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Survey of Historical Incidences with Controls-Structures Interaction and Recommended Technology Improvements Needed to Put Hardware in Space

G. L. Ketner

March 1989

Prepared for
Controls-Structures Interaction Office,
National Aeronautics and Space Administration,
Langley Research Center
under a Related Services Agreement
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SURVEY OF HISTORICAL INCIDENCES WITH CONTROLS-STRUCTURES INTERACTION AND RECOMMENDED TECHNOLOGY IMPROVEMENTS NEEDED TO PUT HARDWARE IN SPACE

G. L. Ketner

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Prepared for
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SUMMARY

Pacific Northwest Laboratory (PNL) conducted a survey for the Controls-Structures Interaction (CSI) Office of the National Aeronautics and Space Administration's (NASA) Langley Research Center. The purpose of the survey was to collect information documenting past incidences of problems with CSI during design, analysis, ground development, test and/or flight operation of space systems in industry. The survey was conducted to also compile recommended improvements in technology to support future needs for putting hardware into space.

Aerospace companies throughout the nation were contacted and interviewed. The data collected suggested the following conclusions:

- CSI problems arose at various times in a project life cycle. The incidences were not limited to flight, but occurred during detailed design and testing as well.
- The impact of the CSI problems varied from none to near loss of the mission.
- Current methodologies do not often detect problems in the early phases of design where the most leverage for solutions exists and the most options are available, and when the impact on cost, risk, and schedule is least.
- Current methodology does not gracefully solve CSI design problems at any stage of a project. Typically, solutions are compromised and allow higher than normal risks. To guarantee success, highly conservative designs of the structure and controller are usually required. Consequently, reduced control bandwidth, performance, and stability tend to be accepted.

The assessment of current and future needs indicates the following:

- Designers require simpler and less costly hardware that can do more and requires less space and weight.
- Structural analysts need more accurate/less computationally intensive models. Nonlinear models are inadequate at this time. The aerospace industry is not sure that a centralized software tool is needed yet. Control designers cannot agree on the guarantee of stability and performance of a system.

- Low-gravity test capability is nonexistent. Multibody testing is difficult. Testing needs to be done in a closed loop fashion. System identification is limited by the accuracy and repeatability of sensors.
- Advancement in space-qualified real-time computer hardware is needed. Understanding of centralized versus distributed hardware control is lacking.
- The capability to experiment in space and qualify hardware and control techniques is crucial. The consequences of component failure during in-orbit operation is not well understood.

CONTENTS

1.0 INTRODUCTION

The space age is barely three decades old and spacecraft have grown from tiny rigid bodies capable of transmitting basic electronic signals to complex, multibodied vehicles capable of performing a vast array of important science, military, and commercial functions. The evolution of guidance and control technology to support these missions has been correspondingly dramatic. Yet, as systems get larger, impose tighter pointing and station keeping requirements, and rely on autonomous operation, they will require new controls approaches that actively suppress structural responses resulting from known and unknown disturbances.

To understand the historical development of controls-structures technology over the years, the Controls-Structures Interaction (CSI) Office of the National Aeronautics and Space Administration's (NASA) Langley Research Center commissioned Pacific Northwest Laboratory (PNL)(a) to survey the aerospace industry for CSI incidences. PNL was also chartered to inquire what is needed for further CSI developments to successfully put hardware in space.

The survey of CSI incidences was to include aspects regarding design, analysis, ground development, test, and flight operation of actual or intended flight hardware. The survey was not to include paper studies, missiles, aircraft, or launch vehicles. The survey was performed by first compiling a list of aerospace companies. These companies were contacted by phone, resulting in visits and interviews of key aerospace personnel. A list of question areas was derived prior to all visits and used as a baseline to perform the survey.

The primary focus of this survey was to collect actual hardware experiences of CSI. Because only successes are typically documented in literature, a literature search was not performed.

This report contains three sections. In Section 2.0, the collected cases of CSI incidences are presented. The current and future CSI needs as industry sees them are presented in Section 3.0.

(a) Operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

2.0 CONTROLS-STRUCTURES INTERACTION INCIDENCES

Information on the incidences discussed in this section was gathered by interviewing members of the aerospace community (listed in the Appendix). The incidences represent their experiences, their knowledge of others, or literature they presented. These incidences, presented in some detail and in historical order, have not been verified beyond the interviews.

