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SLOSH SUPPRESSION

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FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion.

Individual components of this work will be issued as separate monographs as soon as they are completed. A list of all previously issued monographs in this series can be found at the end of this document.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that the criteria sections of these documents, revised as experience may indicate to be desirable, eventually will become uniform design requirements for NASA space vehicles.

This monograph was prepared under the cognizance of the Langley Research Center. The Task Manager was A. L. Braslow. The author was H. N. Abramson of the Southwest Research Institute. A number of other individuals assisted in developing the material and reviewing the drafts. In particular, the significant contributions made by J. Admire and H. Buchanan of NASA George C. Marshall Space Flight Center, H. F. Bauer of Georgia Institute of Technology, H. S. Curtis of McDonnell Douglas Corporation, D. Jensen of North American Rockwell Corporation, R. E. Martin of General Dynamics Corporation, G. Morosow of Martin Marietta Corporation, L. J. Pulgrano of Grumman Aircraft Engineering Corporation, H. M. Satterlee of Lockheed Missiles & Space Company, G. D. Stephens of NASA Langley Research Center, and R. Wells of Chrysler Corporation are hereby acknowledged.

Comments concerning the technical content of these monographs will be welcomed by the National Aeronautics and Space Administration, Office of Advanced Research and Technology (Code RVA), Washington, D.C. 20546.

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SLOSH SUPPRESSION

1. INTRODUCTION

Sloshing is defined as the periodic motion of the free surface of a liquid in a partially filled tank or container. In launch vehicles or spacecraft, sloshing can be induced by tank motions resulting from guidance and control system commands or from changes in vehicle acceleration, such as those occurring when thrust is reduced by engine cutoff or when the vehicle encounters wind shears or gusts.

If the liquid is allowed to slosh freely, it can produce forces that cause additional vehicle accelerations. These accelerations are then sensed and responded to by the guidance and control system, forming a closed loop that can lead to an instability. A slosh-induced instability may lead to structural failure, premature engine shutdown or inability of the spacecraft to achieve upper-stage engine start through loss of propellant head at the drain port, and loss of propellant through the tank vent system. Even in a low- or near-zero-gravity environment, where the slosh frequencies are quite low and the torques exerted on the vehicle may not be great, instability can occur so that the long-term liquid motions can build up to amplitudes which cause some of these failures.

The failure of several booster vehicles has been attributed to inadequate slosh suppression. For example, an early Jupiter flight was unsuccessful because a stepped-pitch program had stepping intervals near the fundamental propellant-slosh frequency; the pitch-reinforced slosh caused the vehicle to go out of control. A Blue Streak single-stage vehicle failed in flight because a slosh-induced instability resulted in structural failure. Although the effect of propellant sloshing had been calculated for the original design, it was not reevaluated after a number of vehicle design changes had been made. There was a premature engine shutoff during the first Saturn I flight because a rotatory slosh was induced by a coupling with the roll-control loop of the guidance system, and the propellant drain line was momentarily uncovered.

Slosh-suppression devices, therefore, are used to damp the liquid motions and prevent these kinds of instability. The proper choice of control-system sensing elements and gain values can enhance vehicle stability, thus reducing damping requirements (and therefore baffle weight). Devices are also used to reduce the structural loads induced by the sloshing liquid, to control liquid position within a tank, or to serve as deflectors to protect tank bulkheads or other structures from liquid-impact loads caused by nonperiodic motion. Slosh-induced forces and moments can also be effectively reduced by alterations in tank design, such as compartmentation, thus reducing the mass of the sloshing liquid and shifting the slosh frequencies.

The primary parameters influencing the design of slosh-suppression devices are: (1) the vehicle's mission profile and trajectory; (2) the damping requirements for specified tank- or liquid-slosh-motion amplitudes at various liquid levels; (3) the physical characteristics of the tank, including its geometry, elastic deformation, and insulation; (4) the liquid system's functional characteristics, including filling and draining requirements and venting and liquid-boiling requirements; (5) the physical and chemical properties of the liquid; and (6) the handling, slosh, and impact loads that must be sustained by the devices, as well as the device weight, material properties, and manufacturability.

This monograph is concerned with the problems of providing a specified amount of damping of liquid-slosh motions by means compatible with all other vehicle systems. The slosh-damping requirements are derived from analyses of vehicle dynamics and hence are not treated in this monograph. The determination of structural loads acting either on the vehicle structure or on the suppression devices themselves as a result of liquid sloshing is discussed in a companion monograph (ref. 1). Another important liquid-tank interaction termed pogo will be discussed in a monograph on suppression of coupled longitudinal instabilities.

2. STATE OF THE ART

2.1 General Background

Several types of slosh-suppression devices have been employed successfully to increase the damping of liquid sloshing induced by vehicle motions, while numerous other types have undergone developmental testing or have been used in other applications, and may be applicable for use in launch vehicles or spacecraft. These devices include rigid-ring baffles (of various geometries and orientation), cruciform baffles, deflectors, flexible flat-ring baffles, floating cans (also lids and mats), positive-expulsion bags, and diaphragms. Gels, packed fibers, and foams have been employed in nonspace applications but are not now being used for space vehicles. A few simple baffle configurations are shown in figure 1. The effectiveness of any particular suppression device is usually expressed as a single parameter (damping factor) and is utilized in some mathematical model intended to simulate slosh loads.

In addition to devices that increase slosh damping, changes in tank configuration that reduce the sloshing mass and alter the slosh frequencies may achieve suppression by decoupling propellant sloshing from the control-system response. Another method of

