Dynamics Modeling and Simulation of Korean Communication, Ocean, and Meteorology Satellite

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Abstract

COMS (Communication, Oceanography, and Meteorology Satellite) is the first Korean multi-purpose satellite which is planned to be deployed at the altitude of geosynchronous orbit above the Korean peninsular. Noting that COMS is composed of the main BUS structure, two deployable solar panels, one yoke, five reactions wheels, COMS is treated as a collection of 9 bodies and its nonlinear equations of motion are obtained using the multi-body dynamics approach. Also, a computer program is developed to analyze the COMS motion during the various mission phase. Quite often, the equations of motion have to be derived repeatedly to reflect the fact that the spacecraft dynamics change as its configuration, and therefore its degree of freedom varies. However, the equations of motion and simulation software presented in this paper are general enough to represent the COMS dynamics of various configurations with a minimum change in input files. There is no need to derive the equations of motion repeatedly. To show the capability of the simulation program, the spacecraft motion during the solar array partial and full deployment has been simulated and the results are summarized in this paper.

Key Words : Satellite attitude motion, Multi-body dynamics, Nonlinear Simulation, Solar array deployment

Introduction

High fidelity modeling and simulation capability of a spacecraft attitude dynamics is very important for every stage of satellite systems development. In many cases the spacecraft attitude controller design is based on the relatively simple model of spacecraft dynamics but its performance is verified through the nonlinear simulation studies. The required level of modeling fidelity is quite different depending upon the purpose of use and the maturity of development stage.

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A simple rigid body model would be sufficient for the purpose of obtaining attitude control laws or estimator design. But their performance verification should be desirably based on the more complicated model which reflects the spacecraft configuration and mass properties very precisely. This process implies that the mathematical model, i.e., equations of motion have to be derived repeatedly, and this process is prone to the unintended error. Therefore, this warrants the development of a generic model for the spacecraft attitude dynamics and a general-purpose nonlinear simulation software.[1,2]

The purpose of this paper is to present the procedure of obtaining the equations of motion of a generic multi-body system of arbitrary configuration and apply it to the simulation of COMS (Communication, Oceanography, and Meteorology Satellite) spacecraft attitude motion. This paper is organized as follows. In Section 2 the equations of motion are formulated using the tree-type multi-body system, and then they are applied to the COMS dynamics modeling in the section followed. Finally, the simulation results of partial and full solar array deployment procedure are presented.

Multi-Body Dynamics

2.1 Multi-body system topology

Referring to the generic multi-body system shown in Fig. 1 an arbitrary body is chosen as a base body. If the system contains any closed loop, then one of the joints in each loop may be cut so that the entire system consists of "chain" or "open" tree configurations only. The system topology or configuration can be easily described using the concept of the path matrix and reference body operator.[3]. An inboard body connected to the body j is defined as the one leading to the base body and outboard body as the one leading away from the base body. If the position and attitude of body j is referred to its inboard body, then the body j' s inboard body is also called as the body j' s reference body. In this way, the whole system configuration and kinematics, such as how they are connected to each other and how its motion is described, can be effectively defined.

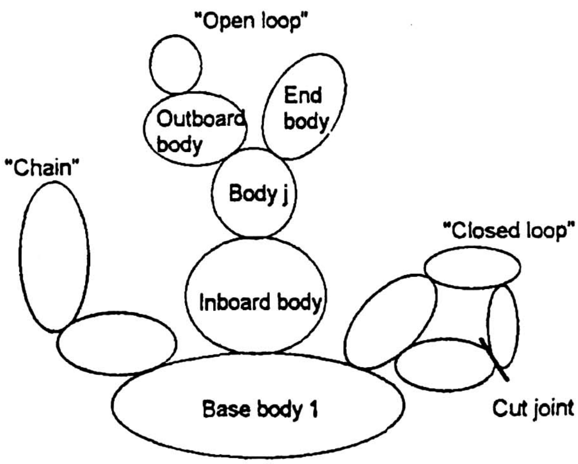

Fig. 1. Generic multi-body system

2.2 Formulation of equations of motion

While Newton−Eulerian mechanics have been used successfully for decades to obtain the equations of motion of s single or multi−body system, the Lagrangian approach is also favored by many who seek to use computer aided automatic generation of generic equations of motion. No matter what formalism is used, the final outcome is the equations of motion in the form of

