NRC·CNRC

NRC Publications Archive
Archives des publications du CNRC

Bifilar swinging experiment

Card, T.

For the publisher's version, please access the DOI link below./ Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/8895325
Laboratory Memorandum (National Research Council of Canada. Institute for Marine Dynamics); no. LM-2000-01, 2000

NRC Publications Archive Record / Notice des Archives des publications du CNRC :
https://nrc-publications.canada.ca/eng/view/object/?id=56d7a1e3-bed5-423f-9828-a13b7468d3ad
https://publications-cnrc.canada.ca/fra/voir/objet/?id=56d7a1e3-bed5-423f-9828-a13b7468d3ad

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at
PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research Council Canada Conseil national de recherches Canada

Canada

National Research Council Canada
Institute for Ocean Technology

Conseil national de recherches Canada
Institut des technologies océaniques

Laboratory Memorandum

LM-2000-01

Bifilar Swinging Experiment

T. Card

June 2000

Canada

National Research Council Canada
Conseil national de recherches Canada

Institute for Marine Dynamics
Institut de dynamique marine

BIFILAR SWINGING EXPERIMENT

LM-2000-01

Taran Card

June 2000

DOCUMENTATION PAGE

REPORT NUMBER	NRC REPORT NUMBER	DATE
LM-2000-01		June 2000

REPORT SECURITY CLASSIFICATION	DISTRIBUTION
Unclassified	Unlimited

TITLE
BIFILAR SWINGING EXPERIMENT

AUTHOR(S)

Taran Card

CORPORATE AUTHOR(S)/PERFORMING AGENCY(S)

National Research Council – Institute for Marine Dynamics

PUBLICATION

SPONSORING AGENCY(S)

IMD PROJECT NUMBER	NRC FILE NUMBER

KEY WORDS:	PAGES	FIGS.	TABLES
Bifilar, experiment	28	12	

SUMMARY:

The purpose of this report is to document the evolution of an experimental procedure. The specific experiment being addressed is a bifilar swinging experiment for the determination of the physical properties of a submarine model. However, the procedures developed in the course of this experiment are applicable to any type of model or object for which the physical properties must be known.

ADDRESS: National Research Council
Institute for Marine Dynamics
P. O. Box 12093, Station 'A'
St. John's, NF
A1B 3T5
Tel. (709) 772-2479 Fax: (709) 772-2462

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The purpose of this report is to document the evolution of an experimental procedure. The specific experiment being addressed is a bifilar swinging experiment for the determination of the physical properties of a submarine model. However, the procedures developed in the course of this experiment are applicable to any type of model or object for which the physical properties must be known.

This report contains a description of the different types of setups used in the experiment and the various advantages and disadvantages thereof. Each method tried required different equipment and techniques in order to attain the required accuracy of results.

The primary research, which has gone into the generation of the data presented here, was performed in the form of a six-week test series. The test series consisted of the actual experimentation and data gathering procedure as well as the continual analysis of that data to ensure the consistency and validity of the results.

It was determined through the course of this testing procedure that the bifilar swinging of complex models can be a reliable and relatively accurate method for the determination of their physical properties. The major drawback to this type of experiment is the accuracy, which is required in the setup of the equipment. Controlling the location of the center of gravity was discovered to be very important to the final accuracy and reliability of the results. This level of control requires that the apparatus be

assembled with as much attention to precision as possible. Every measured distance that is a part of the experiment must be controlled at least down to the millimeter. Full advantage must also be taken of the accuracy of each electronic component, in this way, the maximum repeatability and accuracy of the experiment can be ensured.

INTRODUCTION

PURPOSE

The purpose of this experiment was to develop an experimental method for determining the physical properties, mass, location of CG, radius of gyration and moment of inertia of a free flooding underwater vehicle: Also, the experimental method and equipment had to be developed and a complete set of experimentally-determined physical properties found for a model under various appendage conditions.

The Design and Fabrication office at the Institute for Marine Dynamics has recently begun to implement a new solid modeling package, which should be able to mathematically determine the physical properties of a model. The experimentally determined values will eventually be used as a comparison for the solids package in order to determine its accuracy and the effect to which it can model the effect of floodwater.

HISTORICAL INFORMATION

Bifilar swinging is not the only method for determining the physical properties of an object. Previously a variety of swinging frames and brackets have been used to support the model, captive in all axes but that of the desired motion, and to swing it in harmonic motion from a known point ***(Figure 1)***. Since the framework was of a known mass its effects could be canceled out and the parallel axis theorem used to fit the data to the model axis.

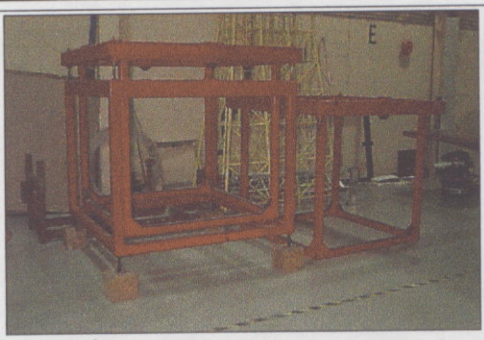


Figure 1: This shows one of the frames previously used for swinging. It can be seen that the mass of the frame is hardly negligible, in this experiment the aluminum frame (on the right) would have eight times the inertia of the model in the roll configuration.

This method proved impractical however due to several properties of the apparatus itself:

- In order to support the weight of the models the apparatus was made of steel. This means that the effect of the apparatus itself was very large, and even though it was known, made the resolution of the experiment suspect when attempting to find small moments of inertia. Even when the frame was made from aluminum the effect of the frame was almost an order of magnitude higher than what was to be measured.
- Controlling the position of the model's CG inside the test frame was often very difficult. Since the larger models, which would be tested in this framework, had to be lifted in by crane or forklift, it would have been a highly difficult procedure to position them to better that 3-mm.

The bifilar method has been employed with success on various yacht models, however several factors have made it so that the accuracy of the experiment has never been verified to the level required in this test:

- Since the model could only be hung in the bare hull condition the effects of the appendages had to be added in mathematically. These effects were calculated based on the measured physical characteristics of the appendages. (Mass, CG, etc.) And these characteristics themselves contained an unknown amount of error.
- Since the yacht dynamometer is attached to the frame but is constrained in certain degrees of freedom its effect on the properties of the model are almost impossible to determine. This is the major source of error in the previous experiments.

- Because the effect of the yacht dynamometer was not known, it was never deemed necessary to measure the period of the motion to a higher accuracy than could be achieved by eye with a hand stopwatch.

Therefore, in order to reach the desired level of accuracy the equipment employed in the test had to be expanded and modified and the procedure altered to eliminate as many variables as possible.

SCOPE

This report is meant to outline the procedures that were developed in order to determine the physical characteristics of a submarine model. Included in this document is an account of the different methods for executing the experiment, their respective strengths and weaknesses, and the refinement processes that lead to the eventual final method. Also included is a complete set of results from the final series of tests and a discussion of their importance. Finally a set of recommendations is included which are to try and make yet more improvements to the experiment and to remove the last known sources of error.

METHODOLOGY

In each experiment there were three important measured outcomes. For each configuration a measurement was taken for the total mass of the model, the location of its center of gravity and the period of its motion in the bifilar swinging setup. The general outline of the measurement procedure will be given here, with more detailed descriptions of the refinements to be discussed later.

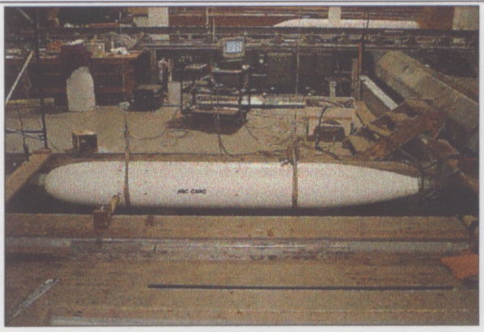


Figure 2: This shows the dry model in the yaw orientation. Here it is shown in the bare-hull configuration.

