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CONSTRAINED SLOSHING OF LIQUID MERCURY IN A FLEXIBLE SPHERICAL TANK

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E-9540

Abstract

The mercury propellant tank system developed for use with solar electric propulsion was studied to analytically determine the resonant frequencies of the tank system and compare them with the anticipated control natural frequency of the spacecraft. The system consisted of a stainless steel spherical shell and a hemispherical elastomeric diaphram which separates the mercury propellant and the gaseous nitrogen pressurant. The major analytical tool used was the NASTRAN program. Six mathematical models, which represent various amounts of mercury in the tank system were developed. Resonant frequencies for six harmonics were obtained for each of the six models considered. The results show that the lowest resonant frequency for the tank system is about an order of manitude greater than the anticipated control frequency of the spacecraft.

Introduction

As the energy requirements for advanced spacecraft become increasingly higher, the use of solar electric propulsion appears more attractive. Ion thrusters used for the propulsion system could be fueled by mercury propellant which could be stored as a liquid in some type of spherical tank. To achieve a positive expulsion of the mercury, it would be necessary to equip the tank with an elastomeric diaphram. Such a propellant system has been flown successfully on the Space Electric Rocket Test II (Sert II) Mission launched in February of 1970, and is operating successfully. Figures 23 and 24 of Ref. 1 show a cross section of the main feed tank and the neutralizer feed tank of Sert II. An important consideration in the use of this type of system is the evaluation of the liquid sloshing characteristics of the partially loaded tank. The major sloshing concern will generally occur when some of the mercury has been expended after the spacecraft has been in orbit. In the design of a spacecraft from initial concept to final launch, many flight parameters can and do change. Thus, a certain size tank may initially be designed to be 97% to 98% filled with mercury propellant at launch. In this configuration, although the system is subjected to a broad range of input frequencies, the ability of the mercury to slosh is limited. However, if mission plans change and the amount of mercury required must be reduced, the propellant tank can be offloaded in two ways. The preferred method would be to add a mission dependent bladder support liner as shown in Fig. 14 of Ref. 2. The other method would be to simply offload the tank without changing the support liner. This method would only be used in an emergency because the partially filled tank would be prone to sloshing during the launch environment.

The purpose of this investigation was to analytically determine the resonant slosh frequencies of liquid mercury in flexible spherical tanks with varying amounts of mercury and an elastomeric diaphram which is kept in contact with the mercury by a gaseous nitrogen pressurant. The propellant system studied in this work was that proposed for the 30 cm diameter ion thrusters which were to be used for high energy missions.

Previous Work

The only paper that was found in a literature search on the sloshing of mercury in spherical tanks was the experimental project of Ross and Womack.[3] In their work, a preliminary investigation was conducted to evaluate the slosh characteristics of mercury propellant in a 23 cm diameter tank with a positive expulsion diaphram. Their model had the same characteristics as the model reported in this paper. Ross and Womack showed that the resonant frequencies are a function of (a) the ullage, i.e., the percent of tank volume not containing liquid, (b) the stiffness of the elastomeric diaphram, (c) the static deformed shape of the diaphram, and (d) the nitrogen pressure. They also reported that analytical techniques for predicting the configuration of the interface due to the pressure-mercury-bladder interaction do not exist. In addition, no analytical results have been found on the constrained sloshing of liqquids in partially filled flexible spherical tanks.

Belytschko[4] reviewed the state of the art for the analysis of fluid structure systems. The techniques reviewed have particular utility in reactor safety analysis. However, it is felt that much of the development taking place in this area can be of use in the problem being investigated here. One of the items brought out by Belytschko is the necessity of coupling the work being done in the development of structural analysis algorithms with the work being done in the development of fluid analysis algoritms. Another item which is receiving attention is the relationship between the Eulerian and Lagrangian mesh systems which have been used in the fluid and structural mechanics formulations. Studies are now being conducted on the manner in which they must be modified so that effective rezoning can be accomplished at every solution time step.

Approach

The basic analytical tool used in this work is the NASTRAN program.[5] In the formulation of the governing equations, the motions of the fluid are assumed to be small compared to the dimensions of the container so that non-linear terms in the

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equations of motion can be neglected. Another restriction is that the shape of the container must be axisymmetric. However, there is no implication that the motions of the fluid and the structure are axisymmetric. The restriction regarding the container shape was introduced to simplify the equations governing the fluid solid system. The simplification enables the governing partial differential equations to be separated such that a series of two-dimensional problems can be solved in which the Fourier harmonic becomes an input parameter.

