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FREE GYROSCOPE EXPERIMENTS OF TWO IMMISCIBLE LIQUIDS IN A PARTIALLY FILLED CYLINDER

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December 1985

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US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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Gyroscope experiments have been conducted to measure the yaw growth rate in a cylinder filled with two immiscible liquids (silicone oil and water). The experimental data were obtained by measuring the yawing motion of a free gyroscope when the spin is held constant. The yaw history was processed to obtain the yaw growth rate induced by the liquid. Yaw histories were obtained for a 90% filled cylinder (height = 25.78 cm and diameter = 8.24 cm) spinning at 50
(continued)

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) rev/sec. The aspect ratio (height/diameter) of the cylinder was 3.126. The composition of the liquid payload was changed by varying the oil to water ratios - ratios of 100/0, 85/15, 75/25, 30/70, 15/85, and 0/100 were tested.

The experimental data were found to be consistent with a recent theory by Murphy. However, a small, but consistent, bias was observed between the measured and predicted values of yaw frequency at the maximum growth rate; the experimental values were slightly larger.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

The effects of liquid payload motion on the flight behavior of a projectile have been of concern to the Army for many years. For the past 25 years, there has been a systematic effort within the Army to solve liquid payload problems and the effort has included both experimental and theoretical approaches. Much of the earlier work has been published in Reference 1 which is an Engineering Design Handbook (1969) for liquid filled projectiles. Reference 2 contains an excellent bibliography of much of the significant research including more recent contributions. Although many facets of the problem have been addressed, most of the past effort has been directed toward the case of a single component liquid payload. Scott[3] considered a two-component inviscid system, derived relations for the liquid eigenfrequencies, and obtained fair agreement with experiment. Murphy[2] provided a formulation of the effect of liquid motion on projectile stability by computing liquid moments from the internal cavity wall pressures and wall shear stresses. This work was applicable to a fully spun-up liquid (solid body rotation) in a completely- or partially-filled cylinder with a solid or air central core. More recently, Murphy[4] considered two immiscible, viscous liquids in a rotating cylinder. The effects of viscosity are approximated by boundary layer treatments based upon the work of Wedemeyer.[5] Viscous effects are limited to the boundary layer on the cylinder walls and to the viscous shear layer at the interface of the two liquids.

The recent theoretical advances for a two-component liquid and the practical applications were motivating factors for this experimental investigation. Therefore, the objective of this experimental investigation was to provide an initial data base for a two-component liquid-filled cylinder and to provide experimental data which could be compared to theory.

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1. *Engineering Design Handbook, Liquid-Filled Projectile Design, AMC Pamphlet No. 706-165, U.S. Army Materiel Command, Washington, D.C., April 1969. (AD 853719)*

2. *Charles H. Murphy, "Angular Motion of a Spinning Projectile with a Viscous Liquid Payload," Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-03194, August 1982. (AD A125332) (See also Journal of Guidance, Control, and Dynamics, Vol. 6, July-August 1983, pp. 280-286.)*

3. *W. E. Scott, "The Inertial Wave Spectrum in a Cylindrically Confined, Inviscid, Incompressible, Two Component Liquid," Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Report 1609, September 1972. (AD 752439) (See also Physics of Fluids, Vol. 16, No. 1, January 1973, pp. 9-12.)*

4. *Charles H. Murphy, "Side Moment Exerted by a Two-Component Liquid Payload on a Spinning Projectile," AIAA Paper 84-2115, August 1984. (See also ARBRL-TR-02624, December 1984, AD A149845.)*

5. *E. H. Wedemeyer, "Viscous Corrections to Stewartson's Stability Criterion," Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Report 1325, June 1966. (AD 489687)*

II. EXPERIMENT

A. The Laboratory Gyroscope.

The liquid-filled cylinder at full spin is shown in Figure 1. The cylinder was filled to 90%, leaving an air core of approximately 31% of the cylinder radius. The liquids have different densities which cause the heavier liquid to centrifuge toward the outer region of the cylinder and force the lighter liquid inward. The two liquids, oil and water, are immiscible and an interface is formed at the radius b_1. The cylindrical container is located within the rotor of the freely gimballed gyroscope shown in the photograph of Figure 2. The rotor is fairly massive and weighs approximately 30 times as much as liquid. Rings of varying mass can be added to the rotor to change the spin moment of inertia and, hence, change the natural frequency of the system. The rotor is mounted inside a non-rotating cage with ball bearings at each end. A DC, variable speed motor, attached to the bottom of the cage drives the rotor at the desired spin rate. A threaded spindle is situated on the top of the cage so that non-spinning weights can be positioned to vary the transverse moment of inertia, I_y, which also changes the natural frequency of the system. The gimbal pivots consist of crossed-leaf springs (flexural pivots), which are instrumented with strain gages. The strain gage output is linear with angle for small yaw angles. The pivots have very small spring constants and, therefore, little influence on the gyroscope motion.

B. Data Acquisition.

The axis of the rotor, at zero yaw, is in the vertical position. The inner gimbal, which includes the rotor, is held in the vertical position while the rotor is spinning at the desired rate. After sufficient time has elapsed for the liquid to achieve solid body rotation, the inner gimbal is released with care so as not to impart a disturbance. Any significant unstable motions are self-starting and do not require an initial disturbance. As the coning (yaw) motion grows in amplitude, the yaw histories are recorded on a digital oscilloscope. The strain gage output from one flexural pivot is shown in Figure 3. If the data are of satisfactory quality, they are stored on a floppy disc. Weights on the spindle are then moved so that another yaw frequency can be obtained and the above procedure is repeated until enough data is acquired to define yaw growth rates over the desired range of coning frequencies.

