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FINITE ELEMENT DESIGN OF A RESEARCH TESTBED FOR MANIPULATOR-COUPLED SPACECRAFT

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Abstract

This paper describes the design and analysis of a research testbed developed to study the control of manipulator-coupled spacecraft with independent attitude control systems. This scenario could present itself in the assembly of Space Station Freedom (SSF). SSF assembly calls for a rendezvous of the Space Shuttle (SS) with SSF. Part of the assembly process requires that both spacecraft be coupled via the Space Shuttle Remote Manipulator System (RMS). An additional criterion that poses increased complexity is that the Space Shuttle controls and Space Station controls can not communicate. The technical issue involved is unwanted vibrations of the coupled-configuration that occur during retraction and the complications due to non-interacting control systems. To understand these vibrations and possible complications, a research testbed has been built at the Marshall Space Flight Center in Huntsville, AL. To build the testbed, the manipulator links, joints, and vehicles that represent the Space Shuttle and Space Station had to be designed. The goal of this paper is to provide NASA with an analytic preliminary design of the testbed. This paper presents a method for the finite element design of the links based on natural frequencies and verification of the design method. The finite element design was performed using a commercially available computer code called ANSYS. The ANSYS methodology was verified by developing the Lagrangian equations of motion.

1. Introduction

Space Station Freedom is essential for advancing human exploration in space. Continued progress in the human exploration of space will require the use of a permanently manned space station for multi-year studies of human adaptation, testing of life support equipment, and the acquisition of experience needed to build and maintain a large manned space station. The assembly process of SSF will require extensive use of the Space Shuttle. Currently there are 17 assembly flights with four Advanced Solid Rocket Motor flights scheduled for early 1996 [1]. SSF assembly calls for a rendezvous of the shuttle with SSF. The capture and berthing of a controlled spacecraft using a robotic manipulator is an important technology for proper assembly of SSF. The berthing operation considered assumes that, first, the Space Shuttle Remote Manipulator System grapples Space Station. Next, the brakes are applied at the RMS joints and the combined station, RMS, and shuttle stack are maneuvered to a torque-equilibrium attitude using the Station Reaction Control System jets. Finally, the RMS brakes are released and the partially assembled SSF is retracted for berthing in the payload bay. The unusual characteristic of this operation is that attitude control of the coupled configuration is accomplished by the SSF Control Moment Gyro's (CMG's) during retraction of the RMS. The technical issue involved is unwanted vibrations of the coupled configuration that occur during retraction. Control of the RMS is located on the Space Shuttle, and it is desired to have the CMG's and RMS controllers cooperate in an attempt to suppress these vibrations. Operations in space involving the SS, RMS, and payloads has been limited to payloads with inactive

attitude control capability. Experience is needed wherein control of the coupled configuration could be shared between the payload and handler. This would be the case of the berthing operation of the SS to SSF. Langley Research Center (LaRC) has been investigating the approach of using inertial components attached to the payload end of telerobotic manipulators for vibration damping to aid in precision telerobotic tasks with highly flexible space-based manipulators. The dynamics and control of spacecraft that are manipulator-coupled with each spacecraft having independent attitude control systems is not well understood. Therefore, NASA is currently involved in analytic and experimental research using a two-dimensional ground-based facility at the Marshall Space Flight Center (MSFC). The flat-floor facility provides an environment in the horizontal plane, much like that in a weightless environment. NASA Langley Research Center, in cooperation with MSFC, is assembling a testbed to conduct research in the areas of berthing operations and the control of multi-body configurations that are loosely coupled with flexible manipulator linkages. The goal of this paper is to provide NASA with an analytic preliminary design of the testbed using elementary analysis models, ANSYS finite element analysis, and the Lagrangian equations of motion.

1.1 Testbed Description

The research testbed has been designed to be a model of the berthing process where the Space Shuttle and Space Station are coupled via the RMS, but restricted to movement within the horizontal plane. The SSF Mobility Base is an existing MSFC air bearing vehicle that has a mass of 116.088 Slugs, is maneuvered by vehicle reaction jets and controlled by joint motors and a CMG. The vehicle is suspended using low flow-rate air bearings, and has a single axis gimbal CMG for attitude control. The vehicle moves in the translational and rotational directions by use of cold gas reaction jets. Sensors on board the vehicle include a laser position scanner, a rate gyro, and accelerometers for feedback control. The joints of the arms are connected by Harmonic drives and are driven by Inland DC servo motors and are suspended by air bearings. To gain early experience, an interim testbed has been designed where the SS Mobility Base has been eliminated and attached to the fixed wall of the testbed. The other end of the manipulator is attached to the SSF Mobility Base.