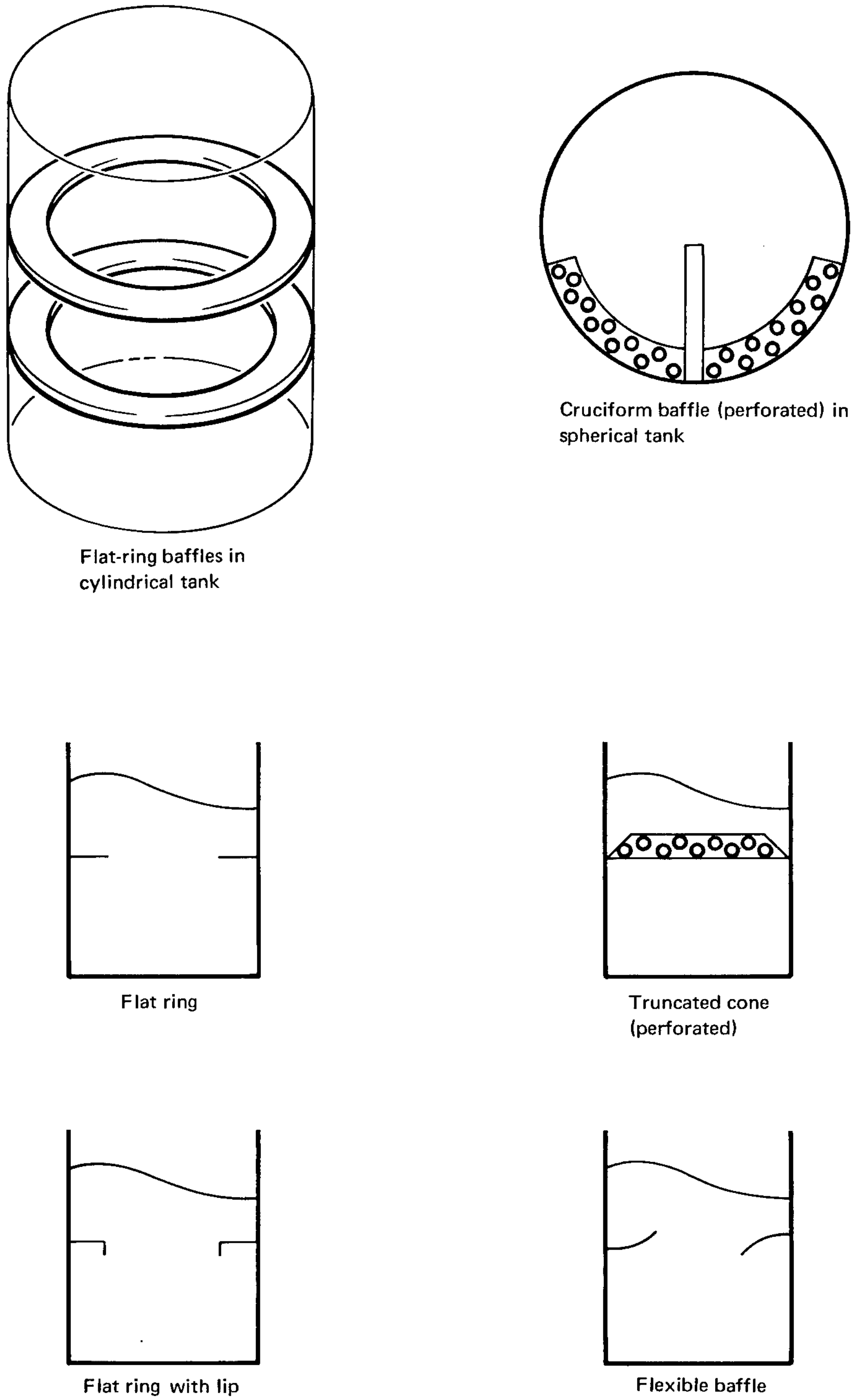


Figure 1.
Various ring-baffle configurations in cylindrical and spherical tanks

achieving slosh suppression is by the use of feedback from lateral accelerometers or fluid-differential pressure transducers into the flight-control system. Attitude-control system optimization by gain changes may also be quite effective in minimizing damping requirements.

The selection and design of suppression systems require quantitative knowledge of the slosh characteristics. A comprehensive treatment of slosh characteristics is given in reference 2, which covers virtually all aspects of liquid-dynamic behavior in moving containers. The effective inclusion of slosh characteristics in control-system stability analyses and simulations is usually accomplished through equivalent mechanical (analytical) models that represent the forces and moments exerted by the sloshing liquid on its container. The model parameters are functions of tank geometry and acceleration environment, and have been derived for a variety of tank configurations by analogy to either a system of spring-mass elements or of pendulum elements. These mechanical analogies consist of one or more fixed masses and one or more moving (sloshing) masses connected to the tank by springs and dashpots. Values of the model parameters representing masses and inertias, spring rates, pendulum lengths, slosh-mass locations, fixed-mass locations, and damping constants are selected to provide the same resultant force and moment to the tank, with corresponding resonant frequencies and damping ratios as those provided by the resultant hydrodynamic-pressure forces of the sloshing liquid. The forces and moments can be determined either from the governing hydrodynamic equations (refs. 2 to 5) or from test data.

Slosh-model parameters for first-mode lateral sloshing for several axisymmetric tanks are given in graphic and tabular form in reference 1. Included are cylindrical tanks, cylindrical-ring tanks, and ellipsoidal, spherical, and conical tanks. Additional data for higher modes and for other tank configurations are available in the literature. The basic theoretical analyses and model developments are given in considerable detail in reference 2; references 3 and 6 to 10 present information on slosh models for several tank configurations, including circular cylindrical and compartmented cylindrical tanks, and spheroidal tanks. The results of small-scale tests to confirm or further define slosh-model parameters are given in references 8, 9, and 11 to 15; digital computer programs that derive slosh-model parameters based on the hydrodynamic equations for axisymmetric tanks of arbitrary geometry are given in references 16 and 17. An equivalent mechanical model for the representation of liquid sloshing in cylindrical tanks in a weightless or near-weightless condition has recently been developed and confirmed by small-scale experiments (ref. 18). Equivalent mechanical models have been used for control-system stability studies of both rigid and elastic vehicles (refs. 2, 7, 19, and 20). Experiments (ref. 21), including flight experience, have indicated that slosh dynamics are adequately defined in terms of equivalent mechanical models (refs. 21 and 22). Since slosh damping is a function of slosh-wave amplitude, the required damping will be specified for a specific slosh-wave amplitude, or, alternately, for a specific slosh-mass or lateral-tank amplitude. These three amplitudes can be related to each other through analysis or test data.

The most generally employed means of providing slosh damping is to install baffles in the tank at a point slightly below the anticipated surface level of the liquid at the time that suppression is required. These baffles may be designed as independent devices, or they may simply be tank wall-stiffener rings required for structural reasons and increased in size to provide adequate damping. The damping ratio provided by submerged flat-ring baffles in cylindrical tanks can be predicted by semiempirical methods to within approximately 10% for the range of baffle geometries, slosh amplitudes, and acceleration levels normally experienced in launch vehicles. For other geometries or suppression devices, fewer empirical data are available and therefore somewhat less accuracy can be expected.

The following sections discuss various means of providing slosh suppression, the degree of effectiveness in achieving suppression, and design considerations.

2.2 Damping Without Slosh-Suppression Devices

The slosh damping resulting only from the liquid viscosity in various containers without baffles is significant because wall damping alone may be sufficiently large that suppression devices may not be required or their design may be less critical. Several extensive investigations of viscous damping of liquid oscillations in circular cylindrical tanks (refs. 23 to 26) have shown that the damping ratio is given quite closely by a relationship involving the liquid's kinematic viscosity, the tank radius, the liquid height, and the tank acceleration. For liquid heights less than one tank radius, the relationship is made more complex because of the dependence of liquid frequency to height.

Similar empirical relationships have been developed for many other geometries, differing from the described relation only in the value of a proportionality coefficient (ref. 2). Some of the geometries for which data are available are those of spherical (refs. 11, 25, and 27), oblate spheroidal (ref. 28), conical (ref. 25), and toroidal tanks (ref. 29). The damping characteristics of liquids in tanks of the more complex geometries are usually difficult to estimate accurately because such factors as slosh amplitude are strongly affected by tank shape and liquid height.

The presence of any hardware in the interior of vehicle tanks may, of course, increase slosh damping by a large amount. Such hardware may be a consequence of fabrication of the tank structure or may consist of supply or ancillary equipment of a wide variety of types. The additional damping of liquid motion provided by internal hardware has been used to satisfy at least part of the overall damping requirement, but there is lack of agreement regarding the need to account for this effect and the advisability of relying upon it without experimental verification.

2.3 Damping With Slosh-Suppression Devices

2.3.1 Rigid-Ring Baffles

Ring baffles are widely used as slosh-suppression devices. Usually, such baffles have been designed to be essentially rigid, but flexible baffles have been widely studied. The companion monograph on propellant slosh loads (ref. 1), which is concerned primarily with the loads on the tank and on baffles resulting from sloshing, includes a brief review of the state of the art regarding the damping provided by slosh baffles; a more detailed review of this topic is given here.

2.3.1.1 Circular Cylindrical Tanks

The damping provided by a rigid-ring (annular) baffle (fig. 1) has been studied in considerable detail. The damping forces measured in reference 30 for two-dimensional plates were used by Miles (ref. 31) to develop a semiempirical relationship for flat rings in a circular cylindrical tank which has been widely used to predict ring-baffle damping. The basic validity of this equation has been experimentally confirmed in numerous studies (refs. 32 and 33).

Miles' equation gives damping ratio as a function only of tank and baffle geometry and slosh-wave characteristics; thus, other similarity parameters are not included. An attempt to incorporate such effects into a modified form of the equation was made in reference 34, while the results of various model tests that reflect such effects to one degree or another are given in references 35 and 36. A summary of data on the influence of Reynolds number on baffle damping is given in reference 37. One interesting feature of these experimental data (also reflected in ref. 34) is that baffle-damping effectiveness decreases with an increase in the tank acceleration.

