Nonuniform Propellant Distribution in Multiple Tank Rocket Feed Systems

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Nomenclature

a = axial acceleration
l = propellant feed line length
P = pressure
R, r = distance from spacecraft centerline to propellant tank centerline and propellant tank radius, respectively
t = time
$W, \dot{w}$ = weight of propellant in tank and propellant flow rate, respectively
γ = propellant density
Δ = indicates difference between parameters
θ = direction of resultant force vector or thrust misalignment angle
μ = propellant viscosity
ω = spacecraft angular velocity

Dimensionless ratios

A^* = $r\omega^2/a$
γ^* = γ_2/γ_1
h^* = $\Delta P/\gamma_1 r$
Δl^* = $(l_2 - l_1)/l_1$
μ^* = μ_2/μ_1
R^* = R/r
ΔR^* = $\Delta R/r$
r^* = r_1/r_2
ΔW^* = $\Delta W/(\frac{4}{3}\pi r^3 \gamma_2)$
$\Delta W(t)^*$ = $\Delta W(t)/(\dot{w}_T t)$
l^* = l_2/l_1

Subscripts

1 = component one
2 = component two (opposite one)
m = maximum
R = residual
T = total amount

Theme

MANUFACTURING tolerances on propulsion system components and variations in operational environment result in differing amounts of propellant in each tank of a manifolded multiple tank system. This propellant difference causes a mass unbalance which cannot be completely compensated for prior to launch and has been neglected on the majority of spacecraft; however, precision pointing accuracy on communication satellites requires that they be very accurately balanced.[1-3] This paper surveys the various causes of propellant unbalance between tanks and presents corresponding estimates.

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Content

For a given system variation (Table 1), the magnitude of the resulting unbalance is a function of both the engine operating mode and the amount of remaining propellant; i.e., at least three distinct modes can be isolated: 1) no flow, 2) flow, and 3) depletion. For the purposes of this paper, the governing equations have been simplified in the case of no propellant flow by considering only the equilibrium case when the propellant level is at or near the tank centerline (maximum unbalance condition). During propellant flow to the engine, two limiting extremes were analyzed: "long" and "short" engine burn times. These simplifications allow derivation of relatively simple, approximate equations which can then be used to provide order of magnitude estimates of unbalance.

A. Temperature Effects

A temperature difference between opposing tanks of the same size and distance from the centerline will produce a difference in hydrostatic heads since, when propellant exchange ceases, the hydrostatic pressures (not head) at the outlet of each tank are equal. Since a temperature difference causes a density difference, and the hydrostatic pressure is a product of the head and density, there must be an attendant head difference between tanks. The maximum propellant weight difference between tanks (assuming small density differences) is

$$\Delta W_m^* = (1 - \gamma^*)/4 \tag{1}$$

There is no propellant residual since the tanks deplete simultaneously. Although this effect is present whenever the propellant tanks are in an acceleration field, driving forces are small and the equilibrium condition per Eq. (1) may not be realized.

During engine operation, a temperature difference will also cause a viscosity and density difference in the propellant flowing from each of the tanks. Propellant will be removed at a higher rate from the higher temperature tank until the

Table 1 Unbalance contributors

Phenomena	Nonspinning spacecraft		Spinning spacecraft	
	Thrusting	Coasting	Thrusting	Coasting
Temperature differences				
Hydrostatic head	X		X	X
Viscosity	X		X	
Surface tension	X	X	X	X
Bladder characteristics	X	X	*a*	*a*
Acceleration fields				
Drag	X	X	X	X
Thrusting	X		X	
Thrust misalignment	X		X	
Geometric variations				
Tank volume	X		X	X
Tank location	X		X	X
Line lengths	X		X	

[a] Not applicable since spinning action is used to locate propellant.

hydrostatic head difference between tanks counterbalances the difference in pressure drops between lines. Since, when the flow rates have equalized, the pressure drops in both tanks are equal, the relationship between the head heights in the tanks may be found (assuming laminar flow which is typical of designs to minimize line pressure drop), and hence, the unbalance calculated. Since the density change is negligible relative to the viscosity change, the maximum differential propellant is

$$\Delta W_m^* = 3h^*(1 - \mu^*)/4 \tag{2}$$

During short engine burn times, however, a better estimate may be obtained by assuming the initial flow rate difference is maintained throughout engine burn, i.e., the hydrostatic heads are constant at their initial value. The rate of increase of unbalance is then found to be (again for density differences negligible relative to viscosity changes)

$$\Delta W(t)^* = (1 - \mu^*)/2 \tag{3}$$

The corresponding propellant residual is

$$W_R^* = 3[h^*(1 - \mu^*)]^2/4 \tag{4}$$

noting that $h_t \ll r$ at propellant depletion.

