N91-12406

7. MICROGRAVITY AND ITS EFFECTS ON RESIDUAL MOTIONS IN FLUIDS

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ABSTRACT

The primary reason for conducting many materials science experiments in space is to minimize or eliminate undesirable effects that might result owing to convective motions in fluids that are driven by buoyancy effects. Of particular concern are the low frequency accelerations caused by the Earth's gravity gradient field, spacecraft attitude motions, and atmospheric drag. In order to gain a limited understanding of the effects of these accelerations we have calculated the Stokes' motion of a spherical particle in a fluid for various types of spacecraft attitudes. In addition, we have assessed the effect of slowly rotating the experimental system relative to the spacecraft in order to reduce the rate at which the particles accumulate against the container wall.

NOMENCLATURE

q_{K*} - position of the spacecraft mass center with respect to the geocentric inertial frame.

x_{K*} - position of the particle with respect to the origin of the geocentric inertial frame.

x_K - position of the particle with respect to the origin of the spacecraft frame.

x_k - position of the particle with respect to the origin of the experimental frame.

R_{kK} - rotation of the spacecraft frame into the experimental frame.

A_{KK*} - rotation of the geocentric frame into the inertial frame.

G_{kK} - Gravity gradient tensor expressed in terms of the experimental frame.

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$q = G_c M_e$, where G_c is the gravitational constant, and M_e is the mass of the earth.

ω_b - angular speed of the spacecraft.

$\alpha = 4.5 \ \mu/\rho_s \omega_b \ R^2$, is the dimensionless Stokes coefficient.

$\delta = (\rho_s - \rho_f)/\rho$ is the buoyancy coefficient.

$\bar{\rho} = \rho_s - (\rho_f/2\rho_s)$.

R - radius of the particle (assumed to be small compared to the size of the experimental system).

μ - fluid viscosity.

ρ_s - particle mass density.

ρ_f - fluid mass density (assumed to be constant)

1. INTRODUCTION

The accelerations experienced within experimental systems aboard orbiting spacecraft occur over a broad range of frequencies. Of particular concern to materials scientists are the low frequency accelerations since it is known that these can give rise to sustained fluid motion[1,2,3]. Sources of residual accelerations include the effects of the Earth's gravity gradient tides, spacecraft motions, and atmospheric drag, to the higher frequency "g-jitter" caused by machinery vibration, cooling systems, spacecraft vibrations, and ephemeral disturbances such as crew motions and thruster firings.

In order to improve our understanding of the effects of some of the low frequency accelerations (for certain types of spacecraft attitude there will be steady accelerations) we examine the Stokes motion of a spherical particle subject to the effects of the earth's gravity gradient field, atmospheric drag, and spacecraft attitude motions. In addition, we also investigate the possibility that the residence time of a particle in a given region of the fluid may be increased by a continuous rotation of the experimental system relative to the spacecraft. It is assumed that the fluid is "spun up".

For an experiment aboard a spacecraft in gravity gradient stabilized attitude it is found that rotations of the experiment at rates corresponding to twice, and one-half the orbital rate can substantially reduce the extent of the particle motion relative to the experimental frame of reference. The most effective rotation appears to be about an axis perpendicular to the orbital plane, at twice the orbital rate, and in the opposite sense to the direction of motion of the spacecraft.

2. FORMULATION

2.1 Frames of Reference and Coordinate Systems

We shall refer to three frames of reference in this work (see Figure 1). The first is an inertial geocentric frame, the second is a moving frame which is rigidly attached to the spacecraft and may rotate with respect to the inertial frame. The third frame is the experimental frame which is free to rotate with respect to the spacecraft. Each frame of reference will be characterized by a cartesian coordinate system such that the position of a particle at time t will be denoted by either $\tilde{x}_k$, $\tilde{x}_K$, or $\tilde{x}_{K*}$, k, K, K* = 1,2,3, where a miniscule subscript refers to the spacecraft frame and an asterisk superscript on a majescule subscript refers to the geocentric inertial frame.