C. Data Processing.

Data are transferred from the local oscilloscope medium to a VAX 11-780 minicomputer for processing. The data reduction program provides the capability of digital filtering which is usually necessary; also, windowing is sometimes required to discard obviously bad data. The program selects an initial yaw amplitude, K_{10} to be used in scaling all successive amplitudes, K_1. The data are plotted as $\ln(K_1/K_{10})$ versus time increment, and fitted by a linear least squares procedure over the desired interval. Figure 4 shows such a plot and the interval of linearity is seen to be approximately from 3 to 9 seconds. A linear variation of $\ln(K_1/K_{10})$ with time indicates a constant growth rate. Usually the yaw amplitudes are small (in the range of 0.2 to 1.5 degrees). Typically, the response of the gyroscope is carefully examined for the maximum yaw growth rate ($\tau_{I_{max}}$) and the coning frequency at which maximum yaw growth rate occurs ($\tau_{R_{max}}$). A summary of the test conditions is provided in Table 1. Approximately 20 to 24 yaw histories were obtained for each test condition.

TABLE 1. TEST CONDITIONS.

$c/a = 3.126$

$a = 41.21$ mm

$I_x = 86.82$ g·m²

$f = 0.9$ typical value

$Re = 534000$

$\dot{\phi} = 50$ rev/sec

$\rho_1 = 1.0$ g/cc, (1.0 cs water)

$\rho_2 = .812$ g/cc, (1.0 cs oil)

$\rho_2 = .960$ g/cc, (100 cs oil)

Oil/Water	ν oil	f	b_2/a	b_1/a
100/0	1.0 cs	.895	.324	1.000
85/15	1.0 cs	.886	.337	.935
75/25	1.0 cs	.886	.338	.883
30/70	1.0 cs	.901	.315	.607
15/85	1.0 cs	.898	.319	.488
0/100	1.0 cs	.901	.315	.315
15/85	100 cs	.901	.315	.484

III. ACCURACY

Table 2 provides estimates for some of the errors. The aspect ratio (c/a) of the cylinder was determined from physical measurements and is believed to be accurate to within ±.05%. This small uncertainty in c/a is equivalent to almost 1% error in ($\tau_{R_{max}}$) and slightly more than 1% error in yaw growth rate. The fill ratio, f, of the cylinder was determined from height measurements using a cathetometer equipped with a sighting scope and a precision vernier scale. The cathetometer has a resolution of .01mm, but repeated measurements indicated an uncertainty on the order of 0.2mm which corresponds to less than 0.1% in fill ratio. The yaw frequency and spin rate which determine the dimensionless yaw growth rate are believed to be accurate and should not be a significant factor in evaluating comparisons with theory. Yaw damping tares, due to the flexural pivots, were obtained for the empty cylinder but were not applied to the experimental data. If the tare values had been applied, peak values of predicted growth rate would have decreased by approximately 1%.

A small offset of the rotor center of gravity from the gimbal pivot axis produces a gravity moment; the restoring force of the flexural pivots also produces a moment. These moments are equivalent to an external moment which influences the gyroscopic stability of the system. From some of the tare runs, a slow mode yaw frequency could be detected in addition to the fast mode frequency. Some estimates of the gyroscopic stability factor determined from the two frequencies indicated a gyroscopic stability factor (s_g) of almost -10.

TABLE 2. ESTIMATED ERRORS.

Independent Variable	Error	Resultant Error in τ_R	Resultant Error in τ_I
c/a	±.05%	±.9%	±1.2%
f	±.08%	±.2%	±.5%
$\dot{\phi}$	±.02%	±.02%	----
coning rate	±.03%	±.03%	----
tare damping	-.00002	-----	-1%
$-1/s_g$ damping	-.00006	-----	-3%
repeatability	-------	-----	*

*Occasional errors in τ_I larger than the above values

A value of s_g = -10 decreases the growth rate predicted by the theory[4] by approximately 3% but does not noticeably change the yaw frequency. The computational and experimental data were not corrected for the gyroscopic stability factor. Computationally, the gyroscopic stability factor is assumed to be infinite.

Occasionally some values of yaw growth rate fall below the well-defined trend of the experimental values. For example, Figure 8 shows two obvious points (circles) which are 5-10% below their expected level. The cause of this type of error has not been identified but the number of occasions is not sufficient to alter the trend of the data. None of the identifiable errors are of sufficient magnitude to explain the observed frequency bias between the experiment and theory.

IV. RESULTS AND DISCUSSION

All of the computational results shown in the graphical presentations were obtained using Murphy's theory.[4] The two-component liquid for most of the tests consisted of Dow Corning 1.0 cs oil and water (also 1.0 cs). This combination may at first not seem too interesting because the physical properties of the liquids are not greatly different. However, computations show that substantial changes in the yawing rates and growth rates occur for various oil to water ratios. Because of the boundary layer approximations in theory, the low viscosity fluids (which have higher Reynolds numbers) should give conditions where the theory performs well. Also, the theory, at the time of the experiments, was more rigorous for the case of equal kinematic viscosities. (Previously, an average Reynolds number was used for the endwall boundary layer calculations, but recent methods properly match the viscous regions of the two liquids on the endwalls of the cylinder.)

