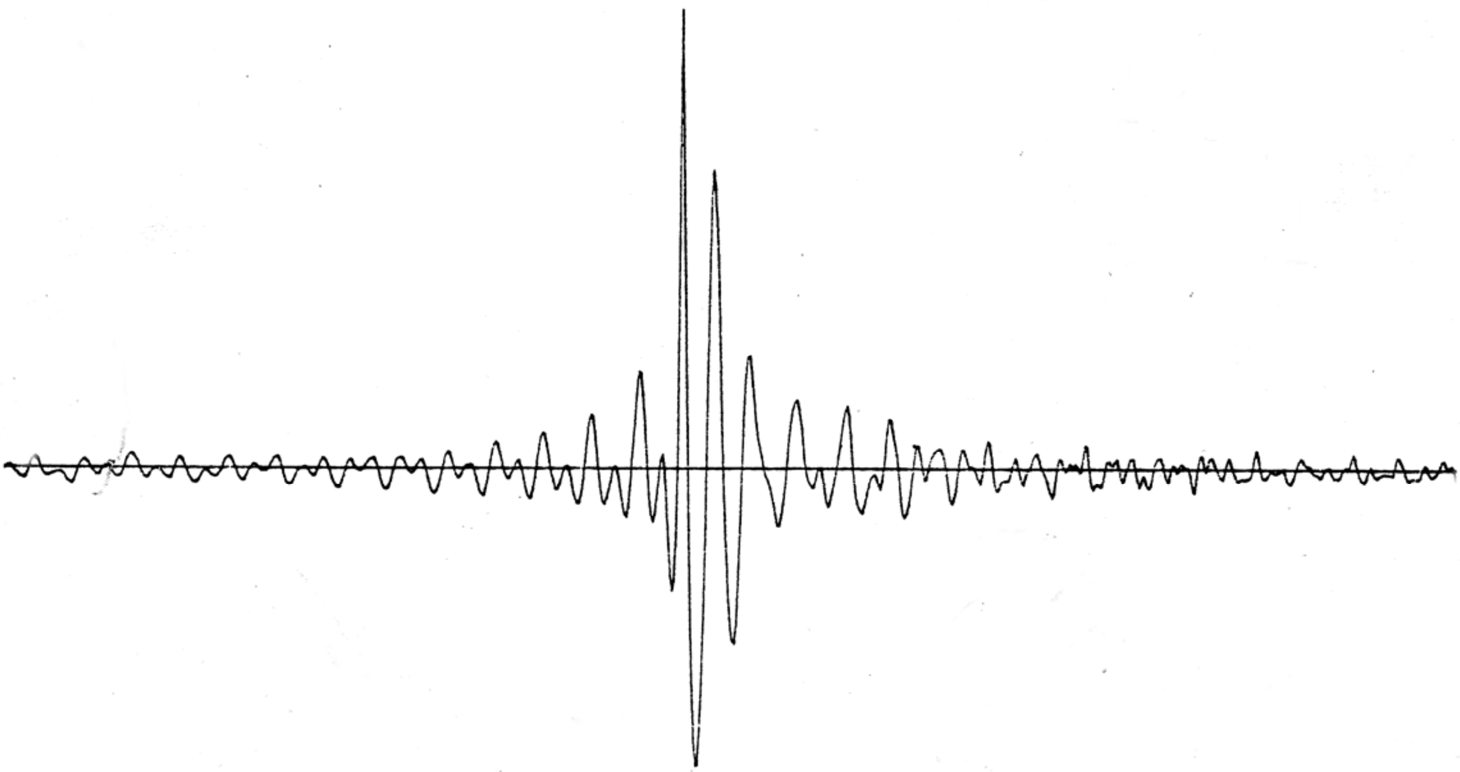
Edinburgh Wave Power Project

Fourth Year Report
Volume 2 of 3



July 1978

EDINBURGH UNIVERSITY

WAVE POWER PROJECT

FOURTH YEAR REPORT 1978

VOLUME 2 OF 3

SLAMMING TESTS

CONTENTS

INTRODUCTION

We wanted to understand how ducks behave in extreme conditions.

We generated the largest, steepest wave possible in the narrow tank.

We varied mounting compliance, position, power take-off and attitude of the model.

We measured forces and movements and took sequences of photographs.

The data is presented to show some features of the behaviour and to allow further analysis. A continuing problem was to decide when to stop doing the experiments. Every answer posed two more questions.

MAIN CONCLUSIONS

(1) There is no hydrodynamic law which prevents plunging breakers in deep water. Vertical walls of water are credible and we believe inevitable. Longuet-Higgins[1] and Cokelet[2] predict them on the basis of analytical work. There is anecdotal evidence from seamen[3] supported by photographs taken at sea.[4] We have ways of generating waves with length to height ratios of 4.6 to one.

(2) Ducks are not troubled by steepness. Force coefficients in very steep waves are about half those measured for small waves.

(3) There are strong forces acting to submerge free floating ducks.

(4) When an extreme wave hits a duck on a yielding axis the ratio of surge movement to wave height is about .9. The ratio of heave movement to wave height is about .25.

(5) The biggest forces do not occur at the time of the steepest part of the wave sequence, but usually happen during the second trough as the duck recovers from capsize.

(6) The biggest forces are directed at an angle of about 45^{o} below the forward horizontal.

(7) There is a notable absence of force in the upper waveward quadrant.

(8) Failed power take off does not cause problems with duck forces but may lead to high angular velocities.

(9) The concept of the capsized condition being a survival attitude is misleading.

(10) About 5000 steep wave sequences were generated during the series of experiments. To do this in the natural wave environment would have taken about a quarter of a million years.

THE WAVE

If we try to make big regular waves by increasing wavemaker drive we find that they break by spilling at a length to height ratio of 7 before reaching the model. However, if the phase of each component of a spectrum is carefully chosen we can arrange for them all to combine at a particular place and time and to reach that place without premature breaking. This produces a splendid plunging breaker which is shown in photographs 1, 2, 3 and 4.

The components we selected were as follows:

#	Freq (hz)	Start phase (deg)	#	Freq (hz)	Start phase (deg)	#	Freq (hz)	Start phase (deg)	#	Freq (hz)	Start phase (deg)
1	0.66	125	9	0.82	99	17	0.98	120	25	1.13	194
2	0.68	75	10	0.84	54	18	1.00	81	26	1.15	162
3	0.70	25	11	0.86	9	19	1.02	44	27	1.17	131
4	0.72	336	12	0.88	325	20	1.04	6	28	1.19	101
5	0.74	287	13	0.90	282	21	1.05	330	29	1.21	71
6	0.76	239	14	0.92	240	22	1.07	295	30	1.23	42
7	0.78	192	15	0.94	199	23	1.09	261	31	1.25	14
8	0.80	145	16	0.96	159	24	1.11	227	32	1.27	347

TABLE 1: Frequencies and Starting Phases of components of the Steep Wave

Before doing any tests with the model, wave records were logged with a gauge at each of the positions that the axis would subsequently occupy.

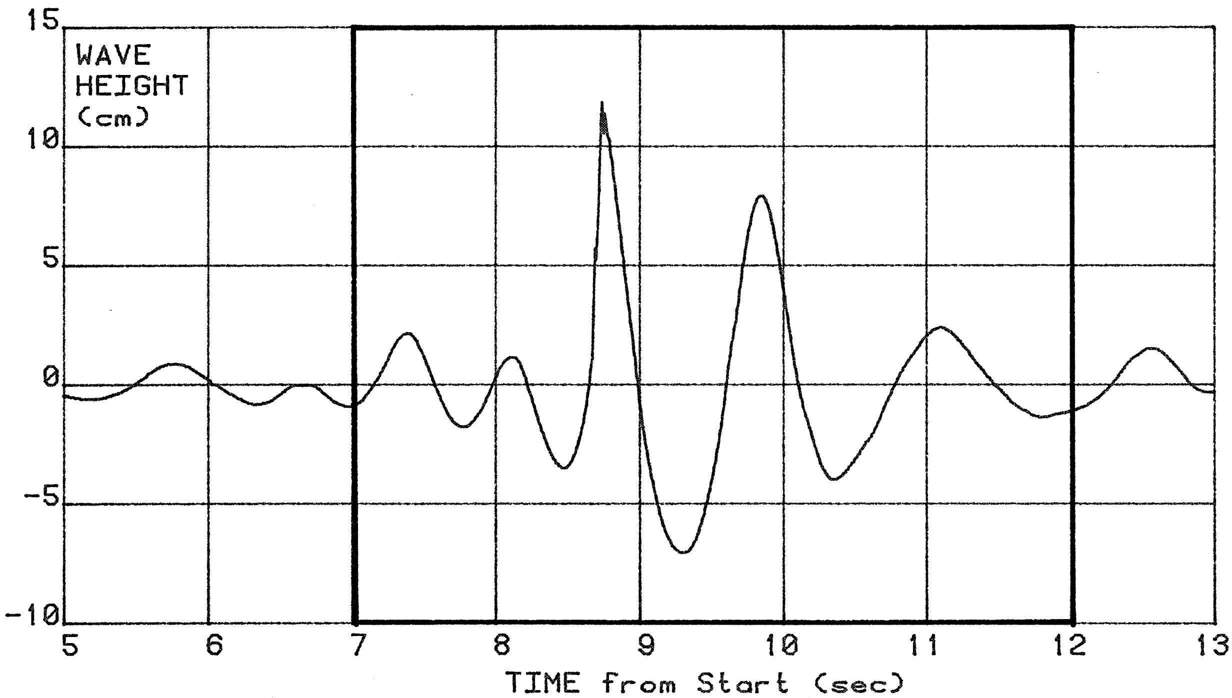


FIG 1: THE WAVE (Gauge at nominal break position)

Fig 1 above shows the wave record at the nominal breaking position. The inset area shows the time period used for force measurements.

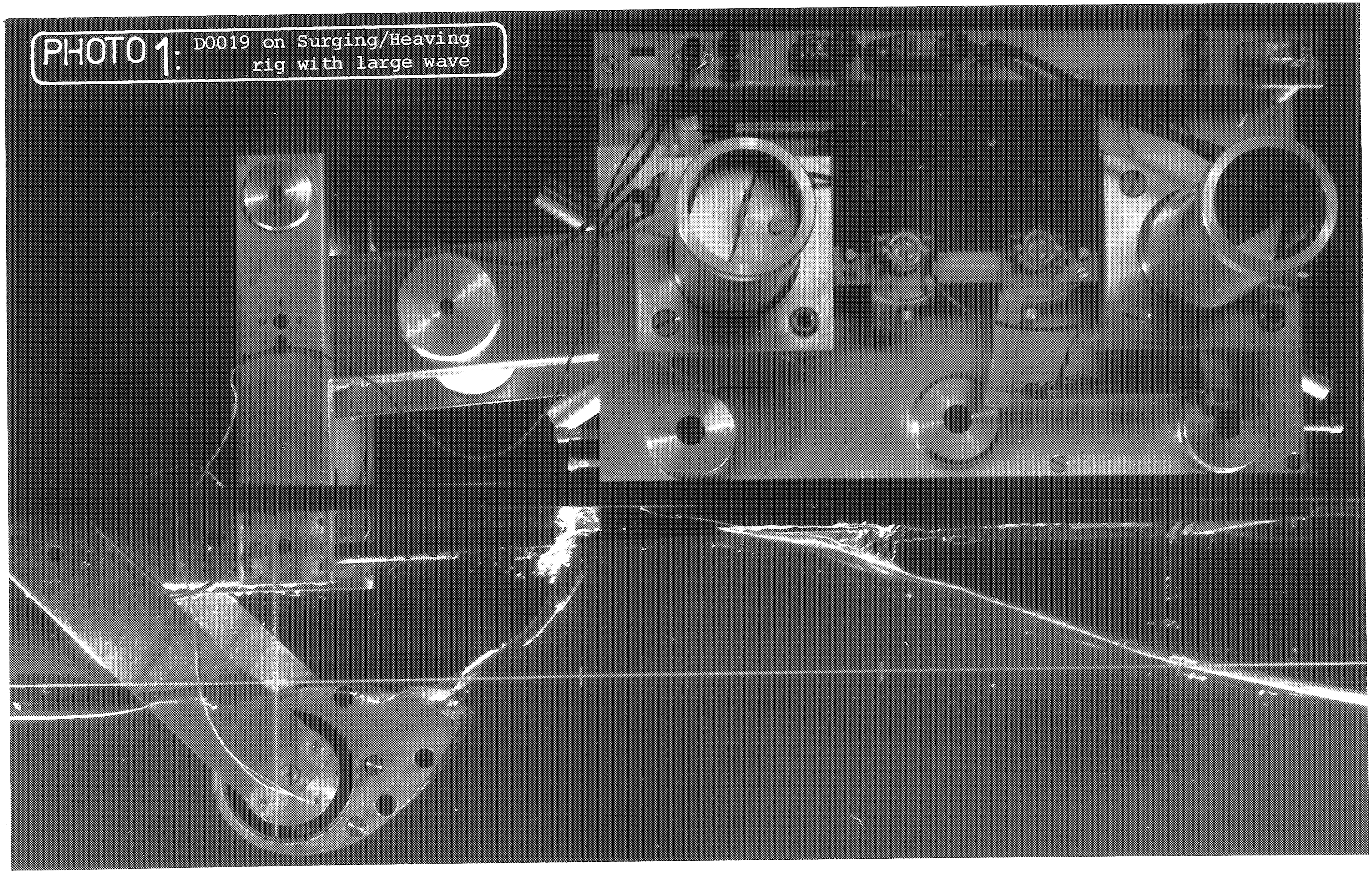


PHOTO 1: D0019 on Surging/Heaving rig with large wave

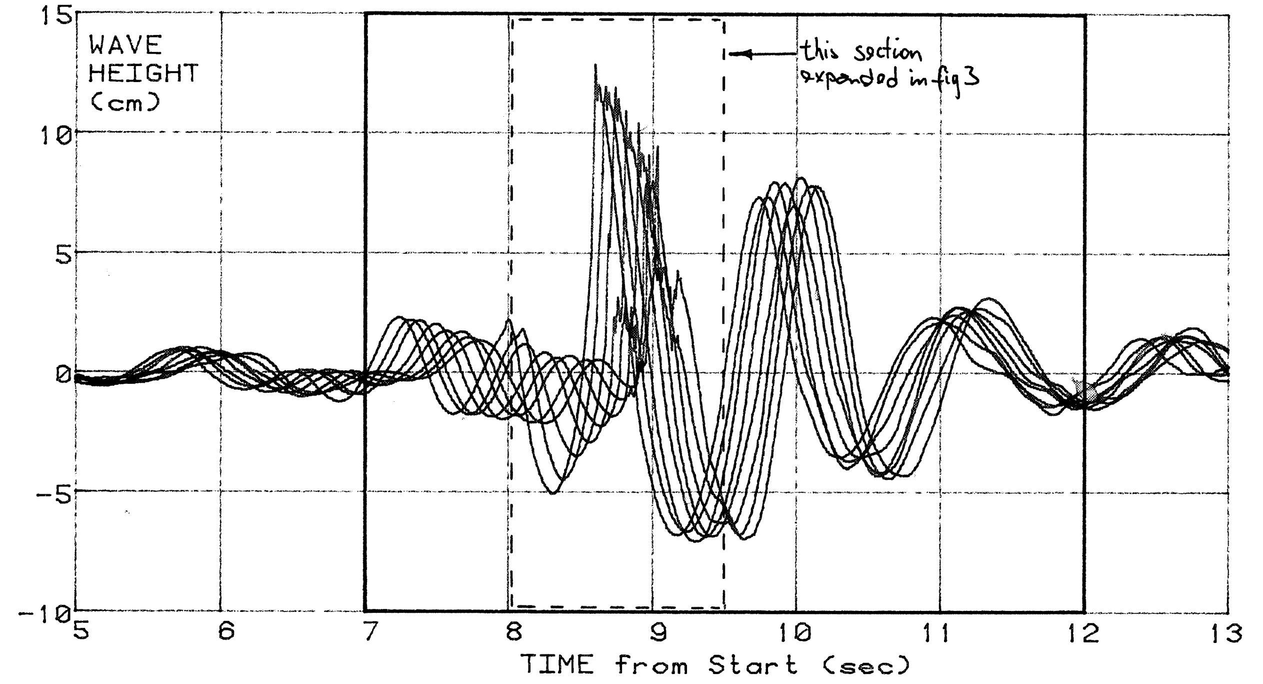


Fig 2 shows superimposed records at each of eight test positions.

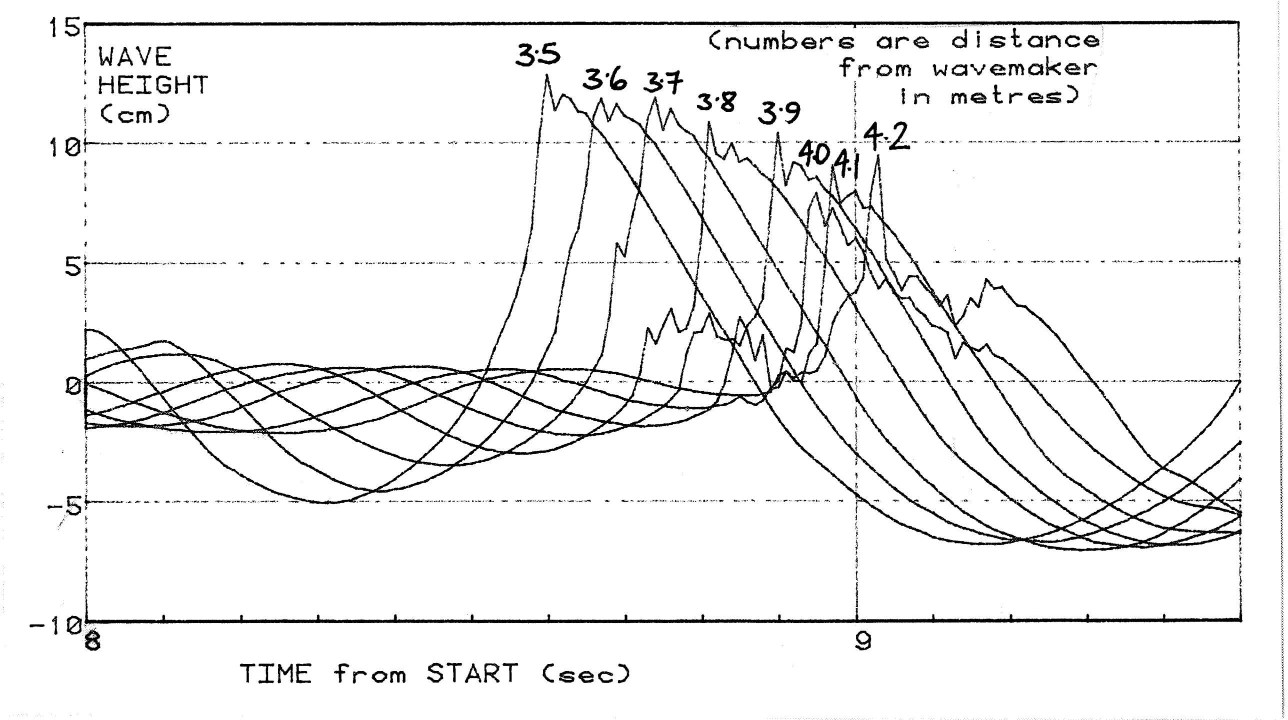


Fig 3 shows an expanded view of the main crest.

THE MOUNTING

Photographs 1 and 3 show the general arrangement used for these tests. The model, DOO19 (ballast as on p3.2 of volume 1 of this report) was mounted on the surging-heaving rig (2nd year report p26.15). The axis depth was 6.5cm.

Strain gauges in the linkages of the rig measure surge and heave forces transmitted from the duck and through its axis to the rig. For rigid axis tests the rig was locked, so that forces were still transmitted through the strain gauges.

Compliance is supplied both from physical springs and electric motors responding to the displacement of the duck axis. The contribution from the physical spring remains constant, but that from the motor is subject to limiting above a selected threshold.

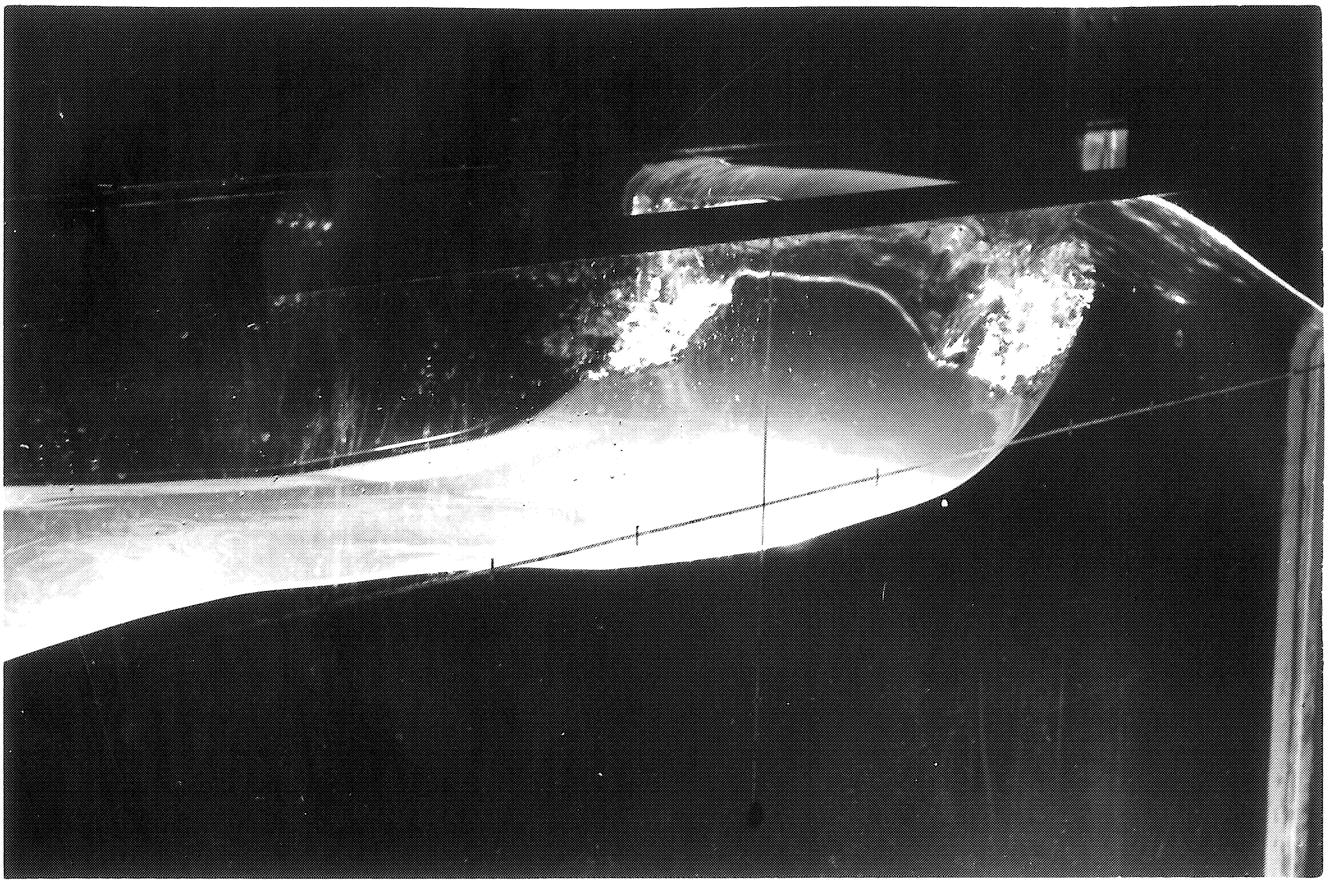
The test conditions are summarised below.

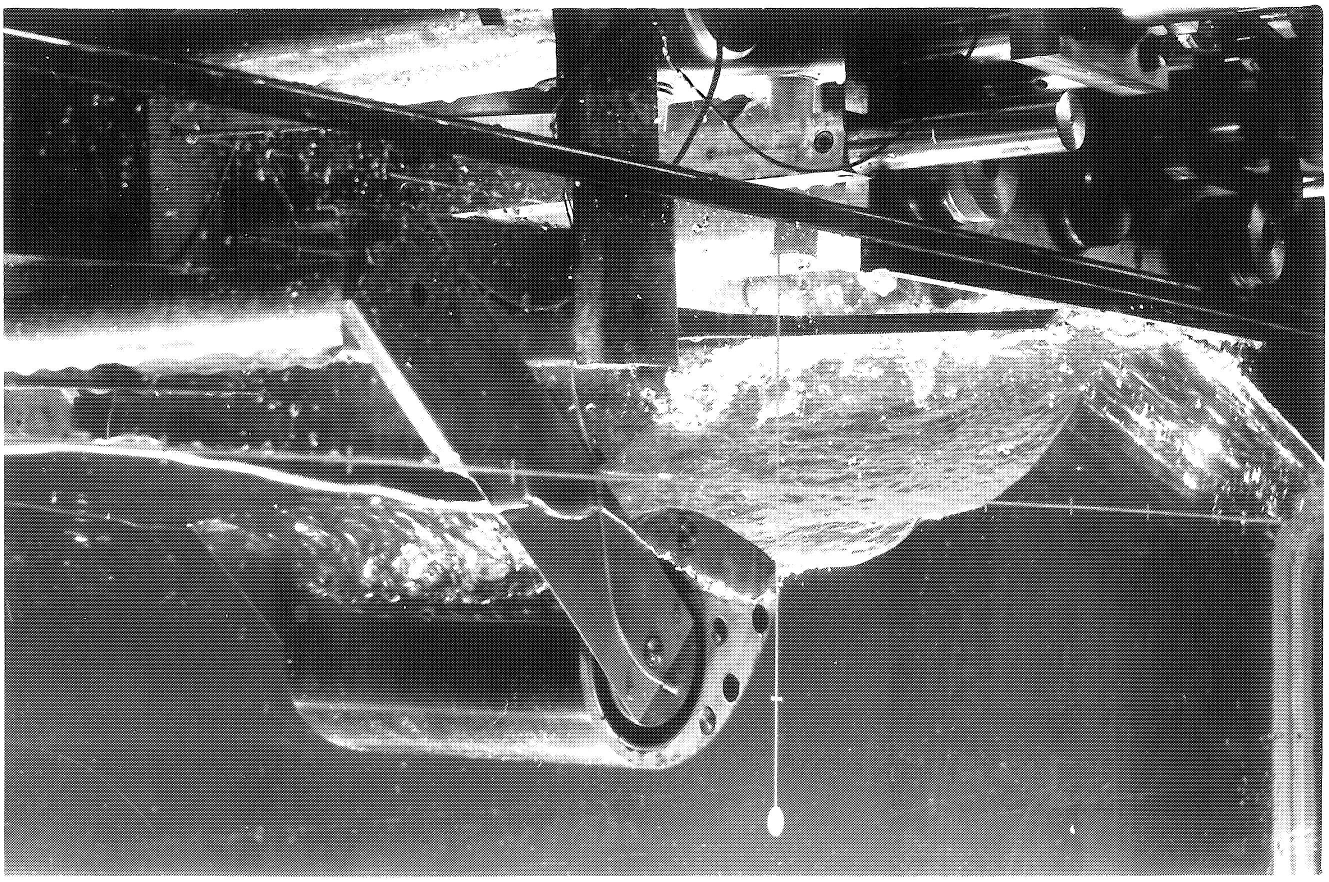
	Tank value for 293mm wide model	Full scale value (per metre) assuming 1/150	Full scale value (per metre) assuming 1/100
Duck diameter	10cm	15m	10m
Axis depth	6.5 cm	9.75m	6.5m
Damping	6.5×10^{-2} NM/rad/sec	9.1N/Rad/sec x 10^{6}	2.2N/Rad/sec x 10^{6}
Compliance: physical	5×10^{-3} M/N	9.8×10^{-6} M^2/N	14.7×10^{-6} M^2/N
Compliance: electrical	0.5×10^{-3} M/N	0.98×10^{-6} M^2/N	1.47×10^{-6} M^2/N
Electrical compliance limiting force	3N	0.23N/M x 10^{6}	0.10N/M x 10^{6}

In all cases signals were measured over a 5 second period, starting 7 seconds after the start of the wavemaker command signal. A storage oscilloscope was also used to watch out for any transients that were too fast for the computer sampling of 100hz. None were noticed.

