Development and Verification of Key Technologies for the Success of Agile Space Missions

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Introduction

Future generations of NASA and DoD spacecraft will require a high level of agility and precision of line-of-sight (LOS) pointing. Simultaneous requirements on agility and pointing, as well as on size and weight present a significant technical challenge for spacecraft designers. LOS control for these spacecraft will typically be needed over a wide range of motions (in both amplitude and frequency). Submicroradian jitter requirements to satisfy payload performance objectives must be balanced with large payload fields of view (i.e., 50 to 1000 microradian) and fields of regard (2 to 50 degrees). In addition, many missions will have multiple gimballed payloads, that must maintain precise pointing despite large maneuvers of the main spacecraft and other appendages. Dynamic range and bandwidth considerations demand a dimensionally stable structure with multiple overlapping control subsystems. Many missions will require at least four levels of control: slew, attitude, shape, and vibration.

Conventional spacecraft design techniques in the areas of structures, materials, and control systems are incapable of meeting these future space mission requirements. Improvements are required in all areas, and the new approaches need to be integrated and verified through hardware test. In particular, an integrated design approach is needed in order to exploit the potential synergy among the disciplines while minimizing mission risk due to harmful control/structure interactions.

The challenge of the upcoming agile spacecraft missions demands development, integration, and verification of a wide range of techniques. This paper summarizes the status of several of the key technologies that address this challenge.

Simultaneous Structural/Control Design

Conventional spacecraft design techniques are based on sequential design of inter-related disciplines (see Figure 1a). Usually the structure is designed first with little or no regard for either mission-threatening adverse control/structure interactions or beneficial control/structure synergy. A control system (i.e., sensors, actuators, and control laws) is then grafted onto the predefined structure. This approach has been successfully employed on many past spacecraft where mission requirements permitted the luxury of a generous separation between structural frequencies and control bandwidths.

The trend toward simultaneous requirements of large size, light weight, rapid slew, and precision pointing precludes designs that rely solely on control/structure frequency separation. Also, the given structure may unduly restrict the type and location of control sensors and actuators. Iterating the sequential structure/control design procedure may, depending on requirements, finally lead to an acceptable design. However, for demanding missions, the sequential design procedure will usually lead to a spacecraft that is far from optimal in terms of weight, size, power, performance, robustness, and design/production cost.

For missions with stringent requirements, an integrated approach to the spacecraft structure/control design (Figure 1b) is beneficial. This approach blurs the traditional but largely artificial distinction between the structure and control system. Instead, the design is of a "controlled structure", with the procedure incorporating the inherent interactions of the disciplines. Structure/control design iterations are performed continuously, rather all at once. In this way, harmful interactions between the disciplines can be identified and avoided and the synergies can be more fully exploited.

Integrated design opens up a range of new options and approaches. For example, in the conventional sequential design procedure, the structure is often designed to achieve a specified first modal frequency, based on structure/control frequency separation. Total system weight can often be reduced, however, by combining the structural design with active shape control to achieve the required total stiffness. Neither the passive structure nor the active control alone meets the requirement, but together they do. Likewise, bandwidth and robustness of the attitude control loops can be increased by incorporating active or passive damping into the structure. LOS jitter can be reduced, without placing unrealistic requirements on attitude control system bandwidth, by designing in active or passive dampers or isolators to reduce vibrations at their source. As a last example of potential synergistic effects of integrated design, the placement of the slew actuators can be coordinated with the structural design and slew profiles to minimize excitation of flexible modes during slew.

System Identification

System identification is a necessary step in the design of high performance control systems due to the uncertainty in modeling flexible structural dynamics and to the uncertainty of the space environment. The on-orbit identification of input/output mappings is crucial to achieving precise pointing control of flexible structures. Both off-line and real-time system identification techniques need to be validated for use on future space missions.

