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Laboratory Memorandum

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R. Pallard and K. Brett

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Canada

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SUMMARY:

This report presents the results of tests done to assess the effect of a counter-weight system on the performance of the IMD sailing yacht dynamometer.

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LIST OF ABBREVIATIONS AND SYMBOLS

ACD	Drag Area, m^2
ACL	Lift Area, m^2
Mw	Mean value of parameter measured with counter-weight
Mwo	Mean value of parameter measured without counter-weight
P	precision limit for the mean value of repeated runs, calculated as $2*Stdev_{PAR}/SQRT$(No of repeats)
Q	dynamic pressure, N/m^2
V_M	model speed, taken as carriage speed, m/s
VOK	Roll Moment Volume, m^3
VON	Yaw Moment Volume, m^3
θ	Trim or Pitch Angle, deg
ρ	water density at test temperature, kg/m^3

EFFECT OF A COUNTER-WEIGHT SYSTEM ON THE PERFORMANCE OF THE IMD SAILING YACHT DYNAMOMETER

1.0 INTRODUCTION

Current practice at IMD is to choose a model scale that gives a minimum test displacement of about 1100 kilograms. While increasing the size of models has advantages in terms of reducing scale effects, there is a price to be paid due to the following factors:

- Increased initial cost of the model;
- greater long-term storage cost;
- greater risk of distortion of the model;
- lower tank productivity due to the increased wait times;
- compromise in the test program due to overload of load cells or insufficient data at higher speeds.

Much effort has been expended to make the sailing yacht dynamometer and the models used with it lighter so that the system could be used with lower displacement or smaller scale models. There has been a 37 percent reduction in the mass of the dynamometer that must be supported by the model between the Mk.1 version used for the Fluid Thinking project in 1993 through 1995 and the Mk.3 version currently in use. Modifications to the standard construction technique used for sailing yacht models have been tried with one of the IMS series models which reduced the mass of the canoe body by about 20 percent but increased the cost of construction by about 15 percent.

A further reduction of model displacement can be achieved by means of a counter-weight system.

This report presents the results of a short series of experiments done to assess the effect of a counter-weight system on the performance of the IMD sailing yacht dynamometer. This test was done on August 5th and 6th, 1999.

2.0 MODEL DESCRIPTION

An existing large scale model, designated IMD Model 504, was used for these experiments. The model, built in 1996 and modified to its present shape in 1997, was constructed as described in IMD Standard Test Method, GM-1v2, [Ref. 1], except that the model had two layers of fiberglass instead of three layers. The model was fitted with an aluminum dynamometer frame. Due to the proprietary nature of the design of the hull and its appendages, no lines plan or hydrostatics are included in this report.

The appendage package, also built in 1996, consisted of a T-type keel and bulb and a rudder. The keel was built of RenShape-550 laminated onto a steel tang and NC milled. The bulb was built of RenShape-350 laminated onto an aluminum mounting plate and NC milled. The two components were mated prior to final finishing. The rudder was built as described in IMD Standard Test Method, GM-1v2

3.0 DESCRIPTION OF DYNAMOMETER AND COUNTER-WEIGHT APPARATUS

The IMD sailing yacht dynamometer is described in detail in Reference 2. The changes in the Mk.3 version of this dynamometer simplify the installation and improve the repeatability and consistency of the setting of yaw angle. There was also a significant reduction in both the "sprung" and effective weights of the dynamometer. The "sprung" weight of the dynamometer is what must be supported by the displacement of the model. The effective weight of the dynamometer is the force that the drag load cell of the dynamometer would "see" if it were possible to pitch the dynamometer to 90 degrees. A schematic diagram of the dynamometer is shown in Figure 1.

The counter-weight apparatus consists of a pair of posts, each of which have a gear sprocket supported by a low friction bearing, mounted on each side of the dynamometer adapter. A linear rail and car assembly is mounted on one side of each post. A ballast platen and clamp that can support up to 150 kg of custom shaped lead ballast is mounted to each car. A short length of triplex chain connects the car to a length of 5/32" diameter stainless steel aircraft cable attached to a mount on the T-shaped (ground) side of the dynamometer. The upward force is measured with S-type load cells fitted inline with the cable and chain. A diagram of the arrangement is shown in Figure 2.

3.1 Installation And Calibration

3.1.1 Dynamometer

The dynamometer was installed as described in IMD Work Instruction TNK-01. A full calibration of the dynamometer was done prior to the start of this series of experiments. At the end of the experiments with the counter-weight attached, a drag calibration was done.

3.1.2 Model without counter-weight

The model was ballasted to a displacement of 1161 kg. The trim angle was 0.689 degrees down by the stern. The freeboard gauges were adjusted with the model at rest so that it would be possible to return to this floatation condition after installation of the counter-weight apparatus.

3.1.3 Counter-weight apparatus
The counter-weight apparatus was installed as described in IMD Work Instruction TNK-01. The inline load cells were zeroed prior to installation in the apparatus.

3.1.4 Model with counter-weight
Since the effective weight of the dynamometer without counter-weight is 1956 N, it was decided to limit the amount of counter-weight applied to less than that value to avoid negative effective weight. The inline load cells were metered with the counter-weight ballast attached and the vertical component of the load calculated. Ballast was assembled that was equal to the vertical component of the inline loads and added to the model with its longitudinal center of gravity below the attachment point of the counter-weight. The freeboard gauges were checked to confirm that the model was at the same condition as tested without the counter-weight. A small adjustment of ballast distribution was done to get the model to the same trim angle as measured by the encoder during the previous set-up.

3.1.5 Longitudinal inclining of the model
After any change in the effective weight of the dynamometer, a longitudinal inclining experiment must be done to determine the new effective weight. Even though the purpose of this experiment is simply to determine a constant that relates the measured drag force to the pitch angle, it is essential that this experiment be done with the model at constant displacement. It is not essential for the model to be at the test displacement and trim or for the ballast being moved to cause the variation in pitch angle to be at the same vertical center of gravity. With ballast location adjusted to five individual trim conditions, drag and pitch angle were measured. The results of the inclining experiment are shown in Table 1 and Figure 3.

4.0 DESCRIPTION OF EXPERIMENT

In order to assess whether or not the counter-weight apparatus has a measurable effect on the results of a sailing yacht test, it was necessary to establish a basis for comparison. This basis was established by selecting four upright, zero leeway speeds that corresponded to points on the drag area curve that were of particular interest and one heeled and yawed speed that was a typical upwind sailing condition.

The model scale upright speeds selected were chosen for the following reasons:

- 2.0 m/s – lowest speed of real interest;
- 3.0 m/s– typical speed in normal conditions;

- 3.7 m/s – drag increasing rapidly at this speed – drag area slope very high;
- 4.3 m/s – just past the main hump of the drag area or CT curve.

The heeled and yawed condition selected was 3.0 m/s model scale, 20 degrees heel, 4 degrees leeway with 4 degrees of rudder.

Two rough-up runs at 3.0 m/s were done, followed by five repeats at each of the upright speeds and ten repeats at the upwind sailing condition speed. The scope of the test matrix was dictated by what could reasonably be achieved in a regular shift using the wait time schedule developed for sailing yacht tests. At the end of this series, the counter-weight apparatus was attached to the model and the displacement and trim verified as described in Section 3.1.4

The following morning, a final check of displacement and trim was done prior to repeating the test series with the counter-weight apparatus attached. The tests at the upwind sailing condition speed were aborted after the seventh repeat in order to repeat the longitudinal inclining experiment and the drag calibration experiment and still have time to de-commission the model and dynamometer.

5.0 ANALYSIS

The tabulated results of the upright and upwind sailing condition tests are given in Tables 2 and 3 for the experiments without the counter-weight apparatus and in Tables 3 and 4 for the experiments with the apparatus.

The mean values of the sailing yacht force and moment parameters were converted to areas and volumes by dividing by dynamic pressure, Q, where

$$Q = \tfrac{1}{2}\rho_M V_M^2$$

ρ_M is the density of water at the test temperature and V_M is model speed, taken as carriage speed. Statistical analysis of the mean values of the repeated tests was done to assess the variability of the data from run to run. The tabulated results of this analysis is presented in Tables 6-8 and shown in Figure 4.

