The Journal of Undergraduate Research

Volume 4 *Journal of Undergraduate Research, Volume 4: 2006* | Article 8

2006

Virtual Prototype of Shuttle Bay Door

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ABSTRACT

This study analyzed the motion of the Space Shuttle free floating in space after one of its bay doors is opened and closed. Kane's method and Autolev motion simulation software were used to carry out simulation and analysis. The Space Shuttle has two large bay doors that open simultaneously, but for our study we analyzed a hypothetical situation, in which only one door functioned properly, in order to achieve amplified results. To model this system we used a rigid body to resemble the Shuttle and an attached rotating flap to resemble the door. Since the Shuttle is free floating in space with no external forces, the rigid body has six degrees of freedom. The rotating flap has one degree of freedom, therefore giving the system a total of seven degrees of freedom. Through the use of Autolev dynamic analysis software, we were able to program the system to output codes compatible with Matlab in order to graph the motion of the multibody system.

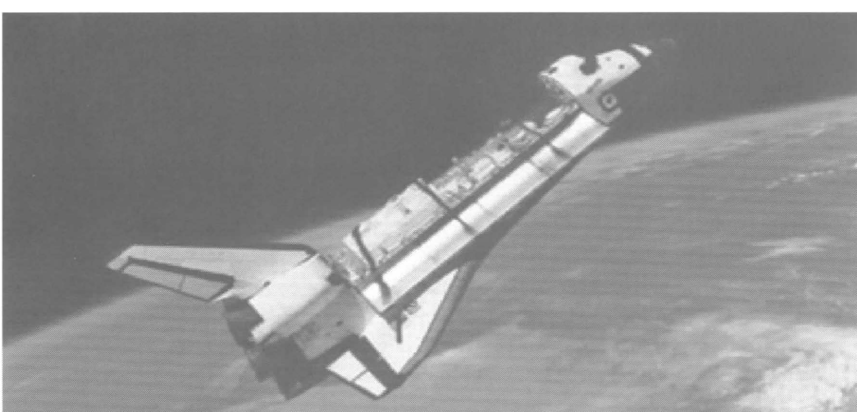

Figure1: Picture of a space shuttle bay door

INTRODUCTION

Putting hardware into space is an important task for our way of life. Satellites of all kinds allow people to do scientific research, communicate and do many other vital things that keep our society running. However, the act of putting hardware into space is difficult and costly. In the case of physical testing of dynamic behavior of large mechanical systems [1; 2], for example, the deployment and manoeuvring of large spacecraft, system size, the presence or absence of gravity, presence of temperature and the atmosphere all contribute to make testing of full scale hardware unmanageable and expensive. Here accurate, efficient and affordable computer simulation is indispensable.

In addition, what most people don't realize is that once a piece of equipment has been put into space, it must also be controlled. Controlling consists of keeping the spacecraft on a designated orbit. The problem with keeping the spacecraft in control is that there is no gravity. The spacecraft is thus subject to uncontrollable tumbling along its three axes. Thrusters are used keep the craft in control and in orbit. Fortunately, this complicated control procedure can also be simulated virtually on a computer at less cost.

OBJECTIVE

Simulate and analyze the motion of a particular object in space. Specifically, the space shuttle when one of its large bay doors open. The space shuttle has two large payload doors that open to allow access. The doors are designed to open simultaneously in order offset each other's motion. In order to magnify the motion of the shuttle, we created a hypothetical situation in which only one of the doors open. Similar malfunctions could occur on other spacecraft; for example, if a satellite had twin solar arrays and one was to jam when operating. The purpose being that a realistic situation would be analyzed virtually before costly physical prototyping is carried out.

KANE'S EQUATIONS

In the last fifty years, improvements in the speed and memory of computers have been enormous. These improvements were required for progress in the discipline of multi- rigid-body dynamics. Because of the increased computing power it is possible to promote the theories and, especially in the last years, to write large and fast computer software to simulate and analyze the dynamic behaviors of complex and large-size mechanical systems at less cost.