It is convenient to formulate this problem in terms of non-dimensional variables[3]. Distance is scaled using a_o, the initial value of the osculating semi-major axis* of the spacecraft orbit, and to scale time using $(\gamma/a_o{}^3)^{1/2}$ which physically corresponds to the angular speed, ω_o, of the spacecraft in a circular orbit of radius a_o. An additional length scale "d", a characteristic distance within the spacecraft, is also used which is used to scale distance within the spacecraft. The dimensionless variables and parameters are:

$$x_{K*} = \tilde{x}_{K*}/a_o, \quad q_{K*} = \tilde{q}_{K*}/a_o, \quad t = \tilde{t}(\gamma/a_o{}^3)^{1/2}$$

$$\epsilon\, x_k = A_{kK*}(x_{K*} - q_{K*}), \quad \epsilon = d/a_o << 1. \tag{1}$$

*Since the spacecraft is subject to an atmospheric drag force the spacecraft gradually spirals in toward the earth. As a result the orbital elements cannot be defined in the usual sense. The instantaneous values of these elements are referred to as the osculating elements.

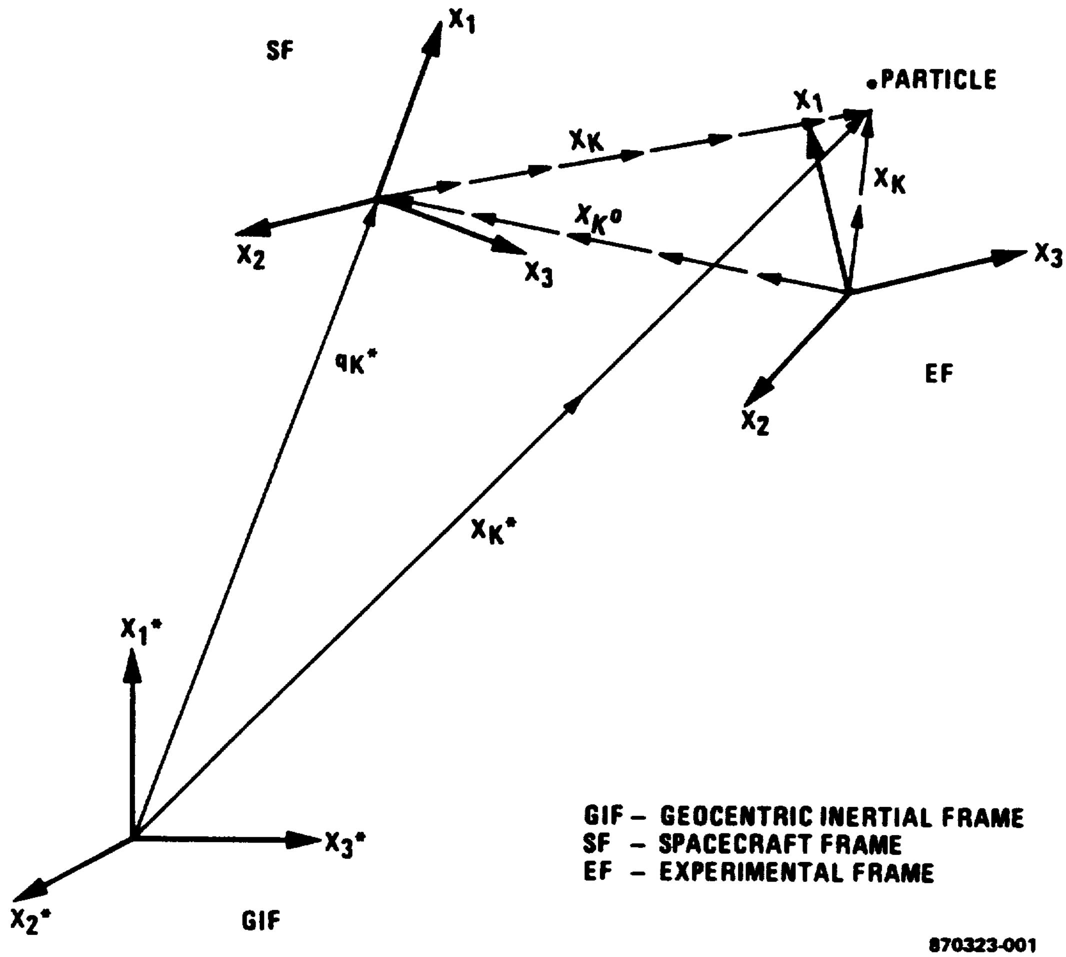

FIGURE 1. FRAMES OF REFERENCE

2.2 The Gravity Gradient

The body force acting on a particle at $k_{K^*}(t)$ is taken to be

$$F_{K^*}(x_{K^*}) = -(1/r^3)x_{K^*}, \quad K^*, = 1,2,3, \tag{2}$$

where

$$r^2 = x_{M^*}x_{M^*}. \tag{3}$$

Similarly, the body force acting at the mass center of the spacecraft is assumed to be

$$F^o{}_{K^*} = -(1/r_o{}^3)q_{K^*}, \quad K^*, = 1,2,3, \tag{4}$$

where q_{K^*} is the position of the mass center of the spacecraft in the geocentric inertial frame.

$$r_o{}^2 = q_{M^*}q_{M^*}. \tag{5}$$

If $x_{K^*} - q_{K^*}$ is small, we can expand (2) in a Taylor series about $x_{K^*} = q_{K^*}$ and obtain

$$F_{K^*} = F^o{}_{K^*} + \epsilon\, G_{K^*M^*}A_{mM^*}x_{m^*} + O(\epsilon^2), \quad K^*, = 1,2,3, \tag{6}$$