$$\boldsymbol{M}\ddot{x} = \boldsymbol{f}(x, \dot{x}, t), \tag{1}$$

where $\boldsymbol{M}$ is the generalized mass matrix, $\boldsymbol{x}$ is the vector of generalized coordinates Eq. (1) is augmented by a set of additional constraint equations,

$$\boldsymbol{A}\dot{x} = \boldsymbol{g}(x, t), \tag{2}$$

in order to reflect the possible relative motion between bodies , which is mainly due to the type of joints that connect each body. In some case, one of bodies may have a prescribed motion.

In this paper, referring to Fig. 2, Newton' s laws of motion are used to obtain the equations of body k' s absolute translational and rotational motions, and they are written as follows:

$$\begin{bmatrix} m_k & (\tilde{r}_{kc}C_k)^T \\ \tilde{r}_{kc}C_k & I_k \end{bmatrix} \begin{bmatrix} \ddot{R}_k \\ \dot{\omega}_k \end{bmatrix} = \begin{bmatrix} F_k^e + F_k^c + F_k^i \\ M_k^e + M_k^c + M_k^i \end{bmatrix}, \tag{3}$$

where

m_k, I_k = mass and inertia matrix of body k,
$\tilde{r}_{kc}$ = position vector of body k' s mass center in its body−fixed frame,
R_k = absolute position vector of the body k' s reference point,
ω_k = absolute angular velocity vector of body k
C_k = direction cosine matrix
F_k^e, F_k^c, F_k^i = external, internal, constraint force vectors acting on body k
M_k^e, M_k^c, M_k^i = external, internal, constraint moment vectors acting on body k

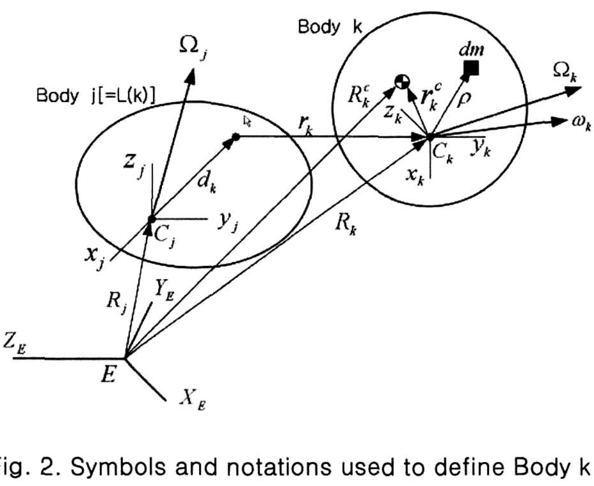

Fig. 2. Symbols and notations used to define Body k

For a multi−body system consisting of n bodies, we may stack up Eq. (3) to get the equations of motion at the system level as

$$\boldsymbol{M}\ddot{\boldsymbol{x}} = \boldsymbol{F} + \boldsymbol{F}^c , \tag{4}$$

where $\boldsymbol{M}$ is the generalized mass matrix, $\boldsymbol{x}$ is the generalized coordinate vector, $\boldsymbol{F}$ is the generalized force vector, $\boldsymbol{F}^c$ is the generalized constraint force vector. One should note that $\boldsymbol{F}^c$ is unknown and due to the bodies that are attached to the body k. The unknown constraint force vector $\boldsymbol{F}^c$ is related to the constraint equation that defines the possible motion of the system. It is shown that one can relate the constraint force $\boldsymbol{F}^c$ to the constraint matrix $\boldsymbol{A}$ in Eq. (2) using the concept of Lagranian multiplier vector $\boldsymbol{\lambda}$ as in below [4,5],

