NASA Technical Memorandum 102117
AIAA-89-2727

Modeling of Pulsed Propellant Reorientation

(NASA-TM-102117) MODELING OF PULSED PROPELLANT REORIENTATION (NASA. Lewis Research Center) 19 p CSCL 20D

N89-26178

Unclas

G3/34 0219601

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Prepared for the
25th Joint Propulsion Conference
cosponsored by the AIAA, ASME, SAE, and ASEE
Monterey, California, July 10–12, 1989

NASA

E-4892

MODELING OF PULSED PROPELLANT REORIENTATION

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ABSTRACT

Optimization of the propellant reorientation process can provide increased payload capability and extend the service life of spacecraft. This paper proposes the use of pulsed propellant reorientation to optimize the reorientation process. The ECLIPSE code has been validated for modeling the reorientation process and is used to study pulsed reorientation in small-scale and full-scale propellant tanks. A dimensional analysis of the process is performed and the resulting dimensionless groups are used to present and correlate the computational predictions for reorientation performance.

INTRODUCTION

During coast in Low-Earth-Orbit (LEO), liquid propellants can collect in the forward end of a spacecraft propellant tank due to atmospheric drag. To preclude vapor ingestion by the engine, a propellant acquisition system is required to assure that sufficient liquid will be positioned over the tank outlet prior to main engine firing. Passive acquisition systems typically provide channels and baskets inside the tank and rely on surface tension to hold liquid in the desired position within the structures. These structures add complexity to the design and increase the launch weight of the spacecraft. Active acquisition requires the firing of auxiliary thrusters to accelerate the vehicle and is usually referred to as impulsive reorientation or settling. The acceleration vector is oriented so that the induced relative motion between the propellant and the tank positions a pool of liquid over the main tank outlet. Since each reorientation maneuver requires the expenditure of propellant, optimization of the settling process can increase payload capability and extend spacecraft service life.

Existing studies of impulsive reorientation have focused on settling performance under the influence of a constant imposed acceleration. For a steady acceleration applied to the propellant tank, the standard practice (Reynolds and Satterlee, 1) for computing the time required to settle propellant is based on the following equation derived from a rigid body dynamics analysis:

$$T_s = (\tau)(2L/a)^{1/2} \qquad (1)$$

where (τ) = the number of times the tank accelerates past the liquid

T_s = settling time, s
L = tank length, cm
a = imposed acceleration, cm/s^2

An estimate of the time required for safe engine firing is obtained by using (tau) = 5. For complete propellant settling, (τ) = 10.

The retentive property of surface tension provides a region of stability in which the liquid-vapor interface remains static under the influence of gravitational or acceleration-induced forces. For certain low values of Bond number, there exists a curved interface which is a position of stable equilibrium. For the case of vertical, cylindrical walls and zero contact angle, numerical analyses performed by Bretherton (2)* and Gluck and Gille (3) computed the critical Bond number to be less than 0.842 for hydrostatic stability.

The vehicle velocity increment or delta-V incurred during the reorientation maneuver is a good measure of performance since it is proportional to the propellant expenditure required to complete the maneuver (4). Using vehicle delta-V as the criteria, Sumner (4) concluded that optimal settling would occur for low Bond numbers between 3 to 5 for the configurations evaluated in the study. This reference also presented an empirically based method for computing settling performance.

Pulsed settling provides the possibility of standard thruster sizes for a variety of spacecraft and optimal acceleration levels for the duration of an entire mission. Even if auxiliary thrusters are customized for each hardware configuration, they cannot provide the optimal conditions for the entire mission. As propellant is depleted, the tank filling changes and so does the optimal acceleration level. The key idea behind pulsed reorientation is to use the propellant's inertia to integrate the impulses provided by intermittent thruster firing to provide a desired "effective" acceleration level. For pulsed settling, a relationship analogous to Equation (1) is derived in Patag (5):

$$T_s = n/f_p \qquad (2)$$

where n = the number of cycles required to achieve reorientation

f_p = thrusting frequency, Hz

A literature review revealed no previous investigations of pulsed reorientation. Experimental study of this proposal is extremely difficult since it requires simultaneous modeling of inertia, viscous, and surface tension forces in a time dependent environment. By contrast, the ECLIPSE Code provides a suitable tool for evaluating the performance of pulsed reorientation. Its accuracy in modeling impulsive reorientation due to the steady firing of thrusters has been demonstrated by Hochstein et al (6). It can be used to model small-scale drop tower experiments and small-scale flight experiments as well as full-scale spacecraft tanks.

The results reported in this paper are for a sequence of "typical" OTV tanks. The development of the ECLIPSE Code has been closely coupled to the other projects being pursued under the reduced gravity fluid management technology program sponsored by NASA LeRC. The sequence of tanks reflects the evolution of a flight experiment designed to study a variety of fluid management technology issues.

ECLIPSE CODE

The ECLIPSE code is being developed to model the fluid dynamic, heat transfer, and thermodynamic processes associated with cryogenic propellant management in a reduced gravity environment. It is based on NASA-VOF2D (7), a computer program designed for solving laminar two-dimensional, transient flows with free surfaces. It models incompressible flows with free boundaries using the Volume-Of-Fluid (VOF) method and can accommodate multiple free surfaces. NASA-VOF2D includes models for surface tension and wall adhesion (7,8). It also includes a partial cell treatment for modeling curved boundaries and internal obstacles.

Although ECLIPSE now contains heat transfer and thermodynamic models (9,10), only minor modifications to the baseline code were required to study impulsive reorientation. Variables have been added to permit the investigator to specify a time-dependent acceleration environment and output files are generated specifically to help track the reorientation process. The accuracy of ECLIPSE in modeling the impulsive reorientation process has been documented by comparison to the experimental data for small-scale tanks (5,6).