The off-line method that TRW used in the past with notable success is a frequency domain curve fitting technique. Experimental frequency responses are curve fit with Chebyshev polynomials and a coprime factorization is used to derive the resulting state space model. The method was validated for single-input/multi-output systems [1] and can be extended to multi-input/multi-output systems. However, the method applies only to time invariant systems or possibly slowly varying plants. One useful application for this method is for designing disturbance rejection controllers at steady state operating points.

The rapid retargeting maneuvers that are critical for future space missions dictates the use of adaptive on-line identification techniques, since system dynamics vary significantly during and following the maneuvers. A promising adaptive identification technique for agile spacecraft is based on the vector-channel lattice filter [2]. The main advantage of the least-squares lattice filter is that the algorithm is recursive in both time and order, thus allowing filter order to be updated without reprocessing previous data. This order recursive property is fundamental in flexible structures applications in which the effective system order varies with the number of structural modes excited at one time. In this context, effective system order is twice the number of significantly excited modes. Lattice filters have been successfully used on the TRW truss experiment for identifying fundamental frequencies and for detecting variations in effective order during an abrupt configuration change [1]. The next step is to integrate on-line identification and control design in order to adaptively control pointing errors.

Active/Passive Vibration Suppression

The performance and robustness of agile spacecraft can be improved by utilizing local damping to isolate disturbance or eliminate troublesome modes within the bandwidth of the pointing and maneuvering control loops. Along these lines, passive and active members were employed for vibration suppression.

The passive members consists of composite members with viscoleastic material (VEM) held in with a constraining layer [3]. By forcing the dynamic axial load to travel through the VEM, a significant level of damping can be achieved. Static axial loads are taken up by the composite material itself to prevent creep of the VEM. With this approach, use of passive damping results in no loss of stiffness or strength.

The active members consist of composite members with piezoelectric sensors and actuators [4]. Local loops with suitable compensators are tied around each set of sensors and actuators in a single member. When the local loops are closed, the sensors associated with the pointing and maneuvering control loops see a structure which has a large amount of damping due to the active members. In a number of system level studies, a factor of 50 improvement in settling time following a maneuver can be achieved using active members with strictly local loops.

A high speed multi-channel digital Structural Control Processor (SCP) has been developed to provide enhanced performance and additional capabilities for the active members. The SCP, in conjunction with system identification, allows on-orbit adjustment of the local loop compensators to provide improved performance and adaptation to both slow (aging and thermal cycles) and rapid (multi-body spacecraft motion) changes in system dynamics. In addition, the SCP allows coordination of the local loops in a hierarchical manner to provide overall shape control. Based on test results with a six channel breadboard, the existing technology can support 50 local loops, each at a cycle rate of at least 15000 Hz.

Testbed Definition

In order to demonstrate in hardware the key technologies that will enable the success of future agile space missions, it is necessary to have a testbed with performance requirements similar to those of the agile space missions. A survey of the next generation of space missions was conducted and a set of requirements for the testbed was derived. These requirements were:

- Slew acceleration: 1 - 20 deg/sec/sec
- Precision pointing: 0.01 - 10 μrad
- Precision alignment: 0.01 - 50 μmeter
- Fast slew: 0.5 - 10 deg/sec

In addition, it was desirable to have a modular structure that could handle additional capability at a future date and would have easily interchangeable members.

The testbed that was designed and built was a nine bay 18 foot long truss (see Figure 2). An air bearing with associated motor and electronics was used to simulate control moment gyro slew torques at the base of the truss. The truss uses STAR*NET Structures joints so that single members can be removed and replaced without disassembling the entire truss. The baseline truss has all members made out of aluminum, though composite passive and active members can be readily incorporated into the truss. Reaction wheels, along with passive and active members can be mounted on the truss to demonstrate the level of precision pointing and slew that can be accomplished. Optical sources and targets were used for shape control and to verify the performance level of the truss with various configurations of control hardware. The sources were mounted at the base of the truss with targets located at the tip and mid-span of the truss. An appendage drive system can be mounted to the backing structure to simulate a solar array or gimballed payload.