PHOTO 2 (TOP): The Wave: Plunging Breaker in deep water

PHOTO 3 (BOTTOM): Wave about to break over the model





HOW TO READ RESULTS

Time marks are given at the top and bottom of the page and a plastic ruler laid vertically allows the records of force or movement to be related in time to the wave.

Photograph times are shown in the scale below the wave record, and appear in the photographs themselves. This allows a photograph to be found for an interesting force value and a force value for an interesting photograph. Times given are seconds into the sequence for a 15 metre duck. Rescaling rules are given on p10. The photographs include a graticule to show mean sea level, the nominal breaking point and tic marks at intervals of one duck diameter.

Each trace has an arrow marker pointing to its maximum and the value of this is printed at the end of the record.

The units are Newtons x 10^6 per metre for force density and metres for rig movement and wave height. Force coefficients (see p2.2 of our 1976 report and p6.13 of our 1978 report) are given for force records and movement ratios for the compliant rig experiments.

Damped and undamped records are displayed to show the effects of power take-off.

Surge and heave forces are shown separately plotted against time. We also show the modulus of the resultant force. The direction of the resultants may be judged from the surge v. heave point plot on the right hand pages. Dots are drawn at time intervals corresponding to .122 second at full scale. Even numbered seconds are shown as dots with squares around them and the times are indicated where convenient. This allows the surge v. heave plot to be tied to particular photographs. The closeness of the dots allows the rate of change to be judged. Slubber bearings would be unhappy with prolonged large values i.e. close dots at a big radius.

The ray diagrams were drawn in an attempt to assess how evenly loads are shared around the bearing. Force directions are split into 5° intervals and lines are drawn along each direction with lengths proportional to force magnitude times duration. A composite ray diagram for all the tests is given in graph number 9b.

To get the most out of the test results it is necessary to jump from photographs to records. We will be happy to supply unbound sets of photographs so that comparisons can be made more easily. Some comments are included with the force and movement records.

how to read the graphs

special scale to help correlate graphs & photos

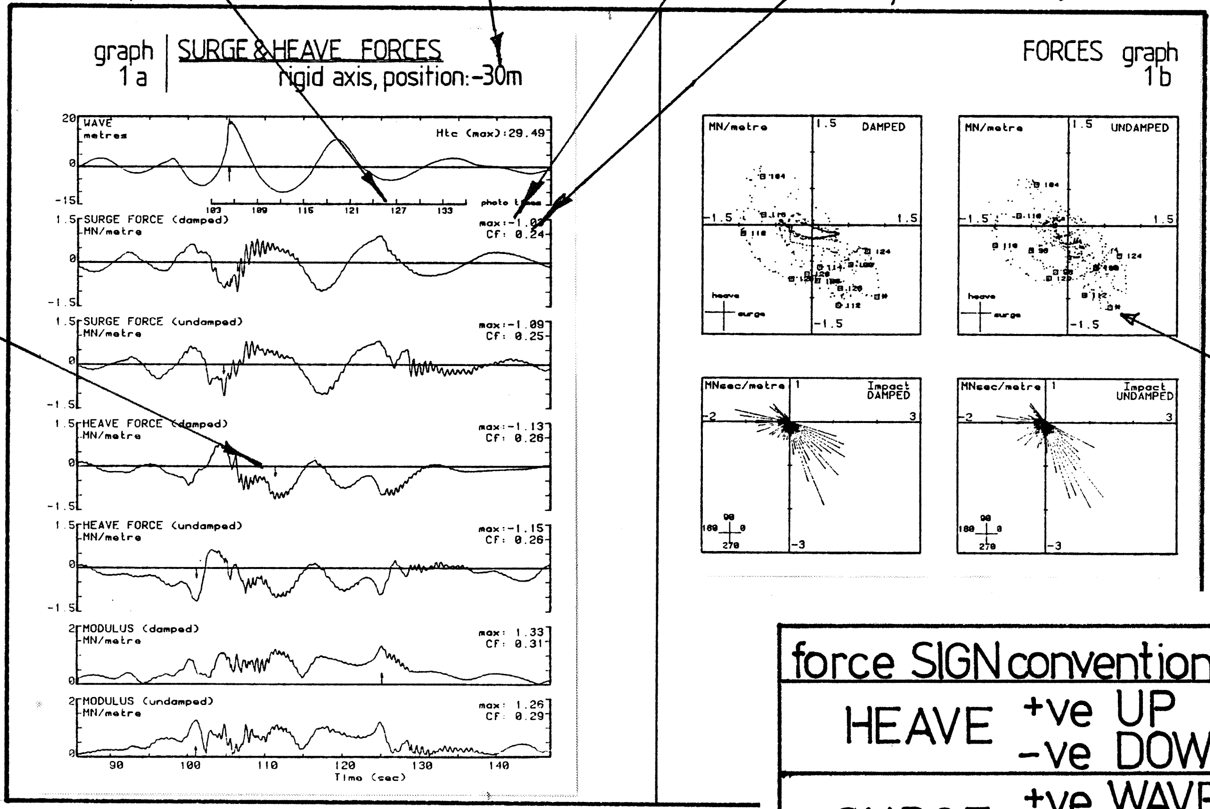
position of model relative to reference position

maximum value of each parameter

force coefficient $C_f = F_{MAX} / (W \rho g D H_{tc\,max})$

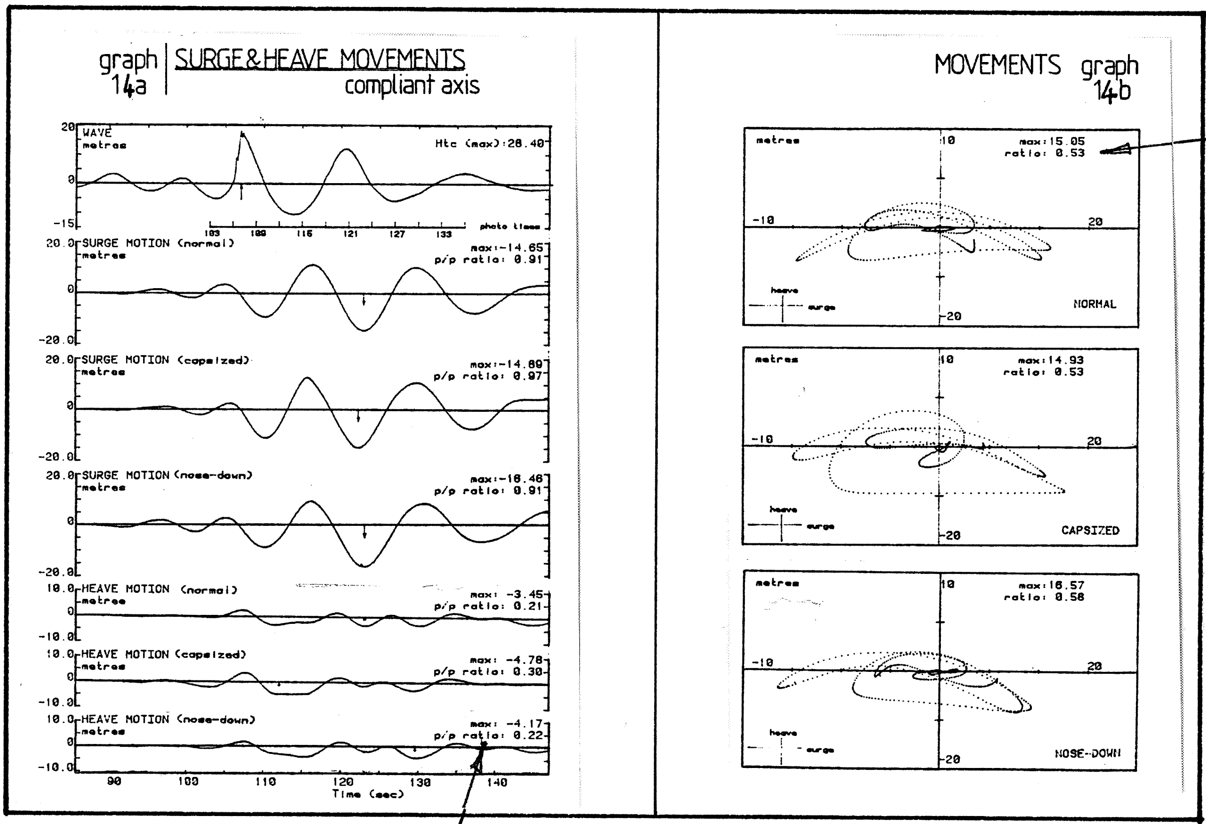
little arrow shows time of maximum values

maximum modulus shown by asterisk



force SIGN convention:	
HEAVE	+ve UP -ve DOWN
SURGE	+ve WAVEward -ve BEACHward

ALL UNITS AS FOR 15metre DUCK



ratio = max excursion / H_{TC}

P/P ratio = peak to peak motion / H_{tc}

PHOTOGRAPHY

The good repeatability of the wave meant that apparently sequential photographs could be taken on different runs of the wave. We wanted to use composite negatives for printing the photographs, and a suitable arrangement used 6 sections cut from 35mm negatives mounted on a photo-etched stainless-steel carrier. We use 2 such photographs to illustrate each sequence and 2 different time intervals, as follows:

	Tank time interval	Equiv time @ 1/150	Equiv time @ 1/100
Small time step	0.082 sec	1.0 sec	0.82 sec
Big time step	0.245 sec	3.0 sec	2.45 sec

On the photo captions times are written as for 1/150.

The secret of good wave photographs is to light up the meniscus by using a lot of light from below. We used 3 electronic flashes below the glass tank bottom, and 2 to illuminate the apparatus from the front. The effective speed of the units was about 1/500th of a second, and the blurring of the wave in some of the images suggests that faster units should have been used. A special timer, started by the wavemaking computer, triggered the flashes at the required time, but sent an earlier pulse to the camera shutter solenoid, so that it was open in time for the flash.

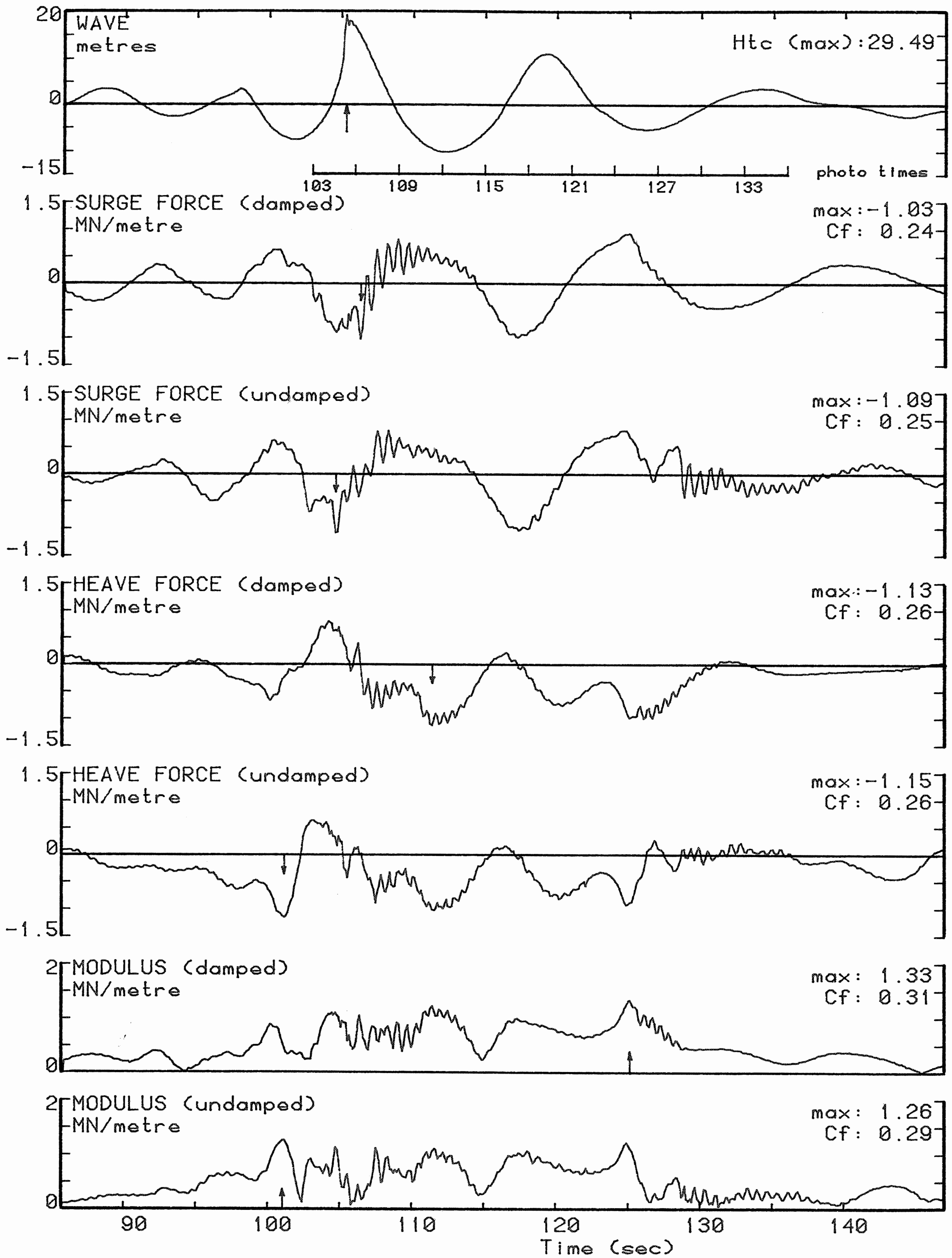
A NOTE ON SCALE

When these tests were started we were designing for 15 metre ducks and using a tank scale of 1/150. Subsequent design work, and the South Uist data, show that the new 10 metre diameter duck can do as well as our old 15 metre one. We now consider narrow tank tests to be at 1/100 scale. The chart below gives conversion factors.

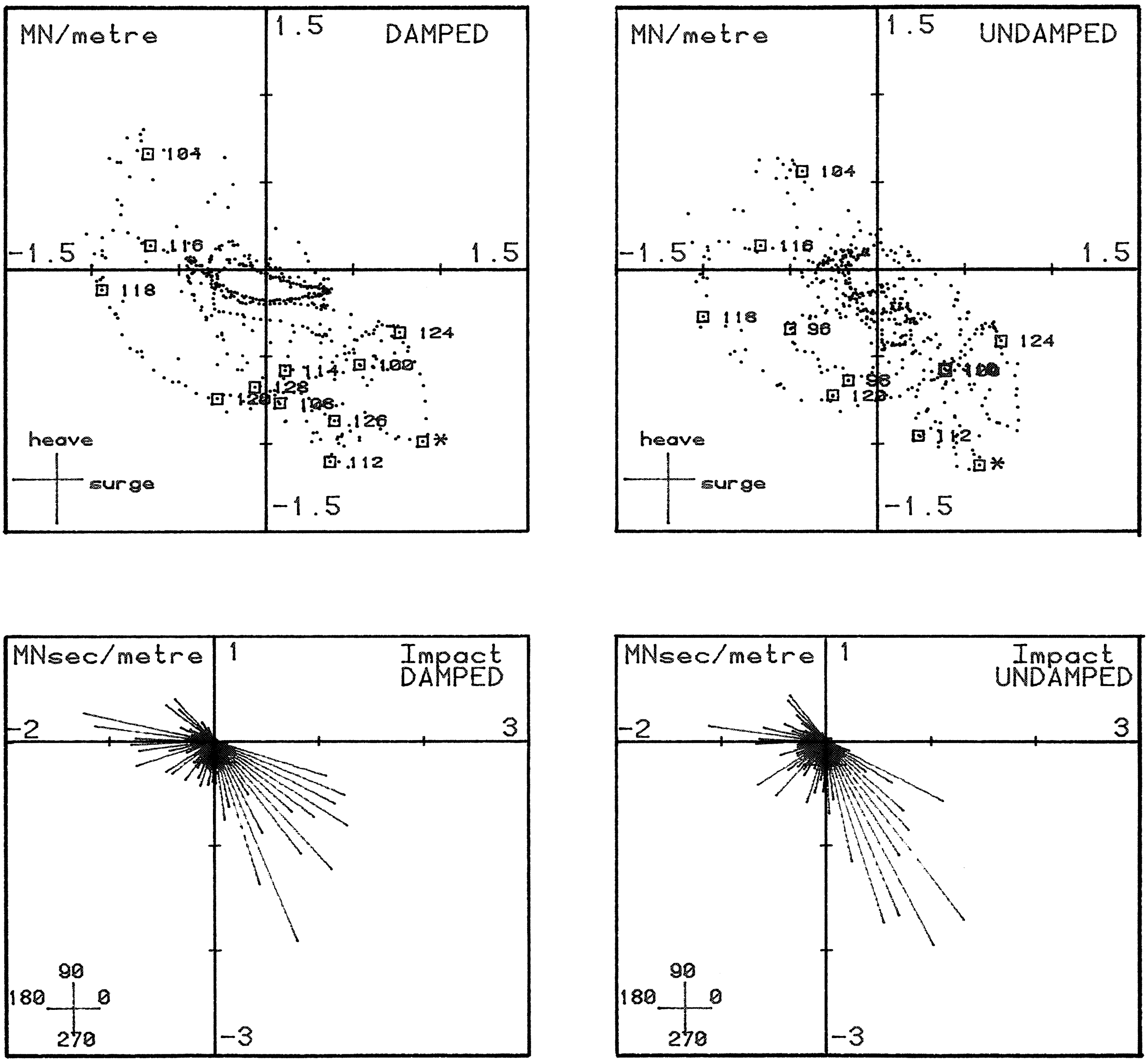
PARAMETER	INDEX OF SCALE	MULTIPLY BY THIS NO. TO GO FROM 1/150 to 1/100	UNIT
Wave Height	1	0.67	Metres
Force Density	2	0.44	Newton/Metre x 10^6
Time	0.5	0.82	Seconds
Movement	1	0.67	Metres
Force Coefficient	0	1.0	None
Stiffness Density	1	0.67	Newton/Metre^2
Compliance Density	-1	1.5	Metre^2/Newton
Damping Density	3.5	0.24	Newton Seconds/Radian x 10^6
Impact	1.5	0.54	Newton Seconds/Metre x 10^6

graph 1 a | SURGE & HEAVE FORCES

rigid axis, position: -30m



FORCES graph 1b



(See Photograph 5)

This record was made at two duck diameters forward of the nominal break point. The undamped test is shown in photograph 5.

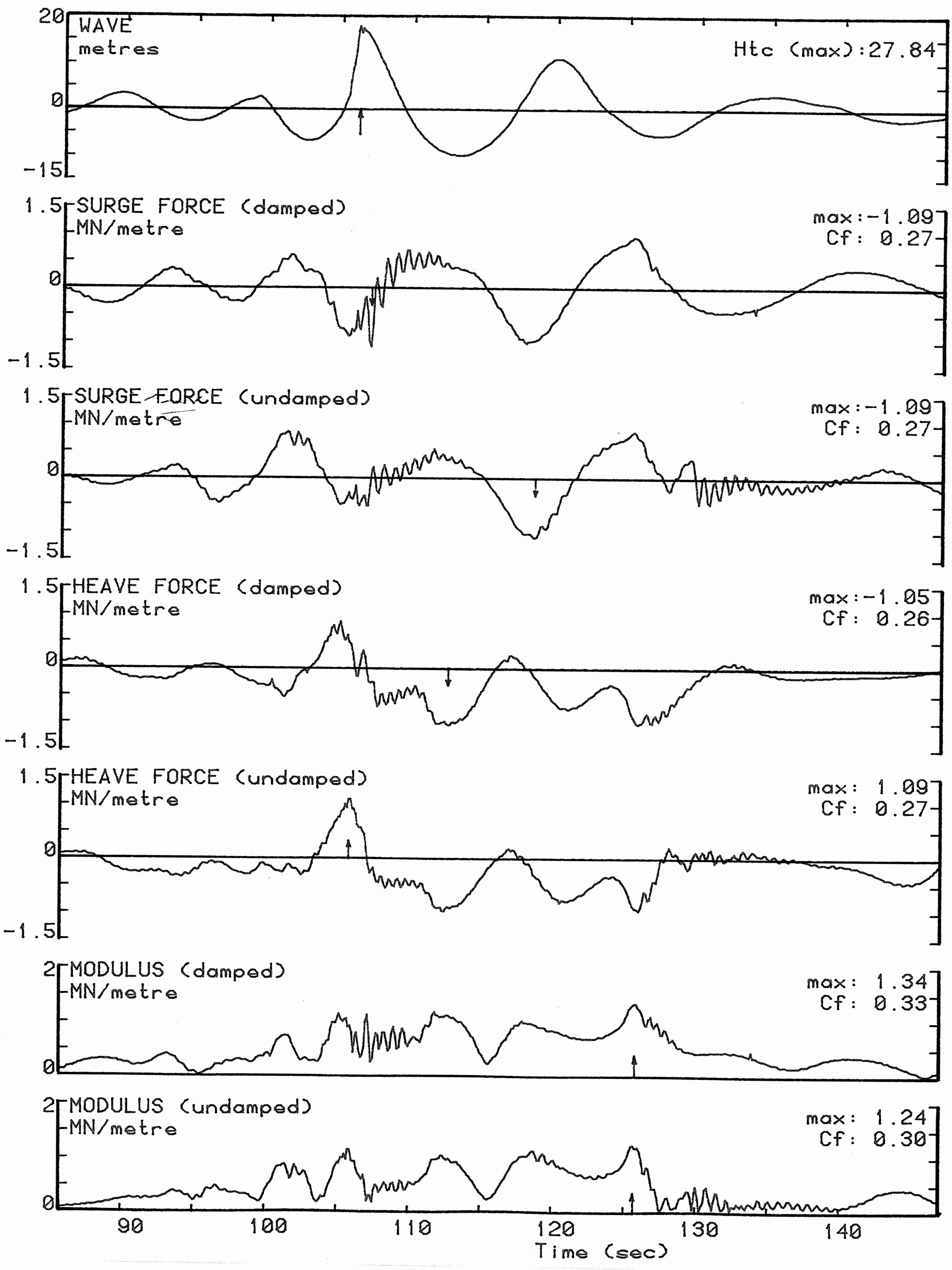
The surge force record looks like an inverted version of the wave record with some superimposed vibrations.

Damping makes little difference.

