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Operational Factors Affecting Microgravity Levels in Orbit

R. E. Olsen* and J. Mockovciak, Jr.†
Grumman Aerospace Corp., Bethpage, N.Y.

Microgravity levels desired for proposed materials processing payloads are fundamental considerations in the design of future space platforms. Disturbance sources, such as aerodynamic drag, attitude control torques, crew motion, and orbital dynamics, influence the microgravity levels attainable in orbit. The nature of these effects is assessed relative to platform design parameters such as orbital altitude and configuration geometry, and examples are presented for a representative spacecraft configuration. The possible applications of control techniques to provide extremely low acceleration levels are also discussed.

Introduction

THE development of large space platforms containing materials processing payloads will require very low acceleration levels during on-orbit operations. A review of proposed payloads indicates desired acceleration requirements spanning three orders of magnitude, from 10^{-5} to $10^{-8}g$'s, with the latter levels considered a goal.

The purpose of this paper is to evaluate the implications of relevant platform design characteristics which affect acceleration levels during orbital operations.

Discussion

The accelerations level experienced at any point on or within an orbiting structure is the net effect of all the forces acting at that point. The primary sources of these forces may be grouped into four general types: 1) environmental, caused by forces such as aerodynamic drag or solar pressure; 2) orbital dynamics, caused by the gravitational effect on points not co-orbital with the center of mass of the configuration‡; 3) rotational effects, caused by attitude maneuver rates and accelerations; and 4) crew motion, caused by reactive forces which result from crew activities.

The following sections discuss these sources individually as a function of spacecraft characteristics followed by an evaluation of their combined effect.

Environmental

For platforms in low Earth orbits, the dominant environmental effect is the aerodynamic drag force which is primarily a function of the area and drag coefficient of the configuration, the orbital altitude, and the date. The date is particularly significant because of the solar cycle which produces a large variation in atmospheric density.

The acceleration level produced by aerodynamic drag is shown in Fig. 1 as a function of orbital altitude for a family of configurations which vary from a power module with large, low mass solar arrays to a lower area-to-mass ratio, large space structure platform. These data are based on maximum nominal density values in the solar cycle.

A goal of $10^{-8}g$ has been indicated as a desired g level for future materials processing experiments. For purposes of illustration, the $10^{-8}g$ line shows where a power module (PM) and materials experiment module (MEM) would be in relation to the two curves shown. Circular orbit altitudes of at least 630 km are thus needed for the PM/MEM combination based on consideration of aerodynamic drag alone. Note that a variation in orbit altitude of about 175 km results in an order of magnitude change in g level, as indicated in Fig. 2, independent of the mass to cross-sectional area ratio.

The possible incorporation of spacecraft design techniques that will actively compensate for the drag force is discussed later.

The other environmental disturbance effect is solar pressure that exerts a force on the spacecraft proportional to the projected solar area during the daylight portion of the orbit only. The magnitude of this effect, which is essentially constant with altitude, is shown in Fig. 1. It drops to zero during the night portion of the orbit.

The net effect of the aerodynamic drag and solar pressure forces is to produce a cyclic effect during each orbit with a magnitude and period related to orbital altitude, as illustrated in Fig. 3.

Thus, desired maximum levels of acceleration as low as $10^{-8}g$ caused by environmental disturbances are attainable by operating at altitudes above 740 km.

Orbital Dynamics

For a nonspinning body in a perfectly circular orbit about the Earth, a zero-g condition is only produced at points in the body that are in the same orbit plane and at the same orbital altitude as the center of mass of the body, i.e., points that lie along the orbital path of the center of mass. The acceleration at other points results because the gravitational attraction is not perfectly balanced by the centrifugal acceleration.

From the Clohessy-Wiltshire equations[1] for a circular orbit, the following expressions are derived in terms of acceleration in g's per meter of displacement from the spacecraft's center of gravity:

$$\text{max in-plane acceleration} = 2(\omega^2/9.8)$$

$$\text{max out-of-plane acceleration} = (\omega^2/9.8)$$

where ω is the orbital rate in rad/s. The maximum total acceleration per meter is then $\sqrt{5}(\omega^2/9.8)$.

Figure 4 illustrates the variation of this attainable acceleration level as a function of orbital altitudes up to geosynchronous and the mounting distance of the experiment from the c.g. At an altitude of 740 km, the experiment must be kept within 3.4 centimeters of the c.g. to meet a $10^{-8}g$ level requirement. To provide $10^{-8}g$'s at 1 m from the c.g. would require an altitude of about 14,800 km.