As mentioned earlier, the deformed shape of the bladder was not known for a particular ullage, but was assumed to be the shape shown for each model in table 1. The work of Ross and Womack was used as a guide in determining the deformed bladder geometry. Graphical representations of the six mathematical models used in the investigation are shown in Figs. 1-6. The diameter of the stainless steel spherical tank was 20 inches and the wall thickness was 0.060 inch for each model. The tank was assumed to be supported by a ring at the horizontal diameter such that translations were not permitted in any direction. The bladder was clamped to the stainless steel tank at the ring level.

In using the NASTRAN program, the mercury propellant was modeled as fluid elements which are treated as bodies of revolution. In Figs. 1-6, these elements are designated by the 200 series numbers. The fluid element may have 2, 3, or 4 nodes. In using the fluid elements in conjunction with the structural elements in the NASTRAN program, symmetry permits the specification of only a portion of the structural model. In Fig. 7, the structural idealization of one quarter of the spherical shell is shown. The elements were modeled with flat plate elements. In Fig. 8, the structural idealization of one quarter of the bladder for model 1 is shown.

Appropriate boundary conditions were specified for the structural models to account for the use of one quarter of the stainless steel tank and the bladder for both the even and odd harmonics.

To model only one quarter ofthe structure, it is necessary to specify for the even harmonics that at the initial and final edges, $\theta = 0^{o}$ and 90^{o}, the circumferential translational, and circumferential and longitudinal rotations are zero. For the odd harmonics, the initial edge has the same boundary conditions specified above. At $\theta = 90^{o}$, the radial and circumferential translations, and the longitudinal rotation are specified as zero.

As an example, we have included in the appendix a listing of the input cards for the second harmonic for model 1.

Results

In table 1, the resonant frequencies for the various models as a function of the Fourier Harmonic numbers are given. The results show the effect of the amount of mercury and the bladder shape on the response. For the system studied in this work, thelowest resonant frequency was found to be 0.593 hertz, which is favorably higher than the lowest design frequency that is considered for the spacecraft. (0.015 Hz the natural frequency at the root of the solar array drive.)[6]

Conclusions and Recommendations

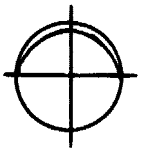
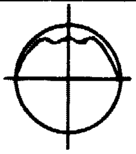
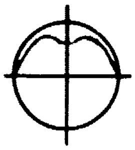
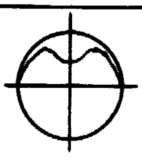
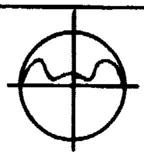
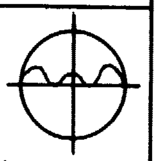
The results presented here indicate that the NASTRAN program can be used to determine the resonant frequencies of solid-fluid systems when the structural configuration is known. The main computational deficiency discovered was the large amount of computer time required to determine the resonant frequencies. Some frequency determinations required two hours on the UNIVAC 1110 System. It is not clear whether these time requirements were due to the eigenvalue algorithms used in the NASTRAN Program, its basic overhead and file structure, or the speed of the UNIVAC machine itself. However, a recent paper (Ref. 7) dealing with eigenvalue dedeterminations with the NASTRAN Program indicates that more efficient algorithms would significantly reduce the computing time.

The results presented here should be followed with a parametric study to assess the influence of the tank and bladder thicknesses. Another item which should be studied is the effect of using shell or three-dimensional brick elements to model the tank and the bladder. Finally, a convergence analysis must also be performed to insure that the results obtained are valid.