TERMINOLOGY

Pulsed settling refers to the process of liquid repositioning due to intermittent firing of auxiliary thrusters. Upon thrust initiation, the liquid leading edge travels smoothly along the tank walls. As it reaches the bottom of the tank a pool of propellant forms. The criterion for reorientation or settling time, T_s, is defined in this study as the time it takes for the propellant leading edge to reach 20% of the tank height as measured from the outlet end along the tank centerline. The velocity increment, or delta-V is the proposed measure for propellant consumption. It is the change in vehicle velocity between thrust initiation and satisfaction of the settling criterion.

IMPULSIVE SETTLING: SPACE BASED OTV

One application of current interest to NASA is the settling of liquid propellant in an Orbit Transfer Vehicle (OTV). The conceptual OTV, as its name implies, will be used as a space "tug," therefore requiring numerous engine restarts. Two Boeing OTV propellant tank prototypes (11) were modeled in this study. The first is the Boeing Space-Based (SB) OTV. The second tank is the Boeing Short SB OTV with elliptical heads.

Hochstein et. al. (6) presented a series of analyses on the reorientation of propellant in these tanks using the ECLIPSE code. A representative case from their paper is reproduced here for comparison. Figure 1 presents the mesh used by them to represent a 0.25 scale model of the SB OTV fuel tank with a liquid hydrogen fill level of 50%. Figure 2 shows the reorientation of propellant in this tank using thrust levels predicted to be optimum by the work of Sumner (4). Only a moderate geyser is formed and after approximately 100 seconds the fluid is settled.

PULSED SETTLING: SPACE BASED OTV

The remaining question is how to achieve this optimal low-level thrust given the minimum acceleration capability of most spacecraft thrusters. (The space shuttle auxiliary RCS thrusters with thrusts of 7.85 cm/sec_2 were used as representative.) A viable solution is to operate the thrusters in an intermittent mode. The parameter values used for this part of the study are shown in Table 1. The 0.25 scale SB OTV tank was again modeled using a propellant fill level of 50%. At this point in the analysis, NASA suggested keeping the same fineness ratio of 1.4, but changing the hemispherical tank heads to elliptical. An acceleration magnitude of 7.85 cm/sec^2 was combined with pulse durations of 0.1 and 0.2 seconds over a thrusting frequency range of 0.1 to 1.5 Hz.

Figure 3 shows bulk liquid motion resulting from the application of a 7.85 cm/sec^2 thrust for a duration of 0.1 seconds at a frequency of 0.1 Hz. The liquid can be seen to move smoothly down the tank wall, forming a small geyser without any vapor entrainment. The settling criterion was satisfied within 60 seconds of thrust initiation. For this case delta-V = 4.0 cm/sec. Figure 5 displays the code prediction when the thrusting frequency level is increased to 0.7 Hz. The reorientation criterion was met within 20 seconds. However, the delta-V to accomplish settling is now 10.5 cm/sec, more than double that of the previous case. Examining the propellant motion, it can be seen that the leading edge progresses smoothly along the wall. A large geyser is formed, indicating excessive energy imparted to the fluid. A similar sequence of flow fields can be seen in Figure 5. For this case, frequency was increased to 1.4 Hz. The liquid reoriented in less than 14 seconds, yielding a delta-V value of 14.8 cm/sec. Severe geysering and violent surface foaming can be observed, again indicating inefficient reorientation.

The question arose as to what would happen if, for the same acceleration level, the thrust duration was doubled and the thrusting frequency was correspondingly halved. In response to this query, Figure 6 presents liquid motion due to a 0.2 second pulse duration and a 0.7 Hz thrust frequency. Comparing this bulk propellant motion with the case illustrated in Figure 5, it can be seen that the liquid motion is similar. This simulation resulted in reorientation time of 13.2 seconds and delta-V of 14.5 cm/sec. These values are almost identical to the results of the case illustrated in Figure 5.

The balance of the frequency range from 0.1 to 1.5 Hz was studied using pulse durations of 0.1 and 0.2 seconds. Settling time and delta-V values were recorded for each case. A plot of settling time versus thrusting frequency is shown in Figure 7. Two other curves were added to the plot representing calculations performed using the equations 1 and 2 (4) for settling time. Figure 7 shows that the equations 1 and 2 over predicts the settling time. It also shows that the same reorientation time may be achieved by a combinations of pulse duration and thrust frequency which satisfy the condition:

$$a(t_{p1})f_{p1} = a(t_{p2})f_{p2} \quad (3)$$

where a = imposed acceleration, cm/s^2
t_p = pulse duration, s
f_p = thrusting frequency, Hz

This condition is satisfied by values derived from equation 2 as well. Figure 8 shows a graph of settling time versus delta-V. As the settling time decreases, more energy is expended as represented by an increase in delta-V. For low frequency values, changes in delta-V values are small relative to changes in T_s values. The converse is true for the higher frequency range.

PULSED SETTLING: SHORT SPACE BASED OTV

Redesign led to the Short SB OTV, the dimensions of which are shown in Figure 9. Analyses were performed using full and 0.215 scale tank models in order to gain insight into liquid behavior during pulsed settling. Areas of particular interest were liquid behavior in both high and low frequency ranges, and effects of acceleration magnitude, pulse duration, fill level, and tank scaling on reorientation time. The parameter values used are shown in Table 1. Thrust levels between 10^{-3} and 10^{-4}g were studied. Pulse durations used were 0.1 and 0.2 seconds. Fill levels of 25%, 50%, and 70% were examined.

Figure 10 is a plot of T_s versus frequency for the full scale Short SB OTV propellant tank with a fill level of 50%. At the low frequency ranges, surface tension forces are more predominant, thereby causing erratic behavior of the propellant. Four distinct curves can be seen representing four permutations of pulse duration and acceleration magnitude. Figure 11 shows a plot of T_s versus delta-V for full scale and 0.215 scale tanks. Similar to Figure 8, the values of T_s are higher and are more sensitive to changes in values of delta-V at the low frequency ranges, i.e., low values of delta-V. The curve appears to be flattening out as higher values of delta-V are approached. Ultimately, combinations of thrust, frequency, and pulse duration will approximate steady acceleration. Settling time will therefore approach a minimum value corresponding to the application of a steady thrust. For the same acceleration level, delta-V values are equal for combinations of pulse duration and thrusting frequency satisfying Equation 3. An equivalent acceleration can be defined

$$a_e = a(t_p)f_p \quad (4)$$

where a_e = effective acceleration, cm/s^2

Equation 3 can be rewritten as

$$a_{e1} = a_{e2} \quad (5)$$

Equation (5) states that for equal values of effective acceleration, propellant consumption required to accomplish reorientation is equivalent.