The very small magnitude of the surface tension forces usually results in an insignificant propellant migration. (This effect could be significant in systems relying on surface tension devices for zero g propellant control.)

B. Bladder Characteristics

Propellant control bladders may exhibit residual manufacturing stresses and/or variable spring rates which could cause differential propellant expulsion during engine operation and/or propellant migration during nonoperative periods. The large number of variables involved requires that these forces be experimentally determined for each candidate configuration. In practice, these effects may be minimized by selective grouping of bladders with similar characteristics.

C. Acceleration Fields

Atmospheric drag causes a uniform deceleration and hence encourages propellant transfer between tanks.

For a nonspinning spacecraft, if we assume that the drag component parallel to the thrust vector is negligible relative to the thrust and find the maximum unbalance (for small values of θ expected in design), we get

$$\Delta W_m^* = 3R^*(\sin\theta)/2 \tag{5}$$

Since the propellant surfaces are not parallel to the plane defined by the tank centerlines there will be a propellant residual. For small θ, the residual is given by

$$W_R^* = 3(R^* \sin\theta)^2 \tag{6}$$

If the spacecraft is spinning, there will be propellant sloshing but no propellant migration. Also, there will be no propellant residual; however, the sloshing may cause two-phase flow near propellant depletion.

If, on a nonspinning spacecraft, the thrust vector is misaligned, the thrust has the same effect as drag forces. Consequently, Eqs. (5) and (6) are applicable here also where the angle θ is the thrust misalignment angle.

On a spinning spacecraft, any component of thrust perpendicular to the spin axis rotates with the spacecraft. Since the propellant sloshing caused by corresponding spacecraft coning is outside the scope of this paper, the following analysis considers only the effects of the nonuniform acceleration field.

Analyzing the worst case when the thrust misalignment vector is in the plane defined by the centerlines of the tanks and noting that, in design, the thrust vector has very little influence on surface geometry relative to the radial acceleration vector, the maximum unbalance is

$$\Delta W_m^* = 3(\sin\theta)/4A^* \tag{7}$$

for small values of θ.

The corresponding propellant residual occurs when gas reaches the propellant outlet in one of the tanks. The residual is

$$W_R^* = 3(\sin\theta/A^*)^2/4 \tag{8}$$

D. Geometric Variations

If one tank has a larger diameter than its opposite member, it will contain more propellant when the tanks are filled to the same level. The maximum unbalance is

$$\Delta W_m^* = 3(1 - r^*)/2 \tag{9}$$

In practice, this effect can be minimized by either matching opposing tank pairs according to volume or holding stringent manufacturing tolerances. The volumetric variation does not contribute to residuals since the tanks empty simultaneously.

In a spinning spacecraft, the tank location relative to the spin axis must be carefully controlled since the nonflow equilibrium condition dictates that the propellant surfaces be at an equal distance from the spin axis. The maximum resulting unbalance is

$$\Delta W_m^* = 3\Delta R^*/4 \tag{10}$$

since $\Delta R \ll r$. The location variation also produces a corresponding propellant residual which is given by

$$W_R^* = 3(\Delta R^{*2})/4 \tag{11}$$

Propellant feed lines of different lengths will also produce a flow rate variation between feed lines during engine thrusting. The maximum unbalance is

$$\Delta W_m^* = 3h^* \Delta l^*/4 \tag{12}$$

At propellant depletion, the corresponding residual propellant is

$$W_R^* = 3(h^* \Delta l^*)^2/4 \tag{13}$$

For short engine burn times, the cumulative differential propellant is

$$\Delta W(t)^* = (1 - l^*)/2 \tag{14}$$

An order-of-magnitude comparison of the different unbalance effects was obtained by estimating the magnitude of the independent variables, as seen in current spacecraft design. The most detrimental effect was found to be the temperature difference between tanks. Line lengths and volume differences are an order of magnitude less important and are followed by tank location tolerances and thrust vector misalignment.

References

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