The Model

The model being tested was IMD M497, a model of the DREA standard submarine. The model is constructed of several interchangeable sections so that the instrumentation package that is mounted inside the parallel mid-body does not have to be removed in order to change the configuration of the model ***(Figure 2)***. The length of the model is 4.5 m and its 'dry' mass is about 400 kg; its mass when flooded is approximately 790 kg. For the purposes of these tests there are four configurations for the model:

Figure3: This shows the fully appendaged model in the Roll orientation.

- **Bare Hull -** consisting of only the parallel mid-body with the nose and tail cones corresponding to M497.
- **Hull & Sail –** this consists of the bare hull with the conning tower appendage attached.
- **Hull, Sail & Fins –** this is the fully appendaged condition, a set of four control fins is added to the aft end of the model. ***(Figure 3)***
- **Hull & Fins –** this condition consists of only the bare hull and the four control fins.

Test Conditions

The bifilar swinging of the model must be completed in each of the three axis of motion (Pitch, Yaw, and Roll). This means that each configuration must be tested in each axis. It was also desired to test the model both dry and full of water.

A full test matrix for this model therefor consists of:

- **Yaw** (dry) – 4 configurations
- **Yaw** (wet) – 4 configurations
- **Pitch** (dry) – 4 configurations
- **Pitch** (wet) – 4 configurations
- **Roll** (dry) – 4 configurations
- **Roll** (wet) – 4 configurations

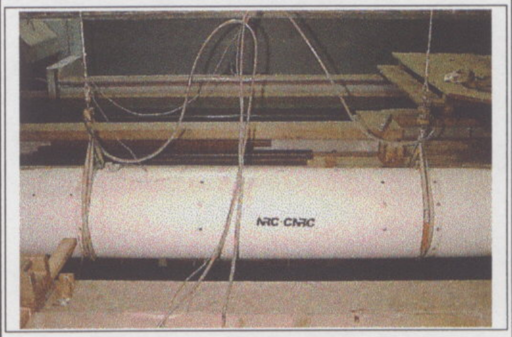


Figure 4: This shows the model in the sling suspension. Also shown are the identical hardware and the care taken to suspend the instrument wires so that they do not influence the result.

Figure 5: Here the roll configuration is shown with the shorter wires and the instrument wires supported by the crane. Note how the wires must be splayed to avoid contacting the fins.

Equipment and Measurements

For bifilar swinging the model must be suspended from two points. In this experiment steel cables were used to hang the model at the desired level. The cables themselves were produced with particular care being paid to having the two cables be an equal length. Identical hardware (e.g. shackles) was also used on each cable to ensure that the when the model was finally suspended the two cables would be as close to the same length as possible ***(Figure 4)***.

For tests conducted with the model in a horizontal orientation (pitch and yaw) 5.5 m cables were made so that once the appropriate hardware was added the model would hang at a level that is convenient to work on while suspended from the roof trusses over the CWTT. Since the model is almost 4.5 m long itself, using these same long cables for the roll orientation is not feasible. For this reason another set of cables was made specifically for the roll configuration; these cables were made four metres long, and allowed just enough room for the model to be suspended vertically without interference ***(Figure 5)***. It was noted that in order to eliminate as many of the eccentric frequencies as possible, the cables should be attached as far away from the CG of the model as possible. Again care was taken to ensure that identical hardware was used on either side to ensure that the weight was evenly distributed.

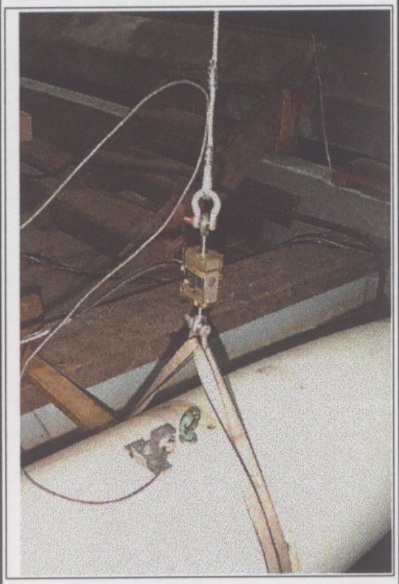


Figure 6: Here the load-cell and accelerometer are shown in position in the first series of tests.

In order to be able to measure the mass of the model and determine the location of the CG, the load cells were placed on the model end of each of the suspension cables ***(Figure 6)***. The load cell readings used were intended to indicate the location of the CG by showing the difference between the two readings. The method of achieving this to the required accuracy is one of the major changes that had to be made in the experimental procedure and will be discussed later in this report.

Measurement of the period of motion was achieved by attaching an accelerometer to the model in order to measure the lateral accelerations ***(Figure 6)***. Because of the small scale of the motion, yaw oscillation initial displacement was approximately six or seven degrees, it is necessary to have a highly sensitive accelerometer. The resolution on the accelerometer used in this experiment was set to 0.025 g. In order to induce as much motion in the accelerometer as possible, in the horizontal orientations it was placed as far from the LCG as possible, but in the vertical orientations, many of the undesired eccentric motions were not picked up if the accelerometer was placed directly on the LCG.

A data acquisition unit and the appropriate software are required to acquire the signals from the three sensors. The G-PLOT functions of the GEDAP software were then used to filter and smooth the signals from the accelerometer. The signal is low-pass filtered to remove any frequencies higher than 1.2 Hz. (Except for the roll orientations where no filtering is required.) This signal is then analyzed in order to determine the average period of the motion. The data is accumulated over a 50-sec sample time, which gives an average of 10 oscillations per test. Of these 10 cycles at least five must be taken into account to ensure the validity of the final calculations. Seven separate tests were performed for each of the conditions in order to ensure that at least five were sufficiently close to give confidence in the validity of the readings. For these experiments a limit of 0.009-sec standard deviation on the measured period was required in order to qualify as an accepted result.

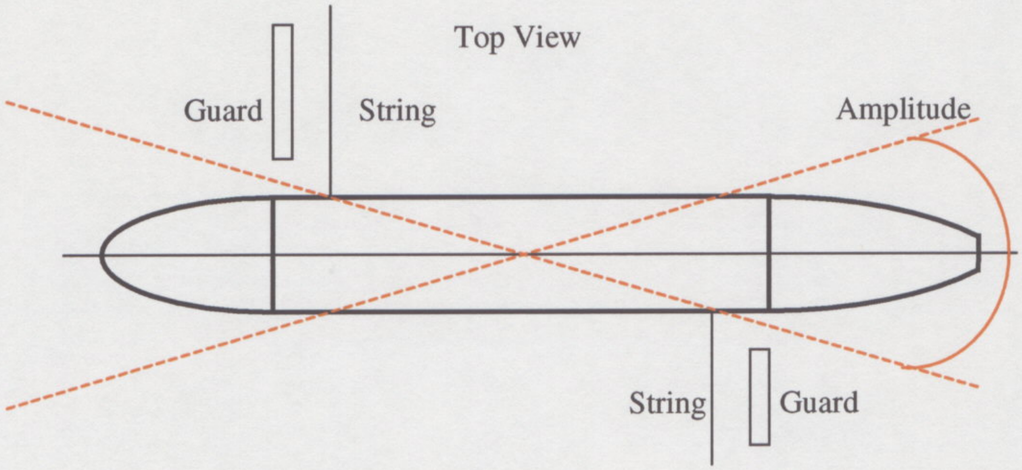
Analysis

Once the period of an orientation has been found, it is then used to calculate the radius of gyration:

$$K_y = \frac{dT_y}{2\pi}\sqrt{g/L}$$

K_y- Radius of gyration T_y- Period of motion L- Length of wires

d- Spacing of wires g- Acceleration of gravity



Limitations

There are several practical limitations on this series of experiments, most of them are concerned with the flooded condition.

