Conclusions

This Note has established some stability properties of second-order models along with an easily computed stabilizing control law. These results are related to the concept of a positive real system, for which we have shown that negative output feedback with any positive definite gain matrix satisfies a linear-quadratic optimality criterion.

Acknowledgment

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Measurement of the Passive Attitude Control Performance of a Recovered Spacecraft

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Introduction

WE report a direct measurement of the attitude-stability of the Long Duration Exposure Facility (LDEF) using a novel silver detector. The University of Alabama in Huntsville (UAH) experiment A-0114, designed primarily to investigate reactions of atmospheric atomic oxygen with materials' surfaces in orbit,[1] also carried a passive device to record the attitude of the vehicle in its orbit. The device showed that the LDEF maintained a very stable attitude during its flight of almost six years. There was a permanent stable offset of 8.0 ± 0.4 deg from nominal in the yaw plane and 1 deg in pitch. The LDEF was a hollow, cylindrical, 12-sided spacecraft, 9.1 m (30 ft) long, 4.3 m (14 ft) in diameter, weighing 9,720 kg (21,400 lb). It was built by NASA Langley Research Center and was launched at an altitude of 480 km by the Space Shuttle Challenger in April 1984 and retrieved by the Columbia in January 1990 at an altitude of 310 km. The spacecraft carried neither a telemetry system nor active attitude measuring and control systems. The facility was designed to stabilize in orbit in the gravity-gradient mode with its long axis parallel to the Earth radius. Predicted rotation about this axis was uncertain.

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Background

A long cylindrical object in a circular orbit readily stabilizes about its pitch and roll axes such that its long axis (now that of yaw) is pointing toward the Earth's center. Three-axis stabilization (including the yaw axis) may be achieved if the moments of inertia about the pitch and roll axes differ by a suitable amount. When forced to rotate at orbital rate by gravity gradient torques, a spacecraft will tend to move, that is, rotate about its yaw axis toward the orientation of maximum moment of inertia. The LDEF spacecraft was stabilized in this way by placing weights on the front and back surfaces. In addition, a magneto-viscous damper was used to absorb unwanted angular momentum. This attitude stabilization allowed placement on the LDEF front surface of several experiments to study the effects of atmospheric gases (mostly atomic oxygen at those altitudes) on materials' surfaces. The effects, including erosion of carbon and polymers, corrosion of silver, and oxide film growth on many metals, may be dependent on incidence angle of the gas atoms at the surface. Thus the angular offset of the LDEF attitude in its orbit must be known. Predictions of the capture and attitude stability of the LDEF had been performed,[2,3] including the effects of orbit eccentricity, solar pressure, aerodynamic forces, magnetic dipole, and the magnetically anchored rate damper. Predictions of offsets in pitch, roll, and yaw, and oscillations about these offsets were also made. Although residual damping torques from the magnetic damper were not negligible after attitude stability was achieved, the predicted offsets were dominated by aerodynamic forces. These result when the center of mass of the spacecraft does not coincide with the center of pressure (assumed to be at the geometric center). Displacement of these centers along the yaw axis (local vertical) results in pitch offset, and displacement along the pitch axis results in yaw. The yaw offsets and uncertainties are much larger since the restoring torques are two orders of magnitude less than those for pitch. Predicted maximum offset angles for the final configuration were 1 to 2 deg in pitch and up to 30 deg in yaw.[3] Roll errors were small but in any event unmeasurable by the UAH device.

Experimental Measurement

The atmosphere at altitudes of several hundred kilometers consists predominantly of oxygen atoms produced by dissociation of O_2 molecules by solar ultraviolet photons. As a satellite moves through this thin but chemically reactive atmosphere, oxygen atoms impinge on its front surface at satellite velocity (approximately 8 km/s), modified somewhat by the random thermal velocities of the atoms themselves. The sensing device uses the property of silver to adsorb oxygen atoms with high efficiency, being converted to silver oxide. The optical appearance, transmission, reflectivity, and electrical properties of silver films are drastically changed during this process. The phenomenon has been used to measure atomic oxygen concentration on sounding rockets[4] and to measure the angular distribution of 5 eV (8 km/s) oxygen atoms scattered from a solid surface in low Earth orbit.[5] This is the first application of the technique to attitude sensing on orbital vehicles.

