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Monitoring multi-axial vibrations of flexible rockets using sensor-instrumented reference strain structures

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ABSTRACT

Strain sensors (e.g., fiber optic strain sensors) can be used to measure the deformation of flexible rockets during launches, in order to monitor and control rocket flight attitude. In this paper, strain sensors are instrumented on multi-axial reference strain structures for a convenient monitor of rocket bending vibrations. The reference strain structures are attached longitudinally along the outer surface of thin-walled flexible rockets. As the medium between the sensors and rocket, the structural design of the reference strain structures, as well as the sensor spacing along them, is optimized using an integrated multi-objective optimization approach, which ensures that the reference strain structures will accurately track the deformation of the rocket surface. In addition, kinematic equations are developed to allow for an accurate prediction of the bending deflection of the rocket center axis by using the strain data measured on the rocket surface. Finally, the performance of the optimal reference strain structure is evaluated using different numerical simulations of the flexible rocket.

1. Introduction

In current launch vehicle attitude control systems, inertial measurement units (IMU) are used to measure the rigid-body kinematics of a rocket [1]. The data that IMUs can measure are still limited. In particular, the bending vibration of flexible rockets needs to be accurately monitored and considered in rocket attitude control. Recently, Fiber Optic Strain Sensors (FOSS) based on Fiber Bragg Grating have been used to measure the distributed strain of aerospace structures, such as rocket bodies and flexible aircraft wings [2–4]. One of the advantages of using FOSS arrays for measurement is their capability of providing a reliable sensitivity to strains of mechanical structures [5,6]. Another advantage of FOSS arrays is their small cost in weight. FOSS arrays are lightweight and may be embedded at various locations of a structure without a large weight penalty. Recent applications of FOSS arrays in aerospace structures include direct measurement of structural strains/temperatures or structural health monitoring [2–4,7]. At the same time, with the advent of FOSS array interrogation systems that have a wide bandwidth of more than 1,000 Hz [8], integration of attitude control systems of flexible rockets with FOSS arrays becomes possible. In such systems, FOSS arrays may not only provide the ability to observe the rocket deformation through strain measurements, but also potentially facilitate the vibration control of the flexible structure using the measured data.

In doing so, a method is needed to improve the bending monitoring along flexible rockets with proper and convenient implementation of the fiber optic strain sensors. Even though there are advantages of applying fiber optic strain sensors for monitoring the bending vibrations of flexible rockets, it becomes obviously inconvenient to directly install the sensors on the rocket surface. To address the convenience of operation and maintenance, an indirect measurement approach can be considered. In this work, a modular design of the reference strain structures (RSS) has been considered. Fiber optic strain sensors are instrumented on the reference strain structures, which are further attached to the rocket surface. Obviously, the concept of reference strain structures is implemented to provide spanwise placement freedom for the sensors. The fiber optic sensors directly measure strains of the reference structures. This measurement is used to indirectly track the real bending/torsional curvatures of the rocket surface. Therefore, in order for this measurement to function reliably and properly, the placement of reference structures and fiber optic sensors needs to be properly

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Nomenclature

A	Cross-sectional area of rocket	m^2
$\boldsymbol{A_u}, \boldsymbol{A_v}$	Coefficient matrices of shifted Legendre polynomials	
b	Width of RSS beam	m
d	Uniform sensor spacing on each RSS beam	m
E	Young's modulus	GPa
f_i	Optimization objective function	
G	Shear modulus	GPa
h	Thickness of RSS beam	m
I	Moment of inertia	m^4
l	Longitudinal linkage spacing between RSS beams and rocket	m
n_{sensor}	Number of sensors on each RSS beam	
$\boldsymbol{P}$	Shifted Legendre polynomials	
p	Order of Legendre polynomials	
r	Radial linkage spacing between RSS beams and rocket	m
S_{BX}, S_{BY}, S_θ	Bending and torsional sensitivities	
$\boldsymbol{u}$	Bending deflection in the x direction	m
$\boldsymbol{v}$	Bending deflection in the y direction	m
x_d	Design variable for RSS design optimization	
x_s	Design variable for sensor placement optimization	
ε_0	Measured strain from 0-degree oriented sensor	
ε_{45}	Measured strain from 45-degree oriented sensor	
ε_{axial}	Axial strain, from FE simulation	
ε_{BX}	Bending strain about the x axis, processed from sensor measurement	
ε_{BY}	Bending strain about the y axis, processed from sensor measurement	
ε_s	Shear strain of each RSS beam, processed from sensor measurement	
ε_{xy}	Shear strain, from FE simulation	
ε_s^{ref}	Average shear strain of RSS beams	
ε_0^{ref}	Axial strain of rocket reference axis (positive compressive)	
η	Modal coordinate	
θ	Angular spacing between each RSS beam	
$\kappa_x, \kappa_y, \kappa_z$	Bending curvatures about the x and y axes and twist curvature about the z axis	
ν	Poisson's ratio	
ρ	Material density	kg/m^3
φ	Linear mode shape	
ω	Natural frequency	Hz

