Engineering Notes

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Acceleration and Pulse Control in Simulated Spacecraft Docking Maneuvers

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Introduction

DOCKING maneuvers have traditionally been simulated and ultimately performed in a "pulse" control mode. That is, thrusts of a prescribed magnitude (duration) were commanded by deflection of a hand controller regardless of deflection angle or duration. Subsequent burns were only possible after release of the joy-stick to its rest position. NASA Space Shuttle pilots currently are instructed to use pulse control presumably for fuel consumption and safety reasons.[1,2]

Nevertheless, all previous experimentation by the authors involved acceleration control in which thruster commands were sent for the duration of the deflection.[3-8] This study involved a formal comparison between pulse control and acceleration control to determine which is better for fuel consumption, mission duration, safety, and other considerations.

In the current study, the trials were organized in APPA and PAAP orders where A denotes a series of 18 simulated dockings using acceleration control and P corresponds to a series with pulse mode. Subjects who began with acceleration mode continued with two blocks of pulse mode before returning to their final block with pulse mode (i.e., APPA). Subjects beginning with pulse mode did the opposite (i.e., PAAP).

One of the intents of this format was to unearth any potential asymmetrical transfer that may be present in the study. Asymmetrical transfer would be evident if a control mode x order (mode x first mode) effect were found.[9] It specifically means the effect of practice with one control mode on subsequent performance with the other control mode is different for the two possible sequences of activity (i.e., a PA sequence vs an AP sequence). This could occur, for example, if subjects who began with pulse mode achieved lower mission duration values when they later flew in acceleration mode than those who began with acceleration mode and followed with pulse mode. Such a finding would be useful for identifying which control mode to use for training as opposed to flight. Additionally, a control mode x range interaction would indicate which mode would be better depending upon initial range of the mission. Preliminary data indicated that learning might be easier in pulse mode but better performance characteristics are achieved with acceleration control. Asymmetrical transfer effects can also cloud comparison of control modes since the subjects' asymptotic performance may not be accurately reflected by the experimental data.

Method

Nine commercial airline pilots served as paid test subjects in this study. Pilots were used because of the expectation that the manual control, attention, discipline, and intelligence skills typically associated with flying would enable them to be superior subjects. In purely subjective terms (without rigorous and detailed statistical analysis of dependent variables), however, they performed no better than any other previous group of simulated spacecraft pilots. For example, neither learning nor performance was consistently better than previous groups of subjects.

The study was performed in the Space Station Proximity Operations Simulator at NASA Ames Research Center. The facility simulates a proximity operations control room on a space station. A PDP 11/60 computer in conjunction with an Evans and Sutherland PS II picture system drove three windows. These windows displayed a simulated view out the $-V$-bar (negative velocity vector) of a space station in a 270 n.m. circular orbit around the Earth. An accurate star field was visible with representatives down to the fifth magnitude.

A three-degree-of-freedom displacement hand controller was used to command thruster firings on a simulated orbital maneuvering vehicle (OMV) remotely. Buttons on the hand controller were used to control the thruster characteristics independently for each coordinate axis. Thruster values toggled among 1.0, 0.1, and 0.01 m/s. The subjects used a joy-stick-mounted trigger to begin each trial.

A head-up display (HUD) containing flight data was superimposed on the center window. Mission duration, velocity increment, three-axis range and rate, slant range and rate, and thruster values were presented to the subjects.[10-12]

Test subjects performed simulated docking maneuvers of an OMV to a space station from three different ranges on the $-V$-bar. Each subject used both control modes in blocks of 18 consisting of three ranges (50, 100, and 150 m) times 6 repetitions in a Latin-squares configuration. Five subjects began with acceleration control and four began with pulse control. A test session consisted of two blocks with each control mode. The blocks were arranged in APPA and PAAP orders. This yielded a total of 72 trials for each subject. Success was operationally defined as meeting certain terminal range and rate specifications in three dimensions. All unsuccessful missions were reflown. Experimentation required about 5 h per subject.

Results

Five-way mixed analyses of variance (ANOVA) with one between factor, first mode, and four within factors, mode, block, range, and trial, were performed on the data. All statistically significant effects at the .05 level for the complete data set are summarized in Table 1. Trial refers to consecutive presentations of identical experimental treatments. Mode, range, and block were the same for a group of six trials. Block distinguished between both groups of 18 consecutive trials with the same control mode. The blocks were designated as first half and second half.