where

$$G_{K^*M^*} = DF_{K^*}(q_{M^*}), \quad K^*, M^* = 1,2,3, \tag{7}$$

is the gravity gradient tensor. It can be shown that[3,5]

$$G_{K^*M^*} = -(1/r_o{}^3)I_{K^*M^*} + (3/r_o{}^3)e_{K^*}e_{M^*}, \tag{8}$$

where $e_{K^*}(t)$ is a unit vector parallel to q_{K^*}, and $I_{K^*M^*}$ is the identity tensor.

In the experimental frame of reference the gravity gradient force can be expressed as:

$$G_{km}(x_m - x^o{}_m) = R_{kK}A_{kK^*}G_{K^*M^*}(x_{M^*} - q_{M^*}), \tag{9}$$

where $R_{kK}A_{kK^*}$ is the rotation of the geocentric inertial frame into the experimental frame about an axis passing through the origin of the experimental frame.

2.3 Equations of Motion for a Spherical Particle Subject to a Stokes Drag

The accelerations, relative to the experimental frame experienced by the particle, are given by[3,7]

$$\frac{d^2x_k}{dt^2} = \delta F^{(b)}{}_k + \alpha \frac{dx_k}{dt} \tag{10}$$

where δ is the buoyancy coefficient that includes the effects of added mass, α is the dimensionless Stokes' coefficient, and $F^{(b)}{}_k$ is the effective buoyancy force given by

$$\begin{aligned} F^{(b)}{}_k = {} & \left(\frac{dQ_{km}}{dt} + Q_{kp}Q_{mp}\right) x_m + 2Q_{km}\frac{dx_m}{dt} + R_{kK} \quad 2W_{KM}R_{KM}\frac{dx_m}{dt} \\ & + \left(W_{KP}W_{MP} + \frac{dW_{KM}}{dt}\right) R_{mM} \left(x_m - x^o{}_m\right) \quad + \\ & G_{km} \left(x_m - x^o{}_m\right) = f^{(d)}{}_k, \end{aligned} \tag{11}$$

where Q_{km} and W_{KM} are skew tensors that represent the rates of rotation of the experimental frame with respect to the spacecraft frame and the rate of rotation of the spacecraft frame to the geocentric inertial frame. It is implicit in the above equations that we have neglected the "history integral" which appears in the Basset-Boussinesque-Oseen equations[7].