Independent performance measurements during slew is provided by a laser interferometer system mounted on an optical bench. Precision performance measurement during the settling phase is provided by an inductive measurement system (also mounted on the optical bench) with a probe mounted on the truss. The truss, air bearing, backing structure, pedestal, and optical bench were located in an acoustically quiet, siesmically isolated room to facilitate precise performance measurement.

Figure 3 compares simulated performance of the truss, with and without active damped members, for a 60 degree slew maneuver. A trapezoidal (jerk limited) torque profile was used. Inherently low damping of the all aluminum truss results in high levels of vibration during and after the slew. Replacing six members with active composite members with local feedback loops results in the drastic improvement in settling time illustrated in Figure 3. Additional performance improvements could be attained by employing a slew torque profile better suited to the dynamic characteristics of the actively damped truss.

References

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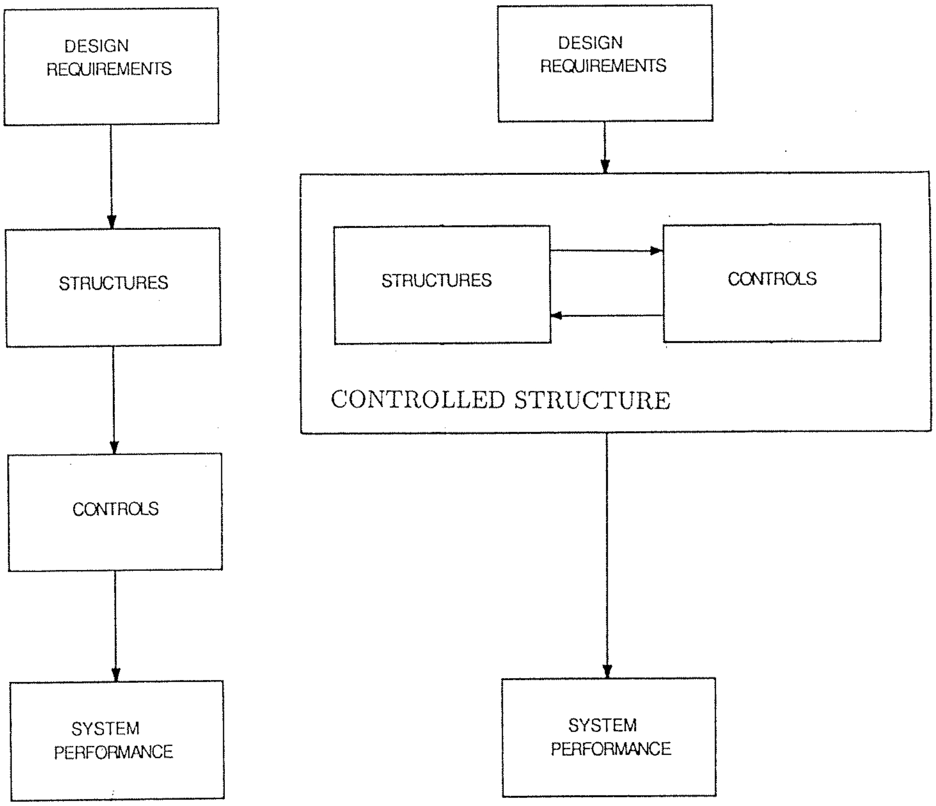


