Natural Frequencies of an Orbiting Space Station

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Theme

THE natural modes and frequencies of a structurally complex space station are found. The paper demonstrates the development and application of a modal synthesis method for economical digital simulation of this multi-degree-of-freedom system. Modeling the system as a hybrid assemblage of rigid modules joined by massless elastic constraints and flexible modules characterized by continuous deformation functions is shown to yield practical results. The method is applied to the Skylab space station. Frequencies of the lowest 65 modes are given.

Contents

The vibrational analysis of space stations is difficult because of their structural complexity. The large number of members in these structures presents a challenge for accurate mathematical modeling in order that digital computer techniques may be applied with reasonable core storage requirements and execution times. In addition, space stations are typically composed of structural modules with widely varying flexibilities. Long arrays of solar cell units are attached to relatively massive space vehicles. This situation can lead to numerical inaccuracy in the solution procedure. The formulation of the problem must avoid the pitfall of overshadowing the stiffness properties of the more flexible members by the stiffer members. In addition, the choice of generalized coordinates for the model must be made so that low-frequency behavior is accurately described without using too many of the available degrees of freedom for higher frequency motion of the stiff members.

The paper presents a vibration analysis of a large space station. A number of papers have appeared on methods of analysis for structural systems (for example, Ref. 1). However, the literature on the actual solution of a complex three-dimensional system with many components is sparse. This paper gives a practical method, utilizing the modal synthesis technique, for finding the modes and frequencies of a space station consisting of a number of clustered modules with appended flexible structures.

In the modal synthesis method, component or substructure displacement functions are used to model the entire assembly. For application of this method to space stations, the key to formulating a model of manageable size, which will accurately represent low-frequency behavior, is the proper selection of functions to use as generalized coordinates of the system. The assumption was made that the space station consists of both rigid and flexible modules, interfacing at planar surfaces. This assumption is suitable for clustered space structures where the requirements of small launch volume lead to docking and deployment of modules and subsystems, so that interfacing is confined to localized areas. For such a situation it is valid to consider the flexibility lumped at the interface.

The rigid substructures are characterized by natural frequencies well above the highest frequency of interest for the complete structure. The deformation functions for these bodies are the six rigid-body motions. The flexible substructures are restricted to cantilevered structures characterized by lower frequencies, such as deployed solar arrays. The deformation functions for these bodies are elastic displacement functions such as natural mode shapes or static responses to inertial loads.

The equations of motion of the space station were derived using the Lagrangian approach. The potential and kinetic energy of the system were formulated in terms of the two sets of generalized coordinates.

The equations of free motion were synthesized and solved with a digital computer program (DISCUS) written for this purpose. The program assembles the mass and stiffness matrices of the system and solves the eigenvalue problem for modes and frequencies (using the Householder method). The predominant substructure mode characterizing each system mode was found by computing the percentage of kinetic and potential energy in each substructure. The program also produced schematic diagrams illustrating each mode, using the Stromberg-Carlson 4020 plotter. The results reported

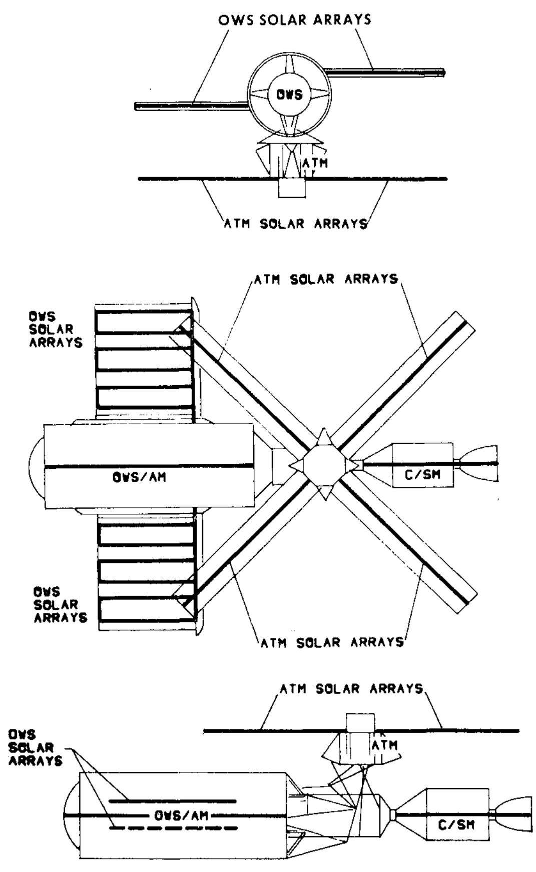

Fig. 1 The Skylab Space Station (three views).