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*Senior Engineer, Guidance & Control Section. Member AIAA.
†Program Manager, Civil Space Programs. Member AIAA.

‡The orbital dynamics force is distinguished here from the "gravity gradient" torque which is caused by the differential effect of the forces due to gravity.

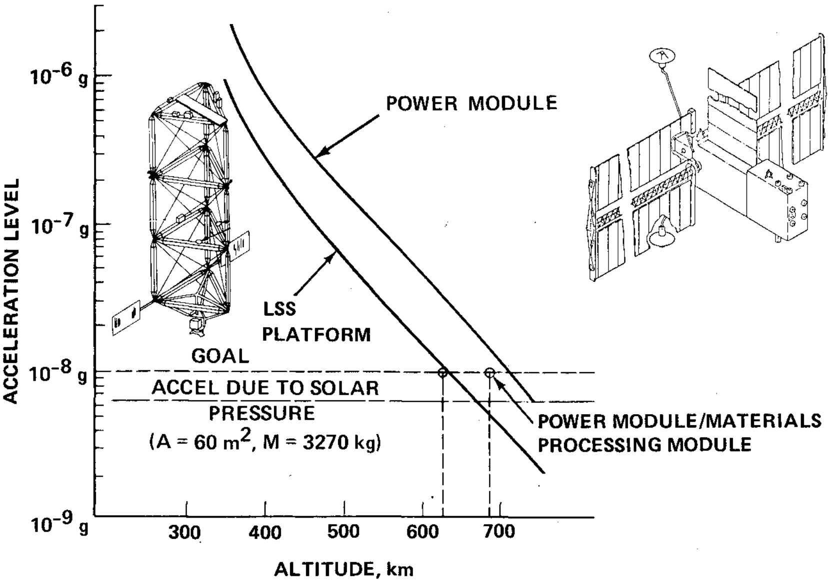

Fig. 1 Aerodynamic drag effects.

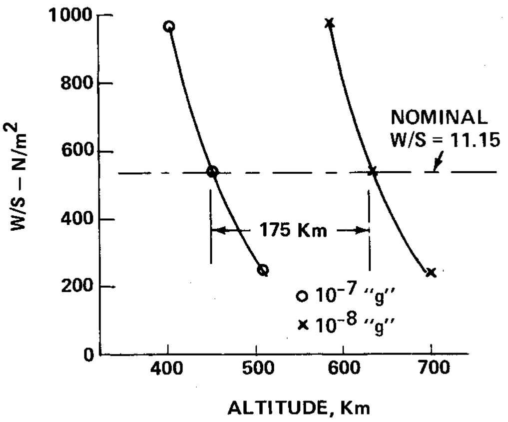

Fig. 2 Dynamic pressure variation.

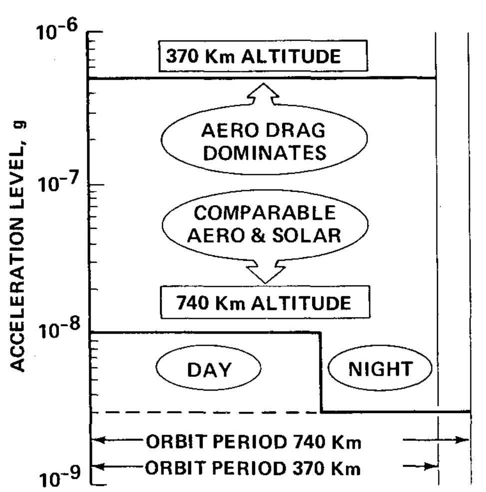

Fig. 3 Environmental effects.

Rotational Effects

Rotational motion of a space platform causing accelerations on materials processing experiments are primarily caused by attitude control and maneuver torques and rates. Slewing of other gimballed payloads that result in reactive torques on the platform are also included in this category.

The acceleration a_c induced at a distance r from the c.g. by attitude control torques is

$$a_c = r\alpha$$

where α is the rotational acceleration.

For a representative space platform configuration with a moment of inertia of 1.0×10^7 kg m^2, and a peak control torque of 220 N-m corresponding to a Skylab-type control moment gyro (cmg), the resulting acceleration vs distance from the c.g. as a function of percentage of control torque is as shown in Fig. 5. The particular peak control torque is a function of disturbance torque levels, control authority level, and the nature of the control system design, e.g., passive gravity gradient stabilization vs active momentum management with periodic unloading. Reduced control torque levels may be possible by using reaction wheels and continuous magnetic unloading in certain applications.

