final black and white solution. One popular and efficient material model is so-called penalized, proportional stiffness model or simply SIMP-model (solid isotropic material with penalization) [10].

Two important numerical problems need to be solved in *topology optimization*; checkerboard problem and dependency of results to mesh density. Checkerboard problem can be accomplished using filtering methods or second order elements. Finer mesh reveals more details in optimum topology although, it will increase computational effort. In this study second order elements and finest mesh possible has been used to solve the problem in less than one day run on available personal computers.

The use of *topology optimization* for thin-panel antenna structures is conditional to results that clearly indicate the nearest manufacturable design with relatively low cost. Thus, for a typical thin-skinned, planar structure similar to an antenna, the topology-optimized results are to be immediately recognizable by high density element arrangements. *Topology optimization*, readily does the same as in shape optimization for a larger family of feasible structural domains. This class of domains should provide certain boundaries with different shapes, and various possible combinations to decide where to put a new boundary.

3. PROBLEM DEFINITION

The primary concept of the tension truss is that the lengths of the elements determine the shape of the faceted, paraboloidal surface and not the pre-stress distribution[11]. Geometry of the tension truss can be sufficiently pre-stressed by springs oriented normal to the reflecting surface. Based on the *tensegrity* concept, the structure is pre-stressed by tension ties connecting the two tension trusses.

The particular structure that is studied is a paraboloid of revolution with aperture diameter of 1.5 m bearing an inward surface pre-stress of 10kgf. The outer surface of the antenna design domain was considered to support distributed loads, while the interior of the structure consisted entirely of an assumed tensile volume which further revealed the positions the tension ties. The shell domain is discretized by quadrilateral mesh. *Topology optimization* formulation is derived for this set up over a wide range of volume constraint in order to ensure sufficient accuracy of the result.

Our procedure consists of three main steps. First, finding the self-equilibrium shape of the tension surface, while assuming that the thickness of the top and bottom skins is constant. For convenience, the topology optimization is conducted over a 30 deg. Sector of the paraboloid, constrained by symmetric boundary condition along the edges. (**FIG. 3.1**). Second, finding the supporting structure pattern (e.g. struts), using an equilibrium surface onto at membrane elements (**FIG. 3.2**). Finally, the profile of the tension ties is obtained by subjecting to a distribution of forces equal and opposite to the edge reactions required for the equilibrium of the membrane.

A number of topology optimization runs has been performed and a framework was created to compare the results. The purpose of the volume constraint is to fix the sum of the element densities in the structure and hence control the amount of material present. Hence, for thin-panel tension truss considered in this paper, the topology results give a quick indication of the basic shape of an efficient structure. Nevertheless, it cannot provide a detailed model of the final design.

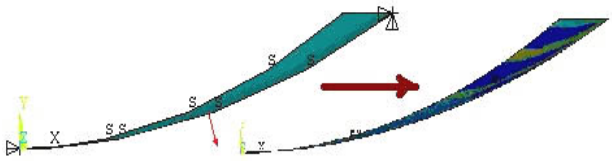

FIG. 3.1. 30 deg. Sector model for topology optimization and boundary conditions

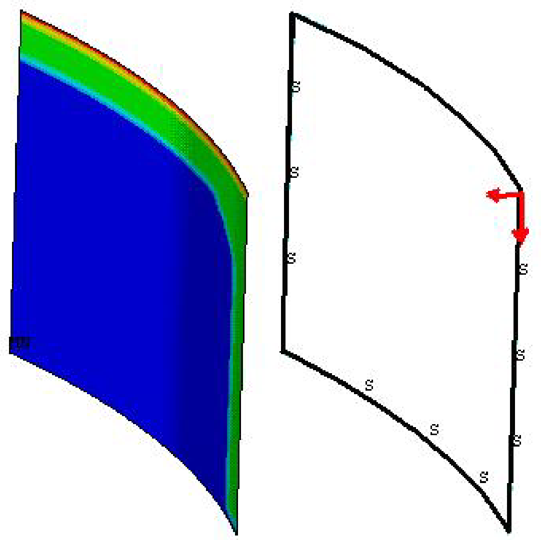

FIG. 3.2 Support structure model for topology optimization and boundary conditions

4. RESULTS

Different case studies show that the optimized topologies consist of well shaped cavities surrounded by a closed element (mesh) (**FIG. 4.1 a.**). Furthermore, the location of the interior net structure was mostly correlated near the edge, i.e. most of the interior structure was aligned in the perimeteric direction.