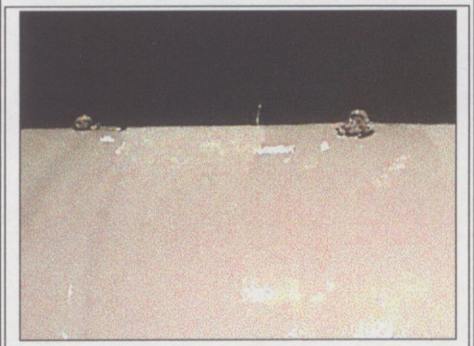


Figure 7: This shows the water being forced through holes intentionally left open in the upper part of the model to ensure that the model is completely full.

- Keeping the amount of water inside the model constant is a problem. The model was not made to be watertight. Therefore, it had to be sealed as well as possible in order to for the model to fill. Even so, there were inevitably leaks, which meant that the water had to be continually flowing into the model ***(Figure 7)***. The main problem though is that since there are many places inside the model where air could conceivably become trapped it is very difficult to keep the amount of water constant each time the model is filled. This is due simply to the method of construction used to build the model.

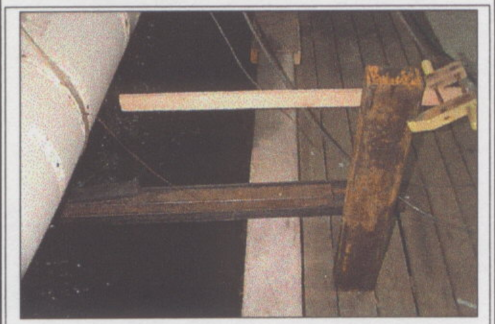


Figure 8: This shows one guide setup used to control the position to which the model is pulled before being released into motion.

- Starting the motion in both the dry and flooded condition is a two-person operation in this experiment. Each person stands at one end of the model (bow and stern) level with the support cables and pulls the model a set distance out from the resting midline (until it is just touching a set of guides ***Figure 8***). Then they must simultaneously release the model in order to start it in the desired mode of swing. Since it is not possible to release it perfectly every time there is always some eccentric motion.
- Due to small offsets in the vertical and transverse CG of the model, the sway component of the swing develops over time. After four oscillations there appears to be a complex system of energy exchange between the two modes which causes a type of "fishing" motion, where the model appears to swim. But since the sway period is very close to the bifilar period, there is no way to tell what effect, if any it is having on the measured period.

PRIMARY METHOD

Suspension

In the original method it was proposed that slings hanging from the ends of the cables would support the model. Slings were selected instead of wire loops because it was thought that the model would slide too much in a wire loop ***(Figure 6)***. With the nylon slings it was possible to slide them along the model while under load.

Balancing

The data acquisition software used in this experiment was capable of giving a continuous reading in real-time from the load cells. This streaming readout was used to balance the model. By comparing the readings from the forward and aft load cells it was possible to tell whether the CG was off center. The slings were then adjusted until the two readings were roughly equal.

Problems

- Visual comparison of the load cell readings proved to be far too inaccurate as a basis for balancing. Because of the rate at which the values were streaming it was impossible to get the readings to match to better than about 30 N.
- The "softness" of the slings proved to be a problem as well. Because of the flexibility of the sling system they could not be positioned to better than four or five mm at each end. This translates into a variability of up to one cm at the CG. The addition of the sail to the bare hull only changes the mathematical CG by three mm so it is obvious that the resolution of the experiment must be at least that good.
- Because the slings have no stability in the direction of the rotation of the model there is no way to ensure that the model is perfectly vertical. Also, each time the position of the supports is altered it is possible that the model has rotated slightly in the slings.

ACCURACY TEST

In order to determine the precision that is required in performing the experiment the properties of a known shape were measured and compared to those calculated mathematically.

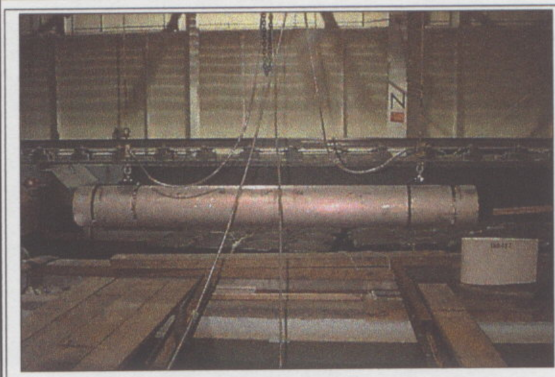


Figure 9: This shows the suspended aluminum test sample.

Test Sample

A solid aluminum cylindrical bar was found which had a mass that was close to the mass of the submarine model in the dry configuration ***(Figure 9)***. This was an eight-foot length of 10" diameter aluminum bar. Since the bar was solid and of a regular shape it was simple to calculate the expected properties.

Suspension and Adjustment

For this testing a way had to be found to control the position of the cables to better than one mm resolution. In order to accommodate that, a set of Harken® traveler block systems were attached at points equidistant from the known CG; this allowed the cables to be positioned exactly ***(Figure 10)***. Instead of comparing the streaming results of the load cells, 10 sec (1000 sample) data files were generated and loaded into Excel which allowed the averages of the load cell readings to be found and compared. This method, though more time consuming, allows the full accuracy of the load cells to be taken advantage of. It is not difficult to achieve a balance where the average difference between load cells over five samples is as low as 0.7 N with a standard deviation of less than one Newton. This

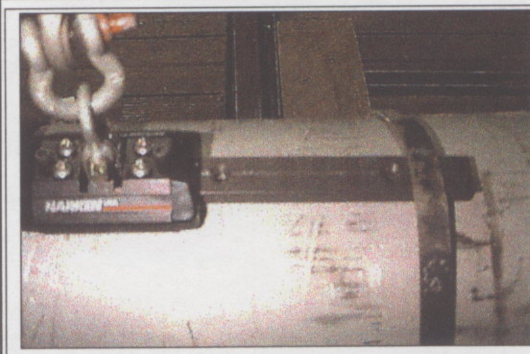


Figure 10: This shows the Harken® traveler system used to precisely control the position of the cables. The track has been marked with 1.0 mm divisions and a pair of clamp-screws have been added to secure the car in position.

translates to an accuracy in the location of CG of better than a mm which is what is required by the experiment.

Variables

The test sample was used to evaluate the effect of various cable positions:

- **Parallel cables:** the initial test performed had the cables equidistant from the CG and as perfectly parallel as was achievable.
- **Splayed cables:** two conditions were examined where the lower ends of the cables were at wider spacing than the upper ends. A total splay of 5 cm and 10 cm were tested.
- **Pinched cables:** one condition was tested where the lower end of the cables were spaced a total of 10 cm closer than at the upper end.
- **Offset CG:** two conditions were explored where the cables were parallel but offset by known amounts from being equidistant from the CG; 5 cm and 1 cm offsets were used.

Also checked was the accuracy of the load cells. Since the mass of the sample was known by weighing it on a platform scale it was a simple procedure to get the Excel spreadsheet to find the total mass recorded. By comparing this to the known mass it was determined that at the level where we were operating the load cells could resolve down to approximately 1.5 N which is well within the required accuracy.

Results

Parallel Cables: The experiment where the system was as close to ideal conditions as possible showed a highly accurate result with very small deviations in the measured periods and no other indications of other errors. However, it was noted that there was a constant offset between the expected value for K and the measured value. It was decided that this was the inherent offset caused by the experiments' equipment. Since this offset was going to remain constant for each experiment, regardless of the test subject, a correction factor was incorporated into the equation in the form of an adjusted L (length of suspension wire) in order to make the measured K equal to the expected one. By incorporating this into all following tests we can be reasonably certain that any change is due to the altered geometry of the setup and nothing else.