An important limitation on the application of Miles' equation results from the inherent assumption that the baffle is submerged deep enough that surface effects are negligible. Baffle uncovering during sloshing is the most significant of the near-surface effects. Test data from references 32 and 33 show that the damping ratio reaches a peak value when the baffle is located just slightly below the quiescent free surface, decreasing sharply for other baffle depths; the liquid's resonant frequency is a minimum for this same baffle location. When the baffle is partly uncovered during slosh, a modified form of Miles' equation has been developed (ref. 38), although agreement with experiment when free-surface effects govern is still not good. The information contained in reference 38 is, however, of considerable value since it constitutes an excellent compilation of calculated damping ratios as a function of baffle geometry, baffle depth, and slosh-wave height.

A series of flat-ring baffles is the most frequently used slosh-suppression configuration in cylindrical tanks. Damping ratios for a series of flat-ring baffles, calculated on the basis of linear superposition, are included in reference 38. As spacing between the baffles becomes smaller, perhaps less than one baffle width, the superposition does not accurately predict damping.

Damping provided by rigid-ring baffles with various other cross-sectional geometries in circular cylindrical tanks has been determined experimentally and is reported in references 15, 32 to 34, and 39. Reference 33 also shows the variation in damping factor and resonant frequency of the liquid with ring-baffle depth, as well as how the perforation of the baffle affects its performance. Baffle perforation is important for weight minimization; baffle performance depends upon both the perforation hole size and the percentage of material removed (refs. 32, 33, and 35). Inclined baffles (ref. 32) are used to provide damping effectiveness under some circumstances, while other configurations (e.g., truncated cones, as studied in ref. 35) may also prove at times to be quite attractive.

2.3.1.2 Spheroidal and Toroidal Tanks

Only a small amount of general information has been obtained concerning the damping provided by baffles in spherical, oblate and prolate-spheroidal, toroidal, and other tanks that differ from the circular cylinder. Some test data on baffle effectiveness in specific vehicle tank geometries are available in varying degrees of completeness and accuracy, and are summarized in reference 2.

References 13 and 40 present experimental data on damping values for various baffle configurations in spherical tanks. The baffle arrangements used in reference 13 involved perforated flat rings oriented as lines of longitude, and thus, for shallow liquids, had the same form as cruciform baffles. Experimental data on damping effectiveness are given for this tank-baffle configuration, with the north-south axis of the tank being directed both vertically and horizontally. It was found that the latter leads to a much greater reduction in slosh force. The damping provided by flat-ring baffles oriented in a spherical tank as lines of latitude was examined in reference 40; a number of parameters were varied, and both single- and multiple-baffle configurations were tested.

The damping provided by flat-ring baffles oriented as lines of latitude in oblate spheroids is examined in reference 28; additional data for both oblate and prolate spheroids are reported in reference 14.

Slosh-damping effectiveness provided by baffles in specific vehicle-tank configurations has been measured. For example, test results for an S-IVB LO_2 tank are given in reference 41; reference 42 compares unbaffled and baffled slosh characteristics in a model of the Centaur LH_2 tank for several different baffle configurations.

2.3.2 Flexible-Ring Baffles

Although flexible baffles have not yet been used in a space vehicle, they may offer substantial advantages in terms of both increased damping effectiveness and reduced baffle weight (refs. 32, 36, 40, 43, and 44). The data indicate that the damping effectiveness of flexible baffles depends upon both a period parameter (proportional to slosh-wave amplitude divided by baffle width) and a flexibility parameter (proportional to baffle deflection divided by baffle width). In general, flexible baffles provide substantially higher damping values than rigid baffles of the same width (except when located quite near the liquid surface) and appear to be most efficient when the baffle's natural frequency equals the liquid's slosh frequency.

2.3.3 Ring-Baffle Design

A rather extensive discussion of the baffle design process is given in reference 43. While the primary interest in this analysis is in the flexible baffle concept, the general process is equally applicable to rigid baffles. This discussion also points out that the underlying basis of the design (namely, Miles' equation) is empirical to a large extent, and hence some care must be employed in applications. The results obtained for large-size tanks and reported in reference 36 may be useful in evaluating some aspects of this problem of handling the empirical and model test data. Reference 38 gives information on the damping provided by single and multiple baffles having various values of the geometric and other parameters calculated from Miles' equation.

Annular-ring baffles in cylindrical tanks have been designed both as integral parts of the structure to provide structural stability for the thin tank shell (structural baffles) and as separate devices that are independent of the primary tank structure (nonstructural baffles). Baffle loads resulting from propellant slosh are reviewed in reference 1, and knowledge of them is necessary to ensure an adequate structural design. Other design considerations result from tank deformation as a consequence of the pressure-temperature environment, and from flight loads acting on the entire vehicle.

Structural baffles normally consist of three primary members: (1) the outboard cap that is attached to the tank wall; (2) the inboard cap which may be supported by some substructure or gusset system (especially in large-diameter tanks); and (3) the web plate that is attached to the two caps. The plate may be stiffened by corrugations, beads, or radial ribs, and may be perforated to reduce weight. Special attention is given to attachment design when baffles are to be placed in spheroidal and other similar tanks or in the domed end sections of cylindrical tanks.

Nonstructural baffles need only withstand slosh and other imposed loads without the necessity of also providing any contribution to overall vehicle stiffness or strength.

Rigid nonstructural baffles constructed of nylon fabric have been successfully employed in the LH_2 tank of the Saturn S-IVB stage (ref. 45), and have been proposed for other similar applications. The fabric is strengthened by radial tension cords sewn into the baffle and run from inboard eyelets to outboard studs. Baffle segments are joined together along radial lines by lacing, while the inboard and outboard edges of the fabric are hemmed around circumferential tension cords. This type of baffle offers weight advantages over more conventional metal baffles and appears to be equally rigid. Manufacture is also facilitated when the baffle components must pass through small spaces to enter the tank for later assembly. For flexible baffles, a critical design consideration involves the tearing stresses at the baffle's outboard and inboard edges (refs. 43 and 44).

To provide for propellant drainage, nearly all baffle designs specify some gap between the baffle and the tank wall. Test data, however, have shown that there may be considerable loss in damping efficiency with increasing gap (ref. 32).

2.3.4 Cruciform Baffles, Deflectors, and Other Suppression Devices

Damping produced by cruciform baffles is described in references 13, 28, and 32. These baffles are located physically in the same manner as stringers, so that for the circular cylinder there is the advantage of damping that is independent of liquid height. Cruciform baffles in spherical tanks (ref. 13) were discussed in the preceding sections of this monograph. Cruciform baffles generally provide only a relatively small amount of damping, except when the tank is nearly empty. In fact, cruciform baffles have been put to their greatest use in the latter case as devices to suppress rotatory motions and vortex formation near the tank-drain outlet (ref. 46).

Deflectors have been placed above the liquid's surface level corresponding to engine cutoff to suppress the large-amplitude liquid motions which may be excited by the engine cutoff or by the pulsing of attitude-control engines during orbital coast (refs. 45 and 47). Such deflectors, designed as wide, inverted conical-ring baffles, are intended to prevent liquid propellant from reaching the tank vent and to facilitate propellant drainage; when submerged, deflectors may also contribute to liquid damping.

Several other types of slosh-suppression devices have been proposed for or are actually installed in propellant tanks. These include various kinds of movable devices or devices that always act at the liquid's free surface (such as floating objects or porous mats). All of these devices, however, have been shown to be either less effective than conventional baffles or to involve increased complexity and/or weight penalties. A floating-can type of device is compared with fixed baffles in reference 35; some other devices, such as asymmetrical baffles, are described briefly in reference 2.

2.4 Tank Compartmentation

It is sometimes necessary to shift the liquid's resonant frequencies into a more desirable range and, at the same time, to reduce the magnitudes of the sloshing masses. One exceptionally attractive tank configuration to accomplish these purposes is the circular cylinder, compartmented into sectors by means of radial walls (refs. 7 and 48 to 50). (Compartmentation into ring tanks by annular walls has also been proposed in ref. 3.) To reduce weight, the sector walls can be perforated. As with rigid-ring baffles, the degree of perforation can be optimized with respect to both the hole size and the percentage of wall area removed. Excessive perforation may, however, significantly lower the liquid's resonant frequencies to a point at which the underlying reason for employing the partitions is defeated (ref. 51). Slosh-induced pressures on the walls of compartmented tanks may lead to roll-induced coupling between the propellant and the vehicle motion, and must therefore be carefully considered during stability and control analyses.