References

1. Zavesky, R. J., and Hurst, E. B., "Mechanical Design of SERT II Thruster System Tested on SERT II Spacecraft," NASA TM X-2518, 1972.
2. Cake, J. E., Sharp, G. R., Oglebay, J. C., Shaker, F. J., and Zavesky, R. J., "Modular Thrust Subsystem Approaches to Solar Electric Propulsion Module Design," NASA TM X-73502, 1976.
3. Ross, R. G., Jr., and Womack, J. R., "Slosh Testing of a Spherical Mercury Propellant Tank With Positive-Expulsion Diaphragm," Jet Propulsion Laboratory, JPL TM-33-632, July 1973.
4. Belytschko, T., "Methods and Programs for Analysis of Fluid-Structure Systems," Nuclear Engineering and Design, Vol. 42, 1977, pp. 41-52.
5. McCormick, C. W., ed., "Nastran Users Manual (level 15) to Describe Structural Modeling Techniques and Computer Programming Operations," NASA SP-222 (01), May 1972.
6. Peoschel, R. L., Hawthorne, E. I., et al., "Extended Performance Solar Electric Propulsion Thrust System Study, Volume I - Executive Summary," NASA CR-135281, 1977, p. 16, Table 4.
7. Coppolino, R. N., "A Numerically Efficient Finite Element Hydroelastic Analysis," in Nastran: Users' Experiences, NASA TM X-3428, 1976, pp. 177-206.

TABLE 1. RESONANT FREQUENCIES FOR THE MERCURY PROPELLANT TANK IN CYCLES PER SECOND

FOURIER HARMONIC NUMBER	MERCURY PROPELLANT RESONANT FREQUENCY, HERTZ					
	MODEL OF MERCURY PROPELLANT TANK SYSTEM					
N	1 See Fig 1 - Ullage=1.5%	2 See Fig 2 - Ullage=2.8%	3 See Fig 3 - Ullage=4.3%	4 See Fig 4 - Ullage=8.1%	5 See Fig 5 - Ullage=28.2%	6 See Fig 6 - Ullage=35.2%
						
1	0.7377	0.6174	0.7079	0.5926	1.0138	0.9594
2	0.8888	0.7436	0.8481	0.6749	1.1484	0.9726
3	1.4774	1.3673	1.4683	1.2951	1.8618	1.7459
4	1.8796	1.7555	1.8740	1.6025	2.531	2.2789
5	2.3086	2.2205	2.2963	2.0400	2.9574	2.8674
6	2.0084	1.9247	1.9910	1.7535	2.5533	2.3693

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                                  S O R T E D   B U L K   D A T A   E C H O
 CARD
 COUNT      .  1  ..  2  ..  3  ..  4  ..  5  ..  6  ..  7  ..  8  ..  9  ..  10  .
    1-      AXIF    2       386.4   .0152707        NO                              +AX
    2-      +AX             2
    3-      BDYLIST         AXIS    114     113     112     111     104     103     +BDY
    4-      +BDY    102     101     AXIS
    5-      CFLUID2 201     105     101
    6-      CFLUID2 203     106     105
    7-      CFLUID2 206     108     106
    8-      CFLUID2 210     115     108
    9-      CFLUID2 214     118     115
   10-      CFLUID2 218     114     118
   11-      CFLUID3 202     105     102     101
   12-      CFLUID3 205     107     103     102
   13-      CFLUID3 209     110     104     103
   14-      CFLUID3 217     112     111     117
   15-      CFLUID3 220     113     112     119
   16-      CFLUID4 204     106     107     102     105
   17-      CFLUID4 207     108     109     107     106
   18-      CFLUID4 208     109     110     103     107
   19-      CFLUID4 211     115     116     109     108
   20-      CFLUID4 212     116     117     110     109
   21-      CFLUID4 213     117     111     104     110
   22-      CFLUID4 215     118     119     116     115
   23-      CFLUID4 216     119     112     117     116
   24-      CFLUID4 219     114     113     119     118
   25-      CORD2C  2               .0      .0      .0      .0      .0      1.0     +2C
   26-      +2C     1.0     0.0     1.0
   27-      CORD2S  3               .0      .0      .0      .0      .0      1.0     +2S
   28-      +2S     1.0     0.0     1.0
   29-      CQUAD2  101     11      1       5       6       2
   30-      CQUAD2  102     11      2       6       7       3
   31-      CQUAD2  103     11      3       7       8       4
   32-      CQUAD2  104     11      5       1041    1042    6
   33-      CQUAD2  105     11      6       1042    1043    7
   34-      CQUAD2  106     11      7       1043    1044    8
   35-      CQUAD2  301     31      1041    1042    1112    1111
   36-      CQUAD2  302     31      1042    1043    1113    1112
   37-      CQUAD2  303     31      1043    1044    1114    1113
   38-      CQUAD2  304     31      1111    1112    1122    1121
   39-      CQUAD2  305     31      1112    1113    1123    1122
   40-      CQUAD2  306     31      1113    1114    1124    1123
   41-      CQUAD2  307     31      1121    1122    1132    1131
   42-      CQUAD2  308     31      1122    1123    1133    1132
   43-      CQUAD2  309     31      1123    1124    1134    1133
   44-      CQUAD2  310     31      1131    1132    1142    1141
   45-      CQUAD2  311     31      1132    1133    1143    1142
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SLOSH ANALYSIS OF FEED TANK
MODEL 001