The device consisted of a hemispherical stainless steel cup, radius 32.5 mm (1.28 in.), coated on the inside surface with an evaporated Ag film 5 μm thick. The cup, facing forward in the nominal orbital direction, was mounted behind a plate with a hole, 0.5 mm (0.020 in.) in diameter, positioned at the center of the hemisphere. This aperture admitted the atomic oxygen flux into the device during the entire 5.75 years of the flight, though the planned duration was only 10 months. Though the silver film was severely overexposed, nevertheless the impact zone of the orbital-velocity oxygen atoms on the film is clearly evident in Fig. 1. During the flight, it is estimated that 2×10^{19} oxygen atoms entered the device. These atoms diverged from the orifice with an angular distribution dependent on gas temperature and satellite velocity as previously described.[6] They struck a zone on the hemisphere approximately 0.8 cm in diameter. This provided a dose of 4×10^{19} atoms cm^{-2} to the Ag film in this zone, enough to heavily oxidize the film. Oxygen atoms were then diffusely reflected by the Ag_2O surface and again off the back of the aluminum mounting plate. Since the entire Ag film in the detector was heavily oxidized, as clearly seen in the photograph, recombination of atoms to O_2 (which does not significantly react with Ag) is not a dominant process. There was evidence of fresh silver revealed behind portions of peeled Ag_2O film. Though all portions of the film have received large doses of atomic oxygen, the area struck by the fast atoms entering the device is qualitatively different and produced a visible elliptical spot of more adherent oxide seen in Fig. 1. The dimensions of this spot are shown diagrammatically in Fig. 2, and its offset with respect to the center of the circle, which is the projection of the detector hemisphere, were recorded. The device was placed on the spacecraft so that if the attitude of LDEF had been nominal, the oxidation spot would have been in the center of the disk. Angular offset of the vehicle from nominal results in an equal angular displacement of the centroid of the spot from the center of the disk. The size and shape of the spot are related to both the temperature of the orbital gas and to the stability of the vehicle about its mean position. Oscillation about either yaw or pitch axis

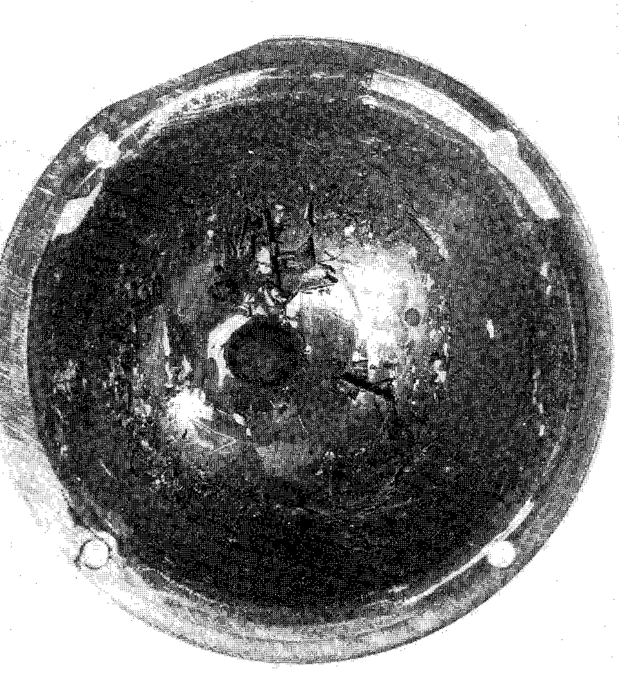

Fig. 1 Photograph (plan view) of the exposed attitude-measuring device after retrieval from orbit. The impact zone of the orbital velocity oxygen atoms is visible as an ellipse slightly off center.

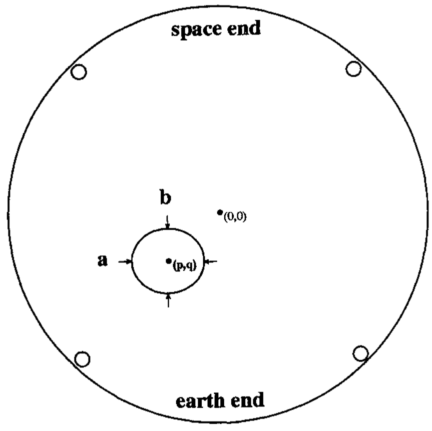

Fig. 2 Diagrammatic representation of Fig. 1 showing the coordinates referred to in Table 1.

would cause elongation of the spot in orthogonal directions. The viewer sees both Figs. 1 and 2 in the same sense, looking backward along the velocity vector, as if looking at the inside of the cup through the small aperture in the front plate. The point (0,0) in Fig. 2 is the center of the flat projection of the hemispherical cup, while (p, q) is the geometric center of the elliptical oxide spot observed. If the orientation of LDEF had been perfect, (p, q) and (0,0) would have coincided.

Measurements were made in two ways. The silver cup was directly viewed with a digital image analysis system using a 512 $\times$ 512 CCD camera. The centroid of the circular image of the cup was found, and its separation from the centroid of the slightly elliptical spot was measured. In the second method, a photographic image of Fig. 1 (made with a Mamiya 645 camera and 80 mm Macro lens) was directly measured. The combined results are shown in Table 1. Corrections for curvature were insignificant over the angular range of interest and were not included.