Theoretical analyses of sloshing in compartmented tanks (refs. 7, 48, and 49) give values of liquid-resonant frequencies that are generally higher than measured values; this is a consequence of nonlinear effects associated with finite-excitation amplitudes (ref. 50). These differences between calculated and measured slosh frequencies may be of importance in the overall design problem with respect to the proximity of other system frequencies. Further discussion of compartmented tanks is given in reference 2.

2.5 Positive-Expulsion Bags and Diaphragms

Positive-expulsion bags and diaphragms are being increasingly employed as liquid-management devices in control and life-support systems under low-gravity conditions. However, diaphragms and bags have not been used in large propellant tanks typical of launch vehicles. Generally, the damping ratio increases with increasing diaphragm thickness and excitation amplitude and decreasing tank diameter. Peak slosh forces occur at successively higher values of excitation frequency as diaphragm thickness increases (refs. 52 and 53).

Expulsion bags and diaphragms present significant problems in terms of material selection and design details. Diffusion of propellant or pressurant gas through the bag or diaphragm material, resistance to tearing under loads, maintenance of material properties at cryogenic temperatures, the presence of instrumentation or other hardware, and the requirement to vent cryogens represent some of the design problems (see, e.g., ref. 54). Metallic bellows have been used in some applications and offer promise in others as a means of alleviating these kinds of problems, although with some sacrifice in weight (ref. 55).

2.6 Slosh-Suppression Testing

Investigation of the dynamic characteristics of all kinds of liquid-fueled rockets is now conducted routinely, employing both full-scale and model vehicles. Various similitude parameters have been shown to be important for different kinds of tests, but each test has to be designed and performed according to the considerations peculiar to that particular test. Discussions of the similitude requirements and experimental techniques for such tests are given in references 2, 34, 35, 37, 56, and 57; an example of the satisfactory correlation of small-scale and full-scale data can be obtained by comparing references 7 and 35.

2.7 Low-Gravity Slosh Suppression

Even though the damping ratios may be higher under low-gravity conditions, liquid sloshing may remain a significant problem in control-system design and propellant management because the natural frequencies of liquids in low gravity are quite low and a long time is thus required for a disturbed liquid to return to the quiescent state.

Low-gravity sloshing is characterized by the relative importance of the surface-tension forces, the contact angle, and the curved free surface of the liquid. Whether the acceleration is low enough to require consideration of the effects of these parameters can be determined by using the Bond number B_o – the ratio of the gravitational forces to the liquid's surface-tension forces. While there is no sharply defined line of demarkation, Bond numbers much larger than unity indicate that gravity forces dominate and Bond numbers much less than unity indicate that surface-tension forces dominate. In actuality, surface-tension effects can be neglected only for Bond numbers much larger than unity; therefore, Bond numbers as low as 100 would indicate that low-gravity effects *may* be of some significance, and Bond numbers as low as 10 would *require* consideration of low-gravity effects.

A comprehensive discussion of low-gravity fluid mechanics is given in reference 2, including a variational formulation for the determination of sloshing frequencies, mode shapes, and fluid pressures. An equivalent mechanical model for the representation of propellant sloshing in cylindrical tanks in a near-weightless condition ($B_o > 10$) is given in reference 18. Various recent theoretical and experimental studies dealing with liquid slosh under low-gravity conditions are reported in references 47 and 58 to 62. The simulation parameters important in conducting experimental investigations of low-gravity slosh phenomena and the scaling laws important in extrapolating model data to full-scale spacecraft systems are discussed in reference 63.

Slosh frequencies and damping in unbaffled tanks have been the subject of much investigation, both by analysis and by experimentation with models. Reynolds (ref. 2) derived a widely used equation for natural slosh frequency in cylindrical tanks as a function of Bond number. Under low-gravity conditions where Bond-number effects are significant, an increase in forces due to surface tension with a decrease in Bond number increases the slosh frequency compared with the frequency calculated neglecting Bond-number effects. Dodge (ref. 18) has developed a slightly different theory. The slosh frequencies predicted by the two theories agree quite well with test data and agree with each other within about 5%. In spherical tanks, the natural frequency approaches zero as B_o approaches zero, as compared with cylindrical tanks for which the frequency approaches a finite value as B_o approaches zero. Slosh-damping data for unbaffled tanks are presented in references 2, 18, and 60 to 63. Viscous wall damping increases with decreasing Bond number.

Flight tests of liquid behavior under low-gravity conditions are reported in references 64 to 71. Some preliminary data from a manned spacecraft (ref. 64) and a sounding rocket (ref. 65) show that a slosh baffle can be extremely effective in damping low-gravity slosh. Full-scale tests of cryogenic-propellant sloshing behavior in a baffled tank were conducted with an S-IVB stage hydrogen tank on the Saturn IB AS-203 vehicle (refs. 66 to 69). This experiment was designed to simulate as closely as practical the propellant-sloshing environment expected in the Saturn V/S-IVB stage. The slosh-suppression devices employed in this experiment included a conical baffle located slightly above the point corresponding to the liquid level at booster-engine cutoff and an inverted conical deflector located high in the tank to prevent liquid from covering the vent outlet. A continuous acceleration level of 2×10^{-5} g ($B_o \approx 70$) was provided by continuous venting of hydrogen boiloff gases through propulsive vents to ensure propellant settling. Slosh amplification resulting from this reduction in acceleration at main-engine cutoff was minimized by use of a two-step thrust reduction, with the thrust reductions separated by three-fourths of a slosh cycle. To minimize propellant geysering and sloshing, propellant feedlines and recirculation return lines were designed to provide diffusion of backflow into the tank during thrust decrease or chilldown (ref. 45).

Other discussions and analyses concerned with propellant positioning and control in orbiting vehicles are given in references 70 to 72.

3. CRITERIA

3.1 General

Slosh-suppression devices shall be designed to provide the specified levels of slosh damping, to function compatibly with all other systems in the space vehicle, and to maintain structural integrity under all applied loads.

3.2 Guides for Compliance

3.2.1 Damping Effectiveness

The configuration of the slosh-suppression device, including such factors as shape, size, number, stiffness, perforations, gaps, and location, shall account for the effects on damping of the following additional factors:

- Slosh amplitude or amplitude of tank motion.
- Slosh frequency.
- Tank acceleration.
- Liquid level.
- Tank size and geometry.
- Physical properties of liquid.
- Internal hardware and structural components.

3.2.2 System Compatibility

Slosh-suppression devices shall be compatible with the requirements and characteristics of the liquid system, including, but not limited to, such parameters and design constraints as the following:

- Liquid drainage and settling.
- Liquid boiling, bubble entrapment.
- Internal tank insulation and heat transfer.
- Vent location and configuration.

The design of slosh-suppression devices shall also accommodate all interactions with the control system, including, but not limited to, such parameters as:

- Control-system frequencies.
- Control-system sensor characteristics and locations.
- Control-system gain values.

3.2.3 Structural Integrity

The structural design of slosh-suppression devices shall account for the following conditions, as applicable:

- Liquid slosh and impact loads.
- Inertia loads.
- Temperature and pressure.
- Thermal shock and fatigue.
- Tank-wall structural stability.
- Assembly (man) loads.
- Material compatibility with liquids.
- Local vibration.
- Ease of manufacture.
- Versatility in design to permit inspection and/or reconfiguration as a consequence of revised flight missions.

3.2.4 Tests

The degree of damping provided by slosh-suppression devices during the entire flight profile shall be confirmed by appropriate existing experimental data or tests appropriate to the proposed configuration.