In Figure 12, delta-V is plotted against a_e for both full and 0.215 scale tank models with fill levels of 50%. As can be seen from the plot, for all cases associated with the full scale tank, if the same a_e is used, delta-V values will be identical. The same result holds true for all cases modeling the 0.215 scale tank. Thus, the performance of the full- and small-scale tanks can be represented by a single curve for each tank.

DIMENSIONAL ANALYSIS

Several numerical groupings were evaluated in attempts to non-dimensionalize and thereby collapse the data for reorientation time. The most successful grouping which emerged from this search is presented in Equation 6.

$$T_s* = (T_s/R)*(a_e*h)^{1/2} \tag{6}$$

This group was derived by analogy to Fr number where a characteristic velocity is divided by a representative acceleration. Figure 13 shows a plot of delta-V versus T_s*. The T_s*value increases as delta-V varies from approximately 0 to 2 cm/sec. The curves for all three fill levels then "spike" upwards at $T_s* = 1.4$. As can be seen, values appear at the base on both sides of the peak. For low frequencies, small variations in a_e result in large variations in T_s*. Although intuition leads to the hypothesis that higher settling times may be expected for $T_s* > 1.4$, this is not always true. For T_s* values greater than 1.4, a closer review of the data reveals that T_s is high coupled with relatively high values of a_e. For lower values of T_s*, relatively small a_e are coupled with again high values of T_s. What is presumed to be happening is that the fluid oscillates due to opposing surface tension forces thereby resulting in a longer reorientation time. Examination of Bond numbers for flows with delta-V values close to zero reveal that operation is near, and at times, even below **Bo** critical based on steady acceleration studies.

To get a better understanding of T_s*, two cases which occur in the vicinity of the spike were examined. For values of $T_s* \leq 1.41$, but in the vicinity of the spike, all tests predicted the formation of a small to moderate geyser without any vapor entrainment or any undesirable fluid motion. This indicates efficient reorientation. Figure 14 shows predicted liquid motion for Case 1. The full-scale tank has a fill level of 70% and is accelerated at 10-3g for a 0.2 second duration at $f_p = 0.040$ Hz. The fluid is seen to form a moderate geyser with relatively small liquid velocities. The value of T_s* is 1.41 for this simulation. Keeping all other parameters constant, increasing the frequency results in severe geysering as shown in Figure 15 for Case 2. Although fluid velocities are similar to Case 1, excess energy has been imparted to the fluid causing the geyser to rebound off the top of the tank. Settling time is lower but $T_s* = 1.45$. Based on these evaluations, it appears desirable to operate in the area to the left of the spike.

For T_s* less than, but in the vicinity of 1.4, liquid for both full-scale and small-scale tanks is predicted to form a small geyser. Most of the predictions having higher values of T_s* are for a fill level of 25%. Figure 16 shows propellant motion in a small-scale tank with a 25% fill level. This particular simulation yielded $T_s^* = 5.59$. A thin film of liquid moves down along the tank wall. Prior to satisfying the reorientation criteria (20% of tank length), most of the fluid had been collected at the tank bottom. If the reorientation criteria had been defined at 0.1L instead of 0.2L, settling times for all fill levels, though not proportional, would have been reduced greatly. Reviewing the input parameters of T_s^*, lower settling times would presumably reduce the data scatter resulting in a more definite spike in Figure 14.

SUMMARY

The propellant reorientation process associated with pulsed firing of auxiliary thrusters has been studies using computational predictions provided by the ECLIPSE code. The analyses included both small-scale and full-scale tanks and were performed for a range of fill levels. A square-wave pulse was assumed and the magnitude, duration, and frequency of the pulse was varied to study the effect of these parameters on reorientation performance. The predicted performance is displayed as velocity field sequences for selected cases and summarized in plots of vehicle delta-V vs. frequency and settling time vs. frequency. It is concluded that, except at very low effective acceleration levels, combination of pulse duration, frequency, and magnitude which result in equal values of effective acceleration produce the same reorientation performance.

The results of the computational predictions were used to test the validity of using proposed dimensionless groups for modeling the pulsed reorientation process. One group, T_s^*, appears to collapse all of the data when plotted against vehicle delta-V. The value of delta-V spikes upward as a value for T_s^* of 1.4 is approached from below. Review of predicted flow fields indicates that this corresponds to formation of geysers which indicates inefficient reorientation. It is therefore proposed that configurations which produce values of T_s^* less than, but close to, 1.4 are highly desirable. Reorientation is accomplished relatively quickly for a low expenditure of auxiliary thruster propellant.

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TABLE I. - TEST PARAMETERS

Parameters	Boeing SB OTV	Boeing short SB OTV
Fill level, %	50	25, 50, 70
Propellant	Liquid hydrogen	Liquid hydrogen
a, cm/sec^2	7.85	9.81×10^{-1}, 9.81×10^{-2}
t_p, sec	0.1, 0.2	0.1, 0.2
f_p, Hz	0.100 to 1.500	0.001 to 4.000
Settling criteria, L	0.2	0.2
Tank size	0.25 scale	Full, 0.215 scale

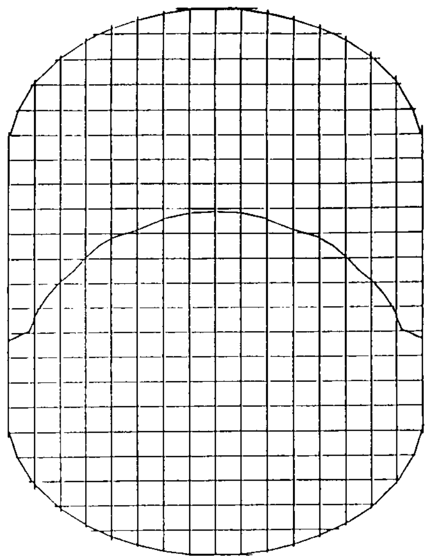

FIGURE 1. - BOEING SB OTV PROPELLANT TANK, 0.25 SCALE. FINENESS RATIO = 1.4; L = 146.69 CM; D = 106.68 CM.

