JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 26, No. 4, July–August 2003

Historical Review of Air-Bearing Spacecraft Simulators

Jana L. Schwartz*
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
Mason A. Peck†
Honeywell Space Systems, Glendale, Arizona 85308
and
Christopher D. Hall‡
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

An overview of air-bearing spacecraft simulators is provided. Air bearings have been used for satellite attitude determination and control hardware verification and software development for nearly 45 years. It is interesting to consider the history of this technology: how early systems were first devised and what diverse capabilities current systems provide. First a survey is given of planar systems that give a payload freedom to translate and spin. Then several classes of rotational air bearings are discussed: those which simulate three-axis satellite attitude dynamics. The subsequent section discusses perhaps the most interesting facilities: those that provide both translational and three-dimensional rotational freedom. The diverse capabilities each style of air-bearing testbed provides, the many settings they can be found in, and ways to improve facility performance are described.

Introduction

AIR bearings have been used for spacecraft attitude determination and control hardware verification and software development for nearly 45 years, virtually coincident with the beginnings of the space race. Facilities vary widely, ranging from prodigious government laboratories to simple university testbeds. In this paper, we present the results of our investigation into the historical development of these facilities, including what technologies have been incorporated into spacecraft simulators, what capabilities have been developed, and what functionality current systems provide. This information can serve as a benchmark for the development and use of future testbeds.

There are many solutions to the problem of simulating the functional space environment. Air bearings offer only one of the possibilities. Particular techniques may be more applicable in one situation than another: Whereas the underwater test tank provides an invaluable part of an astronaut's training, the usefulness of submerging a satellite is obviously limited. Certainly air bearings cannot provide the full experience of microgravity; however, they do allow for the manipulation of hardware in a minimal-torque environment. A low-torque environment is often central to the success of high-precision systems, but duplicating it on the ground to validate controls concepts is difficult. Programs that might benefit from hardware demonstration and testing often forego these stages because the influence of gravity and friction render Earth-based behavior unrealistic. An air bearing offers a nearly torque-free environment, perhaps as close as possible to that of space, and for this reason it is the preferred technology for ground-based research in spacecraft dynamics and control. Depending on the type of air bearing, some combination of virtually torque-free rotational motion and force-free translational motion can be achieved. Magnetic suspension systems and gravity offload devices can also produce low-torque dynamic environments, but such systems typically offer a smaller range of motion than that provided by an air bearing.

Test facilities supported by air bearings are intended to enable payloads to experience some level of rotational and translational freedom. Pressurized air passes through small holes in the grounded section of the bearing and establishes a thin film that supports the weight of the moving section. This slow-moving air imparts virtually no shear between the two sections of the bearing. Thus, the air film is an effective lubricant. An air bearing that can support a payload weighing several thousand pounds may require air pressurized to only about 100 psi with a flow rate of only a few cubic feet per minute. A familiar example of such a device is an air-hockey table. These planar air-bearing systems provide one rotational and two translational degrees of freedom for a plastic puck.

Spherical air bearings are one of the most common devices used in spacecraft attitude dynamics research because (ideally) they provide unconstrained rotational motion. As the name implies, the two sections of the bearing are portions of concentric spheres, machined and lapped to small tolerances. One spherical section rotates on an air film bounded by the other section in three degrees of freedom. The rotating surface is rarely a 4π steradian sphere because equipment affixed to the bearing limits the range of motion. Of course, other mechanical arrangements can serve a similar purpose—ball-and-socket joints, for example—but air bearings yield much lower friction. Systems of multiple gimbals can be used for this purpose but such arrangements introduce the problem of gimbal lock. Even if rotational freedom is constrained to avoid this situation, the gimbal dynamics will still interact with the payload dynamics through some nonlinear function of gimbal angle, which makes realistic simulation much more difficult. Spherical air bearings provide a payload rotational freedom without the friction or the singularities inherent in these other mechanical examples while enforcing an analogous level of constraints on the configuration.

The primary objective of air-bearing tests is faithful representation of spacecraft dynamics. With the problem of a representative plant addressed, experimenters have used these simulators to evaluate control schemes ranging from rigid-body dynamics and control of a single spacecraft to jitter suppression in flexible systems. Some have considered problems of relaying laser light for communications or for transferring power; others have used air bearings for fluid-damping measurements, for missile-defense and formation flying demonstrations, and for testing the viability of agile spacecraft attitude control. Regardless of their scientific or engineering merits,

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Received 6 March 2003; revision received 5 May 2003; accepted for publication 5 May 2003.

*National Science Foundation Fellow, Department of Aerospace and Ocean Engineering, 215 Randolph Hall (0203); jana@vt.edu. Student Member AIAA.

†Principal Fellow, 19019 N 59th Avenue; mason.peck@honeywell.com. Member AIAA.

‡Professor, Department of Aerospace and Ocean Engineering, 215 Randolph Hall (0203); cdhall@vt.edu. Associate Fellow AIAA.

air-bearing-based simulators have proven to be valuable pedagogical tools and have, from time to time, played a marketing role during the proposal stages of commercial and government space programs.

In this paper, we provide an overview of air-bearing spacecraft simulators. Natural distinctions among testbed capabilities are used to organize the paper. First, we present a survey of planar systems that give a payload freedom to translate and spin. These facilities are ideal for the understanding of tasks such as formation flying, rendezvous, and on-orbit construction. We then discuss several classes of rotational air bearings, which allow for the simulation of three-axis satellite attitude dynamics. We follow these sections with a discussion on perhaps the most interesting facilities: those that provide both translational and three-dimensional rotational freedom. Within these three sections we outline the diverse capabilities air-bearing testbeds provide and the varied facilities which house them. We focus on the use of air bearings in support of manned space flight in a separate section. Finally, we note that air-bearing performance can be enhanced through careful facility design. We discuss how such improvements have been achieved before offering some concluding thoughts and closing.