The standard deviation of the time histories of sinkage and trim was calculated for each run to assess if the counter-weight had any effect on the steady-state motions of the model. For each set of repeat runs, the basic statistics - mean, standard deviation, minimum, maximum and range - of the standard deviation of sinkage and trim was calculated. The tabulated results of this analysis are shown in Table 9.

The unpaired *t*-test compares the mean of two groups and determines the likelihood of the observed difference occurring by chance. The chance is reported as the *p* value. A *p* value close to 1 means it is very likely that the two groups have the same mean, since it is very likely that such a result would happen by chance if the null hypothesis of no difference between groups is true. A small *p* value (for example, 0.01) means it is unlikely (only a one in 100 chance) that such a difference would occur by chance if the two groups had the same mean. In such a case, there is a significant difference between the two means. The *t value* expresses the difference between the means difference and the hypothesized value in terms of the standard error. [Ref. 3].

The results of the unpaired *t*-test analysis for the upright data-set is shown in Table 10 and for the upwind sailing condition data-set in Table 11. The normal distribution of the means of the drag areas with and without the counter-weight at various speeds is shown in Figures 5 and 6.

6.0 DISCUSSION OF RESULTS

The analysis of the drag area of the upright runs, shown in Tables 8 and 9, indicate that the data variation within each set, defined by the ratio of the standard deviation to the mean is less than 0.3% for all the sets. At 2.0 and 3.7 m/s, there is less than 0.02% difference between either system. With the counter-weight apparatus installed, there is 0.09% less variation at 3.0 m/s while at 4.3 m/s, there is 0.11% more variation.

At 3.0, 3.7 and 4.3 m/s, the means of the repeats with and without the counter-weight are within +/- 0.25% while at 2.0 m/s, the difference increases to 0.68%. The greatest magnitude of the difference in drag area occurs at 2.0 m/s and is 0.00027 m^2.

As can be seen in Tables 2 and 4, all speeds, except 3.7 m/s, show random scatter in measured drag. At 3.7 m/s, however, drag increased with each successive run. Without the counter-weight, measured speed during this set increased by 0.0015 m/s; with the counter-weight system in place, measured speed during the set was constant. The magnitude of the increase in drag area was 0.76% without the counter-weight and 0.69% with the counter-weight.

The percentage variation for sinkage is higher than for drag area but the magnitude of the variation for sinkage is within the range of calibration error for the instruments used. Like drag area, each system shows less variation at certain speeds than the other but there is no clear trend.

For trim at 2.0 and 3.0 m/s, the percentage variation with the counter-weight is twice that measured without the counter-weight. At 3.7 and 4.3 m/s, there is no measurable difference in the variation. The maximum difference in trim was 0.0055 degrees and occurred at 4.3 m/s.

For the heeled and yawed condition, the difference in the percentage variation of the analyzed parameters, with and without the counter-weight, is less than 0.2% for all parameters except yaw moment volume and Lift/Drag.
The results of the *t*-test show that there is a significant, in the statistical sense, difference in the drag area results obtained at 2.0 m/s with and without the counter-weight. At the other speeds, the results fall within the 95% confidence band and hence the hypothesis that there is no difference between the results with and without the counter-weight is valid. With respect to the results obtained at 2.0 m/s, it should be noted that the difference in the means of drag area corresponds to 0.5 N on a measured drag of 80 N (0.6%), and was measured using a 2200 N load cell.

7.0 CONCLUSIONS

The counter-weight apparatus has little effect on the quality of the data measured using the sailing yacht dynamometer. While there does appear to a speed dependency to the difference in upright drag area, the magnitude of the difference at the lowest speed, 0.5 N, is within the performance band of the load cell. At the higher speeds, the percentage difference between the two setups is similar to the variation within a setup.

There is no appreciable difference in measured sinkage with either setup at any speed and only a slight increase in variation in trim at the two lower speeds.

In a typical sailing condition, the difference in the results with and without the counter-weight apparatus are within the range of expected repeatability without the apparatus. Except for trim, the percentage difference in the measured parameters between the two setups is less than the variation within either setup.

The counter-weight apparatus can be used for sailing yacht tests to reduce the size of the model with the following recommendations:

- The amount of counter-weight applied should not exceed 2000 N
- The amount of counter-weight applied must be constant for a series of experiments so that the same dynamometer effective weight is used throughout the test.

8.0 FUTURE WORK

The series of experiments at $V_M = 3.7$ m/s showed a trend which could indicate a flaw in the wait time schedule at that particular speed. This effect was evident with and without the counter-weight and could be assessed during any future sailing yacht test.

Experiments in regular waves should be done to determine if counter-weighting can be used for sea-keeping tests without compromising the quality of the data.

9.0 REFERENCES

1. "Construction of Models of Ships, Offshore Structures and Propellers" IMD Standard Test Method - GM1v2, Dec. 1998
2. Parsons, B.L. and Pallard, R. "The Institute for Marine Dynamics Model Yacht Dynamometer". The Thirteenth Chesapeake Sailing Yacht Symposium, 1997
3. Abacus Concepts. Using StatView. Berkeley: Abacus Concepts, Inc., 1996.
4. Walpole, Ronald E. Introduction to Statistics, 3rd ed. New York: Macmillan Publishing Co., Inc., 1982

TABLES

Results of experiment to derive effective weight of dynamometer with counter-weight attached

Pitch Angle, θ [deg]	$\sin\theta$	Drag [N]
1.254	0.0219	-27.37
0.545	0.0095	-28.57
-0.301	-0.0053	-29.79
-1.156	-0.0202	-31.70
-2.010	-0.0351	-32.43

Results of Tests without Counter-weight Apparatus
Heel = 0 degrees - Yaw = 0 degrees
Model 504

Test Temperature: 17.90 deg C
Date: 5-Aug-99

Test Name	Time	Rudder [deg]	Trim Moment [Nm]	Vertical Force [kgf]	Vm [m/s]	Drag [N]	Lift [N]	Roll Moment [Nm]	Yaw Moment [Nm]	Sinkage [m]	Trim [deg]	Sinkage St. Dev'n [m]	Trim St. Dev'n [deg]
CW_001	9:06:56	0	1571	0	2.9838	210.02	7.12	9.87	0.60	0.0236	0.181	0.0003	0.0101
CW_002	9:17:28	0	1571	0	2.9842	209.03	7.28	7.76	0.85	0.0243	0.181	0.0002	0.0104
CW_003	9:27:05	0	1464	0	1.9871	79.61	1.11	0.45	0.84	0.0084	0.193	0.0003	0.0103
CW_004	9:33:16	0	1464	0	1.9871	79.99	0.56	-0.58	1.37	0.0081	0.194	0.0003	0.0070
CW_005	9:39:18	0	1464	0	1.9871	80.04	0.70	-1.67	1.43	0.0086	0.194	0.0002	0.0058
CW_006	9:45:18	0	1464	0	1.9872	79.66	0.58	-1.48	1.39	0.0079	0.195	0.0002	0.0057
CW_007	9:51:03	0	1464	0	1.9871	79.83	0.75	-2.45	1.58	0.0084	0.194	0.0004	0.0073
CW_008	9:58:31	0	1571	0	2.9843	208.53	6.38	6.79	0.50	0.0234	0.179	0.0008	0.0116
CW_009	10:08:29	0	1571	0	2.9842	208.19	6.23	7.71	0.66	0.0243	0.179	0.0004	0.0101
CW_010	10:18:55	0	1571	0	2.9842	207.21	7.00	8.21	1.81	0.0238	0.178	0.0003	0.0093
CW_011	10:28:05	0	1571	0	2.9842	207.21	5.71	5.30	0.36	0.0243	0.177	0.0004	0.0111
CW_012	10:38:02	0	1571	0	2.9839	207.31	7.36	8.31	1.24	0.0233	0.178	0.0003	0.0113
CW_013	10:49:08	0	1821	0	3.6484	468.94	14.11	13.16	-23.17	0.0414	0.834	0.0005	0.0142
CW_014	11:01:01	0	1821	0	3.6488	469.34	16.08	15.26	-23.45	0.0411	0.836	0.0005	0.0136
CW_015	11:13:04	0	1821	0	3.6489	470.55	14.16	12.84	-23.61	0.0412	0.840	0.0004	0.0132
CW_016	11:26:05	0	1821	0	3.6501	471.46	13.58	12.92	-23.75	0.0414	0.847	0.0007	0.0169
CW_017	11:38:02	0	1821	0	3.6499	472.96	12.84	11.83	-21.22	0.0414	0.849	0.0008	0.0132
CW_018	11:50:14	0	2963	0	4.3141	785.18	20.05	15.60	-38.05	0.0480	1.522	0.0011	0.0180
CW_019	12:04:08	0	2963	0	4.3143	784.42	21.05	17.47	-38.00	0.0471	1.521	0.0013	0.0187
CW_020	12:18:01	0	2963	0	4.3140	785.61	21.84	19.16	-37.48	0.0466	1.526	0.0012	0.0223
CW_021	12:32:01	0	2963	0	4.3140	785.58	23.28	21.48	-36.83	0.0471	1.525	0.0013	0.0199
CW_022	12:46:34	0	2963	0	4.3143	785.20	21.52	19.20	-38.79	0.0471	1.521	0.0009	0.0191