The experimental results, in tabular form, are presented in Table 3 (see pages 14-17). The yaw growth rate parameter (ε), and the fast mode liquid side moment parameter (C_{LSM*}) are included in the tabulation but were not shown in graphical form along with theory. Additional parameters are needed to compute ε and C_{LSM*} from τ_I and, therefore, decrease the accuracy of ε and C_{LSM*} with respect to τ_I. Using τ_I provides a more accurate comparison of theory and experiment. The parameters ε and C_{LSM*} are defined as follows:

$$\varepsilon = \tau_I/\tau \qquad\qquad C_{LSM*} = \varepsilon/(m_L a^2/I_x)$$

D'Amico[6] has shown that the liquid side moment coefficient is equivalent to the above equation with the following assumptions: (1) no external damping or Magnus moments exist; (2) the dimensionless coning frequency is equal to I_x/I_y; (3) ε is relatively small. For the present experiment, values of maximum C_{LSM*} were typically 6% smaller than predicted values of the liquid side moment coefficient.

Experimental liquid eigenfrequencies for 90% and 100% filled cylinder obtained by Scott[3] are shown in Figure 5. The parameter b_1/a indicates the location of the interface for the two liquids (the heavier fluid occupies the outer region and the lighter fluid occupies the inner region). For b_1/a = 1.0, the cylinder contains all light liquid and for b_1/a = 0 (100% fill) or b_1/a = .316 (90% fill) the cylinder contains all heavy liquid. The trend of the experimental results agree well with theory but the experimental eigenfrequencies are noticeably higher. Murphy[2] shows that a small change in aspect

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6. *William P. D'Amico, Jr., "Instabilities of a Gyroscope Produced by Rapidly Rotating, Highly Viscous Liquids," Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-03285, June 1983. (AD A130874)*

ratio, c/a, of the cylinder can dramatically change the yaw rates. For this case, if the computational aspect ratio is increased from 3.127 to 3.150 (or 0.7%), the agreement becomes very good at all six data points.

Results from the present test are shown in Figures 6 - 9. Figure 6 shows results for three liquid compositions of oil/water = 100/0, 85/15, 75/25. The data illustrate the substantial change in growth rate and yawing frequency (τ_R) for the different compositions. The experimental data are compared with the computations which are shown as the solid curves. The amplitude of the growth rate agrees well with the computation but the predicted yaw frequencies are consistently lower for all cases. The aspect ratio was increased by a small amount (0.29%) and the computations were repeated. For the 100/0 case, the correction was not quite sufficient and the 75/25 case was slightly over corrected but on the average the bias was completely removed.

Figure 7 is another set of data for three liquid compositions of oil/water = 30/70, 15/85, and 0/100. The results are qualitatively identical to the results of Figure 6. The same consistent frequency bias is seen to exist, but a 0.29% increase in c/a slightly overcorrects the data for all three cases. The measured yaw frequencies ($\tau_{R_{max}}$) are about 3% to 4% larger than predicted values. The identifiable errors of Table 2 are not sufficient to account for the discrepancy but could account for about one third of that amount. The errors are, however, expected to be random in nature and therefore are not helpful in explaining the bias.

Figure 8 shows the results of one experiment in which the kinematic viscosity of the oil was substantially increased. The liquid oil/water ratio was 15/85 with the oil at a kinematic viscosity of 100 centistokes (cs) compared to 1.0 cs for water. To illustrate the effect of the more viscous oil, the experimental results for 1.0 cs oil are also shown on the same figure. The effect of increasing the viscosity is seen to decrease the growth rate and also to decrease $\tau_{R_{max}}$ by a substantial amount. A comparison of computation and experiment again shows a frequency bias. Increasing the aspect ratio by 0.29% brings the computed frequency up to the experimental value but now the experimental growth rate is seen to be slightly low.

The values of $\tau_{R_{max}}$ were obtained at the maximum growth and are shown in Figure 9 as a function of b_1/a (oil-water interface). The result is qualitatively similar to the results of Scott (see Figure 5) but the frequency bias of the present study is smaller by a factor of 2.5 (.29% vs .7%) based on the c/a correction. Figure 9 illustrates the precise agreement in the trend of liquid eigenfrequencies with different oil/water compositions. The figure also summarizes the consistent frequency bias between experiment and computation.

The frequency bias illustrated in Figures 6 to 9 has been previously observed and is discussed in Reference 2. The aspect ratio (c/a) adjustment seems to correct the appropriate parameters but whether or not the effective aspect ratio should be slightly different from the measured value, has not yet been determined. A reasonably constant correction of 0.29% was adequate for the present experiments but other experiments have required different corrections.

Figures 6-8 show that an increase in c/a causes an increase in the predicted growth rate which could make the experimental data appear low. However, if the tare damping and the gyroscopic stability factor, discussed in the error analysis, were accounted for, the effect would be to decrease the predicted value and thus improve the agreement.

V. SUMMARY

1. An initial set of data, believed to be of good quality, has been acquired for gyroscope experiments with two immiscible liquids in a right circular cylinder.

2. The experimental data were found to be consistent with recent theoretical predictions.

3. Experimentally determined yaw frequencies are consistently higher than predicted values by three to four percent.

4. Further investigations are needed to properly explain the reasons for the frequency bias in both single and two component liquid systems.

TABLE 3. EXPERIMENTAL DATA.

