AUTOMATED DESIGN OPTIMIZATION OF NEW ANTENNA STRUCTURES FOR PERFORMANCE REQUIREMENTS+

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INTRODUCTION

In the 18 years since Von Hoerner's (1) pioneering definition of antenna homology and introduction of an approach to achieve homologous designs, major advancements have been made in the technology of automated antenna structure design. It is now known, for example, that although an homologous design is a theoretically ideal condition that provides insights into the characteristics of desirable response, it is not possible, nor even desirable, to achieve this in practice. This follows from a) the multitude of diverse loadings imposed upon an antenna by gravity and wind, which precludes designs that can respond homologously to all of these loadings, b) the differences between homologous designs that reduce microwave pathlength errors and the designs required to either limit antenna boresight pointing errors, or maintain minimum natural frequencies adequate for the control system, and c) the economical restrictions associated with manufacture that either limit the designers' choice of the structural members to those commercially available or impose the need to emphasize repetition rather than optimal variation in the fabrication process.

This paper describes state-of-the-art automated design optimization procedures that have been used to design recently or soon-to-be completed 34-m and 70-m NASA Deep Space Network X-Band (8.45 ghz) antennas. The primary software tool for these designs is the JPL-IDEAS (Iterative Design of Antenna Structures) finite element computer program. The program provides many features that a) automate substantive performance analysis of antenna and related structures and b) to perform in-depth design optimization selection of the structural member size properties to meet a variety of multiple constraints on antenna compliance and safe stress.

STRUCTURE AND PERFORMANCE ANALYSIS

Large order sparse systems of linear equations are solved via a matrix wavefront (2) structural stiffness matrix decomposition algorithm with provisions for resequencing the stiffness matrix to enhance efficient processing (3). The finite element types consist of one-dimensional rods (these predominate in antenna structure construction), triangular and quadrilateral membrane plates, and shear plates. The occasional beam members

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[+] The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

are simulated by sets of rod caps and shear plate webs. The I/O and data management strategy allows for computer models that contain the thousands of degrees of freedom and finite element members needed for antennas with diameters in the 34-m to 100-m range. An automatic feature of the program can be invoked to synthesize the response and design of the complete structure from the response of inexpensive-to-analyze half structure models.

Thermal deflection and natural frequency analyses are available. The latter can be by either the inverse power or simultaneous iteration methods, and can treat either the conventional "locked rotor" or the "free rotor" configurations. Special additional output (4) facilitates follow-on analysis of transient response, component mode synthesis, and control system interaction modeling.

Antenna performance analysis includes microwave pathlength deformation analysis (5) of gravity, wind, or thermal loading on antenna-reflector backup structures and the determination of the least squares best fitting surface. Special output data developed from this least squares analysis can be used to determine the relative importance of each fitting parameter. The responses to gravity loadings for azimuth/elevation antennas over the elevation angle range are automatically synthesized (6) as linear combinations of the responses to one loading parallel to the reflector focal axis and a second loading perpendicular to elevation and focal axes. A loading parallel to a third axis is included for the synthesis of hour angle/declination antenna gravity loadings and a matrix of rms pathlength errors as a function of hour and declination angles is printed. The optimum (6) rigging angle, which is the antenna elevation angle where the surface panels are adjusted in the field to conform as closely as possible to the ideal surface, is automatically computed to comply with several available user options.

Antenna boresight pointing error calculations are also automated and these can contain the pointing error contributions of subreflector and feed translation offsets and subreflector rotations. Additionally, both axial and lateral offsets of the subreflector from the location of the best-fitting focal point are also computed and printed. The correlation coefficient is computed and printed for all pairs of pathlength analysis case pathlength error vectors. This coefficient makes possible an accurate computation for the response to a particular wind- attitude loading in conjunction with the gravity loading at the specific elevation angle when responses to the loadings are analyzed independently. The correlation coefficient also permits calculations of response to combined loading when the wind load is scaled to a speed different from the one modelled by the input data.

STRUCTURE OPTIMIZATION

The optimization problem consists of choosing design variables to minimize an objective function subject to implicit primary and explicit secondary constraints on the selection of design variables. For our antenna structures the design variables are the areas of the rods and the thicknesses of the plates. The objective, which is an approximate measure of cost, is to minimize the total weight of structural members. The primary constraints can be chosen from any of the following type of compliance effects: a) rms microwave pathlength error from the best fitting surface, (accounting for the rigging angle in cases of gravity loading), b) antenna pointing error, c) any arbitrary linear function of specific displacements, (which can be made to include member stresses as a special case) d), rms deformations from a plane, and e) minimum natural frequency for a specified vibration mode. Except for the natural frequency constraint, any mixture of up to 50 of these constraints can be invoked simultaneously and applied individually or in combination to a set of external loadings. The side constraints consist of minimum and maximum values for the design variables and the linking of sets of individual members into single design variable groups within which each member will have the same value of design variable. Typically we also treat member allowable tension and buckling stress by updating a set of minimum allowable side constraints to reflect requirements of the current design during an iterative process. This is equivalent to the "fully-stressed, stress-ratio" design method and is usually adequate for high performance antenna structures because of the low incidence of overstresses. The stress side constraints are applied to all the loadings of a particularly designated (survival) set, which can be different from the set (operating) to which primary compliance constraints are assigned.

A virtual work methodology is used to express the primary constraints as equal to the virtual work associated with the environmental load (wind, gravity) and the displacements for a virtual load that is unique for each constraint. The virtual work is decomposed into a contribution from each design variable and the sum of these contributions is equal to the value of the associated compliance. The virtual loadings for microwave pathlength (7), pointing angle (8), planar deformations and natural frequency (9) are generated within the computer program. The user is required to supply the virtual ("dummy") load only in the case of the linear function of displacement type of constraint. This type of constraint is most frequently used to limit the translational or rotational compliances of alidade, pedestal, or quadripod structures.

The method of Lagrange multipliers is used to minimize a function of the structure weight objective augmented by a set of constraint functions associated with each constraint. The multipliers are found by solving a set of simultaneous nonlinear equations using Newton's method, or variations thereof, in conjunction with a number of strategies (10, 11). Optimality criteria (12) are then used to determine the design variables directly from the multipliers. Linearization of the design procedure for the typical statically indeterminate structure makes it necessary to design iteratively with several analysis-design cycles. In each cycle the analysis is updated to reflect the current status of the design variables. The extent of redundancy typical for antenna structures usually requires from four to eight cycles for convergence.

An important option allows the user to supply sets tables of commercially available structural shapes for rod member design variable selection (8). Since each entry in the tables is accompanied by the radius of gyration for that shape and the length is known within the program, the stress allowed by a column buckling formula is computed. Consequently an appropriate stress side constraint is established by the smallest member in the table that satisfies the buckling requirement.

CONCLUSION

The automated analysis and design capabilities just described transfer most of the effort from the engineer to the computer. As the result of the automation, more comprehensive analyses and better designs are produced by a smaller engineering staff in shorter time schedules.

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