S O R T E D   B U L K   D A T A   E C H O

CARD COUNT	. 1 ..	2 ..	3 ..	4 ..	5 ..	6 ..	7 ..	8 ..	9 ..	10 .
46-	CQUAD2	312	31	1133	1134	1144	1143			
47-	CQUAD2	401	11	1041	1031	1032	1042			
48-	CQUAD2	402	11	1042	1032	1033	1043			
49-	CQUAD2	403	11	1043	1033	1034	1044			
50-	CQUAD2	404	11	1031	1021	1022	1032			
51-	CQUAD2	405	11	1032	1022	1023	1033			
52-	CQUAD2	406	11	1033	1023	1024	1034			
53-	CQUAD2	407	11	1021	1011	1012	1022			
54-	CQUAD2	408	11	1022	1012	1013	1023			
55-	CQUAD2	409	11	1023	1013	1014	1024			
56-	CTRIA2	107	12	1	2	9				
57-	CTRIA2	108	12	2	3	9				
58-	CTRIA2	109	12	3	4	9				
59-	CTRIA2	313	32	1141	1142	1151				
60-	CTRIA2	314	32	1142	1143	1151				
61-	CTRIA2	315	32	1143	1144	1151				
62-	CTRIA2	410	12	1012	1011	1000				
63-	CTRIA2	411	12	1013	1012	1000				
64-	CTRIA2	412	12	1014	1013	1000				
65-	EIGC	1	INV	MAX						+EI
66-	+EI	0.0	0.0	0.0	10.0	15.0	1	1		
67-	FLSYM	4	S	S						
68-	GRID	1	3	10.0	30.0	.0	3			
69-	GRID	2	3	10.0	30.0	30.0	3			
70-	GRID	3	3	10.0	30.0	60.0	3			
71-	GRID	4	3	10.0	30.0	90.0	3			
72-	GRID	5	3	10.0	60.0	.0	3			
73-	GRID	6	3	10.0	60.0	30.0	3			
74-	GRID	7	3	10.0	60.0	60.0	3			
75-	GRID	8	3	10.0	60.0	90.0	3			
76-	GRID	9		0.0	.0	10.0				
77-	GRID	1000		0.0	.0	-10.0				
78-	GRID	1151		0.0	.0	8.5				
79-	GRIDB	1011			.0		2		101	
80-	GRIDB	1012			30.0		2		101	
81-	GRIDB	1013			60.0		2		101	
82-	GRIDB	1014			90.0		2		101	
83-	GRIDB	1021			.0		2		102	
84-	GRIDB	1022			30.0		2		102	
85-	GRIDB	1023			60.0		2		102	
86-	GRIDB	1024			90.0		2		102	
87-	GRIDB	1031			.0		2		103	
88-	GRIDB	1032			30.0		2		103	
89-	GRIDB	1033			60.0		2		103	
90-	GRIDB	1034			90.0		2		103	

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SLOSH ANALYSIS OF FEED TANK
MODEL 001