Splayed and Pinched Cables: It was found that when the cables deviated from parallel there was a measurable change in the detected radius of gyration (K). There did not appear do be an appreciable difference between the splayed and the pinched conditions; both showed increased

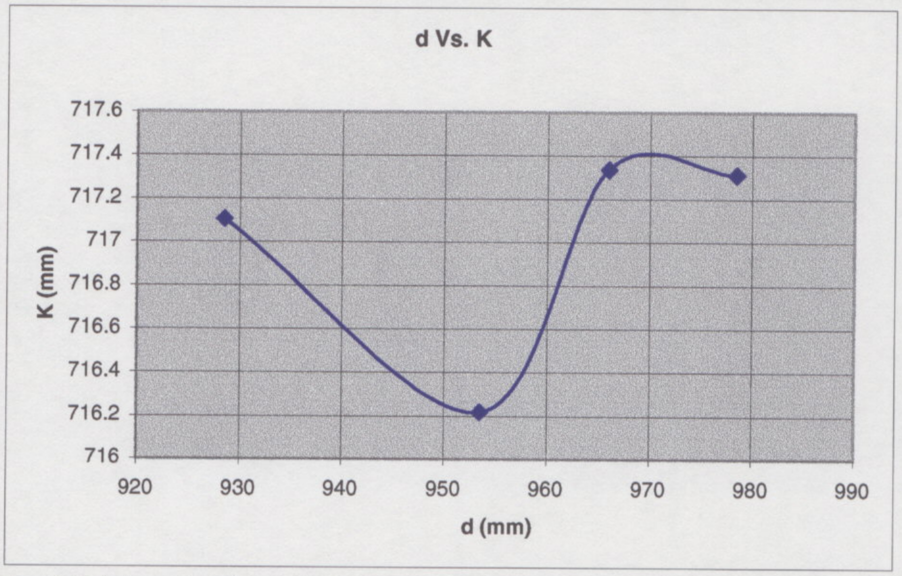


Chart 1: This shows the influence of splaying and pinching the cables on the radius of gyration. Clearly illustrated in the chart is the dip present for the parallel cable condition. Also shown is the limit of K as the spacing is increased past a point.

results. More interesting was the discovery that the relationship was non-linear. This means that the value of K did not simply increase in proportion to the spacing. There appears to be an initial hump before which the K value shows little change and after which the value of K again becomes relatively insensitive but at an offset from the calculated value. This proved that having the cables in the parallel condition is a very important aspect in terms of the accuracy of the experiment. It also shows that there is a relatively small range in which the results of the experiment can be accurate.

Offset CG: The experiments where the effect of offset CG was measured showed that this too was a very important factor in ensuring the accuracy of the experiment. Even small offsets of the CG (on the order of the accuracy of the previous experiment) showed a change in the measured K on the order of 2 mm.

Another interesting observation in this series of experiments was the fact that all of the conditions resulting in a change in cable spacing or CG position showed a noticeable change in the standard deviation of the periods of motion. This can be explained in the case of the CG offset tests by the fact that the eccentricity of the CG could induce an exchange in the energy between various modes of the motion. This would cause the mass to begin to orbit points that were not coincident with the midpoint of the span. In the case of the splayed cables I would hypothesize that having the cables on angles could cause tension to be developed in the horizontal direction; not present if the cables are perfectly vertical. This component of the tension would serve to induce eccentric motions that would cause a shift in the results.

Aluminum Cylinder (Accuracy check of experiment)

Horizontal Orientation:									
	Mass: Measured	Rad Gy	Track & Bands	Position		Trolleys & Hardware		Inertia	
	[kg]	[m]		frd	aft	frd	aft	[kgm^2]	(adjusted)
Measured Parallel	3409.04	0.7162	0.7998	0.907	0.907	0.411	0.411	1748.73	1747.10
Splayed 5cm	3409.04	0.7173	0.7998	0.932	0.932	0.434	0.434	1754.20	1752.53
Splayed 10cm	3409.04	0.7173	0.7998	0.957	0.957	0.457	0.457	1754.07	1752.36
Pinched 10cm	3409.04	0.7171	0.7998	0.857	0.857	0.367	0.367	1753.06	1751.53
Off Center 5cm	3409.04	0.7178	0.7998	0.957	0.857	0.457	0.367	1756.61	1754.99
Off Center 10cm	3409.04	0.7167	0.7998	1.007	0.807	0.507	0.325	1751.27	1749.64

Expected Inertia:	1747.50 kgm^2

The most important outcome of this test series was the fact that it allowed the effect of the suspension equipment to be eliminated. Since the mathematically derived value for the moment of inertia could be considered perfect, when the parallel cable test showed some deviation in the measured moment of inertia this could confidently be ascribed to the effect of the equipment. Since the bifilar equation assumes that all equipment is massless this had to be removed. In order to eliminate this a 'virtual' L was used in the calculation to eliminate this error. This L was then used in all calculations since the hardware was the same.

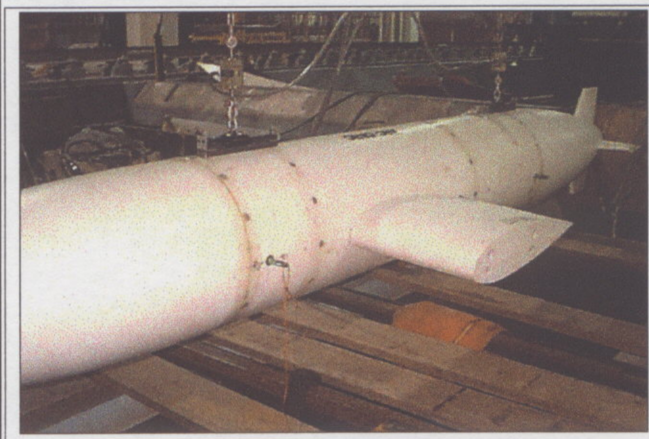


Figure 11: Here the model is shown using the final equipment fully appendaged in the pitch configuration.

FINAL EXPERIMENT

Now that the required accuracy of the experiment was known a system could be developed to ensure that all parameters could be controlled as precisely as possible.

Suspension and Balancing

Since it was very important that the CG of the model be controllable with better than 1-mm precision it was decided to utilize the Harken® traveler system in order to allow the cable suspension point to be finely adjusted and to increase the rigidity of the system ***(Figure 11)***. This system also ensures that the model will be held at the angle desired. The tracks were etched with a set of 1mm incremented lines in order to provide a gauge for the movement of the travelers ***(Figure 10)***. Also necessary in the case of the final model was the inclusion of a pair of set screws to ensure that the traveler could be clamped into position. In the case of the submarine model it was necessary for the tracks to extend, on occasion, past the end of the mid-body. This made it necessary to produce a pair of steel support bars capable of supporting the weight of the model over an overhang of 15-cm ***(Figure 12)***. Once this was done the CG could be supported uniformly for any configuration, wet or dry, with a very high degree of accuracy.

Figure 12: This shows the steel support bar and one of the smaller overhangs it was required to support.

The Excel spreadsheet was also used in order to ensure that the model was centered on the load cells. When supporting the dry model the load cells could resolve down to 1.5 N while in the flooded condition that resolution fell to 3 N to 3.5 N; this is considered to be the range of five sets of data taken without altering the model.

Swinging

The only alteration to the original swinging method was that the guides which are used to indicate when the model has been pulled back to the starting position were tilted out of the way following the release. This allows for the model to shift modes while swinging and not corrupt the acquired data by striking the guide.