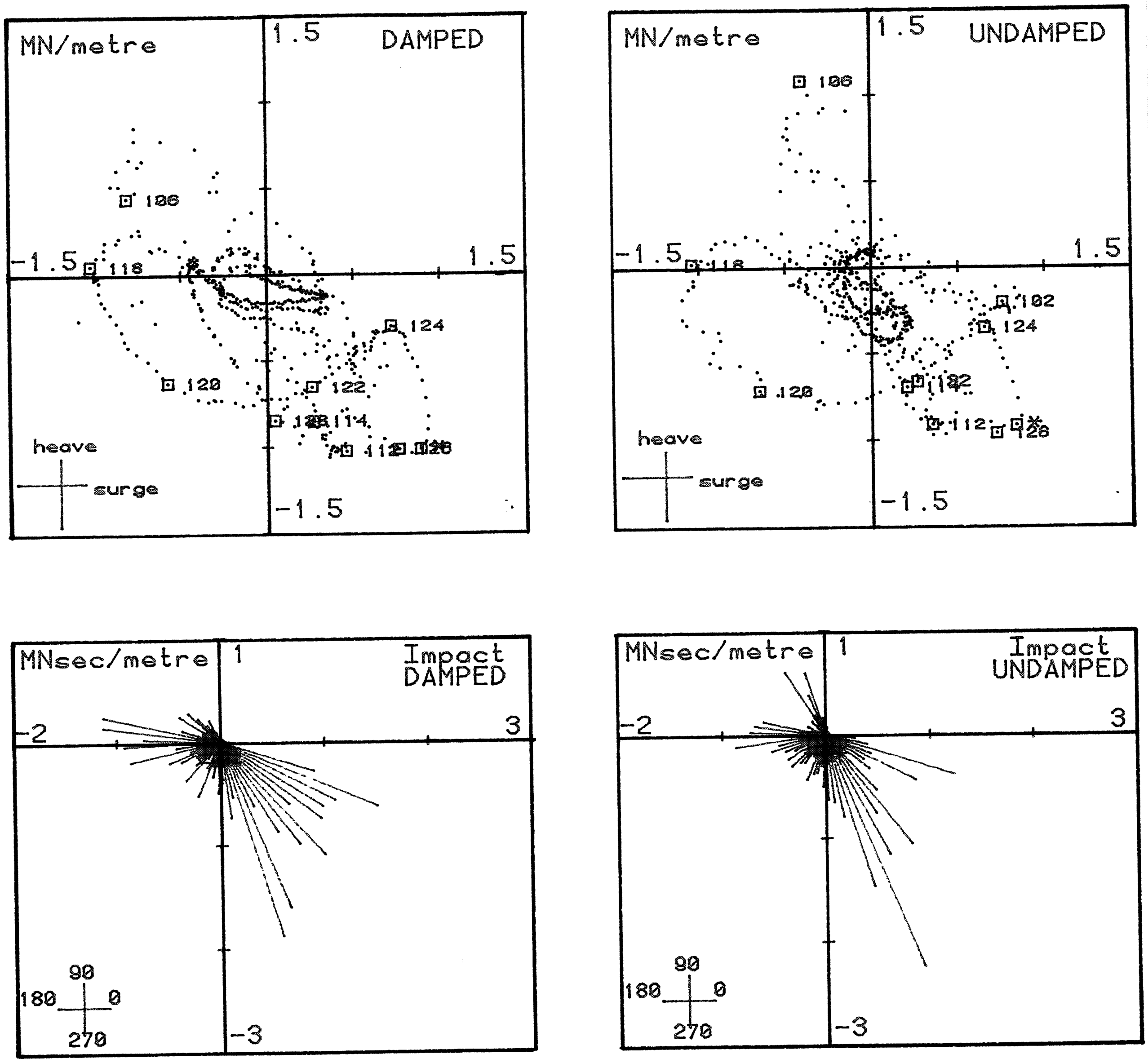
The heave record shows strong rectification resulting in a large sinking force.

This position shows more vibrations than any other record. It shows the lowest force coefficients (see graph 11) and the highest wave.

graph 2 a | SURGE & HEAVE FORCES rigid axis, position: -15m



FORCES graph 2b



(No Photograph)

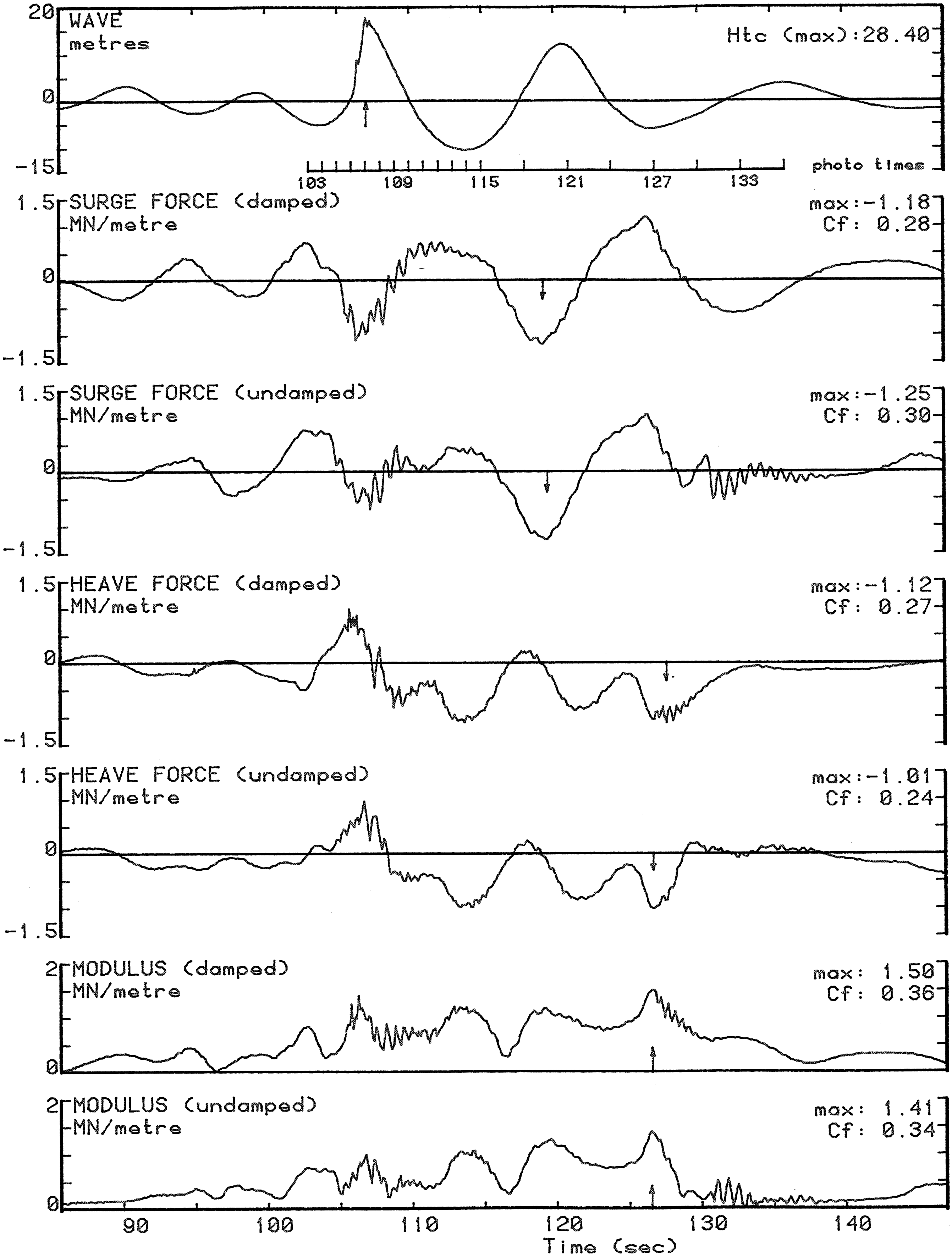
The change in position to 15 metres before the break has made little difference to the force records.

Force coefficients are still very low.

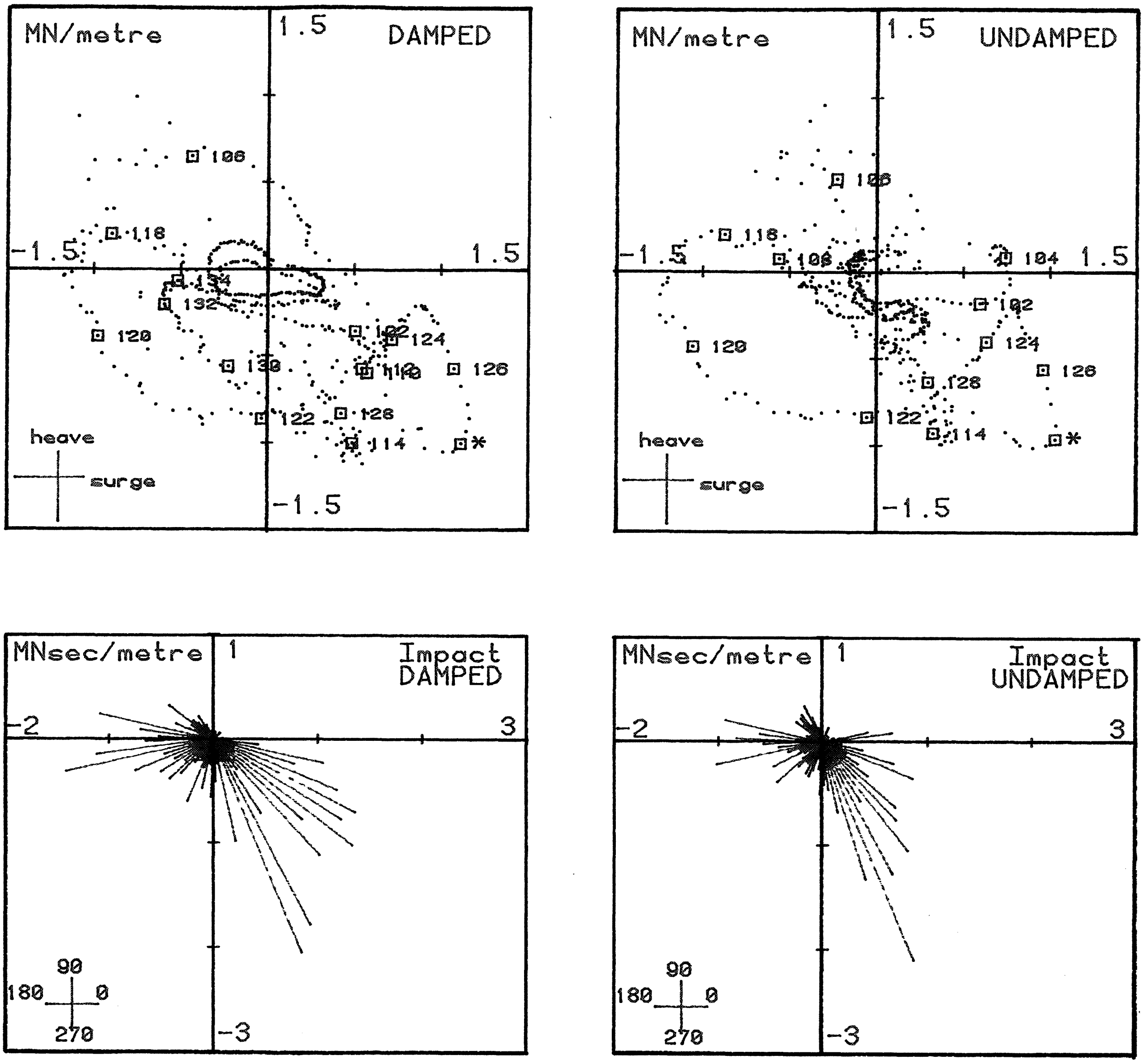
For this and all subsequent normal attitude tests the modulus maximum occurs much later than the wave maximum. Only with the capsized and nose down test do all the maxima occur together.

Several of the force records show vibrations like those at 105 to 110 seconds. They have a frequency of about 18Hz at model scale. Comparisons between graphs 1a and 2a show that these vibrations are often in phase from test to test. This suggests that they are caused by the wave maker and are not hydrodynamic in origin.

graph 3 a | SURGE & HEAVE FORCES
rigid axis, position:0m



FORCES graph 3b



(See Photograph 6 for 3 second intervals and Photograph 9 for one second steps during the middle of the sequence)

This test was at the nominal breaking point of the wave. The maximum height measured at this position is 28.4m whereas 29.49m was measured 30m up wave.

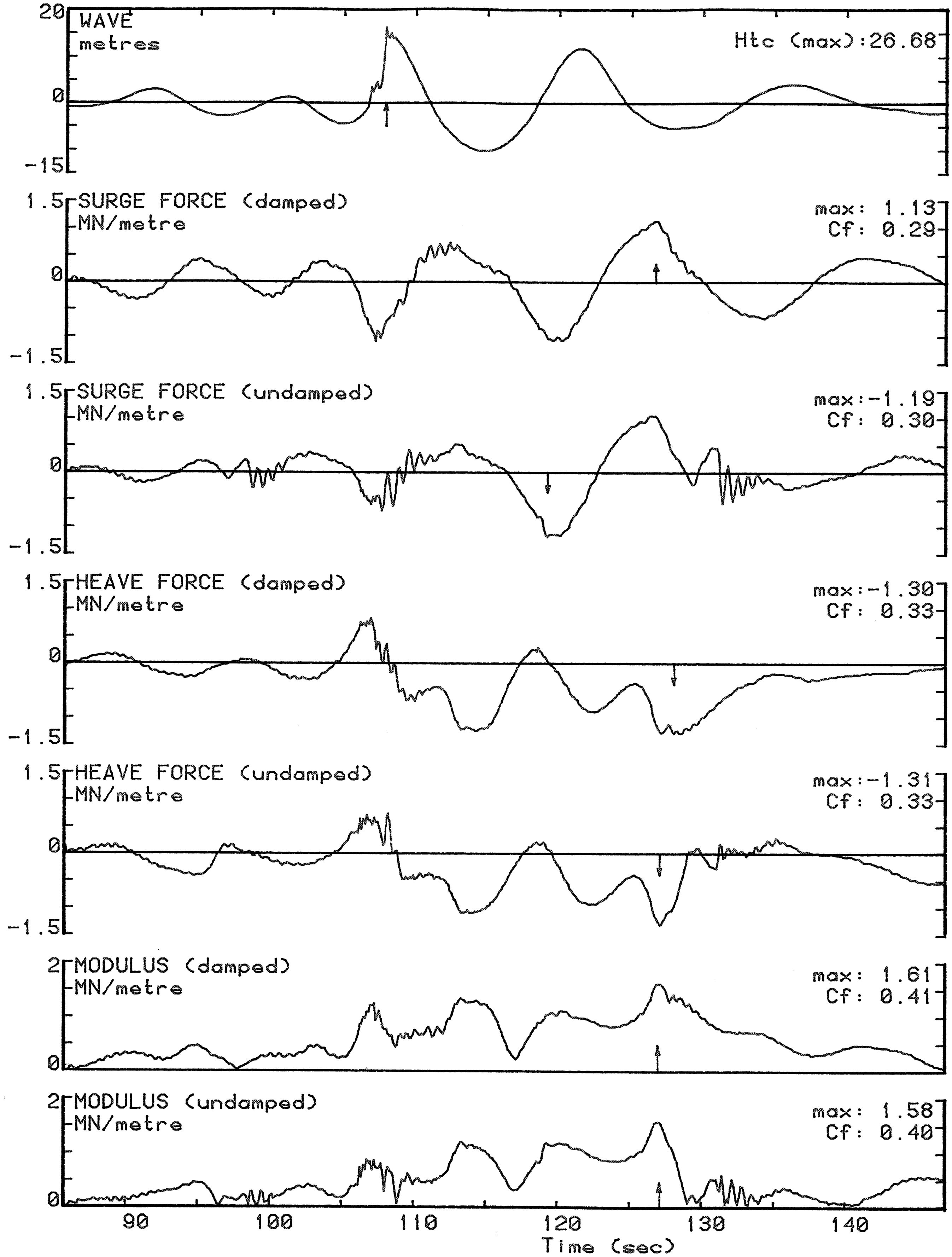
Photograph 6 for 118 seconds shows the maximum duck angle recorded. This is also the time for maximum surge force. The undamped record has the highest value of surge force for the series of tests.

Force coefficients (see graph 11) have begun to rise.

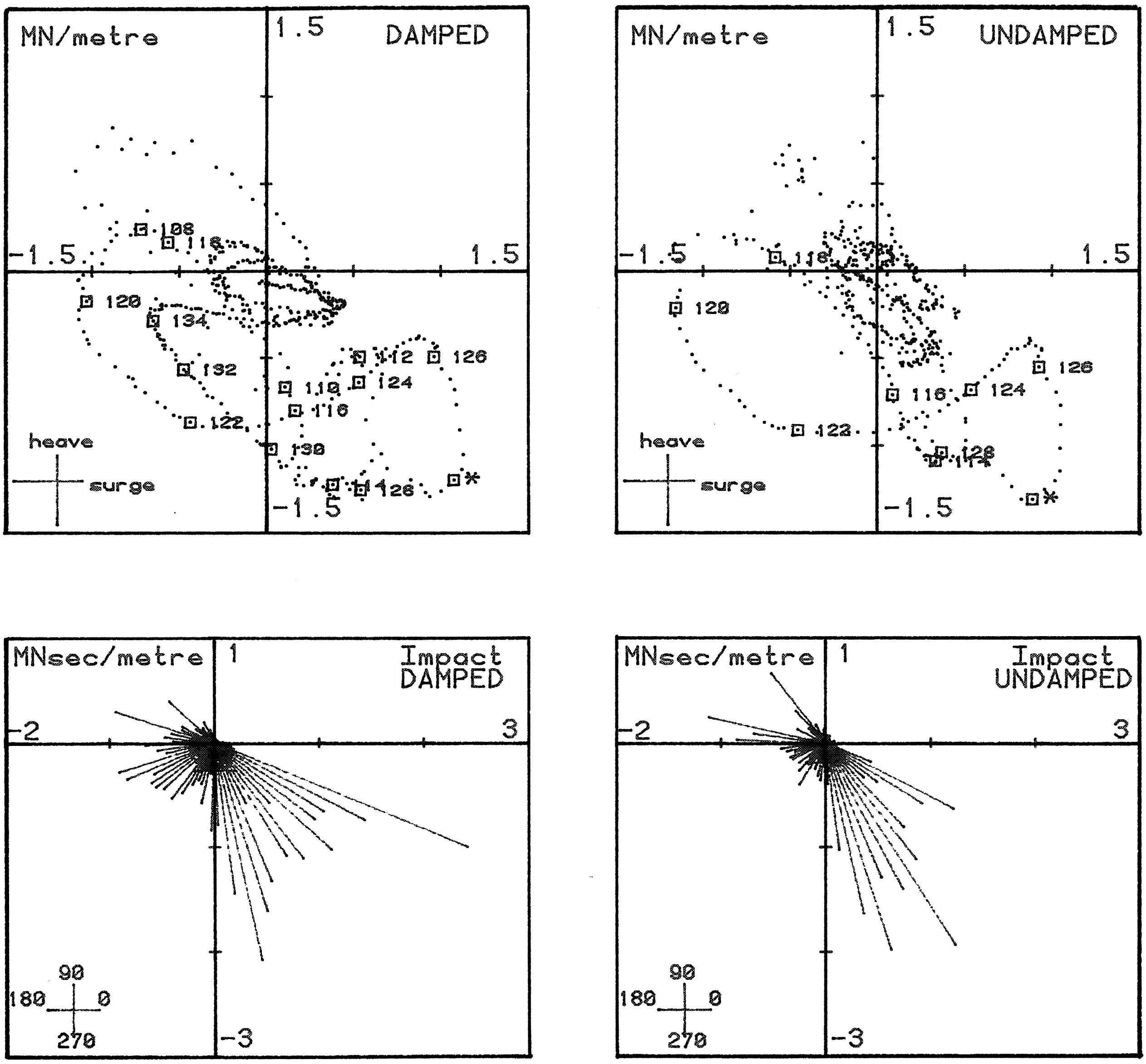
The photographs for 112 seconds show a distinctive pattern of three puffs of foam to leeward. The repeatability between photographs 6 and 9 is satisfactory.

graph 4 a | SURGE & HEAVE FORCES

rigid axis, position: +15



FORCES graph 4b



(No Photograph)

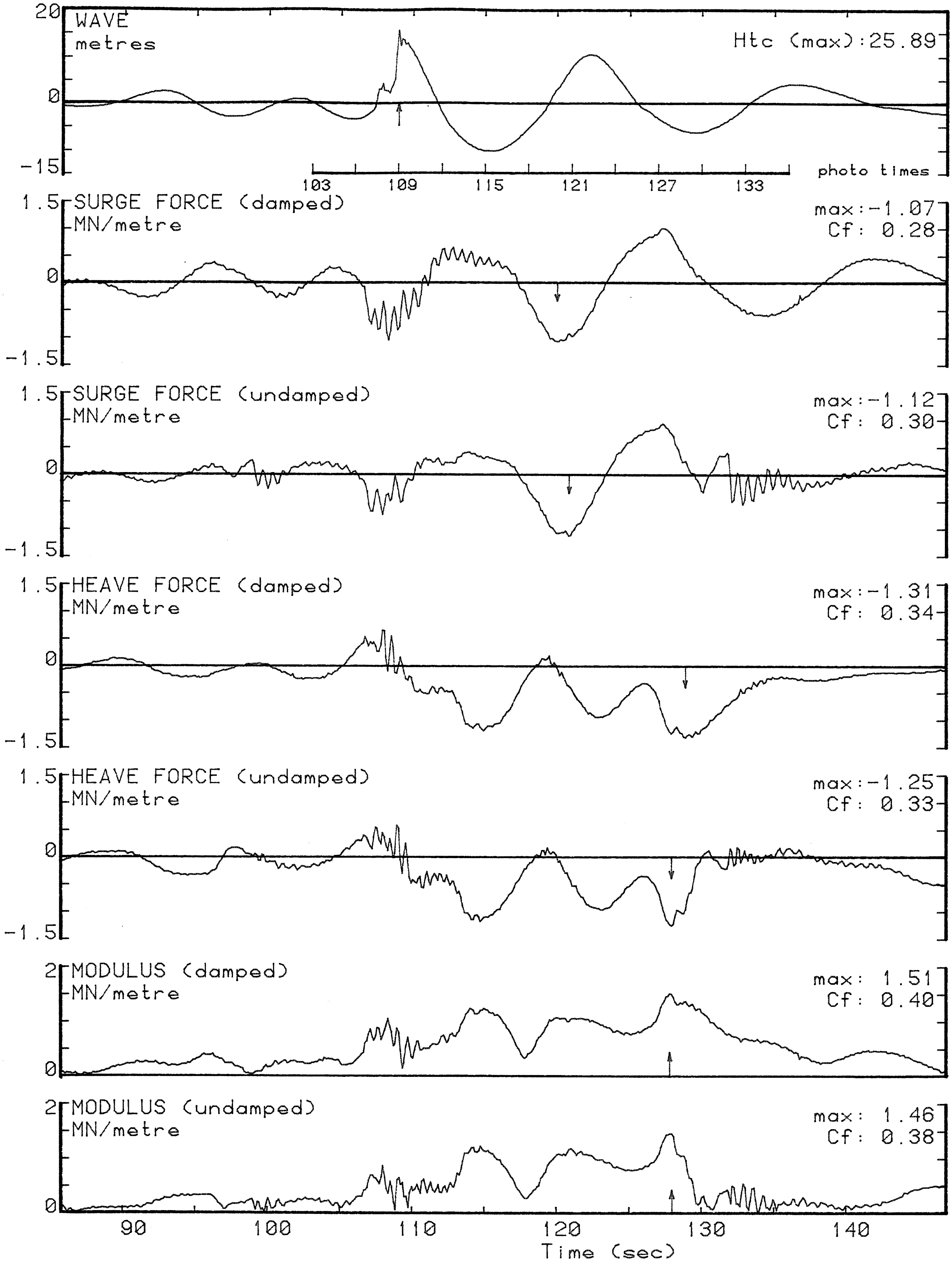
There is still little change in behaviour, but the rise in force coefficients continues.

The discontinuity of the wave record at 107 to 108 seconds corresponds to the arrival of the main body of foam. It was necessary to switch off half the flash tubes to maintain even exposure.

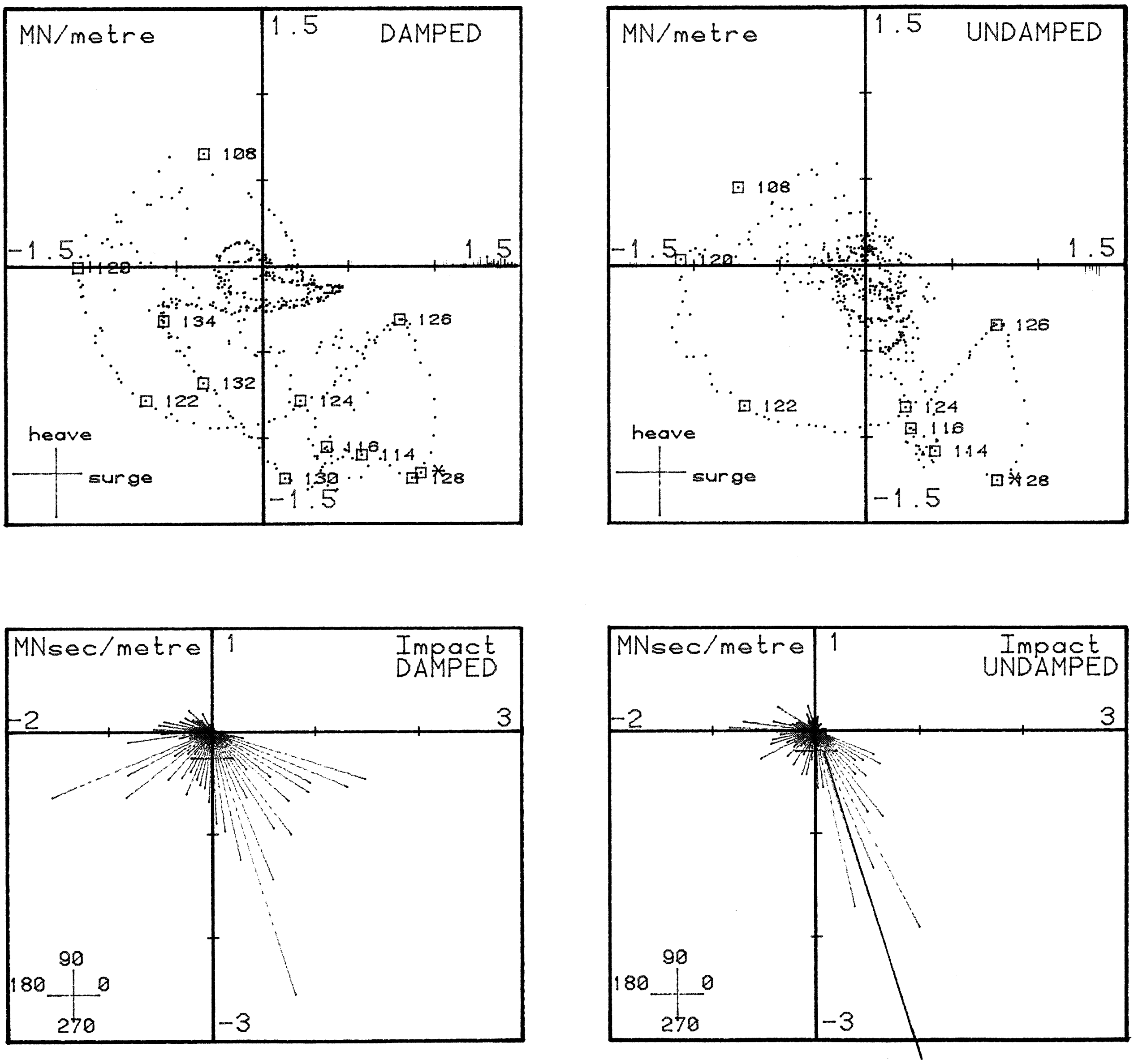
While previous impact records show little difference this position shows an unusually long line 25^{o} below the forward horizontal for the damped case. It is surprising to see such a large ray with no contribution in the next sector.