OIL/WATER = 100/0, 1.0 CS OIL

τ	τ_I	ε	C_{LSM*}
0.0544	0.000273	0.00501	0.1861
0.0548	0.000335	0.00610	0.2268
0.0552	0.000456	0.00826	0.3067
0.0558	0.000660	0.01183	0.4395
0.0563	0.000789	0.01403	0.5211
0.0568	0.000904	0.01591	0.5911
0.0573	0.000962	0.01679	0.6239
0.0577	0.000979	0.01699	0.6311
0.0581	0.000996	0.01716	0.6374
0.0584	0.000945	0.01618	0.6010
0.0585	0.000943	0.01613	0.5993
0.0589	0.000848	0.01440	0.5349
0.0595	0.000729	0.01226	0.4556
0.0598	0.000595	0.00994	0.3693
0.0599	0.000523	0.00872	0.3239
0.0605	0.000371	0.00614	0.2282
0.0609	0.000324	0.00533	0.1978
0.0613	0.000256	0.00418	0.1553
0.0619	0.000205	0.00331	0.1229
0.0629	0.000127	0.00202	0.0749

OIL/WATER = 85/15, 1.0 CS OIL

τ	τ_I	ε	C_{LSM*}
0.0718	0.000342	0.00476	0.1768
0.0714	0.000467	0.00654	0.2430
0.0709	0.000805	0.01136	0.4219
0.0702	0.000921	0.01313	0.4877
0.0699	0.001146	0.01639	0.6091
0.0696	0.001168	0.01677	0.6230
0.0697	0.001247	0.01788	0.6644
0.0691	0.001329	0.01925	0.7152
0.0688	0.001307	0.01898	0.7052
0.0684	0.001330	0.01944	0.7222
0.0681	0.001338	0.01963	0.7294
0.0680	0.001275	0.01876	0.6971
0.0676	0.001251	0.01851	0.6878
0.0674	0.001156	0.01714	0.6368
0.0669	0.001059	0.01584	0.5884
0.0667	0.000878	0.01315	0.4887
0.0664	0.000742	0.01118	0.4154
0.0658	0.000618	0.00939	0.3483
0.0655	0.000440	0.00672	0.2496
0.0655	0.000377	0.00576	0.2140
0.0649	0.000291	0.00448	0.1665

TABLE 3. EXPERIMENTAL DATA (Continued)

OIL/WATER = 75/25, 1.0 CS OIL

τ	τ_I	ϵ	C_{LSM}*
0.0705	0.000314	0.00446	0.1658
0.0710	0.000468	0.00659	0.2448
0.0714	0.000623	0.00874	0.3246
0.0716	0.000834	0.01164	0.4324
0.0718	0.000994	0.01384	0.5140
0.0721	0.001023	0.01419	0.5270
0.0723	0.001103	0.01525	0.5665
0.0730	0.001316	0.01804	0.6702
0.0742	0.001389	0.01871	0.6952
0.0731	0.001403	0.01918	0.7126
0.0745	0.001434	0.01924	0.7149
0.0745	0.001510	0.02027	0.7529
0.0739	0.001441	0.01949	0.7241
0.0761	0.001448	0.01902	0.7066
0.0744	0.001459	0.01961	0.7286
0.0748	0.001320	0.01765	0.6556
0.0751	0.001348	0.01795	0.6668
0.0755	0.001163	0.01539	0.5719
0.0754	0.001066	0.01414	0.5255
0.0756	0.001014	0.01341	0.4981
0.0761	0.000783	0.01029	0.3823
0.0766	0.000436	0.00569	0.2113

OIL/WATER = 30/70, 1.0 CS OIL

τ	τ_I	ϵ	C_{LSM}*
0.0752	0.000216	0.00288	0.1069
0.0748	0.000230	0.00308	0.1144
0.0745	0.000195	0.00262	0.0972
0.0741	0.000371	0.00501	0.1861
0.0736	0.000486	0.00661	0.2454
0.0732	0.000618	0.00843	0.3132
0.0728	0.000787	0.01080	0.4012
0.0726	0.000960	0.01323	0.4916
0.0724	0.001040	0.01436	0.5336
0.0721	0.001102	0.01528	0.5678
0.0720	0.001229	0.01707	0.6341
0.0718	0.001323	0.01842	0.6844
0.0716	0.001386	0.01935	0.7191
0.0713	0.001450	0.02034	0.7557
0.0711	0.001459	0.02054	0.7630
0.0707	0.001489	0.02107	0.7828
0.0705	0.001510	0.02142	0.7957
0.0702	0.001502	0.02139	0.7947
0.0704	0.001491	0.02118	0.7871
0.0700	0.001487	0.02123	0.7887
0.0694	0.001428	0.02059	0.7651
0.0690	0.001371	0.01986	0.7378
0.0686	0.001204	0.01756	0.6523
0.0680	0.000914	0.01343	0.4990
0.0668	0.000381	0.00570	0.2120

TABLE 3. EXPERIMENTAL DATA (Continued)

OIL/WATER = 15/85, 1.0 CS OIL

τ	τ_I	ε	C_{LSM^*}
0.0594	0.000182	0.00306	0.1138
0.0599	0.000357	0.00596	0.2214
0.0605	0.000504	0.00833	0.3094
0.0607	0.000648	0.01067	0.3965
0.0613	0.000806	0.01315	0.4884
0.0616	0.000997	0.01619	0.6017
0.0620	0.001100	0.01775	0.6594
0.0624	0.001165	0.01865	0.6930
0.0632	0.001328	0.02101	0.7805
0.0639	0.001308	0.02046	0.7603
0.0640	0.001262	0.01972	0.7326
0.0640	0.001220	0.01907	0.7084
0.0640	0.001220	0.01907	0.7084
0.0644	0.001072	0.01663	0.6177
0.0647	0.001040	0.01607	0.5972
0.0649	0.000992	0.01528	0.5676
0.0651	0.000930	0.01428	0.5305
0.0653	0.000837	0.01283	0.4766
0.0655	0.000751	0.01146	0.4259
0.0659	0.000591	0.00897	0.3332
0.0661	0.000483	0.00739	0.2746
0.0665	0.000395	0.00593	0.2205
0.0670	0.000321	0.00478	0.1777
0.0673	0.000163	0.00242	0.0901