a) Sequential Design

b) Integrated Design

Figure 1. Structure/Control Design Procedures

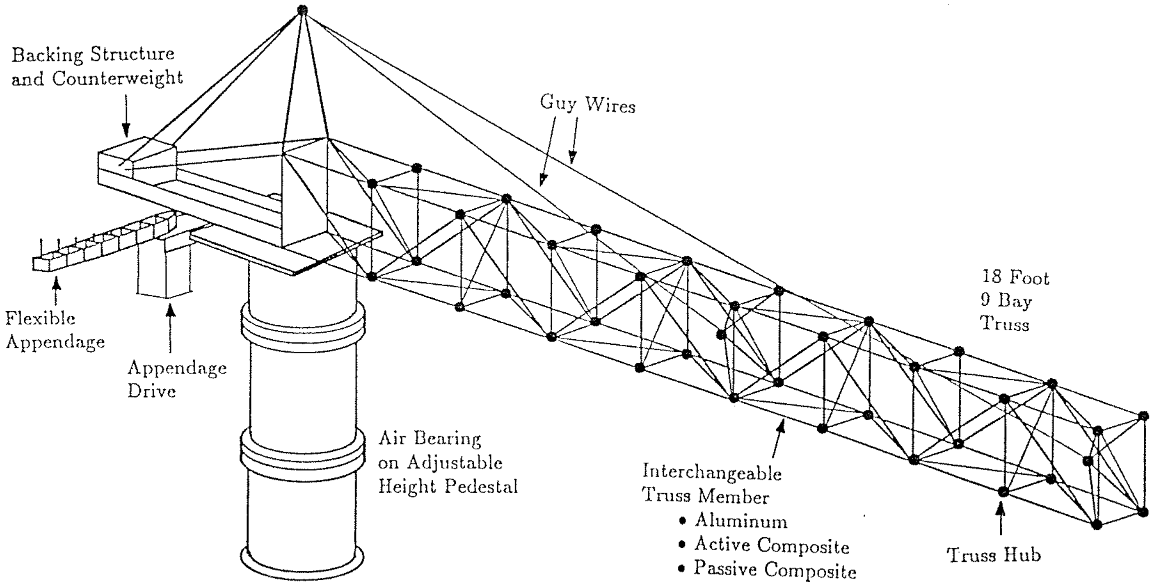