But in spite of all the improvements in the computer hardware, software, and theories in multibody dynamics, the requirements are always higher than the actual achieved effort. This is not surprising because humanity has always had the need to improve the achieved results to increase the living standard, safety, and knowledge. It was a great success when Neil Armstrong, Michael Collins, and Edwin Aldrin landed on the moon in 1969. Although it doesn't matter how big the success was, the requirements for today's space explorations are much higher. Nowadays the software has to deal with complex real-time applications. To accomplish these, it is necessary to have more efficient computer software than before because computer software is developed from algorithms and theories that the algorithms are based on. The best way to write fast computer software is to have an effective theory, which has enough power to solve the demands. Another requirement for software is that it is algorithmic or in other words, easy for the programmer to write powerful programs. If this isn't possible, then it becomes unrealistic to write complex programs in an acceptable period of time.

Kane's method [3] could fulfill these conditions. Kane's method can be viewed as an automated version of the Motion Law, where no analysis is required to produce a minimal set of dynamic equations in which workless constrained forces can be automatically eliminated. The key concept underlying Kane's method is that of generalized speeds, partial velocities, and partial angular velocities. The symbol manipulation program AUTOLEV, was created expressly to facilitate motion analyses or virtual prototyping based on Kane's method.

Kane's equations for an n degree-of-freedom multibody system can be presented as:

$$F_r + F_r^* = 0 \qquad (r = 1,\ldots,n) \tag{1}$$

$$F_r^* = \sum_{k=1}^{N} (\vec{\omega}_r^{B_k} \cdot \vec{T}^{B_k^*} + \vec{v}_r^{\bar{B}_k} \cdot \vec{R}^{\bar{B}_k^*}) \qquad (r = 1,\ldots,n) \tag{2}$$

$$F_r = \sum_{k=1}^{N} (\vec{\omega}_r^{B_k} \cdot \vec{T}^{B_k} + \vec{v}_r^{\bar{B}_k} \cdot \vec{R}^{\bar{B}_k}) \qquad (r = 1,\ldots,n) \tag{3}$$

$$\vec{R}^{\bar{B}_k^*} = -m^{B_k} \vec{a}^{\bar{B}_k} \tag{4}$$

$$\vec{T}^{\bar{B}_k^*} = -\bar{\bar{I}}^{\bar{B}_k} \cdot \vec{\alpha}^{B_k} - \vec{\omega}^{B_k} \times \bar{\bar{I}}^{\bar{B}_k} \cdot \vec{\omega}^{B_k} \tag{5}$$

$$\vec{\omega}^{B_k} = \sum_{r=1}^{n} \vec{\omega}_r^{B_k} u_r + \vec{\omega}_t^{B_k} \tag{6}$$

$$\vec{v}^{\bar{B}_k} = \sum_{r=1}^{n} \vec{v}_r^{\bar{B}_k} u_r + \vec{v}_t^{\bar{B}_k} \tag{7}$$

$$u_r \overset{\Delta}{=} \sum_{s=1}^{n} Y_{rs} \dot{q}_s + Y_r \qquad (r = 1,\ldots,n) \tag{8}$$

$$\dot{q}_i = \sum_{s=1}^{n} X_{is} u_s + X_i \qquad (r = 1,\ldots,n) \tag{9}$$

where, by definition:

$\vec{\omega}_r^{B_k}$ is the r[th] partial angular velocity of body k respect to q_r in inertia frame.

$\vec{\omega}_t^{B_k}$ is the partial angular velocity of body k respect to time t in inertia frame.

$\vec{v}^{\bar{B}_k}$ is the r[th] partial velocity of mass center of body k respect to q_r in inertia frame.

$\vec{v}_t^{\bar{B}_k}$ is the partial velocity of mass center of body k respect to time t in inertia frame.

n is the number of degree of freedom of multibody system.

$\vec{R}^{\bar{B}_k}$ is the resultant force acting on the mass center of body k.

$\vec{T}^{B_k}$ is the resultant moment acting on body *k*.
m^{B_k} is the mass of body *k*.
$\vec{\vec{I}}^{\bar{B}_k}$ is the tensor of inertia of body *k*.
F_r represents the rth generalized active forces acting on the multibody system.
F_r^* represents the rth generalized inertia forces acting on the multibody system.
Y_{rs}, Y_r, X_{is}, X_j, $\vec{\omega}_r^{B_k}$, $\vec{\omega}_t^{B_k}$, $\vec{v}^{\bar{B}_k}$, $\vec{v}_t^{\bar{B}_k}$ are all the function of $q_1, \ldots, q_n$ and *t*.

