INVESTIGATION ON LARGE SIZE DEPLOYABLE ANTENNA TRUSS MECHANISM

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by

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Dedicated to

my dear parents for their continuous love, support and blessings

my loving wife & wonderful kids who supported me at each step to go ahead to complete this research work

And

The Gracious Almighty GOD

Certificate

This is to certify that the thesis entitled **Investigation on Large size Deployable Antenna Truss Mechanism** being submitted by **Mr. Hemant Arora** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** in Mechanical Engineering is a bonafide record of original research work carried out by him under my supervision in conformity with rules and regulations of the institute. This work has not been submitted to any other University or Institute for the award of any Degree or Diploma.

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"There are no limitations to the mind except those we acknowledge"

—Napoleon Hill

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Abstract

High-bandwidth satellite-based telecommunication demands large-diameter antenna reflectors (LDR). Launching of monolithic LDR antennas of sizes 6m or more is limited by the launch vehicle's payload fairing space. A foldable antenna with space deployment mechanisms is hence used. The deployment process of the antenna is the process of transition from folded and strapped structure to a locked structure, which is complicated because of the presence of backlash, friction, and misalignment due to manufacturing accuracy. An attempt has been made to explore the various foldable configurations reported in the literature for smooth and effective deployment motion with a focus on configurations with space heritage. Mesh antennas are preferred for large-size deployable reflectors due to low manufacturing complexity, ease in deployment operation, and high deployed-to-stowed ratio. The AstroMesh configuration is seen to be the simplest configuration to investigate further through kinematics and dynamic analysis. The spatial configuration is converted to planar by introducing a transformation relationship between two adjacent bays to solve the kinematics. The 12m diameter configuration is analyzed for the given position, velocity, and acceleration parameters, which are used as an example. The deployment cable pull force, which estimates the amount of force required to achieve a fully deployed configuration, is predicted through dynamic analysis. Design parameters are identified and parametric optimization of configuration with the objective of achieving a compact stowed configuration is carried out. The parametric optimization study for a prototype configuration of 3m diameter leads to a volumetric efficiency of 99.7%. The optimized design configuration is then evaluated for structural requirements of space launch environmental specifications. A linearized formulation for support net

analysis is carried out and an efficient numbering scheme was evolved to save memory and computation. Dynamic stiffness of stowed and deployed configurations is computed using the finite element method. The first fundamental mode of the stowed configuration of the 12m diameter truss structure is predicted to be 40 Hz. A prototype of a 3m diameter is realized to demonstrate the concept of the deployment mechanism. An SMA-based hold-down and release mechanism is also evaluated for functional aspects and hold-down capacity. Demonstration of deployment on 3m antenna reflector with support net and mesh configuration showed up issues with smooth deployment. To mitigate some of the problems, the use of tape flexure-based hinges is investigated. The buckling behavior of curved tapes is studied analytically with corresponding experimental strain measurement for equal sense and opposite sense bending cases under transverse loading. The absolute error between analytical formulation and experiments is found to be 9% and 19% for equal and opposite senses within the elastic limit. Characteristics of opposite and equal sense bending with combinations of a single and a double layer of tapes are analyzed in FEM for varying material options with CRFP and Ni36CrTiAl alloy seen to have benign stresses for 90° rotation hinges. The feasibility of the concept is demonstrated with prototypes of joints incorporating tape flexures.