Accelerations caused by periodic platform attitude maneuvers that may be required in support of certain mission operations result in an acceleration a_m at a distance r from the c.g. that is

$$a_m = r\omega^2$$

The variation of this effect is presented in Fig. 6 which shows that higher slew rates (greater than 0.5 deg/s) result in fairly high acceleration levels (about $10^{-6}g$'s) at distances over 1.3 m from the c.g. The goal of 10^{-8} is obtainable only with very low slew rates, e.g., 0.01 deg/s, and even then distance from the c.g. must be limited to a few meters.

Crew Motion

The unwanted acceleration resulting from crew motion is a function of the mass of the spacecraft and the nature of the crew activity. The magnitude of this effect vs spacecraft mass is shown in Fig. 7 for deep breathing, console operating, translating, and sneezing based on Skylab T-013 crew motion experiments.[2] In general, these effects exceed the range of desired acceleration levels by significant amounts.

Combined Effects

The total acceleration profiles over one orbital period as a result of the combined effect of the disturbances just discussed are presented in Figs. 8a and b for 370 km and 740 km altitudes, respectively. The relative order of these effects compared to the desired range of 10^{-5}-$10^{-8}g$'s is made evident in these figures.

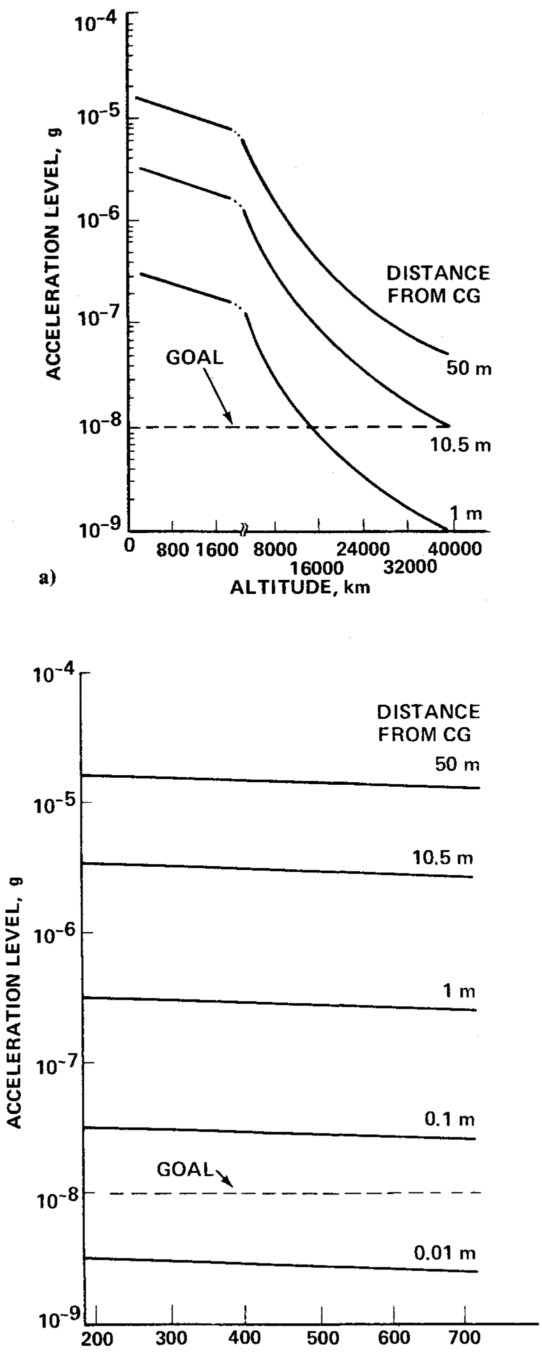

Fig. 4 Induced accelerations; a) high altitude orbital effect, b) low altitude effect.

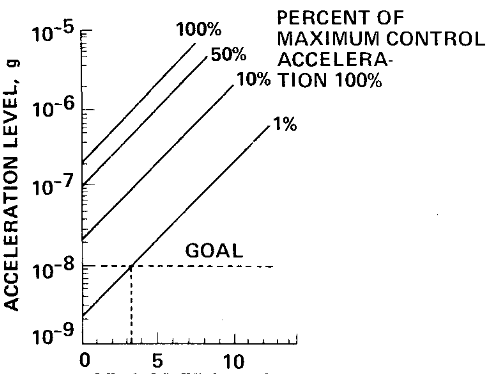

Fig. 5 Control; induced acceleration.