S O R T E D   B U L K   D A T A   E C H O

CARD COUNT	. 1 ..	2 ..	3 ..	4 ..	5 ..	6 ..	7 ..	8 ..	9 ..	10 .
91-	GRIDB	1041			.0		2		104	
92-	GRIDB	1042			30.0		2		104	
93-	GRIDB	1043			60.0		2		104	
94-	GRIDB	1044			90.0		2		104	
95-	GRIDB	1111			.0		2		111	
96-	GRIDB	1112			30.0		2		111	
97-	GRIDB	1113			60.0		2		111	
98-	GRIDB	1114			90.0		2		111	
99-	GRIDB	1121			.0		2		112	
100-	GRIDB	1122			30.0		2		112	
101-	GRIDB	1123			60.0		2		112	
102-	GRIDB	1124			90.0		2		112	
103-	GRIDB	1131			.0		2		113	
104-	GRIDB	1132			30.0		2		113	
105-	GRIDB	1133			60.0		2		113	
106-	GRIDB	1134			90.0		2		113	
107-	GRIDB	1141			.0		2		114	
108-	GRIDB	1142			30.0		2		114	
109-	GRIDB	1143			60.0		2		114	
110-	GRIDB	1144			90.0		2		114	
111-	MAT1	21	2.8+7		.3	7.25-04				
112-	MAT1	315	1.+03		.498	1.03-04				
113-	PQUAD2	11	21	.060						
114-	PQUAD2	31	315	0.060						
115-	PTRIA2	12	21	.060						
116-	PTRIA2	32	315	0.060						
117-	RINGFL	101	1.0		-9.94987					
118-	RINGFL	102	5.0		-8.66025					
119-	RINGFL	103	8.66025		-5.0					
120-	RINGFL	104	10.0		.0					
121-	RINGFL	105	1.0		-8.66025					
122-	RINGFL	106	1.0		-5.0					
123-	RINGFL	107	4.0		-5.0					
124-	RINGFL	108	1.0		.0					
125-	RINGFL	109	4.0		.0					
126-	RINGFL	110	7.0		.0					
127-	RINGFL	111	9.0		3.0					
128-	RINGFL	112	7.0		6.0					
129-	RINGFL	113	4.0		8.0					
130-	RINGFL	114	1.0		8.5					
131-	RINGFL	115	1.0		3.0					
132-	RINGFL	116	4.0		3.0					
133-	RINGFL	117	7.0		3.0					
134-	RINGFL	118	1.0		6.0					
135-	RINGFL	119	4.0		6.0					

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SLOSH ANALYSIS OF FEED TANK
MODEL 001

                                   S O R T E D   B U L K   D A T A   E C H O
CARD
COUNT     .   1   ..   2   ..   3   ..   4   ..   5   ..   6   ..   7   ..   8   ..   9   ..  10   .
 136-     SPC1    3       123     1041    1042    1043    1044
 137-     SPC1    3       345     4       8       1044    1034    1024    1014    +PC1
 138-     +PC1        1011    1021    1031    1041            5       1
 139-     SPC1    3       345     1111    1121    1131    1141    1144    1134    +PC2
 140-     +PC2        1124    1114
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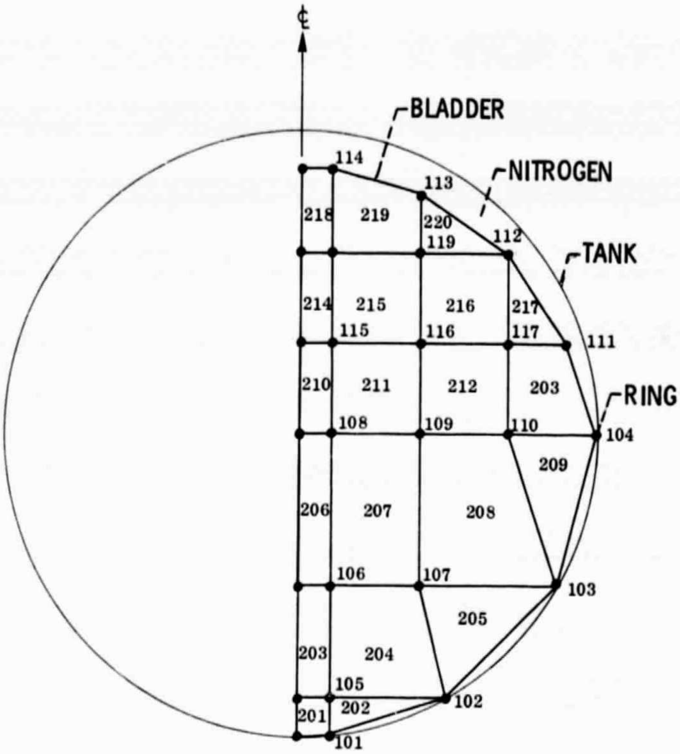

Figure 1. - Model 1 of mercury propellant tank system.