$$\boldsymbol{F}^c = -\boldsymbol{A}^T\boldsymbol{\lambda} , \tag{5}$$

Then, Eqs, (2) and (5) can be combined and written as

$$\begin{bmatrix} \boldsymbol{M} & \boldsymbol{A}^T \\ \boldsymbol{A} & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{x}} \\ \boldsymbol{\lambda} \end{bmatrix} = \begin{bmatrix} \boldsymbol{F} \\ \dfrac{\partial \boldsymbol{g}}{\partial t} + \dfrac{\partial \boldsymbol{g}}{\partial \boldsymbol{x}}\dot{\boldsymbol{x}} - \dfrac{\partial \boldsymbol{A}}{\partial t}\boldsymbol{x} + \dots \end{bmatrix} , \tag{6}$$

COMS Dynamics Modeling

3.1 COMS Mission and Configuration

The COMS satellite is the geostationary three−axis body−stabilized platform which can support three main missions such as meteorological service, ocean monitoring, and satellite communication. Figure 3 shows its concept of operation. COMS mission phase is further decomposed into first orbit sequence, boost phase, acquisition phase, and on−station phase. Especially during the first orbit phase, the COMS undergo several configuration changes as shown in Fig. 4.

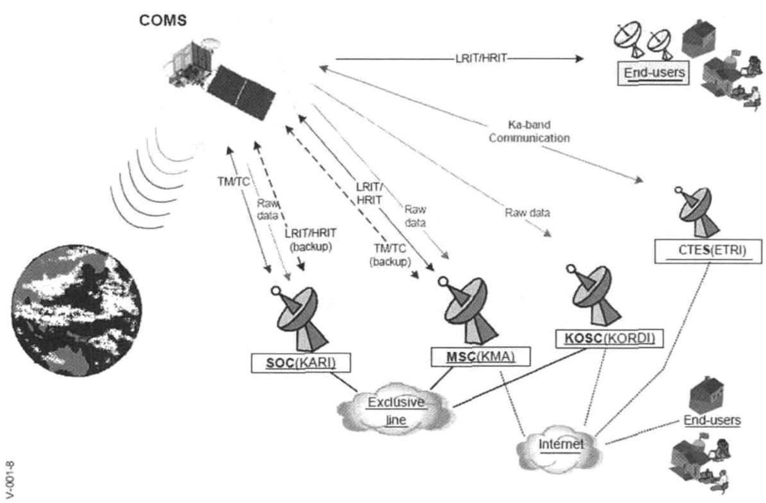

Fig. 3. COMS Concept of Operation

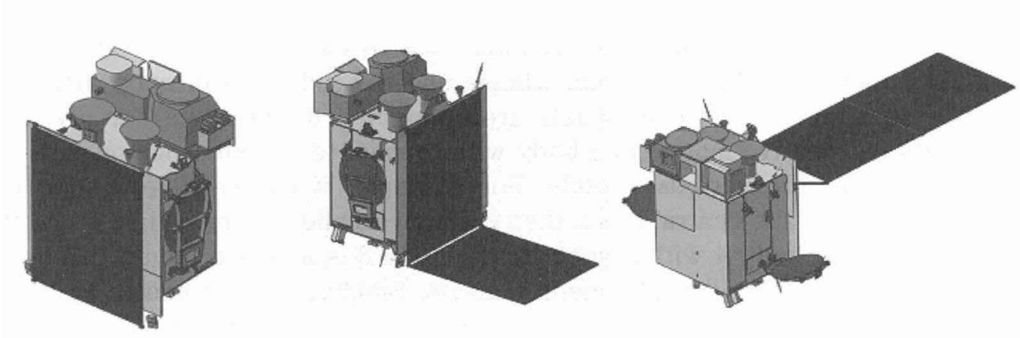

Fig. 4. COMS Configuration Change during the First Orbit

Although a simple rigid body model can be used to represent the COMS dynamics with appropriate consideration of its mass property change, accurate prediction of the spacecraft motion, for example, during solar array deployment is inherently impossible with such a simple model. Furthermore, the COMS uses 5 reaction wheel for its attitude control when it enters into the on-station mode. Obviously, a single rigid body model is not sufficiently enough to model the COMS attitude dynamics. Therefore, one needs to repeatedly work on obtaining the dynamics model which is adequate only for a particular purpose if a generic mathematical representation of the COMS dynamics is not available.