The absence of impact in the first quadrant continues. Undamped impact records are also deficient in the third quadrant. The fourth quadrant is always the most heavily used.

graph 5 a | SURGE & HEAVE FORCES rigid axis, position: +30m



FORCES graph 5b



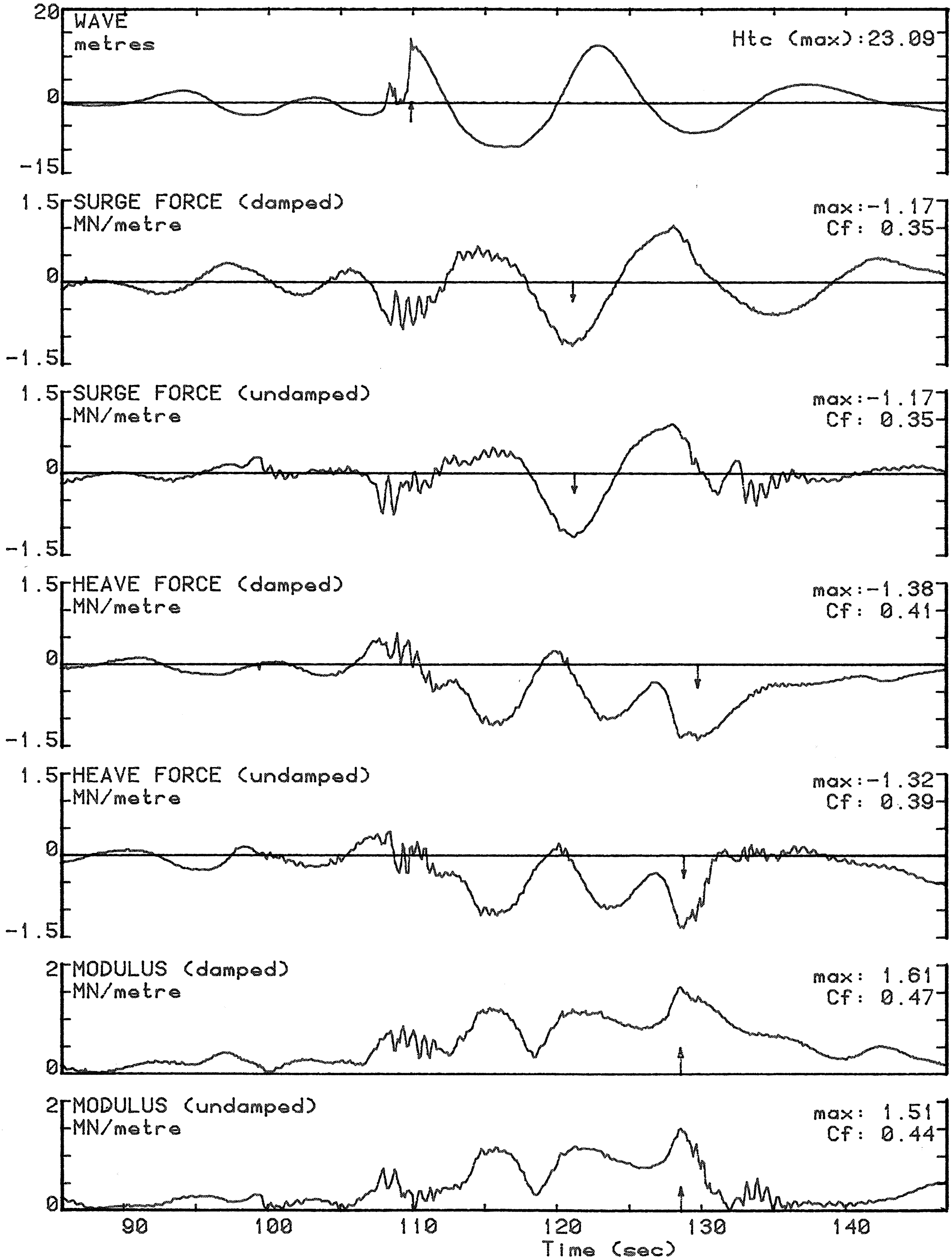
(See Photograph 7)

The force records show little change.

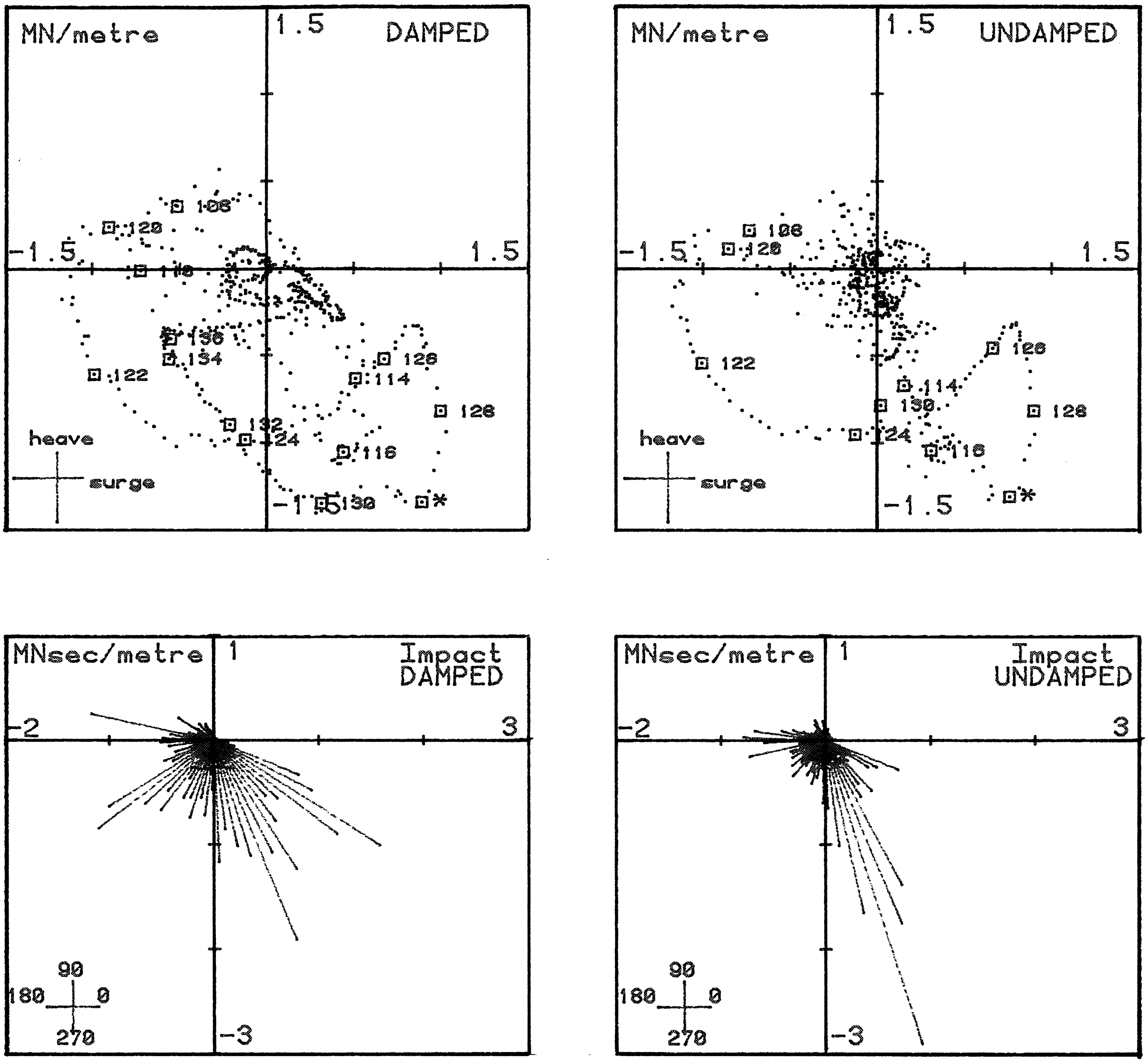
The force coefficients have dropped slightly. However the undamped impact record shows an unusual concentration at 75^{o} below the forward horizontal.

graph 6 a | SURGE & HEAVE FORCES

rigid axis, position: +45m



FORCES graph 6 b



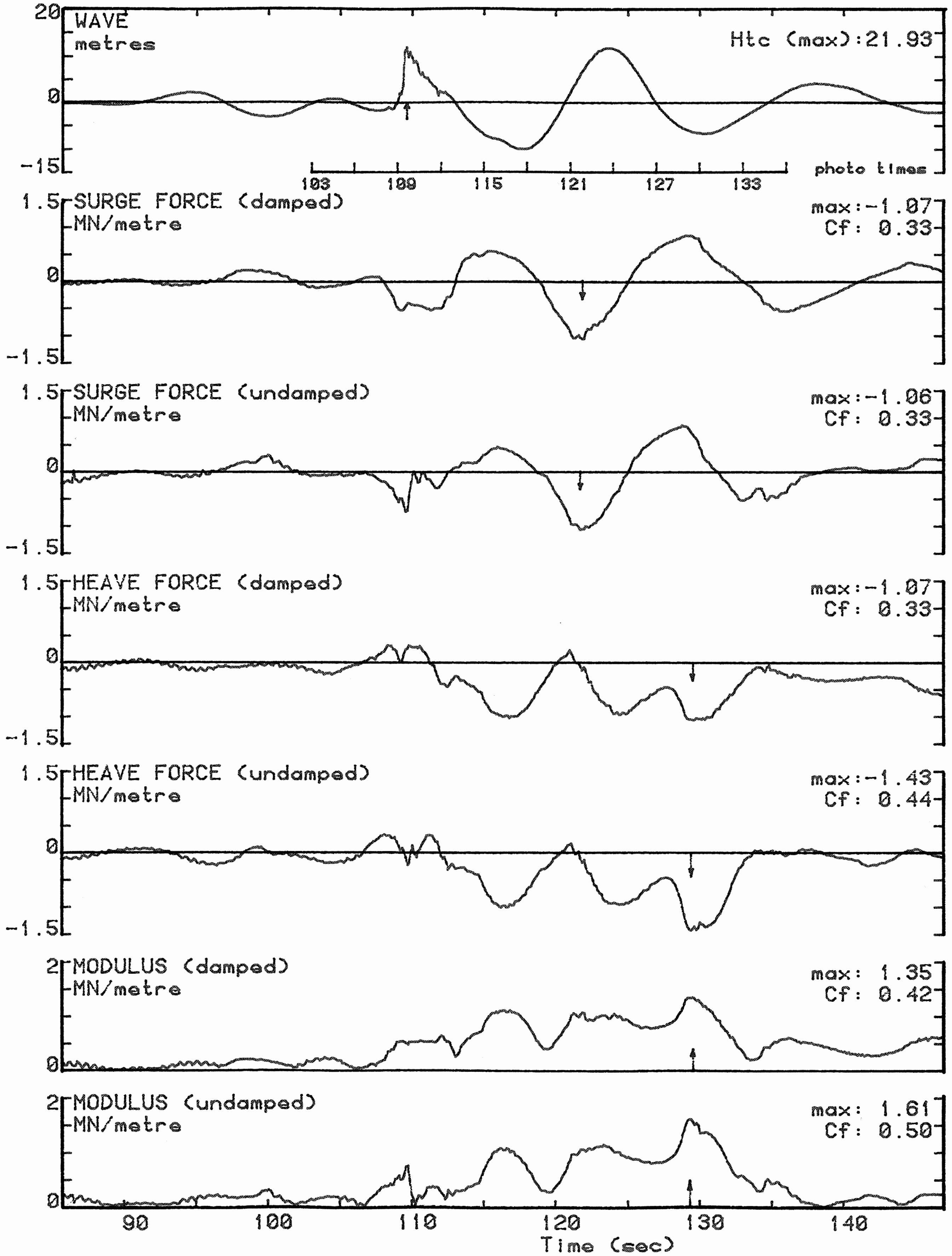
(No Photograph)

There is now a small upward trend in the force coefficients.

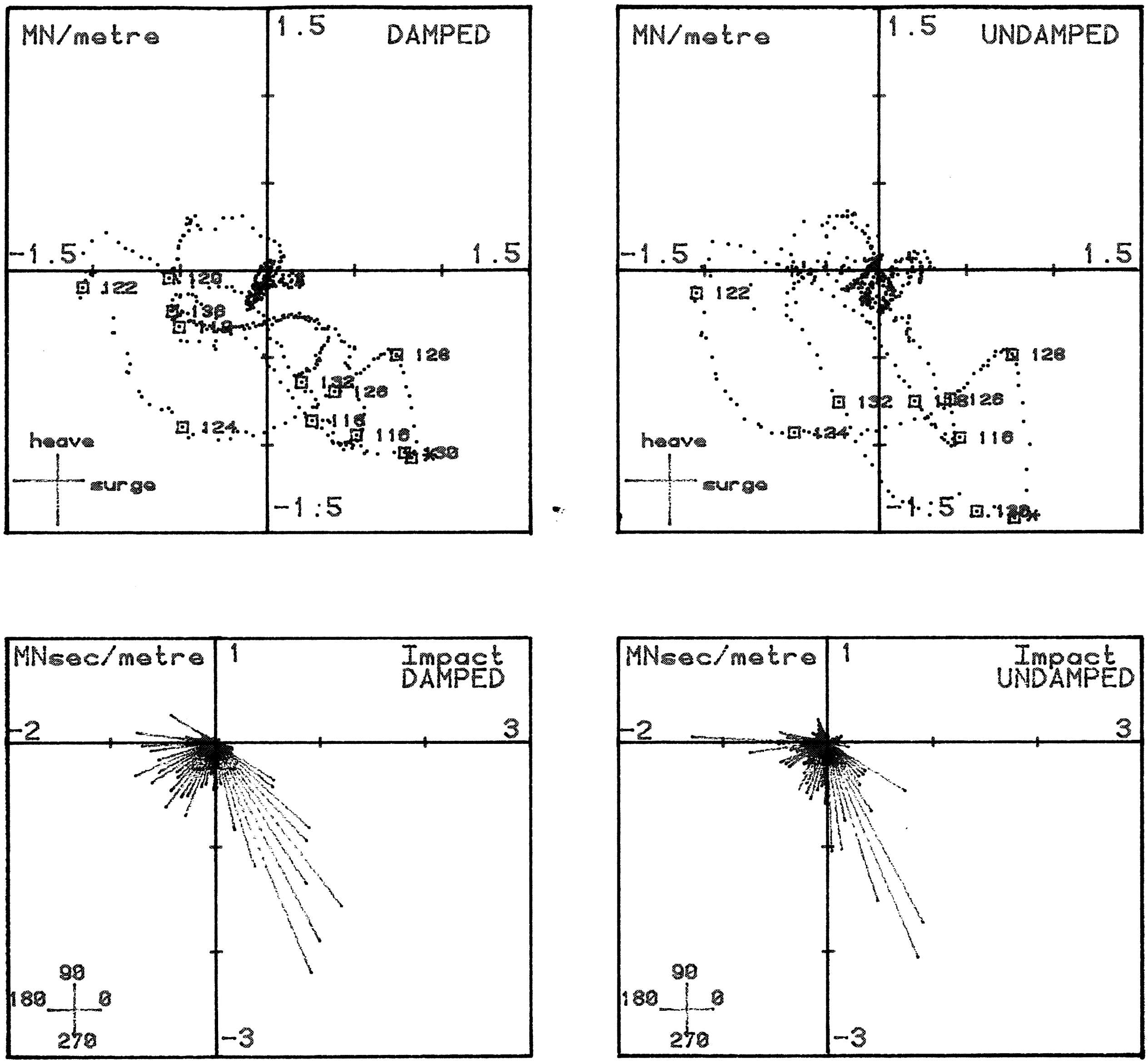
The impact record shows very similar results to the previous test with a large 75^{o} spike in the undamped test.

The discontinuity of the wave record at 109 seconds is as would be predicted from photograph 4.

graph 7 a | SURGE & HEAVE FORCES
rigid axis, position: +60m



FORCES graph 7b



(See Photograph 8)

This record has the smallest measured wave height. The first crest is much reduced. Perhaps as a result the upward heave pulse at 109 seconds is less than in earlier tests.

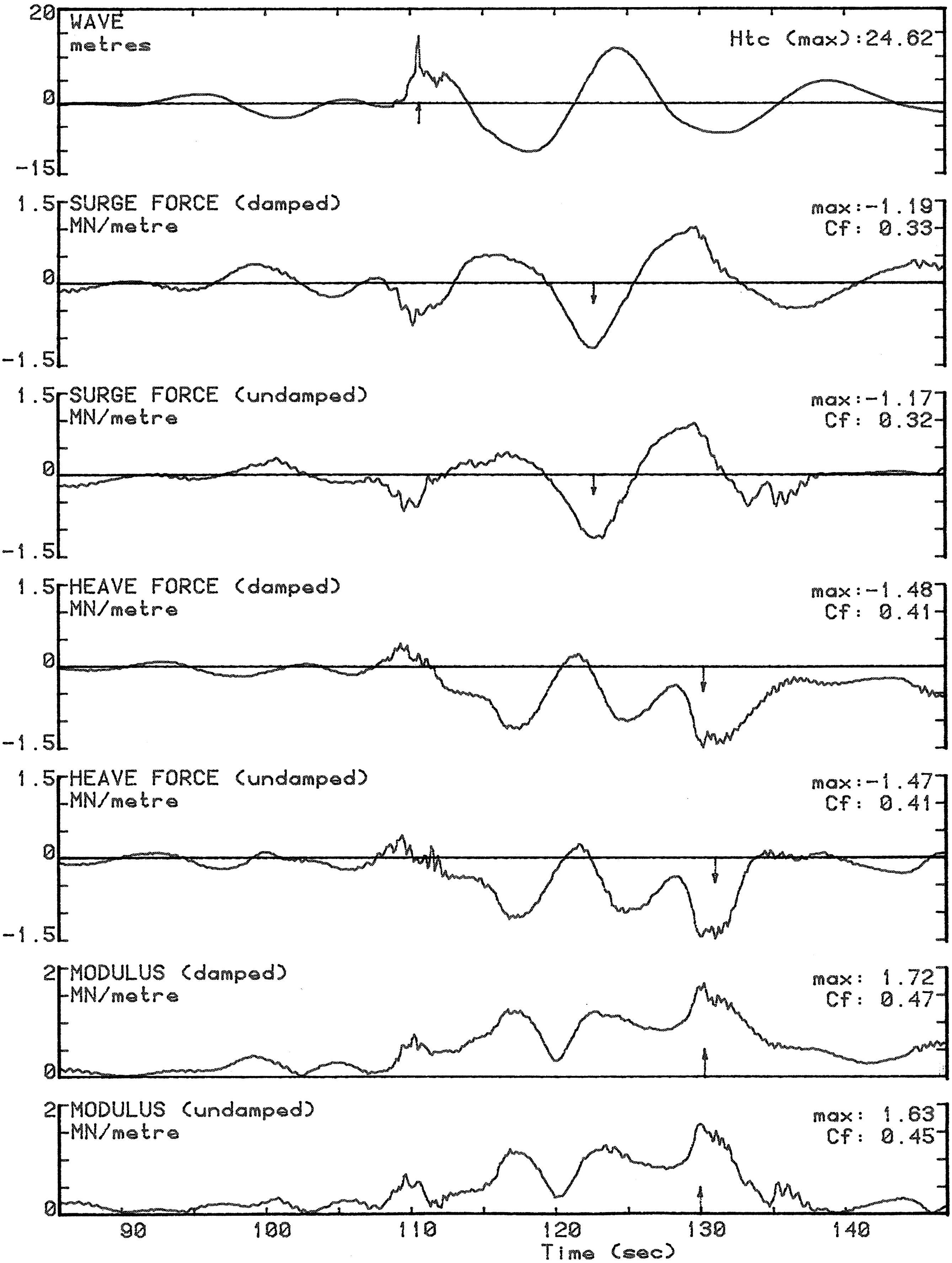
Force coefficients are still high but the impact diagrams are showing a more even distribution of force.

The photograph for 106 seconds shows a vicious whip-like breaker. While the photograph of 109 looks very frightening its force modulus is only one half of the maximum for the test.

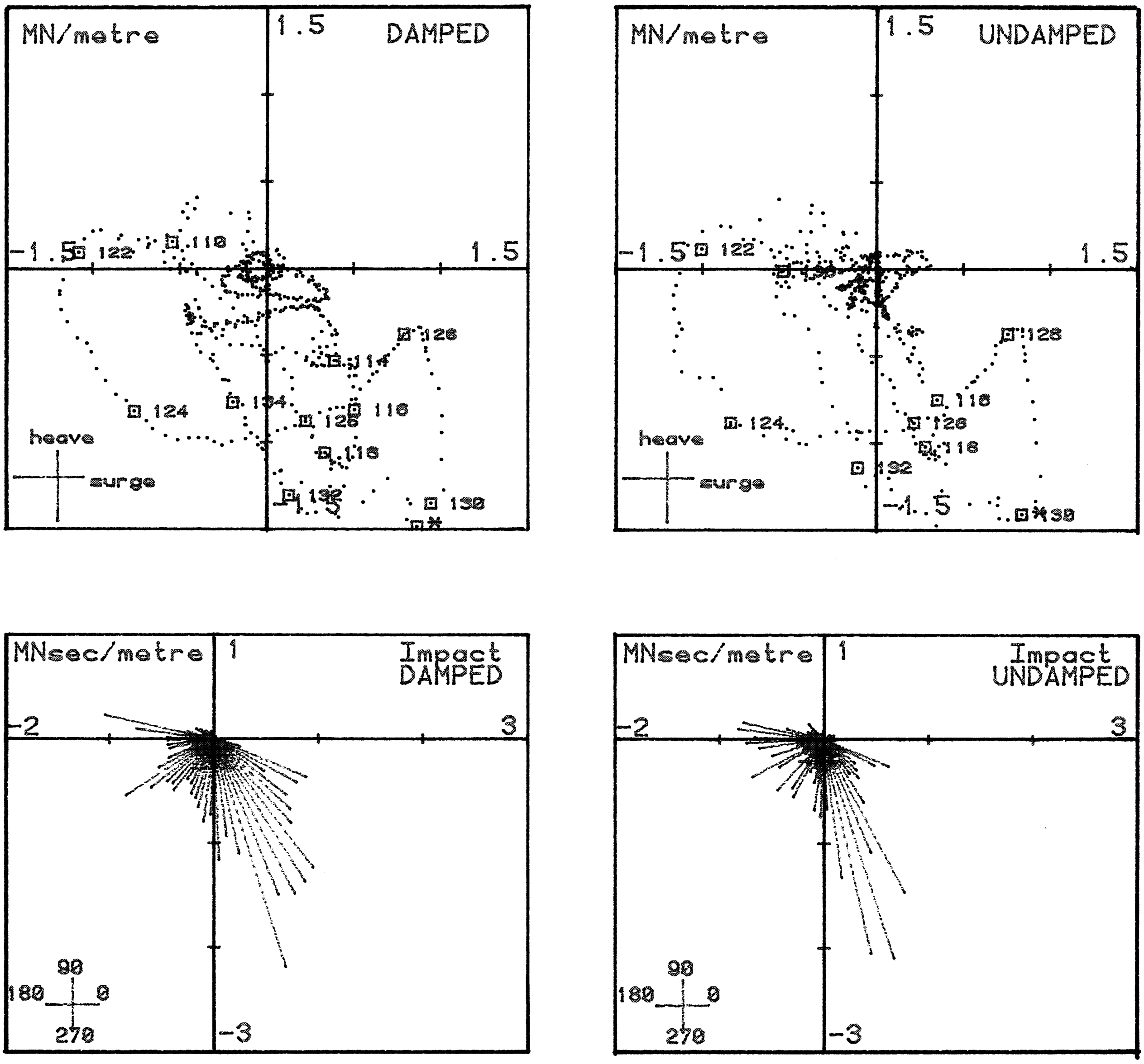
The photograph for 130 seconds shows a duck being left behind by the wave. This is the time for maximum force but would not have occurred with a free string, which would have submerged.