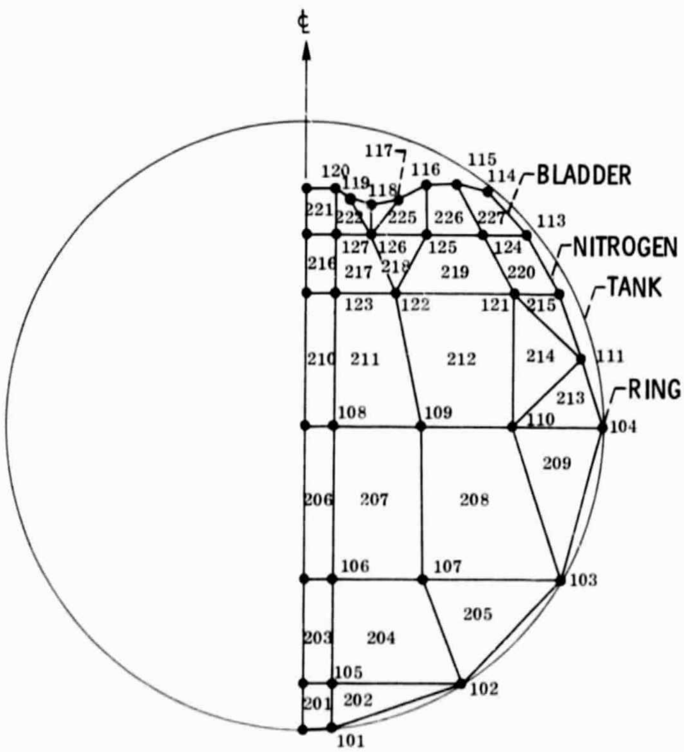

Figure 2. - Model 2 of mercury propellant tank system.

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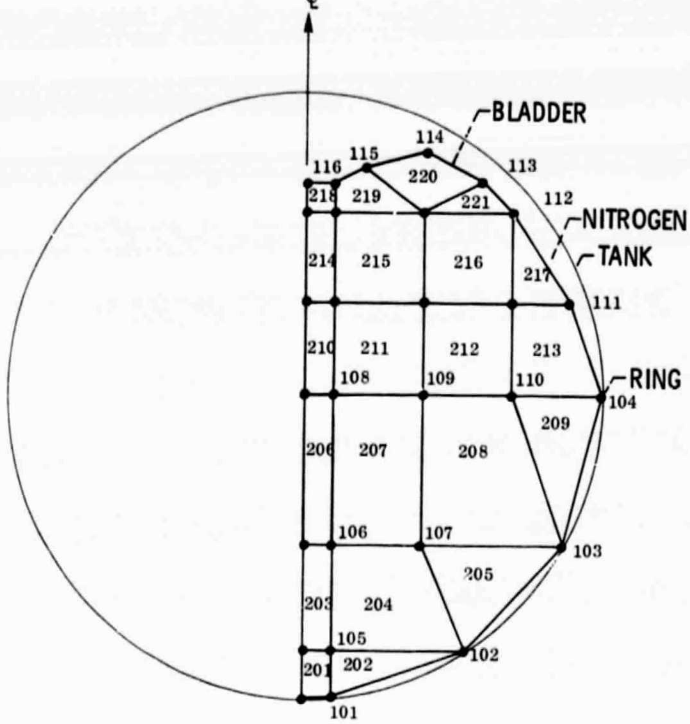

Figure 3. - Model 3 of mercury propellant tank system.