Planar Systems

Planar motion, one rotational and two translational degrees of freedom, is of interest for simulations of rendezvous and docking. The other two axes of rotation and out-of-plane translation are arguably less important in the investigation of relative orbital dynamics, at least for the level of effort required. In almost all cases, the test body carries its own air supply and produces its own cushion of air, allowing it to hover on a polished surface. Although we have not found many specific historical references on these testbeds, such facilities were common enough by the mid-1970s to warrant a NASA technical memorandum on how to pour large floors that are sufficiently smooth and level for floating air-bearing vehicles.[1] We have also found documentation on the design of a payload support pad capable of floating 200-lb manned and unmanned test vehicles. This system was designed and manufactured by the Space Maneuvering Devices section of the Space Division of North American Rockwell Group in 1967 for NASA Marshall Space Flight Center.[2]

There are many contemporary planar air-bearing facilities being used to investigate topics in orbital rendezvous. These facilities typically float small, low-mass, generic test bodies because they are more commonly used for controller validation than inertia-equivalent simulation of a flight payload. Researchers at Stanford University's Aerospace Robotics Laboratory (ARL) have several air-bearing test facilities used to investigate many topics. One such subject of interest involves the challenges inherent in the use of robotics for on-orbit construction, servicing, assembly, and repair. A crucial topic in the development of robotic construction techniques is the level at which human operators should be involved. Currently, space robots such as the space shuttle remote manipulator system are controlled by human teleoperation. This technique takes full advantage of the particular abilities that only a person can bring to a closed-loop control system. However, doing so leads to higher levels of cost and risk than would be present in an autonomous system. Experiments to define the useful envelope for human-assisted control are performed using a two-link manipulator arm operating on a passive, free-floating object. As shown in Fig. 1, the arm and target body are able to travel freely on a 6 × 12 ft polished granite table.[3]

Another current area of interest in the field of on-orbit rendezvous is the problem of capturing a damaged satellite. Solving this problem is substantially more difficult than that of construction because the target may be maneuvering autonomously and likely does not have effective grappling points. The Tokyo Institute of Technology is investigating this topic on a 10 × 16 ft plate glass planar air-bearing table with a pair of seven-degree-of-freedom articulated arms; one arm randomly executes commands in simulation of a failing spacecraft, while the other attempts to capture it.[4]

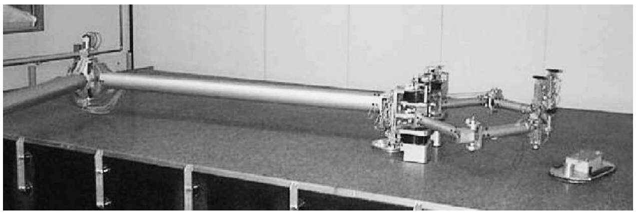


Fig. 1 Two-link manipulator arm at Stanford University's ARL.[3]

The University of Victoria has a planar air bearing that hosts a single robotic arm. It is being used to investigate the optimal joint trajectory of an articulated arm to minimize vibration excitation within the arm elements during a designated maneuver. Through this experimentation they have proven that joint trajectory optimization can significantly reduce the total strain energy incurred within structural elements during point-to-point motions.[5]

The Naval Postgraduate School's Flexible Spacecraft Simulator includes a rigid central body and a two-link appendage, representative of a satellite with a flexible antenna. The main body can float on a set of air pads or remain fixed, and the arm is floated at each articulation point. This facility has primarily been used for the investigation of vibration suppression within the arm.[6] It has recently been adapted for use in investigating formation flying.[7]

Formation flying of two or more functional satellites presents its own set of optimization challenges. The autonomous extravehicular robotic camera (AERCam) is intended to fly freely about the space shuttle and International Space Station to provide video images of external features without requiring an extravehicular activity (EVA). AERCam Sprint was teleoperated within the payload bay during a 1997 space shuttle mission; AERCam II is intended to complete preassigned tasks autonomously during a future mission. Engineers have ground tested control algorithms for AERCam II on an air-bearing table equipped with six global positioning system (GPS) pseudolites for real-time position and velocity sensing.[8]

Similarly, a joint venture among three Japanese corporations has produced a 12 × 18 ft planar testbed, which is being used to test control laws for another EVA-replacement free-flying telerobot concept.[9] At Stanford University, investigation of the use of GPS measurements in formation flying algorithms on a 9 × 12 ft polished granite table top hosting three independent prototype spacecraft is underway. These prototypes are modeled from their ORION microsatellite also intended for launch on the space shuttle.[10]

A useful testbed that has complete freedom in all six degrees is an unlikely achievement within the confines of an Earth-based laboratory. Therefore, students from the Massachusetts Institute of Technology took their Synchronized Position Hold, Engage, and Reorient Experimental Satellites (SPHERES) project on NASA's KC-135A Reduced Gravity Research Program for short-term six degree-of-freedom experimentation in microgravity. Furthermore, SPHERES is manifested to fly on the International Space Station and space shuttle (ISS-12A.1/STS-116). Initial experimental work, however, took place on a planar air-bearing table. Up to three SPHERES were floated on the 4 × 4 ft glass air-bearing table. Figure 2 shows a SPHERES unit mounted on a float interface for the planar testbed.[11,12]

A tethered satellite system offers several design features: gravity gradient stability, vibration and electromagnetic isolation of subsystems, power production, and propulsion. Unfortunately, there has been only one successful tethered space system to date, TiPS, the Tether Physics and Survivability Satellite Experiment. Another effort from Stanford University's ARL, this time to understand some of the complications that lead to tether system failures, led to the development of a planar air-bearing testbed that simulates the microgravity field experienced by a 1.25-mile-long tethered satellite. One end of the tether is fixed, and the natural dynamics of the free end are used to control the attitude of the payload.[13]

Researchers at the University of Washington have investigated the usefulness of microelectromechanical system (MEMS) actuators for docking in the low-torque translational environment provided by a planar air bearing. Each "puck" consists of a set of vertically stacked decks, floating by means of an onboard air system. Two cameras provide stereoscopic imagery for range finding. The effectiveness of such MEMS actuators scales: These experiments have proven their

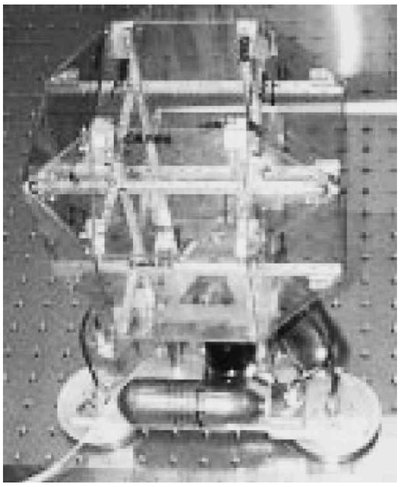
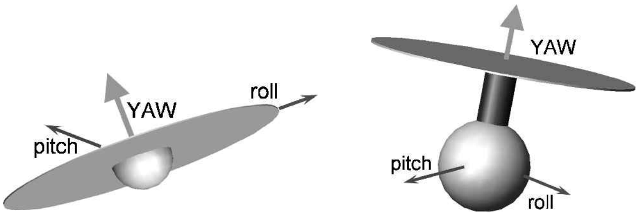


Fig. 2 One of MIT's SPHERES during a planar test.[12]



a) Tabletop b) Umbrella

Fig. 3 Full freedom in yaw platforms.