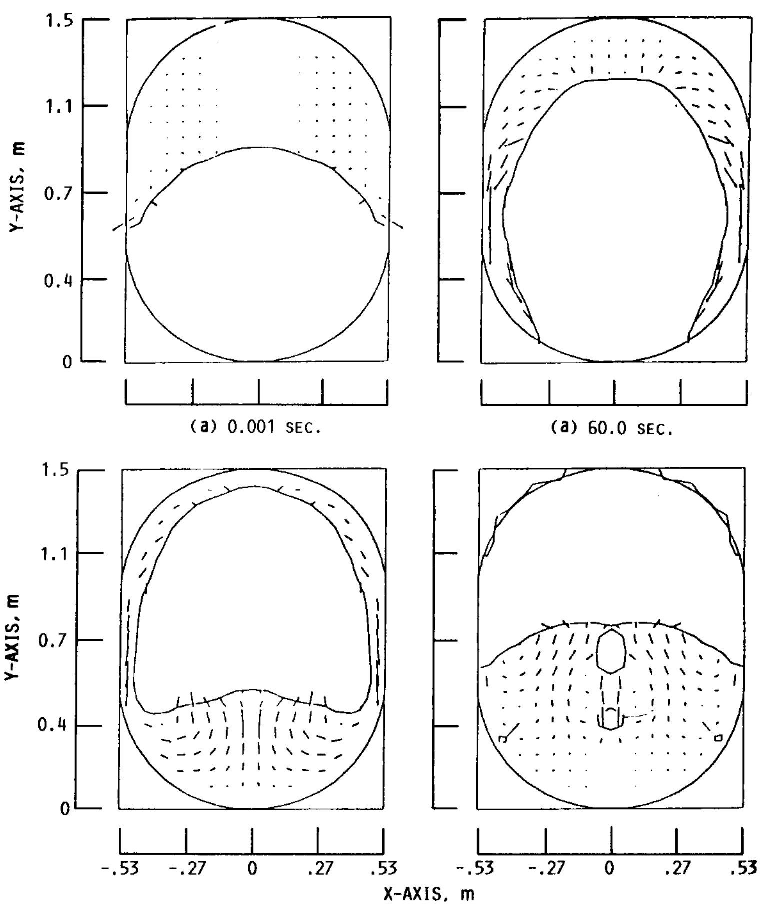

FIGURE 2. - SETTLING IN 0.25 MODEL OF SB OTV DUE TO OPTIMAL ACCELERATION ($a = 3.7x10^{-5}g$).

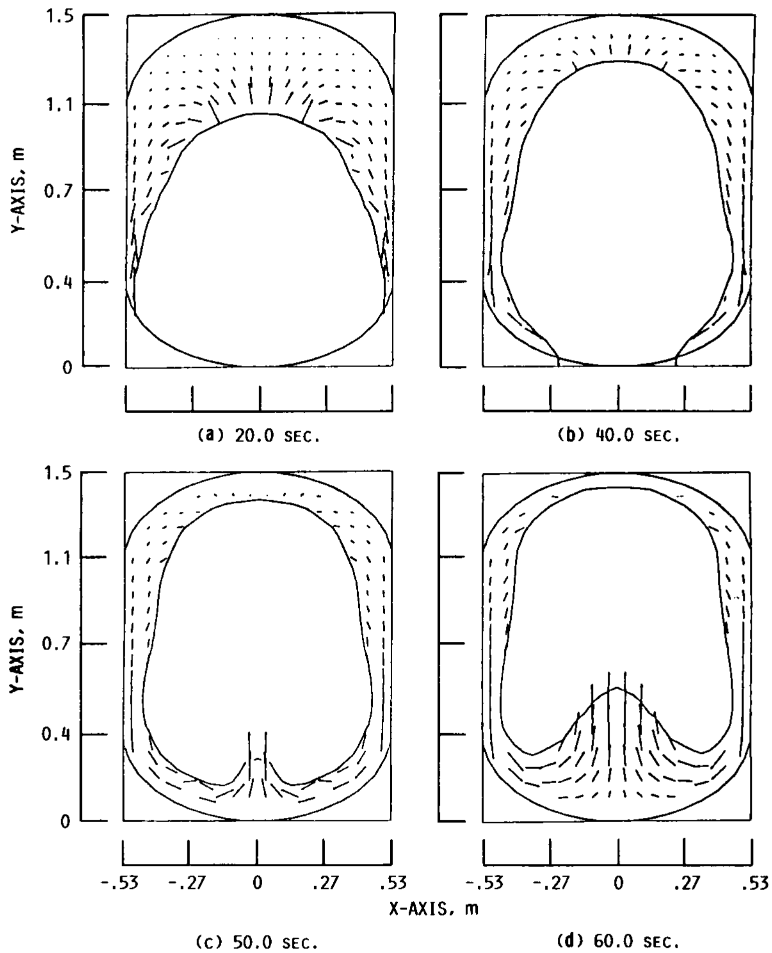

FIGURE 3. - SETTLING IN 0.25-SCALE SB OTV WITH **a** = 8.0x10^{-3} g, tp = 0.1 SEC, f_p = 0.1 Hz.

