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The establishment and application of direct coupled electrostatic-structural field model in electrostatically controlled deployable membrane antenna

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ABSTRACT

The electrostatically controlled deployable membrane antenna (ECDMA) is a promising space structure due to its low weight, large aperture and high precision characteristics. However, it is an extreme challenge to describe the coupled field between electrostatic and membrane structure accurately. A direct coupled method is applied to solve the coupled problem in this paper. Firstly, the membrane structure and electrostatic field are uniformly described by energy, considering the coupled problem is an energy conservation phenomenon. Then the direct coupled electrostatic-structural field governing equilibrium equations are obtained by energy variation approach. Numerical results show that the direct coupled method improves the computing efficiency by 36% compared with the traditional indirect coupled method with the same level accuracy. Finally, the prototype has been manufactured and tested and the ECDMA finite element simulations show good agreement with the experiment results as the maximum surface error difference is 6%.

1. Introduction

With the development of science and technology and deepening of universe exploration, the demands of deployable space antenna are increasingly higher and higher. Low weight, large aperture and high precision have been the most important technical specifications for space antenna. Compared to other space deployable antennas (mesh antenna [1], inflatable antenna [2], etc), the electrostatically controlled deployable membrane antenna (ECDMA) has its own unique advantages such as much higher precision and active controllable features [3,4]. The ECDMA membrane surface is accurately tensioned by electrostatic forces which can be actively controlled by varying the voltage between membrane surface and basic electrodes. Obviously, the membrane deforms by electrostatic forces meanwhile the electrostatic field strength changes by membrane deformation which is a nonlinear coupled problem. It will be great guiding significance for ECDMA membrane surface high precision control to figure out the electrostatic-structural coupled problem by a uniform description.

The electrostatic-structural coupled problem research achievements have been focused on Microelectromechanical Systems (MEMS) aspect previously. The electrostatic-structural solver ESSOLV of the finite element analysis software ANSYS is applied by Zahed [5] to solve the coupled electrostatic-structural problem where electrostatic field and structure are analyzed by finite element method (FEM) separately, but this sequential method is not so applicable for nonlinear strong coupled problem. Lee et al. [6] used boundary element method (BEM) and FEM to analyze electrostatic field and structural field respectively which is also a sequential method, this method reduced the calculating degrees of freedom however increased the complexity of computation. In order to avoid a sequential analysis for the strong electrostatic-structural coupled problem, some direct coupled approach have been proposed. Gyimesi & Ostergaard [7], Gyimesi et al. [8], and Avdeev [9] applied the coupled reduced order electrostatic-structural elements of ANSYS say trans126 and trans109 to convert energy from electrostatic domain into a structural domain (and vice versa), however they are only suitable for two-dimensional problems. Rochus [10] has studied the MEMS electro-mechanical coupled problem by a monolithic method but it can not be directly applied to the ECDMA electrostatic and membrane structure coupled problem.

Prior studies for electrostatically controlled membrane structure had not taken into account the electrostatic-structural coupled problem, they assumed that the distance between membrane surface and basic electrodes is constant, the electrostatic force is given by the parallel plate capacitor relationship [11–14]. After that, Gu et al. [15] calculated the electrostatic force with an improved parallel plate capacitor relationship, however, the computational accuracy is not so satisfied. Inspired by the

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MEMS electro-mechanical coupled research lately, Liu et al. [16,17] established the ECDMA electrostatic-structural coupled model by an indirect coupled method. Although the indirect coupled method can figure out the coupled problem of ECDMA, the electrostatic field and membrane structural field must be analyzed separately. On the one hand the indirect coupled method is not so appropriate for nonlinear strong coupled problem, on the other hand the iteration process is complicated.

The purpose of this paper is to work out the coupled problem in ECDMA using a direct coupled method. The structure of this paper is as follows: In Section 2, the membrane structure mechanical field and the electrostatic field electrical properties are uniformly described by energy and the direct coupled electrostatic-structural field governing equilibrium equations are obtained by energy variation approach. The direct coupled method solution procedure, accuracy and computation time are compared to the indirect coupled method in detail in Section 3. In Section 4, a 2-meter curved ECDMA prototype is proposed and tested to verify the validity of the direct coupled model of ECDMA. Some remarking conclusions and further study suggestions are summarized in Section 5.

2. Theory

2.1. Membrane structural field energy

Geometric nonlinearity is considered for structural field analysis because the flexible membrane deforms largely under vertical loads. Meanwhile assuming the membrane is thin enough, the membrane analysis can be considered as a plane stress problem [18]. The position of any point in membrane structure is set as a vector $\mathbf{x}_m = [x\, y\, z]^T$, moreover both the displacement vector $\mathbf{u} = [u\, v\, w]^T$ and the strain vector $\boldsymbol{\varepsilon} = [\varepsilon_x\, \varepsilon_y\, \gamma_{xy}]^T$ are corresponding to the point. In Cartesian coordinates, the strain-displacement equations of ECDMA membrane structure are given as

$$
\begin{aligned}
\varepsilon_x &= \frac{\partial u}{\partial x} + \frac{1}{2}\left(\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial x}\right)^2\right) \\
\varepsilon_y &= \frac{\partial u}{\partial y} + \frac{1}{2}\left(\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial y}\right)^2\right) \\
\gamma_{xy} &= \frac{1}{2}\left\{\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right\} + \frac{1}{2}\left(\frac{\partial u}{\partial x}\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\frac{\partial v}{\partial y} + \frac{\partial w}{\partial x}\frac{\partial w}{\partial y}\right)
\end{aligned}
\tag{1}
$$