OIL/WATER = 0/100, 1.0 CS OIL

τ	τ_I	ε	C_{LSM^*}
0.0525	0.000641	0.01222	0.4540
0.0535	0.000806	0.01507	0.5597
0.0538	0.000992	0.01843	0.6849
0.0542	0.001001	0.01845	0.6855
0.0546	0.001111	0.02034	0.7558
0.0549	0.001108	0.02016	0.7490
0.0552	0.001106	0.02002	0.7438
0.0555	0.001042	0.01876	0.6970
0.0561	0.001042	0.01876	0.6970
0.0560	0.000998	0.01782	0.6621
0.0562	0.000924	0.01644	0.6108
0.0564	0.000910	0.01612	0.5990
0.0565	0.000693	0.01226	0.4557
0.0568	0.000710	0.01251	0.4648
0.0569	0.000592	0.01041	0.3867
0.0570	0.000445	0.00781	0.2902
0.0573	0.000486	0.00849	0.3155
0.0575	0.000335	0.00582	0.2162
0.0579	0.000342	0.00591	0.2194
0.0581	0.000320	0.00551	0.2046
0.0584	0.000210	0.00360	0.1336
0.0585	0.000200	0.00341	0.1268
0.0594	0.000094	0.00158	0.0585

TABLE 3. EXPERIMENTAL DATA (continued)

OIL/WATER = 15/85, 100 CS OIL

τ	τ_I	ε	C_{LSM}
0.0517	0.000320	0.00620	0.2303
0.0524	0.000419	0.00800	0.2971
0.0531	0.000548	0.01033	0.3837
0.0535	0.000599	0.01119	0.4159
0.0540	0.000674	0.01249	0.4640
0.0545	0.000726	0.01332	0.4948
0.0549	0.000724	0.01319	0.4901
0.0552	0.000700	0.01268	0.4710
0.0554	0.000758	0.01367	0.5079
0.0557	0.000758	0.01361	0.5058
0.0560	0.000691	0.01234	0.4585
0.0563	0.000742	0.01318	0.4898
0.0568	0.000672	0.01183	0.4397
0.0571	0.000604	0.01057	0.3925
0.0578	0.000524	0.00907	0.3370
0.0585	0.000446	0.00762	0.2832
0.0592	0.000370	0.00625	0.2320
0.0599	0.000274	0.00457	0.1700
0.0607	0.000181	0.00298	0.1108
0.0613	0.000184	0.00300	0.1114

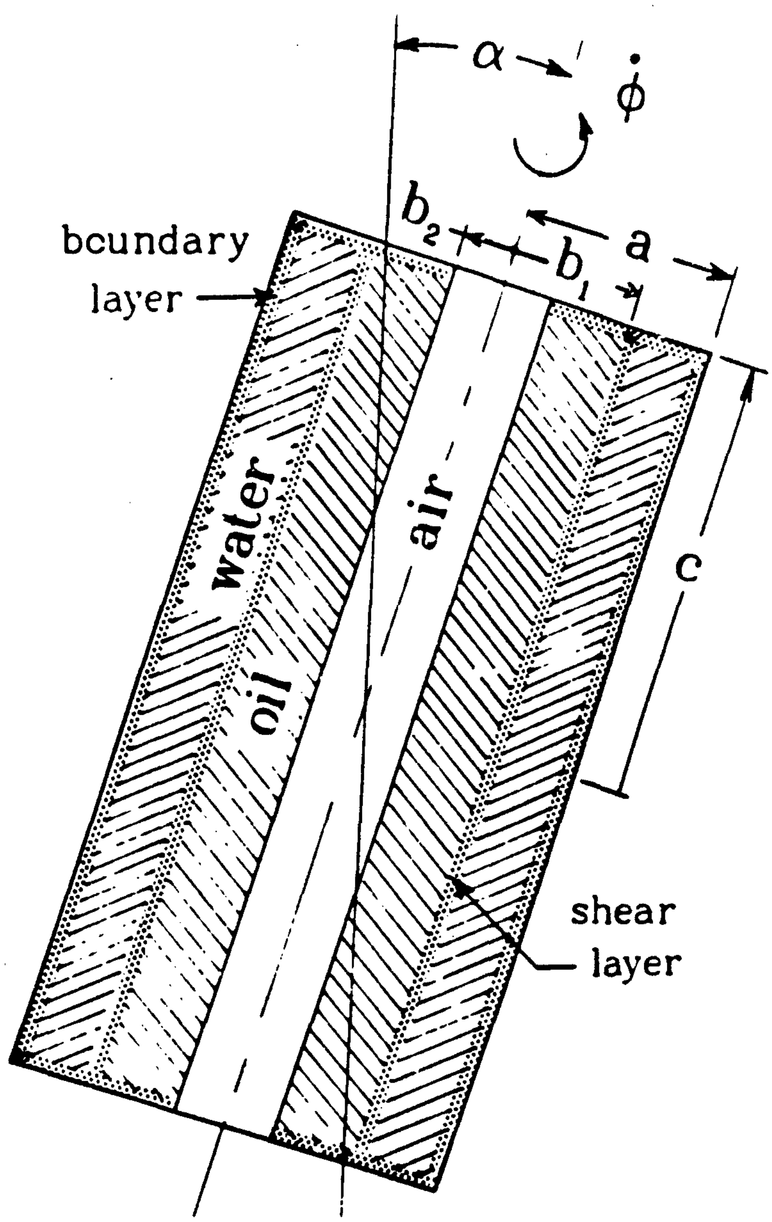

Figure 1. Sketch of a Spinning Partially Filled Cylinder with Two Immiscible Liquids.