1.2 Background

In this section a survey of previous work which is related to the development of the Lagrangian equations of motion and finite element modeling of a two link, three joint, free floating mechanical manipulator is presented.

Much research has been performed on robots as rigid systems [2] and [3]. In this paper we will study the modeling of robot manipulators with elastic joints and rigid links. The mathematical model is derived using two basic assumptions regarding dynamic coupling between the actuators and the links. According to [4] the elasticity in the joints is of greater importance than the gyroscopic interactions between the

motors and the links. The proper choice and analysis of mathematical models is crucial to proper mechanical design and control. In this paper we will study the case of revolute joints driven by DC motors whose rotors are elastically coupled to the links. According to [4] we can assume the following:

1.) The kinetic energy of the rotor is due mainly to its own rotation. Equivalently, the motion of the rotor is a pure rotation w.r.t. an inertial frame.

2.) The rotor/gear inertia is symmetric about the rotor axis of rotation so that the gravitational potential of the system and also the velocity of the rotor center of mass are both independent of rotor position.

Our model reduces to the usual rigid body model found in numerous literature, when the joint stiffness tends to infinity, proving the accuracy of our assumptions. The main point of these assumptions is to model the dynamic effects that are dominant, in our case the joint elasticity.

Very little research has been performed in the area of finite element analysis on Harmonic drives. The only finite element research found on Harmonic drives is presented by Hashimoto, Kiyosawa, and Paul [5]. In this research, a finite element formulation of the Flexspline is presented.

2. Design Using Finite Element Analysis

A Parametric study based on natural frequencies was performed using ANSYS, a finite element computer code, to design the arm linkages. To define the physical design requirements for the arm linkage, the maximum first natural frequency that could be dampened by the CMG was determined. The target first system bending mode was on the order of 0.05 Hz for the cantilevered system with the rotors locked. This margin was chosen by NASA to allow for frequency increase due to the additions of the joint controllers and to allow for evolution into a two air bearing vehicle configuration that the experimental set-up will later be turned into.

2.1 Model Construction

An ANSYS model of the two link manipulator, flexible joints, motors, and rigid air bearing vehicle was constructed from the overall system model. The modal analysis option (Kan = 2) was chosen in ANSYS. The modal analysis solves for both the system natural frequencies and mode shapes. The structure must be linear elastic, and any damping is ignored. The ANSYS model contains the two link manipulator, flexible joints, motors, and the rigid air bearing vehicle. In order to model the manipulator correctly, three element types in ANSYS were used. These elements are referred to as Stiff# in ANSYS. The linkages were modeled as beam elements, which are three-dimensional structures with six DOF at each node and are called Stiff4 elements in ANSYS. The mass and mass moments of inertia of the joints and air bearing vehicle were modeled using Stiff21 mass elements with six DOF at each node. The joint stiffness was approximated using Stiff14 spring elements with a Uy translational degree of freedom. The joints were modeled as shown in figure 1, to produce the appropriate load paths between the arm linkages,

motors, and Harmonic drives. In all the models, the system was cantilevered to the wall with the air bearing vehicle restricted to planar motion in the x-y plane. The motor rotors were either locked to the motor housings, brakes on, or free to rotate, brakes off. In reality the joint controllers will act as springs between the rotors and the housings and the actual system natural frequency will be between the brakes on and brakes off cases. Figure 1 shows the ANSYS approximation of the testbed set-up.