4. RECOMMENDED PRACTICES

The design of a liquid-tank combination is an iteration that involves dynamic stability, guidance and control, slosh loads, and liquid management. Evaluation of these considerations may be accomplished by analytical models (mechanical analogies). The values of the parameters for these models may be determined by tests of physical models of the liquid-tank combination, and/or hydrodynamic theory. The results should indicate the magnitude of damping required. A suppression device should then be selected which satisfies these requirements and in addition ensures structural integrity and compatibility with vehicle systems. The following subsections present recommendations concerning damping effectiveness, system compatibility, and structural integrity.

4.1 Damping Effectiveness

4.1.1 Wall Damping

Slosh damping in tanks of various geometries without baffles may be described generally by a semiempirical equation of the form

$$\zeta = C\nu^{\frac{1}{2}} a^{-\frac{3}{4}} g^{-\frac{1}{4}} = C G_A^{-\frac{1}{2}} \tag{1}$$

where ζ is the damping ratio (logarithmic decrement divided by 2π); a, the tank radius; g, the longitudinal acceleration; ν, the liquid's kinematic viscosity; G_A is called the Galileo number ($G_A = \nu^{-1} a^{\frac{3}{2}} g^{\frac{1}{2}}$); and C is a numerical coefficient that takes on different values depending upon tank geometry and liquid height h. For values of $h/a > 1$, the value of C is often taken as 0.79. Other values for C are given in table I; supplementary information, which depends on liquid height, is given in figure 2 in terms of the additional parameters C_2, C_3, C_4, and C_5.

Table I
Values of Numerical Coefficient C for Estimating
Viscous Damping in Various Tanks
(Normal or High Gravity)

Tank shape	Coefficient C	Reference	$\frac{h}{a}$
Cylindrical (flat bottom)	0.56	23	>1
Cylindrical (flat bottom)	0.79	25	>1
Cylindrical (flat bottom)	0.83	26	>1
Cylindrical (spherical bottom)[a]	$0.79 \times C_2$	26	all
Sphere	$0.79 \times C_3$	25	all
Cone	$0.79 \times C_4^{-\frac{1}{2}} \times C_5$	25	–

[a]Center of sphere inside tank

Viscous damping in a half-full sphere may also be estimated from the equation (ref. 11)

$$\zeta = 0.021\left(\frac{10^4}{2\sqrt{2}\; G_A}\right)^{0.359} \tag{2}$$

The damping ratios obtained from equation (2) are about two to three times greater than those obtained from equation (1) and table I for typical values of G_A. Damping in spheroidal and toroidal tanks may be estimated from the data given in references 28 and 29. No specific recommendations can be made regarding choices between all the wall-damping data because of the widely varying conditions under which the data were obtained. Generally speaking, if baffles are provided, it is not necessary to consider wall damping; however, if all of the required damping must be provided by wall damping, a conservative choice is recommended.

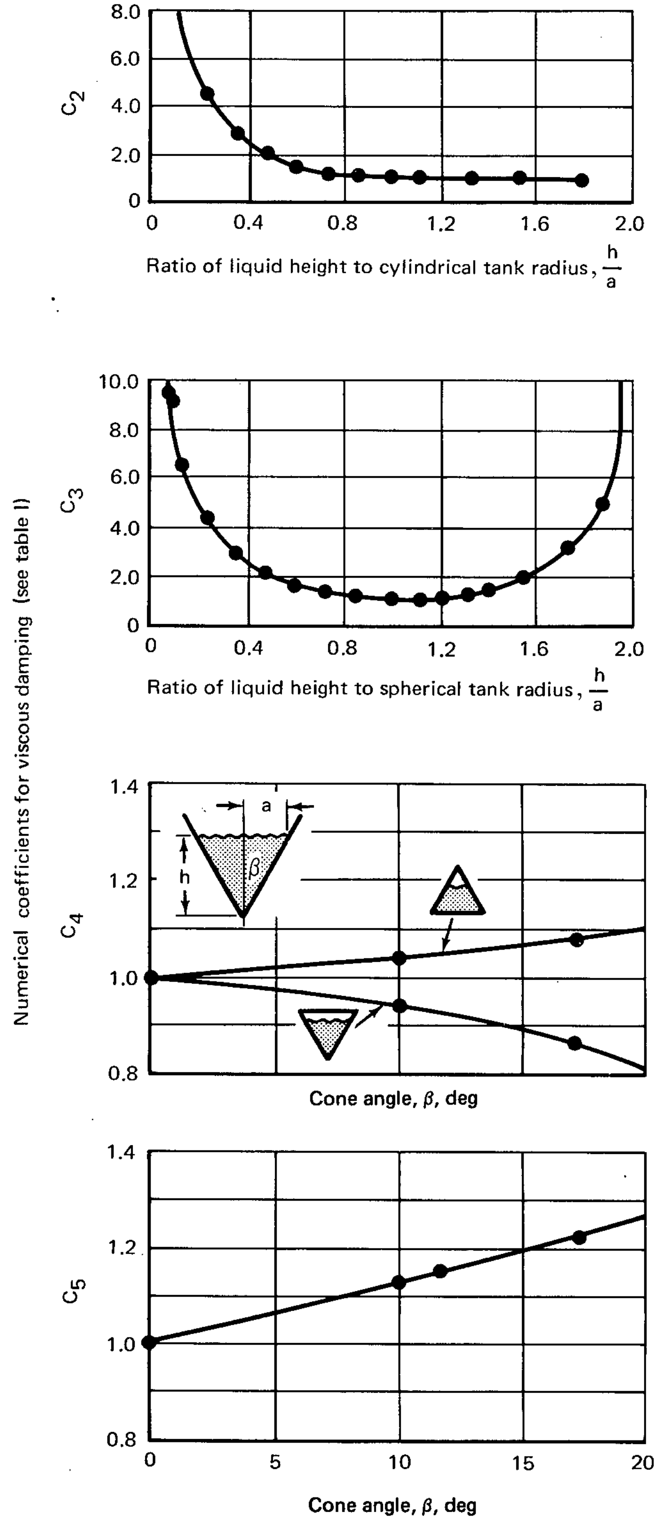


Figure 2.
Values of numerical coefficients for wall damping

For small Bond numbers B_O, corresponding to low-gravity conditions, a similar general form of an equation for correlation of damping data (ref. 62) is

$$\zeta = C G_A^{-\frac{1}{2}} \left(1 + C_1 B_O^{-\frac{3}{5}}\right) \tag{3}$$

where C_1 is another numerical coefficient. Viscous wall damping therefore increases with decreasing Bond number. The following values for C and C_1 (ref. 62) may be used for unbaffled cylindrical tanks filled to various heights:

$\frac{h}{a}$	C	C_1
$h/a \geqslant 1$	0.83	8.20
$h/a = \frac{1}{2}$	1.23	2.20
$h/a = \frac{1}{4}$	1.65	1.22

