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Laboratory Memorandum

LM-2003-15

A Finite Element Model for Predicting Submarine Model-Sting Clearance

J. Bell, B. Rawlings, C. Williams

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A Finite Element Model For Predicting Submarine Model-Sting Clearance

AUTHOR(S)

J. Bell, B. Rawlings, C. Williams

CORPORATE AUTHOR(S)/PERFORMING AGENCY(S)

National Research Council, Institute for Marine Dynamics, St. John’s, NL

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SUMMARY

This report describes a finite element model for predicting the deflection under load for the aft end of a submarine model sting mounted on a six-component balance. This report also describes the deflection versus load measurements that were made to determine if the tail section of the submarine model was making contact with the sting during model testing. The results of the physical tests are compared to the predictions of the finite model.

ADDRESS

National Research Council
Institute for Marine Dynamics
P. O. Box 12093, Station 'A'
St. John's, Newfoundland, Canada
A1B 3T5
Tel.: (709) 772-5185, Fax: (709) 772-2462

A FINITE ELEMENT MODEL FOR PREDICTING SUBMARINE MODEL-STING CLEARANCE

LM-2003-15

John Bell, Bill Rawlings,
Christopher Williams

April 2003

1.0 INTRODUCTION

Underwater video taken during the testing of the Albert submarine model raised the concern that the model tail section was making contact with the sting during testing. This could result in clipped data because the contact would ground the force measurement balance and higher forces would not be recorded.

This report describes an experiment that measured the deflection of the aft end of the Albert submarine model with respect to the sting under loading conditions expected during testing.

This report also describes the finite element model that was developed for predicting these same deflections.

The results of the experiment are compared with the results obtained from the finite element model prediction.

This report assumes that the reader is familiar with the IMD facilities, 20-inch submarine, six component, balance and the Albert submarine model and sting. A detailed layout of the test setup is saved in:

Cad_User\Projects\42_945_10_Victoria \Jbell\Cadkey\Albert\Albert_Model_GA.ckd.

2.0 TEST OBJECTIVE

The objective of this experiment was to find out if the Albert submarine model deflected enough during testing that the model tail section would make contact with the sting and thus clip the load measurements from the 20-inch balance.

A second objective was to measure the load versus deflection relationship at the tail – sting interface. This information would then be used to verify the predictions from a finite element model of the test setup. Once the finite element model was verified it could be used to predict the minimum clearance necessary for future tests.

3.0 TEST SETUP

The Albert model, balance and sting were taken to the Model Prep Shop and mounted so that the defections under load would approximate conditions in the Clearwater towing tank.

To do this the sting, with the Albert submarine model and balance attached, was mounted horizontally on two steel frames in the Model Prep Shop area.
The frames were spaced 2.0m apart and supported the sting in the same locations as the struts of the Marine Dynamic Test Facility.

The clamping arrangement, which held the sting to two welded frames, was done with long slender rods. The rods allowed the sting to bend over the supports and thus the beam was simply supported. See Figure 1.

For loading in the model Y-axis a load frame was anchored to the concrete floor at approximately right angles to the leading edge of the aft fairwater fins of the model. A strap was passed around the tail of the model ahead of the fairwaters (center line at 15mm) and then attached to a wire, which ran out to the load frame over a pulley and down to the load pan (5.5 kgs). Calibrated lead weights were placed in the pan to apply load. See Figures 1 & 4.

For vertical down loading the strap around the tail section was allowed to hang down and attached directly to the weight pan. Calibrated lead weights were placed in the pan to apply load. See Figure 2.

For vertical up loading the strap around the tail was attached to an Intercomp CS3000 crane scale. The crane scale was suspended from a manually operated hydraulic hoist. Raising and lowering the hoist applied the loads. See Figure 3.

A plunge style dial indicator was mounted on a bar attached to the sting just aft of the model. The indicator shaft touched the highest point on the surface of the starboard fairwater, thus it measured the vertical deflection of the tail section 120 mm ahead of the aft end of the tail section. The indicator measured the movement, in .001-inch steps, of the model tail with respect to the sting. The indicator was adjusted to read horizontally or vertically as required. See Figure 4.

Figure 1. Side Pull Set Up

Figure 2. Vertical Down Loading

Figure 3. Vertical Up Loading

Figure 4. Dial Gauge Set Up for Side Pull

4.0 MODEL STING

The original model sting was modified for this experiment. The sting was cut in two pieces ahead of the forward strut position. An adjustable locking coupling, Ringfeder 306-IN 5-15/16, was fitted to the two halves of the sting and allowed for assembly of the model without having to split the model tail section into two pieces. The coupling also allowed for indexing and adjustment of the model in roll without disassembling the tail section in situ under the tow carriage. Details of the coupling assembly are contained in an efile with the address:

Cad_User\Projects\42_945_10_Victoria\Wardle\Cadkey\Albert\ Sting Modification.prt. Deflection of the sting due to the coupling was not measured.

5.0 20 INCH SUBMARINE BALANCE ASSEMBLY

The upper and lower box beams of the 20-inch submarine balance were reworked in September, October of 2002 for this project. The load cell pads for the 20-inch submarine balance were removed, new steel welded in and the pads were re-machined on the Titan boring mill. The load cells were then installed along with new flexible links and the location and alignment of each combination was adjusted to within +/- .005 inches at either end of each flexible link. Minor adjustments were then made to the length of each flexible link – load cell combination to achieve a +/- .005 inch alignment between the sting flange and the model mounting tube flanges. The model mounting flanges were originally machined with .003-inch radial clearance fit to the inside of the model tube to allow for assembly. Thus the overall error in pitch or yaw orientation of the model due to the balance assembly was +/- .012 degrees.

The flange that connects the balance to the sting was also checked and found to be within +/-.002 inches over a 12-inch diameter. Thus the error for the sting to flange connection was +/- .01 degrees in pitch and yaw.

6.0 LOAD CELL DESCRIPTION

The forward vertical and the aft side force load cells were Sensotec Model 31 10,000 lbs capacity button style miniature load cells.

The two aft vertical and single forward side force load cells were Sensotec Model 31 5,000 lbs capacity load cells.

The drag load cell was a Sensotec Model 31 500 lbs capacity load cell.

7.0 BALANCE "AS BUILT" DRAWING

An efile drawing of the as assembled balance with load cells and flexible links was done and stored on Cad_User\Common\As Built Drawings\20 inch sub balance\Albert_Dyno_as_built.prt. See Figure 5.