सार

उच्च बैंडविड्थ उपग्रह आधारित दूरसंचार बड़े व्यास वाले एंटीना रिफ्लेक्टर (एलडीआर) की मांग करता है। 6 मीटर या उससे अधिक आकार के एलडीआर एंटेना का प्रक्षेपण, वाहन के पेलोड फेयरिंग स्पेस द्वारा सीमित है। इसलिए अंतरिक्ष परिनियोजन तंत्र के साथ एक फोल्डेबल एंटीना का उपयोग किया जाता है। एंटेना की खुलने की प्रक्रिया, मुड़ी हुई और बंधी हुई संरचना से एक पूरी तरह से विकसित संरचना में संक्रमण की प्रक्रिया है, जो निर्माण सटीकता के कारण बैकलैश, घर्षण और मिसलिग्न्मेंट की उपस्थिति के कारण जटिल है। अंतरिक्ष विरासत के साथ विन्यास पर ध्यान देने के साथ सहज और प्रभावी परिनियोजन गति के लिए साहित्य में रिपोर्ट किए गए विभिन्न फोल्डेबल कॉन्फ़िगरेशन का पता लगाने का प्रयास किया गया है। मेश एंटेना को बड़े आकार के परिनियोजन योग्य परावर्तकों के लिए पसंद किया जाता है क्योंकि कम विनिर्माण जटिलता, तैनाती संचालन में आसानी और उच्च अनुपात में तैनात होने के कारण। किनेमेटिक्स और गतिशील विश्लेषण के माध्यम से आगे की जांच करने के लिए एस्ट्रोमेश कॉन्फ़िगरेशन को सबसे सरल कॉन्फ़िगरेशन के रूप में देखा गया है। किनेमेटिक्स को हल करने के लिए दो आसन्न खण्डों के बीच परिवर्तन संबंध शुरू करके स्थानिक विन्यास को प्लेनर में बदल दिया गया है। मीटर व्यास विन्यास का विश्लेषण दी गई स्थिति 12, वेग और त्वरण मापदंडों के लिए किया गया है, जो एक उदाहरण के रूप में उपयोग किए गए हैं। परिनियोजन केबल पुल बल, जो पूरी तरह से परिनियोजित कॉन्फ़िगरेशन को प्राप्त करने के लिए आवश्यक बल की मात्रा का अनुमान लगाता है, का अनुमान गतिशील विश्लेषण के माध्यम से की गई है। डिज़ाइन मापदंडों की पहचान की गई है और एक कॉम्पैक्ट संग्रहीत कॉन्फ़िगरेशन प्राप्त करने के उद्देश्य से कॉन्फ़िगरेशन का पैरामीट्रिक अनुकूलन किया गया है। 3 मीटर व्यास के एक

प्रोटोटाइप विन्यास के लिए पैरामीट्रिक अनुकूलन अध्ययन से %99.7की वॉल्यूमेट्रिक क्षमता प्राप्त हुई है। फिर अंतरिक्ष प्रक्षेपण पर्यावरण विनिर्देशों की संरचनात्मक आवश्यकताओं के लिए अनुकूलित डिजाइन विन्यास का मूल्यांकन किया गया है। समर्थन शुद्ध विश्लेषण के लिए एक रैखिक रूप से तैयार किया गया है और स्मृति और गणना को बचाने के लिए एक कुशल नंबरिंग योजना विकसित की गई है। परिमित तत्व विधि का उपयोग करके संग्रहीत और परिनियोजित कॉन्फ़िगरेशन की गतिशील कठोरता की गणना की गई है। 12 मीटर व्यास ट्रस संरचना के संग्रहीत विन्यास का पहला मौलिक मोड हर्ट्ज होने 40का अनुमान लगाया गया है। तैनाती तंत्र की अवधारणा को प्रदर्शित करने के लिए मीटर व्यास का एक प्रोटोटाइप 3दिखाया गया है। कार्यात्मक पहलुओं और होल्डडाउन और -आधारित होल्ड-डाउन क्षमता के लिए एक एसएमए- रिलीज तंत्र का भी मूल्यांकन कियागया है। सपोर्ट नेट और मेश कॉन्फिगरेशन के साथ मीटर 3 एंटेना रिफ्लेक्टर पर तैनाती का प्रदर्शन सुचारू तैनाती के साथ समस्याएँउत्पन हुई है। कुछ समस्याओं को कम करने के लिए, टेप फ्लेक्चर आधारित-जोड़ के उपयोग की जांच की गई है। घुमावदार टेपों के बकलिंग व्यवहार का विश्लेषणात्मक रूप से अनुप्रस्थ लोडिंग के तहत समान अर्थ और विपरीत अर्थ झुकने वाले मामलों के लिए प्रयोगात्मक तनाव माप के साथ अध्ययन किया गया है। लोचदार सीमा के भीतर समान और विपरीत इंद्रियों के लिए विश्लेषणात्मक सूत्रीकरण और प्रयोगों के बीच पूर्ण त्रुटि %9और %19पाई गई है। सिंगल और डबल लेयर के टेप के संयोजन के साथ विपरीत और समान अर्थ झुकने की विशेषताओं का विश्लेषण FEM में CRFP और Ni36CrTiAl मिश्र धातु के साथ अलग अलग सामग्री विकल्पों के लिए किया-गया है, जिसमें 90 डिग्री रोटेशन जोड़ो के लिए सौम्य तनाव देखा जा सकता है। अवधारणा की व्यवहार्यता को टेप फ्लेक्सर्स को शामिल करने वाले जोड़ों के प्रोटोटाइप के साथ प्रदर्शित किया गया है।