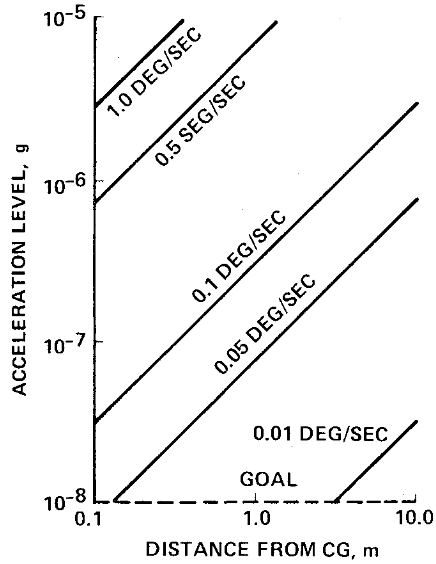

Fig. 6 Slew rate; induced acceleration.

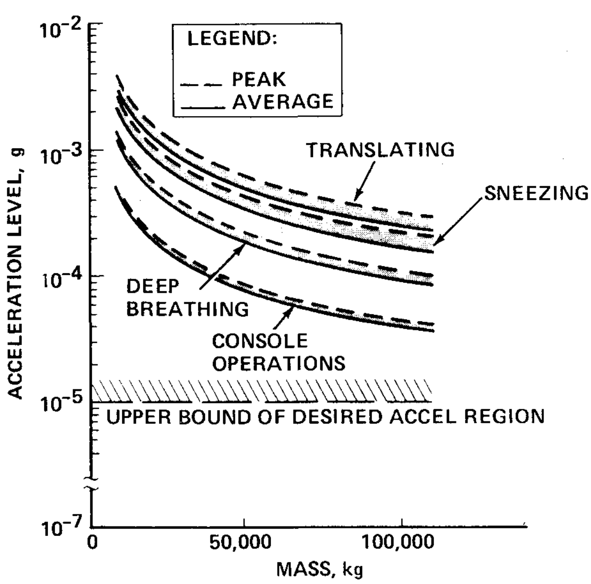

Fig. 7 Crew motion; induced accelerations.

Intermittent crew motion is seen to be the dominant effect causing unacceptable levels of acceleration. It is unreasonable to expect that quiet, resting crew conditions can be mandated for the long periods, e.g., hours, requried for most materials processing experiments. Either the crew must not be present, i.e., an unmanned spacecraft, or improved crew motion isolation technology must be developed.

Without further consideration of crew motion, the remaining disturbance effects will now be considered relative to Figs. 8a and b. The peak total acceleration from these effects are 1×10^{-6} and 0.5×10^{-6} g's for the 370 and 740 km altitudes, respectively. In both cases, the orbital dynamics and control torque effects are significant, being the dominant effects for the higher altitude. For the lower altitude, the aerodynamic drag force is the dominant effect. The solar pressure effect, which is generally the least significant, happens to equal the lowest desired acceleration value for the reference configuration.

Platform Design Implications

The primary sources of unwanted accelerations have been shown to generate levels of acceleration that are in conflict with anticipated requirements for materials processing in