This record shows the least amount of 18Hz vibration.

graph 8 a | SURGE & HEAVE FORCES
rigid axis, position: +75m



FORCES graph 8 b

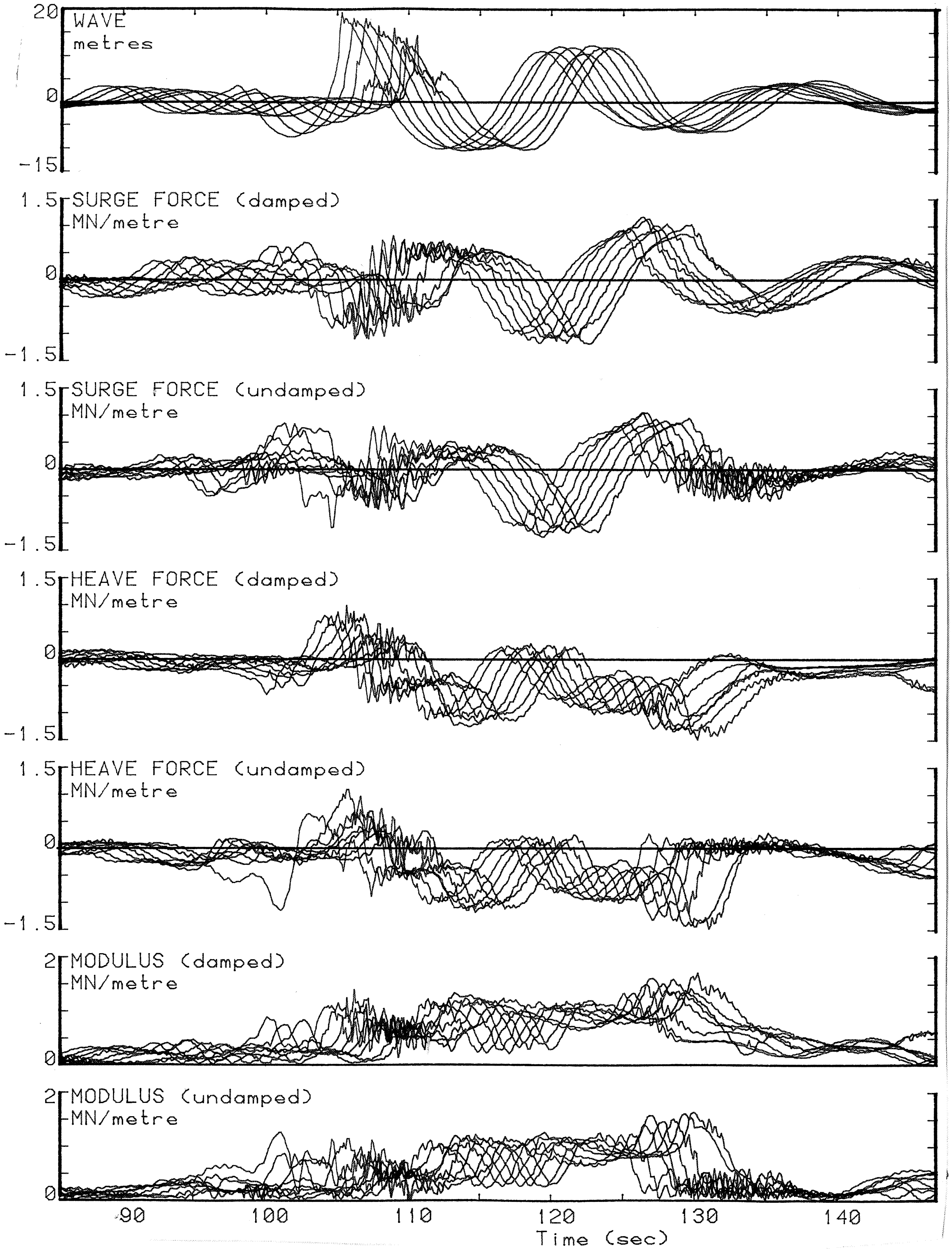


(No Photograph)

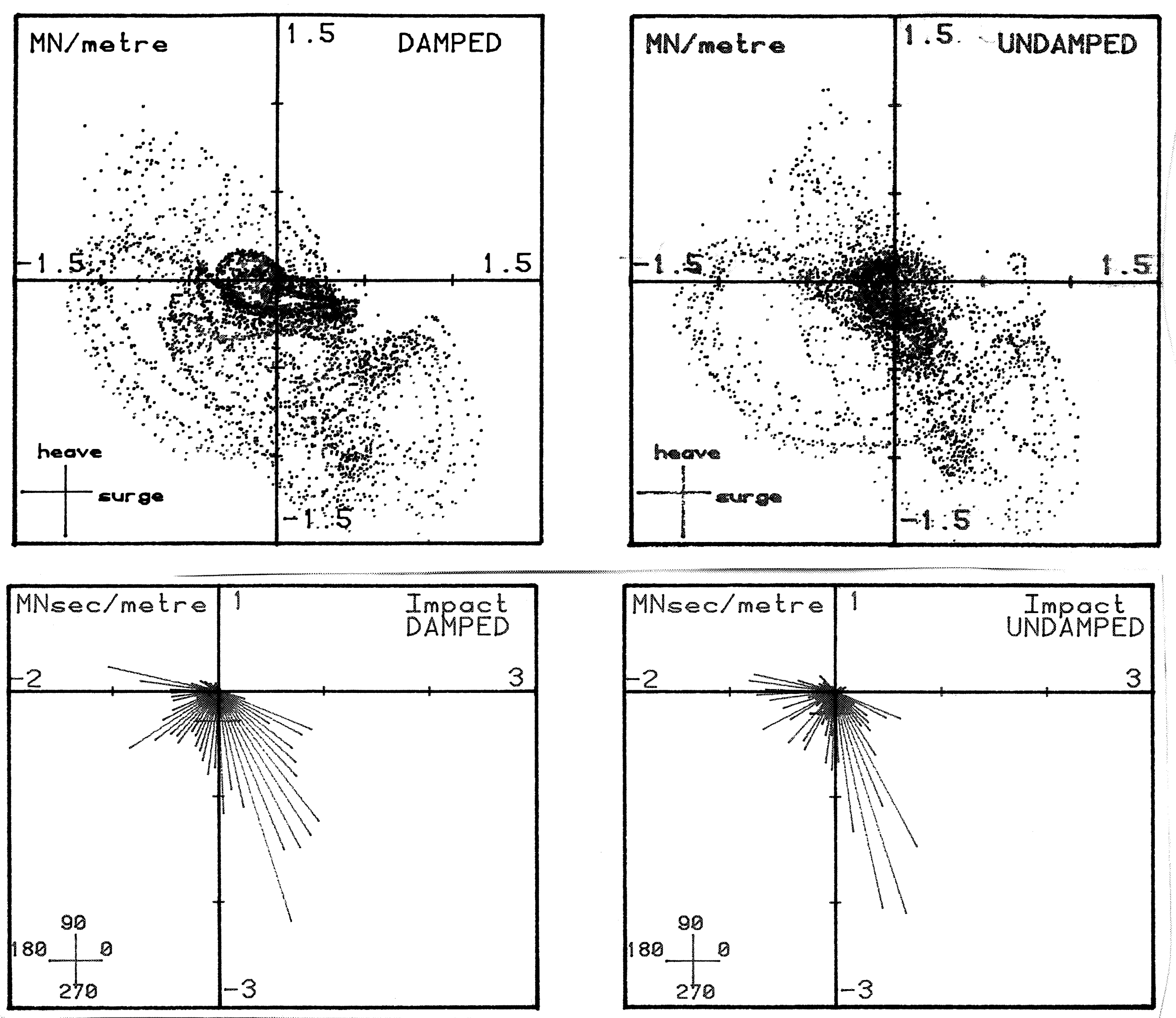
This position is five duck diameters back from the breaking wave. Its force coefficients are the highest for the normal attitude tests but are still typical by the standards of the P.M. spectrum test of volume 1 of the 1976 report.

The narrow spike in the wave record at 111 seconds is suspect. The corresponding pictures in photograph 4 show foam going outside the field of view and cine film showed droplets rising to heights equivalent to 100 metres above sea level.

graph 9a | SURGE&HEAVE FORCES rigid axis COMPOSITE of graphs 1–8



composite FORCES graph 9 b



<u>Composite Results</u>

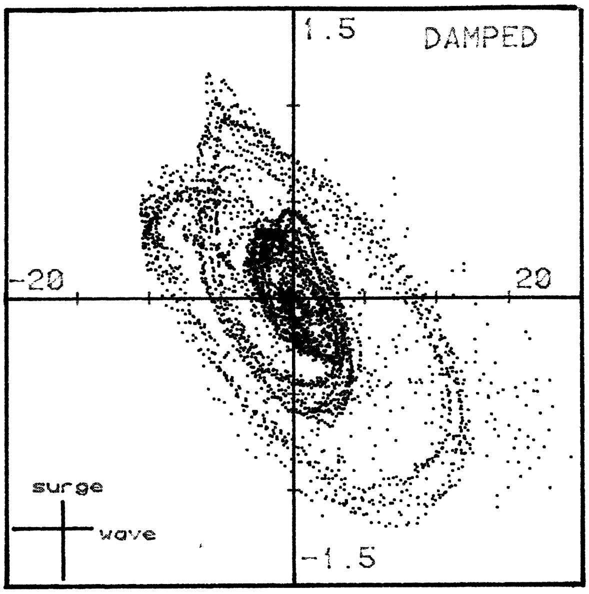
These plots show data from all experiments except those with changed duck attitude. The superposition highlights trends and anomalies. We noticed the following points:-

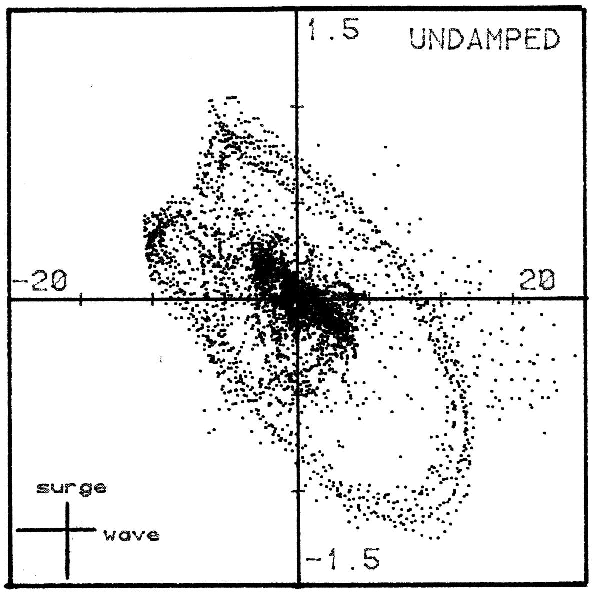
1. While the heights of the first crest taper downwards the amplitudes of the rest of the wave sequence are very similar.
2. High frequency vibrations are often in phase.
3. All tests show strong downward heave.
4. There is a crescendo in both force modulus traces. Perhaps we are being misled by considering only the vertical displacement of the water. A horizontal gauge might give a different picture.
5. The abnormal results are from the forwardmost undamped records between 95 and 105 seconds.

The surge v heave point plots and the impact ray diagrams show nothing new.

graph 10a | FORCES plotted against WAVE COMPOSITES from data of graphs 1-8 (RIGID AXIS)

SURGE



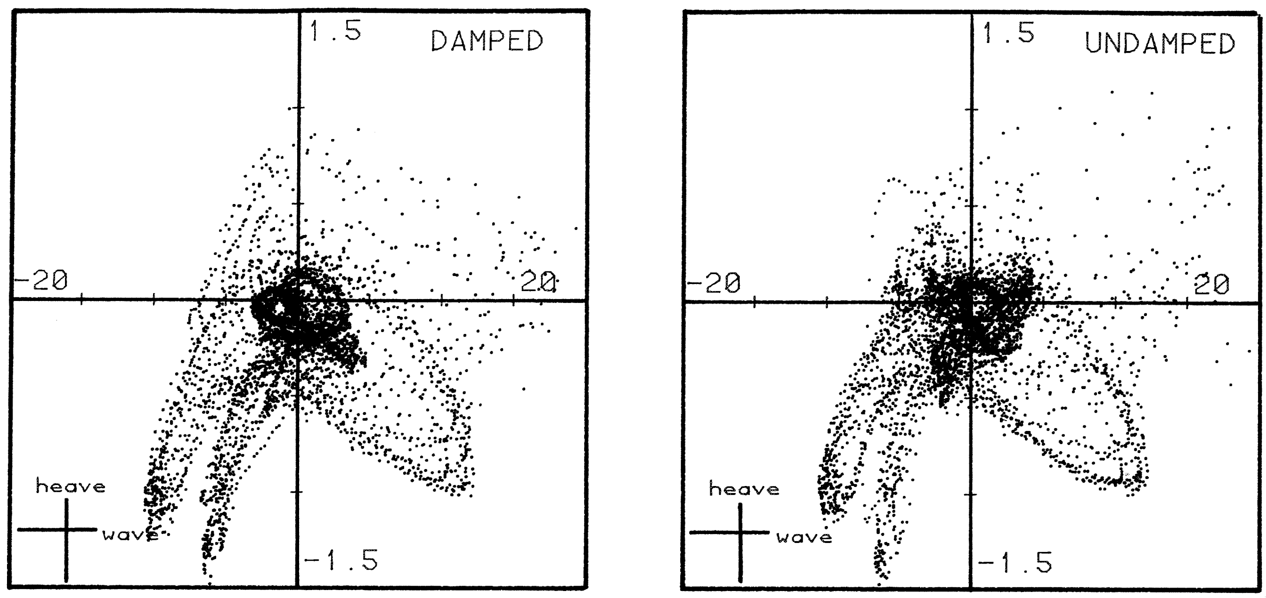


Composite Results for Surge Forces Against Water Position

In this swarm record we plot every instantaneous value of surge force against the position of water so that correlations would be revealed. If force was solely determined by water position the results would lie on a straight line. In fact most results lie on an ellipse with an aspect ratio of about 2.25. There is a tendency towards concentration in a central area and an outer track. We call this the pony club effect.

composite FORCE/WAVE graph 10b

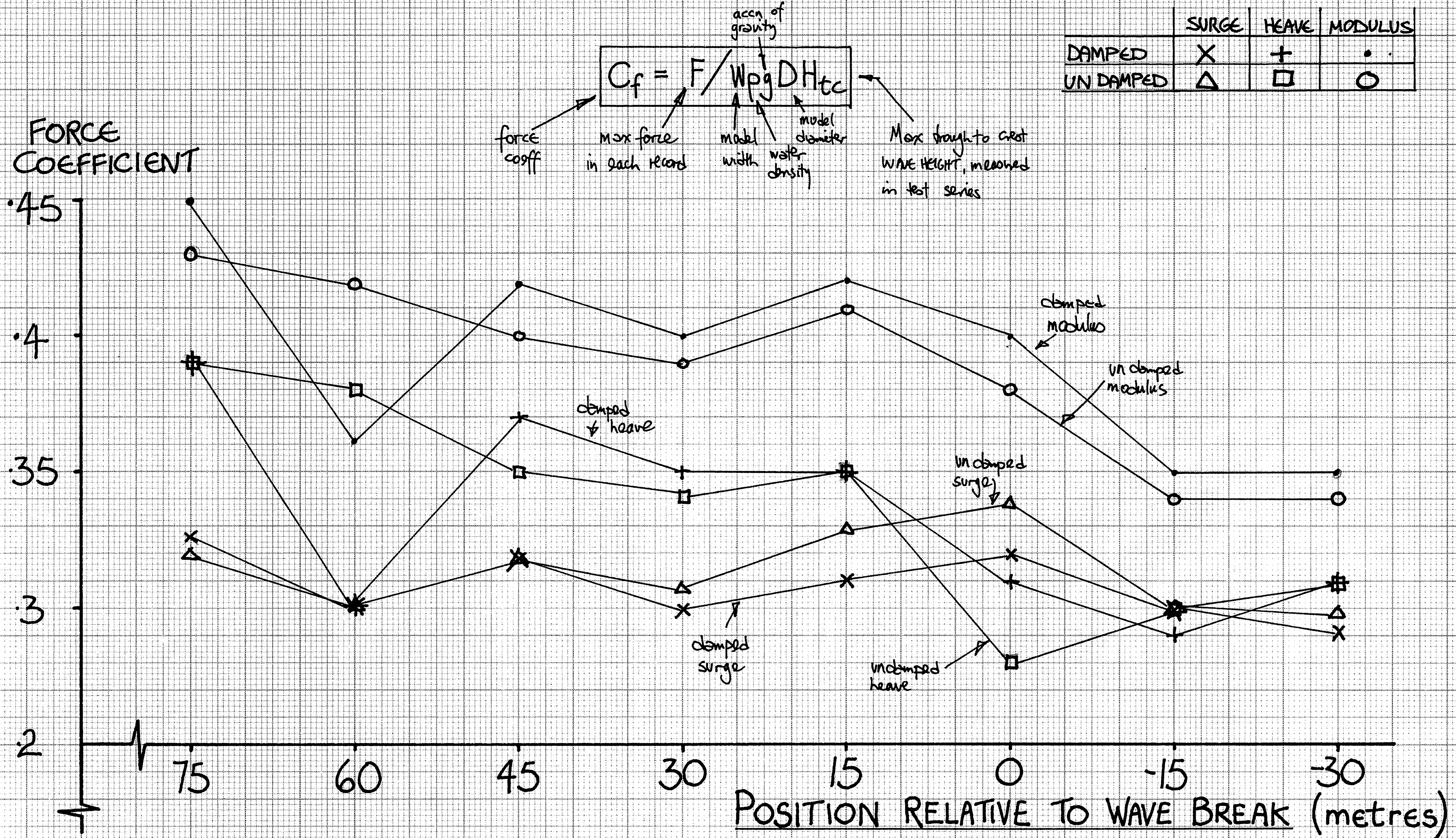
HEAVE



Composite Results for Heave Force Against Water Position

There could be no better way to demonstrate the downward rectifying effects for heave force. The small forces are concentrated in a roundish central blob while the larger ones follow an inverted U.

graph 11: FORCE COEFFICIENTS against position from graphs 1-8



Graph 11

Force Coefficients As A Function Of Position

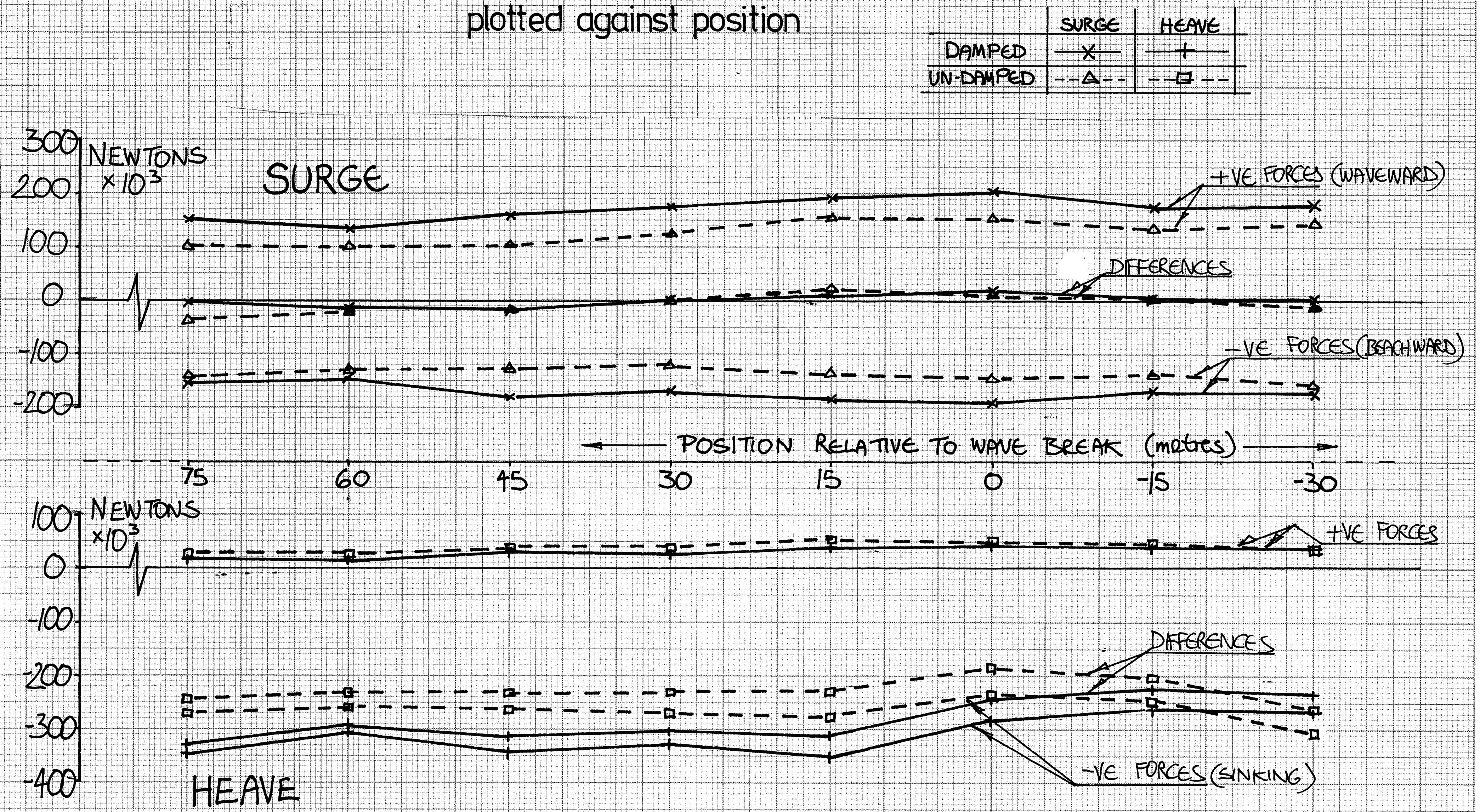
Force coefficients (see p 2.2 of our 1976 report and p 6.13 of the 1978 report) are calculated from the highest value (29.49m) of trough to crest height which was measured at the forwardmost position. We calculated them for heave, surge and modulus forces for damped and undamped ducks. Results are plotted against position.

We were surprised to see that in general the coefficients are lower than those calculated for less spectacular waves, and that they are lowest of all in what we might have expected to be the most dangerous parts of the wave. If we had calculated the coefficients on the basis of waves measured for each duck position instead of the highest wave of the whole test series this variation between positions would have been even more marked, but the leeward values would have been in line with our earlier results. Steepness itself does not appear to be dangerous. Indeed if we have to deal with 30 metre waves we would prefer to have them steep and breaking on top rather than in front.

The modulus coefficients are very slightly higher for damped models but the other coefficients show little difference. The effect is caused by the damped models having their forces in phase. We conclude that a failed power take-off need not cause bearing problems between duck and backbone. But the higher velocities may cause problems for the gyros.

graph 12: AREAS UNDER THE FORCE CURVES

plotted against position



Graph 12

Areas Under The Force Curves

The force coefficient calculations of graph 11 are based on the single highest value of force and so are peak sensitive. It is interesting to calculate a second indicator based on the area under the force curve divided by the time of the experiment. We have calculated separately the areas above and below the zero line. This gives us a general wear and tear figure for calculations involving the deflation rate of a slubber pad or the accelerations of a system dominated by inertia.

We have also calculated the difference between the force areas above and below, divided by the time of the experiment. This would give an indication of the mooring and the sinking forces.

We observe that there is a reduction in force at the forward positions.

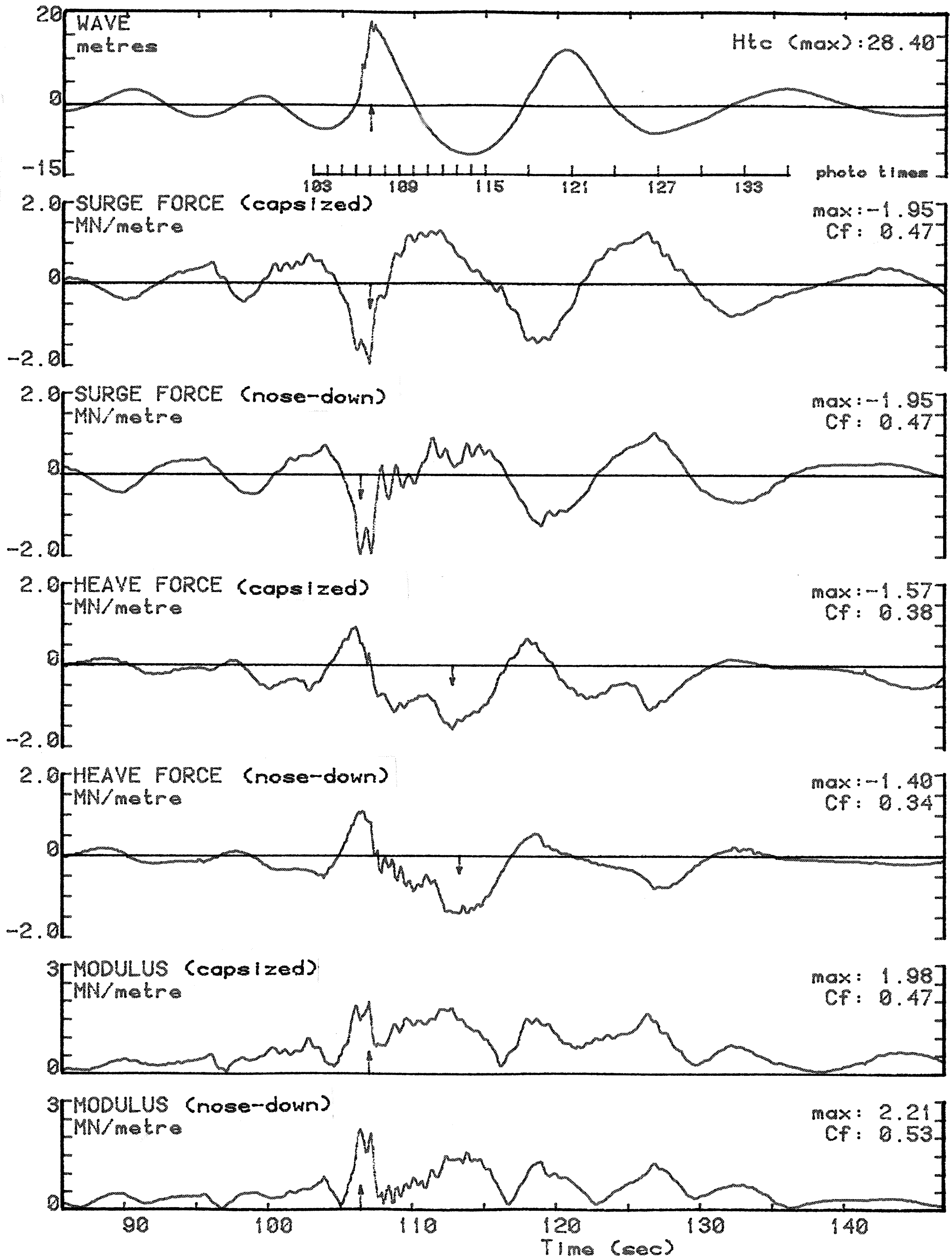
We find that even though the experiment is short (61.2 seconds at 15m and 50 seconds at 10m) the residual mooring force is very small and can be of either polarity. The residual sinking force exceeds the buoyancy margin of the duck. A free floating duck string would sink.