2.1 HISTORICAL OVERVIEW

Explorer 1 (1958), the first U.S. satellite, was intended to be spin stabilized. The spin stabilization about its axis of symmetry was about a minor axis of inertia. Unexpected structural energy dissipation occurred due to the flexibility of the four whip antennas protruding perpendicular to the spin axis. This, in turn, caused the satellite to tumble in an undesirable manner about its major axis of inertia in a reduced state of kinetic energy (Likins, Bouvier, 1971; Hughes, 1986).

Mariner (1962) was a spin stabilized satellite. Flexibility of the solar panels coupled with burn maneuvers could have resulted in a transient motion of the center of gravity. The transient center of gravity produced high angular rates that could have saturated the gyros. The problem was detected at the design stage and solved by adjusting the stiffness of the elastomeric dampers. The resulting operational risk was high. During flight operation the gyros did saturate but damped out with time. The system did operate successfully.

Alouette 1 (1962) and Explorer XX (1964) were spin stabilized satellites. Rapid spin decay was observed and was explained by solar motoring. This is a torque caused by periodic thermally induced distortions from solar radiation heating coupled with periodic solar radiation pressure (Likins, Bouvier, 1971; Hughes, 1986).

1963-22a (1963), or TRANSIT-5A, was a gravity gradient stabilized satellite launched into near-earth orbit. It was the first two-axis stabilized satellite. It achieved, through gravity capture and transient decay, a steadystate pointing error of approximately 6° within a week. In addition to predicted disturbances, differential thermal heating of the stabilizing booms was detected to be a significant source of agitation. The warped booms induced attitude errors. Thermal flutter also occurred due to entering and exiting earth's umbra, causing an additional oscillation of up to 5°. Because the period of these boom-induced oscillations was greater than any other dynamic interaction, its effect was minimal. The source of the thermal flutter was traced to the open cross section of the booms and their radiative absorptivity (Likins, Bouvier, 1971; Hughes, 1986).

OGO III (1966) had a reaction wheel attitude control system. Interaction between the flexible booms, reaction wheel control system, and the solar array drive controller caused excessive oscillations in attitude (Likins, Bouvier, 1971).

OV1-10 (1966) was a three-axis gravity gradient stabilized satellite placed in a nearly circular orbit. It was designed with three long booms positioned in the pitch, roll, and yaw axes. The OV1-10 suffered periodic inversions to an upside-down position and large, sometimes rapid, excursions in yaw. Four possible sources of the behavior were identified: 1) boom flutter due to umbra; 2) a near-resonant interaction between the residual onboard magnetic dipole and earth's magnetic field; 3) small biases in the springs at the base of the damping booms; and 4) slightly crooked damping booms. These causes were shown analytically to be sufficient to produce large yaw excursions and occasional tumbling (Likins, Bouvier, 1971; Hughes, 1986).

OGO IV (1966) was a gravity gradient stabilized satellite. Solar radiation forced an oscillation of the 60 foot boom antenna at its bending frequency. This produced a pitching oscillation, i.e., planar coupled bending-torsion, of the spacecraft of up to ±2°. The oscillation disappeared when the spacecraft entered umbra.

TACSAT 1 (1969) was the first dual spin (gyrostat) stabilized prolate satellite. Energy dissipation in the bearing assembly caused an unexpected 1° wobble. The system did perform as designed (Likins, Bouvier, 1971; Hughes, 1986).

ATS 5 (1969) was a spin stabilized satellite with an active nutation damper. There was a large amount of heat dissipation and very little fluid in the system's heat pipes. The unexpected energy dissipation in the heat pipes due to capillary action caused an unstable flat spin (Likins, Bouvier, 1971).

DMSP (1972) was designed with three-axis torque balance for attitude control. The design of the system was based on rigid body dynamics only. This allowed interaction between the attitude controller, a solar array flexible mode of approximately 0.5 Hz and an onboard 6 Hz disturbance. The system still performed within specification.

Mariner 10 (1973) was a spacecraft that observed a colocation problem. The attitude control system (ACS) reaction control jets were located at the end of the solar arrays while the gyros were placed on the bus. Bang-bang control of the ACS coupled with the high flexibility/low damping of the solar array torque tubes caused the roll axis of the ACS to become unstable after high rate slews. The instability resulted in fuel depletion of the roll maneuver reaction control jets. The mission was almost lost.

NTS 2 (1976) and T1ME 3 and 4 (1977) were gravity gradient stabilized spacecraft. System identification found the structural damping (2%) to be conservative to the modeled structural damping (0.5%). This allowed better modeling for future flights.