Results of Tests without Counter-weight Apparatus
Heel = 20 degrees - Yaw = 4 degrees
Model 504

Test Temperature: 17.90 deg C
Date: 5-Aug-99

Test Name	Time	Rudder [deg]	Trim Moment [Nm]	Vertical Force [kgf]	Vm [m/s]	Drag [N]	Lift [N]	Roll Moment [Nm]	Yaw Moment [Nm]	Sinkage [m]	Trim [deg]	Sinkage St. Dev'n [m]	Trim St. Dev'n [deg]
CW_023	13:05:38	4	1464	35	2.9860	255.35	1079.83	1534.17	93.52	0.0224	-0.495	0.0005	0.0119
CW_024	13:19:02	4	1464	35	2.9859	254.47	1128.16	1592.97	100.84	0.0225	-0.502	0.0003	0.0093
CW_025	13:33:05	4	1464	35	2.9860	255.70	1096.32	1557.54	89.59	0.0225	-0.498	0.0004	0.0088
CW_026	13:47:01	4	1464	35	2.9858	254.31	1105.64	1568.73	89.39	0.0223	-0.499	0.0002	0.0095
CW_027	14:01:02	4	1464	35	2.9860	255.72	1095.74	1557.57	85.96	0.0228	-0.498	0.0004	0.0089
CW_028	14:15:03	4	1464	35	2.9860	254.84	1101.95	1561.04	89.33	0.0228	-0.502	0.0003	0.0086
CW_029	14:29:01	4	1464	35	2.9861	255.33	1098.52	1561.91	85.04	0.0226	-0.499	0.0003	0.0076
CW_030	14:42:59	4	1464	35	2.9861	255.21	1095.17	1554.87	86.82	0.0227	-0.496	0.0003	0.0100
CW_031	14:56:02	4	1464	35	2.9858	255.45	1105.72	1568.71	88.93	0.0229	-0.498	0.0004	0.0098
CW_032	15:10:02	4	1464	35	2.9861	254.78	1099.23	1562.01	87.23	0.0222	-0.497	0.0003	0.0090

Results of Tests with Counter-weight Apparatus
Heel = 0 degrees - Yaw = 0 degrees
Model 504

Test Temperature: 17.90 deg C
Date: 6-Aug-99

Test Name	Time	Rudder [deg]	Trim Moment [Nm]	Vertical Force [kgf]	Vm [m/s]	Drag [N]	Lift [N]	Roll Moment [Nm]	Yaw Moment [Nm]	Sinkage [m]	Trim [deg]	Sinkage St. Dev'n [m]	Trim St. Dev'n [deg]
CW1_001	9:09:36	0	1571	0	2.9861	210.66	4.54	6.67	1.51	0.0245	0.178	0.0001	0.0054
CW1_002	9:20:19	0	1571	0	2.9860	208.82	4.21	2.94	1.20	0.0245	0.180	0.0001	0.0060
CW1_003	9:29:43	0	1464	0	1.9890	79.54	1.11	2.36	1.54	0.0088	0.197	0.0003	0.0091
CW1_004	9:36:03	0	1464	0	1.9888	79.17	0.03	1.68	1.77	0.0080	0.196	0.0002	0.0050
CW1_005	9:42:23	0	1464	0	1.9888	79.50	0.79	1.36	2.58	0.0084	0.195	0.0002	0.0053
CW1_006	9:48:20	0	1464	0	1.9887	79.25	1.25	1.64	2.45	0.0081	0.199	0.0001	0.0052
CW1_007	9:55:20	0	1464	0	1.9888	79.62	1.56	1.72	1.53	0.0088	0.197	0.0002	0.0060
CW1_008	10:04:56	0	1571	0	2.9858	207.91	4.49	3.02	0.75	0.0246	0.176	0.0004	0.0081
CW1_009	10:14:45	0	1571	0	2.9856	207.69	5.44	4.59	1.56	0.0242	0.178	0.0003	0.0075
CW1_010	10:24:05	0	1571	0	2.9856	206.78	4.86	3.52	-0.76	0.0245	0.177	0.0001	0.0061
CW1_011	10:34:02	0	1571	0	2.9857	207.25	7.30	6.87	2.03	0.0245	0.172	0.0002	0.0069
CW1_012	10:44:04	0	1571	0	2.9856	207.39	6.90	5.26	3.47	0.0241	0.177	0.0003	0.0097
CW1_013	10:54:02	0	1821	0	3.6504	469.40	14.69	12.29	-16.79	0.0414	0.829	0.0003	0.0099
CW1_014	11:06:05	0	1821	0	3.6505	470.31	13.05	12.19	-18.78	0.0416	0.836	0.0006	0.0117
CW1_015	11:18:01	0	1821	0	3.6505	469.95	12.55	10.56	-19.36	0.0416	0.839	0.0007	0.0111
CW1_016	11:31:05	0	1821	0	3.6503	471.74	9.93	9.11	-19.03	0.0416	0.845	0.0008	0.0134
CW1_017	11:43:02	0	1821	0	3.6502	472.59	9.72	7.76	-20.00	0.0415	0.844	0.0006	0.0132
CW1_018	11:55:02	0	2963	0	4.3143	786.00	14.55	12.68	-30.80	0.0484	1.514	0.0010	0.0166
CW1_019	12:09:02	0	2963	0	4.3139	784.54	14.39	12.65	-32.02	0.0474	1.517	0.0015	0.0175
CW1_020	12:27:27	0	2963	0	4.3137	787.91	10.45	7.75	-31.46	0.0475	1.517	0.0008	0.0177
CW1_021	12:41:04	0	2963	0	4.3140	787.74	15.17	9.02	-32.66	0.0479	1.521	0.0007	0.0196
CW1_022	12:55:02	0	2963	0	4.3141	786.40	15.68	13.50	-32.64	0.0471	1.518	0.0009	0.0172

Results of Tests with Counter-weight Apparatus
Heel = 20 degrees - Yaw = 4 degrees
Model 504

Test Temperature: 17.90 deg C
Date: 6-Aug-99

Test Name	Time	Rudder [deg]	Trim Moment [Nm]	Vertical Force [kgf]	Vm [m/s]	Drag [N]	Lift [N]	Roll Moment [Nm]	Yaw Moment [Nm]	Sinkage [m]	Trim [deg]	Sinkage St. Dev'n [m]	Trim St. Dev'n [deg]
CW1_023	13:08:37	4	1464	35	2.9856	253.24	1080.14	1537.83	90.77	0.0223	-0.460	0.0005	0.0152
CW1_024	13:22:09	4	1464	35	2.9859	255.09	1112.52	1576.58	92.36	0.0226	-0.466	0.0003	0.0089
CW1_025	13:36:01	4	1464	35	2.9857	255.92	1101.52	1566.49	90.38	0.0230	-0.467	0.0001	0.0079
CW1_026	13:50:03	4	1464	35	2.9858	255.15	1093.36	1555.43	81.68	0.0224	-0.463	0.0002	0.0079
CW1_027	14:04:02	4	1464	35	2.9856	255.36	1089.83	1552.72	79.87	0.0228	-0.463	0.0002	0.0090
CW1_028	14:18:01	4	1464	35	2.9857	254.73	1088.46	1549.45	82.93	0.0228	-0.468	0.0002	0.0095
CW1_029	14:32:01	4	1464	35	2.9856	255.03	1088.33	1551.12	81.95	0.0227	-0.465	0.0001	0.0091

Table 6

Statistical Analysis of the Mean Values of the Repeat Tests
With and Without Counter-weight

Heel = 0 deg., Yaw = 0 deg.