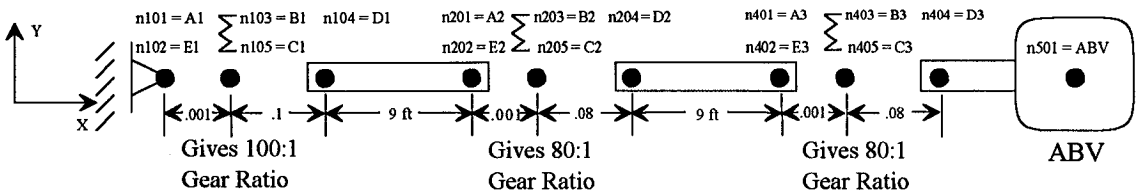

Figure 1 - ANSYS Model

The figure can be explained as follows:

A's = lumped mass of the Rotor, Wave Generator, and Coupling
E's = lumped mass of the Circular Spline, Pitch Bracket, and Input Bracket
D's = lumped mass of the Dynamic Spline, Pitch Bracket, and Output Bracket

The Rotor, Wave Generator, Circular Spline, and Dynamic Spline are all parts of the Harmonic drive. Note that the A's, E's, and D's are modeled as Stiff21 mass elements. Nodes 101 and 103 are coupled together in all six DOF representing a beam structure. Similarly, nodes 104 and 105 are coupled together in all six DOF. Nodes 101, 102, and 104, representing the various parts of the Harmonic drive, are coupled in all directions except, Rotz. For the brakes on case, an additional couple is added which couples nodes 101 and 102 in the Rotz DOF. Joints two and three are connected in the same manor as joint one. Node 102 is connected to the wall and is constrained from movement. Nodes 202 and 402 are connected to the beams representing the Circular Splines. The A's and E's are collocated and the B's and C's are collocated. Nodes 103 and 105 are connected by a linear translational spring that is equivalent to the torsional stiffness of the joint supplied by the joint manufacturer [6]. Joints two and three also utilize a translational spring with a Uy degree of freedom. Node 500 represents the air bearing vehicle and is a Stiff21 mass element. The beams are comprised of 19 Stiff4 Beam elements apiece. Translational springs were used in the ANSYS formulation to model the gear ratio of each joint.

2.2 ANSYS Parametric Study Results

A series of models were studied for preliminary design of the arm linkage by varying the arm length, cross section, and joint angles. In these models, the system was cantilevered to the wall with either the joint motor rotors locked to the motor housing, brakes on, or free to rotate, brakes off. Three joint angle configurations were studied. The three joint angles were 0°, 45°, and 60°. The links were desired to be able to be purchased off the shelf and be stiff in out-of-plane bending. For this reason, I-Beams with 9 and 12 ft. lengths were chosen. Three different I-Beam cross-sections were studied by varying the length, width, and height of the beam.

Tables 1, 2, and 3 list the different configurations along with the calculated natural frequencies. Note that for each of the brakes off cases, the first three modes of vibration were rigid body modes which are not shown. The beam 3 configuration was chosen for the experimental set-up and is shown in bold type in each of the tables.

Configuration 1 (0^0)		Frequency 1	Frequency 2	Frequency 3	Frequency 4	Frequency 5
Beam 1	9 ft. Brakes on	0.1011	0.9418	6.8641	18.0824	26.6039
	9 ft. Brakes off	5.2694	8.0921	13.992	18.3028	22.7557
	12 ft. Brakes on	0.0712	0.8425	4.3814	15.7373	16.0463
	12 ft. Brakes off	4.8932	7.6781	13.865	12.9203	16.0096
Beam 2	9 ft. Brakes on	0.0803	0.7751	6.1125	15.6771	23.7674
	9 ft. Brakes off	4.0012	6.6948	8.1109	15.9316	19.7456
	12 ft. Brakes on	0.0551	0.6861	3.8972	13.9711	14.1166
	12 ft. Brakes off	3.7692	5.9832	7.2298	11.217	13.76
Beam 3	**9 ft. Brakes on**	**0.0599**	**0.5952**	**5.1006**	**13.2287**	**20.6089**
	9 ft. Brakes off	**2.6894**	**4.2768**	**6.0024**	**13.3259**	**19.2529**
	12 ft. Brakes on	0.0408	0.5223	3.2575	11.8673	12.2857
	12 ft. Brakes off	2.4321	4.0013	5.8963	9.5138	11.268