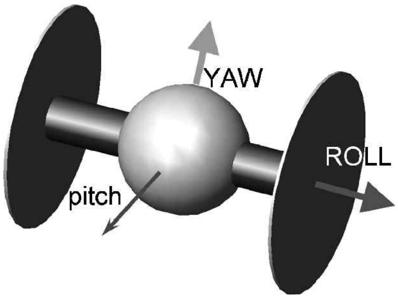


Fig. 4 Dumbbell style: full freedom in yaw and roll.

usefulness in moving a 1-lb puck with an actuator area of 0.3 in.^{2}, and scaling indicates that a patch of only 10 in. radius would be sufficient to position satellites weighing 90 lb when in orbit.[14]

Rotational Systems

The ideal spherical air-bearing testbed would allow its payload unconstrained angular motion in three axes. Actually providing this level of rotational freedom is difficult and in practice requires constraining payload volume. Tabletop- and umbrella-style platforms (Figs. 3a and 3b, respectively) provide full freedom of spin in the yaw axis, but pitch and roll motion are typically constrained to angles of less than ±90 deg. The main structure of a tabletop system usually mounts directly onto the flat face of a hemispherical bearing, and components are mounted to this plate. Umbrella systems interface via an extension rod protruding from the top of a fully spherical bearing, and the primary structure typically extends outward and down, caging the bearing and pedestal like an umbrella held on a very short handle. Careful design of the pedestal and cradle can increase the motion space of these configurations. Another possible style, again on a fully spherical bearing, offsets the mounting area away from the center of rotation by means of two opposing arms, "dumbbell" style (Fig. 4). This configuration greatly reduces structural interference within the rotation space of the payload and thereby provides unconstrained motion in both the roll and yaw axes. Note that the yaw axis for each configuration is defined to be nominally parallel to the gravity vector. For dumbbell systems, the roll axis is defined by the mounting arms; roll and pitch are indistinguishable for tabletop and umbrella systems. The bearings shown in Figs. 3 and 4 must of course each rest on top of a pedestal, not shown here for clarity. We continue the discussion of air-bearing test facilities keeping these geometries in mind.

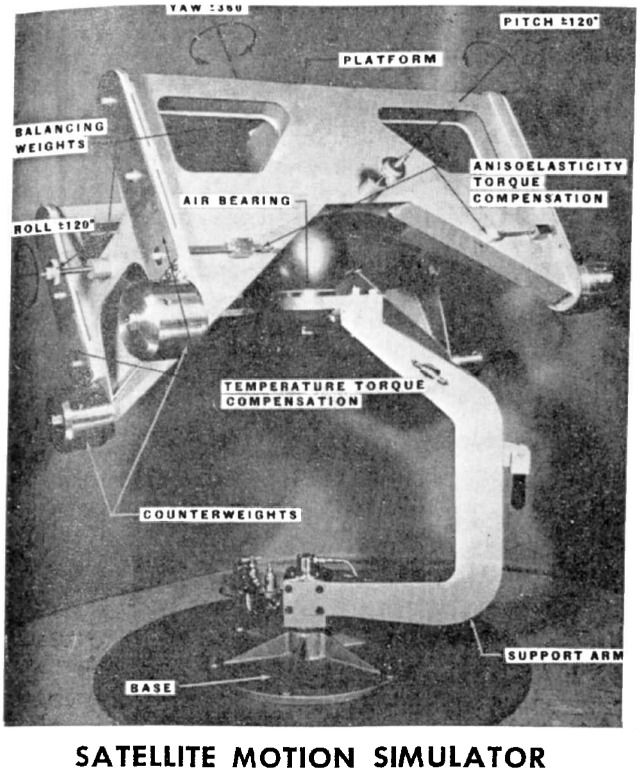


Fig. 5 NASA Marshall Space Flight Center's air bearing, circa 1960.[15]

Tabletops and Umbrellas: Freedom in Yaw

Open documentation is available for more than 10 spherical air bearings in use during the early 1960s. As is often the case with classic engineering, rigorous systems were successfully developed without the benefit of precedent or heritage. The earliest system on which we have complete information is shown in Fig. 5: a three-axis spherical air bearing developed in 1959 at the U.S. Army Ballistic Missile Agency (this facility merged into NASA Marshall Space Flight Center in 1960). This umbrella-style system provided a 900-lb payload full freedom in yaw and ±120 deg in pitch and roll.[15] Such performance is impressive, even by modern standards. This air bearing was used in an experimental case study on the effects of bearing imperfections on disturbance torques[16]; extensions of research on hydrostatic support structures had evolved into investigation of hydrodynamic air bearings by 1960.[17] Researchers at NASA Ames Research Center made use of this testbed along with their own 4000-lb capacity tabletop testbed in the development of control laws for the NIMBUS second-generation weather satellite (nadir pointing) and the proposed Orbiting Astronomical Observatory (inertially pointing).[18–20]

NASA Goddard Space Flight Center developed an early umbrella configuration spherical air bearing designed for measuring energy dissipation. By 1976, poor (or nonexistent) modeling of dissipation effects had caused failures on several spacecraft, including Explorer-1, Applications Technology Satellite-5, and TACSAT-1. Although the problem had been recognized by this time, it had not been well resolved: Modeling the diverse processes that contribute to dissipation effects, including fluid slosh, mechanism movement, and structural bending, is prohibitively complex. Experimental identification of these processes had also proven challenging with previous facilities; measurement of internal dissipation is an area of experimentation where air bearings offer one of only a few possible solutions.[21]

Four types of energy dissipation processes were quantified on this testbed: fuel slosh, passive dampers, reaction wheels, and active nutation dampers. To make the tests as realistic as possible, payload mass properties were tuned to those of the flight vehicle, whereas actuator and sensor suite geometries were configured as per the flight vehicle. The testbed permitted nutation angles of 12 deg. Fuel-slosh tests were performed on six very different vehicle geometries with a range of fill ratios within each physical configuration. Engineering models of fluid-filled nutation dampers were installed on five flight-condition models to measure their effectiveness experimentally. Two reaction wheel designs were tested in simulation of nutation problems encountered during flight. Information gained from these tests led to further development and testing of two active nutation dampers.[21]

The earliest spherical air bearing used at a university was evidently developed at Stanford University in 1975. This tabletop facility was used for center of mass identification in an otherwise fully known physical system. This research evolved from a preceeding planar air bearing project.[22]

These systems represent, at a minumum, the first generation of unclassified air-bearing test facilities. Concurrent literature makes reference to numerous other operational systems for which further documentation is not readily available.[23,24] Early systems were more than likely government classified or company proprietary and hence open documentation does not exist. During that time (and since) many other large- and small-scale air-bearing testbeds were built at the facilities of spacecraft prime contractors including Lockheed Martin Astronautics Hughes Space and Communications (now Boeing Satellite Systems). However, because of the proprietary and often classified nature of those programs, open documentation describing these testbeds is generally unavailable.