At the homepage of the National Aeronautics and Space Administration (NASA), it is described that NASA also uses the Kane's Method for special applications. One application is called A "Kane's Dynamics" Model for the Active Rack Isolation System. Their research leaded to following conclusion: Kane's method appears in general to be distinctly advantageous for complex problems. As a rule, of the above approaches (momentum principles, D' Alembert's Principle, Kane's Method, Hamilton's Canonical Equations, the Boltzmann-Hamel Equations, the Gibbs Equations and the Lagrange's Equations), those that lead to the simplest and most intuitive dynamical equations are the Gibbs Equations and the Kane's Equations. Of those two approaches, the latter is the more systematic and requires less labor. The reduction of labor is particularly evident when one seeks linearized equations of motion (due to the otherwise excessive algebraic burden).

Our project analyzed a space shuttle bay door according to Kane's methods and with Autolev software. The project has offered us first-hand research experience and may be helpful for promoting undergraduate research in this area.

METHOD

1. Simplified Model & Kinematical Analysis

Consider a space shuttle as shown in Figure 1. Our system can be considered as a rigid body with two different parts. To simplify the problem we have chosen to consider only one door. This system has seven degrees of freedom; four rotations and three translations.

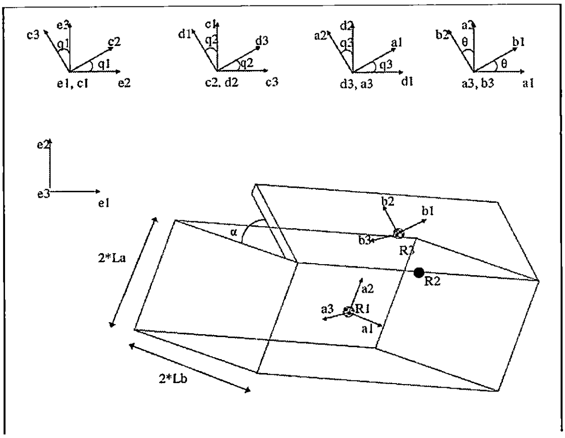

Figure 2. Scheme of the space shuttle.

$$\left.\begin{aligned} {}^{A}V^{P} &= {}^{A}V^{Q} + {}^{A}\omega^{B} \times p^{QP} \\ {}^{A}a^{P} &= {}^{A}a^{Q} + {}^{A}\omega^{B} \times ({}^{A}\omega^{B} \times p^{QP}) + {}^{A}\alpha^{B} \times p^{QP} \end{aligned}\right\} \quad (10)$$

$$\left.\begin{aligned} {}^{A}V^{P} &= {}^{A}V^{Q} + {}^{B}V^{P} \\ {}^{A}a^{P} &= {}^{A}a^{Q} + {}^{B}a^{P} + 2\,{}^{A}\omega^{B} \times {}^{B}V^{P} \end{aligned}\right\} \quad (11)$$

We have two different ways to get the velocity and acceleration of a point on the bay door body B. We can use the formulas (10) of two points fixed in a rigid body or formulas (11) one point moving on a rigid body.

We used formula (10). For example, in our derivation E is Newtonian frame and A is shuttle reference frame, ${}^{E}V^{P}$ is the velocity of the point P fixed on the bay door rotational axis, Q is a point fixed on the rotating bay door or the reference frames B, p^{QP} is the vector from point Q to P, and ${}^{A}\alpha^{B}$ is the angular acceleration of B in A.

Our system is free to move in the space, thus the equations become complicated. That is why we used AUTOLEV to solve the motion equations.

2. *Autolev Codes & Force Analysis*

In order to complete our task, we had to define the different forces acting on our system. Our system is in space so there is no gravity and only has one force acting, which is the force to open and close the door. We defined this force by the force of a spring opening or closing the door. The force to open the door is $F = -k(\theta - \frac{\pi}{2})$ with $\theta_0 = -\pi/2$ and the force to close the door is with $F = -k(\theta - (-\frac{\pi}{2}))$ with $\theta_0 = -\pi/2$.

After describing our system, we invoked AUTOLEV and created a code describing our system and defined the different equations of motion. For example: 'V2Pts (e,d,r2,do)' is used to compute the velocity of D in E with the formula of two points fixed in a rigid body.