Figure 2. Precision Control of Agile Spacecraft Testbed

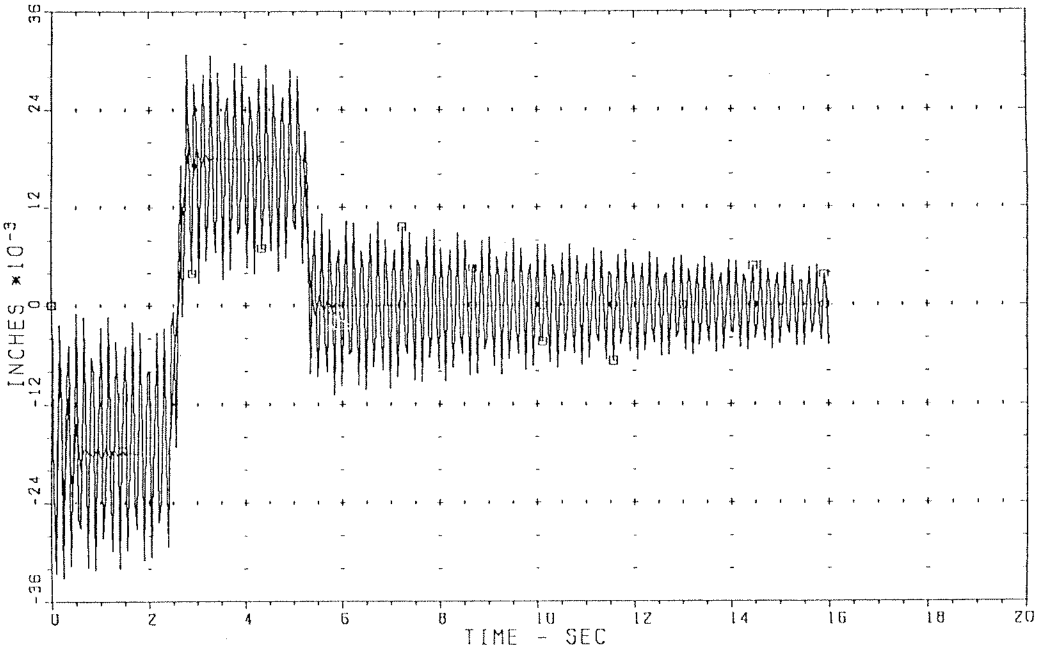
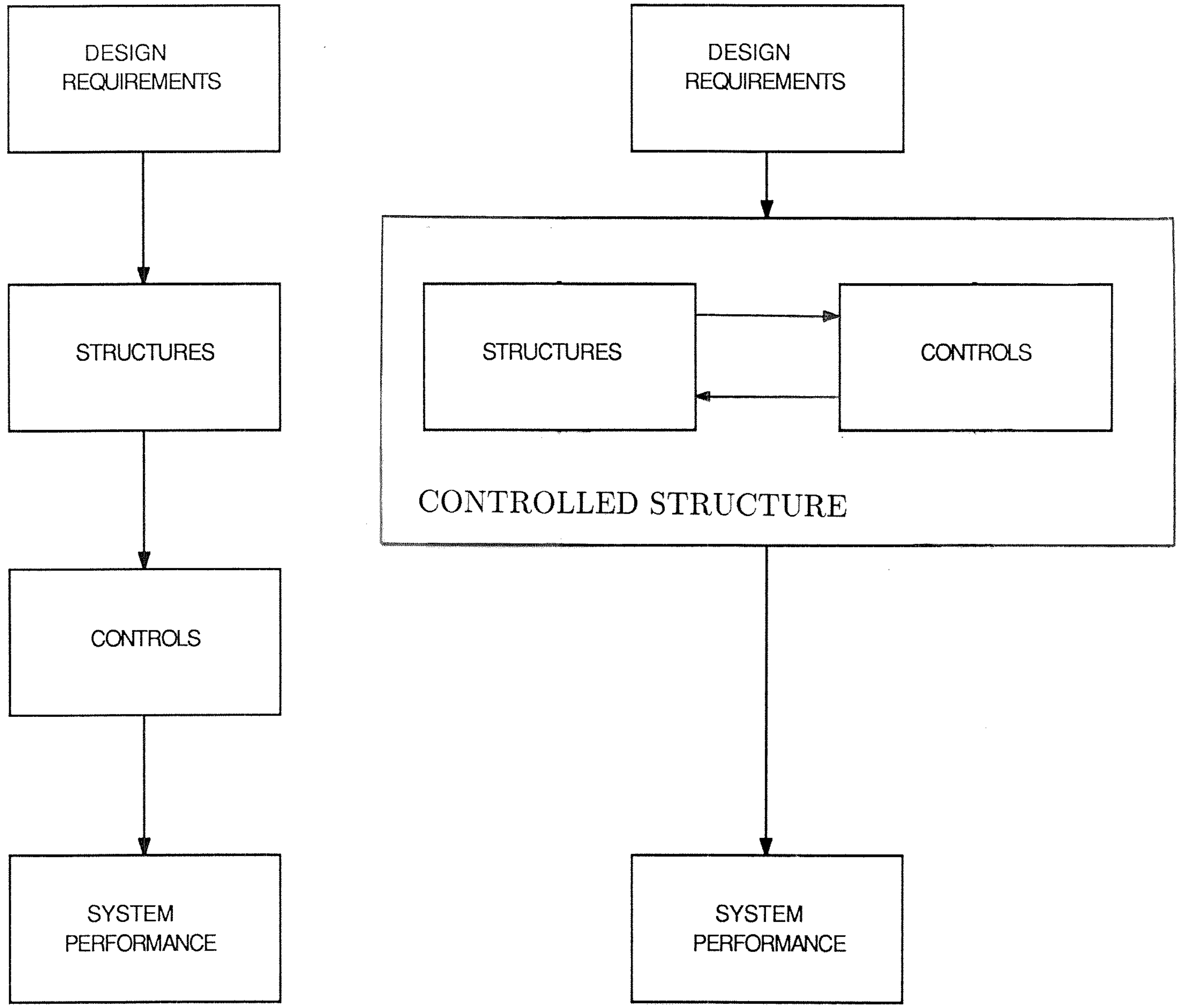