Discussion

Before the size and shape of the spot produced on the silver film in our device may be used to estimate the motions of the spacecraft about its center of mass, we must establish the broadening due to thermal motions of the gas atoms. The angular dispersion of atoms passing through an orifice in an orbiting plate has been calculated as a function of temperature by Peters et al.[6] and is shown in Table 2. The effect of temperature is shown here in the speed ratio S_r, which relates the satellite speed to the most probable Maxwell-Boltzmann speed of the atoms. The width of the angular distribution of atoms passing through an orifice in a plate under these conditions increases markedly with temperature. Gas temperatures at orbital attitudes vary strongly with cyclical solar activity. LDEF was in orbit for a full half solar cycle during which the mean gas temperature may have varied over the range of 700–1500 K, corresponding to angular distributions of 10.4–15 deg. We believe that the minor diameter of the elliptical spot (14.1 deg) is consistent with the gas temperature during the flight, and no evidence exists for broadening caused by significant instability in the spacecraft pitch plane.

The observed ellipticity (1.05) with the major axis in the satellite yaw plane indicates an instability of 0.4 $\pm$ 0.15 deg

Table 1 Measured coordinates and ellipticity of the oxygen atom impact zone [the point (0,0) is at the center of the device]

Coordinates of spot centroid (p,q)		Major, minor axes of spot (a,b)
10^{-3} in.	deg	deg
$-(178 \pm 8, 21 \pm 8)$	$(8.0 \pm 0.4, 1.1 \pm 0.4)$	(14.8, 14.1)

Table 2 Calculations of the angular distribution function for oxygen atoms passing through an orifice in an orbital plane at various gas temperatures

Temperature, K	Speed ratio,[a] s_r	Angular width FWHM,[b] deg
600	9.87	9.60
700	9.13	10.36
800	8.54	11.06
900	8.06	11.70
1000	7.64	12.32
1100	7.29	12.90
1200	6.98	13.44
1300	6.70	13.97
1400	6.46	14.48
1600	6.04	15.44
1800	5.70	16.32
2000	5.40	17.16

[a]The speed ratio of the satellite velocity (with respect to a stationary atmosphere) taken here as 7.77 km/s to the most probable speed for a Maxwell-Boltzmann distribution for O atoms at the given temperature.
[b]Full width at half maximum.

(full width) in this plane over a significant portion of the orbital exposure.‡ Since the detector system records all angular instabilities on top of one another, time-dependent instabilities cannot be resolved. The result is weighted by oxygen-atom exposure rather than just time averaged. Since the O atom density is exponential with decreasing altitude and the LDEF descended in its orbit at an increasing rate, the bulk of the oxygen exposure was accumulated during the last few months before capture. However, the attitude instabilities themselves are most likely to have been caused by aerodynamic forces. These were also at maximum during the latter portion of the flight as the satellite entered the denser regions of the atmosphere. Thus, the yaw instability of ±0.2 deg may only have occurred late in the flight.

Conclusions

Evidence from the passive attitude detector on experiment A0114 showed that the LDEF spacecraft maintained a highly stable attitude during its 5.75-year flight. There was a small offset yaw of 8.0 ± 0.4 deg clockwise from nominal attitude as viewed from space. There also appeared to be an oscillation of ±0.2 deg about this offset yaw.‡ The satellite was pitched slightly forward by about 1 deg (space end leading). Those experiments on the LDEF that depend on orientation relative to the forward direction, such as atomic oxygen reaction cross-section measurements, may need to be corrected for the angular offset. The gravity-gradient mode of spacecraft stabilization has great cost benefits over those using active systems, particularly for long-lived missions, but uncertainty in yaw stability has been a concern for many applications. With demonstration of the high degree of stability about the yaw axis experienced by the LDEF, the instabilities predicted for passively stabilized spacecraft may be reduced.

Acknowledgments

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‡It has been observed[7] that the corotation of the atmosphere with the Earth itself would produce a deviation of ±1.5 deg in incidence angle of the atmosphere with the LDEF front surface as it crossed the equator. Such an effect, which we believe to be real, would be indistinguishable from an oscillation in yaw.

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Observability Under Recurrent Loss of Data

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I. Introduction

THE vehicle management system (VMS) in the future generation aircraft would require highly integrated control (e.g., integrated flight-propulsion and flight-fire controls) and decision (e.g., flight trajectory management) functions that will have direct flight-criticality implications. For example, the integrated flight-propulsion controller must take into account the effects of a strong coupling between the propulsion and aerodynamics to take advantage of propulsive moments and forces for flight maneuverability. These functions, combined with new strategies [e.g., self-repairing and reconfigurable flight control systems, management of actuator failures and surface damage, control surface reconfiguration, and applications of artificial intelligence (AI) techniques to distributed decision support systems], would generate significantly large and distributed computational requirements. A communication network [e.g., Society of Automotive Engineers (SAE) token bus] is needed for information processing between the onboard spatially dispersed computers, intelligent terminals, sensors, and actuators to implement the aforementioned functions.

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