Damping increases force area in the surge direction by almost 30%. This is much more than we would have expected from peak force results.

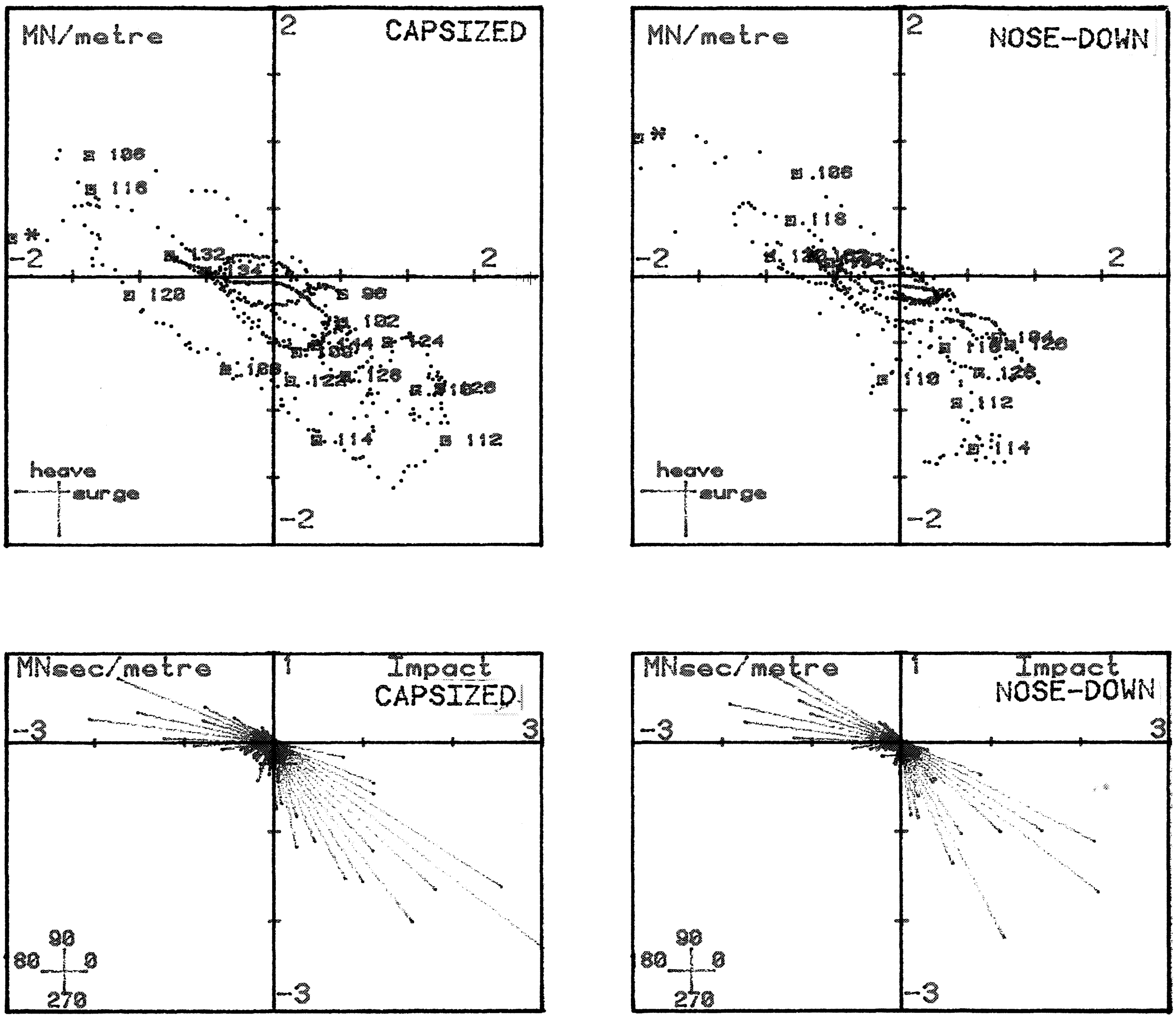
Damping makes little difference to the mooring forces.

Damping increases the sinking force area by about 20%.

graph 13 a | SURGE & HEAVE FORCES rigid axis, capsized & nose down



FORCES graph 13b



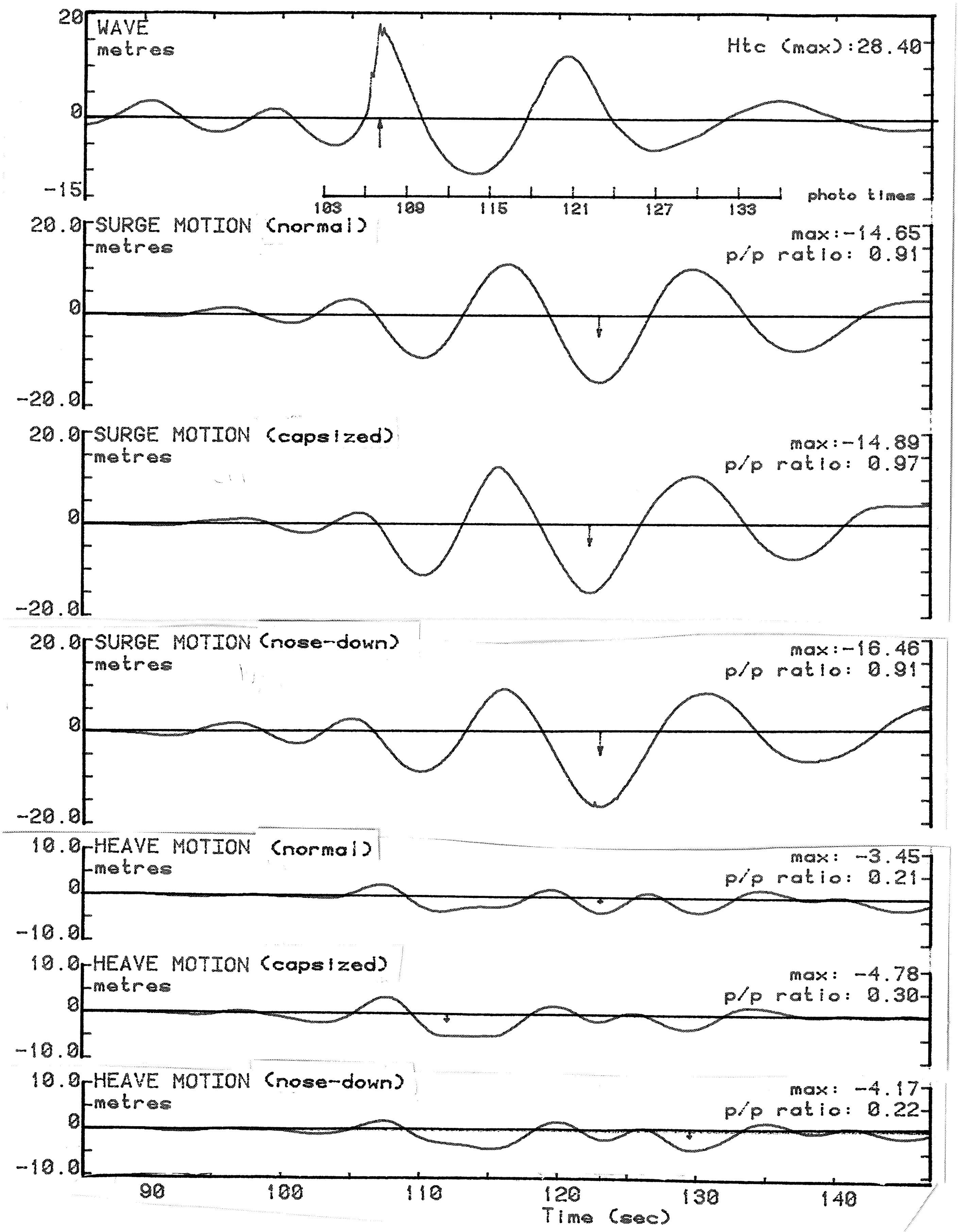
(See Photographs 13 and 14)

It had been suggested that the capsized condition might lead to lower forces. We compared capsized and nose down force records on this graph. The power take-off mechanism was used to hold the duck capsized without changing its ballast. Force coefficients are about twice those measured for normal attitude ducks at the same test positions.

Force measurements on the compliant mounting are difficult to interpret because of the problem of accelerating the mass of the rig. But some tests indicate that a nose down attitude caused by additional ballast in the nose of the duck could reduce wave forces. We added weight equivalent to 24 tons per metre for a 15 metre duck (11 tons per metre for a 10 metre duck) which is about equal to the buoyancy margin. This produced very much smaller angular movements and absence of any capsizing. This test sequence is shown in photograph 13. The duck angular excursion is only about 80^{o}, very comfortable for gyros.

When the tests were repeated on a fixed axis, photograph 14, there were two extraordinary effects. The first was a substantial rise in measured values of force. The second was the double loop. The duck capsizes, fails to recover normally but continues to go backwards underneath the mounting to its original position just in time for the second crest to send it round again for a second complete revolution. This would do the electrical power cables no good at all. No other test conditions produce even a single rotation and as the fixed axis and the excess ballast are both abnormal we do not feel that there is any cause for concern.

graph 14a | SURGE & HEAVE MOVEMENTS compliant axis



Graph 14 (14b on next page)

Movement Records
(See Photographs 10,13 and 14)

If yielding is to be used to run away from big waves we need to know how far to run. For all our experiments the rig is allowed to move at constant force if the force exceeds 23 tons per metre for a 15 metre duck and 10.2 tons per metre for a 10 metre duck.

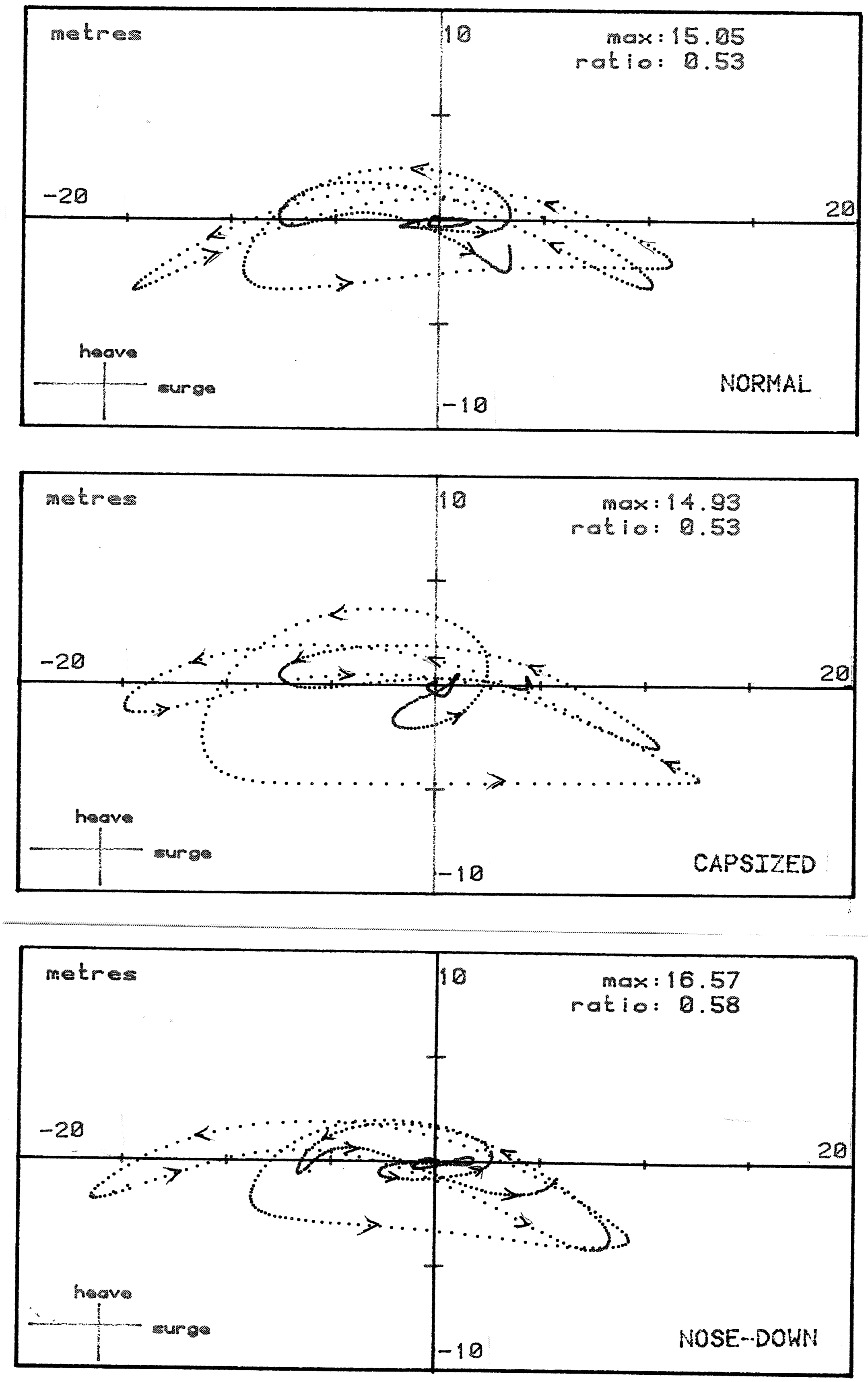
In this experiment we recorded movements in three conditions. One was with a normal damped duck. The second was a duck held capsized by torque in its power take-off motors. The third was a duck held nose down with extra ballast weights. The results are shown in graph 10. They were measured at the nominal breaking position.

There is very little difference in the movement of the three cases. The surge motions continue to increase even though the wave envelope is decaying.

The heave motions have a prolonged downward dwell from 110 to 116 seconds and show a downward bias which comes as no surprise.

The surge movements are about .9 of the wave record whereas the heave movements are only about .25. The nose down attitude (which had the smallest duck angles) has the biggest excursions. As we are concerned about the amount of heave joint angle needed to accommodate large steep waves running along the string the small heave movements are encouraging.

MOVEMENTS graph 14b



COMMENTS ON PHOTOGRAPH SEQUENCES

Photographs are taken at times corresponding to one or three second intervals for a 15m duck (.86 seconds or 2.45 for a 10m duck).

The tick marks on the axes are at divisions of one duck diameter. The horizontal axis marks mean sea level.

Photograph 4

The duckless wave 103 to 114 seconds. The photograph for 105 seconds yields a length to height ratio of 4.6 to one.

Photographs 5, 6, 7 and 8

This group of sequences show fixed axis models in four different positions relative to the break point. Preliminary tests showed no visible difference between damped and undamped ducks. The undamped model was used throughout. The force modulus maximum always occurs between 125 - 129 seconds when the duck is near vertical during recovery. The direction of this force is usually 45° below the waveward horizontal. There is a wall of water behind the duck and a noticeable hole in front. Photographs 6b and 7b at 127 seconds show the effect well.

The most dramatic picture is 109 seconds in photograph 8a but the corresponding records on graph 7 show that the forces are quite moderate. White foam has a lower density than green water.

There is evidence of reflection in photographs 5 at 103 and 130 seconds. The nose re-entry between 128 and 132 seconds causes a splash in all photographs but there is nothing obvious in the force record.

There is an extraordinary "flare" in photograph 7b at 133 seconds, vertically above the duck.

The maximum angular excursion is seen in photograph 6 at 118 seconds and reaches 30° below the leeward horizontal. We would expect a smaller angle on a compliant mounting.

The maximum angular velocity is about 40° per second (0.7 rad per second) between 106 and 109 seconds in photograph 6. The others have maxima of about 30° per second. This agrees with results on p 2.39 of volume 1.

It is worth following the bubble sequence in photograph 6 from 103 to 109 seconds. It starts near the tip of the nose and changes into an arc. We cannot be sure how to interpret this and are planning bubble trace experiments.

Photographs 9, 10, 11 and 12

This set of sequences was carried out to determine the effects of mounting stiffness. The duck position was at the nominal breaking point of the wave. The mounting conditions were as tabled below:

	Heave	Surge
9	Rigid	Rigid
10	Compliant	Compliant
11	Compliant	Rigid
12	Rigid	Compliant

The compliance used was $1.3 \times 10^{-6} m^2/N$ for a 15 metre duck, but the main feature was the yielding to constant force at 23 tons/per metre. (10.2 tons at 10m).

The one second time intervals were chosen to give good resolution in the middle of the sequence.

It is useful to refer to the movement record in graph 14.

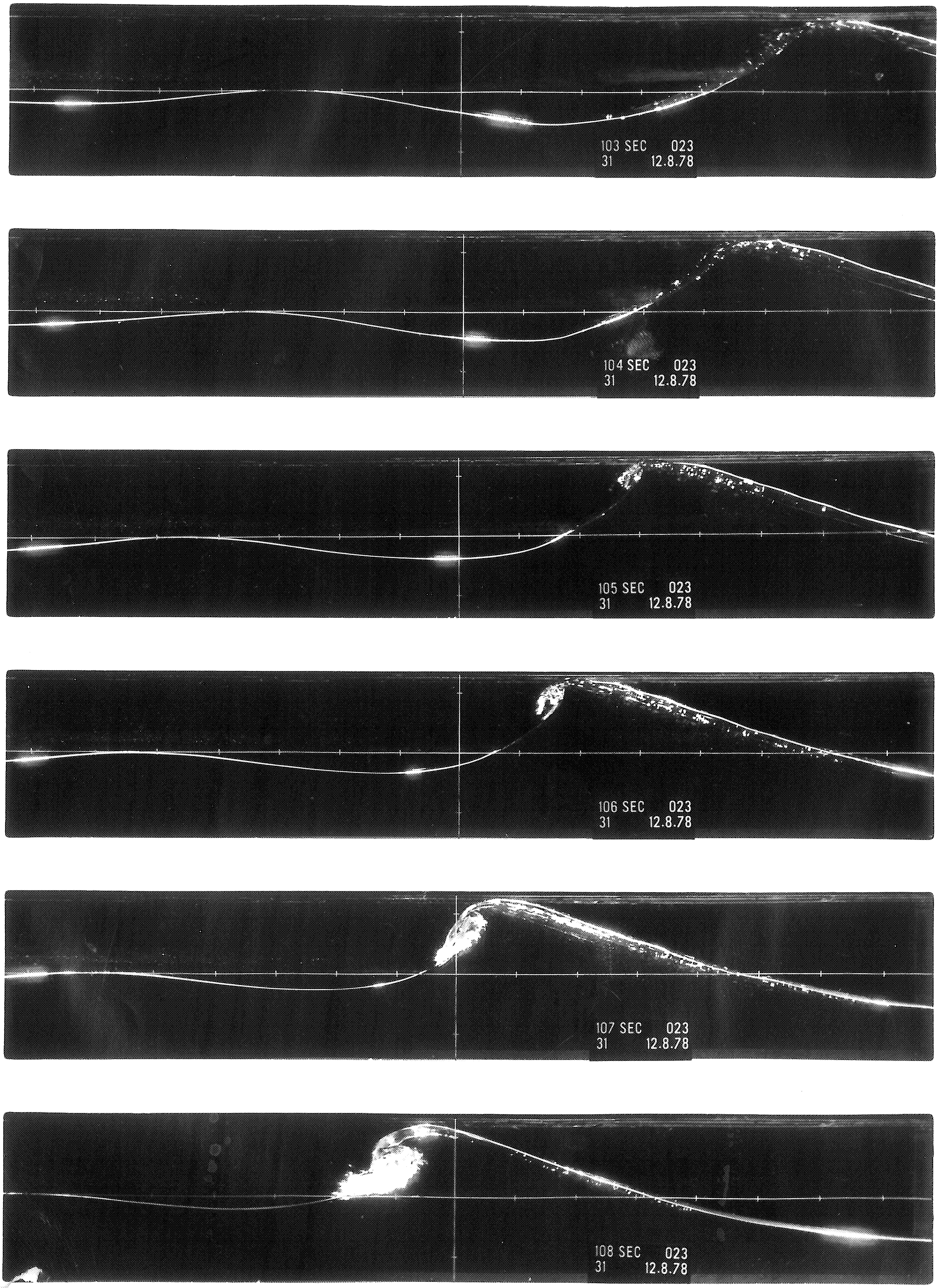
There is little visible difference between the four conditions. But duck angular velocities are lower when both axes are compliant. Up to 107 seconds all duck angles are the same. But at 111 seconds the compliant mounting duck is 60^{o} behind the others.

As gyrated ducks will have problems with high velocities this is a desirable characteristic. We think that 25^{o} per second is a reasonable design maximum for free floating ducks and will try to get it lower.

Photographs 13 and 14

These squares show tests with nose down ballasting on a compliant axis (photograph 13) and a rigid one (photograph 14). We are confident that the double loop effect will not occur with free floating strings. Force measurements for these are given in graph 13.

PHOTO 4a | scale 1/150 | WAVE ONLY



wave only

PHOTO 4b

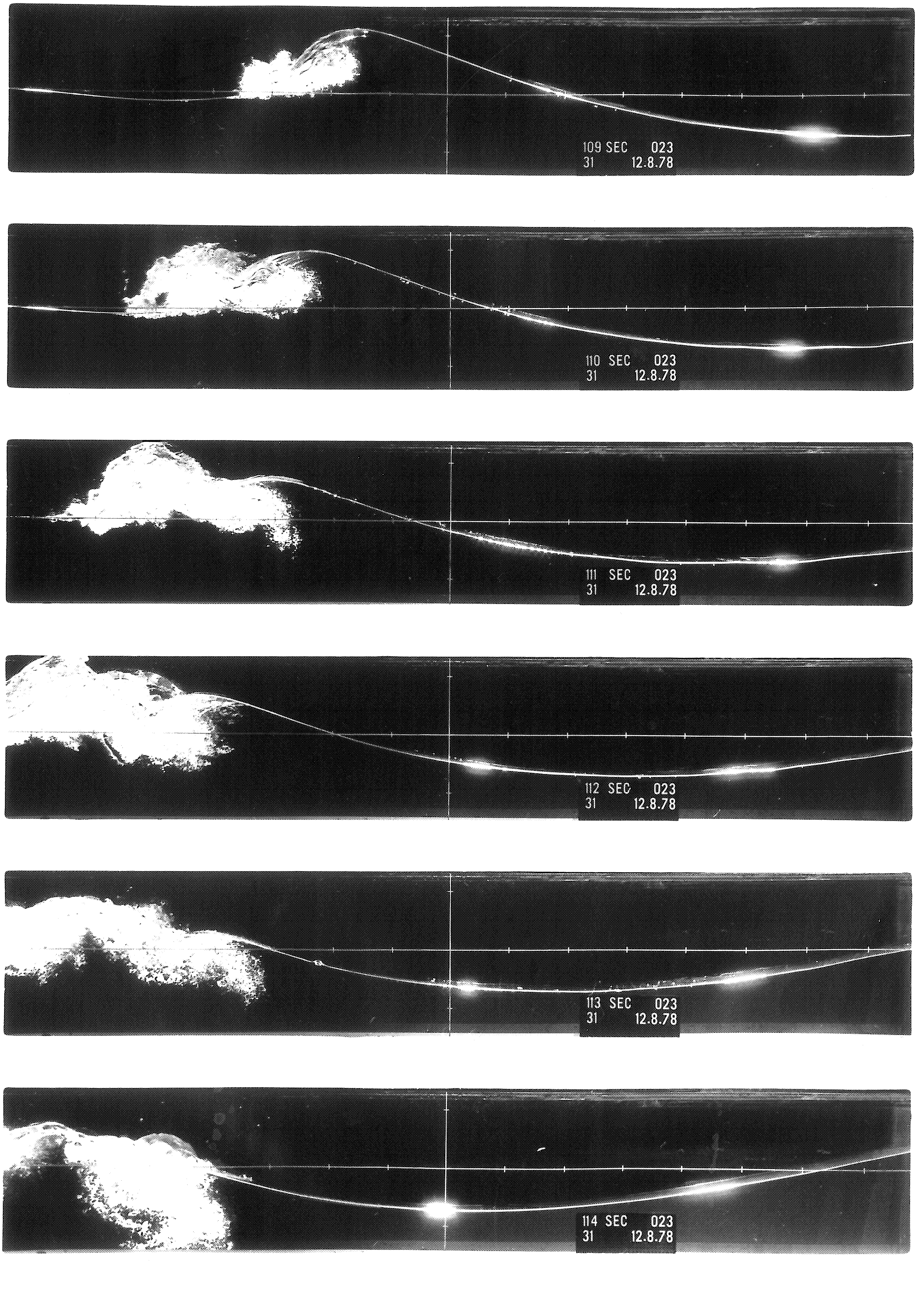
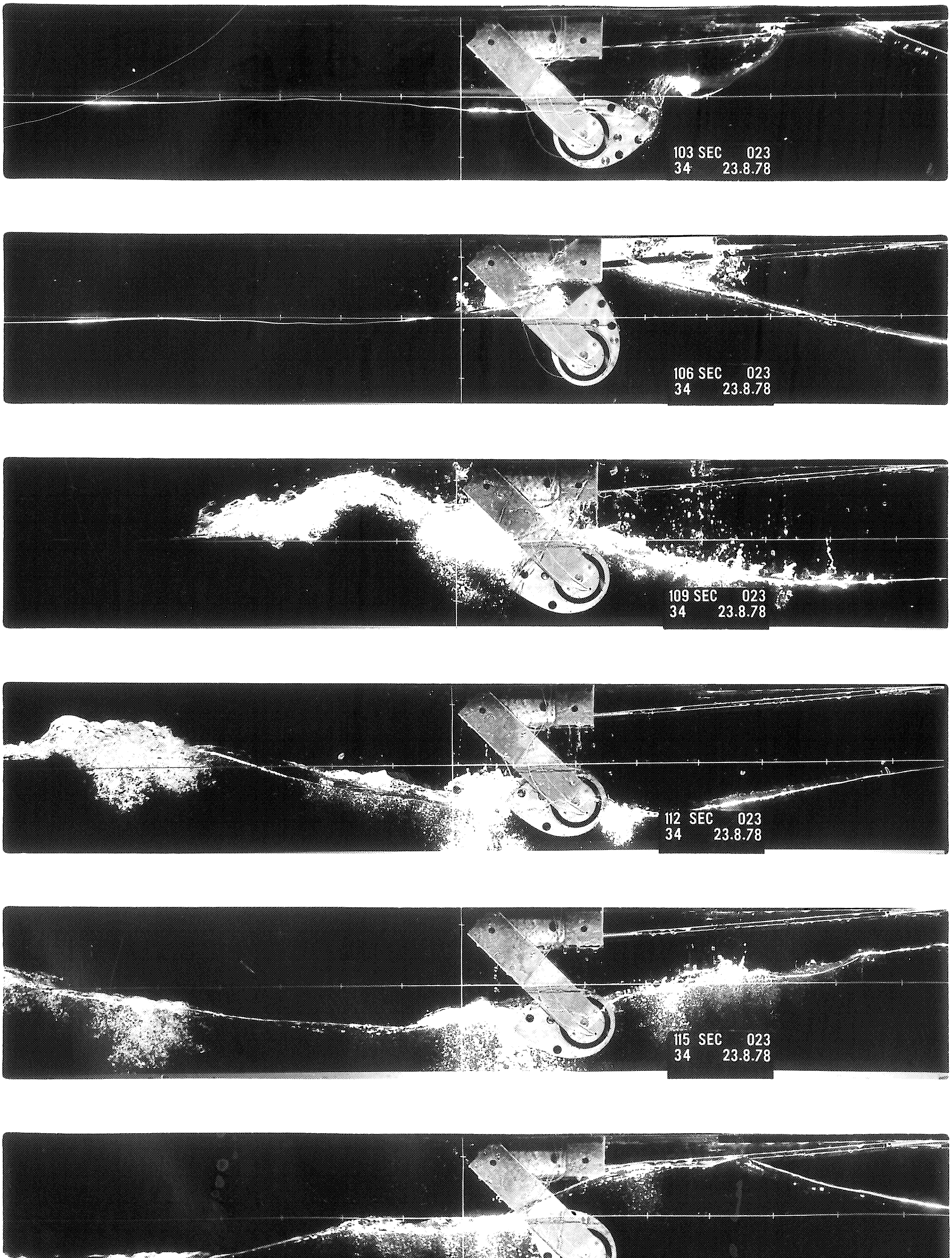