Figure 3. Active Composite Members Reduce Slew Settling Time



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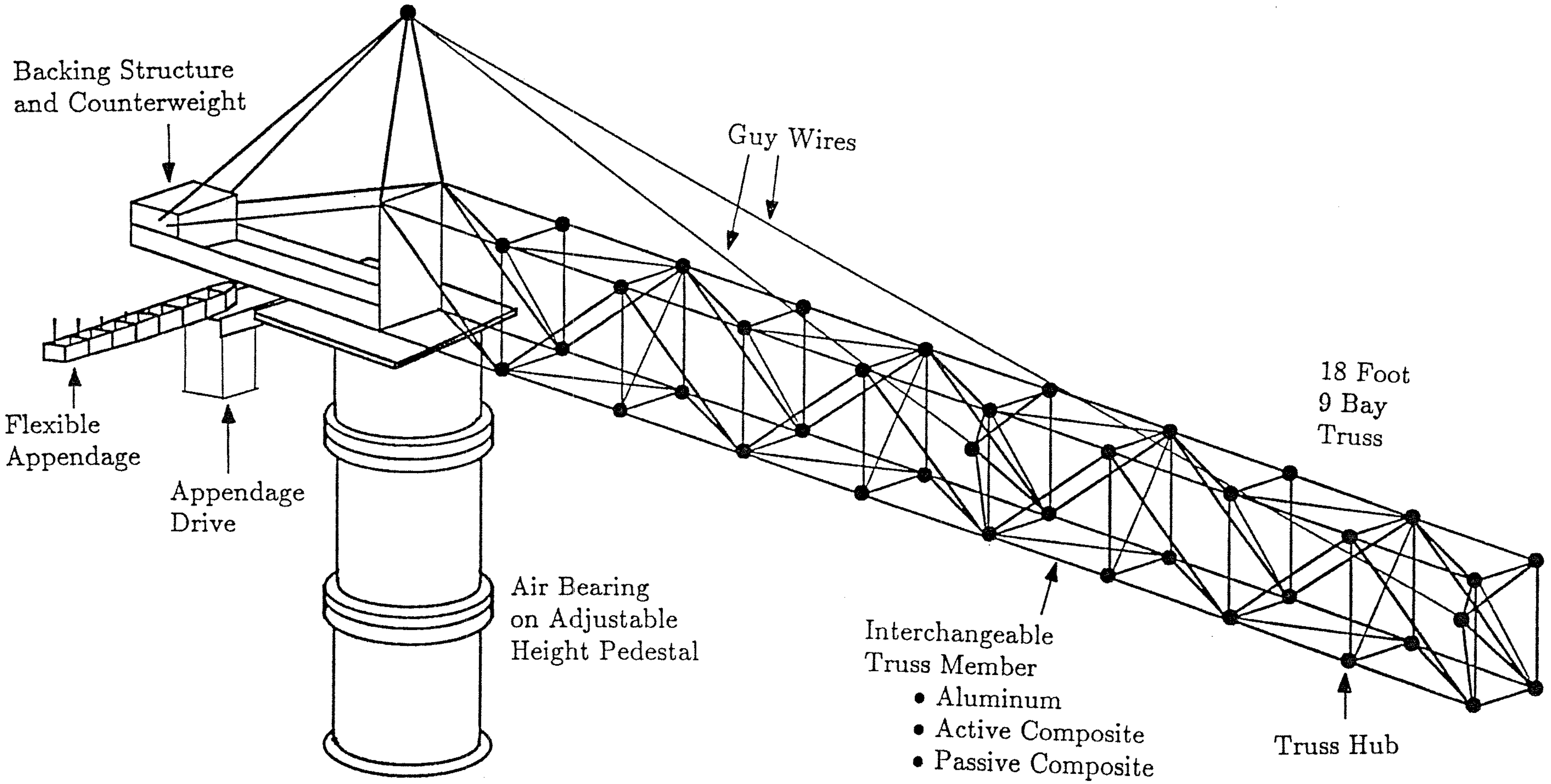