3.2 COMS Modeling

The COMS satellite is basically a typical, open tree-type multi-body system which is composed of 9 bodies as shown in Fig. 5. However, during the launch phase, each body' s motion is constrained and therefore the whole spacecraft can be treated as a single rigid body. Two-body model may be appropriate during the transfer phase while four-body model must be used for the analysis of full solar array deployment. Once all the reactions wheel start operating and the solar array is locked into its position, a single rigid body model can not used any more. It is why the generic multi-body model is necessary if one wants to preserve the consistency in the spacecraft dynamics model.

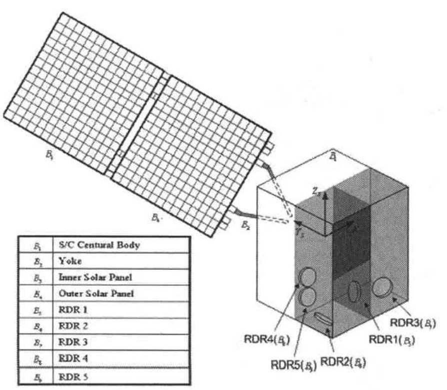

Fig. 5. COMS Configuration

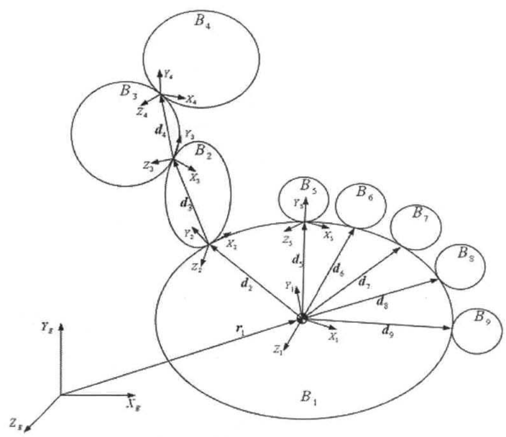

Fig. 6. Multi-body Representation of the COMS satellite

Figure 6 depicts the multi−body model which may be used for all phases of the COMS operation. Five reactions wheels and the yoke are directly attached to the main structure. Two solar panels are connected to the yoke serially. If one constraints the relative motion of a body with respect to its reference or inner body it can represent the various models. For example, if the relative motion of all outboard bodies of the central body, then it simply implies a single rigid body. If the relative motion of body 4 with respect to the body 3 is allowed, then it can be used for the solar array partial deployment analysis. Similarly, if the bodies 2, 3, and 4 are allowed to move, solar array full deployment can be simulated.

Simulation Examples

4.1 Nonlinear Simulation S/W Development

Based on the equations motion in Section 2, a high fidelity nonlinear simulation code, COMSIM, has been written in FORTRAN and its overall structure is shown in Fig. 7. COMSIM is composed of five modules and only "Model Definition Module" needs to be modified depending on the type of spacecraft configuration and scenario to be simulated.

4.2 Simulation Examples and Discussions

During the first orbit after the COMS is separated from the launch vehicle, the attitude control system is automatically initialized to Sun acquisition by the onboard computer. Then, the solar array is partially deployed in order to secure the electrical power needed for the next sequences. Often, the solar array deployment is managed as a single point failure event since there is no alternative. Precise prediction of the spacecraft attitude during and after the solar array deployment is very important.

For simulation of the solar array partial deployment, the spacecraft was treated as two−body system which is composed of the main structure and the outer solar array as shown in Fig. 5. Other bodies such as the yoke and etc. are assumed to be the integral part of the main structure. In the sense of the system constraint equations, this can be easily accomplished by constraining all the relative motions between bodies.