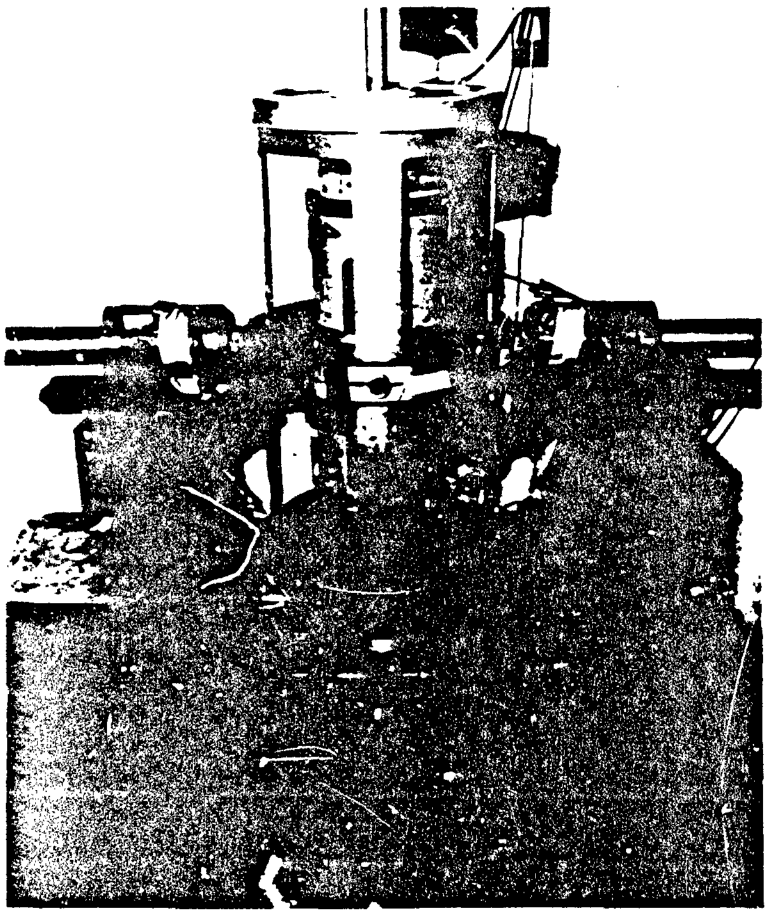

Figure 2. Gyroscope Photograph.

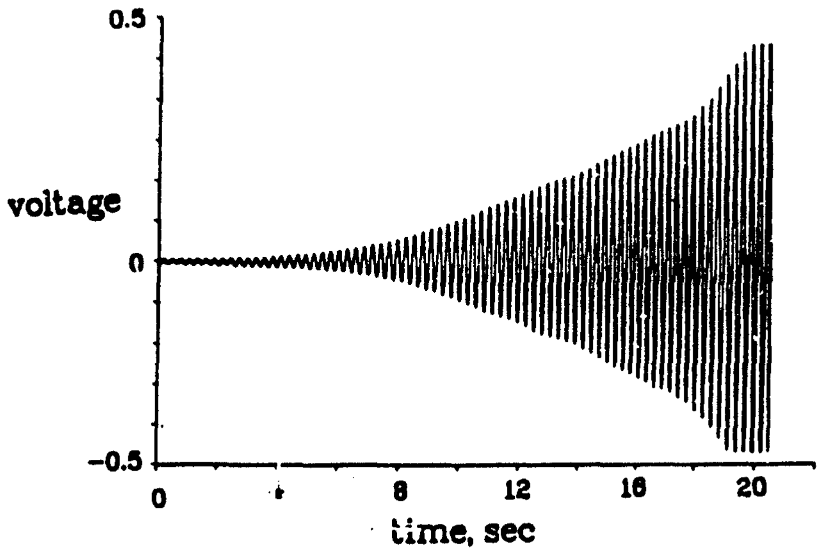

Figure 3. Strain Gage Output from One Flexural Pivot.

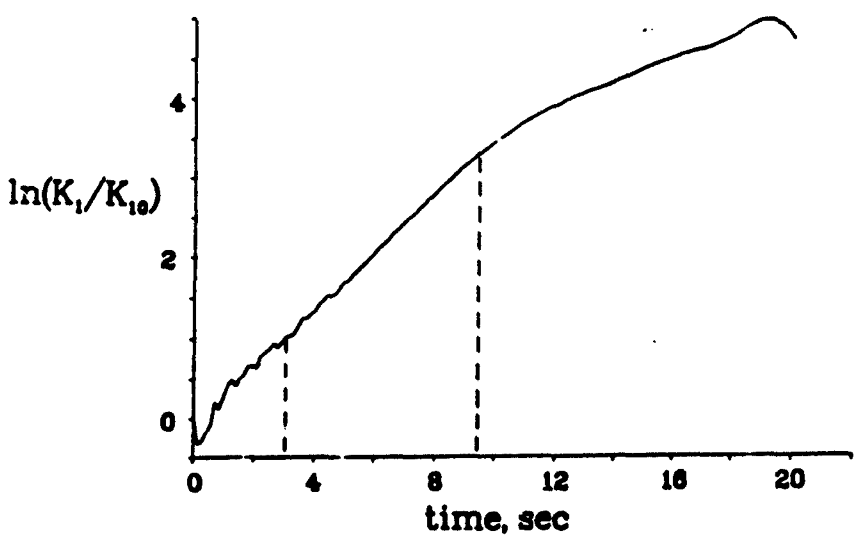

Figure 4. Yaw Growth History, Logarithmic Plot.