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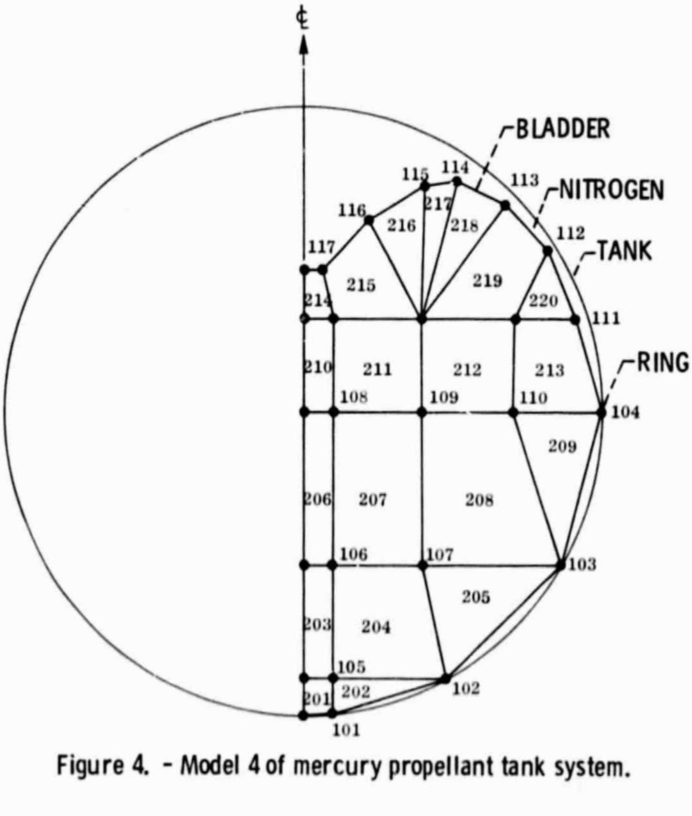

Figure 4. - Model 4 of mercury propellant tank system.

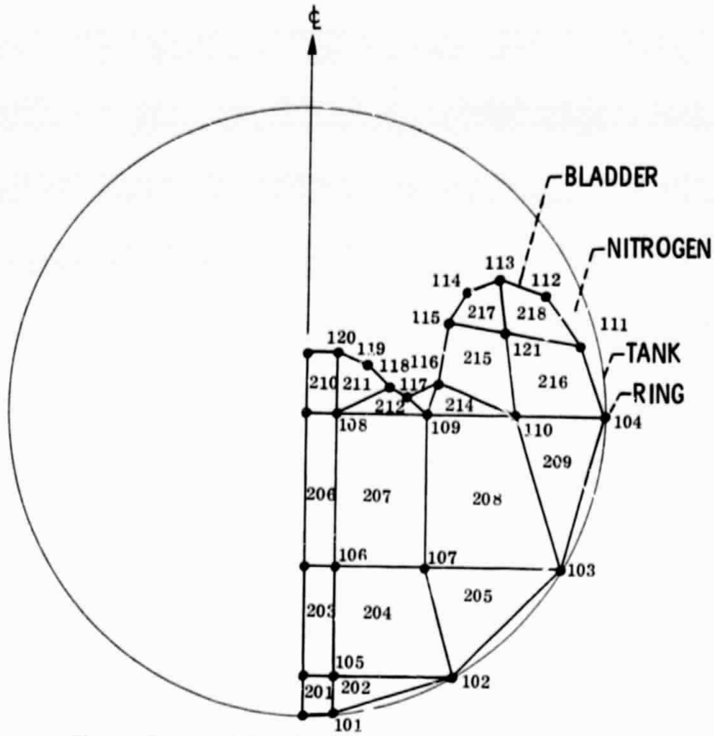

Figure 5. - Model 5 of mercury propellant tank system.