When only the systems for which open documentation is available are considered, however, the initial technological understanding demonstrated in these designs is impressive. Major efforts were made to keep the payload's center of mass coincident with the bearing's center of rotation to minimize gravity effects. Primary mounting decks were designed to maximize the useful rotation space of the systems, but were kept sufficiently rigid to avoid platform flexure with changes in attitude, the anisoelastic effect. Optical and other noncontact sensors were developed specifically for these facilities. This level of attentiveness to design details led to the development of unique, highly capable air-bearing test facilities at McDonnell Douglas Astronautics Company–West, the Jet Propulsion Laboratory, NASA Langley Research Center, United Aircraft Corporation, Grumman Aircraft Engineering Corporation, the General Electric Company, and TRW Systems by the early 1970s.[23,25,26] Each of these systems was custom designed and built. Much of the design and manufacturing information on these early systems has been lost, and the machine shops that fabricated them closed. Modern commercial air bearings do not typically provide the same air gap stability as these original systems; a group at NASA Marshall Space Flight Center has recently been recreating the historical designs and manufacturing processes from available documentation in an effort to regain this lost precision.[27]

Early use of air-bearing systems was largely limited to government and industry laboratories. Now, state-of-the-art systems are common in university settings. The Naval Postgraduate School's Three Axis Attitude Dynamics and Control Simulator, shown in Fig. 6 during an optical relay simulation (with Marcello Romano in the background), is currently used in the Optical Relay Spacecraft Laboratory of Naval Postgraduate School's Spacecraft Research and Design Center. First developed in 1995, this tabletop platform carries a suite of actuators and sensors including three reaction wheels, cold-gas thrusters, rate gyros, a magnetometer, and an optical attitude sensor.[28] The air bearing, a Guidance Dynamics Corporation system, provides a 450-lb payload full freedom in yaw and ±45 deg of tilt in pitch and roll.[29] One objective of the simulator is to demonstrate the dynamics and control of a twin-mirror bifocal relay satellite that receives and retargets laser beams. The school's superintendent, Rear Adm. David R. Ellison, describes the project as the "epitome of the joint, interdisciplinary research efforts that will drive our nation's future military capabilities, and which none of us could do alone" (see Ref. 30). The Naval Postgraduate School has begun development of another spherical air-bearing testbed in support of the bifocal relay mirror spacecraft program; the new facility is intended to verify flight hardware in the loop.[31]

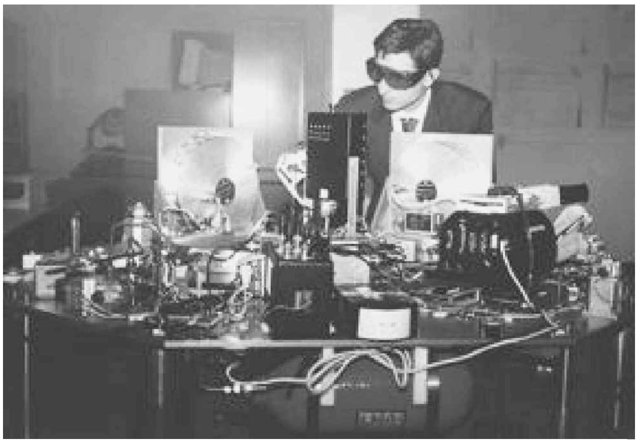


Fig. 6 Naval Postgraduate School's Three Axis Attitude Dynamics and Control Simulator.[30]

Students at Utah State University designed and constructed a custom air-bearing test facility in 1997; initial system requirements were sized for the intent of testing the attitude determination and control system of the Space Dynamics Laboratory's Skipper spacecraft.[32] The tabletop system provides ±45 deg of deviation from the horizon. Through the use of this testbed, "a significant number of integration problems [between spacecraft subsystems] were identified and resolved easily."[33]

The Tele-Education in Aerospace and Mechatronics (TEAM) laboratory is an international project that makes use of modern multimedia and telecommunications technologies to host a virtual laboratory among the seven member universities: three in Canada, the Université de Sherbrooke, the University of Victoria, the University of Toronto, and four in Europe, the University FH Ravensburg–Weingarten, the Università di Bologna, the Aalborg University, and the University of Siegen. One of the laboratory facilities located at the Université de Sherbrooke is TEAMSAT. TEAMSAT is unique among air-bearing spacecraft simulators in that it is representative of the European Space Agency's PROBA spacecraft; all simulator hardware is mounted within the spacecraft's structural bus. Flexible mock solar panels have been added to the design to allow investigation of nonrigid body effects.[34]

The School of Aerospace Engineering at Georgia Institute of Technology (Georgia Tech) has also recognized the value of air-bearing research; they now have two tabletop style air bearings. Georgia Tech's first-generation system was developed to minimum operational capabilities in 2001. This system is primarily being used for undergraduate and graduate education. It was designed and manufactured by Specialty Components, Inc., and provides pitch and roll angles of ±30 deg for a 300-lb payload.[35,36] Georgia Tech's second-generation system is designed with advanced investigations of nonlinear control in mind; it is equipped with a suite of eight cold-gas thrusters and four variable-speed control moment gyros and has the same performance characteristics as their first-generation testbed.[37]

We have presented some of the diverse settings in which air-bearing test facilities can be found. Now we explore some of the many goals that are achieved through their use. Certainly experimental facilities are found to be most useful in the investigation of phenomena for which we do not have effective process models. The equations of motion (and their solutions) for the problem of a rigid spin-stabilized projectile are documented: Solutions can be described by a slow precession mode with a fast nutation.[38] In contrast, analytical models of projectiles with liquid-filled cavities or free-floating internal debris do not lend themselves to simple, closed-form solutions. Thus the accuracy of a testbed for the

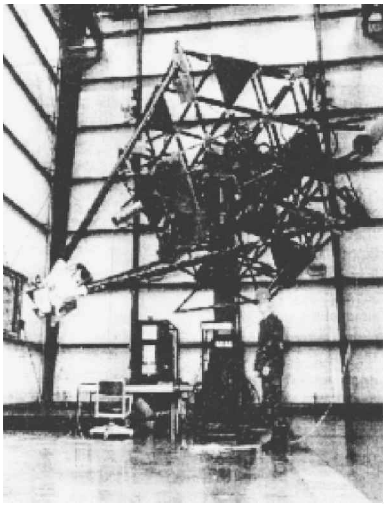


Fig. 7 U.S. Air Force Research Laboratory's ASTREX Testbed.[41]

investigation of real-life projectiles may be verified analytically for simple rigid models and then extended for the investigation of more complex problems. Boeing Satellite Systems (previously Hughes Space and Communications) has for decades been at the forefront of experimental research in fluid/structure interaction. Since the late 1980s, this research has included experimental testing using a small spherical air bearing that supports a dual-spin spacecraft configuration. This rig has successfully predicted damping time constants for several commercial and government spacecraft. Similarly, the Department of Mathematics and Ballistics of the British Royal Military College of Science developed a custom tabletop facility for the experimental study of low-mass (less than 2 lb), liquid-filled projectiles in the early 1980s. When test sections are exchanged, they can investigate various model geometries and slosh materials with coning angles of 10 deg (Ref. 39).