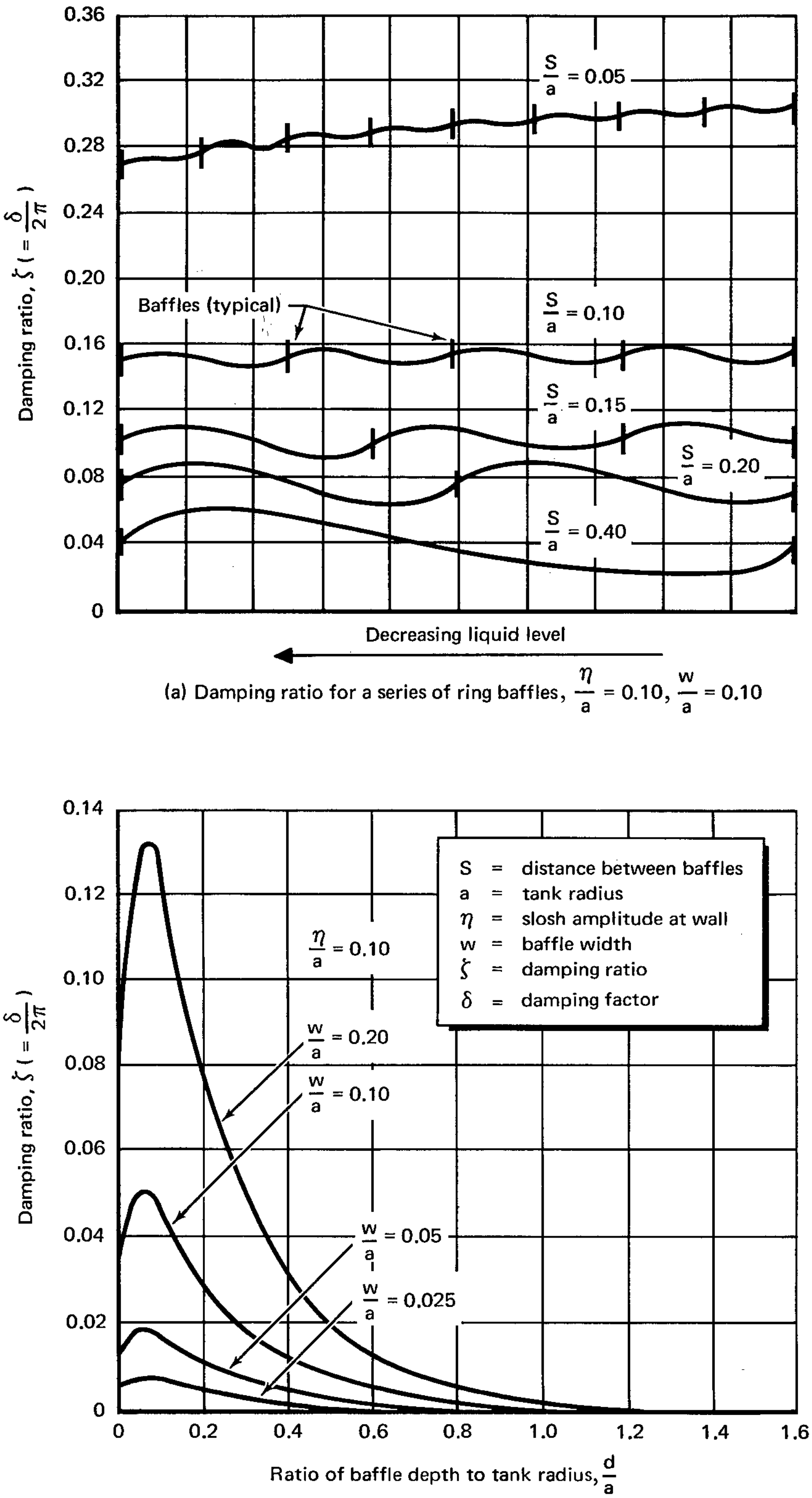
4.1.2 Ring Baffles

The design of ring-baffle slosh-suppression systems is based on selecting baffle width, spacing, and depth of top baffle to give the required damping ratio ζ as a function of liquid level in the tank. For a flat rigid-ring baffle in a cylindrical tank, the damping ratio as a function of baffle depth d should be estimated from Miles' equation (ref 31):

$$\zeta = \frac{\delta}{2\pi} = 2.83\, e^{-4.60\frac{d}{a}} \left[\frac{2W}{a} - \left(\frac{W}{a}\right)^2\right]^{\frac{3}{2}} \left(\frac{\eta}{a}\right)^{\frac{1}{2}} \tag{4}$$

where W is the baffle width; η the maximum slosh-wave height at the wall; and δ, the damping factor (or logarithmic decrement). The term in brackets is the fraction of the tank area covered by the baffle. Typical results calculated from this equation, as modified in reference 38 to include surface effects, are shown in figure 3. The total damping provided by a series of ring baffles may be obtained from equation (4) by linear superposition, although usually only those baffles of less than about two-thirds of a tank radius below the liquid surface contribute significantly to damping and need be considered.

The reduction in liquid-resonant frequency caused by the presence of a baffle near the liquid's free surface should be accounted for (refs. 32 and 33). Perforation of the baffles to reduce weight is permissible, with removal of about 20% to 25% of the baffle area being near optimum, provided that the perforation hole size is compatible with the overall size and geometry, as indicated in references 32, 33, and 35.



(b) Damping ratio for ring baffles as a function of baffle depth

Figure 3.
Ring-baffle damping in cylindrical tanks

Damping factors for flat-ring baffles in tanks of other geometries, or for other conditions, should be estimated from data contained in several of the references cited and/or from experimental measurements.

For conical baffles, which may be required for bubble entrapment or large slosh-amplitude considerations, the damping should be estimated from data in the various references or from experimental measurements, or both.

The practices used in the design of ring baffles vary with mission profile, tank size and geometry, type and location of the baffles, and other factors; most of the possible combinations of these variables were reviewed in Section 2. For the commonly used cylindrical tank, the following are good design principles: locate the first ring baffle at about 0.08 to 0.10 tank radius below the point corresponding to the position of the mean liquid free surface at the time in the mission profile that slosh damping is required, and space the ring baffles at about $s/a \leqslant 0.2$. This will maintain approximately constant damping throughout the period of tank drainage encompassed by the baffle series. Where inclined baffles are used, the largest effectiveness is obtained for the baffles positioned perpendicular to the streamlines in the unbaffled tank.

4.1.3 Cruciform Baffles and Other Suppression Devices

Cruciform baffles and suppression devices other than ring baffles are not recommended for general use. Cruciform baffles may, however, be useful in nearly empty tanks, and other specific applications may indicate their desirability, in which case their effectiveness should be verified by experimental measurements. Although studies of the influence of flexible diaphragms on liquid sloshing in spherical tanks show that significant damping of slosh forces could be achieved, such devices are generally not as effective as are baffle configurations and are therefore not recommended for use primarily as slosh suppressors.

The damping provided by internal hardware may sometimes be relied upon to provide at least a part of the overall damping requirement. In those cases, a suitable method for estimating damping ratios depends upon using an empirical relation for drag coefficient C_D. For flat plates exposed to sinusoidal flow, the data of reference 30 have been fitted to the equation (ref. 23)

$$C_D = \frac{15}{(U_{max}T/D)^{\frac{1}{2}}}, \text{ for } 2 \leqslant \frac{U_{max}T}{D} \leqslant 20 \qquad (5a)$$

$$C_D = 2, \text{ for } \frac{U_{max}T}{D} \geqslant 100 \qquad (5b)$$

which is a function of only the period parameter $U_{max}T/D$, where the fluid velocity is $U = U_{max} \cos \omega t$; T, the period of oscillation ($T = 2\pi/\omega$); and D, the plate width.

These data were obtained using a plate with flow over both edges. To apply equations (5) to wall-mounted hardware, the effective plate width D is equal to 2W, where W is the radial dimension of the protrusion. The period parameter for a flat-ring baffle, for example, is equal to $\pi\eta/W$. Values corresponding to the intermediate range of period parameters must be interpolated.

4.2 System Compatibility

4.2.1 Liquid Systems

Baffle designs should make provision for liquid drainage during launch and ascent, and for bubble escape in boiling cryogenic propellants. These objectives can be achieved by providing gaps between the baffle and the tank wall, inclined baffles, perforated baffles, or a combination of them. Gap size should be large enough to provide adequate liquid drainage but should not be deleterious to slosh damping.

Liquids in large tanks in low-gravity conditions might be displaced away from the drain ends of the tank and must be resettled before main-engine operation. Baffle design should, therefore, endeavor to assist the reorientation flow pattern. For some configurations, gaps between baffle and wall may be advantageous, while for other configurations this technique may not be helpful; care must be exercised in the use of gaps at low Bond-number conditions to avoid fluid entrapment. On the other hand, meridional ring baffles in spheroidal tanks, which are effective slosh-suppression devices, in zero gravity will collect some of the liquid as fillets at the intersection of the tank wall and baffles, and the displaced liquid in the tank, therefore, will tend to follow the baffles into the tank bottom. Also, compartmentation in cylindrical tanks will lead to the collection of liquid at the tank axis (at the sector-wall intersections) which would aid reorientation flow.