	Without Counter-weight					With Counter-weight			
	Q [N/m^2]	Acd [m^2]	Sinkage [m]	Trim [deg]		Q [N/m^2]	Acd [m^2]	Sinkage [m]	Trim [deg]
V_M = 2.0 m/s									
Mean	1971.28	0.04049	0.0083	0.1940	Mean	1974.64	0.04022	0.0084	0.1968
Min	1971.20	0.04038	0.0079	0.1933	Min	1974.47	0.04010	0.0080	0.1954
Max	1971.35	0.04060	0.0086	0.1949	Max	1974.93	0.04032	0.0088	0.1993
Std. Dev.	0.07	0.00010	0.0003	0.0006	Std. Dev.	0.17	0.00010	0.0004	0.0015
Range	0.16	0.00022	0.0007	0.0015	Range	0.46	0.00023	0.0008	0.0038
SD/Mean	0.003%	0.24%	3.21%	0.31%	SD/Mean	0.009%	0.24%	4.47%	0.75%
P	0.06	0.00009	0.0002	0.0005	P	0.15	0.00009	0.0003	0.0013
P/Mean	0.003%	0.21%	2.88%	0.28%	P/Mean	0.008%	0.21%	3.99%	0.67%
					Mw-Mwo	3.37	-0.00027	0.0001	0.0027
					(Mw-Mwo)/Mwo	0.17%	-0.68%	1.69%	1.41%
V_M = 3.0 m/s									
Mean	4445.74	0.04672	0.0238	0.1780	Mean	4450.21	0.04661	0.0244	0.1760
Min	4445.12	0.04661	0.0233	0.1766	Min	4450.04	0.04647	0.0241	0.1724
Max	4446.19	0.04690	0.0243	0.1791	Max	4450.58	0.04671	0.0246	0.1777
Std. Dev.	0.39	0.00014	0.0005	0.0010	Std. Dev.	0.23	0.00010	0.0002	0.0021
Range	1.07	0.00029	0.0011	0.0025	Range	0.54	0.00025	0.0005	0.0054
SD/Mean	0.009%	0.30%	2.03%	0.54%	SD/Mean	0.005%	0.21%	0.89%	1.21%
P	0.35	0.00012	0.0004	0.0009	P	0.21	0.00009	0.0002	0.0019
P/Mean	0.008%	0.26%	1.82%	0.48%	P/Mean	0.005%	0.18%	0.79%	1.08%
					Mw-Mwo	4.47	-0.00011	0.0006	-0.0020
					(Mw-Mwo)/Mwo	0.10%	-0.24%	2.50%	-1.12%

Table 7

Statistical Analysis of the Mean Values of the Repeat Tests
With and Without Counter-weight
Heel = 0 deg., Yaw = 0 deg.

	Without Counter-weight					With Counter-weight			
	Q [N/m^2]	Acd [m^2]	Sinkage [m]	Trim [deg]		Q [N/m^2]	Acd [m^2]	Sinkage [m]	Trim [deg]
V_M = 3.7 m/s									
Mean	6648.18	0.07079	0.0413	0.8410	Mean	6652.33	0.07077	0.0415	0.8387
Min	6645.24	0.07057	0.0411	0.8342	Min	6651.73	0.07056	0.0414	0.8292
Max	6651.33	0.07111	0.0414	0.8487	Max	6652.86	0.07105	0.0416	0.8446
Std. Dev.	2.72	0.00022	0.0001	0.0064	Std. Dev.	0.49	0.00020	0.0001	0.0064
Range	6.08	0.00055	0.0003	0.0146	Range	1.13	0.00049	0.0003	0.0154
SD/Mean	0.041%	0.31%	0.33%	0.76%	SD/Mean	0.007%	0.29%	0.26%	0.76%
P	2.44	0.00020	0.0001	0.0057	P	0.43	0.00018	0.0001	0.0057
P/Mean	0.037%	0.28%	0.30%	0.68%	P/Mean	0.007%	0.26%	0.23%	0.68%
					Mw-Mwo	4.15	-0.00002	0.0003	-0.0023
					(Mw-Mwo)/Mwo	0.06%	-0.03%	0.61%	-0.27%
V_M = 4.3 m/s									
Mean	9291.65	0.08451	0.0472	1.5228	Mean	9291.10	0.08465	0.0477	1.5173
Min	9291.03	0.08442	0.0466	1.5207	Min	9289.87	0.08444	0.0471	1.5143
Max	9292.45	0.08456	0.0480	1.5259	Max	9292.49	0.08481	0.0484	1.5208
Std. Dev.	0.65	0.00006	0.0005	0.0024	Std. Dev.	0.96	0.00015	0.0005	0.0024
Range	1.42	0.00014	0.0014	0.0052	Range	2.63	0.00037	0.0013	0.0065
SD/Mean	0.007%	0.07%	1.10%	0.16%	SD/Mean	0.010%	0.18%	1.07%	0.16%
P	0.58	0.00005	0.0005	0.0021	P	0.86	0.00014	0.0005	0.0021
P/Mean	0.006%	0.06%	0.98%	0.14%	P/Mean	0.009%	0.16%	0.96%	0.14%
					Mw-Mwo	-0.55	0.00015	0.0005	-0.0055
					(Mw-Mwo)/Mwo	-0.01%	0.17%	0.96%	-0.36%

Statistical Analysis of the Mean Values of the Repeat Tests
With and Without Counter-weight
V_M = 3.0 m/s, Heel = 20 deg., Yaw = 4 deg.

Without Counter-weight

	Q [N/m^2]	Acd [m^2]	Acl [m^2]	VOK [m^3]	VON [m^3]	Sinkage [m]	Trim [deg]	Lift/ Drag
Mean	4451.12	0.05731	0.24727	0.35091	0.02014	0.0226	-0.4984	4.3143
Min	4450.58	0.05714	0.24259	0.34466	0.01910	0.0222	-0.5019	4.2289
Max	4451.53	0.05745	0.25347	0.35791	0.02266	0.0229	-0.4949	4.4334
Std. Dev.	0.34	0.00011	0.00273	0.00329	0.00103	0.0002	0.0021	0.0528
Range	0.95	0.00031	0.01088	0.01324	0.00355	0.0006	0.0070	0.2045
SD/Mean	0.008%	0.19%	1.11%	0.94%	5.12%	0.98%	-0.43%	1.22%
P	0.21	0.00007	0.00173	0.00208	0.00065	0.0001	0.0014	0.0334
P/Mean	0.005%	0.12%	0.70%	0.59%	3.24%	0.62%	-0.27%	0.77%

With Counter-weight

	Q [N/m^2]	Acd [m^2]	Acl [m^2]	VOK [m^3]	VON [m^3]	Sinkage [m]	Trim [deg]	Lift/ Drag
Mean	4450.17	0.05728	0.24570	0.34956	0.01926	0.0226	-0.4645	4.2892
Min	4450.13	0.05691	0.24273	0.34558	0.01795	0.0223	-0.4677	4.2653
Max	4450.22	0.05751	0.24995	0.35421	0.02075	0.0230	-0.4596	4.3614
Std. Dev.	0.06	0.00019	0.00236	0.00279	0.00117	0.0003	0.0028	0.0347
Range	0.09	0.00060	0.00722	0.00863	0.00280	0.0008	0.0081	0.0960
SD/Mean	0.001%	0.32%	0.96%	0.80%	6.10%	1.16%	-0.60%	0.81%
P	0.05	0.00014	0.00178	0.00211	0.00089	0.0002	0.0021	0.0262
P/Mean	0.001%	0.24%	0.73%	0.60%	4.61%	0.88%	-0.45%	0.61%
Mw-Mwo	-0.95	-0.00003	-0.00157	-0.00135	-0.00089	0.0001	0.0339	-0.0251
(Mw-Mwo)/Mwo	-0.02%	-0.05%	-0.63%	-0.39%	-4.40%	0.35%	-6.80%	-0.58%