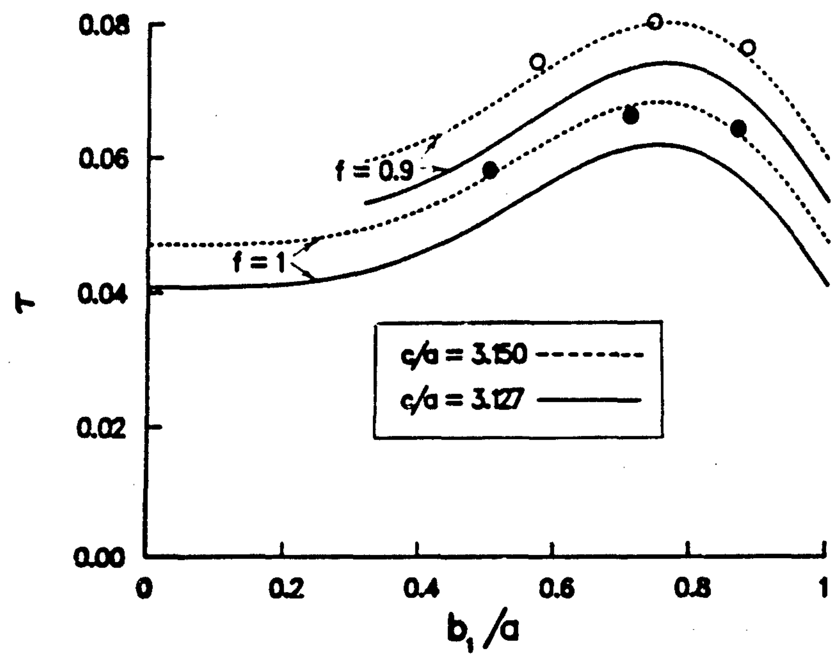

Figure 5. Liquid Eigenfrequencies for a Two-Component Liquid. Theory from Reference 4, Experiment from Reference 3.

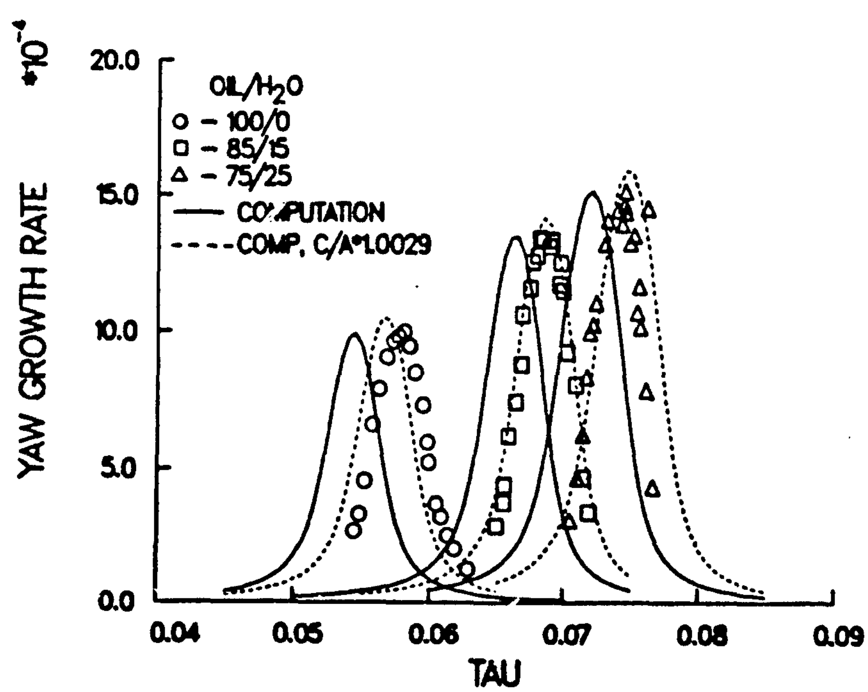

Figure 6. Yaw Growth Rates for Three Liquid Compositions of 1.0 cs Oil/Water = 100/0, 85/15, 75/25; Theory (Ref. 4) and Experiment.

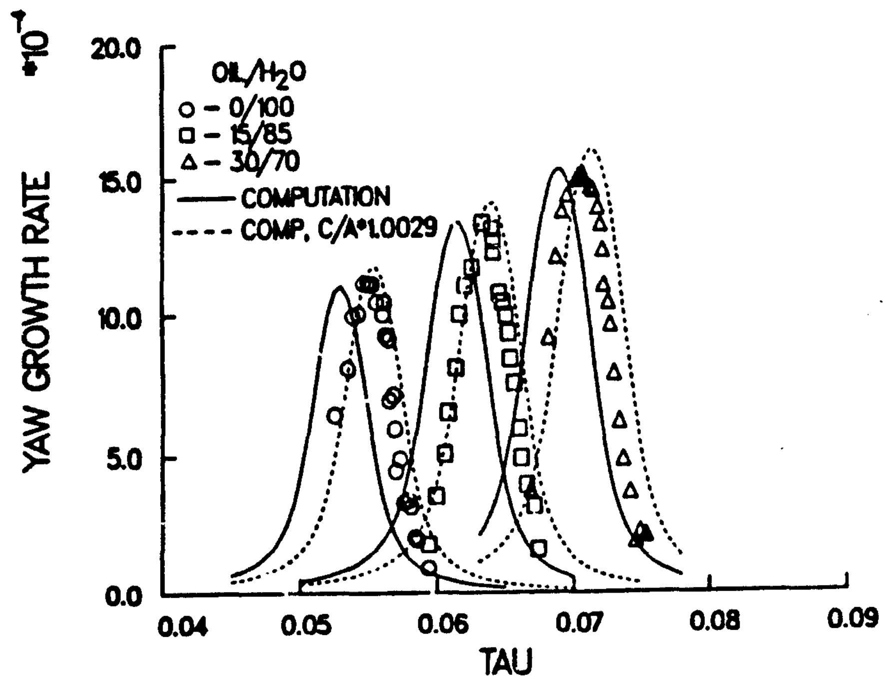

Figure 7. Yaw Growth Rates for Three Liquid Compositions of 1.0 cs Oil/Water = 30/70, 15/85, 0/100; Theory (Ref. 4) and Experiment.