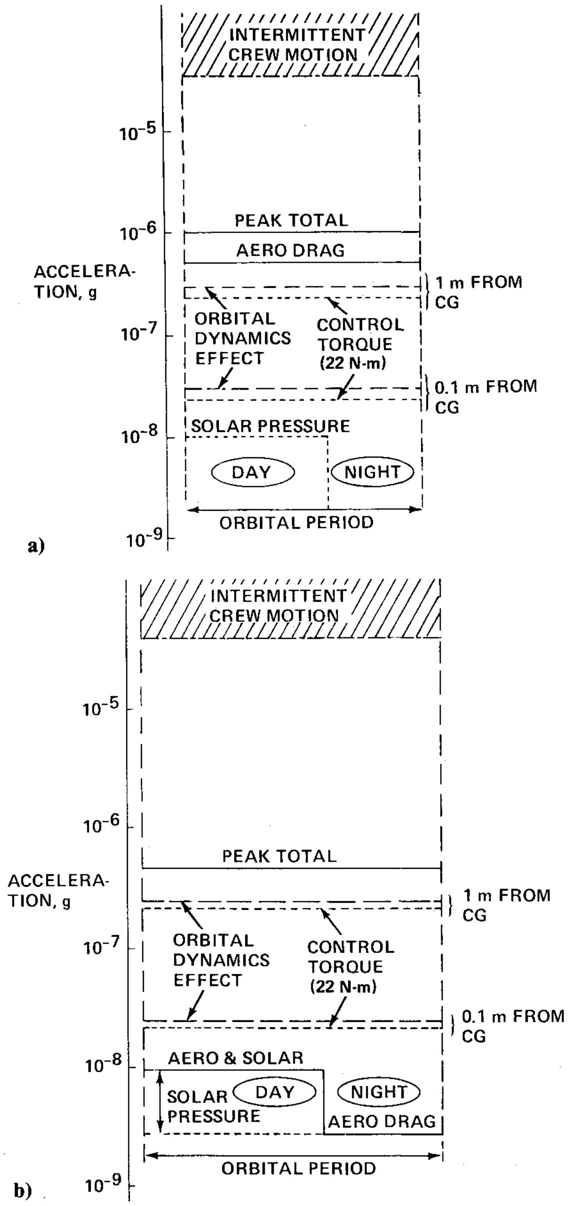

Fig. 8 Total acceleration levels; a) 370 km, b) 740 km.

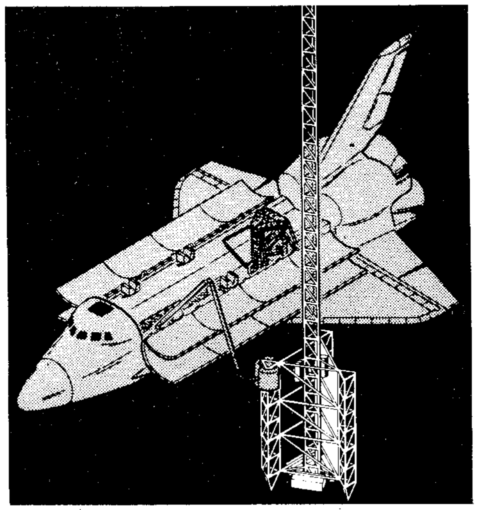

Fig. 9 Platform concept for materials processing.

orbit. The following conclusions relative to platform design may be inferred from the preceding discussion.

Environmental: Minimized area-to-mass ratios and altitudes of at least 740 km are called for to meet desired acceleration levels. Another approach that should be considered is the "drag free satellite" concept demonstrated on the TRIAD spacecraft.[3] Such a concept applied to a platform would require an active thrusting system to compensate for the environmental forces resulting in an orbit only influenced by the Earth's gravitational field. The heart of the system consists of a small enclosed "proof mass" located at the spacecraft c.g. and isolated from the external environment. By sensing the position of this mass, the necessary thrusts may be developed that force the spacecraft to "follow" the proof mass while not actually touching it. The TRIAD flight demonstrated a level of less than 10^{-11} *g*'s for a period of about ten months using this technique.

Orbital Dynamics: In order to minimize the influence of *g* levels caused by orbital dynamics effects, the subject experiments must be located as near to the orbital path of the center of mass of the spacecraft as possible. For payloads rigidly attached to a spacecraft, this would require the spacecraft to be local vertical stabilized with payloads located fore/aft of the c.g. along the flight path. As the mounting distance from the c.g. becomes larger, the payload position departures from the orbital path caused by attitude variations will have a degrading effect on the resulting acceleration. Payload positioning techniques may be required to compensate for attitude motion.

Rotational Effects: This effect may be minimized by careful development of the spacecraft configuration such that a very low disturbance torque environment results with correspondingly low control torques.

Crew Motion: Manned presence is undesirable where low *g* levels are desired.

The result of applying such design principles is illustrated by the platform concept shown in Fig. 9 which is an unmanned, gravity-gradient stabilized spacecraft constructed on-orbit from one-meter beams fabricated by an "automated beam builder" carried in the Shuttle Orbiter. The materials processing payloads are located along the orbital path of the center of mass with a proof mass/sensing system located at the center of mass. An active thruster system provides drag-free flight. Body-mounted solar cells provide the needed electrical power. Revisits by the Orbiter are needed for replacement/retrieval of test specimens with all other operations performed remotely by ground command.

Summary

It is shown that the microgravity levels desired for proposed materials processing payloads present a unique challenge to the designers of future space platforms. The selection of an operational orbit and the design of the platform's physical configuration must consider these payload requirements. In general, an unmanned, Earth-oriented, drag-free design is recommended with the materials processing payloads located along the orbital path of the system center of mass. The attainment of low gravity levels for materials processing in orbit appears possible but only by carefully integrating the payloads into the design of future space systems.

Acknowledgments

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