Complex structural dynamics are also difficult to model accurately without some sample of experimental data for comparison. Two of the largest spherical air-bearing facilities, the U.S. Air Force Research Laboratory's Advanced Space Structure Technology Research Experiments (ASTREX) and the U.S. Naval Research Laboratory's Reconfigurable Spacecraft Host for Attitude and Pointing Experiments (RESHAPE), provide facilities for the investigation of control/structure interaction. Both facilities were developed in the early 1990s.

ASTREX can support massive loads, up to 15,000 lb. Shown in Fig. 7, the core of this umbrella testbed is an 18.9-in.-diam spherical air bearing that provides full freedom in one axis and ±20 degrees of freedom in the other two axes. The initial payload structure was modeled from a three-mirror space-based laser beam expander, a fairly generic yet realistic payload body for engineering questions of current interest.[40] The ASTREX facility has been used to research topics ranging from robust nonlinear control and model reduction techniques to the design and implementation of coupled attitude control/energy storage schemes and lightweight composite structures with embedded sensors.[41]

RESHAPE provides ±30 deg of motion about the horizontal axes for a 2500-lb payload. More modest than ASTREX, this tabletop facility has nonetheless been used successfully in the experimental verification of nonlinear controls of rigid bodies with flexible appendages.[42] RESHAPE has been used to verify the effectiveness of smart structures and was used for early experimental work in GPS attitude determination techniques.[43]

The Honeywell, Inc., Momentum Control System and Line of Sight (MCS/LOS) testbed, shown in Fig. 8, resembles an optical or radar satellite with a large dish at the nadir end. This 1000-lb testbed is the first phase in a project that will culminate in 2003 with a 3000-lb system steered by six 225-ft · lb · s control moment gyros (CMGs). The core of this testbed is an umbrella-style spherical air bearing from Guidance Dynamics Corporation offering unconstrained motion about the vertical and ±30 deg of motion about the horizontal axes. The testbed structure is built of modular truss elements, any of which can be replaced with structural dampers (D-Struts$^{\mathrm{TM}}$). The structure can be reconfigured to represent a number of spacecraft architectures, including those with booms and reflector dishes. Its array of six small CMGs (0.25-ft · lb · s momentum and 1-ft · lb torque) can also be reconfigured to match any array geometry of interest. An array of three flight-quality reaction wheels has also been designed as a modular, drop-in replacement for the six small CMGs if reaction-wheel dynamics are of interest.

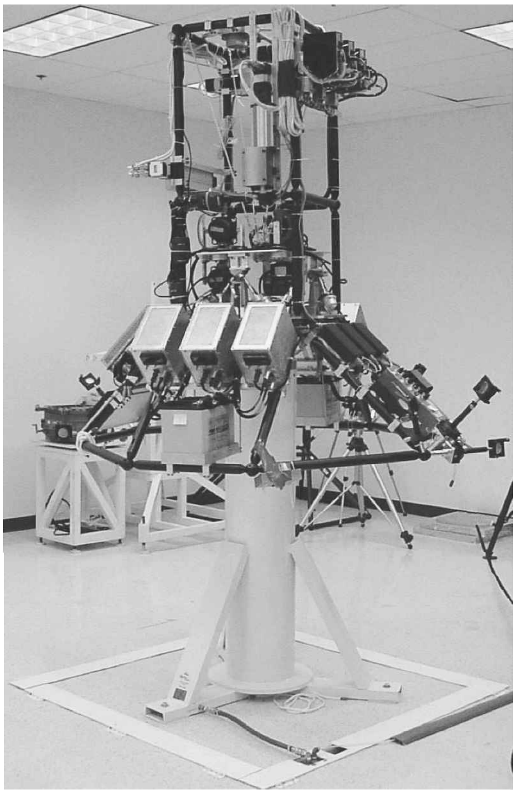


Fig. 8 Honeywell Space Systems's MCS/LOS testbed.[44]

The CMG array is mounted on a hybrid active/passive Vibration Isolation and Steering System (VISS). The combination is known as a momentum control system (MCS). The VISS attenuates CMG-induced disturbances and can be used to augment the attitude control by steering the entire CMG array and introducing passive damping in the structure, generally adding phase to the attitude control. Mirrors mounted on the testbed are used to reflect laser light from a pneumatically isolated table onto three charge-coupled device cameras mounted on the same table. The resulting focal-plane data (six pieces of information) are resolved into submicroradian jitter measurements at a sample rate of up to 30 Hz and, optionally, can be blended and used for attitude feedback as a virtual star tracker via Markley's Fast Optimal Matrix Algorithm (FOAM). The rate sensor is an AG30 ring-laser gyro with less than 1 deg/rt-hr angle random walk.

Phase two of the project will include Honeywell's Miniature Inertial Measurement Unit, which provides less than 0.01 deg/rt · h random walk. Both phases of the project will incorporate the same adaptive, closed-loop mass-balance system: three prismatic actuators with 10–50 lb weights used to eliminate mass-center offset from the air-bearing rotational center to well within 4E-6 in. By the end of 2003, both the current, smaller testbed and the larger one are expected to be operational within the same laboratory, using two air bearings simultaneously. The facility will offer not only MCS and LOS research capabilities but also a testbed for intersatellite communication and relative-attitude steering for formation flying.

The next generation of agile, precisely pointed space systems will demand novel approaches to attitude dynamics and control. The paradigm of ever stiffer, ever more massive designs is likely to give way to active, passive, or hybrid active/passive structural control of

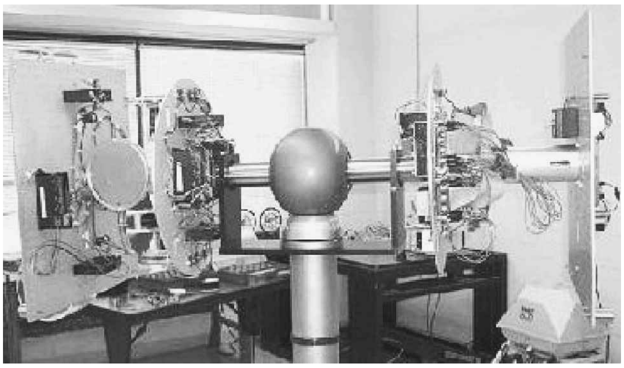


Fig. 9 University of Michigan's Triaxial Air Bearing Testbed.[51]

payloads with soft, well-damped bus-to-payload interfaces. Agility, often achieved through the use of CMGs, can also benefit from the highly damped, readily predictable dynamics characteristic of this new paradigm. The MCS/LOS testbed is designed to assist in research, demonstration, and validation of hardware and software architectures for such spacecraft. It is meant to be available not just to Honeywell, Inc., but also to Honeywell's customers, industry partners, and sponsoring government organizations.[44]