The above equations together with the initial conditions:

$$\frac{dx_k}{dt} = 0, \; x_k = X^o{}_k \tag{12}$$

were solved numerically for various values of the parameters δ and α, and for different rotations of the experimental system relative to the spacecraft, with the orbital parameters given in the appendix.

3. RESULTS

Selected results of our calculations are presented in Figures 2 and 3. For the cases in which the experiment was rotated relative to the spacecraft the axis of rotation passed through the origin of the

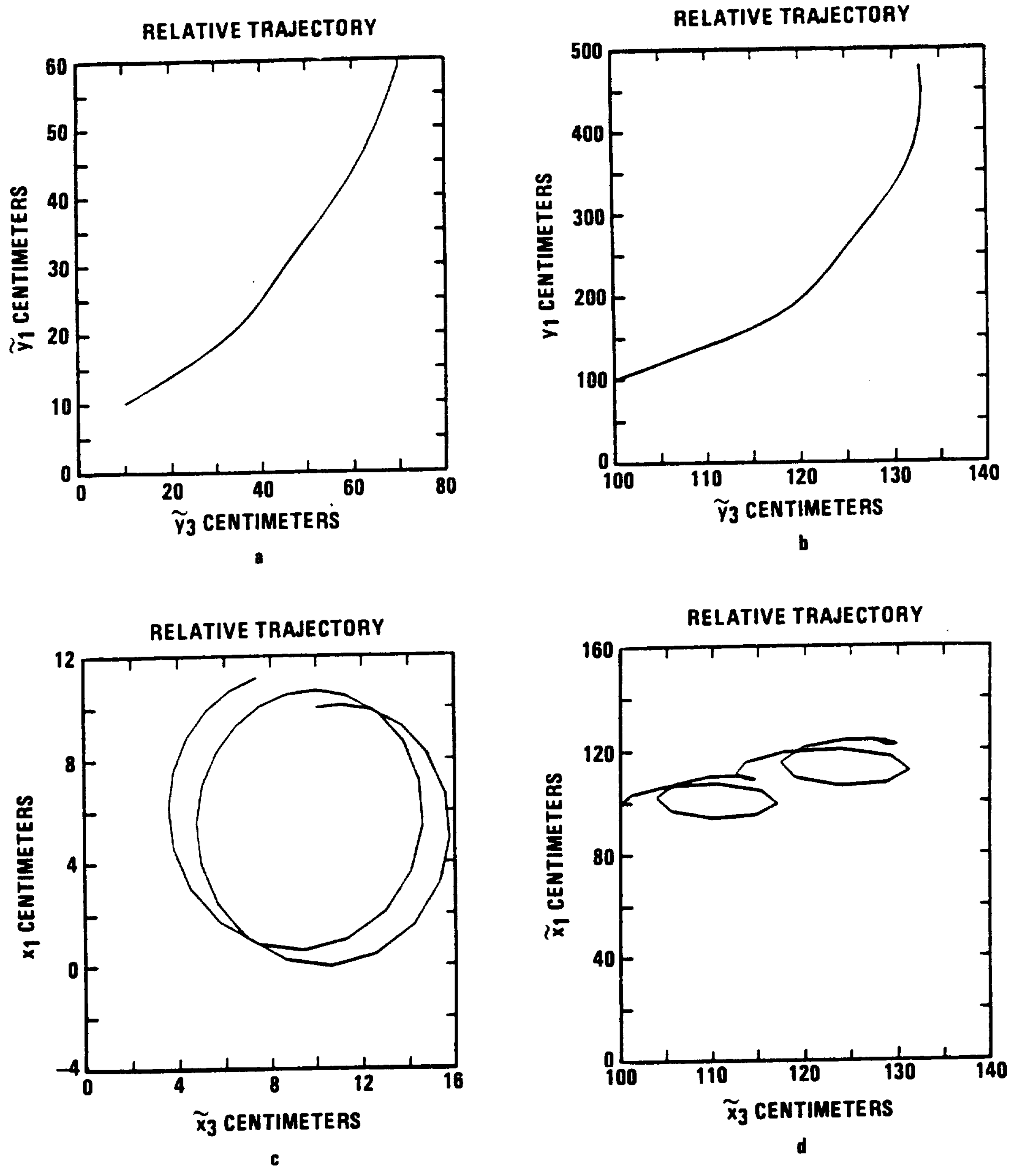

**FIGURE 2. PARTICLE TRAJECTORIES; a, b - RADIAL FRAME
c, d - INERTIAL FRAME**

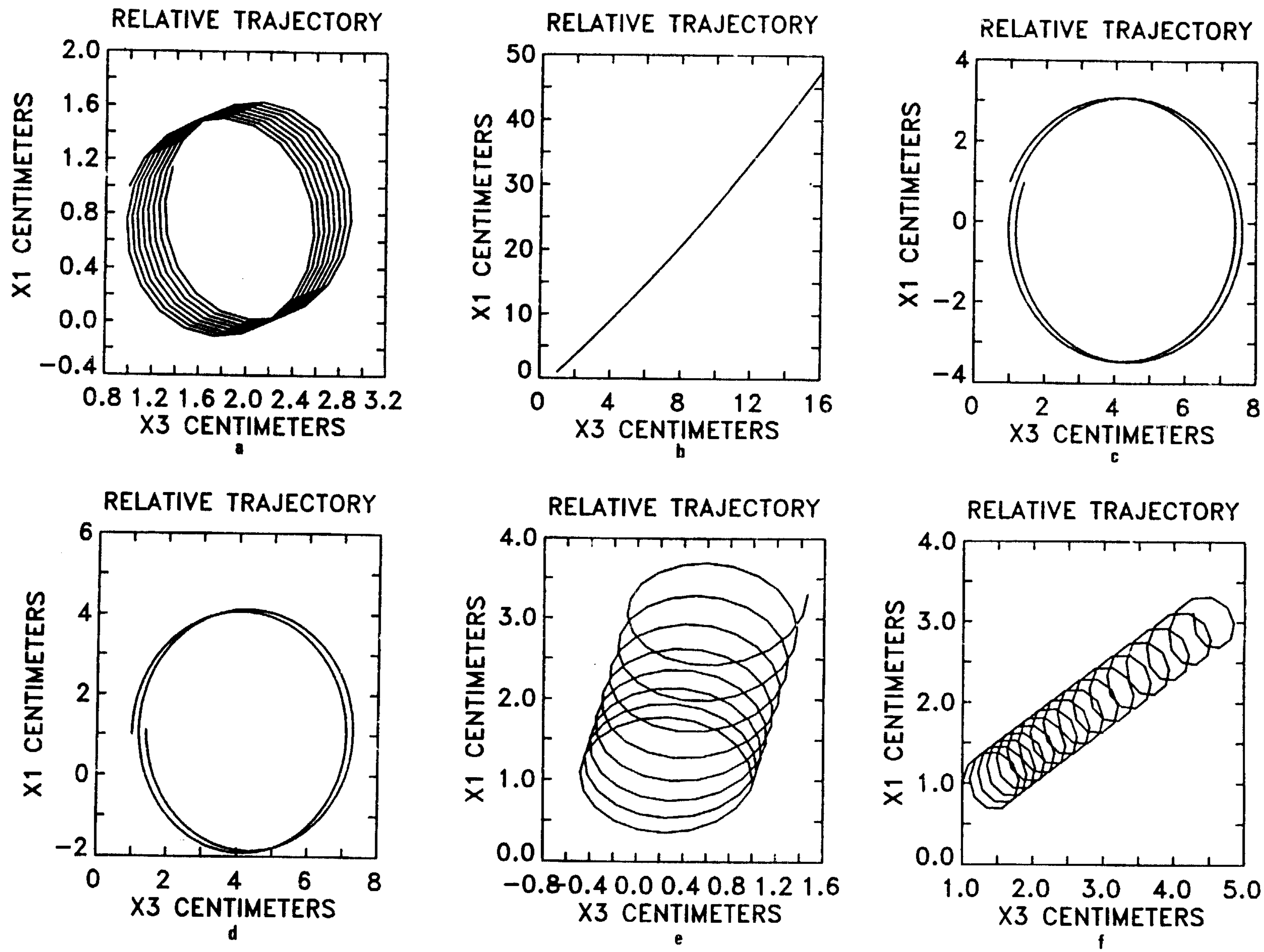

FIGURE 3. PARTICLE TRAJECTORIES: EXPERIMENTAL FRAME

experimental frame of reference and was oriented perpendicular to the orbital plane. Each trajectory is shown as seen by an observer in the experimental frame of reference.

Figure 2 depicts particle trajectories for particles subject to Stokes drag. The dimensionless Stokes coefficient is 20 and the buoyancy coefficient is 0.82 (physically this would correspond to a steel ball of radius 0.25 cm in water). The spacecraft is subject to atmospheric drag. The origin of the experimental frame of reference is taken to coincide with the mass center of the spacecraft. The initial