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here are for a model with 96 degrees of freedom. Subsequently the program was modified to allow 112 degrees of freedom (using about 63,000 words of computer core storage).

The method given here was applied to the Skylab. The Skylab, illustrated in Fig. 1, consists of the Saturn IV-B orbital workshop, mated via an airlock module to the Multiple Docking Adapter, a cylindrical shell structure with a forward conical bulkhead providing forward and lateral ports for docking with the Apollo Command and Service Module. These structures form the main axis of the Skylab. At right angles, pointing sunward, is the Apollo Telescope Mount, consisting of a stiff rack structure supporting the experiment package, a rigid structure bearing a number of telescopic solar experiments. The experiment package is joined to the rack with a gimballed ring system. Four long articulated solar array wings are attached to the Telescope Mount, while the workshop supports two array systems, each with three wings. A series of vibrational studies of the Skylab was made which followed the evolution of the design. The results reported here are based on Ref. 2.

The Skylab was modeled with the Workshop, Telescope Mount, and the Command and Service Module each represented as rigid modules, while the solar arrays and experiment package/gimbal system were represented as flexible modules. Natural modes, found from separate dynamic finite element analyses, were used for flexible module deformation functions. The localized flexibility characteristics of the rigid module interfaces were expressed as 6×6 stiffness matrices, with their coefficients found from static finite element analyses.

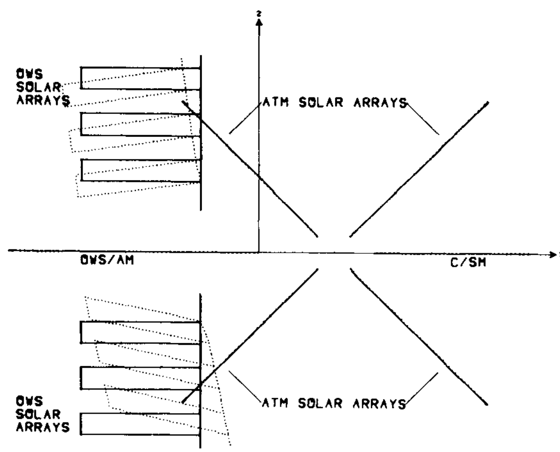

Fig. 2 Plotter diagram of mode 5.

The results are given for the frequencies of the lowest 65 modes in Table 1. Computer run times were of the order of three minutes of CPU times for 96 modes, with about one and one half minutes for plotting all modes. The modes are grouped according to the predominant component motion characterizing the mode. An illustration of one of the mode shapes produced on the plotter is shown in Fig. 2.

All of the lowest 20 modes are predominantly solar array deformation. The spectrum of frequencies falls into groups of almost identical values because the Skylab has multiple solar arrays with nearly the same properties. The lowest mode characterized by motion of a rigid module is mode 21, 0.983 Hz, which is predominantly twisting of the Apollo Telescope Mount about its longitudinal axis. The lowest mode of deformation of the main axis of the Skylab is mode 36, with frequency 1.424 Hz, characterized by bending of the Command and Service Module.

Through the modal synthesis method a comprehensive analysis of a large space station is possible. The results indicate that generally the modes tend to fall into groups with relatively uncoupled motion of separate substructures. A tentative conclusion is that low-frequency motion of appendages may be neglected in studies of the gross motion of the main components.

Table 1 Skylab modes and frequencies

Modes	Frequencies (Hz)	Description
1–4	0.217–0.232	ATM solar array bending
5–6	0.382–0.384	OWS solar array bending
7–8	0.532–0.533	OWS solar array twisting
9–12	0.746–0.770	OWS solar array bending
13–16	0.801–0.842	ATM solar array bending
17–20	0.958–0.963	ATM solar array twisting
21	0.983	ATM twisting
22–25	1.072–1.090	ATM solar array bending
26–31	1.095–1.102	OWS solar array twisting
32	1.185	Canister rotation
33–34	1.314–1.316	OWS solar array bending
35	1.356	Canister rotation
36–37	1.424–1.485	CSM rotation
38–41	1.604–1.628	ATM solar array bending
42	1.923	ATM rotation
43–44	2.338–2.341	OWS solar array bending
45	2.765	ATM rotation
46–49	3.008–3.010	ATM solar array twisting
50–51	3.687–3.687	OWS solar array bending
52	4.072	Canister twisting
53–54	4.321–4.326	OWS solar array bending
55	4.389	Canister Z-translation
56–59	4.410–4.472	OWS solar array bending
60–65	4.797–4.811	OWS solar array twisting

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[2] Bernstein, E. L., "Natural Modes and Frequencies of the Skylab Cluster—December 1970," LMSC-HREC D162774, Jan. 1971, Lockheed Missiles & Space Co., Huntsville, Ala.