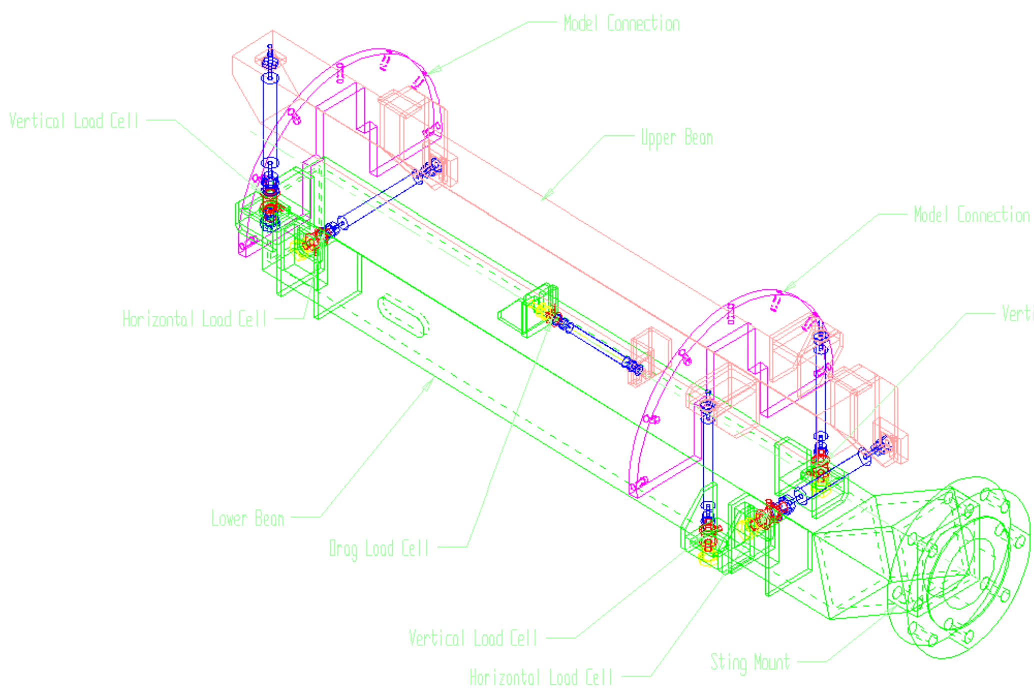


Figure 5. 20" Submarine Balance General Arrangement

8.0 TEST WEIGHTS

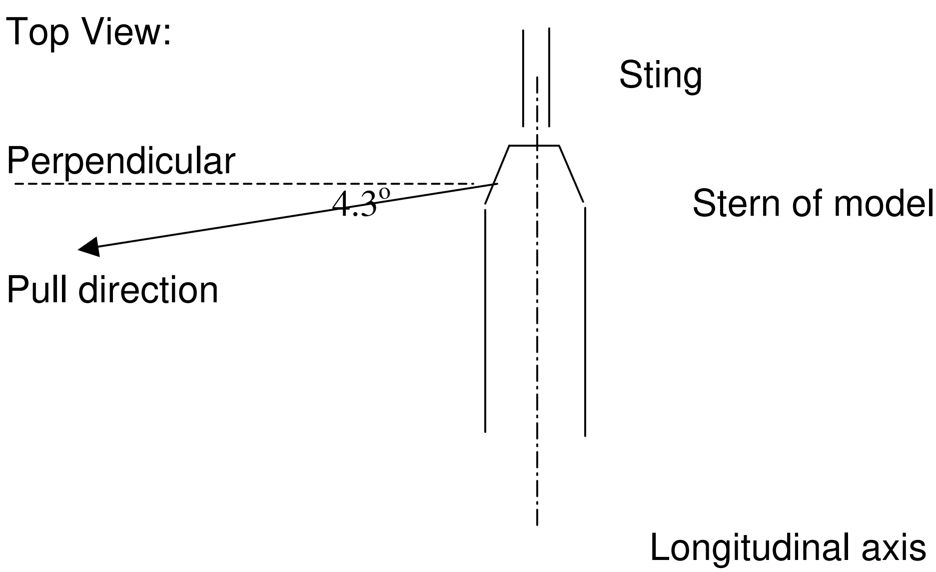
All weights were weighed in kilograms to one decimal place, and therefore are plus or minus 0.05 kg. Therefore, for example, for a total mass of 248.2 kg, the error in this is +/- 0.05 kg for the weight pan, +/- 0.05 kg for the shackle, and +/- 0.05 kg for each of the added weights (13 added weights were used to get up to 248.2 kg). This leads to an error of approximately (13 + 2)*.05 kg = 0.75 kg. Therefore, the actual weight is 248.2 kg +/- 0.75 kg. These errors are only for the starboard and downward pulls, which involved the use of a weight pan. For the vertical upward pulls, the resolution of the electronic hook scale was +/- 0.5 kg.

All alignment of the dial gauges and pulls was done by eye.

9.0 SIDE FORCE PULL RESULTS MARCH 13TH 2003

A series of weights were placed on the weight pan in ascending order and then removed in descending order. The displacement of the model with respect to the sting was read off of the dial gauge. The dial was placed such that it read the displacement of the outer edge of the starboard rear fairwater. See Figure 4. The displacement values and loads were then plotted. See Figure 6. The data is included in appendix A.

Note; The side force pulls were not performed exactly perpendicular to the longitudinal axis to the sub, but instead at approximately 4.3 degrees forward of the perpendicular:



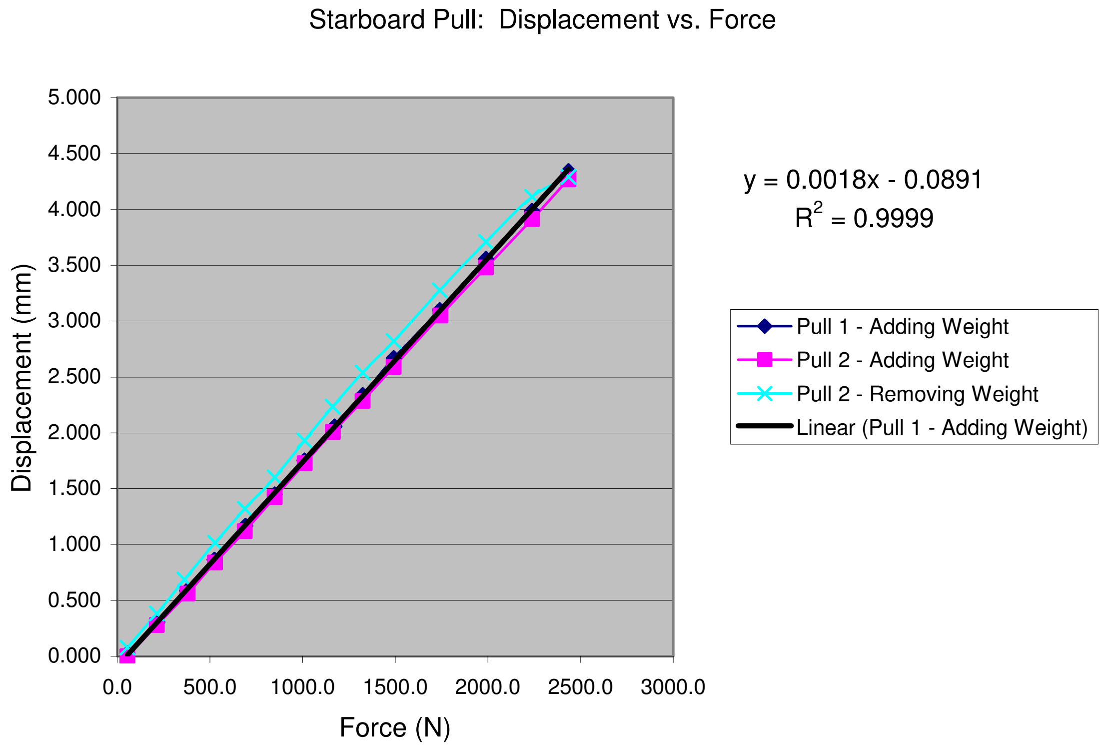


Figure 6. Side Pull Results

10.0 VERTICAL DOWNWARD PULL RESULTS MARCH 17TH 2003

The vertical downward pull was conducted by hanging a weight pan (5.5 kg) off of a strap (0.3 kg) using a shackle (0.2 kg). See Figure 2.

The displacement values and loads were then plotted. See Figure 7. The data is included in appendix A.

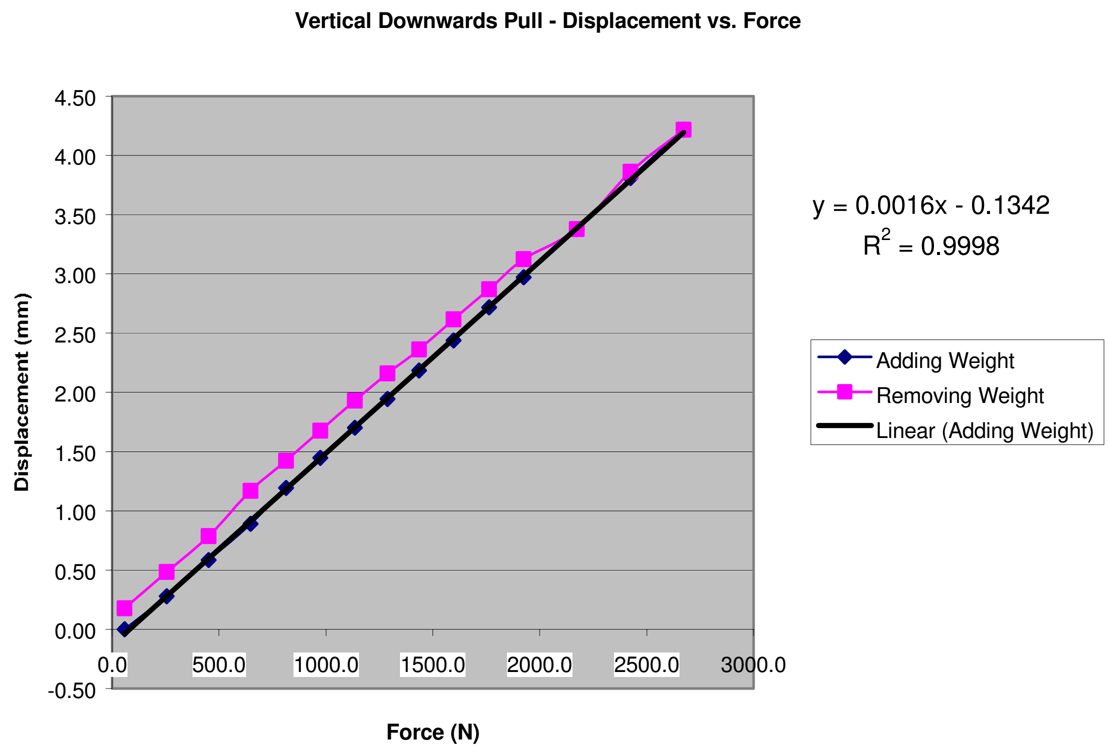


Figure 7. Vertical Down Results

11.0 VERTICAL UP PULL RESULTS MARCH 14TH 2003

The small step in the graph at approximately 2200 N or so is likely due to play in the threads on the flex links as the pull strap takes the weight of the model itself.