The problem of high-speed interception and rendezvous is also difficult to model without experimental validation. Guidance Dynamics Corporation designed and manufactured two tabletop test facilities to address this need. For The Boeing Company North American Space Systems Division, Guidance Dynamics Corporation developed an air-bearing platform with ±5 deg of deviation from the horizontal for a 1000-lb payload. The platform includes 1000 in.^3 of regulated cold gas to feed sixteen 25-lb high-response thrusters. The system also includes an arcminute-adjustable initialization and release system. In support of the U.S. Air Force Brilliant Pebbles Interceptor program, Guidance Dynamics Corporation provided a system that supports a 100-lb payload through ±15 deg slews to Hughes Missile Systems Company. This testbed provides roll accelerations of over 5000 deg/s^2. To keep roll moments of inertia low, the flight guidance electronics were placed offboard, and data are provided via a fiber-optic link.[§]

International use of air-bearing platforms is documented in the same time frame as work in the United States. Topics of interest are also comparable, including experimental validation of attitude control systems[45] and the stability characteristics[46] and controllability[47] of spinning spacecraft. More recent work has involved attitude control by means of an actuated mass center[48] and hardware-in-the-loop testing of modern spacecraft.[49]

Dumbbells: Freedom in Yaw and Roll

Perhaps the most drastic change in air-bearing test facilities since their earliest use is the flexibility to allow a payload unconstrained rotation in more than one axis. Although the facilities described earlier are undeniably useful tools for experimentation in nonlinear rotational dynamics, there are many flight conditions that cannot be adequately simulated with only one complete degree of freedom.

The University of Michigan's Triaxial Air Bearing Testbed, developed in the late 1990s, is based on an 11-in.-diam spherical air bearing produced by Space Electronics, Inc. As shown in Fig. 9, a stiff shaft passes through the center of the sphere and supports a pair of mounting plates; the shaft is hollow, allowing the wiring harness to pass through the center of the bearing and reach hardware on either plate without interfering with the motion of the payload. The dumbbell configuration provides ±45 deg of tilt in one axis, with the other two axes entirely free of motion constraints. The triaxial testbed sensor suite includes a three-axis magnetometer, accelerometer, and rate gyro. Actuators for this 360-lb payload include six custom reaction wheels and four fans used as thrusters. Recent results include new approaches to parameter identification, adaptive control, and nonlinear attitude control.[50–52]

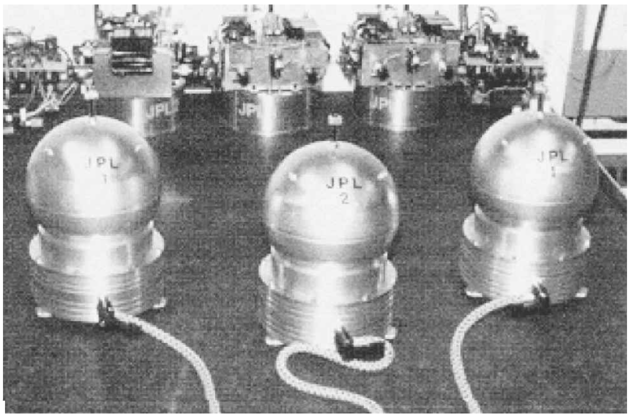


Fig. 10 University of California, Los Angeles/California Institute of Technology model spacecraft spheres.[55]

The U.S. Air Force Institute of Technology's SIMSAT is based on a similar air-bearing system from Space Electronics, Inc.; it can support a 375-lb payload and provides ±30 degrees of freedom about the pitch axis. Developed in 1999, initial work with SIMSAT has involved basic attitude control and the functional multimedia interface; current work is investigating attitude determination requirements to recognize and locate parasite masses added to the system.[53]

Virginia Polytechnic Institute and State University (Virginia Tech) has developed a unique facility comprising two spherical air-bearing platforms, the Distributed Spacecraft Attitude Control System Simulator. Both air bearings are Space Electronics, Inc., models: The smaller is a tabletop bearing supporting a 300-lb payload that can tilt ±5 deg from the horizontal; the larger system is the same model of air bearing being used for SIMSAT. Each air bearing is equipped with three-axis accelerometers and rate gyros for attitude determination. Attitude control options include three-axis momentum/reaction wheels, compressed air thrusters, and CMGs. The payload's center of gravity can be maintained at the bearing's center of rotation via a triad of linear actuators; alternatively, attitude control schemes by center of gravity placement can be investigated. The uniqueness of the Virginia Tech system stems not from particular individual capabilities of either platform, but rather the ability to implement distributed control laws between the two. Coupled with a third, stationary system, it provides an experimental facility for formation flying attitude control simulation. Planar air bearings give the opportunity to test control schemes involving the relative motion of two bodies, but the required coordination in pointing is typically lost. This testbed allows algorithms for relative attitude control to be implemented.[54]

The University of California, Los Angeles/California Institute of Technology model spacecraft testbed uses a unique filled-sphere style, providing even more freedom than a dumbbell configuration. As shown in Fig. 10, in contrast to all of the systems already discussed, this testbed uses hollow spherical bearings with all hardware mounted internally. These small systems provide ±180 degrees of freedom in all three axes. Despite this great advantage in attitude freedom, current tests involve only single-axis rotations. Two of the payloads are floated simultaneously, and spin is controlled by an internal wheel. The "leader" payload is given a predefined series of velocity commands, and the "follower" spacecraft tracks and matches that profile. Future plans include formations with more than one follower spacecraft.[55]

Combination Systems

The most elaborate air-bearing systems combine planar and rotational motion into simulators that provide up to six completely unconstrained degrees of freedom. NASA Marshall Space Flight Center's Flight Robotics Laboratory, described by the NASA Federal

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[§] Data available online, Rasmussen, R. E., "Dynamic Test Plaforms and Air Bearings," http://home.earthlink.net/rerasmussen/dyntestab.htm [cited 6 May 2003].