'Kane()' is the code used to compute Kane's equation. The following are preliminary Autolev codes:

```
% project2 space shuttle
autoz on
newtonian e
frames b,c
bodies s,d
mass s=2,d=2
points o,R2
constant lb,la,k
variables teta'',x{3}'',q{3}''
motionvariables' u{7}'
simprot(e,b,1,q1)
simprot(b,c,2,q2)
simprot(c,s,3,q3)
simprot(s,d,3,teta)
w_b_e>=q1'*e1>
w_c_b>=q2'*b2>
w_s_c>=q3'*s3>
w_s_e>=w_s_e>
inertia s,3,2,4,1,-1,1
inertia d,1,1,3,0,-1,1
inertia(r2)
v_so_e>=dt(p_o_so>,e)
a_so_e>=dt(v_so_e>,e)
v_r2_e>=dt(p_o_r2>,e)
a_r2_e>=dt(v_r2_e>,e)
v2pts(e,d,r2,do)
a2pts(e,d,r2,do)
u1=dot(w_s_e>,e1>)
u2=dot(w_s_e>,e2>)
u3=dot(w_s_e>,e3>)
x1'=u1
x2'=u2
p_o_so>=x1*e1>+x2*e2>+x3*e3>
p_so_r2>=lb*e1>+la*e2>
p_do_r2>=-lb/2*d2>
x3'=u3
q1'=u4-sin(q2)*(u6*cos(q1)-u5*sin(q1))/cos(q2)
q2'=u5*cos(q1)+u6*sin(q1)
q3'=(u6*cos(q1)-u5*sin(q1))/cos(q2)
teta'=u7
torque(s/d,-K*(PI-teta)*s3>)
fr()
frstar()
zero=fr()+frstar()
kane()
```

RESULTS AND DISCUSSION

Now we can look at the different graphs we obtained from the simulations.

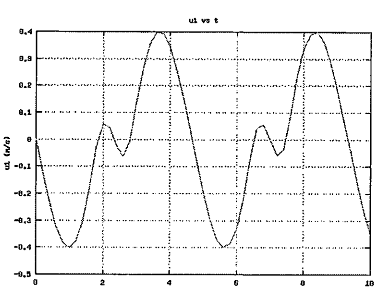

Figure 3. u1 vs. t (closing the door)

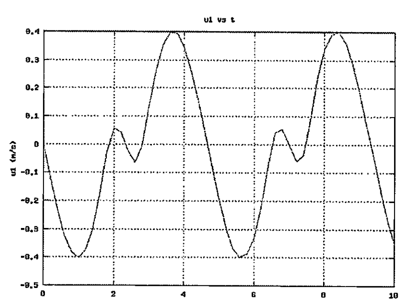

Figure 4. u3 vs. t (closing the door)

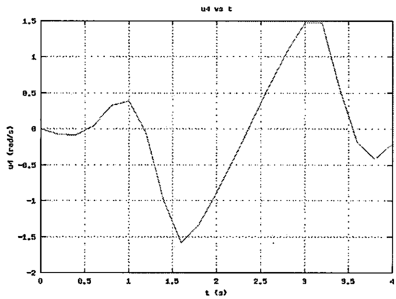

Figure 5. u4 vs. t (opening the door)

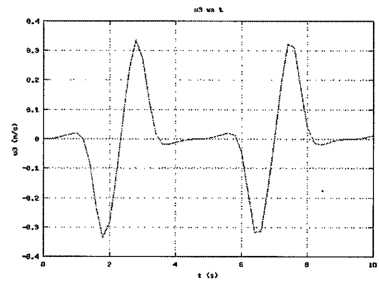

Figure 6. q1 vs. t (opening the door)

Figure 3 shows the generalized speed of the shuttle body in the e1 direction. Figure 4 represents the general speed of the shuttle body in the e3 direction. Figure 5 shows the generalized rotational speed around the e1 vector and Figure 6 represents the movement of the shuttle body in the e1 directions. These graphs define the generalized speeds and generalized coordinate of the shuttle body in space. Computing these different graphs we can see the motion of the shuttle body in space. These different graphs are useful to predict the movement of the shuttle body in space and understand what happens when the door has a spring force applied.

CONCLUSION

In light of the advancement in space technology and increased interest in space exploration, it is advantageous to be able to analyse the motion of spacecraft in a timely manner and remain competitive. Using modern motion analysis software and techniques, we were capable of simulating and analyzing movement of a rigid body in space when a spring force was applied. With the same techniques, more advanced dynamic analysis could be performed on similar spacecraft that could one day send a human to other planets.

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