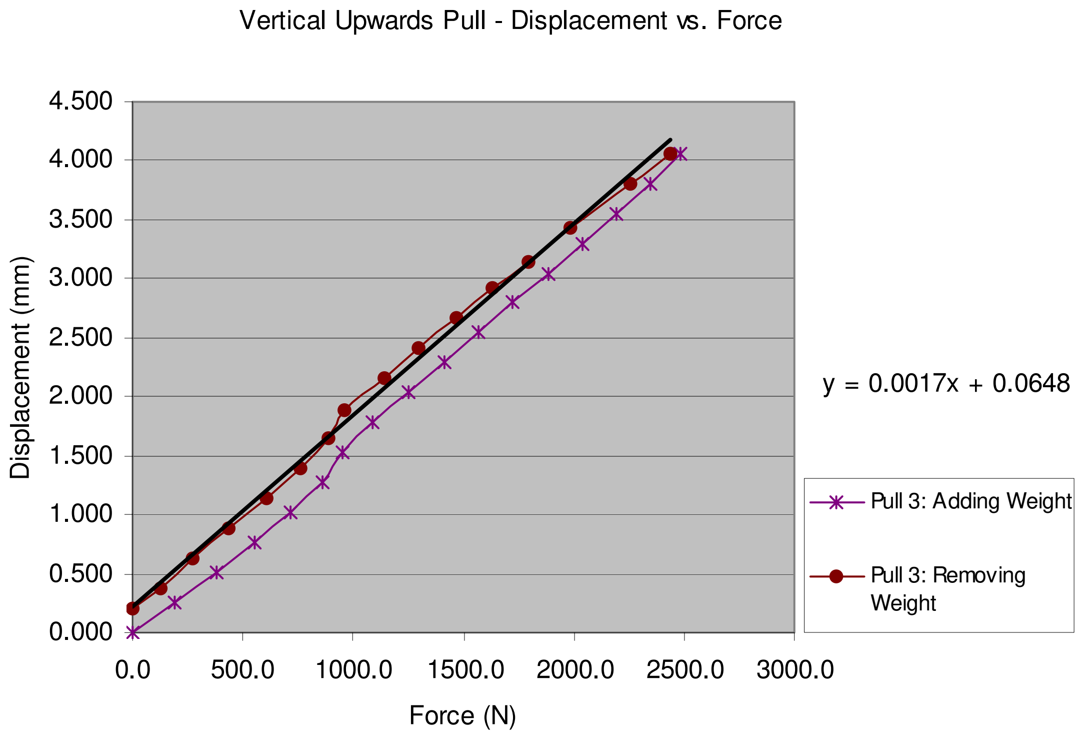


Figure 8. Vertical Up Pull Results

12.0 FINITE ELEMENT MODEL FOR THE 20-INCH SUBMARINE BALANCE, MODEL AND STING

The Victoria Class model was the largest and heaviest model to be tested on the Marine Dynamic Test Facility. Along with the large size was also the intention to test the model at 4 m/sec, which was faster than the 3 m/sec that had been done up to that point in time.

Knowledge of these two facts, during design, resulted in an increase in the clearance allowed around the sting where it passes through the tail configuration of the model. This extra clearance required that some of the trailing edge of the rudders be removed thus reducing lifting surface area.

The above pull tests provided the data needed to confirm a reverse engineered finite element (FE) model of the balance-model-sting system. It is hoped that designers, in the future, can reduce the tail-sting clearance to a minimum using this FE model.

13.0 BEAM ELEMENT MODEL

The engineering requirement was for accurate prediction of displacement. The major components of the sting and balance were long slender pipes and rods. These characteristics suited this problem to a beam finite element model solution.

The Cadkey solid model of the balance, model and sting was used as a template to create the centerlines of all of the major components.

The centerline of the model tube was offset 1-inch to starboard so that the sting elements and model tube and tail elements would not lie one on top of the other. Centerlines on top of one another cause geometry errors that stall the Algor FE processor. The short moment arm created by this approximation did not contribute significant error to the starboard pull because everything was in line. This moment arm did contribute a small amount to the vertical pull error for the FE model however the predicted force in the vertical was only half of the force for the starboard pull and therefore it did not result in a significant error.

The centerlines in Cadkey were grouped according to mechanical and physical properties and each group was given a different colour. The centerlines were then imported as a cad wire frame into Superdraw, Algor's preprocessor.

Superdraw imports the cad wire frame all in one group and sorts the different Cadkey colours into separate layers. Element properties are assigned in Superdraw by group number, therefore the different elements are then updated to different groups using the layer number as a selection filter.

The length of each element with regard to the average length of all elements in the model must be in balance to obtain accurate results. Thus after the group updating is done an element divide is done to keep the element lengths all approximately equal and to insure a smooth progression of element length from long to short and back to long if necessary.

The element type is then assigned to each group. In this FE model all of the elements are beam type elements therefore all groups were identified as beam.

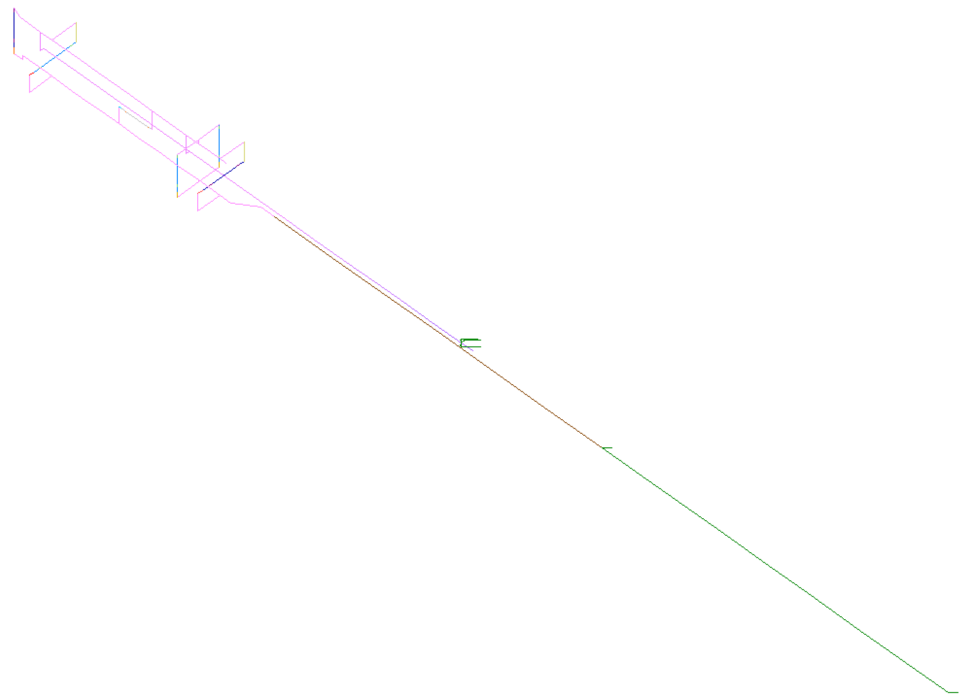


Figure 9. Finite Beam Element Model

14.0 BEAM PROPERTIES

The preprocessor file is stored under Cad_User \ Projects \ 42_945_10_Victoria \ Jbell \ Algor \ Albert Clearance Check Pulls \ Horz Pull Test \ dy1.esd . The following description includes group numbers, element properties and material properties which refers to the Model Data section of Superdraw with the above file opened.