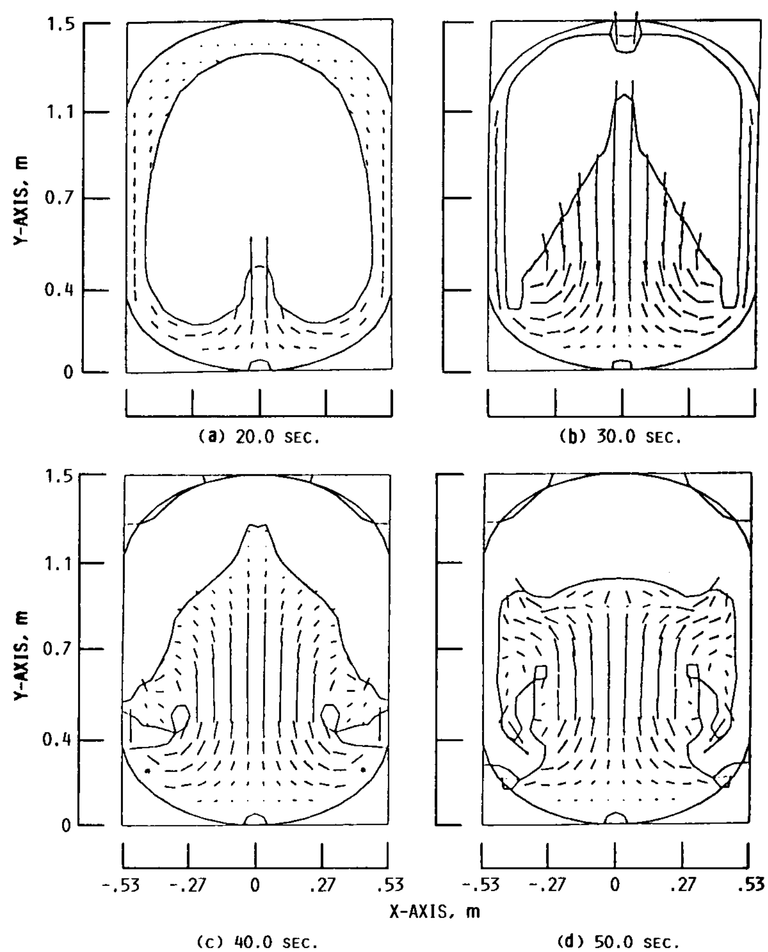

FIGURE 4. - SETTLING IN 0.25-SCALE SB OTV WITH $a = 8.0\times10^{-3}$ g, tp = 0.1 SEC, f_p = 0.7 Hz.

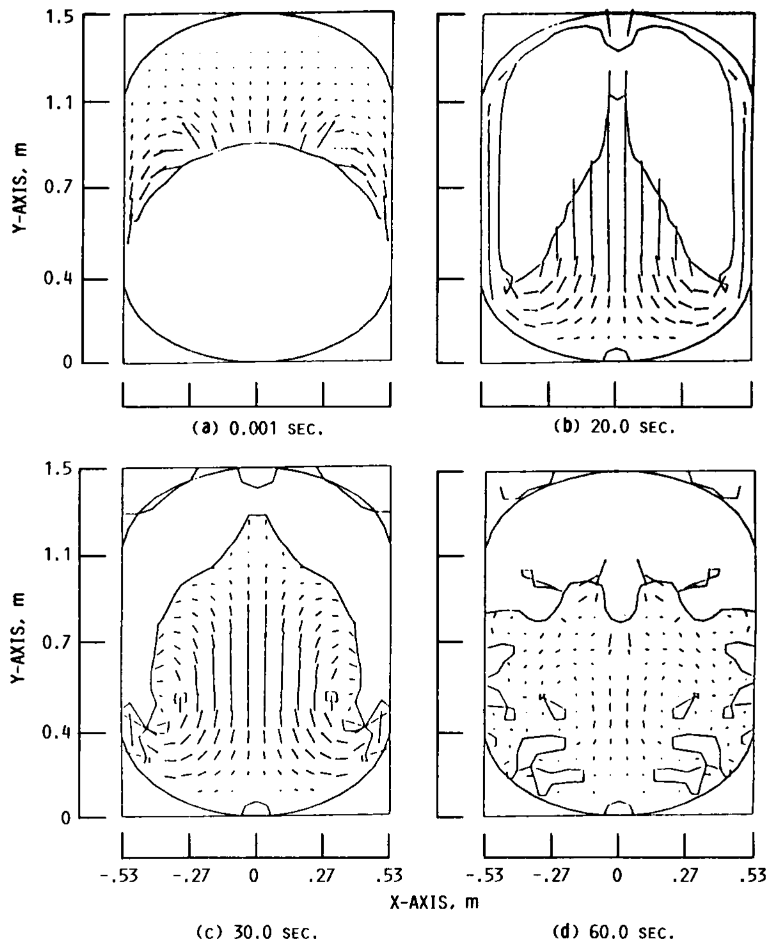

FIGURE 5. - SETTLING IN 0.25-SCALE SB OTV WITH $a = 8.0 \times 10^{-3}$ g, t_p = 0.1 SEC, f_p = 1.4 Hz.