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The important symbols and abbreviations are given below in alphabetical order, where each one is explained. Notational rules followed in this thesis are as follows:

- *Italic* Roman/Greek letters (lower case) refer to scalars.
- **BOLDFACE** Roman/Greek upper-case letters denote matrices and vectors.

Latin Letters	Description
A	Surface Area of Reflector
$\boldsymbol{C_u}$	Connectivity Relationship matrix for free node elements
$\boldsymbol{C_f}$	Connectivity Relationship matrix for fixed node elements
D	Dissipation Function of joints
δ_{rms}	Surface faceting root mean square error
E	Elastic Potential Energy of Torsional Spring and pre-tension of net
e_a	Efficiency of Antenna
F/D	Ratio of Focal length to Diameter of Antenna Reflector
g	Acceleration due to gravity
G	Gain of Antenna
H	Height of Vertical Member of Truss Configuration
i	Degree of freedom
j	Number of Joints
k_1	Stiffness coefficient of torsional spring

k_2	Stiffness coefficient of tension support net structure
k_l	Longitudinal curvature of tape spring
k_t	Transverse curvature of tape spring
λ	Wavelength of Electromagnet Radiation
m	Mass of linkage
m_r	Mass of release nut
M	Bending moment of tape flexure
N	Total number of Links
n	Total number of bays
$\boldsymbol{P_i}$	Co-ordinates of point P in coordinate frame $X_iO_iY_i$
$\dot{\boldsymbol{P}}_\mathbf{1}$	Velocity Matrix of Point P
$\ddot{\boldsymbol{P}}_\mathbf{1}$	Acceleration Matrix of Point P
$\boldsymbol{P_{i+1}}$	Co-ordinates of point P in coordinate frame $X_{i+1}O_{i+1}Y_{i+1}$
$\dot{\emptyset}$	Angular velocity of link
$Q_\emptyset$	Generalized moment corresponding to the generalized coordinates
$\boldsymbol{q}$	Force density vector
R	Reaction force generated by steel ball
$\boldsymbol{T}_{\mathbf{i+1}}^{\mathbf{i}}$	Transformation Matrix
$\boldsymbol{T}_{\mathbf{j}}^{\mathbf{1}}$	Global Transformation Matrix
T	Total Kinetic Energy of Links

t	Total time period of deployment
θ	In-plane Angle of horizontal member of truss
V	Gravitational Potential Energy of System
ε	Damping coefficient

Acronyms

DC	Direct Current
DOF	Degrees of Freedom
EIRP	Effective Isotropic Radiation Power
GSLV	Geo Synchronous Satellite Launch Vehicle
HDRM	Hold down and Release Mechanism
ISRO	Indian Space Research Organization
LDR	Large Diameter Antenna Reflector
NGST	Next Generation Space Telescopes
OPI	Opening Per Inch
PSD	Power Spectral Density
PSLV	Polar Satellite Launch Vehicle
RMS	Root mean square
SAC	Space Applications Centre, Ahmedabad, India
SAR	Synthetic Aperture Radar
SRS	Shock Response Spectrum
SMA	Shape Memory Alloy
SME	Shape Memory Effect
STEM	Storable Tubular Extendible Members
TRW	Thompson Ramo Wooldridge