Table 1

Configuration 2 (45^0)		Frequency 1	Frequency 2	Frequency 3	Frequency 4	Frequency 5
Beam 1	9 ft. Brakes on	0.1285	0.5052	1.0948	26.665	34.0826
	9 ft. Brakes off	5.1925	7.9197	13.228	22.7139	23.3618
	12 ft. Brakes on	0.0901	0.3415	0.9938	15.816	21.1876
	12 ft. Brakes off	4.7091	5.629	12.846	12.9017	13.0958
Beam 2	9 ft. Brakes on	0.1017	0.415	0.913	23.592	31.2527
	9 ft. Brakes off	3.4429	4.8994	9.0455	19.6932	20.278
	12 ft. Brakes on	0.0706	0.2464	0.8209	14.1917	19.5033
	12 ft. Brakes off	2.9001	4.6781	8.9936	11.1989	11.3683
Beam 3	**9 ft. Brakes on**	**0.0757**	**0.3183**	**0.7096**	**20.1261**	**27.6165**
	9 ft. Brakes off	**2.4693**	**4.1039**	**6.8962**	**16.6643**	**17.1929**
	12 ft. Brakes on	0.0522	0.2094	0.6325	12.3515	17.2952
	12 ft. Brakes off	2.1003	3.5691	6.1251	9.4977	9.6421

Table 2

Configuration 3 (60^0)		Frequency 1	Frequency 2	Frequency 3	Frequency 4	Frequency 5
Beam 1	9 ft. Brakes on	0.1587	0.4575	1.149	27.8816	32.8457
	9 ft. Brakes off	5.2695	6.8912	13.45	22.5222	23.051
	12 ft. Brakes on	0.1094	0.3117	1.0289	16.1989	21.212
	12 ft. Brakes off	4.8939	5.698	12.983	12.9604	12.9859
Beam 2	9 ft. Brakes on	0.1221	0.3786	0.9537	24.8923	27.3442
	9 ft. Brakes off	3.6549	4.6002	9.4091	19.4979	20.0132
	12 ft. Brakes on	0.0855	0.2536	0.8479	14.6325	19.4226
	12 ft. Brakes off	3.001	4.7802	9.1094	11.2466	11.2744
Beam 3	**9 ft. Brakes on**	**0.0906**	**0.292**	**0.7383**	**21.1313**	**25.4351**
	9 ft. Brakes off	**2.7701**	**4.1192**	**5.7201**	**16.4506**	**16.9735**
	12 ft. Brakes on	0.0629	0.1929	0.652	12.8065	17.0709
	12 ft. Brakes off	2.2014	3.791	6.2391	9.5342	9.5643

Table 3

The beam that was chosen for the experimental set-up was the beam 3 configuration with a 9 ft. length. The beam is made of aluminum and has a mass of 24.55 lb and an inertia about the rotation axis of 5.1515 slug·ft^2. The first bending mode with brakes on is 0.05992 Hz, and for brakes off is 2.6894 Hz. The beam is stiff in out-of-plane directions and is available off the shelf. The true system frequencies depend on the joint controllers and will be between the brakes on and brakes off frequencies listed in tables 1-3.

3. Lagrangian Verification of the ANSYS Model

The Lagrangian equations of motion were derived for a modified two link manipulator and the natural frequencies were calculated. The first three natural frequencies for the Lagrangian and ANSYS method are as follows:

Frequency	Lagrange	ANSYS	% Difference
f1	0.24	0.23	2.8
f2	1.41	1.59	4.8
f3	5.63	5.29	6.3

Table 4

The results above prove the ANSYS method to be a correct approximation of the mechanical manipulator.

4. Conclusions

The novel feature of the research reported herein is the development of a research testbed for manipulator-coupled spacecraft. This testbed is needed to more completely understand the control of spacecraft coupled by a manipulator to the payload end of the manipulator. This operation is important because it is being considered as a backup for the assembly of Space Station Freedom. An ANSYS approximation to this testbed was developed and verified by the development of the Lagrangain equations of motion. ANSYS was used as a preliminary design tool to size the links of the manipulator that will be used in the research testbed. The matching of the Lagrangian equations and the ANSYS results prove that the ANSYS method is a correct approximation of the actual testbed. Future work will include the construction of the testbed and further verification of the ANSYS results by experimental modal testing on the actual structure.

5. Acknowledgments

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