FIG. 4.1 b. shows a proposed net structure of the surface. This study showed significant influence of the mesh dimensions over the resultant optimized topologies however, it was shown that the lightest and the heaviest of these patterns are all comparable in mass distribution, which will reduce the structural sensitivity to manufacturing errors.

The topology in **FIG. 4.1 a.** consists of a low density block around the center which proposes that a well supported net near the edge and a light core mesh would be a suitable candidate structure for the antenna mesh. However, this study sought to concentrate on topology optimization results with clearly defined interior mesh structure (such as **FIG. 4.1 b.**) rather than the core type interiors (such as **FIG. 4.1a.**).

The resulting mesh surface from *topology optimization* can be interpreted as a net structure that would sufficiently carry the pre-stress of an antenna of the same shape and size.

It would be possible to use a constraint to guarantee the existence of sufficient material on the surface. If there exist sufficient surface elements in the absence of an optimization constraint, it can be assumed that the quantity and distribution of interior structure is efficiently complimenting the skin of the structure.

FIG. 4.2. shows a comparison between the topology optimization results for different antenna spans. As the span increases, a gradual change in the number of elements is perceivable.

FIG. 4.3 shows the topology optimization result of the supporting structure. The density distributions primarily propose a frame structure (**FIG. 4.3** lower right corner) and no internal structure (only top and bottom surfaces). Application of new boundary conditions results in a more truss-like structure (**FIG. 4.3** left), which is topologically optimized but rather different from the conventional *tensegrity* concept [7].

The topologically optimized tension tie profile is shown in **FIG. 4.4.** Different boundary conditions were used on each of the top and bottom surfaces; e.g. free on the top while the bottom remains fixed in all DOF. The ties are characterized by a number of short high-density tensile elements that were bounded by two longer and thicker elements (as in **FIG. 4.4**). The remaining elements had at low-density elements and hence were classified as no internal structure. One advantage of this element arrangement is that the bottom surface net structure would be lighter due to less number of tie attachments.

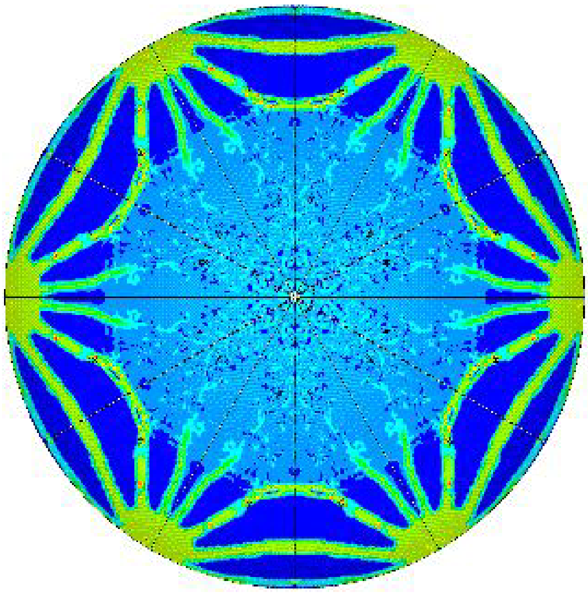

FIG. 4.1 a. Complete antenna mesh result from topology optimization for the 1.5m. span model