Each group represented a beam with either separate mechanical properties or beams made of a different material. The following description of each group includes the commercial description of the material, section and the section properties as they are entered into the Model Data table in the preprocessor. Where the properties are symmetrical the I2 and I3 values will be equal and only the I2 value is quoted here.

The load cells were modeled using a round rod having the same length and spring constant in compression/tension. The Sensotec Model 31 load cells were quoted by the manufacturer as having a deflection under full load of .003 to .004 inches in the 500lbs to 10,000 lbs capacity range. To arrive at a spring constant the load cell capacity was divided by .0035. This number was then equated to the stiffness of a rod (AE/L) to arrive at the area required for a steel rod of the same stiffness. The equivalent diameter is quoted below for each load cell.

The experimental loading was applied to the end of the tapered tail section of the model. The varying properties of the tail were modeled in the FE by dividing the tail into

6 equal length sections. The properties were then estimated for each section based on the outside and inside diameters at the individual section mid point. See the properties for sections 19 through 24.

Group 1 Aft Sting 7" OD x 6" ID DOM A-513 T5 Steel Pipe.

A	10.2
J	108.5
I2	54.2
Z2	15.5
Sa	5.1

Group 2 0.239 dia. 4140 Steel Rod Forward Side Force Load Cell

A	.0448
J	3.2 e-4
I2	1.6 e-4
Z2	.00134
Sa	.0404

Group 3 0.282 dia. 4140 Steel Rod 2 Aft Vertical Load Cells

A	.0625
J	6.21 e-4
I2	3.1 e-4
Z2	.0022
Sa	.0562

Group 4 0.0562 dia. 4140 Steel Rod Drag Load Cell

A	.00248
J	9.8 e-7
I2	4.9 e-7
Z2	1.74 e-5
Sa	.00223

Group 5 Frwd Sting 6" OD x 5" ID DOM A-513 T5 Steel Pipe

A	8.64
J	65.86
I2	32.94
Z2	11
Sa	4.32

Group 6 Not Used

Group 7 0.09 dia. 4140 Steel Rod Drag Flexible Link Small Section

A	.0064
J	6.44 e-6

	I2	3.22 e-6
	Z2	7.16 e-5
	Sa	.0057
Group 8	0.75 dia. 4140 Steel Rod Drag Link Body	
	A	.442
	J	.031
	I2	.0155
	Z2	.0414
	Sa	.4
Group 9	0.32 dia. 4140 Steel Rod 10,000 lbs Link Small Section	
	A	.0804
	J	.001
	I2	.0005
	Z2	.0032
	Sa	.072
Group 10	1.25 dia. 4140 Steel Rod 10,000 lbs Link Body	
	A	1.23
	J	.24
	I2	.12
	Z2	.19
	Sa	1.1
Group 11	1.0 dia. 4140 Steel Rod 5,000 lbs Link Body	
	A	.7854
	J	.098
	I2	.0491
	Z2	.098
	Sa	.707
Group 12	.225 dia. 4140 Steel Rod 5,000 lbs Link Small Section	
	A	.04
	J	.00025
	I2	.00013
	Z2	.0011
	Sa	.036

Group 13	¾ x 3 A36 Steel Flat Bar Side Force Bracket	
	A	2.25
	J	.357
	I2	.1055
	I3	1.6875
	Z2	.281
	Z3	1.125
	Sa	1.875
Group 14	.365 dia. 4140 Steel Rod Frwd Vertical Load Cell 10,000	
	A	.1048
	J	.00175
	I2	.00087
	Z2	.0048
	Sa	.094
Group 15	.423 dia. 4140 Steel Rod Aft Side Load Cell 10,000	
	A	.14
	J	.0031
	I2	.0016
	Z2	.0074
	Sa	.126
Group 16	6 x 6 x .5 Wall CSA G40.21 50W H.S.S.	
	A	11
	J	83.2
	I2	55.9
	Z2	18.64
	Sa	6
Group 17	4 x 4 x .25 Wall CSA G40.21 50W H.S.S.	
	A	3.75
	J	13.2
	I2	8.83
	Z2	4.41
	Sa	2
Group 18	20” OD x 19.25 ID 713 Cast Aluminum Tube	
	A	23.12
	J	2227
	I2	1113
	Z2	111.3
	Sa	11.56

Group 19	20 x 19.7 Fiberglass Tube YM=1,000,000 PR=.3	
	A	9.354
	J	921.5
	I2	461
	Z2	46.1
	Sa	4.68
Group 20	19.8 x 19.5 Fiberglass Tube YM=1,000,000 PR=.3	
	A	9.26
	J	894
	I2	447
	Z2	45.1
	Sa	4.63
Group 21	18.4 x 18.1 Fiberglass Tube YM=1,000,000 PR=.3	
	A	8.6
	J	716
	I2	358
	Z2	38.9
	Sa	4.3
Group 22	17.16 x 16.86 Fiberglass Tube YM=1,000,000 PR=.3	
	A	8.02
	J	580
	I2	290
	Z2	33.8
	Sa	4
Group 23	14.06 x 13.76 Fiberglass Tube YM=1,000,000 PR=.3	
	A	6.55
	J	317
	I2	159
	Z2	22.6
	Sa	3.3

Group 24	9.6 x 9.3 Fiberglass Tube YM=1,000,000 PR=.3	
	A	4.45
	J	99.4
	I2	49.7
	Z2	10.4
	Sa	2.2

15.0 BOUNDARY CONDITIONS

The boundary condition locations were set by the pin locations for the strut connections to the sting. The element lengths for the sting section of the model were arranged so that there was a beam node at both pin locations.

The constraints for the boundary conditions at each location were set to mimic the simply supported condition. To do this translation in all three axes was constrained and rotation about the two axes normal to the long axis of the pipe were designated as free to rotate. The rotation about the long axis of the pipe was constrained to prevent the whole FE model from rotation about the X axis. This condition is represented in Superdraw as Tx,Ty,Tz,Rx.

