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Mechanical properties of multifunctional structure with viscoelastic components based on FVE model

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ABSTRACT

Based on the models of Lion and Kardelky (2004) and Hofer and Lion (2009), a finite viscoelastic (FVE) constitutive model, considering the predeformation-, frequency- and amplitude-dependent properties, has been proposed in our earlier paper [1]. FVE model is applied to investigating the dynamic characteristics of the multifunctional structure with the viscoelastic components. Combing FVE model with the finite element theory, the dynamic model of the multifunctional structure could be obtained. Additionally, the parametric identification and the experimental verification are also given via the frequency-sweep tests. The results show that the computational data agree well with the experimental data. FVE model has made a success of expressing the dynamic characteristics of the viscoelastic materials utilized in the multifunctional structure. The multifunctional structure technology has been verified by in-orbit experiments.

1. Introduction

In our pervious paper, the hyperelasticity [2–7], the dynamic mechanical property [8–12], and the rheology of the viscoelastic material [13–15] utilized in the multifunctional structure have been researched by a series of the tests [16]. Since the dynamic properties of the viscoelastic materials are more complicated than their static properties [17–23], the parameter identification methods of the viscoelastic models have been studied on the basis of the existing viscoelastic models [24,25], such as HN model [26–31] and MFZ model [32–36]. Furthermore, in order to investigate the predeformation-, frequency- and amplitude-dependent material behavior, a FVE model [1] was developed based on Lion and Hofer's models [37,38], . Although the FVE model has been verified by Wollscheid's experimental data [39], it is still not applied in a specific engineering problem.

In this paper, FVE model is utilized to research the dynamic characteristics of the multifunctional structure which includes the viscoelastic components. It is the continued work of our previous paper [1]. A review of the multifunctional structure technology for the aerospace applications is given by Sairajan et al. [40]. The multifunctional structure in present paper is a system which integrates the structure function with the power system. The structure function provides the mechanical load-supporting capability and the power system offer the electrical energy. Traditional battery system of the spacecraft requires containers to align and protect the cells and a tertiary structure to mount it to the spacecraft which could account for about 20%–30% of the total satellite mass and occupy a significant portion of the spacecraft volume. These nonfunctional structures add mass and volume to the spacecraft. Therefore, the MFS, which integrates both structural and battery functions in one component, have the potentiality to remove the discrete components for the purpose of saving mass and volume of the spacecraft. The multifunctional structure pays attention to the replace of the future satellite's bulkhead.

After obtained the dynamic model of the multifunctional structure by combining FVE model with the finite element theory, it is verified by the frequency sweep tests of the multifunctional structure. The results show that FVE model has made a success of describing the viscoelastic properties of the multifunctional structure including the viscoelastic components. It has been launched to the geosynchronous orbit (36000 km) to verify this multifunctional structure technology and still works well until now. Summing up, the purpose of this paper are (i) to describe the multifunctional structure and obtain its dynamic model (Section 2), (ii) to verify the mathematical model by vibration tests [41,42] (Section 3), (iii) to give some conclusions in the last (Section 4).

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2. Multifunctional structure modelling

2.1. Structural description

The multifunctional structure concept is firstly given by Lockheed Martin Astronautics to address the technology needs of the future spacecraft [43–50]. The multifunctional structure in the present paper contains the viscoelastic components, as shown in Fig. 1.

It can be seen from Fig. 1 that the multifunctional structure includes two cover plates, one frame, one battery and some viscoelastic components. The viscoelastic components can be divided into two types, i.e. the cube-shaped parts and the pad-shaped parts. The cover plates and the frame are made of the composite material named T300. The physical parameters of T300 are illustrated in Table 1. The battery is a power storage system composed of the T300 shells, the polymer lithium pouch cells and the silica gel. The battery provides the electrical energy, another function of the multifunctional structure beside the structural function. The viscoelastic components are made from the addition-type silicone rubber (VPDMS cured by PMHS). The dynamic properties of the addition-type silicone rubber have been researched by experiments in our previous paper [16]. The physical parameters of VPDMS and PMHS are listed in Table 2. The chemical structural formulas of VPDMS and PMHS are given in Fig. 2 and the crosslinking reaction between them is shown in Fig. 3.

The multifunctional structure seen in Fig. 1 could be considered as a total multifunctional element. More complicated configuration can be expanded topologically using it. The multifunctional structure element can carry loads since it has strong frames and plates. In addition, it also can be seen as a power system for the polymer lithium battery inside it. That is to say, the structural function and the power system have been integrated into an element. The viscoelastic components dissipate the mechanical energy when the deformations of the viscoelastic components occur.

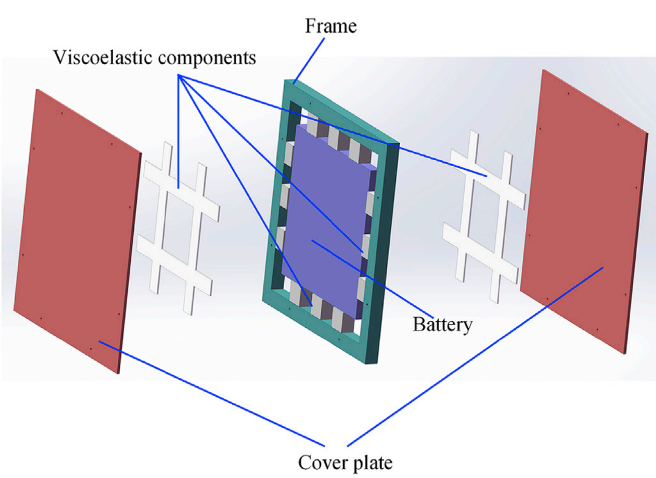

Fig. 1. Multifunctional structure.