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Table 1 Significant effects from ANOVA

Dependent variable	Significant factor(s)	F	p
Mission duration	Mode	12.544	0.0094
	Range	24.156	0.0001
	Trial	4.143	0.0046
	Mode × Block × 1st	5.835	0.0464
Velocity increment	Mode	6.431	0.0389
	Range	34.57	0.0001
	Block × Range	5.792	0.0147
	Mode × bl × r × tr × 1st	2.100	0.0357
X velocity increment	Block	7.118	0.0321
	Range	31.344	0.0001
	Trial	2.653	0.0390
	Block × Range	5.864	0.0141
Y velocity increment	First Mode	31.523	0.0008
	Range	6.861	0.0084
	Range × First Mode	6.721	0.0090
	Mode × Range × Trial	2.308	0.0208
	Mode × r × tr × 1st	2.287	0.0219
	Mode × bl × r × Trial	1.984	0.0481
	Mode × bl × r × t × 1st	2.018	0.0441
Z velocity increment	Range	4.142	0.0429
X rate	Trial	2.759	0.0334

Control mode produced statistically significant, but opposite, effects on mission duration and velocity increment. Mission duration was lower with pulse mode while velocity increment was lower with acceleration mode. Subjects used more fuel to travel faster with pulse mode than with acceleration mode. As in more mundane, Earth-bound, linear environments, greater velocities, leading to reduced mission durations, were paid for with increased fuel consumption. Although the subjects were trained to criterion, further training could most likely be used to reduce mission duration and/or fuel consumption levels. These results gave some indication of what the underlying tendencies were before extensive training.

Mission duration, velocity increment, X velocity increment, Y velocity increment, and Z velocity increment all increased with range. Subjects commanded the OMV to "fly" at faster rates from further distances. These higher average velocities were paid for by increased fuel consumption.

The Z velocity increment, the cumulative total of thrusts used to correct for orbital mechanics effects, increased with initial range. This increase was due to the increase in mission duration with range. More fuel was required to compensate for the orbital mechanics effects when more time was given for them to operate.

The most unusual range effect was the one reflected in the Y velocity increment. The y axis was the out-of-plane component. Since motion along this axis is uncoupled from motion along the other two axes, an object with zero y displacement with respect to a target needs no attention. Although the trials in this study were initialized so that no thrusts along the y axis were required, accidental commands were made from which recoveries had to be made to achieve a successful docking. Most likely, the longer mission durations associated with the greater initial ranges provided the subjects with more time in which to cause a y disturbance.

Although the subjects practiced to criterion prior to experimentation, a practice effect in which subjects improved with experience was still evidenced in the data. Mission duration decreased with trial in a typical learning curve format. Surprisingly, the X velocity increment increased with experience as illustrated. This effect is most likely due to subjects becoming more comfortable with the simulated docking maneuver and consequently using more fuel to travel faster.

The X velocity increment data demonstrated a block effect also. Fuel consumption along the x axis was less in the beginning of testing than in the end. Values from the first 18 trials with a mode were less than those from the second half with means (standard deviations) of 7.7 (4.9), and 8.9 (6.1), m/s for the first half and second half, respectively. This effect was similar to the trial effect with fuel consumption and velocity increasing with experience. It shows the trend following experience not only within blocks as with the trial effect but also between blocks as mentioned here.

Three two-way interactions, two three-way interactions, two four-way interactions, and two five-way interactions also resulted from the data analysis. Higher-order effects are typically difficult to decipher. Of particular interest are the ones containing a mode or first mode term.

The mode x block x first mode interaction for the mission duration data appears in Fig. 1. It shows that the main effect relationship between the modes, namely, the mean for mission duration in pulse mode is less than the acceleration mean only holds for the first half of the data. In the second half of the data, the pulse data for subjects who began in acceleration mode had the same mean as the data from those subjects who began in pulse mode.

The error bars indicate that the data for blocks 2 and 3 for both sets of subjects are not distinct. Essentially, mission duration values for the middle two blocks are the same for both modes. There is also no statistically significant distinction between the data from blocks 1 and 4 in the PAAP group. However, the mission duration mean for block 4 is lower than that for block 1 in the APPA group.

No improvement in mission duration was found for the subjects who began with pulse mode while the data from the acceleration first group display learning. These data support the experimental hypothesis that experience in pulse mode helps performance in acceleration mode. Asymmetrical transfer was found in that the mode transitions could not be predicted solely from the main effect. Both acceleration means in the PAAP group were lower than both acceleration means for the APPA group. The last pulse mission duration means for both subject groups were equal (i.e., block 3 in the APPA group and block 4 in the PAAP group).

Analysis of the transitions between consecutive blocks yielded interesting results. Both PA transitions were of the same positive slope. Although this is illustrative of the main effect (that is, pulse mission duration lower than acceleration mission duration), only one of the AP transitions was significantly downward. The single PP transition was downward, again indicating a learning benefit from a previous experience with pulse. Conversely, the single AA transition was unchanged.