16.0 LOAD CASES

Three load cases were used to coincide with the three directions of pull from the pull tests. The three pull tests corresponded to Y +ive, Z +ive, and Z –ive in model coordinates. Load estimates for the Albert model were scaled from measurements of loads taken from testing done with the DREA standard sub. The DREA standard sub test covered four configurations (BH, HF, HS, HST) using a pitch and yaw range of +/- 30 degrees at 3 m/sec. The load estimates for Albert were scaled from 3 m/sec to 4 m/sec, however, other differences in model length and yaw-pitch range were not accounted for. The maximum load in each degree of freedom for the Albert model was predicted as follows;

Fx	[N]	761	Mx	[N.m]	1438
Fy	[N]	9691	My	[N.m]	2654
Fz	[N]	4379	Mz	[N.m]	4512

Moment about the Z model axis was the worst case for reduced clearance at the model tail – sting intersection. This was represented during the pull tests as a pull at the model tail in the Y +ive direction. From the model drawings the distance from the mid point between the two side force load cells and the point of application of the side pull just forward of the fairwaters was 2.134m. This resulted in the need for 2,114 N at the model tail to meet the required maximum moment for Mz. The nearest standard weight was 248.2 kgs thus a force of 2434.8 N or 547.4 lbs was applied to the FE model for load case 1. With the same weights at hand similar loads were applied for Fz –ive , -600 lbs for load case 2 and 559 lbs for Fz +ive for load case 3.

17.0 FINITE ELEMENT ANALYSIS RESULTS

Once all of the model data (beam properties and material physical properties) was entered the analysis was done using the linear elastic processor SAPP 0 from Algor. The results were output to the post processor Super View. Each load case was handled separately with dithers for displacement and deflected shape of the structure.

The displacements of the nodes at the tail-sting intersection and at the leading edge of the fairwater were inquired separately for each load case. The results were;

Load Case 1 Starboard Pull

0.187 inches Model Tail Displacement
0.024 inches Sting at Tail Displacement

0.163 inches Net Predicted Change in Clearance

Load Case 2 Vertical Down

-0.197 inches	Model Tail Displacement
-0.026 inches	Sting at Tail Displacement
-0.171 inches	Net Predicted Change in Clearance

Load Case 3 Vertical Up

0.184 inches Model Tail Displacement
0.024 inches Sting at Tail Displacement

0.160 inches Net Predicted Change in Clearance

Algor Figure Note;

The diagrams show the deflected shape of the centerlines of the Algor model. The sting is to the right and the 20-inch balance is to the left. The model tail is in the center. The colour dither is coded to show displacement and the displacement key is in the upper right hand corner.