designed and optimized to ensure precise vibration monitoring with the sensor measurements.

Even though studies of accurate and efficient strain/temperature sensing and structural health monitoring with fiber optic strain sensors have been performed [2–7], a reliable method to incorporate such sensors for the application of shape or vibration monitoring of aerospace structures have not been fully explored. Therefore, it is opportune to study and prove the feasibility of FOSS for vibration monitoring applications. In a previous study, a real-time beam bending solution [9] was developed by Su et al. to obtain the instantaneous beam kinematics based on the measurement data from discontinuous FOSS along the beam and a single IMU. Additionally, an algorithm was developed to decouple the combined strain information measured by the FOSS on a beam structure into extensional strain, twist curvature, and bending curvatures [10]. By combining this with the real-time beam bending solution, it enables one to predict deflections of the flexible rocket along the center axis based on the measured strains on the rocket surface.

Since previous studies regarding real-time simulation and control system development using FOSS [8,9] have focused on a scaled beam model, this paper targets to explore how such strain sensors work with full-size flexible rockets using the concept of reference strain structures. While most of the studies involved in this paper will be applicable to other types of sensors, FOSS are considered to be applied for the strain measurement of flexible rockets. To carry out these studies, a full-size flexible rocket with modular reference strain structures will be modeled as a platform for further structural dynamic and control studies. Based on the finite-element model, the first objective of this study is to design and optimize the reference strain structures, with the intent of accurately observing bending deformations of flexible rockets through the indirect measurement. Although the main target of the strain sensor instrumented on RSS is to provide an accurate bending vibration monitoring of the flexible rocket, it is also capable of observing the torsional deformation. Second, the feasibility of the optimal reference strain structure will be demonstrated by evaluating its ability to capture the strain of a flexible rocket. Third, several parameters (such as the sensor placement on the RSS) involved in the prediction of the bending deformations will be optimized to obtain the most accurate estimations out of the RSS-sensor system. Last, transient simulations of the flexible rocket will be performed to evaluate the performance of the optimum reference structure with properly instrumented strain sensors, in terms of the accuracy of its prediction of the bending deflections of the rocket center axis.

Table 1
Wall thickness of each section of the notional rocket.

Rocket section	Thickness (m)
Fairing	0.015
Payload	0.005
Centaur tanks	0.012
ISA	0.005
Oxygen tank	0.005
Fuel tank	0.005
Booster and sustainer	0.01

2. Structural analysis model

In the structural analysis of the current study, a finite-element (FE) model of a notional flexible rocket with multi-axial RSS beams is created in MSC.Patran, based on the published information of the Atlas Centaur Surveyor launch vehicle [11]. Fig. 1 shows the breakdown of the rocket sections. The geometric and material properties are obtained from Ref. [11] and additional reports [12,13]. The rocket model has two main components: the conical fairing and the remaining cylindrical body. CQUAD4 shell elements are used to mesh the cylindrical surface of the rocket model, with 640 and 72 elements in the longitudinal and circumferential directions, respectively. Weight and rigidity distributions of the shell elements are referred to the data in Ref. [11], with all tanks being empty. However, the properties are uniform in each section for simplicity, as shown in Figs. 2 and 3. The thickness of the shell elements in each section is assigned according to Table 1. The Poisson's ratio $\nu = 0.33$ is used for the materials of all sections. Internal tank pressures are applied on oxygen/fuel tanks and the Centaur tank in the following studies, where the values of the pressure are obtained from the lift-off testing described in Ref. [11].

As shown in Fig. 4, an array of three RSS beams is attached to the outer surface of the rocket along the longitudinal direction through rigid links, which separate from each other by 120° along

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