Statistical Analysis of the Time Histories of Sinkage and Trim
With and without Counter-weight
Model 504

	Without Counter-weight				**With Counter-weight**			
	Mean of St. Dev'ns		Range of St. Dev'ns		Mean of St. Dev'ns		Range of St. Dev'ns	
V_M [m/s]	Sinkage [m]	Trim [deg]	Sinkage [m]	Trim [deg]	Sinkage [m]	Trim [deg]	Sinkage [m]	Trim [deg]
Heel = 0 - Yaw = 0								
2.0	0.0003	0.0072	0.0002	0.0046	0.0002	0.0061	0.0002	0.0040
3.0	0.0004	0.0107	0.0005	0.0022	0.0003	0.0077	0.0003	0.0036
3.7	0.0006	0.0142	0.0004	0.0037	0.0006	0.0119	0.0005	0.0034
4.3	0.0011	0.0196	0.0003	0.0043	0.0010	0.0177	0.0007	0.0030
Heel = 20 - Yaw = 4								
3.0	0.0003	0.0093	0.0003	0.0043	0.0002	0.0096	0.0005	0.0073

Results of *t*-Test using Upright Data-set

Unpaired Means Comparison for Acd
Grouping Variable: Conf
Split By: Vm (nom)
Hypothesized Difference = 0
Inclusion criteria: upright from cw.svd

	Mean Diff.	DF	t-Value	P-Value	95% Lower	95% Upper
No, Yes: Total	0.00006	42	0.01124	0.9911	-0.01084	0.01097
No, Yes: 2.0	0.00027	8	4.48610	0.0020	0.00013	0.00042
No, Yes: 3.0	0.00011	8	1.48413	0.1761	-0.00006	0.00028
No, Yes: 3.2	0.00002	2	0.06524	0.9539	-0.00100	0.00103
No, Yes: 3.7	0.00002	8	0.16331	0.8743	-0.00029	0.00033
No, Yes: 4.3	-0.00015	8	-2.03587	0.0762	-0.00031	0.00002

Group Info for Acd
Grouping Variable: Conf
Split By: Vm (nom)
Inclusion criteria: upright from cw.svd

	Count	Mean	Variance	Std. Dev.	Std. Err
No: Total	22	0.05940	0.00032	0.01785	0.00381
No: 2.0	5	0.04049	9.43063E-9	0.00010	0.00004
No: 3.0	5	0.04672	1.89942E-8	0.00014	0.00006
No: 3.2	2	0.04713	2.78421E-8	0.00017	0.00012
No: 3.7	5	0.07079	4.82502E-8	0.00022	0.00010
No: 4.3	5	0.08451	3.13416E-9	0.00006	0.00003
Yes: Total	22	0.05934	0.00032	0.01799	0.00384
Yes: 2.0	5	0.04022	9.33724E-9	0.00010	0.00004
Yes: 3.0	5	0.04661	9.16244E-9	0.00010	0.00004
Yes: 3.2	2	0.04712	8.39877E-8	0.00029	0.00020
Yes: 3.7	5	0.07077	4.13229E-8	0.00020	0.00009
Yes: 4.3	5	0.08465	2.29572E-8	0.00015	0.00007

Unpaired Means Comparison for Drag
Grouping Variable: Conf
Split By: Vm (nom)
Hypothesized Difference = 0
Inclusion criteria: upright from cw.svd

	Mean Diff.	DF	t-Value	P-Value	95% Lower	95% Upper
No, Yes: Total	-0.19559	42	-0.00241	0.9981	-163.92101	163.52982
No, Yes: 2.0	0.40640	8	3.35261	0.0100	0.12687	0.68593
No, Yes: 3.0	0.28680	8	0.84539	0.4225	-0.49552	1.06912
No, Yes: 3.2	-0.21450	2	-0.20558	0.8561	-4.70385	4.27485
No, Yes: 3.7	-0.14820	8	-0.15777	0.8785	-2.31428	2.01788
No, Yes: 4.3	-1.31980	8	-2.02034	0.0780	-2.82621	0.18661

Group Info for Drag
Grouping Variable: Conf
Split By: Vm (nom)
Inclusion criteria: upright from cw.svd

	Count	Mean	Variance	Std. Dev.	Std. Err
No: Total	22	369.81179	72231.22274	268.75867	57.29954
No: 2.0	5	79.82348	.03603	.18981	.08488
No: 3.0	5	207.68900	.38840	.62322	.27871
No: 3.2	2	209.52600	.49005	.70004	.49500
No: 3.7	5	470.65020	2.66034	1.63105	.72943
No: 4.3	5	785.19880	.22991	.47949	.21443
Yes: Total	22	370.00738	72571.71985	269.39139	57.43444
Yes: 2.0	5	79.41708	.03744	.19350	.08654
Yes: 3.0	5	207.40220	.18706	.43251	.19342
Yes: 3.2	2	209.74050	1.68728	1.29896	.91850
Yes: 3.7	5	470.79840	1.75128	1.32336	.59182
Yes: 4.3	5	786.51860	1.90382	1.37979	.61706

Results of *t*-Test using Upwind Sailing Condition Data-set

Unpaired Means Comparison for Acd
Grouping Variable: Conf
Hypothesized Difference = 0
Inclusion criteria: Sailing from cw.svd

	Mean Diff.	DF	t-Value	P-Value	95% Lower	95% Upper
No, Yes	0.00003	15	0.44014	0.6661	-0.00012	0.00018

Group Info for Acd
Grouping Variable: Conf
Inclusion criteria: Sailing from cw.svd

	Count	Mean	Variance	Std. Dev.	Std. Err
No	10	0.05731	1.19557E-8	0.00011	0.00003
Yes	7	0.05728	3.44280E-8	0.00019	0.00007

Unpaired Means Comparison for Acl
Grouping Variable: Conf
Hypothesized Difference = 0
Inclusion criteria: Sailing from cw.svd

	Mean Diff.	DF	t-Value	P-Value	95% Lower	95% Upper
No, Yes	0.00157	15	1.23006	0.2376	-0.00115	0.00429

Group Info for Acl
Grouping Variable: Conf
Inclusion criteria: Sailing from cw.svd

	Count	Mean	Variance	Std. Dev.	Std. Err
No	10	0.24727	0.00001	0.00273	0.00086
Yes	7	0.24570	0.00001	0.00236	0.00089

Unpaired Means Comparison for VOK
Grouping Variable: Conf
Hypothesized Difference = 0
Inclusion criteria: Sailing from cw.svd

	Mean Diff.	DF	t-Value	P-Value	95% Lower	95% Upper
No, Yes	0.00135	15	0.88538	0.3899	-0.00190	0.00461

Group Info for VOK
Grouping Variable: Conf
Inclusion criteria: Sailing from cw.svd

	Count	Mean	Variance	Std. Dev.	Std. Err
No	10	0.35091	0.00001	0.00329	0.00104
Yes	7	0.34956	0.00001	0.00279	0.00105

Unpaired Means Comparison for VON
Grouping Variable: Conf
Hypothesized Difference = 0
Inclusion criteria: Sailing from cw.svd

	Mean Diff.	DF	t-Value	P-Value	95% Lower	95% Upper
No, Yes	0.00089	15	1.64799	0.1201	-0.00026	0.00203

Group Info for VON
Grouping Variable: Conf
Inclusion criteria: Sailing from cw.svd

	Count	Mean	Variance	Std. Dev.	Std. Err
No	10	0.02014	1.06444E-6	0.00103	0.00033
Yes	7	0.01926	1.37815E-6	0.00117	0.00044