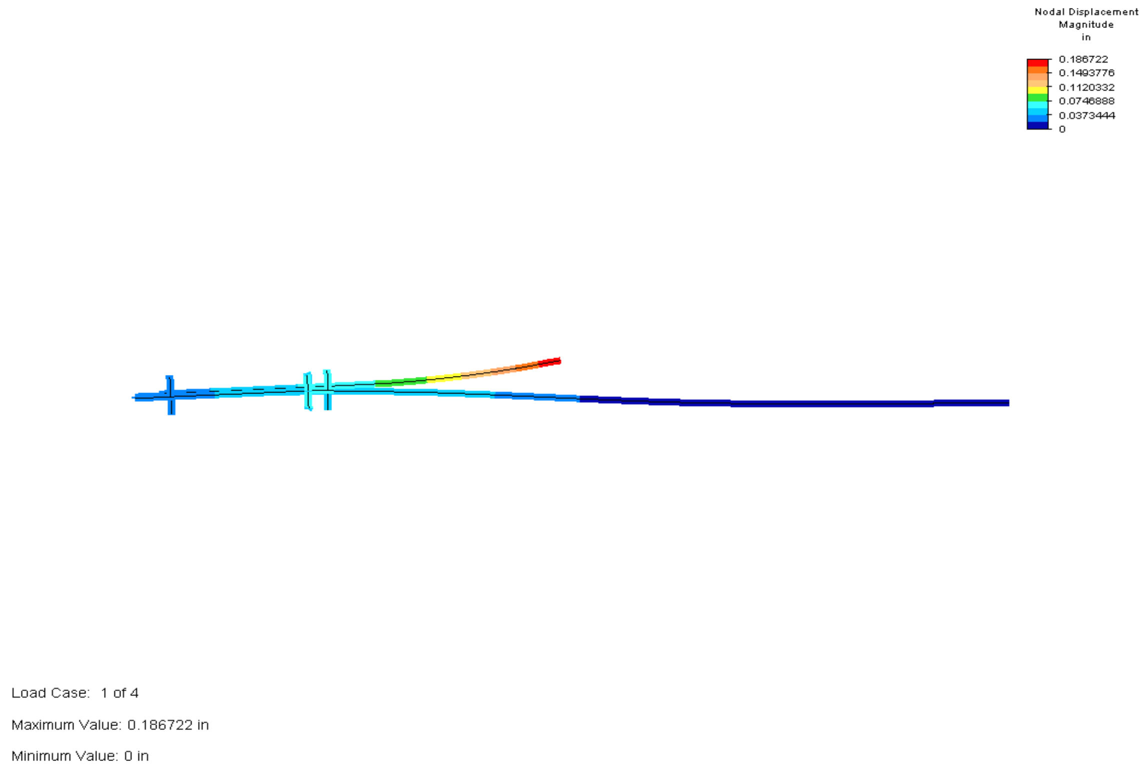


Figure 10. Starboard Side Pull Algor Results

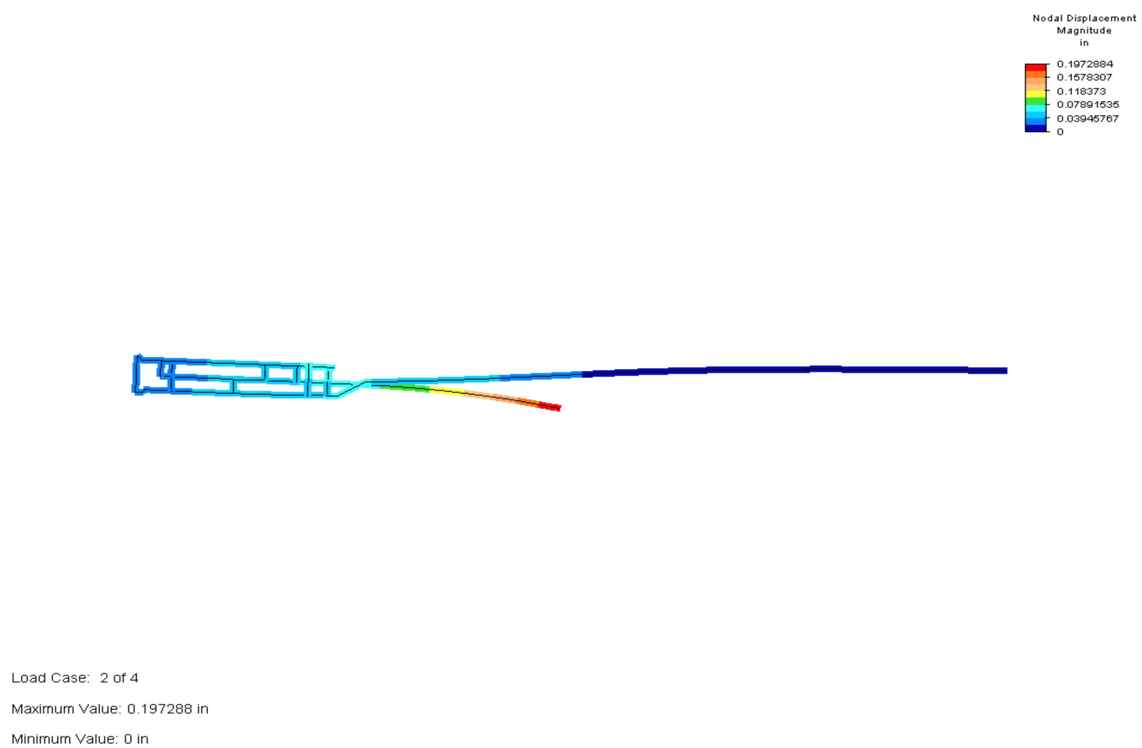


Figure 11. Vertical Down Pull Algor Results

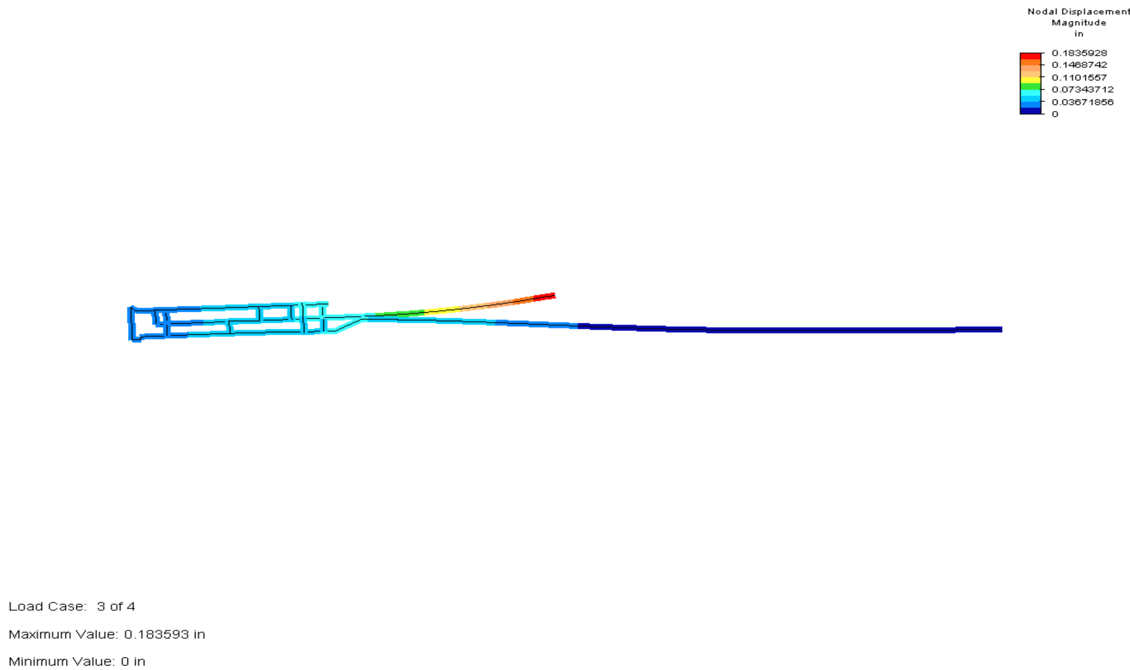


Figure 12. Vertical Up Pull Algor Results

18.0 FINITE ELEMENT MODEL PREDICTION VS MEASURED DISPLACEMENT

The FE predictions were compared to the actual measured displacements to ascertain the level of confidence in using the FE model for predicting the deflection of future models.

Starboard Side Pull

Measured	0.171 inches
Predicted	0.163 inches
Error	0.008 / 5%

Vertical Down Pull

Measured	0.166 inches
Predicted	0.171 inches
Error	0.005 / 3%

Vertical Up Pull

Measured	0.160 inches
Predicted	0.170 inches
Error	0.000 / 0%

19.0 COMMENTS

As can be seen from the level of effort to include six sections all with different properties the predicted displacement errors were sensitive to the properties of the model tail section. Attention should be paid to the tail section properties of a future model for minimum clearance determination.

The beam finite element model is quite good in predicting displacements for a structure of this shape. It can also be used to predict the loads that the individual load cells will see from a certain loading condition. The technique to do this requires that the post processor be used to dither the beam elements for axial stress. The stress level of the rod used to model the load cell can then be inquired. Knowing the stress level a simple F*A calculation will yield the load that has to be applied to achieve that stress level. This load is the load the load cell will read.

This model should not be used to determine the stress in shorter elements within the structure of the balance, especially brackets or fasteners. The stress situation is often complicated by stress concentrations. A brick element model should be used if the intent is to determine stress levels for design purposes.

Appendix A

Applied Force vs Displacement Data

Applied Force vs Displacement Data

13-Mar-03

Albert Model Sub Pulls - Clearance Check

Starboard Pull

All pulls were to starboard. The center of the pull was located 1.5 cm in front of the leading edge of the top rear fairwater.
Displacements are measured in inches, and a positive displacement denotes a shift to starboard, in the pull direction.
The weights of the weight pan and shackle were approximately 5.5 kg and 0.1 kg respectively. This gave the 5.6 kg total at 0 added weight.