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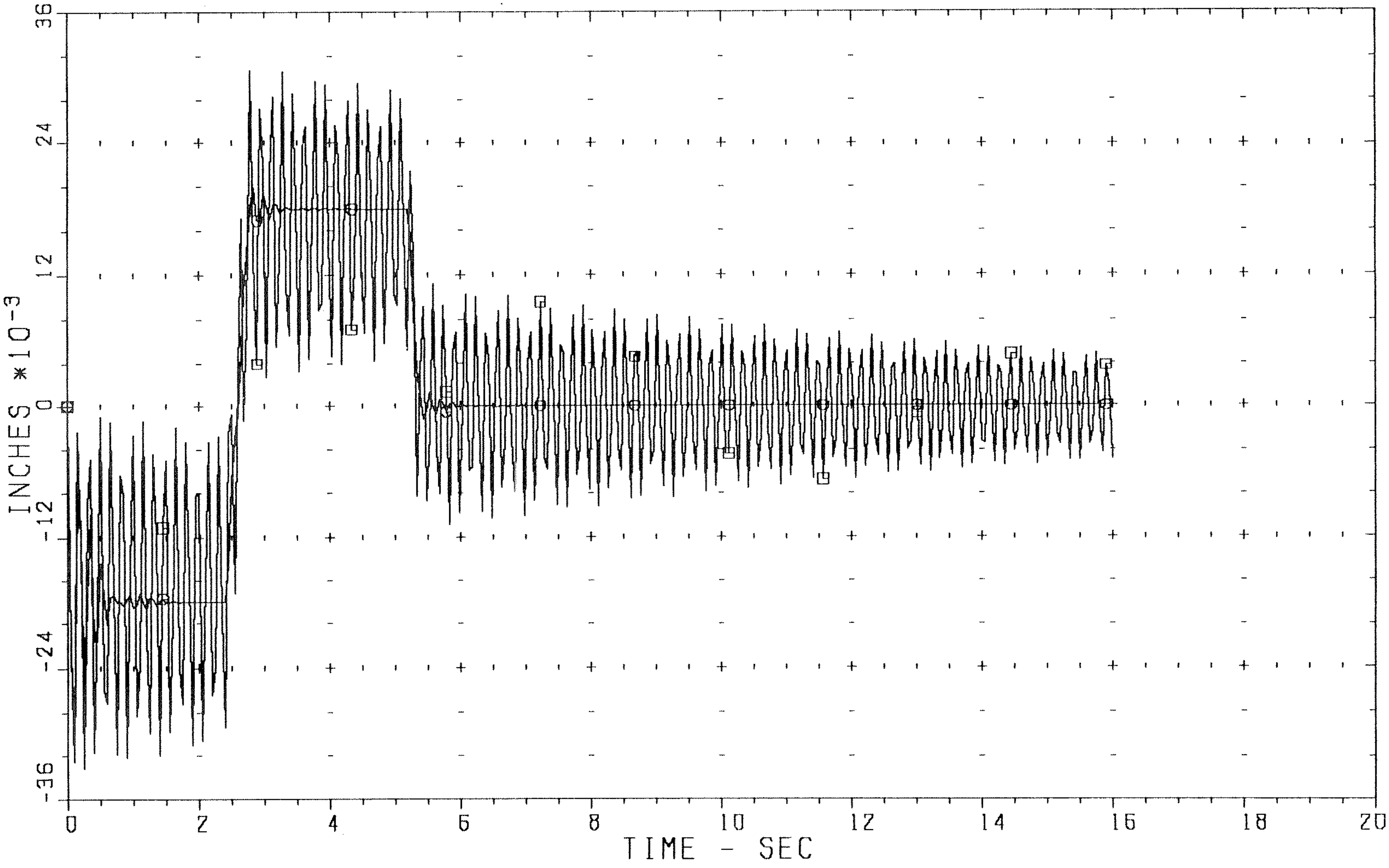

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