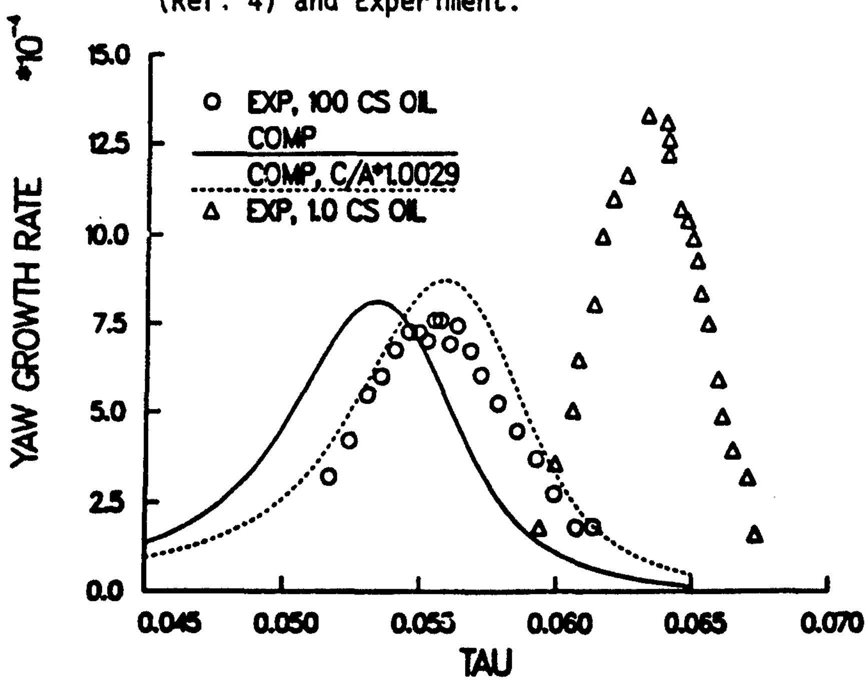

Figure 8. Yaw Growth Rates for a Liquid Composition of 15% 100 cs Oil and 85% 1.0 cs Water; Theory (Ref. 4) and Experiment.

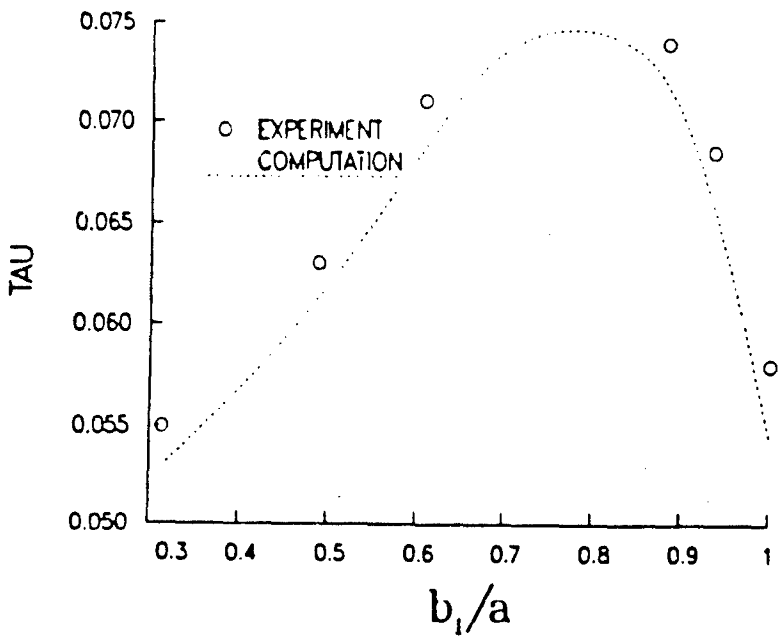

Figure 9. Liquid Eigenfrequencies for the Six Liquid Compositions of Figures 6 and 7; Theory (Ref 4) and Experiment.

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LIST OF SYMBOLS

a	radius of a right circular cylindrical cavity containing liquid
b_1	radius of the liquid interface for a two-component liquid
b_2	radius of the free surface in a partially-filled cylinder
c	one-half of the length of the right circular cylindrical cavity
C_{LSM^*}	approximate liquid side moment coefficient for the fast mode
f	cavity fill ratio; volume liquid/volume cavity
I_x, I_y	axial and transverse moments of inertia of the empty gyroscope rotor
K_1	magnitude of the fast mode yaw arm
K_{10}	initial value of K_1
Re	Reynolds number, $a^2\dot{\phi}/\nu$
s_g	the gyroscopic stability factor
ε	τ_I/τ_R
ν	kinematic viscosity
ρ_1	density of the heavier liquid
ρ_2	density of the lighter liquid
$\tau_{k,n}$	liquid eigenvalue of τ for wave numbers k,n; $k = 1, n = 3$ for this report
τ_I	yaw growth rate/$\dot{\phi}$, (the ordinate parameter for Figures 3, 4, and 5
$\tau_{I_{max}}$	τ_I at peak of bell-shaped curve
τ_R	yawing rate/$\dot{\phi}$, (dimensionless coning rate)
$\tau_{R_{max}}$	τ_R at $\tau_{I_{max}}$
$\dot{\phi}$	rotor spin rate

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