Pull 1

Added Weight (kg)	Total Weight (kg)	Total Force (N)		Displacement (in)	Displacement (mm)
0	5.6	54.9	12.3501	0.001	0.025
16.5	22.1	216.8	48.7388	0.012	0.305
16.3	38.4	376.7	84.68642	0.023	0.584
15.1	53.5	524.8	117.9876	0.034	0.864
16.9	70.4	690.6	155.2584	0.046	1.168
16.2	86.6	849.5	190.9855	0.057	1.448
16.4	103	1010.4	227.1537	0.069	1.753
16.5	119.5	1172.3	263.5424	0.081	2.057
15.5	135	1324.4	297.7257	0.092	2.337
17	152	1491.1	335.2171	0.105	2.667
25.3	177.3	1739.3	391.0131	0.122	3.099
25.6	202.9	1990.4	447.4707	0.14	3.556
25.3	228.2	2238.6	503.2667	0.157	3.988
20	248.2	2434.8	547.3742	0.171	4.343

No controlled removal of weights was conducted.

Pull 2

Added Weight (kg)	Total Weight (kg)	Total Force (N)	Displacement (in)	Displacement (mm)
0	5.6	54.9	0	0.000
16.2	21.8	213.9	0.011	0.279
16.9	38.7	379.6	0.022	0.559
15.1	53.8	527.8	0.033	0.838
16.3	70.1	687.7	0.044	1.118
16.5	86.6	849.5	0.056	1.422
16.5	103.1	1011.4	0.068	1.727
15.5	118.6	1163.5	0.079	2.007
16.4	135	1324.4	0.09	2.286

17	152	1491.1	0.102	2.591
25.6	177.6	1742.3	0.12	3.048
25.3	202.9	1990.4	0.137	3.480
25.3	228.2	2238.6	0.154	3.912
20	248.2	2434.8	0.168	4.267
Removal of Weights:				
0	248.2	2434.8	0.169	4.293
-20	228.2	2238.6	0.162	4.115
-25.3	202.9	1990.4	0.146	3.708
-25.6	177.3	1739.3	0.129	3.277
-25.3	152	1491.1	0.111	2.819
-17	135	1324.4	0.1	2.540
-16.5	118.5	1162.5	0.088	2.235
-15.5	103	1010.4	0.076	1.930
-16.4	86.6	849.5	0.063	1.600
-16.5	70.1	687.7	0.052	1.321
-16.3	53.8	527.8	0.04	1.016
-16.9	36.9	362.0	0.027	0.686
-15.1	21.8	213.9	0.015	0.381
-16.2	5.6	54.9	0.003	0.076

17-Mar-03

Vertical Upward Pulls

The tail of the sub was pulled upwards using an engine hoist with a digital scale mounted to it.
A zero reading denotes a zero reading on the scale with the strap hanging slack.
Centre of pull strap was 1.5 cm in front of the leading edge of the bottom rear fairwater.

Pull 3:

Weight (kg)				
0	Force (N)		Displacement (in)	Displacement (mm)
19.5	0.0		0.0000	0.000
38.5	191.3	43.00482	0.0100	0.254
56	377.7	84.90696	0.0200	0.508
73	549.4	123.501	0.0300	0.762
88	716.1	160.9924	0.0400	1.016
97	863.3	194.073	0.0500	1.270
111	951.6	213.9214	0.0600	1.524
127.5	1088.9	244.7967	0.0700	1.778
144	1250.8	281.1854	0.0800	2.032
159.5	1412.6	317.5741	0.0900	2.286
176	1564.7	351.7574	0.1000	2.540
192	1726.6	388.1461	0.1100	2.794

208	1883.5	423.4321	0.1200	3.048
224	2040.5	458.7181	0.1300	3.302
239	2197.4	494.0041	0.1400	3.556
253.5	2344.6	527.0848	0.1500	3.810
	2486.8	559.0627	0.1600	4.064

Removal of Weight:

248.5			
230	2437.8	0.16	4.064
202	2256.3	0.15	3.810
182.5	1981.6	0.135	3.429
166.5	1790.3	0.124	3.150
150	1633.4	0.115	2.921
132.5	1471.5	0.105	2.667
116	1299.8	0.095	2.413
98	1138.0	0.085	2.159
91	961.4	0.074	1.880
78	892.7	0.065	1.651
61.5	765.2	0.055	1.397
44.5	603.3	0.045	1.143
28	436.5	0.035	0.889
12.5	274.7	0.025	0.635
0	122.6	0.015	0.381
	0.0	0.008	0.203

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Vertical Downward Pull

The zero weight and displacement conditions represent only the weight pan hanging from the leading edge of the rear fairwaters.
The center of the pull strap was located 1.5 cm in front of the leading edge of top rear fairwater.
The weights of the weight pan, shackle, and strap were approximately 5.5 kg, 0.2 kg, and 0.3 kg respectively. This gave the 6.0 kg total at zero added weight.

Adding Weights:

Added Weight (kg)	Total Weight (kg)	Force (N)		Displacement (in)	Displacement (mm)
0	6	58.9	13.23225	0	0.00
20	26	255.1	57.33976	0.011	0.28
20	46	451.3	101.4473	0.023	0.58
20	66	647.5	145.5548	0.035	0.89
16.9	82.9	813.2	182.8256	0.047	1.19
16.3	99.2	973.2	218.7733	0.057	1.45
16.5	115.7	1135.0	255.162	0.067	1.70

15.5	131.2	1287.1	289.3453	0.0765	1.94
15.1	146.3	1435.2	322.6464	0.086	2.18
16.5	162.8	1597.1	359.0351	0.096	2.44
17	179.8	1763.8	396.5265	0.107	2.72
16.4	196.2	1924.7	432.6947	0.117	2.97
25.3	221.5	2172.9	488.4907	0.133	3.38
25.6	247.1	2424.1	544.9483	0.15	3.81
25.3	272.4	2672.2	600.7443	0.166	4.22

Removing Weights:

Added Weight (kg)	Total Weight (kg)	Force (N)	Displacement (in)	Displacement (mm)
	272.4	2672.2	0.166	4.22
-25.3	247.1	2424.1	0.152	3.86
-25.6	221.5	2172.9	0.133	3.38
-25.3	196.2	1924.7	0.123	3.12
-16.4	179.8	1763.8	0.113	2.87
-17	162.8	1597.1	0.103	2.62
-16.5	146.3	1435.2	0.093	2.36
-15.1	131.2	1287.1	0.085	2.16
-15.5	115.7	1135.0	0.076	1.93
-16.5	99.2	973.2	0.066	1.68
-16.3	82.9	813.2	0.056	1.42
-16.9	66	647.5	0.046	1.17
-20	46	451.3	0.031	0.79
-20	26	255.1	0.019	0.48
-20	6	58.9	0.007	0.18