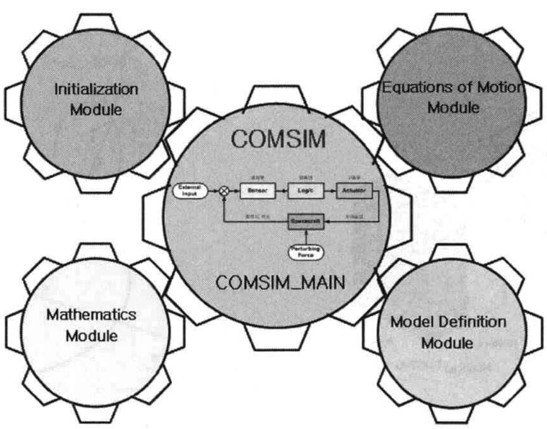

Fig. 7. COMSIM Overall Structure

As for the deployment mechanism, a pre-loaded spring-damper is used as shown in Fig. 8. The deployment torque induced by the spring-damper mechanism can be written as

$$T = k(\theta - \theta^{*}) + c\dot{\theta}, \tag{7}$$

where k and c are adjusted to control the speed and deployment time, and θ^{*} denotes the reference angle when the solar array deployment is completed.

Figure 9 depicts the snap-shots of the solar array partial deployment. One easily sees that the deployment is being successfully carried out. Figures 10 and 11 show the time histories of the kinetic and potential energy. At the beginning, the potential energy is dominant due to the pre-loaded spring-mass deployment mechanism. As the deployment proceeds, the kinetic energy builds up and eventually dies out at the end of deployment due to the damper. One may note that the solar array is rapidly deployed around 5 seconds.