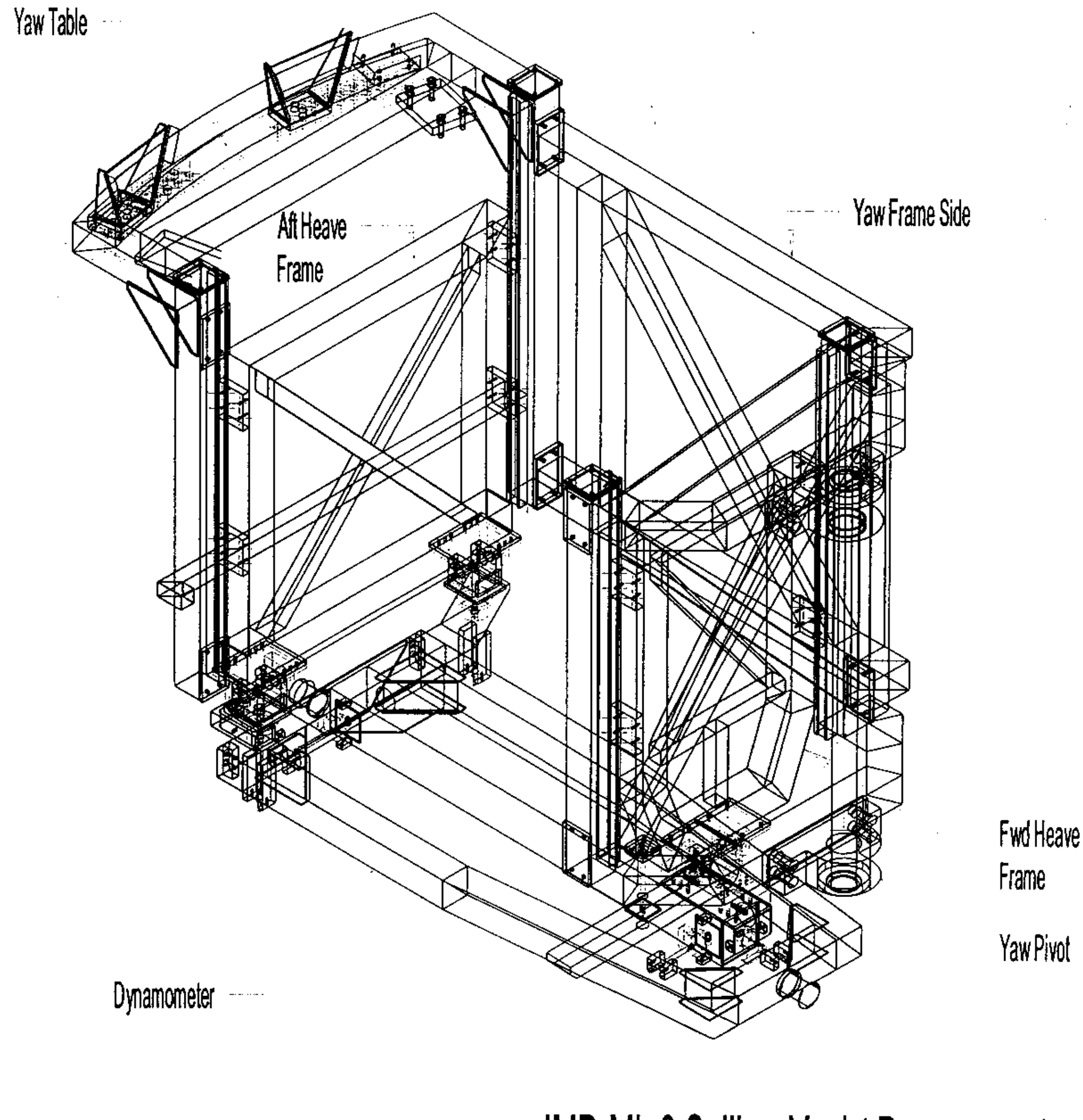
Unpaired Means Comparison for L/D
Grouping Variable: Conf
Hypothesized Difference = 0
Inclusion criteria: Sailing from cw.svd

	Mean Diff.	DF	t-Value	P-Value	95% Lower	95% Upper
No, Yes	0.02513	15	1.09820	0.2894	-0.02364	0.07390

Group Info for L/D
Grouping Variable: Conf
Inclusion criteria: Sailing from cw.svd

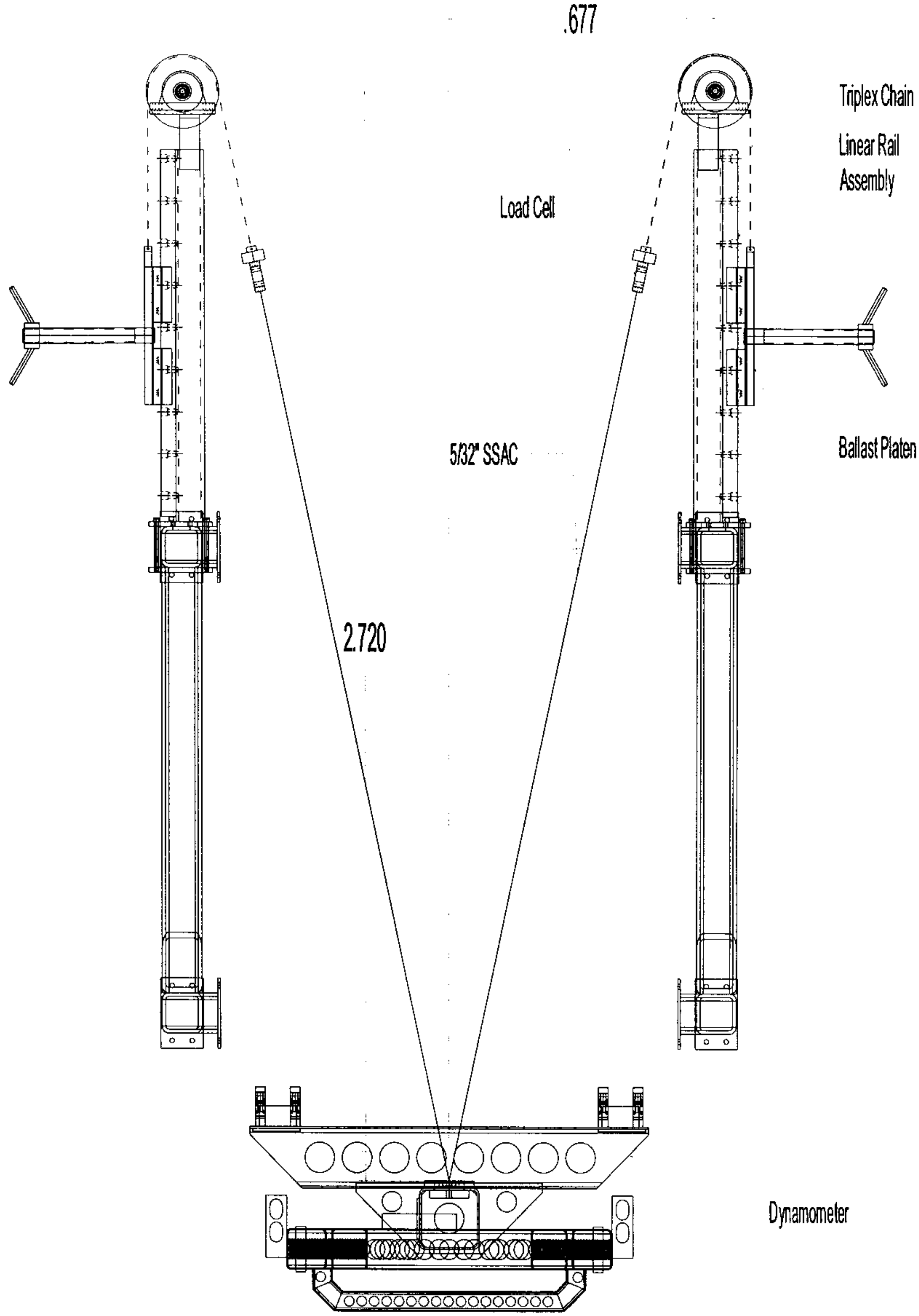
	Count	Mean	Variance	Std. Dev.	Std. Err
No	10	4.31432	0.00279	0.05285	0.01671
Yes	7	4.28919	0.00120	0.03465	0.01310