RESULTS

Bifillar Experimental Results

Configuration:			Mass:	CG:	Rad Gy	Trollies	Frd Bar	Aft Bar	Inertia:	
Dry:			[kg]	[m]	[m]	[kgm^2]	[kgm^2]	[kgm^2]	[kgm^2]	Adjusted
	Pitch									
		Bare Hull:	400.36	1.933	0.797	0.372	2.223	1.945	254.11	249.57
		Hull & Sail:	416.05	1.927	0.790	0.372	2.195	1.971	259.48	254.94
		Hull, Sail & Fins	421.80	1.962	0.816	0.372	2.362	1.819	280.86	276.31
		Hull & Fins:	406.42	1.971	0.820	0.372	2.406	1.781	273.30	268.75
	Yaw									
		Bare Hull:	400.75	1.933	0.785	0.372	2.223	1.945	247.23	242.69
		Hull & Sail:	416.57	1.927	0.774	0.372	2.195	1.971	249.50	244.97
		Hull, Sail & Fins	421.57	1.962	0.802	0.372	2.362	1.819	271.10	266.55
		Hull & Fins:	406.20	1.971	0.810	0.372	2.406	1.781	266.56	262.01
	Roll									
		Bare Hull:	400.75		0.134				7.18	
		Hull & Sail:	416.57		0.147				9.02	
		Hull, Sail & Fins	421.57		0.147				9.13	
		Hull & Fins:	406.20		0.134				7.30	
Wet:										
	Pitch									
		Bare Hull:	871.27	2.005	0.820	0.340	2.576	1.640	585.54	580.99
		Hull & Sail:	882.39	1.995	0.818	0.340	2.525	1.681	590.47	585.93
		Hull, Sail & Fins	888.85	2.012	0.833	0.340	2.611	1.612	616.35	611.79
		Hull & Fins:	873.89	2.017	0.835	0.340	2.637	1.592	609.40	604.83
	Yaw									
		Bare Hull:	874.49	2.005	0.816	0.340	2.576	1.640	582.15	577.59
		Hull & Sail:	889.09	1.995	0.811	0.340	2.525	1.681	584.36	579.81
		Hull, Sail & Fins	895.47	2.012	0.824	0.340	2.611		608.19	603.62
		Hull & Fins:	880.57	2.017	0.829	0.340	2.637	1.592	604.70	600.13
	Roll									
		Bare Hull:	874.49		0.094				7.70	
		Hull & Sail:	889.09		0.104				9.57	
		Hull, Sail & Fins	895.47		0.103				9.56	
		Hull & Fins:	880.57		0.094				7.84	

The results above show a remarkable uniformity. By looking at the changes in moment of inertia for the various configurations there is a definite uniformity of change.

Taking the 'dry' pitch configuration as an example: adding the sail to the bare-hull caused a change of moment of inertia of 5.36 kgm^2. Comparing this to the effect of removing this mass from the fully appendaged condition shows that that changed the moment of inertia by 7.56 kgm^2. This suggests that the experiment can resolve down to approximately 2 kgm^2, which is what can be expected from the measurements taken. The fins also showed changes in the inertia of 19.31 kgm^2 when added and 21.58 kgm^2 when removed, further demonstrating the resolution of the experiment. The 2 kgm^2 deviation is also present in the results for the flooded condition.

The differences found between pitch and yaw configurations is also consistent with the effects of having the eccentric masses of the electronic equipment in the submarine model; since the model is designed to be symmetrical only in port-starboard orientation. This effect had a slightly larger variability, possibly dependent on the amount of mass concentrated at a distance from the CG; the range of this effect was between seven and 10 kgm^2. In the flooded condition this range decreased to between three and six kgm^2. This is due to the effect of the greatly increased mass and the damping effect of the water.

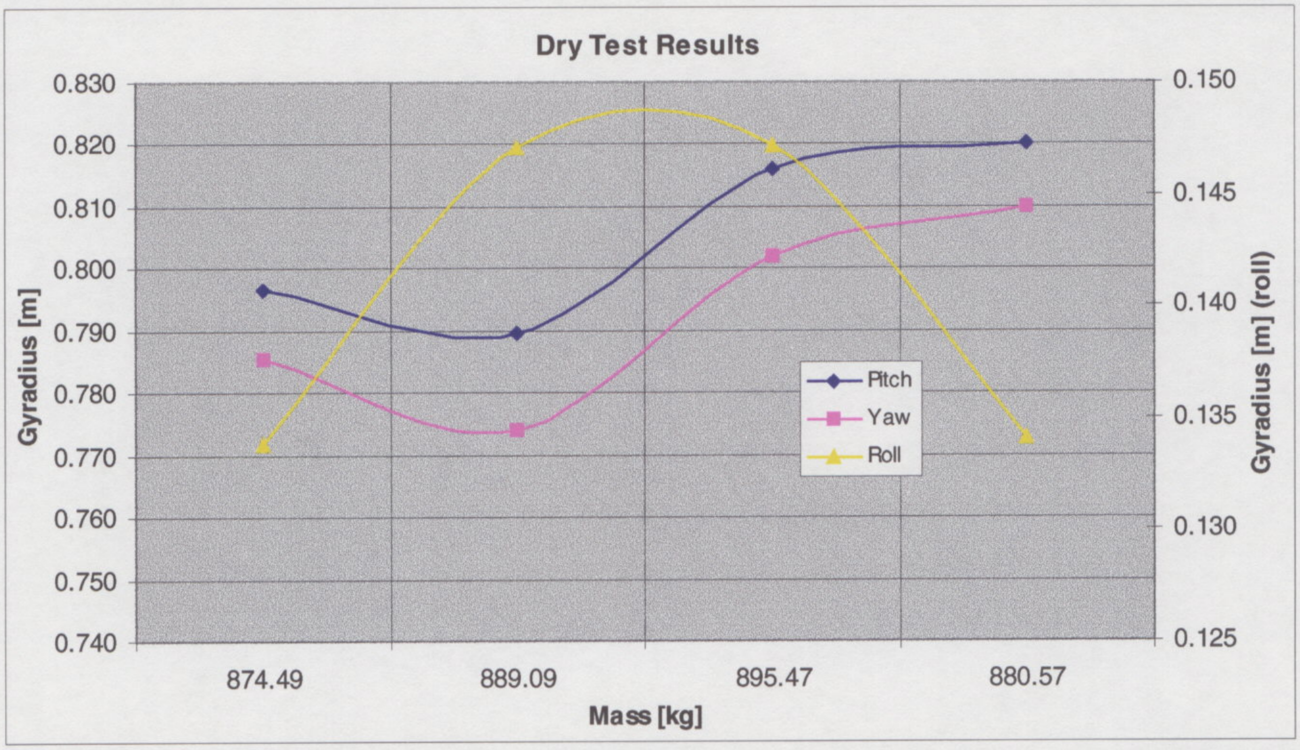


Chart 2: This shows the regular increases of the gyradius due to the inclusion of each of the appendages in the dry condition.