Coordination should be maintained with propulsion-system designers to ensure that the amount of propellant trapped by the baffles during resettling, the effect of the baffles on reorientation flow, and the resulting resettling time have been considered in determining propulsion-system performance requirements.

For internally insulated tanks, the design of the attachment of the slosh-suppression device to the tank wall should be coordinated with the insulation designer to ensure that the heat-transfer characteristics are acceptable.

For tanks that have continuous propulsive venting during orbital coast and for which large slosh amplitudes are expected from such phenomena as control pulses or attitude transients, or slosh amplification from engine cutoff, deflectors may be provided high in the tank to prevent the liquid from reaching the vent. The size of the deflector should be determined by considering the surface tension and capillary forces of the liquid (i.e., Bond number) to ensure that any liquid above the deflector will be returned to the tank bottom as a consequence of the acceleration resulting from venting. Use of an inverted conic section may facilitate the return of the liquid to the tank bottom.

To facilitate liquid control, positive-expulsion systems may be employed in low-gravity flight conditions. Whether an elastomeric or metallic system is employed, the materials utilized should be shown to be compatible with the propellants being used. Each new design should be demonstrated to function properly under simulated operating conditions and cycling.

4.2.2 Control Systems

The design of the slosh-suppression device should accommodate all interactions with the control system. Variations in baffle requirements with changes during design in control-system sensor characteristics and locations and in control-system gain values should be considered. The following design goals are recommended, but may not always be practical:

- The ratio of slosh frequency to control frequency should be greater than unity.
- The ratio of slosh frequency to fundamental bending frequency should be less than unity.

Slosh-frequency data for a variety of tank geometries for high-g conditions are given in reference 1. Compartmentation of tanks enables the designer to shift liquid frequencies to avoid proximity to other resonant frequencies; at the same time, the magnitude of the sloshing mass is reduced (by approximately one-third for the first-mode mass in the quarter tank). Figure 4 shows compartmentation schemes for cylindrical tanks, together with some of their corresponding liquid frequencies (ref. 50). It should be noted that the annular tank lowers the first-mode frequency; the quarter tank also brings the lowest two modes into proximity. These theoretical values may be higher than actual values because of nonlinear effects resulting from finite excitation amplitudes. Perforation of the sector walls should be carefully checked by experiment since large hole sizes and/or large percent perforations may allow sufficient fluid transfer between compartments to negate the basic objective of the compartmentation (ref. 51).

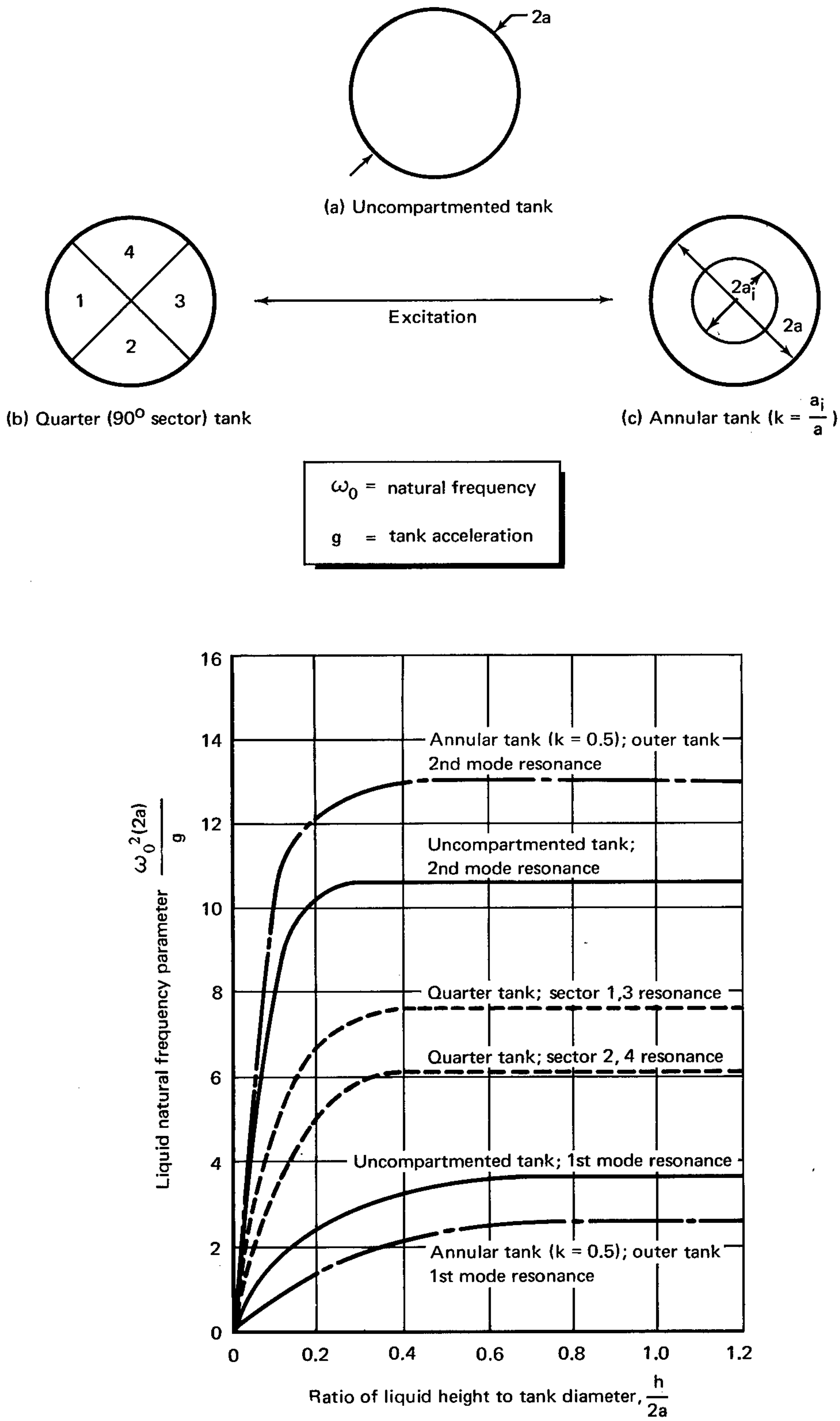


Figure 4.
Variation of liquid natural frequency with liquid height for various compartmented cylindrical tanks

In low-gravity conditions, the natural slosh frequencies of the liquid become a function of Bond number and the lowest frequency in a cylindrical tank should be determined from the relation

$$\omega_o^2 = \frac{\sigma}{\rho a^3}\left(6.25 + 1.84\, B_o - 3.45 \cos\theta\right) \tanh\left(1.84\frac{h}{a}\right) \qquad (6)$$

where σ is the liquid surface tension; ρ, the liquid density; a, the tank radius at the liquid contact point; h, the height of the quiescent liquid; and θ, the contact angle between the liquid and the tank wall. Slosh-frequency data for spherical tanks under low-gravity (Bond number) conditions are given in reference 62.

4.3 Structural Integrity

4.3.1 Structural Devices

Slosh-suppression devices that are integral parts of the tank structure must be designed to ensure adequate strength as would any other structural element. The loads acting on these structural elements are discussed in detail in companion monographs.

The construction of baffles that also serve as structural members normally involves (1) an outboard cap fastened to the tank wall; (2) an inboard cap (may be supported by a strut or gusset system in large-diameter tanks); and (3) a web or plate fastened to the two caps. The web may be stiffened or unstiffened and either solid or perforated. The caps should be so designed as to avoid trapping any propellant.

The baffle assembly must be able to sustain all expected loading conditions. Considering the X-X axis to be parallel to the web and the Y-Y axis to be parallel to the outstanding leg, analyses should be performed for the following loadings:

1. For the outboard-cap stresses, analysis of bending about the X-X axis because of slosh loads, bending about the Y-Y axis because of web-membrane loads (or beaded stiffener loads), and axial-tension loads from tank pressurization.