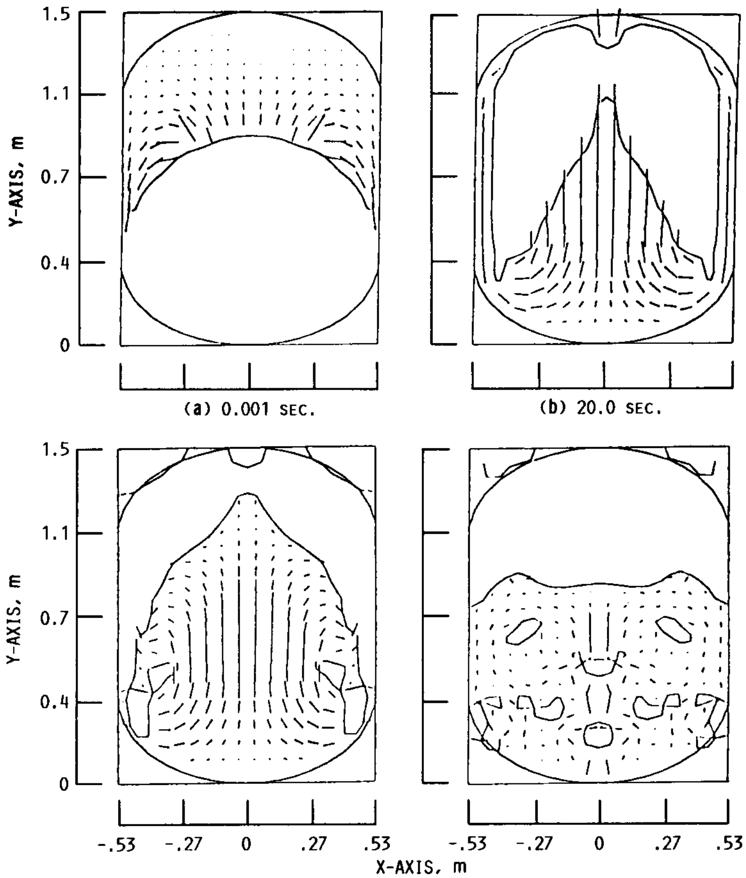

FIGURE 6. -SETTLING IN 0.25-SCALE SB OTV WITH a = 8.0×10^{-3} g, tp = 0.2 SEC, f_p = 0.7 Hz.

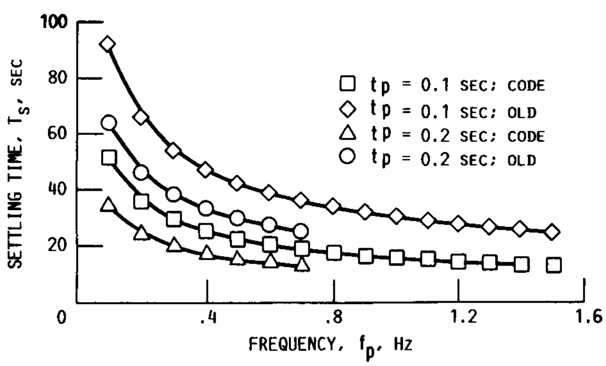

FIGURE 7. - SETTLING TIME VERSUS FREQUENCY, SB OTV, 50 PERCENT FULL.

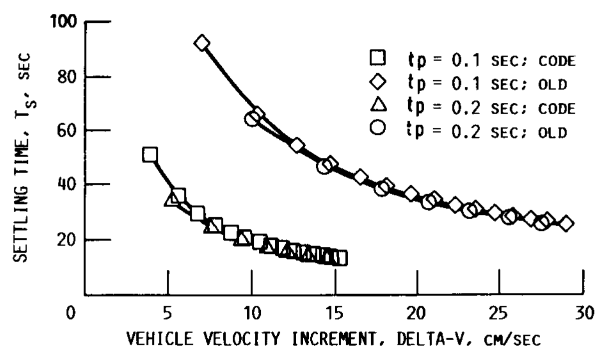

FIGURE 8. - SETTLING TIME VERSUS VEHICLE VELOCITY INCREMENT, SB OTV, 50 PERCENT FULL.

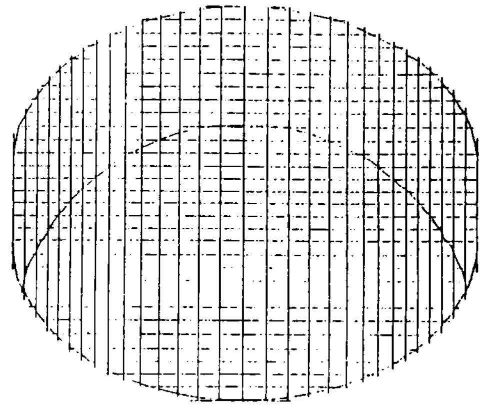

FIGURE 9. - SHORT SB OTV PROPELLANT TANK, FULL SCALE. FINENESS RATIO = 0.87; L = 371.25 CM; D = 426.72 CM.

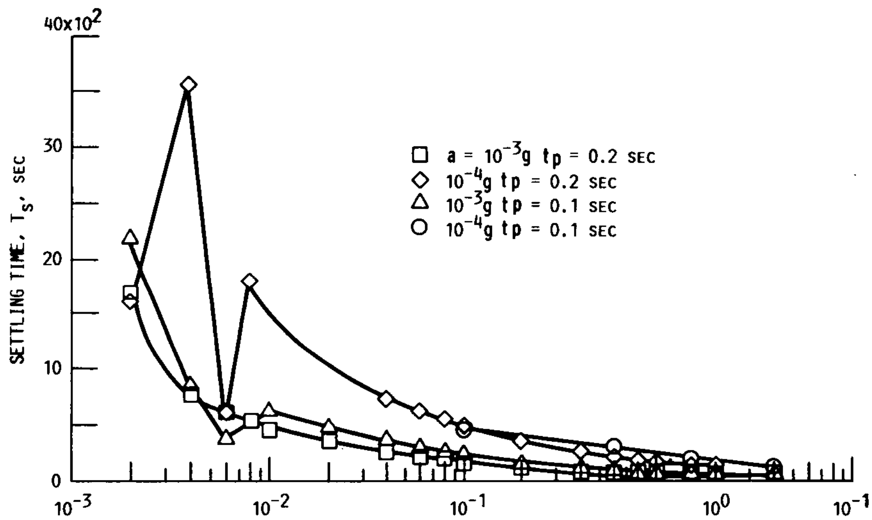

FIGURE 10. - SETTLING TIME VERSUS FREQUENCY, SHORT SB OTV, 50 PERCENT FULL.

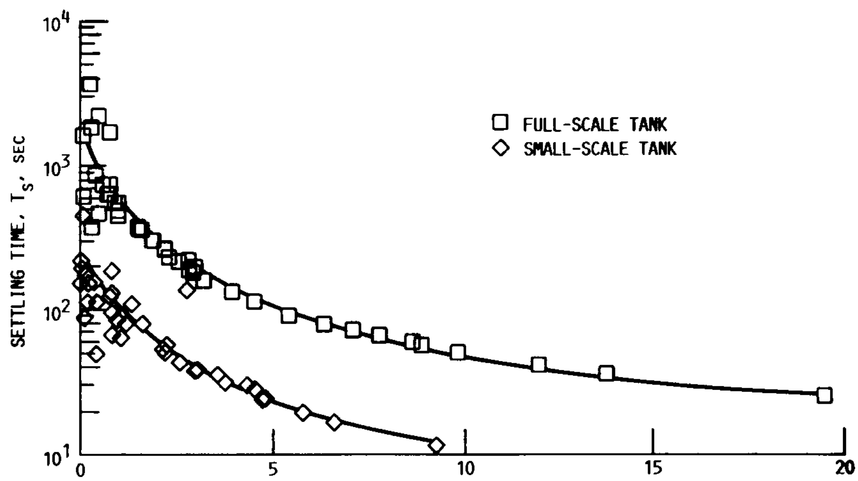

FIGURE 11. - SETTLING TIME VERSUS VEHICLE VELOCITY INCREMENT, SHORT SB OTV, 50 PERCENT FULL.