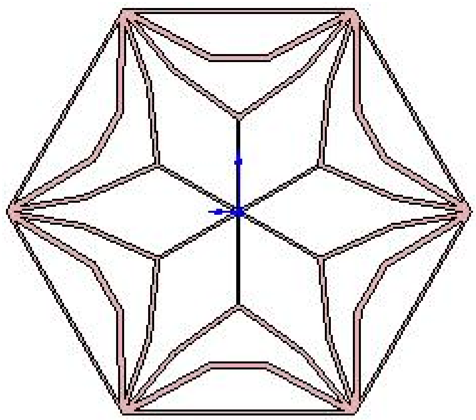

FIG. 4.1 b. A proposed net model based on the topology optimization result

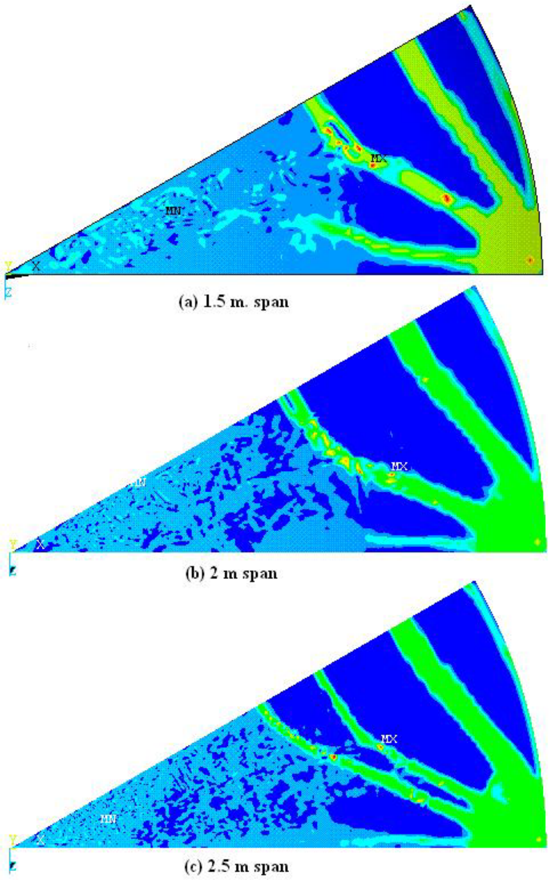

FIG. 4.2. Comparison of the topology optimization patterns a) 1.5m antenna span. b) 2m. antenna span and c) 2.5m. antenna span

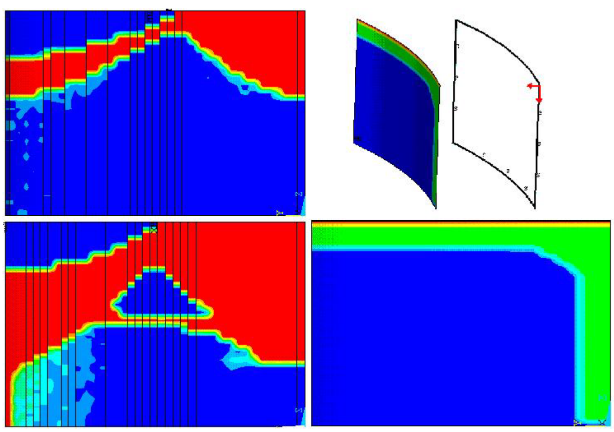

FIG. 4.3. Influence of change in boundary condition on support structure topology optimization

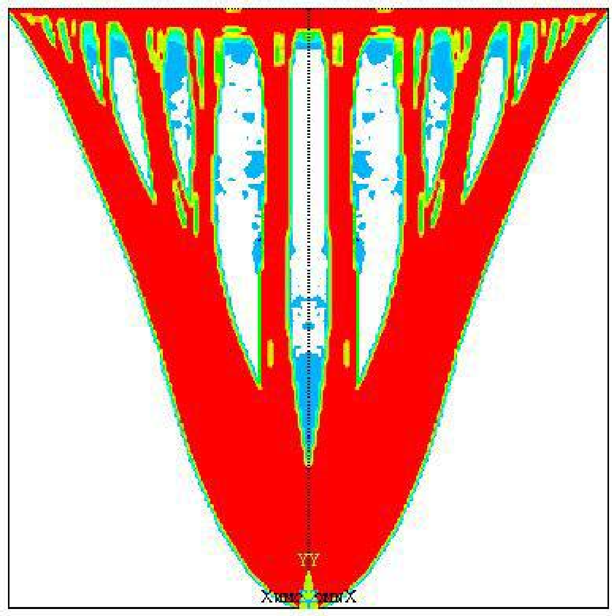

FIG. 4.4. Topology optimization result of tension tie structure

5. CONCLUSION

This work presents the possible application of *topology optimization* method in shape sizing of *tensegrity* antenna structures; including the surface mesh, struts and tension ties. Different case studies show that the material distributions depend on the antenna's span while load carrying paths are easily identifiable. However, it is not straightforward to obtain the most practical structural member sizes and thus the suitable mesh for the evaluation of structural efficiency. On the other hand, the antenna mesh is less affected while proportionally varying the span, which could help evaluate the minimum weight of the structural configuration. For spans lager than 2.5m, the trend in the results start to change compared to that of 1.5m and lower. In overall, the best result is yet to be determined by an appropriate choice of mesh size.

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