Assuming the membrane is isotropic material, the membrane stress vector is set as $\boldsymbol{\sigma} = [\sigma_x\, \sigma_y\, \tau_{xy}]^T$, then the constitutive equations can be expressed as

$$
\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{Bmatrix} \sigma_{x0} \\ \sigma_{y0} \\ \tau_{xy0} \end{Bmatrix} + \begin{bmatrix} H_{11} & H_{12} & 0 \\ H_{21} & H_{22} & 0 \\ 0 & 0 & H_{33} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix}
\tag{2}
$$

where $\boldsymbol{\sigma}_0 = \{\sigma_{x0}\, \sigma_{y0}\, \tau_{xy0}\}^T$ is the initial stress state vector, $\mathbf{H} = \begin{bmatrix} H_{11} & H_{12} & 0 \\ H_{21} & H_{22} & 0 \\ 0 & 0 & H_{33} \end{bmatrix}$ the elasticity matrix, then Eq. (2) can be simplified as $\boldsymbol{\sigma} = \boldsymbol{\sigma}_0 + \mathbf{H}\boldsymbol{\varepsilon}$.

Fig. 1 shows main parts of ECDMA, both the ECDMA membrane surface Ω_m and electrode surface Ω_e are made from a thin film material. For the sake of simplicity, the membrane surface boundary $\Gamma_{\mathbf{u}}$ is considered as fixed that is $\mathbf{u}|_{\Gamma_{\mathbf{u}}} = 0$. Meanwhile, all the electrode surface deflections are ignored here because all the electrodes are mounted to the front net assembly of the AstroMesh structure which is composed of a perimeter truss, a front net structure attached to the truss, an identical bottom net structure attached to the truss, and a series of tensioning assemblies that pull the nets together at the node points [4]. On this occasion, the membrane structure deformation energy can be obtained as follows

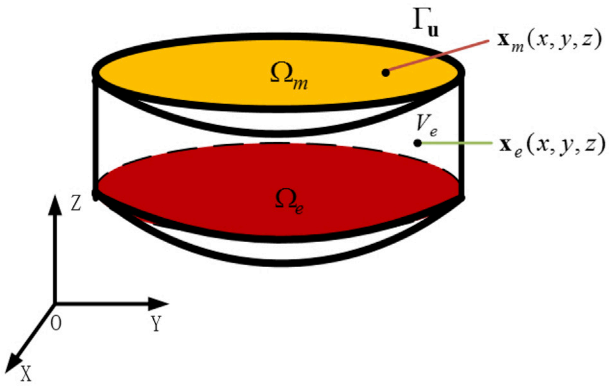

Fig. 1. Schematic view of ECDMA.

$$
W_m = \frac{1}{2}\int_{\Omega_m} \boldsymbol{\varepsilon}^T \boldsymbol{\sigma}\, d\Omega_m
\tag{3}
$$

in which, Ω_m is the whole membrane structure strain energy domain of integration. It is clear that the electrostatic force and the membrane surface deformation will change together, in essence, the work done by the electrostatic field force changes the membrane structure strain energy.

2.2. Electrostatic field energy

Between the membrane surface Ω_m and electrode surface Ω_e is the electrostatic region V_e as is shown in Fig. 1 which is considered including the whole electrostatic field energy if the fringing of the electric field at the edges of the membrane surface and electrode surface is neglected [19]. Any point position in electrostatic region is set as a vector $\mathbf{x}_e = [x\, y\, z]^T$ and the electrostatic field potential $\varphi(x, y, z)$ is corresponding to the point. In Cartesian coordinates, the Laplace's equation can describe the electric potential's distributions in the electrostatic field accurately as follows

$$
\frac{\partial^2 \varphi}{\partial^2 x} + \frac{\partial^2 \varphi}{\partial^2 y} + \frac{\partial^2 \varphi}{\partial^2 z} = 0
\tag{4}
$$

Meanwhile, the electrostatic field strength $\mathbf{E} = [E_x\, E_y\, E_z]^T$ can be expressed as

$$
\mathbf{E} = -\nabla\varphi
\tag{5}
$$

in which, ∇ is the differential operator in Cartesian coordinates.

The electrostatic displacement $\mathbf{D}$ can be derived by $\mathbf{E}$ as follows

$$
\mathbf{D} = \varepsilon_0 \mathbf{E}
\tag{6}
$$

where $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is the permittivity of vacuum.

Generally, the electrostatic field is given by Dirichlet boundary conditions

$$
\varphi(x, y, z) = \begin{cases} \varphi|_{\Omega_m} = \varphi_1 \\ \varphi|_{\Omega_m} = \varphi_2 \end{cases}
\tag{7}
$$

in which, φ_1 and φ_2 are the membrane surface and electrodes voltage respectively.

Then the electrostatic energy stored in the capacitor between membrane surface Ω_m and electrode surface Ω_e can be obtained by

$$
W_e = \frac{1}{2}\int_{V_e} \mathbf{D}^T \mathbf{E}\, dV_e
\tag{8}
$$