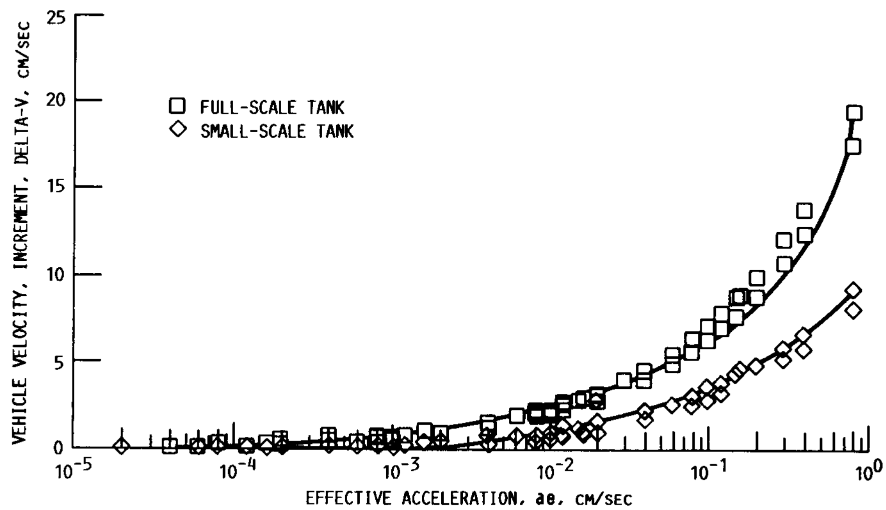

FIGURE 12.- VEHICLE VELOCITY INCREMENT VERSUS EFFECTIVE ACCELERATION, SHORT SB OTV, 50 PERCENT FULL.

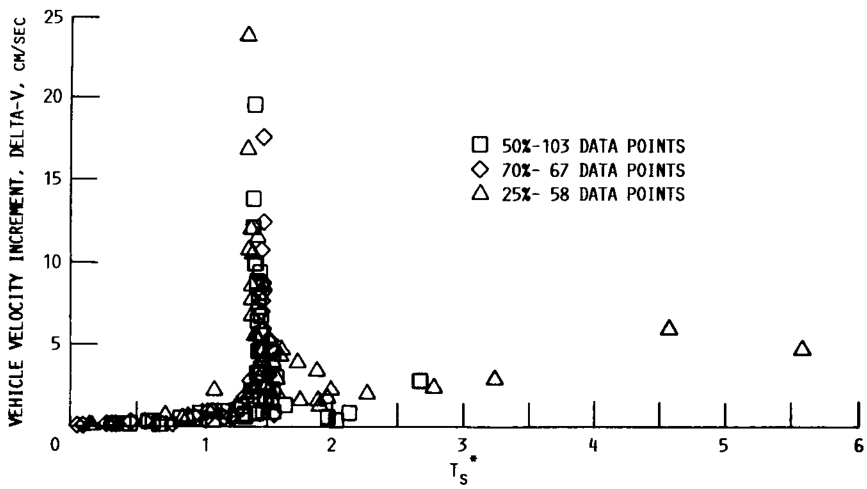

FIGURE 13. - VEHICLE VELOCITY INCREMENT VERSUS T_s^*, SHORT SB OTV, ALL FILL LEVELS.

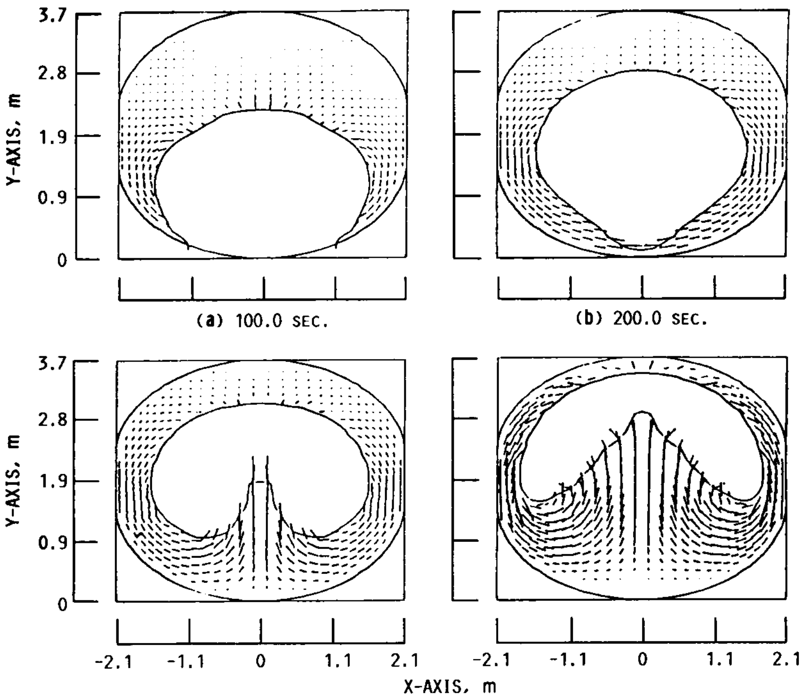

FIGURE 14. - SHORT SB OTV, FULL-SCALE. CASE 1: FILL LEVEL = 70 PERCENT; $a_e = 7.85 \times 10^{-3}$ CM/SEC^2; DELTA-V = 1.77 CM/SEC; $T_s^* = 1.41$; MODERATE GEYSER.