Laboratory Review in 1994 as "a facility that provides a quality, capability, capacity, product, technology, condition, or process recognized by the world aerospace community as among the best in the world" has a 44 × 86 ft precision floor. The air-bearing spacecraft simulator used on the planar floor provides a 400-lb payload six-degree-of-freedom motion via a floating spherical air bearing coupled with a cylindrical lift. To further enhance simulations, the Flight Robotics Laboratory also provides facilities for two-way radio communication and a GPS satellite simulator. The Contact Dynamics Simulation Laboratory provides the finer resolution experimental facility needed to test docking mechanisms. These simulation capabilities can be linked into the Avionics System Testbed, which produces real time simulations of the full mission timeline in the Vehicle Simulation Laboratory, the Engine Simulation Laboratory, and the Actuator Test Laboratory.[56]

Lawrence Livermore National Laboratory has an ongoing effort to foster the development of autonomous, agile microsatellites (defined as satellites with a mass of 20–220 lb). Spacecraft of interest to Lawrence Livermore National Laboratory include those with the ability to perform precision maneuvers autonomously, including rendezvous, inspection, proximity operations, formation flying, docking, and servicing. Payloads up to 70 lb are provided full freedom in yaw, ±15 deg in pitch and ±30 deg in roll on a dynamic air-bearing test vehicle. The vehicle can then either be floated on a 5 × 25 ft glass top dynamic air table (first tested in the late 1990s), or can be mounted on one of two perpendicular 50-ft dynamic air rails (a new development in this test facility). The planar testbed host is shown in Fig. 11. The large-scale, outdoor, linear rail system shown in Fig. 12 yields five relative (four individual) degrees of freedom for a pair of payloads.[57,58]

We have previously discussed the experimental investigation of fuel slosh on three-degree-of-freedom testbeds. These systems enforce a somewhat unrealistic constraint: The center of rotation of the test body is constrained to rotate about the center of curvature of the bearing, a fixed point in an Earth-fixed, rotating reference frame. Generally, the center of mass of the flight payload will be moving with respect to a body-fixed coordinate system due to internal mass motion and propellant usage. Oral Roberts University has developed a four-degree-of-freedom air-bearing test facility for the investigation of coning stability characteristics of nonrigid, spinning spacecraft in the presence of thrust. They have solved the center of mass constraint problem by mounting a custom tabletop air bearing on a turntable. The turntable traverses the air bearing about an 128-in.-diam circular path at a speed of 1 Hz, providing a centripetal acceleration of 6.5 g. Thus the 200-lb payload experiences a simulated thrust composed of the centrifugal and gravitational forces. Modern rocket motors rely on small, active thrusters to control coning motions; this testbed is being used to develop a passive mass–spring–damper control device to eliminate these motions in a less expensive way.[38]

Manned Space Flight

The U.S. manned space flight program has benefitted from the use of air-bearing training facilities from the beginnings of the program. Starting in late 1959, each Mercury astronaut was scheduled for 12 h of "essential" level training on the Air-Lubricated Free-Attitude trainer (ALFA). Designed and developed by the NASA Manned Spacecraft Center, the trainer translated across the floor and had full freedom in roll and ±35 deg in pitch and yaw.[59] Figure 13 shows the trainer. The astronaut would lie in the central open area, above the spherical bearing. The base pads (as in the lower right corner) provided the air cushion for planar motion.

NASA Ames Research Center also had an early rotational motion training platform,[23] and The Boeing Company shortly followed suit in their development of a Lunar Orbiter Attitude Control Simulator.[24]

The manned space program continues to make use of planar air-bearing research. In 1998, a NASA technical publication detailed the use of NASA Marshall Space Flight Center's precision air-bearing floor in experimental evaluation of skill in EVA mass handling. Astronauts were assigned various EVA-related challenges to evaluate their adaptability and skill in handling mass in a low-force environment. Although the planar motion testbed does not provide the same level of freedom as the EVA simulation water tank, it provides an easily instrumentable, low-drag facility.[60]

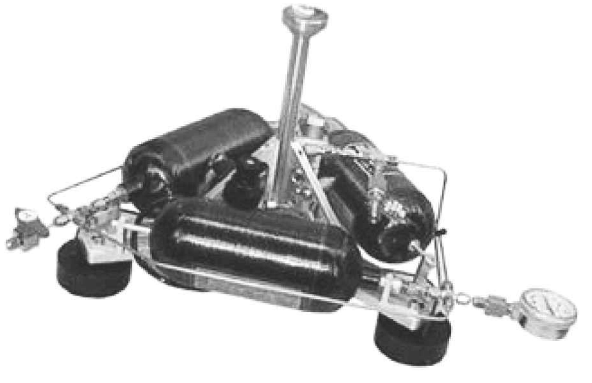

Fig. 11 Lawrence Livermore National Laboratory's dynamic air table host.[58]

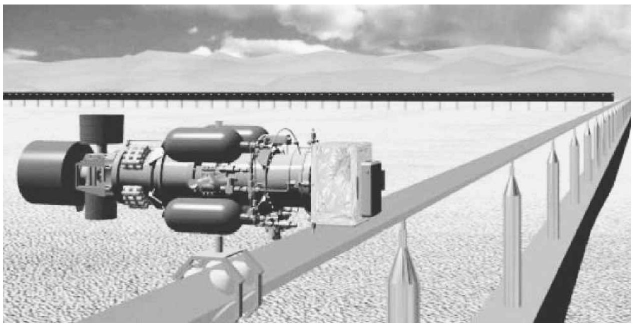

Fig. 12 Lawrence Livermore National Laboratory's dynamic air rail concept.[58]

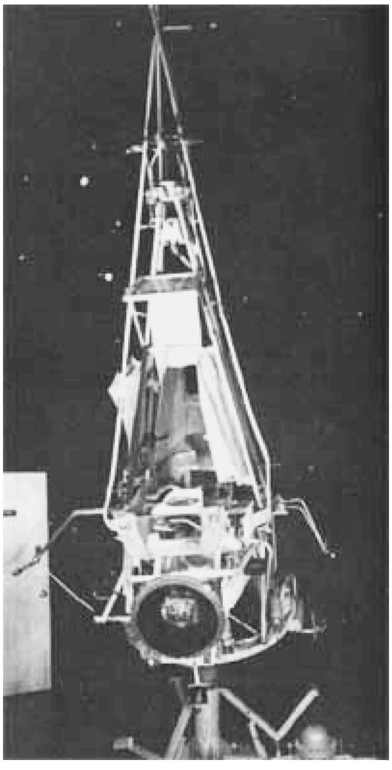

Fig. 13 ALFA Mercury astronaut trainer.[59]

Facility Enhancements

There are many advantages of air-bearing facilities over other mechanical options in providing an unconstrained motion space. However, the low-torque setting provided by the bearing is reasonably only as useful as the facility in which it is housed: Eliminating gravity torque effects from the simulation provides little benefit if other environmental torques affect the motion. Devising ways to mitigate these other disturbance torques is nearly as well developed as the air-bearing facilities themselves. Depending on required precision, it is perhaps in this area that the effectiveness of a facility can be measured. An overview of basic testbed capabilities is shown in Figs. 14 and 15; we discuss some unique design enhancements later.