PHOTO 5a

scale 1/150

4 Different MODEL/WAVE SPACINGS
THIS ONE: 30mRIGHT (cf6,7,8) Rigid axis,0damping



Electrical Stiffness Density HEAVE SURGE	RIGID	Duck Damping (MNm/rad/s/m)	0	Torque Limit (MNm/m)		Time Step (sec)	3	position -30m	PHOTO 5b

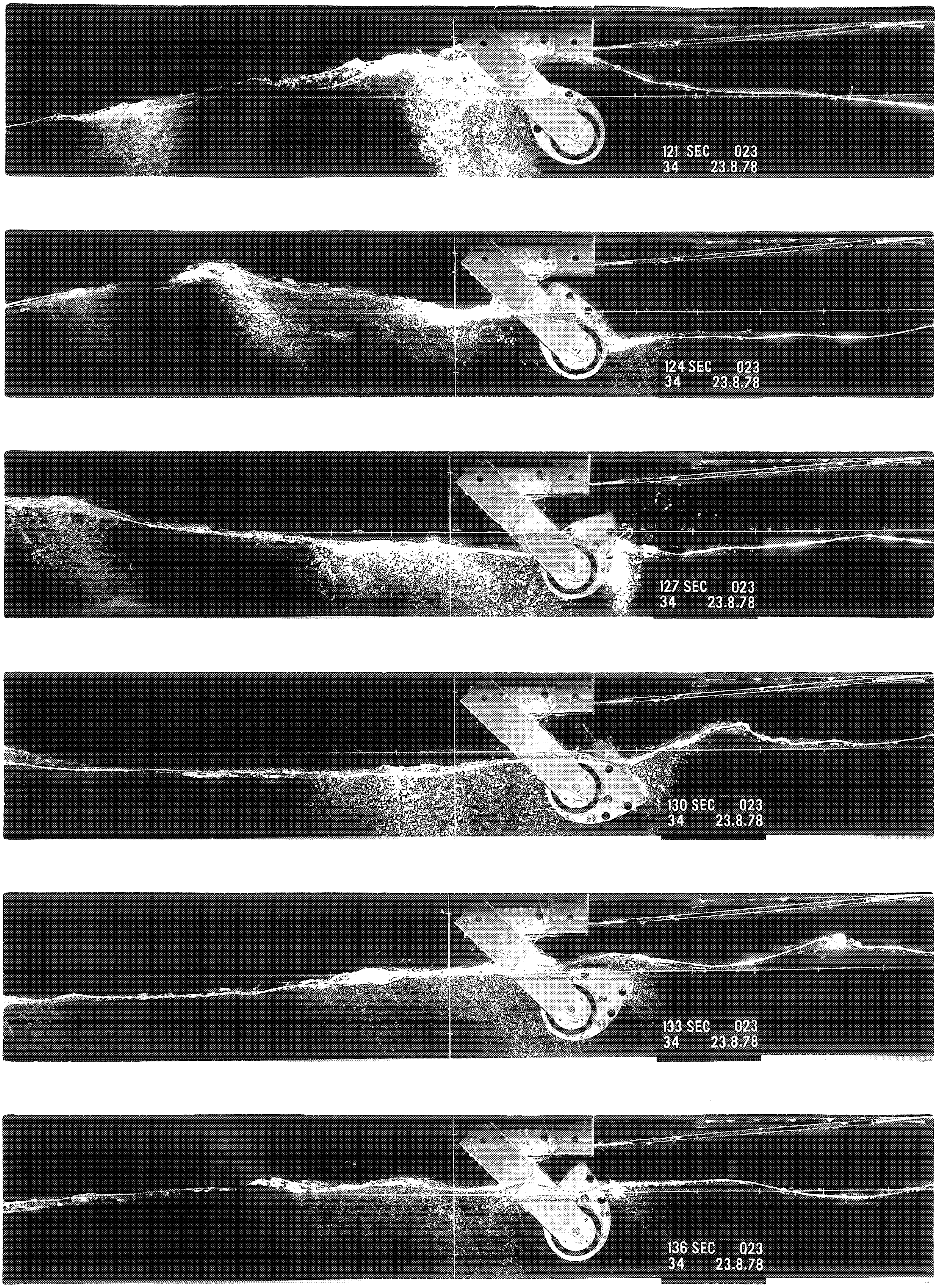
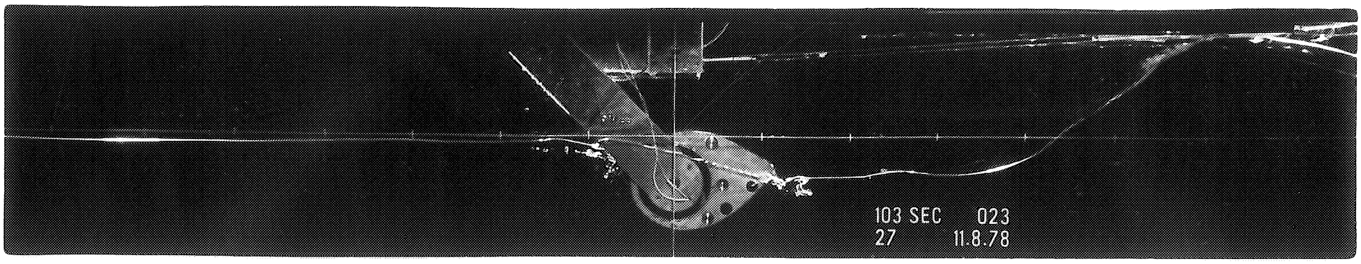
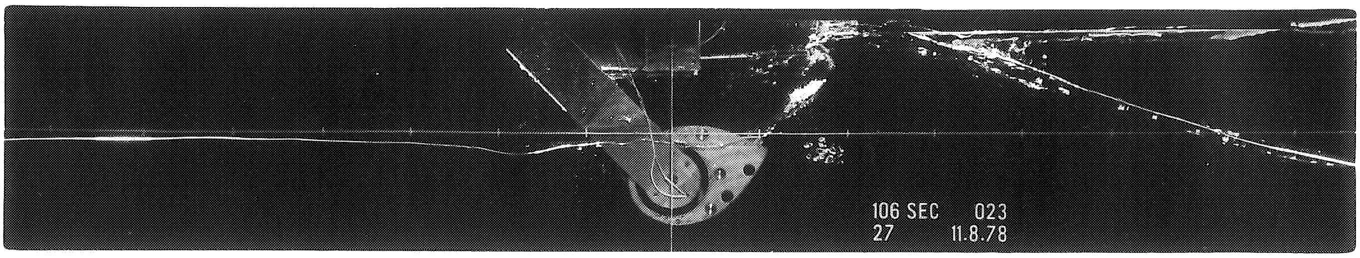


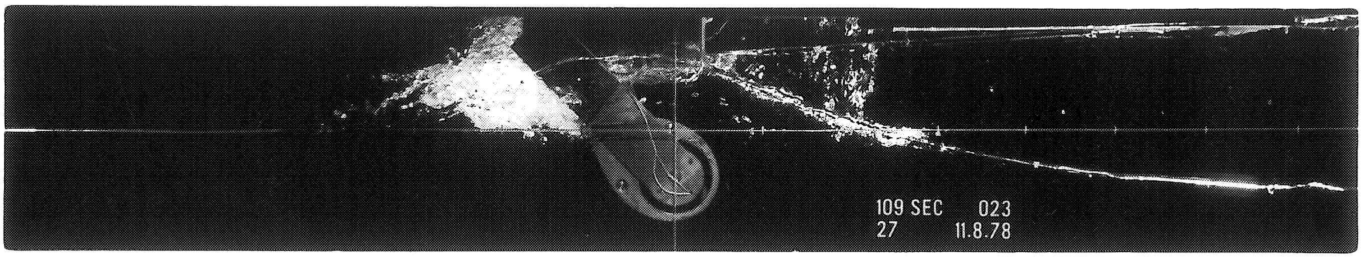
PHOTO 6a

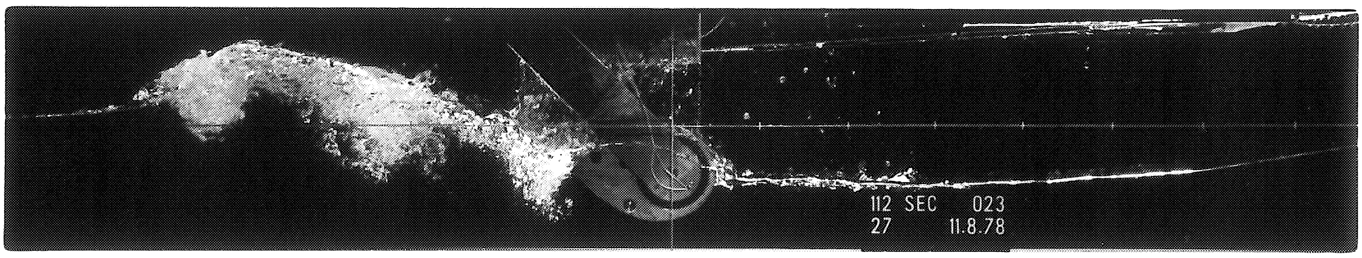
scale 1/150

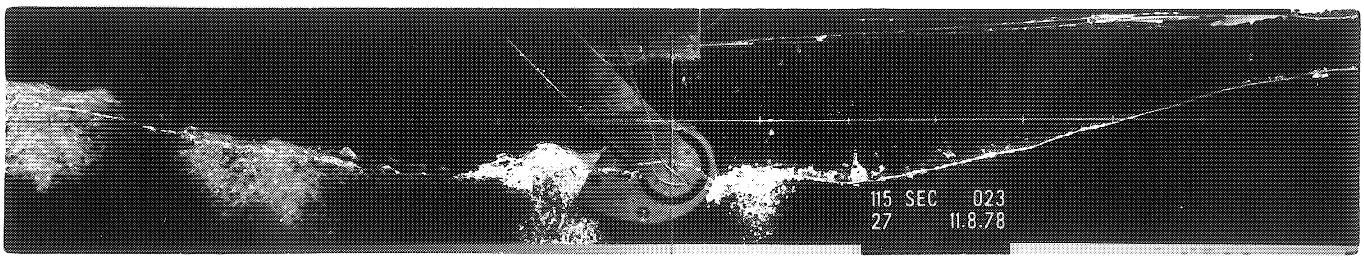
4 Different MODEL/WAVE SPACINGS
THIS ONE: CENTRE (cf 5,7,8)
Rigid axis, 0 damping

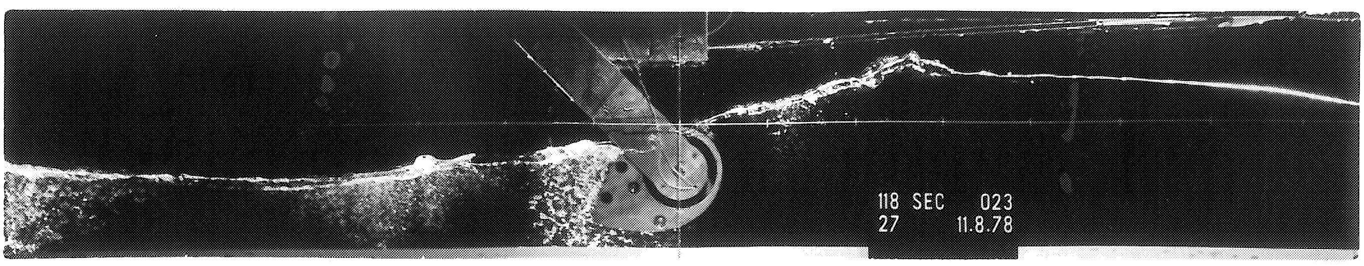




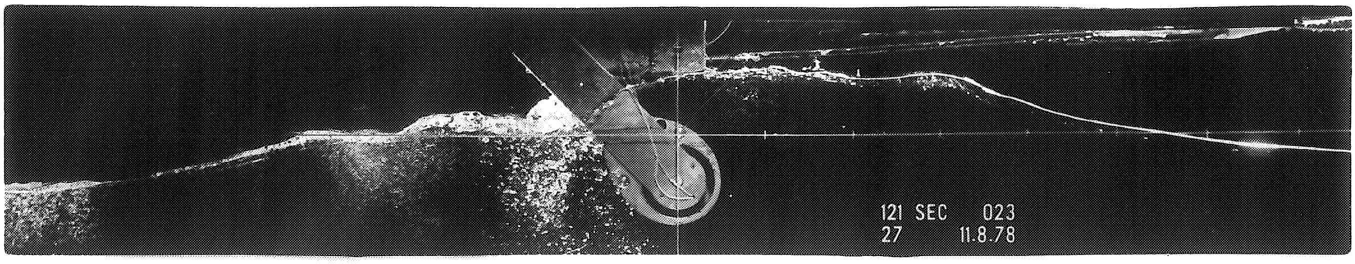


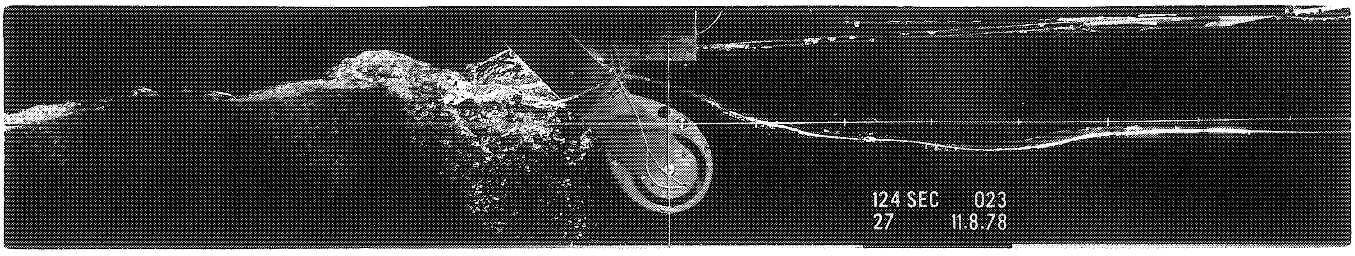


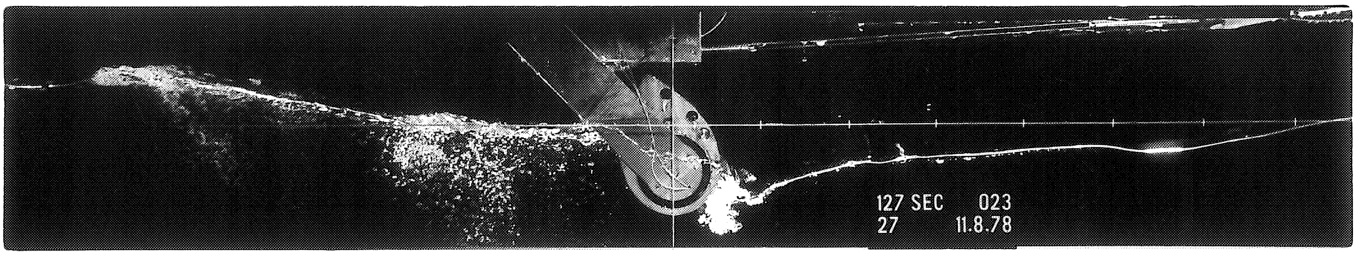


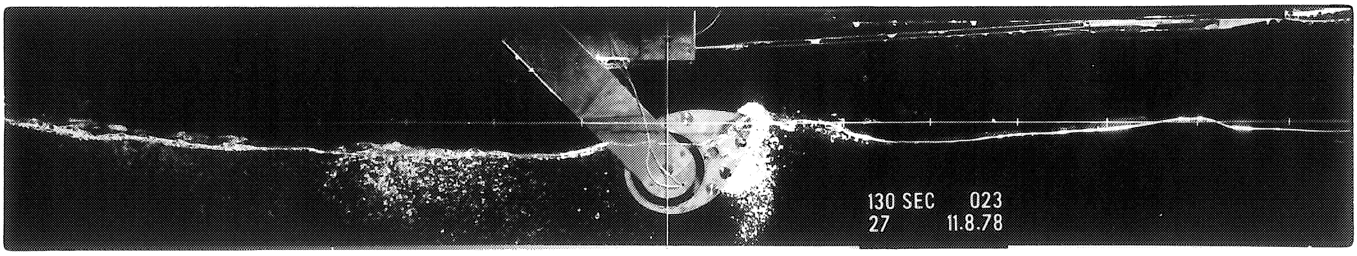


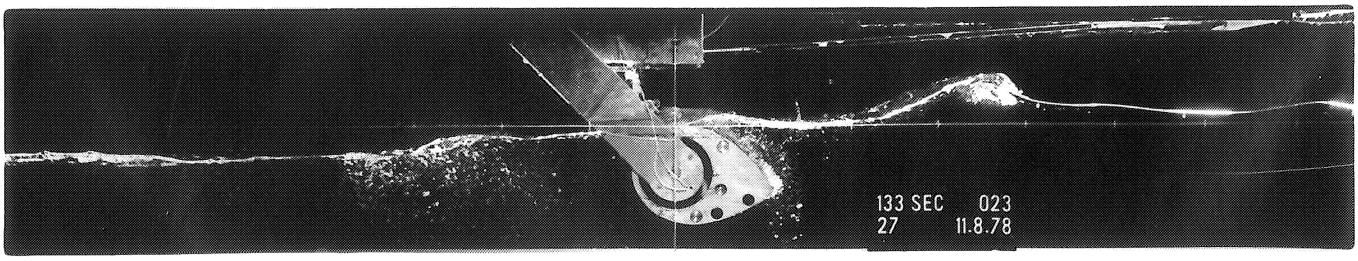
~~Electrical Stiffness Density~~ ~~HEAVE~~ SURGE RIGID	Duck Damping (MNm/rad/s/m) 0	~~Torque Limit (MNm/m)~~	Time Step (sec) 3	position 0 m	PHOTO 6b











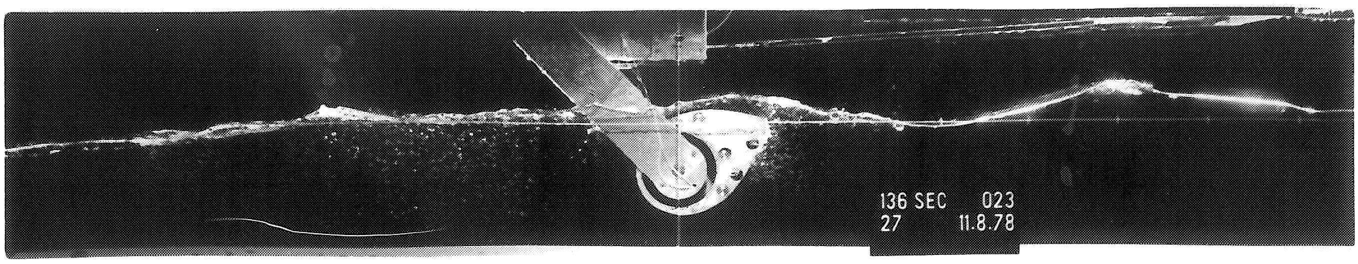


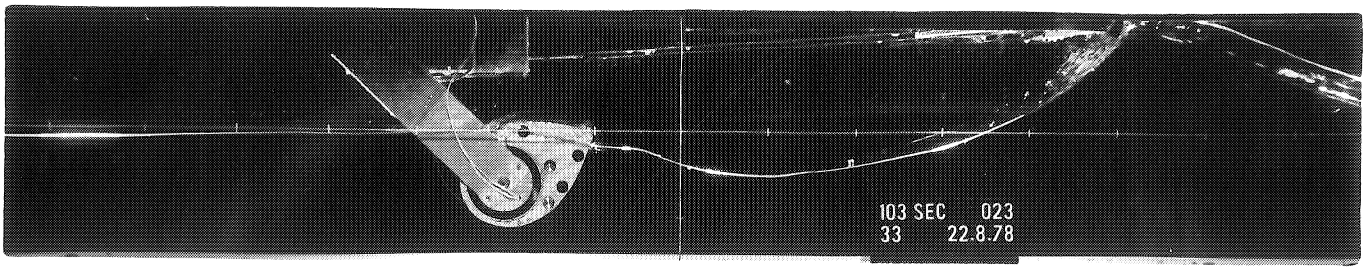
PHOTO 7a

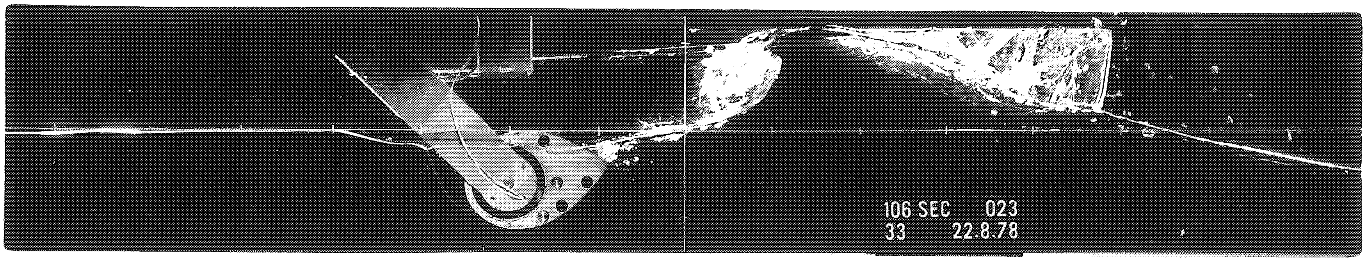
scale 1/150

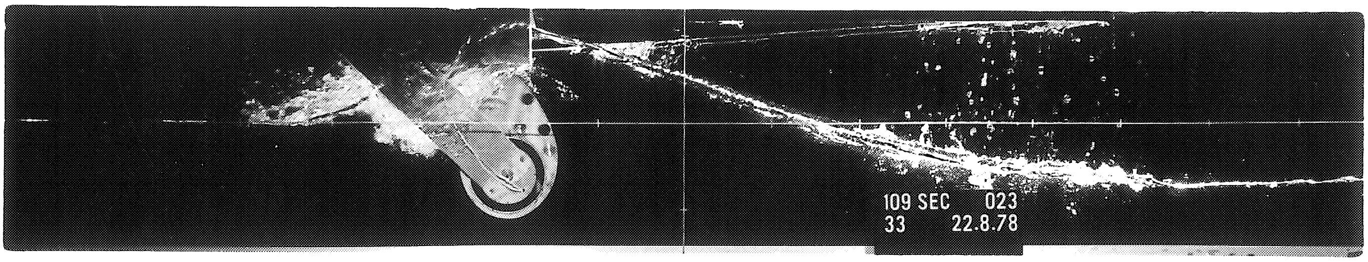
4 Different MODEL/WAVE SPACINGS

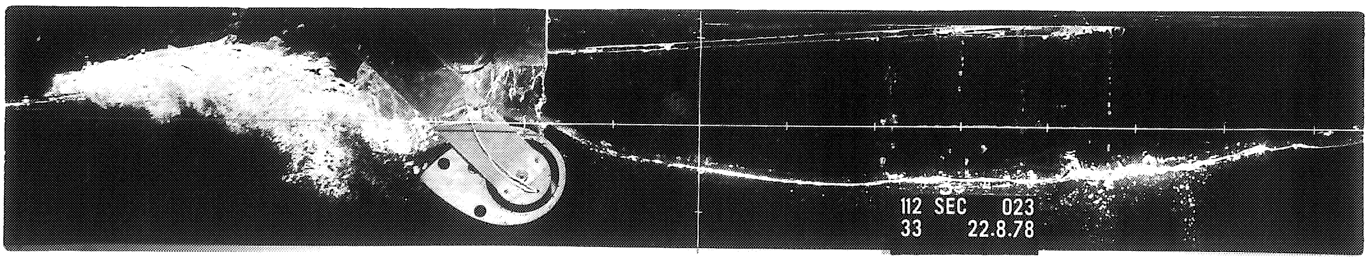
THIS ONE: 30m LEFT (cf 5,6,8)