Voyager (1977) was a deep space probe using bang-bang control with hydrazine thrusters. Thermal flutter of the "stem" boom antenna compromised pointing performance. Inherent curvature of the boom and low torsional stiffness coupled thermal bending with the torsional resonance of the boom. When the system was close to the sun, this coupling resulted in thermal flutter; however, as the system moved away from the sun, the flutter disappeared. Interaction with the control system never occurred. The boom had been designed with zipper locks on its open cross section, to restrict lateral play inherent in torsional motion. Unfortunately, the design was ineffective when the probe was near the sun.

LANDSAT (1982, 1984) observed a 0.1° motion, thermal flutter, of the primary body caused by entering and leaving umbra. This motion was critical for the optics system. The problem was solved by knowing the degree of flutter from system identification and adjusting the optics. The attitude control system was left alone.

LEASAT (1984) was a spin stabilized gyrostat satellite. It was also the first of its size of spacecraft with onboard liquid propellant. Interaction between the payload control system and the propellant slosh modes caused instability during transfer orbit operations. The slosh modes that occurred were not as expected during design. This resulted in new ground testing to model the slosh modes more accurately. Saturation of the motor drive limited the flight instability.

Galileo (1989) is a spin stabilized gyrostat to be launched later this year. The system design was impacted by some CSI issues. Structural frequencies were close to the pointing control bandwidth. Uncertainty in the dynamic models, caused by 1g effects on ground tests and model reductions for control design/simulation, and uncertainty in the stability margin led to a 2-yr extension in the control design phase of the project. Extensive design tradeoffs were required. Abnormally stringent model verification testing was needed, e.g., component stiffnesses without a 1g preload and flight configuration modal analysis. The uncertainties also led to an inflight system identification capability late in the design. The system identification capability was needed to establish confidence in the control system. Even with these added elements, the design is considered risky because any significant model errors found by system identification could compromise the scientific information the probe is designed to return.

Magellan (1989) is a probe designed with attitude control rockets. The initial design of the solar panels ignored the solid rocket motor (SRM) burn. Detailed simulations showed that the panels would fail during rocket burn for Venus orbit insertion (VOI). This required a change in the control law and the hinge design in the solar panels. These changes cost approximately $1 million and 6 to 12 months of additional project time.

Zenith Star (future flight) is an alpha laser system in the design phase. Modal analysis of a 4-m experimental beam expander made of graphite epoxy composite produced four different modal frequencies for the four legs of the expander. This indicated the significance of testing in the design loop. It also pointed out the need to bring the control designers into the loop early so that higher frequency modes are understood and not ignored.

INTESAT VI (future flight) is a spin stabilized dual body system. The two bodies are being designed with spokes between them. Simulations indicated that the flexibility of the spokes caused a higher frequency mode to unintentionally interact with the control system. The solution involves redesigning the spokes with a higher stiffness (Slafer, Challoner, 1988).

The incidences described by respondents in this survey are summarized in Table 2.1.

TABLE 2.1. Summary of CSI Incidences

Year	Satellite	Control Technique	Performance/Impact	Probable Explanation
1958	Explorer 1	Spin stabilized	Unstable	Energy dissipation in whip antennas
1962	Mariner	Attitude thrusters	Stable, gyros saturated	Solar panel flexibility changed center of gravity
1962	Alouette 1	Spin stabilized	Rapid spin decay	Solar torque on thermally deformed vehicle
1963	1963-22a	Gravity stabilized	Vibrations excessive, but within specification	Boom bending due to solar heating
1966	OGO III	Reaction wheel	Excessive oscillations in attitude	Control system interaction with flexible booms
1966	OGO IV	Gravity stabilized	1° to 2° oscillation	Solar radiation induced boom bending
1969	TACSAT 1	Spin stabilized	Limit cycle, but within specification	Energy dissipation in bearing assembly
1969	ATS V	Spin stabilized	Unstable	Energy dissipation in heat pipes
1972	DMSP	3-axis torque balance	Solar array and controller interacted	Design was based on rigid body
1973	Mariner 10	Attitude thrusters	Unstable roll, depleted fuel	Thrusters and gyros noncolocated with flexible panels between
1977	Voyager	Attitude thrusters	Flutter of boom antenna	Thermal bending coupled with low torsional stiffness
1982 1984	LANDSAT	Spin stabilized	0.1° oscillation	Thermal bending induced by entering and leaving umbra
1984	LEASAT	Spin stabilized	Orbit transfer instability	Unexpected liquid slosh modes
1989	Galileo	Spin stabilized	Schedule impacted, system ID added	Structural frequencies close to control bandwidth, models uncertain
1989	Magellan	Attitude thrusters	Design cost and schedule impact, redesign control law	Design of solar panels ignored attitude control system during solid rocket motor burn
(?)	Zenith Star	Attitude thrusters	Nonrepeatable modal frequencies for identical parts	Variability of materials and geometry

2.2 CONCLUSIONS

Problems with CSI have appeared at various stages of a space system project life cycle--analysis, test, and flight operation. The impacts of CSI problems have varied from none to near mission loss. Usually, however, innovation has produced solutions to the problems, allowing the systems to ultimately function as designed.