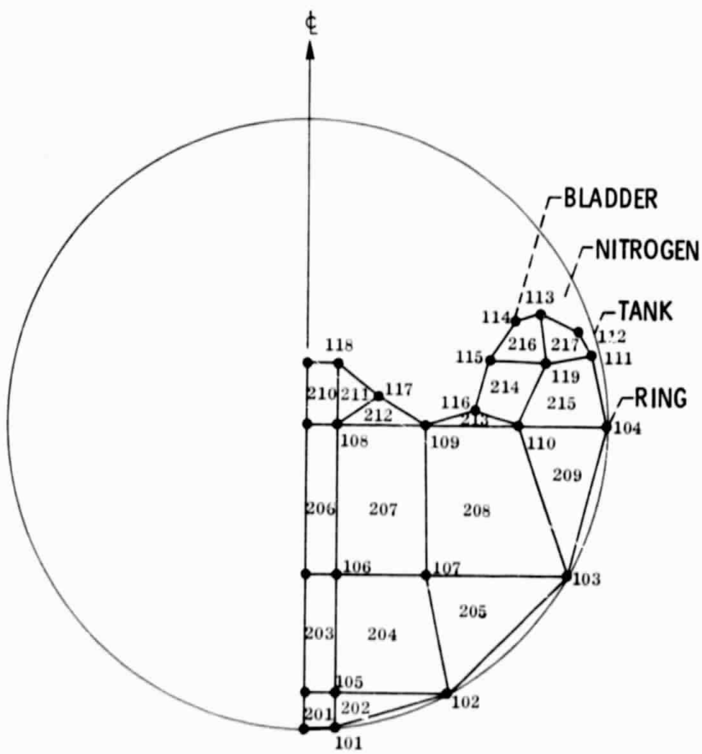

Figure 6. - Model of mercury propellant tank system.

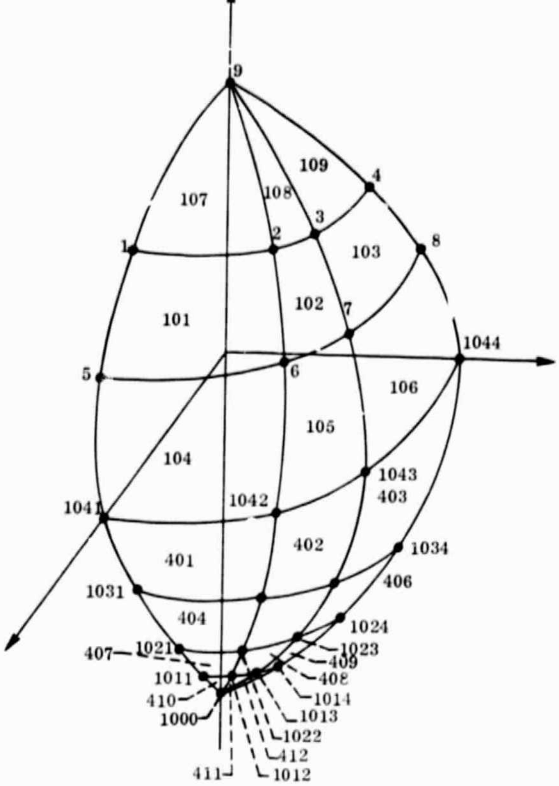

Figure 7. - One quarter model of stainless steel tank.

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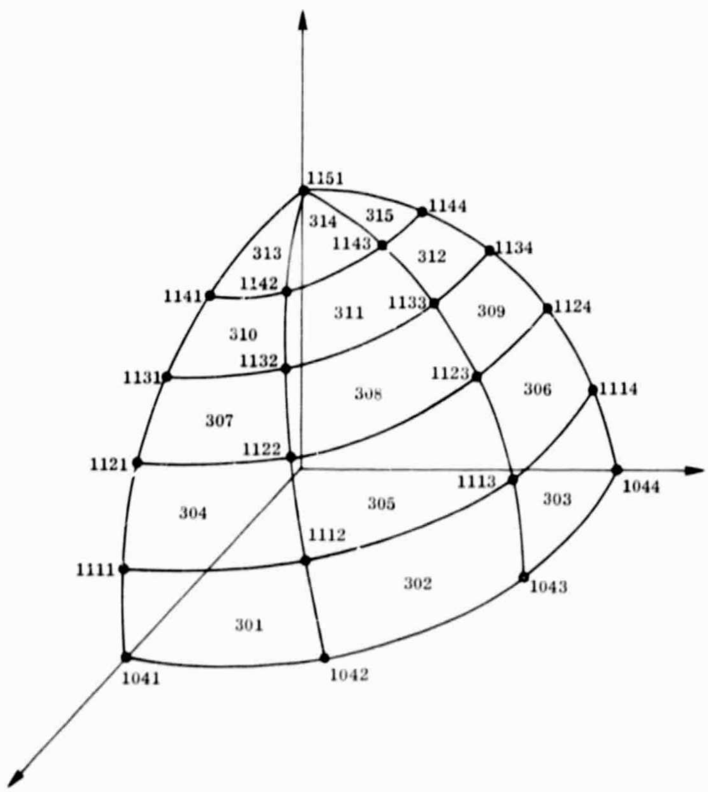

Figure 8. - One quarter model of elastomeric bladder for model 1.