Table 1
Physical parameters of T300.

Items	Value
Young's modulus E_x (GPa)	52.6
Young's modulus E_y (GPa)	50.6
Poisson ratio	0.3
Shear modulus G_{xy} (GPa)	4.76
Density (g/cm^3)	1.5

Table 2
Physical parameters of VPDMS and PMHS.

Physical property	VPDMS	PMHS
Appearance	Ivory-white and semilucent	Transparent
Density (g/cm^3, 25 °C)	1.1	0.98
Viscosity (Pa. S, 25 °C)	33	0.03
Mixing mass ratio	100	4

2.2. Dynamic modelling

In order to carry out the dynamic modelling of the multifunctional structure shown in Fig. 1, the coordinate system should be defined firstly, as given in Fig. 4. In Fig. 4, the origin O is located at the geometric center, which is also the mass center due to the structural symmetry of the multifunctional structure. The OX and OY axes are defined along the frame directions and in the plane paralleled to the cover plates. The OZ axis satisfies the right-handed coordinate system with the OX and OY axes.

As is seen in Fig. 4, the length and the width of the multifunctional structure are much larger than the thickness. And the movement of Z direction of the battery is restricted by the upper and lower plates. In addition, the loads sustained by the multifunctional structure are mainly in the XOY plane. And compared with X and Y directions, the displacement of the battery at Z direction can be ignored.

Since the movements of the viscoelastic components are mainly in the XOY plane, the cover plates are ignored in the modelling process. Thus, we only focus on the dynamic behaviors of X and Y directions in present paper. The battery has a large stiffness, so it is considered as a rigid body. In addition, compared to the damping of the viscoelastic components, the damping of T300 composite material can be ignored.

In the dynamic modelling stage, the multifunctional structure is classified as two assemblies: one is the viscoelastic components and one is the other components. According to the finite element theory and the above analysis, the dynamic model of the structure without the viscoelastic components can be written as [44,45].

$$\mathbf{M}_{\mathrm{no-vis}}\ddot{\boldsymbol{\delta}}_{\mathrm{no-vis}} + \mathbf{K}_{\mathrm{no-vis}}\boldsymbol{\delta}_{\mathrm{no-vis}} = \mathbf{F}_{\mathrm{no-vis}} \tag{1}$$

where $\mathbf{M}_{\mathrm{no-vis}}$ is the mass matrix without the viscoelastic components, $\mathbf{K}_{\mathrm{no-vis}}\mathbf{k}$ is the stiffness matrix without the viscoelastic components, $\boldsymbol{\delta}_{\mathrm{no-vis}}$ is the displacement vector of the nodes without the viscoelastic components, and $\mathbf{F}_{\mathrm{no-vis}}$ is the force vector of the nodes without the viscoelastic components. Note that there is no damping item in Eq. (1).

For the viscoelastic components, their stiffness matrix is computed by FVE model. Therefore, the dynamic model of the viscoelastic components can be given analogously as

$$\mathbf{M}_{\mathrm{vis}}\ddot{\boldsymbol{\delta}}_{\mathrm{vis}} + \mathbf{K}_{\mathrm{vis}}\boldsymbol{\delta}_{\mathrm{vis}} = \mathbf{F}_{\mathrm{vis}} \tag{2}$$

where $\mathbf{M}_{\mathrm{vis}}$ is the mass matrix with the viscoelastic components, $\mathbf{K}_{\mathrm{vis}}$ is the stiffness matrix with the viscoelastic components which is decided by FVE model, $\boldsymbol{\delta}_{\mathrm{vis}}$ is the displacement vector of the nodes with the viscoelastic components, and $\mathbf{F}_{\mathrm{vis}}$ is the force vector of the nodes with the viscoelastic components. Accord to the knowledge of the structural dynamics, the stiffness matrix $\mathbf{K}_{\mathrm{vis}}$ can be given as [51].

$$\mathbf{K}_{\mathrm{vis}} = \frac{S}{L}\boldsymbol{\sigma}_{\mathrm{FVE}}(\boldsymbol{\varepsilon})\boldsymbol{\varepsilon}^{-1} \tag{3}$$

where S is the equivalent area of deformation, L the equivalent length of deformation, $\boldsymbol{\sigma}_{\mathrm{FVE}}(\boldsymbol{\varepsilon})$ is the stress tensor of FVE model, and $\boldsymbol{\varepsilon}$ is the strain tensor. It can be seen from Eq. (3) that the stress tensor $\boldsymbol{\sigma}_{\mathrm{FVE}}(\boldsymbol{\varepsilon})$ is a nonlinear function of the strain tensor $\boldsymbol{\varepsilon}$. FVE model is provided in our previous paper ([1]) and its mathematical expressions are supplied as follows