2. For the inboard-cap stresses, the same analyses as for the outboard-cap stresses, plus additional analyses for bending about the X-X axis because of assembly loads.

3. For the web-plate stresses, analyses of membrane forces for flat sheet and bending forces for beads. The web stiffener will contain bending stresses caused by slosh loads, compression stresses from the membrane reactions, and axial tension from tank-pressure forces.

4. For the inboard-cap support-strut system that is required to maintain the established plane of each ring throughout the life of the vehicle, analyses of the sizing and spacing should be made in conjunction with the optimization study performed on the rings for tank-shell buckling stability (e.g., ref. 73). The loads carried by the strut system are slosh reactions, ring-inertia loads, and assembly (man) loads.

In addition, stresses resulting from temperature changes and from local vibration should be considered for all slosh-suppression device elements. Slosh loads for certain selected configurations may be obtained from the companion monograph (ref. 1).

4.3.2 Nonstructural Devices

The construction of baffles that are not structural members in the vehicle may proceed in any fashion that will provide the desired configuration able to withstand the expected loads (including inertia, tank-deformation, and assembly-handling loads), and will not be deleterious to the tank structure by improper attachment design. When flexible baffles are used, the edge stresses should be made sufficiently low so that tearing does not occur.

4.4 Slosh-Suppression Testing

When insufficient data applicable to a particular configuration are available, scale-model or prototype vehicle tests should be conducted to determine the damping effectiveness of the tank-baffle combination. In either case, slosh suppression should be determined by measuring the logarithmic decay of the liquid oscillations in free vibration or by the forced-response method. The latter requires measurement of a force (or velocity) frequency-response characteristic and then a determination of damping from the peak amplitude at resonance, or by forming a ratio of the bandwidth at the half-power point to the resonant frequency. In general, experimental techniques such as those described in reference 2 are acceptable.

Scale-model testing, depending upon the specific application, may require scaling of the inertial, viscous, and interfacial characteristics of the liquid. Inertial scaling, implying neglect of all other fluid properties, is governed by the time-scale relationship

$$t_r^2 = \frac{a_r}{g_r} \tag{7}$$

where the subscript r denotes the ratio of model to prototype values. This means that a model of any geometric scale can be used to provide data applicable to the prototype by employing the proper time scale.

When viscous scaling is to be accomplished, as most certainly would be the case when wall-damping characteristics are of interest, the kinematic viscosity ν should be included and the corresponding relationship becomes

$$a_r^{\,3} = \frac{\nu_r^{\,2}}{g_r} \tag{8}$$

Or, in other words, the Galileo number ($G_A = \nu^{-1} a^{\frac{3}{2}} g^{\frac{1}{2}}$) should be held constant between model and prototype. For low-gravity problems, the Bond number B_o should be held constant, so that damping is dependent upon both G_A and B_o, as indicated by equation (3).

For assistance in inertial-viscous scaling, equation (8) is plotted in figure 5 in the form of the variation of a_r with g_r for various values of ν_r. The line $\nu_r = 1$ indicates the required geometric- and acceleration-scale ratios if model and prototype contain the same liquid.

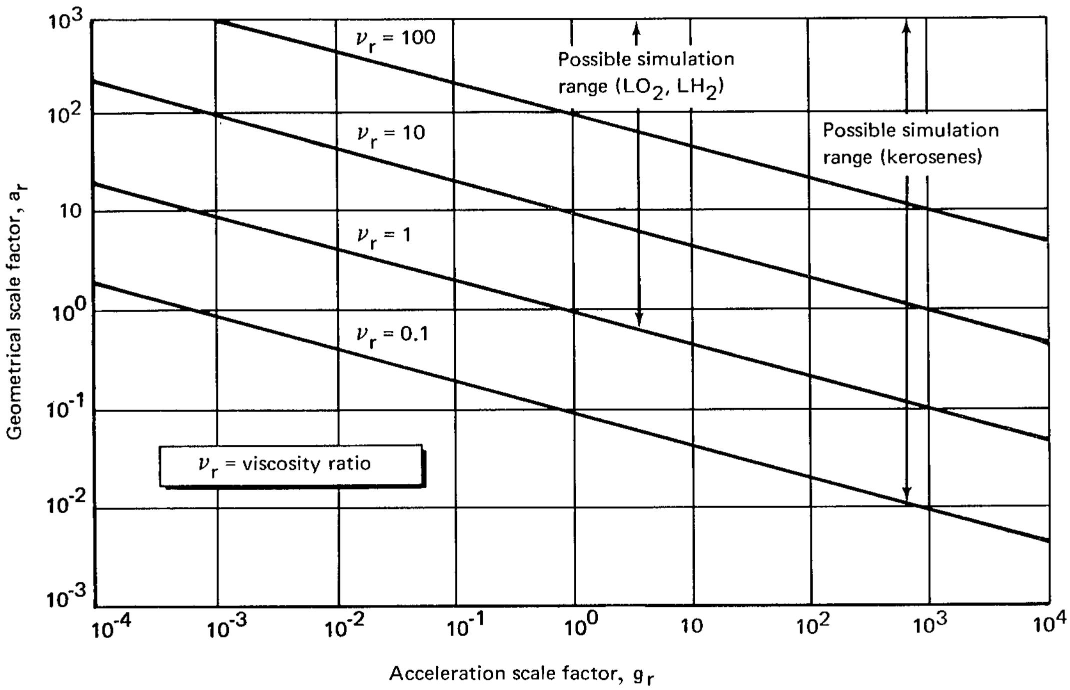


Figure 5.
Simulation plot: inertial-viscous scaling (geometrically similar rigid tanks)

In the event that other similarity parameters are believed to be of importance, the experimental techniques discussed in references 2, 18, 35, 56, and 57 should be employed. One attempt to incorporate such effects into a modified form of equation (4) is made in reference 34, while the results of various model tests that reflect such effects are given in references 35 and 36. A summary of data on the influence of Reynolds number on baffle damping is given in reference 37. In most slosh-suppression testing, however, the scaling laws inherent in equation (4) are adequate.

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SP-8002	(Structures)	Flight-Loads Measurements During Launch and Exit, December 1964
SP-8003	(Structures)	Flutter, Buzz, and Divergence, July 1964
SP-8004	(Structures)	Panel Flutter, May 1965
SP-8005	(Environment)	Solar Electromagnetic Radiation, June 1965
SP-8006	(Structures)	Local Steady Aerodynamic Loads During Launch and Exit, May 1965
SP-8007	(Structures)	Buckling of Thin-Walled Circular Cylinders, September 1965 Revised August 1968
SP-8008	(Structures)	Prelaunch Ground Wind Loads, November 1965
SP-8009	(Structures)	Propellant Slosh Loads, August 1968
SP-8010	(Environment)	Models of Mars Atmosphere (1967), May 1968
SP-8011	(Environment)	Models of Venus Atmosphere (1968), December 1968
SP-8012	(Structures)	Natural Vibration Modal Analysis, September 1968
SP-8013	(Environment)	Meteoroid Environment Model – 1969 [Near Earth to Lunar Surface], March 1969
SP-8014	(Structures)	Entry Thermal Protection, August 1968
SP-8015	(Guidance and Control)	Guidance and Navigation for Entry Vehicles, November 1968
SP-8016	(Guidance and Control)	Effects of Structural Flexibility on Spacecraft Control Systems, April 1969
SP-8017	(Environment)	Magnetic Fields – Earth and Extraterrestrial, March 1969
SP-8018	(Guidance and Control)	Spacecraft Magnetic Torques, March 1969
SP-8019	(Structures)	Buckling of Thin-Walled Truncated Cones, September 1968
SP-8020	(Environment)	Mars Surface Models [1968], May 1969
SP-8021	(Environment)	Models of Earth's Atmosphere (120 to 1000 km), May 1969
SP-8023	(Environment)	Lunar Surface Models, May 1969
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