Current methodologies often do not detect CSI problems in the early phases of design when there is the most leverage for solution, the most options open, and the least impacts on cost, schedule, and risk.

Current methodologies do not gracefully solve CSI design problems at any stage of the project. Compromised design solutions with high risk are typically accepted. Highly conservative designs of the structure/controller are usually required. Reduced control bandwidth, performance, and stability also tend to be accepted.

3.0 CURRENT AND FUTURE CSI TECHNOLOGY NEEDS

The survey of incidences summarized in Section 2.0 revealed problems in CSI technology areas. These areas are design, analysis, test, ground development, and flight operation. Based on information through telephone interviews and site visits, PNL formulated conclusions on the current and future CSI technology needs. ***It should be understood that the results presented are representative of the groups interviewed and are not necessarily the opinions of the author.***

3.1 DESIGN/ANALYSIS

The cost to develop hardware systems for space application today has put a heavy burden on industry to meet contract costs and to stay competitive. This burden is passed on to NASA and the U.S. Department of Defense (DoD) by reduced programs and alternative approaches to design. Within the design cycle, there is a need for simpler hardware with lower costs. The aerospace industry suggests the further development of components having higher performance with less sophistication that weigh less and take less space.

In general, the aerospace industry's structural dynamics groups and controls groups are communicating well. Usually, the groups are still separated by organizational boundaries, but projects tend to bring them together with a good understanding of each other's needs.

Complexity of hardware design typically means greater weight and/or size, and higher risk to system performance. It can also mean a burden for analysis to account for the nonlinearities and sophistication inherent in complex designs.

For aerospace engineers to successfully design spacecraft, they need to know in advance the characteristics and limits of a component or system, e.g., sensors, actuators, thrusters, etc. This means that it is desirable to have available off-the-shelf components. Current availability is limited and means that a designer must not only test the spacecraft, but also test the components in advance or sequentially, which puts the design performance/reliability, cost, and schedule at risk.

Much work in the aerospace industry is being directed to implement smart/integrated hardware such as composites of piezoelectric actuators/sensors or integrated fiberoptic sensors. These systems need to be further developed and proven. Also, new ideas need to be generated for further enhancement of the technology.

Structural modeling has limitations with the accuracy of higher modal frequencies. Tighter specifications make knowledge of higher modes more important. Substructure analysis may have higher frequencies that may be ignored but are significant at the system level to the controller. A critical question is how much accuracy in design calculations is needed to guarantee performance? The aerospace industry suggests that this is not very well understood.

Component characteristics are not often very well defined. It is difficult to know how much damping is needed and expected, and how to accurately model component characteristics within the computational limitations. Nonlinearities caused by joints, sensors, or actuators are also difficult to model accurately. The level of accuracy required of nonlinear modeling is also not well understood.

The aerospace industry also suggests that experience in design optimization of sensor and actuator location is lacking.

3.2 TEST/GROUND DEVELOPMENT

System development and testing requires special methods and equipment to simulate a very low g environment and must not allow damage to occur to systems that cannot support themselves in a 1g environment. New methods are required to suspend a system without causing interaction between the support and the system, yet allowing a wide range of rigid body motion. Multibody system testing is especially in need of development. Liquids are especially difficult to test in a 1g environment.

Further development of scaling techniques is required to test very large systems. The aerospace industry suggests that a better understanding of scaling laws is needed.

Current techniques of ground development and testing do not usually include the sensors and actuators required for control. Therefore, the system is not usually tested for closed loop response until it is put in space.

In the area of system identification, measurements of the system response are only as good as the sensors used. Nonlinearities and loss of calibration can affect the results used to characterize a system. Unknown/unexpected disturbances can affect the system characterization. Separation of linear and nonlinear effects is difficult and can mislead diagnostics of the cause of the response. Overlapping modes are hard to identify and separate. The aerospace industry suggests that further work is needed in learning how to back out the system dynamics.