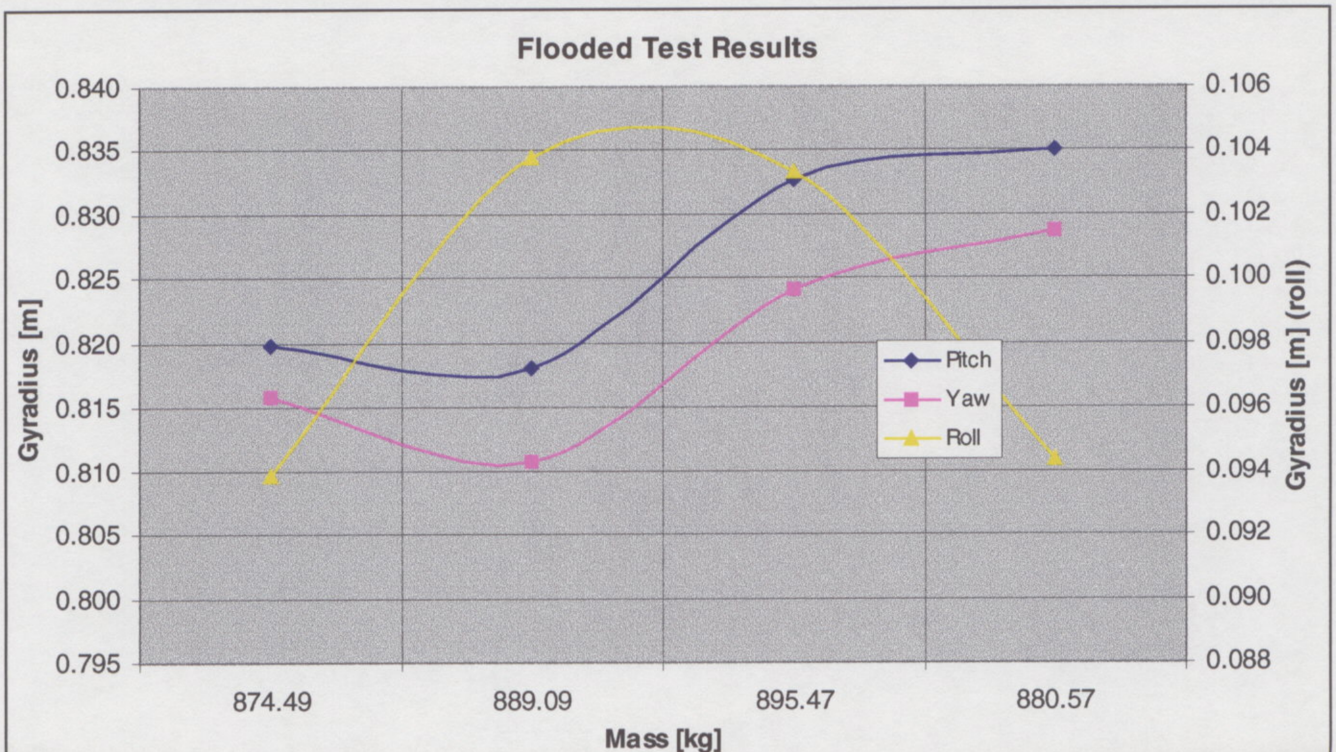


Chart 3: This shows the uniform increases in the gyradius due to the addition of the appendages in the flooded condition. Note the smaller offset due to the increased mass of the submarine body.

CONCLUSION

Mathematical Predictions

Bare Hull

	Roll	Pitch	Yaw	
K	0.13	0.79	0.79	m
Inertia	7.06	251.8	247.0	kgm^2

Hull & Sail

	Roll	Pitch	Yaw	
K	0.15	0.79	0.77	m
Inertia	9.79	259.33	250.33	kgm^2

Hull, Sail & Fins

	Roll	Pitch	Yaw	
K	0.15	0.82	0.81	m
Inertia	9.82	283.48	274.48	kgm^2

Hull & Fins

	Roll	Pitch	Yaw	
K	0.13	0.82	0.82	m
Inertia	7.09	275.54	270.78	kgm^2

These show the mathematically predicted effects of adding the appendages to each of the three conditions. Comparing these to the measured result shows that the trend of each condition is what would be expected from a model under these conditions. The magnitudes of the changes are within the range of results acquired from the experiment. There is a small offset in the actual values attained, however due to the small magnitude of these offsets, they can be explained by the accuracy of the experiment combined with the effects of uncontrolled variables such as leftover water in the model or air currents in the room.

In general the experiment has proved to accurately measure the radius of gyration and moment of inertia of a submarine model, provided that all variables are controlled or known to the accuracy discussed in this document.

RECOMMENDATIONS

These are some suggestions for improvements to the equipment and method, which could help to increase the accuracy and repeatability of the experiment.

- A mechanism could be designed to allow for a one-person release system. A single operator could pull back each side of the model to the desired position and attach it to the release mechanism so that when a button is pushed, both sides are released simultaneously.
- More accurate load cells and accelerometer would allow for better precision of the measurements. Having the accelerometer calibrated to a resolution that is not so close to the limit of its accuracy would also allow it to perform more accurately.
- A better method of filling and waterproofing the model would be a worthwhile step. The present condition of the model demands that it constantly have water flowing into it. This could be causing currents inside the model which may have unknown effects on the results.
- If this type of testing is going to be applied to many more models that have not yet been produced then the use of angle or channel beams would perhaps be more appropriate than the box beams that are presently in this model. The box beams hold water and/or air and make it difficult to get repeatable readings after refilling the

model. At the least the box beam could have a series of drainage holes drilled into it to allow trapped air or water to escape.

- A data acquisition software package that would allow for the data to have simple averaging functions performed on it in real-time would greatly simplify the balancing procedure.
- For the flooded case it would be useful to have some kind of longitudinal-position adjustment screw on the traveler block, since the submarine is so heavy in this configuration, and the traveler can be difficult to move precisely.

APPENDIX A: EQUIPMENT LIST

Suspension Equipment

Push Trolleys: (1000 lbs. rated load) ____________________ x 2

$^5/_8$" galvanized shackles ____________________ x 2

¾" galvanized shackles ____________________ x 2

$^3/_{16}$" stainless steel cable (length 5.5 m) ____________________ x 2

horizontal configurations

(length 4.0 m) ____________________ x 2

roll configurations

1000 lbs. load cell ____________________ x 2

¼" galvanized shackles ____________________ x 6

Harken® Genoa traveler cars (part no. 5011) ____________________ x 2

12" medium weight Harken® track ____________________ x 2

steel support blocks ____________________ x 2

(construction drawings in Appendix C)

¼" x 20UNC flat head screws ____________________ x 6

$^3/_8$" x 16UNC flat head screws ____________________ x 6

Instrumentation Equipment

1000 lbs. load cell______________________________x 2

digital accelerometer (Sunstrand 1400, 0.025 g resolution)________x 1

DAQU unit______________________________x 1

Software:

DaquView 5.0

Microsoft Excel '97

Network connection for access to GEDAP G-PLOT software

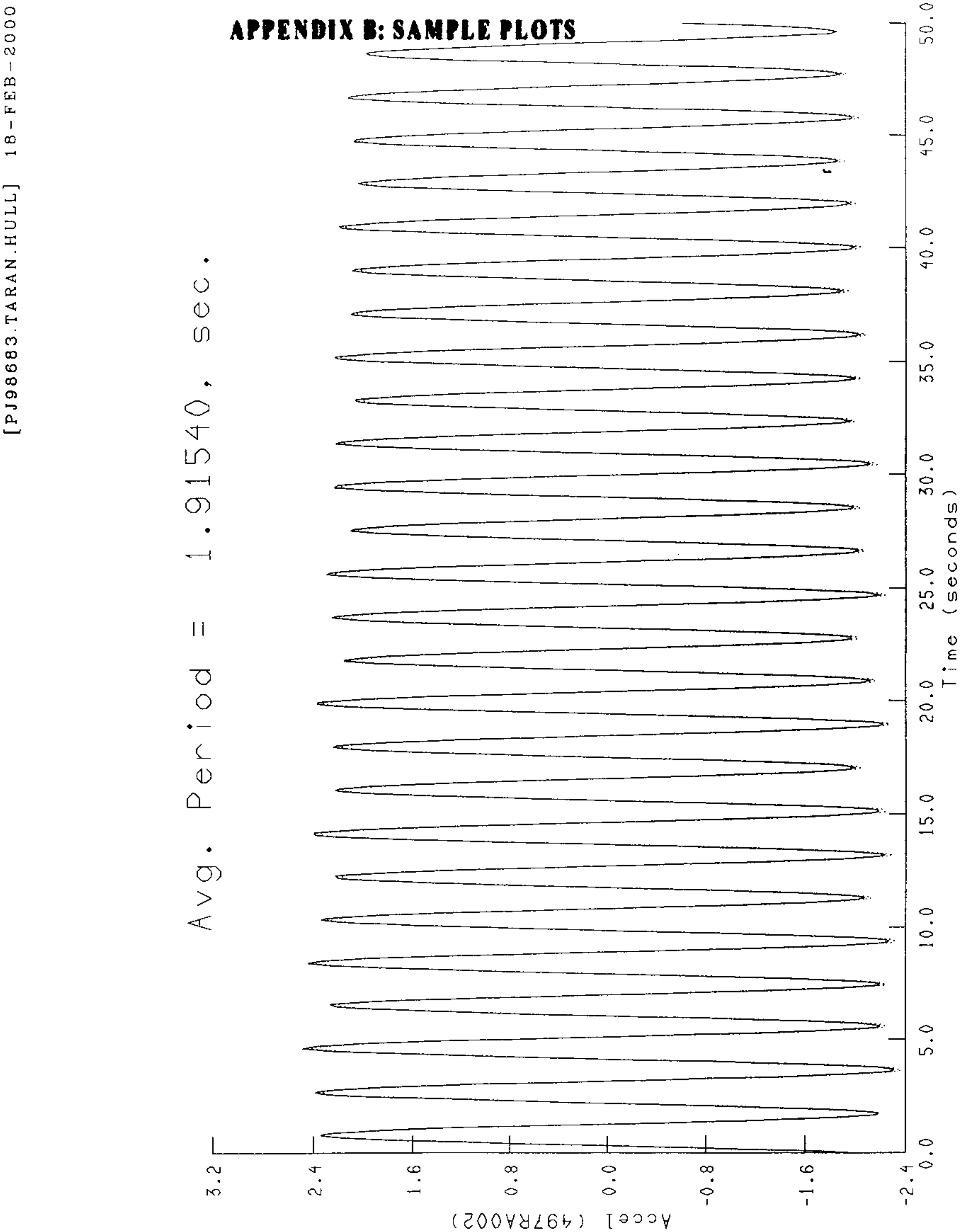
Waterproofing Equipment

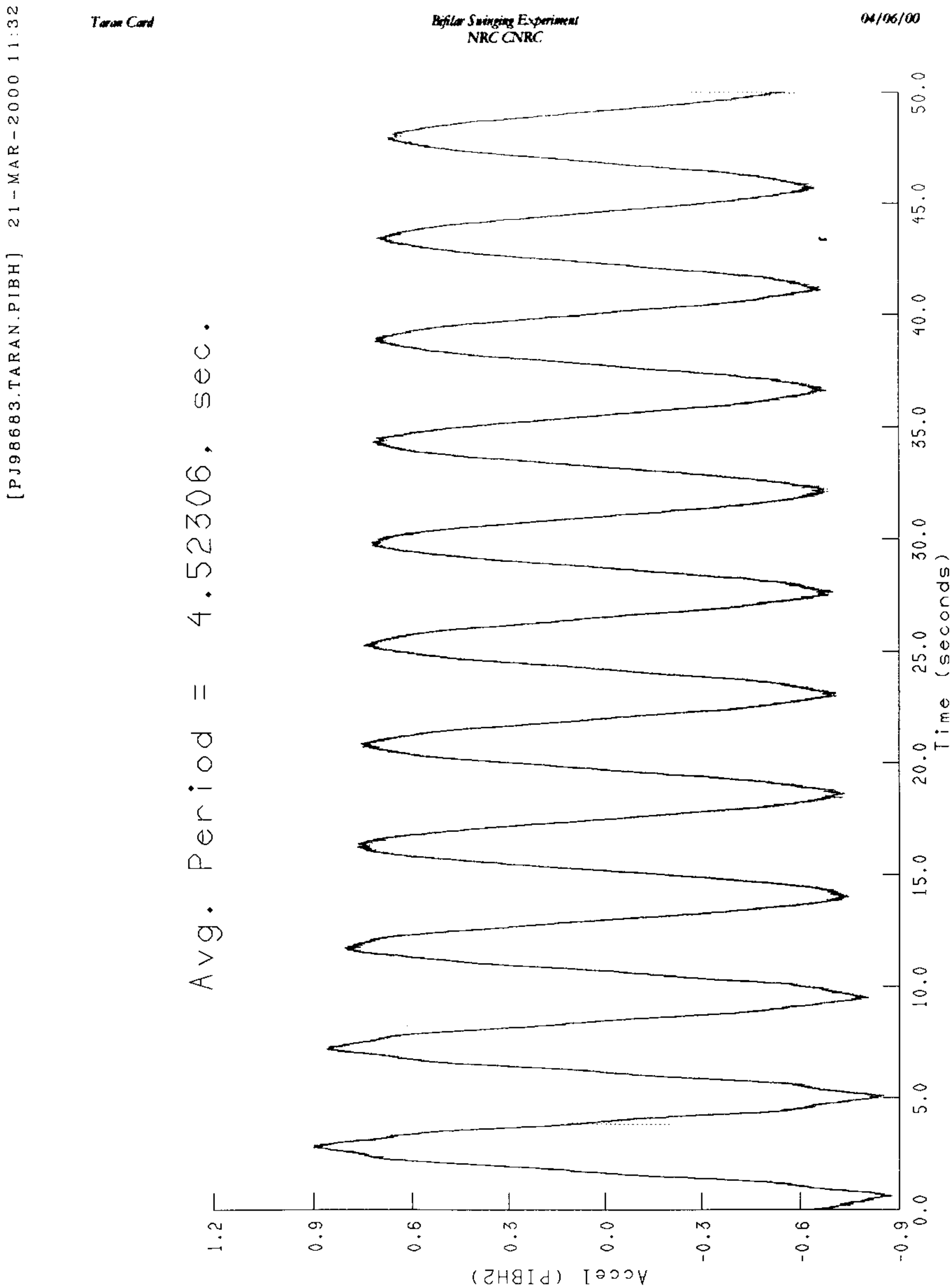
3M Latex Tape______________________________x 3