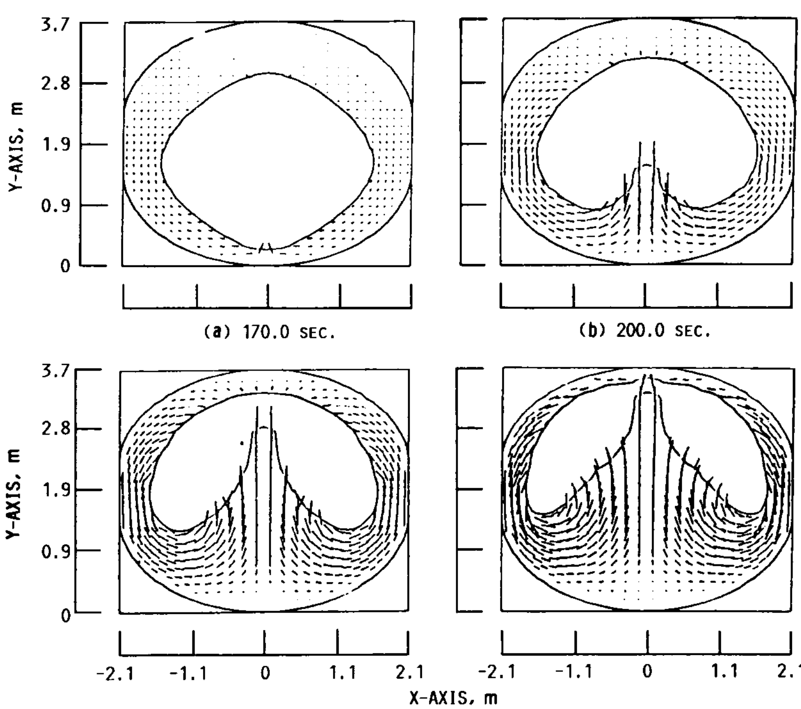

FIGURE 15. - SHORT SB OTV, FULL SCALE. CASE 2: FULL LEVEL = 70 PERCENT; $a_e = 1.18 \times 10^{-2}$ CM/SEC^2; DELTA-V = 2.16 CM/SEC; $T_s^* = 1.45$; SEVERE GEYSER.

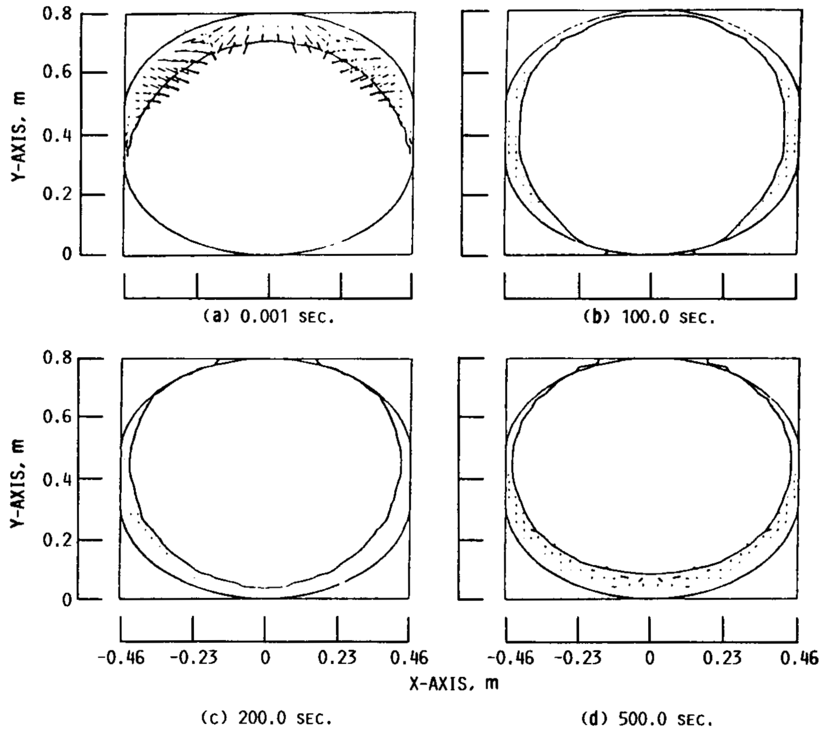

FIGURE 16. - SHORT SB OTV, 0.215 SCALE. CASE 3: FILL LEVEL = 25 PERCENT; $a_e = 7.85\times10^{-3}$ CM/SEC^2; DELTA-V = 4.61 CM/SEC; $T_s^* = 5.59$; NO GEYSER.

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National Aeronautics and Space Administration

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-102117 AIAA-89-2727		

4. Title and Subtitle	5. Report Date
Modeling of Pulsed Propellant Reorientation	
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
A.E. Patag, J.I. Hochstein, and D.J. Chato	E-4892
	10. Work Unit No. 591-23-21
9. Performing Organization Name and Address	11. Contract or Grant No.
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered Technical Memorandum
National Aeronautics and Space Administration Washington, D.C. 20546-0001	14. Sponsoring Agency Code

15. Supplementary Notes

A.E. Patag and J.I. Hochstein, Washington University, St. Louis, Missouri (work funded under Grant NAG3-578); D.J. Chato, NASA Lewis Research Center. Prepared for the 25th Joint Propulsion Conference cosponsored by the AIAA, ASME, SAE, and ASEE, Monterey, California, July 10-12, 1989.

16. Abstract

Optimization of the propellant reorientation process can provide increased payload capability and extend the service life of spacecraft. This paper proposes the use of pulsed propellant reorientation to optimize the reorientation process. The ECLIPSE code has been validated for modeling the reorientation process and is used to study pulsed reorientation in small-scale and full-scale propellant tanks. A dimensional analysis of the process is performed and the resulting dimensionless groups are used to present and correlate the computational predictions for reorientation performance.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Cryogenics Low gravity fluid mechanics Propellant reorientation	Unclassified – Unlimited Subject Category 34

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified	18	A03

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