3.3 FLIGHT OPERATION

Real-time computer hardware is limited by the environment of space, e.g., radiation. This forces the use of 5- to 10-year-old technology. This severely limits the capability to store and compute data. It also impacts the design sophistication of controllers and limits the number of sensors and actuators that can be controlled.

Developments to understand the efficiency, accuracy, and cost of distributed versus centralized control are needed. Having computational capability at each actuator reduces the load of a central control system and allows for much greater diversity of system level control. The aerospace industry suggests that this type of methodology is in its infancy and requires much more understanding.

Space experimentation is imperative to the future success of CSI technology. There is an underlying need to justify the expense of such testing against other means of validation. There is a critical need for verification of hardware functionality in space.

Understanding the effects of in-orbit component failure is required, e.g., the failure of a structural member could result in system instability. An understanding could help designers in accounting for and in minimizing the impact. Industry also suggests that the risks involved from designing an adequate system could be better evaluated.

3.4 AREAS OF UNCERTAINTY

The first area of contention was in the development of an integrated software tool for designing structures and control systems. One side felt that such development is premature because of the inaccuracy and incompleteness of mathematical model building. They also felt that hardware development should have a higher priority. The other point of view desires this technology because of the need for better communication paths between various disciplines. Structures codes do not communicate easily with controls codes. Also, system parameter studies are difficult to evaluate because of the time and effort required for each variation.

The subject of control techniques is not so much a point of contention, but a development of different approaches to solve a problem. Many different approaches were suggested with varying points of emphasis, but with similar results. A real issue area was with the question of performance. One point of view would claim that system robustness is guaranteed, but performance is not. They did not imply that the system would fail, but that required specifications cannot be guaranteed due to model versus real system variations. Their conclusion is that the control techniques need to be tested with real environment conditions to establish what works and what does not. The other point of view believes that robustness can be guaranteed, given adequate models.

3.5 CONCLUSIONS

Hardware development is the area viewed as one critical need to the future success of CSI. State-of-the-art technology cannot be enhanced without qualified hardware. Industry will not invest until the component hardware is better developed. There is a need for a better balance between control/structure theory and hardware development. CSI simply cannot be improved without more research behind gyros, actuators, sensors, joints, and other critical components. These systems also must be tested and flight-qualified for future system designs to improve.

The aerospace industry states that a real need exists for CSI technology development in future systems. Industry representatives also suggest that the level of effort from NASA and the military is less than is needed. That is, little hardware development is being pursued in relation to the requirements to develop CSI in the near future. Industry feels that it has invested a large amount of money and manpower to promote the technology, but that the return has been minimal in terms of real projects.

4.0 REFERENCES

Hughes, P. C. 1986. *Spacecraft Attitude Dynamics*. John Wiley & Sons.

Likins, P. W. and H. K. Bouvier. 1971. "Attitude Control of Nonrigid Spacecraft." *Astronautics and Aeranautics* 9:64-71.

Slafer, L. I. and A. D. Challoner. 1988. "Propellant Interaction with the Payload Control System of Dual-Spin Spacecraft." *Journal of Guidance, Control, and Dynamics*, 11(4):343-351.

APPENDIX

COMPANIES VISITED

APPENDIX

COMPANIES VISITED

The companies and their representatives who were visited during this survey are listed below.

- The Aerospace Corporation, El Segundo, California
  Dr. Terry Brennan, Dr. Geoff Smit, Dr. G. T. Tseng
- Boeing Aerospace, Seattle, Washington
  Dr. Roy Ikegami, Dean Jacot
- General Electric Company, Valley Forge, Pennsylvania
  Dr. A. Das, Roger Harding, Ted Knaak
- General Electric Company, East Windsor, New Jersey
  Niel Goodzeit, Carl Hubert, K. V. Raman
- Harris Aerospace Systems, Melbourne, Florida
  Dave Hyland, John Shipley
- Hughes Aircraft Company, El Segundo, California
  Dr. John Smay
- Integrated Systems, Inc., Santa Clara, California
  Robert Kosut, Michael Lyons
- Jet Propulsion Laboratory, Pasadena, California
  Dr. Robert Laskin, William Laymen, Miguel San Martin
- Lockheed Missiles and Space Company, Palo Alto, California
  Dr. Jean Aubrun, Don Kepler
- Martin Marietta Denver Aerospace, Denver, Colorado
  Charles Deats, Louis Morine, Norman Osborne, Colten Park
- McDonnell Douglas Astronautics Company, Huntington Beach, California
  Edward Riel, Daniel Nowlan
- Rockwell International Corporation, Seal Beach, California
  Dr. Hari Hablini
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