FIGURES



IMD Mk.3 Sailing Yacht Dynamometer

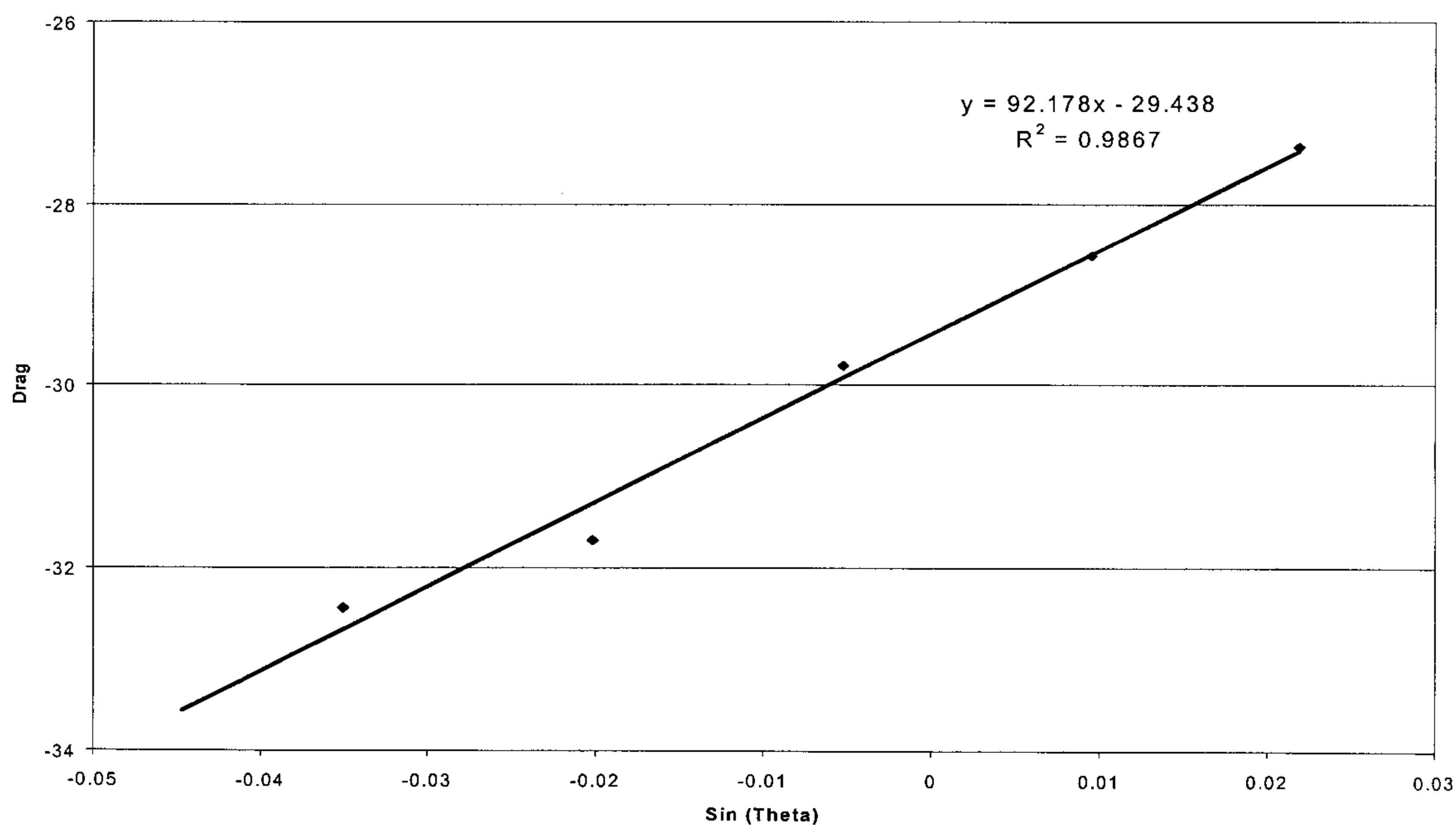
Figure 2



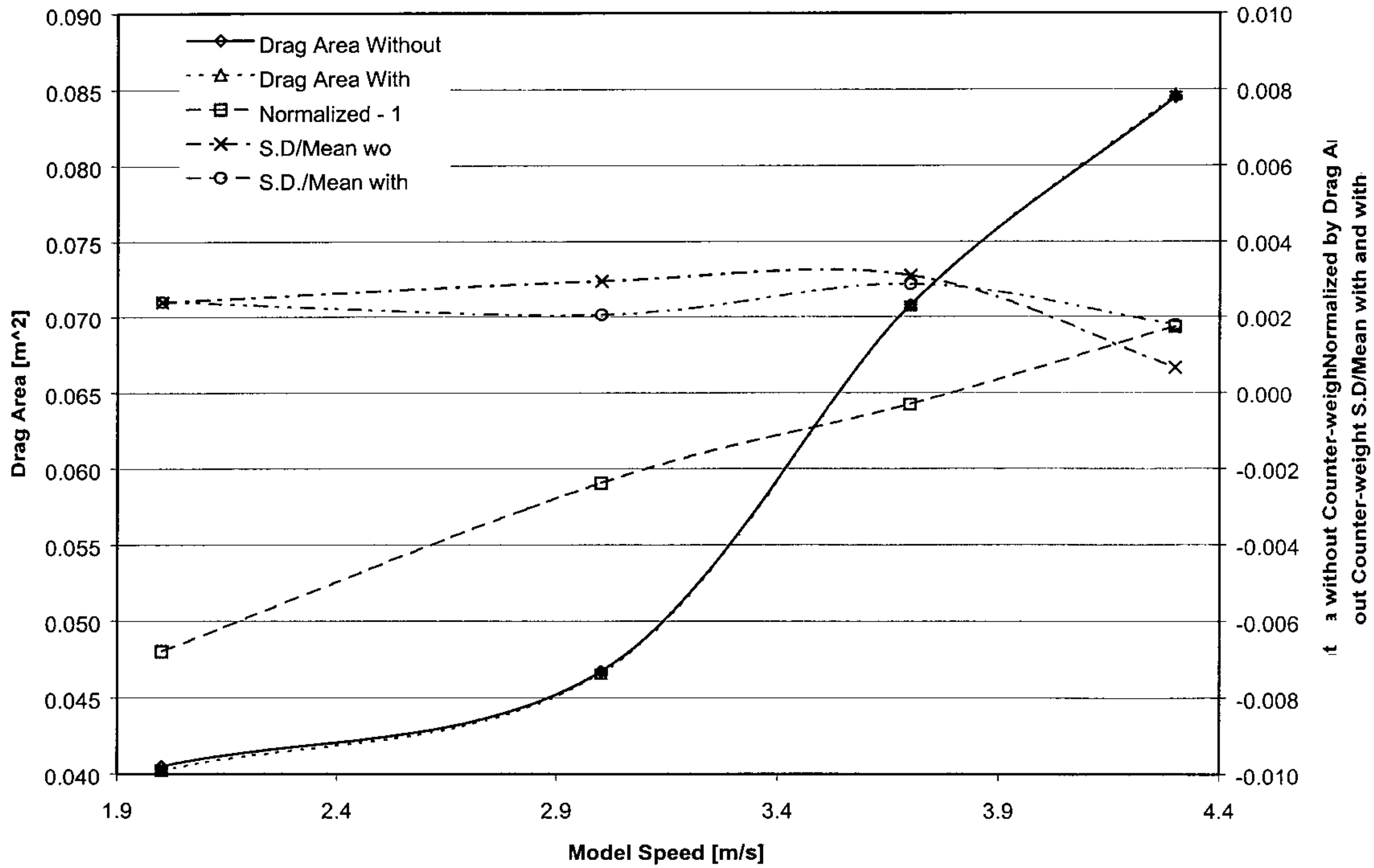
Counterweight Arrangement

Dimensions in meters

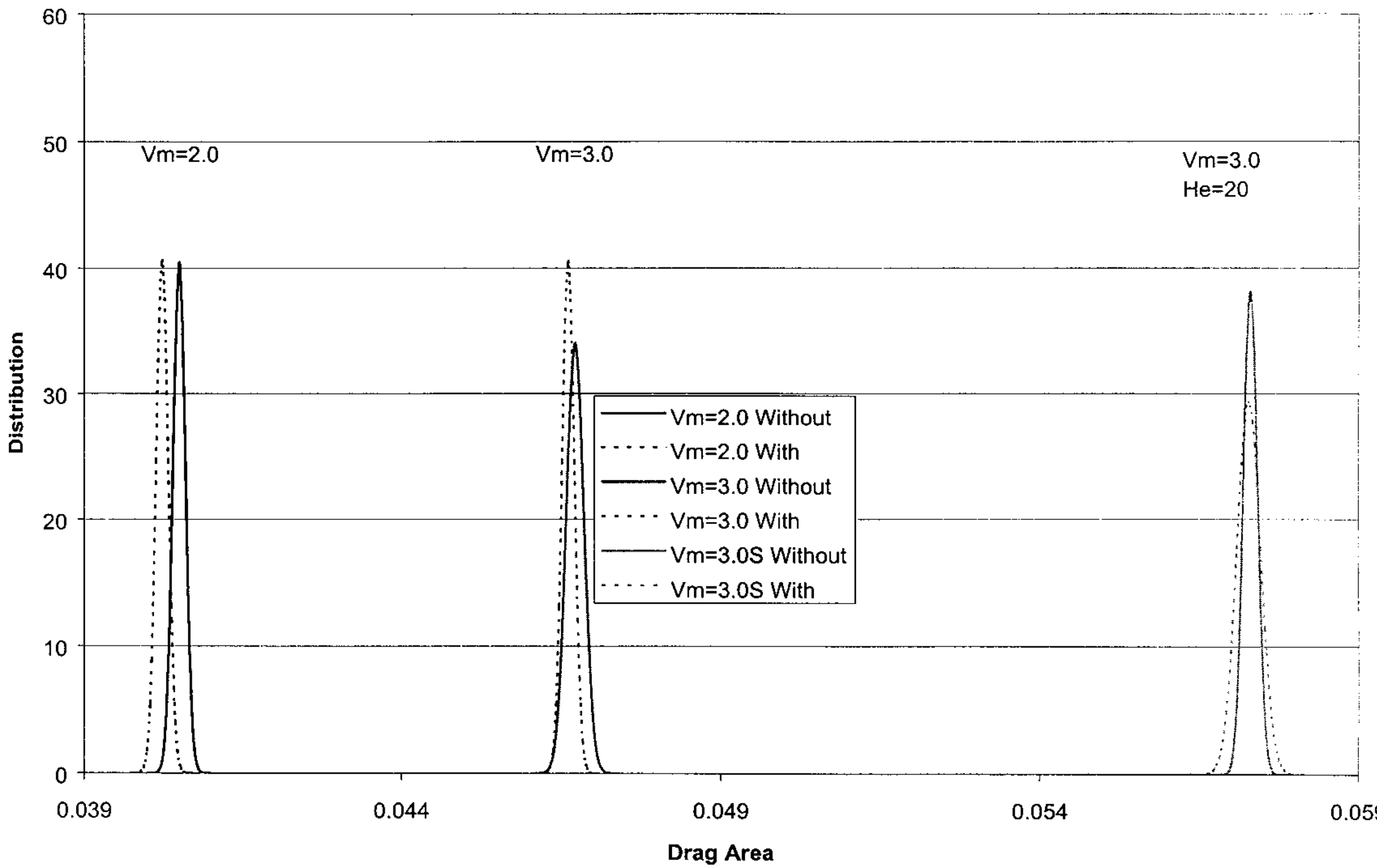
Derivation of Effective Dynamometer Weight with Counterweight Attached

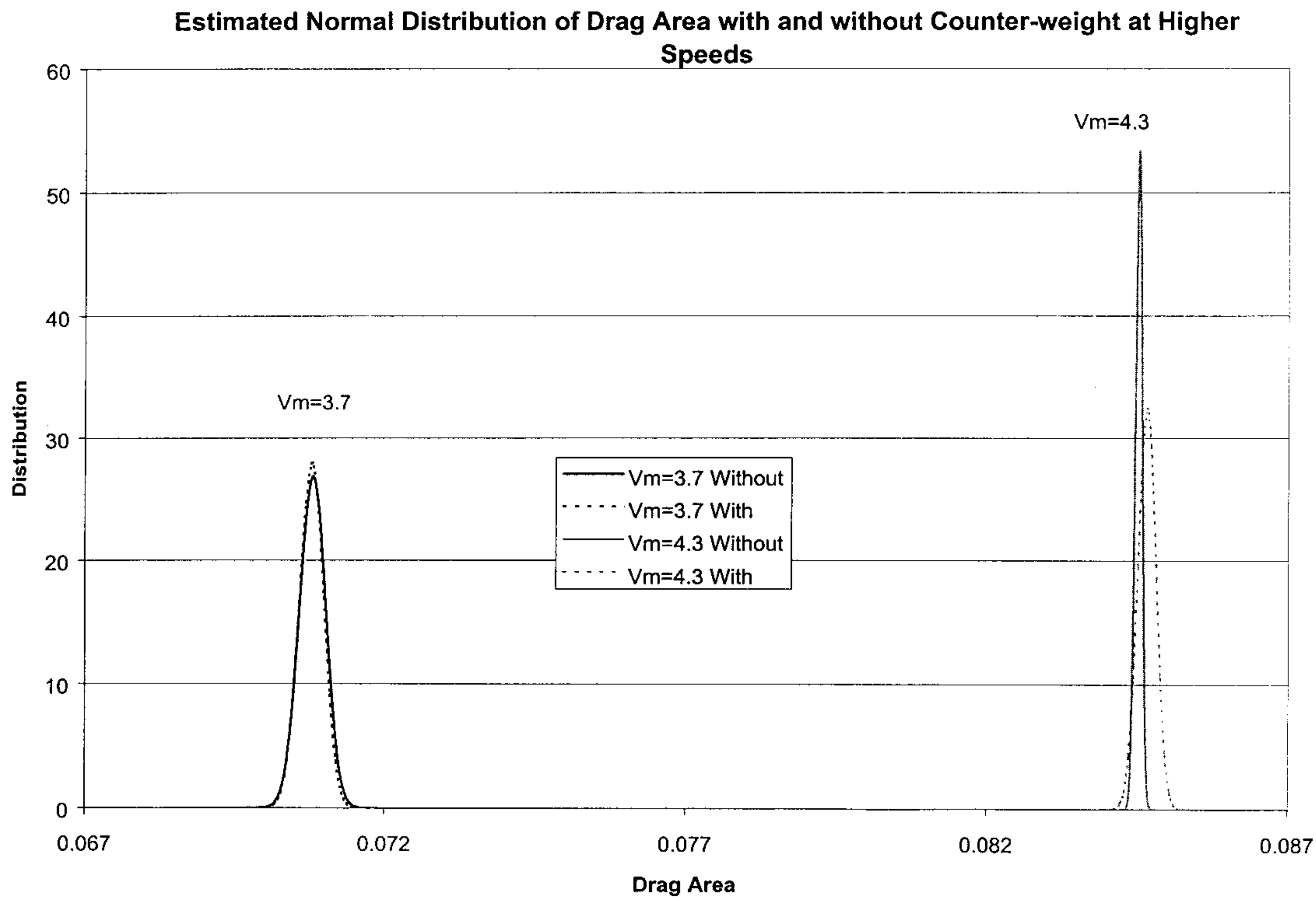


Comparison of Drag Area Upright with and without Counter-weight



Estimated Normal Distribution of Drag Area with and without Counter-weight at Lower Speeds




Estimated Normal Distribution of Drag Area with and without Counter-weight at Higher Speeds
Distribution
60
50
40
30
20
10
0
0.067
0.072
0.077
0.082
0.087
Drag Area
Vm=3.7
Vm=4.3
Vm=3.7 Without
Vm=3.7 With
Vm=4.3 Without
Vm=4.3 With