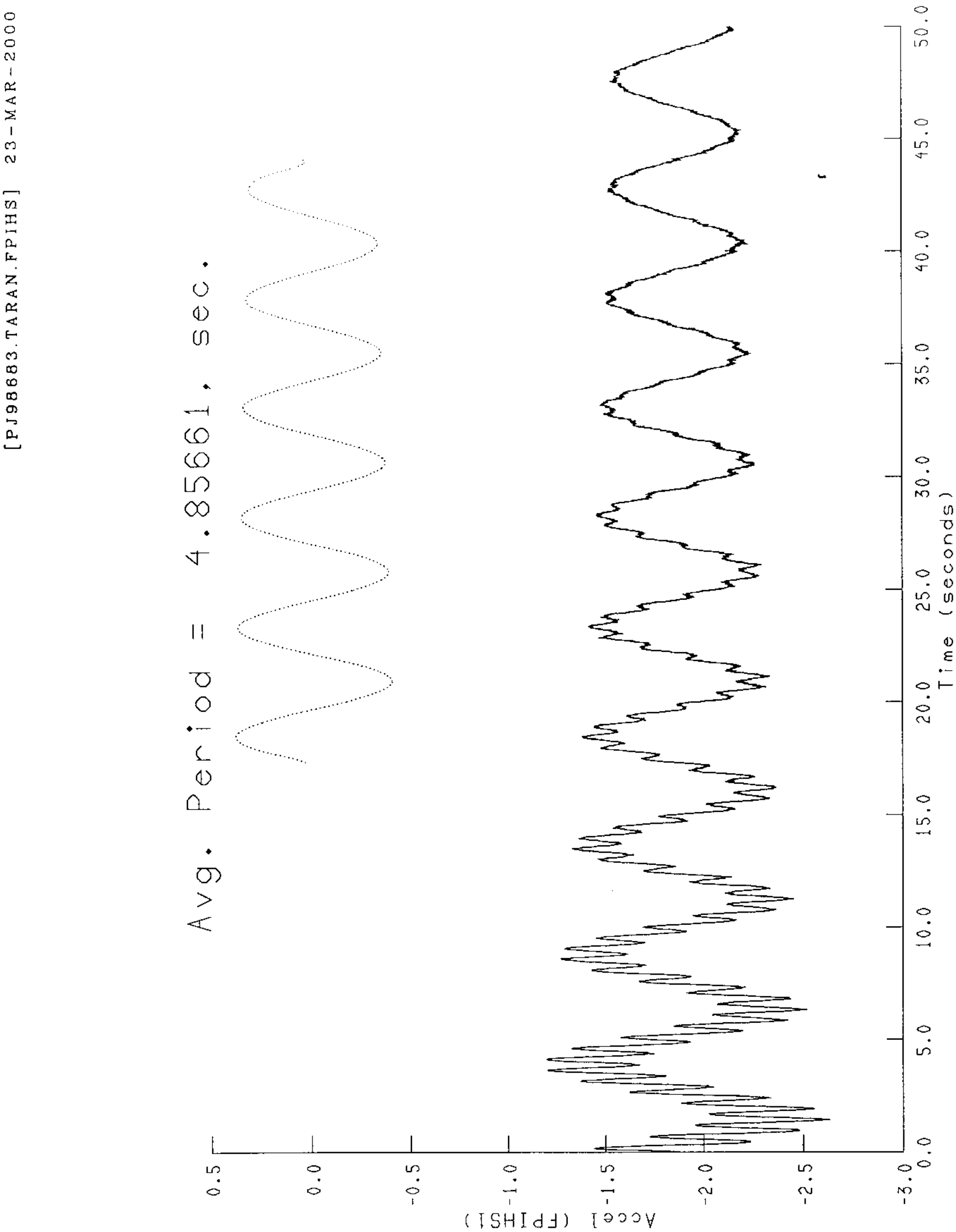
Assorted taps and bolts for plugging holes in the model

Sealant putty and/or clear silicon

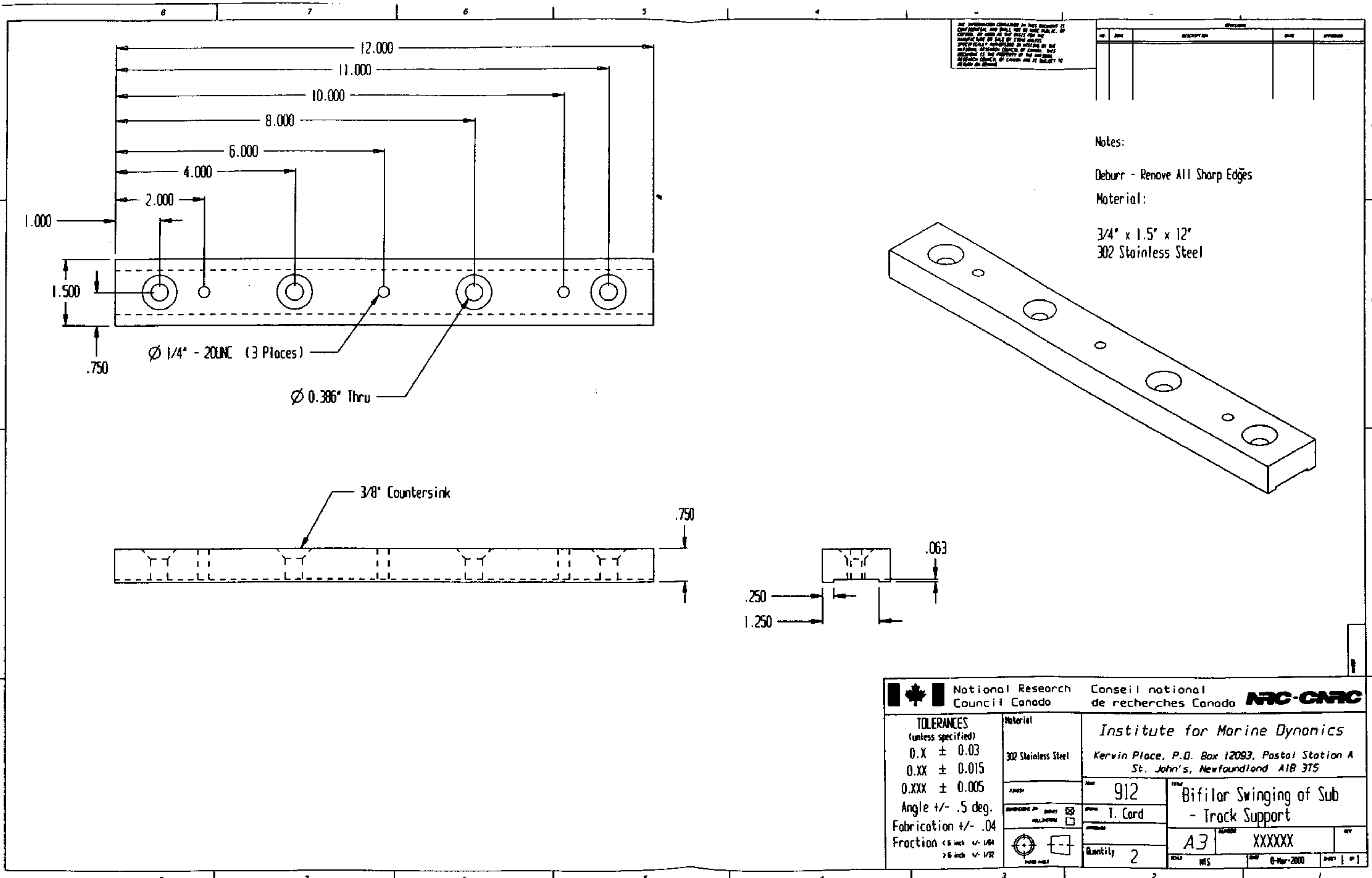
APPENDIX B: SAMPLE PLOTS




[PJ98683.TARAN.PIBH] 21-MAR-2000 11:32
Avg. Period = 4.52306, sec.
Time (seconds)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
Accel (PIBH2)
1.2
0.9
0.6
0.3
0.0
-0.3
-0.6
-0.9


[PJ98683.TARAN.FPIHS] 23-MAR-2000 13:45
Avg. Period = 4.85661 sec.
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
Time (seconds)
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
Accel (FPIHSI)

APPENDIX C: CONSTRUCTION DRAWINGS


12.000
11.000
10.000
8.000
6.000
4.000
2.000
1.000
1.500
.750
Ø 1/4" - 20UNC (3 Places)
Ø 0.386" Thru
3/8" Countersink
.750
.063
.250
1.250
Notes:
Deburr - Remove All Sharp Edges
Material:
3/4" x 1.5" x 12"
302 Stainless Steel
National Research Council Canada
Conseil national de recherches Canada
NRC-CNRC
TOLERANCES
(unless specified)
0.X ± 0.03
0.XX ± 0.015
0.XXX ± 0.005
Angle +/- .5 deg.
Fabrication +/- .04
Fraction <6 inch +/- 1/64
>6 inch +/- 1/32
Material
302 Stainless Steel
Institute for Marine Dynamics
Kerwin Place, P.O. Box 12093, Postal Station A
St. John's, Newfoundland A1B 3T5
912
T. Cord
Quantity 2
Bifilar Swinging of Sub
- Track Support
A3
XXXXXX
NTS
8-Mar-2000
1 of 1