If papers can be defined generationally, the grandfather of this work is a conference paper presented by Smith in 1964.[23] Smith presented a description of several systems, along with an overview of the torques that act on the rotor of an air bearing. Smith defined four classes of disturbance torques and listed particular sources for each group, as follows: 1) torques arising from the platform include static unbalance, dynamic unbalance, anisoelasticity, material instability (stress, temperature, humidity, evaporation), and gravity gradient; 2) torques from the bearing include aerodynamic turbine effect and exhaust air impingement; 3) torques from the environment include air damping, air currents, magnetic fields, vibration, radiation pressure, and equipment motion (solenoids, relays); and 4) torques from the test system include electrical wire to base, mass shift in bearings and loose fits, battery discharge, reaction jet supply discharge, and replacement of components.

Torques from groups 1 and 4 can be mitigated through testbed design: well-designed structures outfitted with well chosen components. Group 2 effects received more attention in the early development of air-bearing systems than they do now; although internal bearing effects may be important in the design and operation of industrial gas bearings, they impart a negligible effect on the classes of systems we are considering. The third class of disturbance torques, those from the laboratory environment, are the most challenging to resolve.

Several facilities have developed large-scale means to mitigate environmental torques. Thermal and air currents often cause the grossest effect and are simplest to eliminate: several NASA facilities are installed within vacuum chambers.[20,21] The facility designed for The Boeing Company's Lunar Orbiter Attitude Control Simulator could not make use of this solution because it was piloted. Instead, the room design included full air circulation and thermal control. Furthermore, the system was mounted on a 90,000-lb concrete slab supported by seven air springs; thus, the system was effectively isolated from seismic effects.[24] NASA Marshall Space Flight Center installed one of their systems within a set of Helmholtz coils to cancel the effect of the terrestrial magnetic field on the payload.[23]

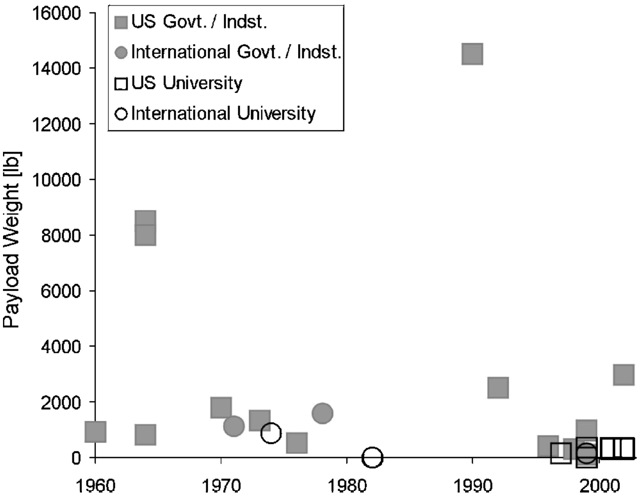

Fig. 14 Overview of air-bearing testbed capabilities: Payload weight (pounds).

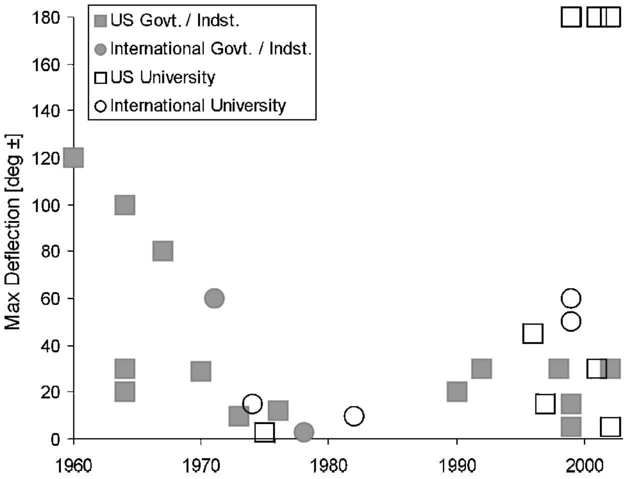

Fig. 15 Overview of air-bearing testbed capabilities: tilt (degrees ±).

Conclusions

Sputnik was launched in 1957. Explorer-1 was launched in 1958. The earliest air-bearing spacecraft simulator is documented in 1960. Truly these systems have played an integral role in improving space technology since the beginnings of space exploration.

Planar air bearings provide an ideal testbed for simulating two-vehicle dynamics. Control techniques for relative orbital maneuvers such as formation flying, rendezvous, docking, space construction, and tethered systems, can be fully developed and tested before launch. Spherical air bearings offer the freedom to experiment with attitude control techniques: pointing, tracking, performing system identification, and compensating for unmodeled dynamics. Facilities that combine these techniques can nearly replicate the actual low-force, low-torque flight environment. Such systems have played a vital role in the development of both manned and unmanned spacecraft.

In Figs. 14 and 15, we attempt to summarize the spherical air-bearing facilities discussed in this historical survey. Two measures of testbed effectiveness, payload weight and angular freedom, are plotted against testbed development date. Because all of the systems provide full freedom in yaw (±180 deg), this value is not indicative of performance; the larger of the pitch and roll angles is plotted. We distinguish four classes of air-bearing systems in these plots. First we group by development setting: systems from government and industry laboratories vs those in university settings. We further subdivide each of these into domestic and international systems. Shaded symbols indicate government and industry facilities, and open symbols indicate university testbeds. Squares represent domestic systems, circles international. Note that the sampling of data in Figs. 14 and 15 may appear inconsistent; this is due to incomplete data recorded in the literature.

The payload weight distribution plot shown in Fig. 14 demonstrates several trends. As might be expected, government and industry facilities were developed several years before the first university facilities. This is likely due to the classified nature of the research and technology validation studies being performed. Also, because university facilities are typically smaller and less equipped than government and industry laboratories, the payloads are necessarily smaller. Figure 15 shows some additional trends. Early government and industry facilities were designed to provide heavy payloads a large motion space to operate in, and each laboratory developed its own testbed. After an overall decline in testbed capabilities in the mid-1970s–1980s, there are now a few highly capable government and industry facilities that are shared by the community. Modern university facilities provide greater angular freedom than those in government and industry, perhaps because university researchers are more interested in the development and validation of new control schemes rather than demonstrating real-world technologies.

The list of references listed here is not exhaustive, though we have included at least one reference for each system. Some systems, ASTREX, for example, have been involved in many research projects that are not cited here. We would encourage anyone interested in this subject to only begin their investigations making use of our reference list. The facilities we have discussed will advance in capability, and new ones will develop. With further research, perhaps additional historical systems can be rediscovered.

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