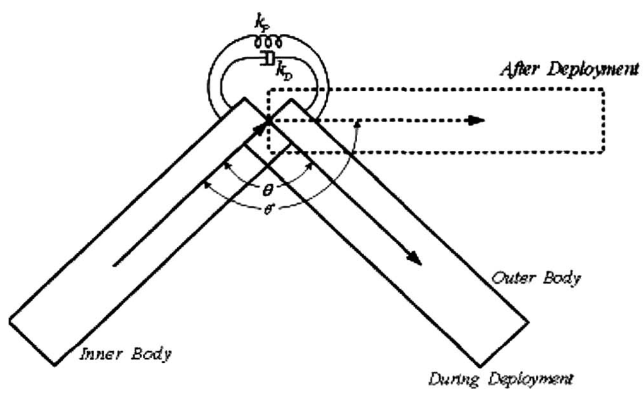

Fig. 8. Solar Array Deployment Mechanism

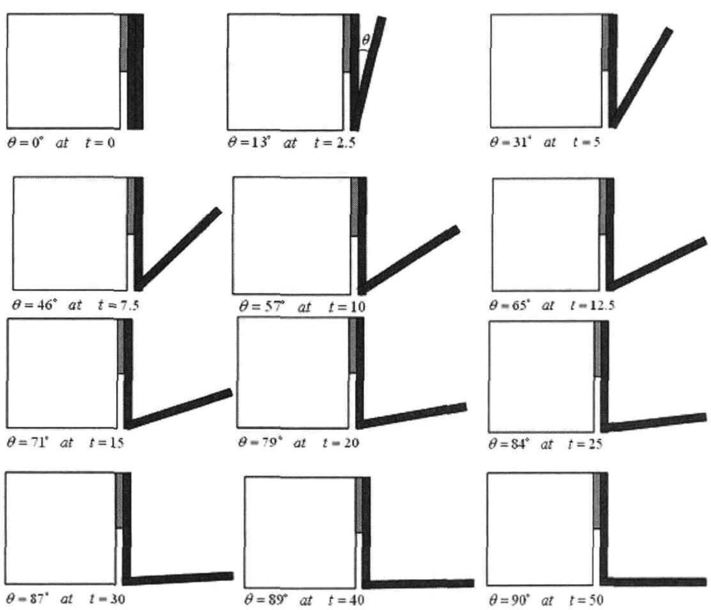

Fig. 9. COMS Configuration during Partial Deployment

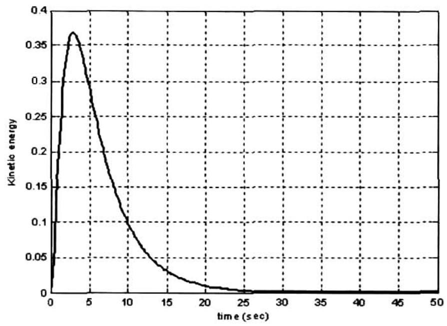

Fig. 10. Kinetic Energy Change During Deployment

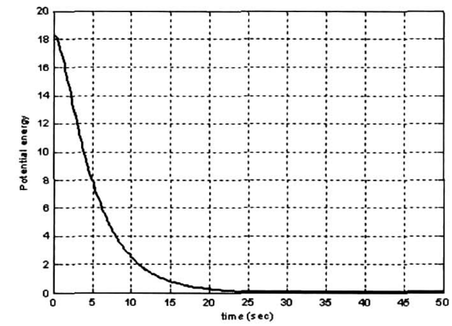

Fig. 11. Potential Energy Change During Deployment

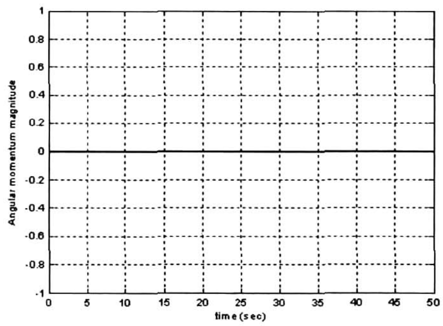

Fig. 12. Angular Momentum Change During Deployment

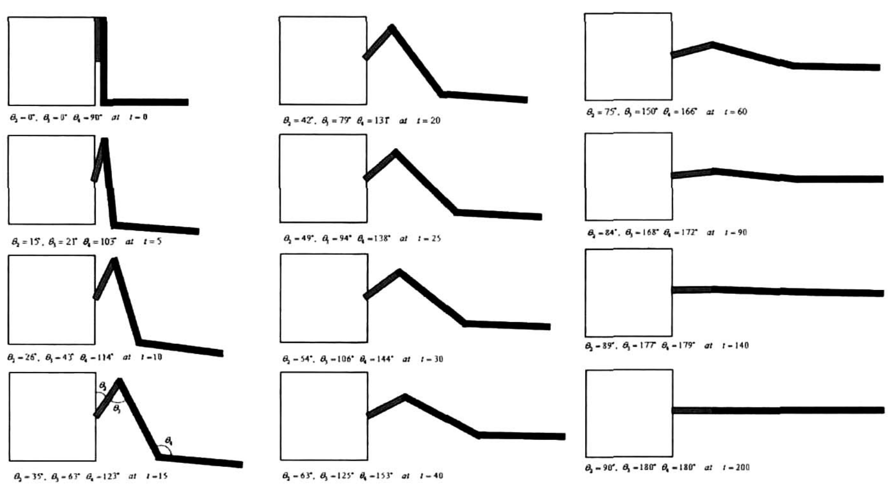

Fig. 13. COMS Configuration during Full Deployment

Many concerns in this kind of simulation are such as 1) are the equations of motion correctly derived ?, 2) is the simulation code reliable? As an indirect way of checking the simulation code, the system angular momentum was monitored during the deployment in this particular example. Since the deployment torque is internal and there is no further external torque and force acting on the spacecraft, it is expected that the system total angular momentum is preserved. Figure 12 supports such expectation.

After the partial deployment, the solar array is fully deployed. Shown Fig. 13 is the snap–shots during the full deployment. Although not shown in this paper, other important aspects of the solar array deployment such as the change in the spacecraft attitude can be easily analyzed.

Conclusions

In this paper, the COMS satellite and its mission are briefly introduced. The COMS was treated as an open–tree type multi–body system and rather general–purpose equations of motion were derived. A nonlinear simulation code based on the general equations of motion is used to simulate the spacecraft motion during the solar array deployment and the simulation results are presented.

Acknowledgments

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