velocity is zero. For Figures 2a and 2b the spacecraft is in a gravity gradient stabilized attitude and hence the spacecraft frame rotates with respect to the geocentric inertial frame. For Figures 2c and 2d the spacecraft frame does not rotate with respect to the geocentric inertial frame (as would occur in the case of the solar inertial attitude).

a) $x_k(0) = (10,0,10)$cm,
b) $x_k(0) = (100,0,100)$cm,
c) $x_k(0) = (100,0,100)$cm
d) $x_k(0) = (10,0,10)$cm

Figure 3 shows trajectories of particles relative to the experimental frame of reference. The origin of the experimental frame of reference is taken to be at $x_k = (1,0,1)$m from the spacecraft mass center. The dimensionless Stokes coefficient is 100, the buoyancy coefficient is 0.5. The initial velocity was zero. The initial position of the particle in the experimental frame is (1,0,1) cm. The motion was calculated for four orbits of the spacecraft about the earth (approximately six hours).

a) Relative rate of rotation: $-2.0\ \omega_0$
b) Relative rate of rotation: 0.0
c) Relative rate of rotation: $-0.5\ \omega_0$ (no atmospheric drag)
d) Relative rate of rotation: $-0.5\ \omega_0$
e) Relative rate of rotation: $2.0\ \omega_0$
f) Relative rate of rotation: $-4.0\ \omega_0$

4. CONCLUSIONS

The residual accelerations associated with the gravity gradient, centrifugal accelerations, Euler accelerations*, and atmospheric drag forces can cause sustained motions in fluids. For a spherical particle immersed in a viscous fluid the residence time of that particle in a given region of the fluid can be increased substantially by an appropriate rotation of the experimental frame relative to the spacecraft frame. The most effective choices of rotation were twice and half the angular speed of the spacecraft. The best was at twice the orbital rate in the opposite sense to the direction of motion of the spacecraft.

5. REFERENCES

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*Apparent accelerations in a rotating frame resulting from a non-constant rate of rotation.

APPENDIX

The spacecraft orbits were calculated using the following parameters:

$$a_o = 6688 \text{ km}, \quad C_D A/2m = 1.02(10)^{-2},$$

where C_D is the drag coefficient, A is the effective cross section area, and m is the mass of the spacecraft. We determined the values of C_D and A appropriate for the space shuttle for the orbits under consideration using data from Mullins[10]. The initial osculating eccentricity was taken to be $(10)^{-6}$. The atmospheric density is a function of altitude. We used a model atmosphere discussed by Sterne[9] and used by Alexander and Lundquist[2].