An ANOVA was performed on the data collapsed across block and trial to determine which combinations of independent variables were more likely to cause an unsuccessful mission. No statistically significant effects were uncovered. Nei-

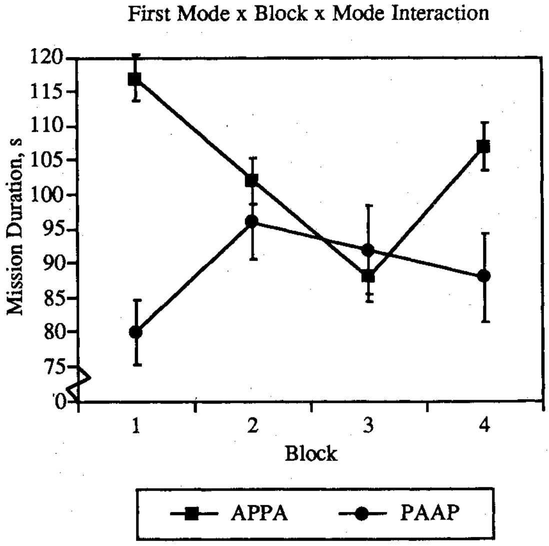

Fig. 1 Mission duration three-way interaction.

ther mode was found to be inherently safer than the other. No combination of range and mode was more conducive to errors than any other.

Discussion

The finding that fuel consumption levels, measured as Δv or velocity increment, were lower in acceleration mode than in pulse mode corroborates the results from the preliminary experimentation. Pulse mode is not inherently more fuel conservative than acceleration mode as one might presume from studying the appropriate NASA manuals.[1,2] This indicates that fuel can be used more efficiently in acceleration mode than pulse mode in a docking operation. This is probably due to the greater dynamic range with acceleration control allowing for greater flexibility and fine-tuning capability.

The asymmetrical transfer discovered here is important for researchers investigating the impact of control modes on spacecraft docking operations. This result should be regarded as a forewarning that investigators should be careful when designing experiments and formulating conclusions. The asymmetry illustrates an inconsistent main effect for which one must account before attributing a result to a control mode. In comparing different control modes, experimenters should be sure to provide sufficient intervening practice to prevent the effects of asymmetrical transfer from contaminating the experimental results.

The data from this study demonstrated that dockings could be performed faster, albeit at the expense of greater amounts of fuel, in pulse mode than in acceleration mode. Although the absolute values of time and fuel were specific to the thruster values that were used, this relationship should be preserved with different thrusters. A whole assortment of studies could be performed to examine the effect that thrusters with different magnitudes from the ones simulated here have on the data. An interaction between thruster size and range might also be revealed. What is clear, however, is that pulse mode is not definitively more fuel efficient than acceleration mode in all situations. Probably the most necessary conclusion to be made at this point is the requirement of further human factors and manual control experimentation before flight protocols are generalized for all vehicles in all situations.

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Atomic Oxygen Protection of Carbon and Polycarbonate Using Boron Carbide Coating

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Introduction

It is now well established that the interaction of atomic oxygen in the low-Earth-orbit (LEO) space environment with spacecraft at orbital velocities causes severe mass loss from many polymeric materials, including polyimides and polycarbonates, used in the construction of spacecraft subsystems.[1] In this Note, work on the measurement of the effects of atomic oxygen erosion on polycarbonate/carbon composite optical filters and the evaluation of protective coatings for these filters is described. This includes the novel application of boron carbide (B_4C) as a protective coating against atomic oxygen erosion.

Reaction Efficiency of Carbon and Lexan

There have been a number of reports of the reaction efficiency of carbon with atomic oxygen from both space-based[2,3] and ground-based[4] experiments. There are comparatively few measurements of the reaction efficiency of polycarbonate materials in LEO or ground-based apparatus. Gregory and Peters[2] measured the reaction efficiency of CR-39 ($C_{12}H_{18}O_7$) in LEO. Hansen et al.[5] measured the weight loss of polycarbonate in a low-energy atomic oxygen asher, and Morel et al.[6] measured the reaction efficiency of Lexan ($C_{16}H_{14}O_3$) in a plasma asher experiment. All published measurements of reaction efficiencies are given in Table 1.

Given the uncertainties in the data base for the reaction efficiency of Lexan, new measurements of the reaction efficiency were carried out using two types of oxygen source: a supersonic atomic oxygen source[7] at 4 km/s, and an oxygen ion beam source at 20 eV[8] (the equivalent energy to a velocity of 8 km/s is 5 eV).

The supersonic source was flux and energy calibrated using a cylindrical mirror analyzer on the front of a quadrapole mass spectrometer.[7] This showed that the source gave a flux of $(1 \pm 0.5) \times 10^{14}$ oxygen atoms cm^{-2} s^{-1} at an energy of 1.0 ± 0.1 eV. As a cross check on the flux calibration, a sample of vacuum deposited carbon on glass was exposed to the source with one-half of the carbon sample covered. After an exposure of 2 h, the thickness of the covered portion of the sample was 1139 ± 53 Å and the uncovered portion 1034 ± 54 Å. Both thicknesses were measured using the Tolansky method with a Varian angstrometer. Taken together with the flux calibration, this gives a reaction efficiency for carbon of

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