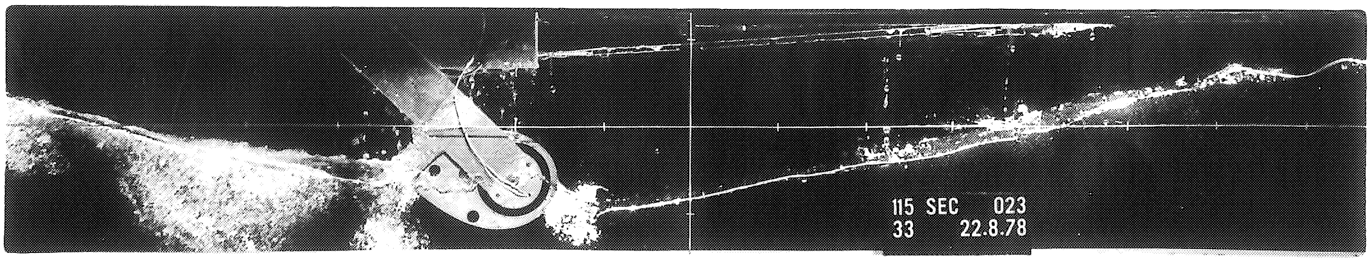
Rigid axis, 0damping

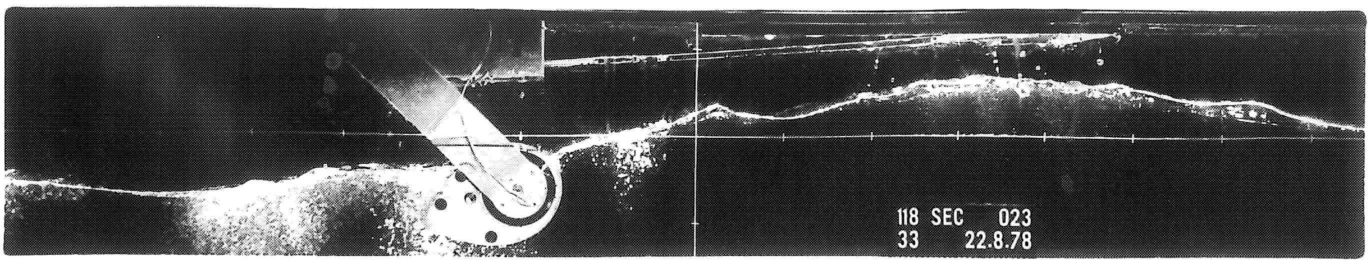












Electrical Stiffness Density	HEAVE SURGE	RIGID	Duck Damping (MNm/rad/s/m)	0	Torque Limit (MNm/m)		Time Step (sec)	3	position +30 m

PHOTO 7b

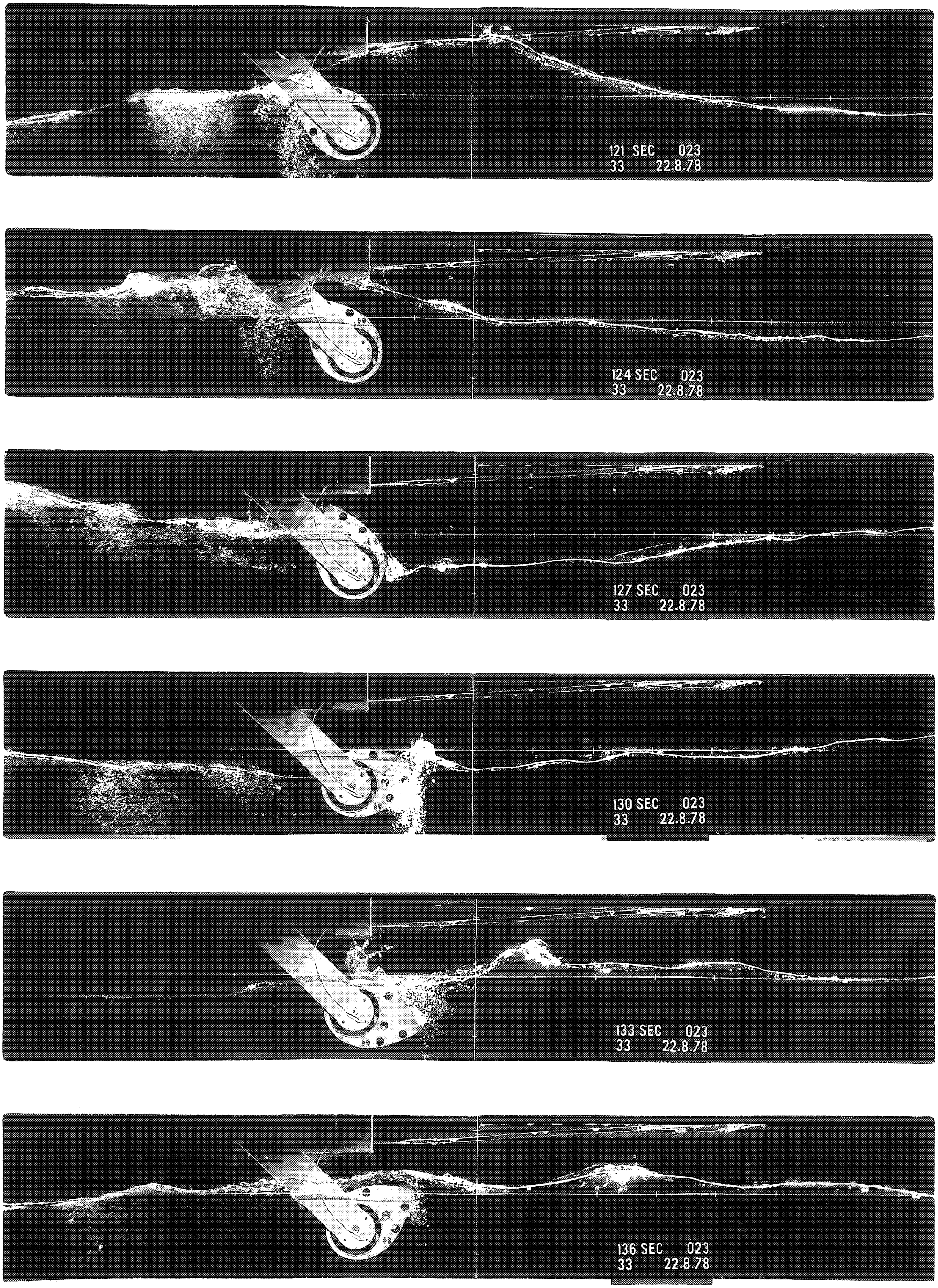


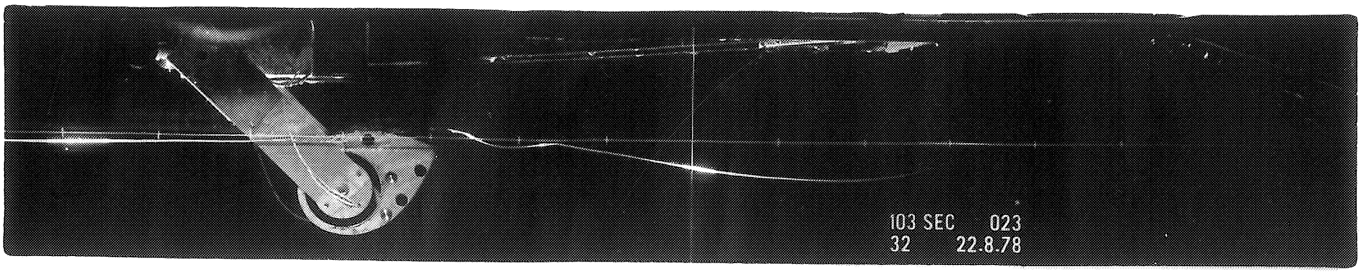
PHOTO 8a

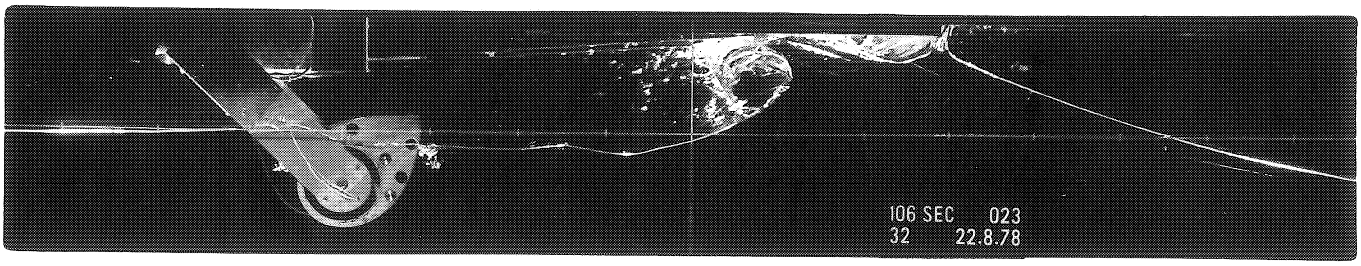
scale 1/150

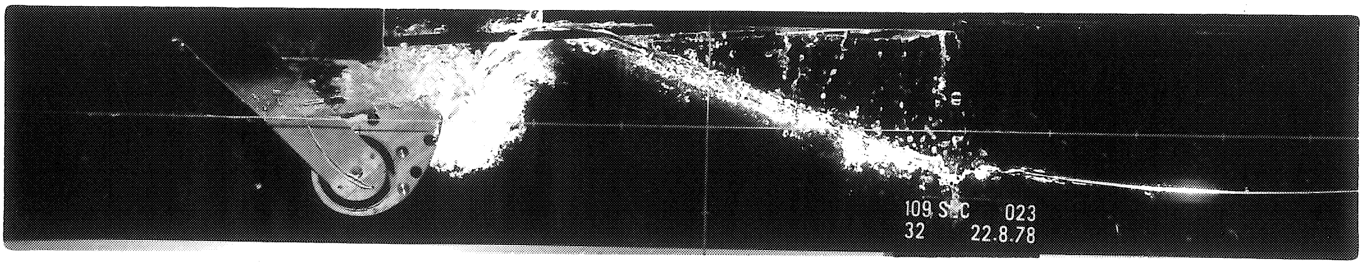
4 Different MODEL/WAVE SPACINGS

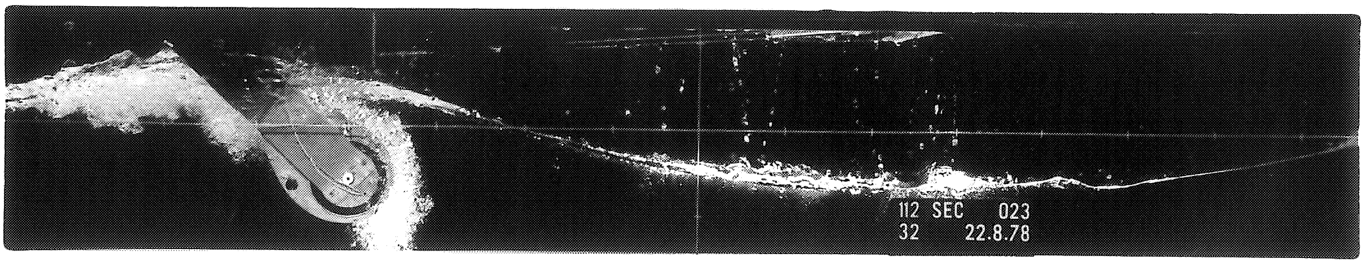
THIS ONE: 60m LEFT (cf 5,6,7)

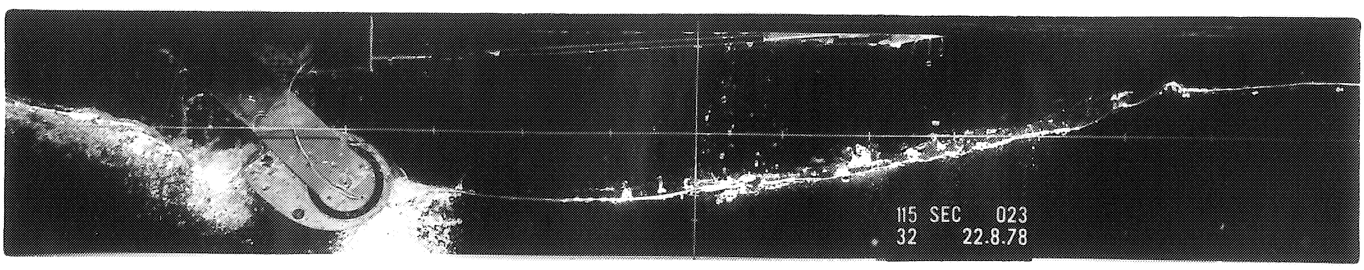
Rigid axis, 0 damping

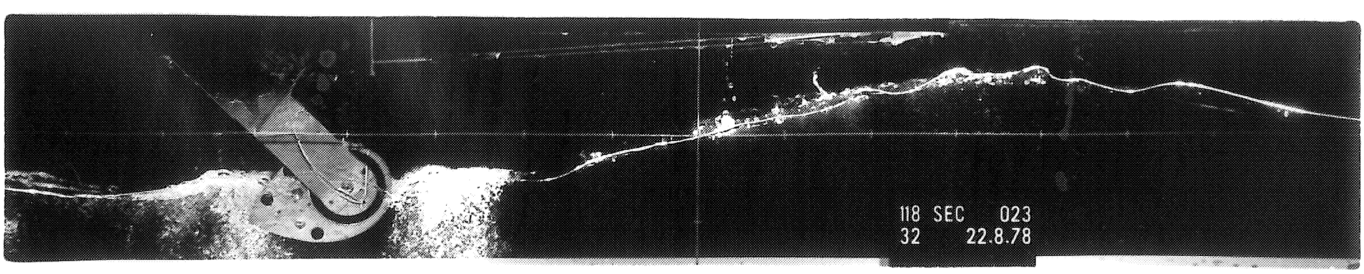






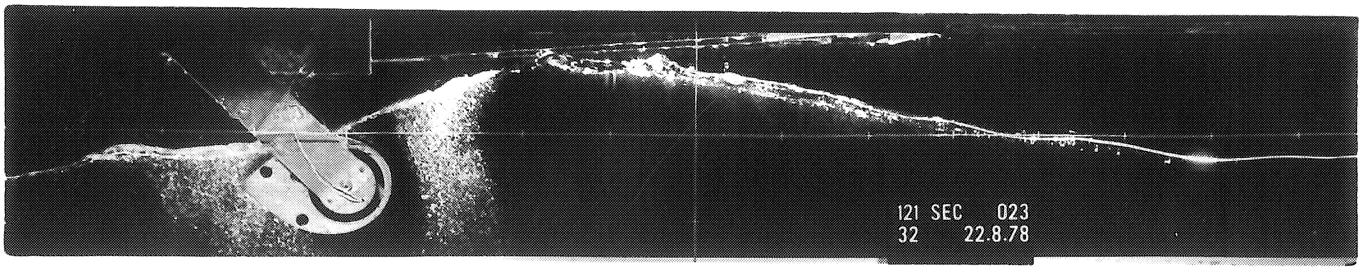


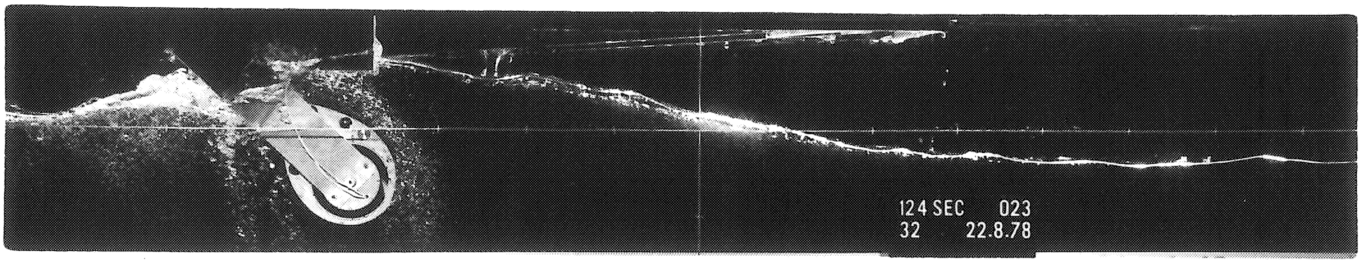


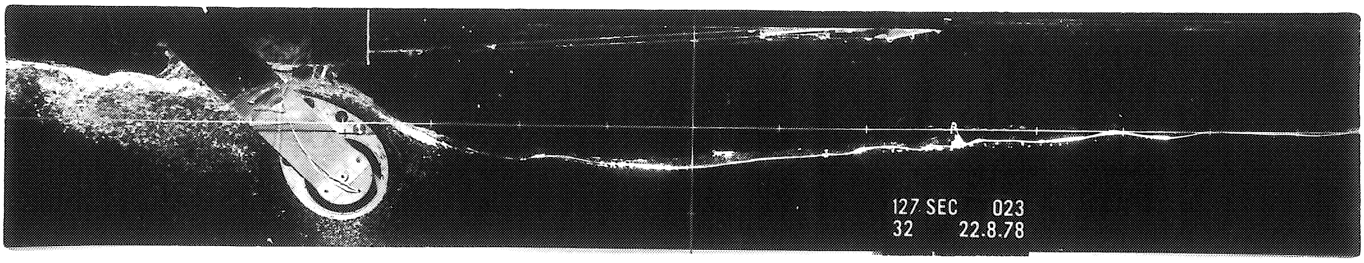


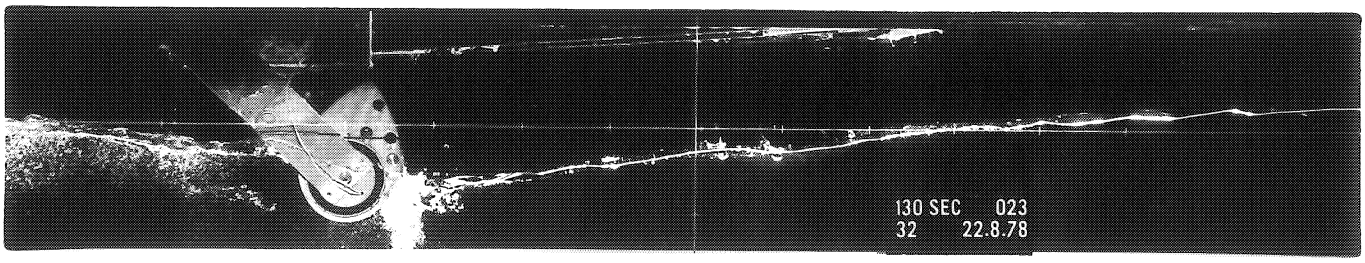
Electrical Stiffness Density HEAVE SURGE	RIGID	Duck Damping (MNm/rad/s/m)	0	Torque Limit (MNm/m)		Time Step (sec)	3	position +60m

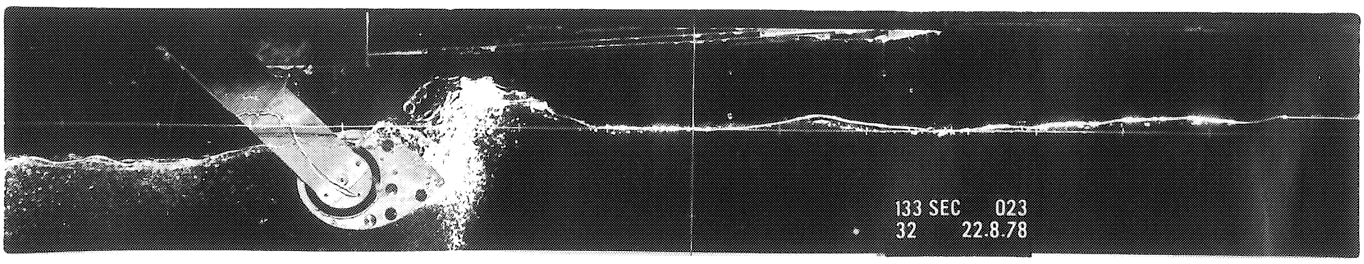
PHOTO 8b











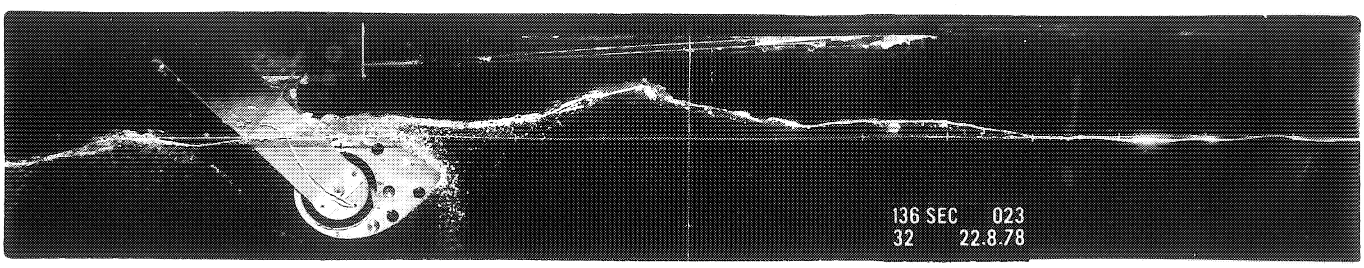
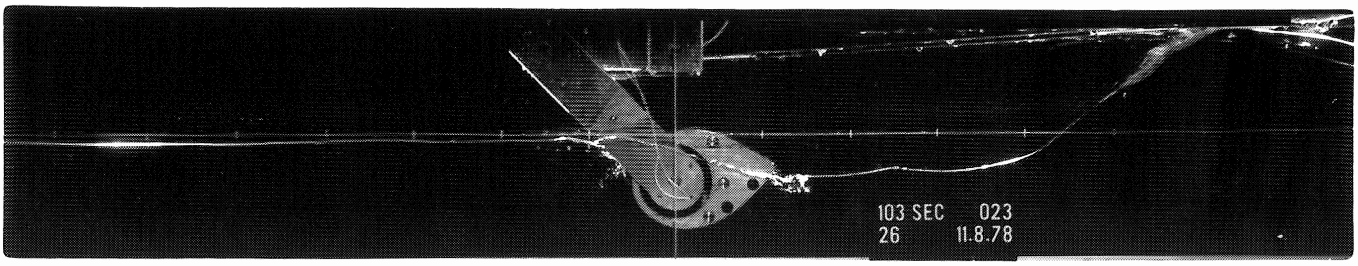
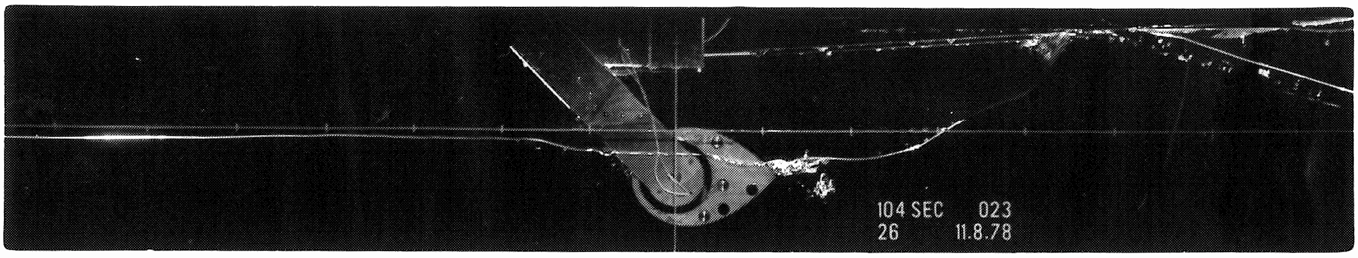
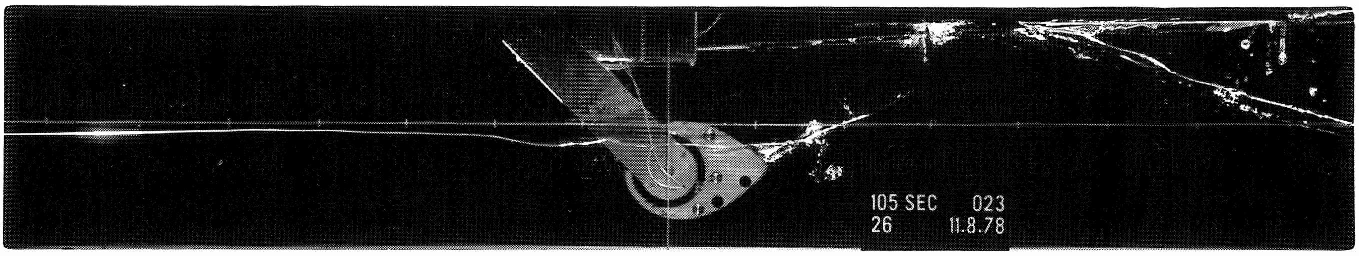
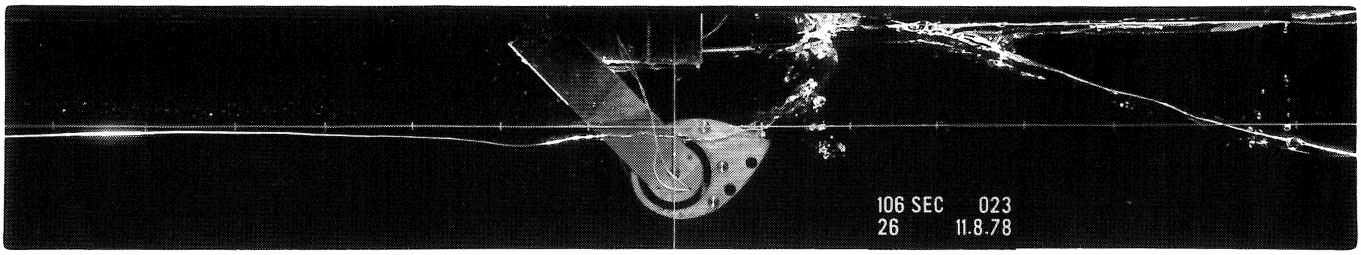


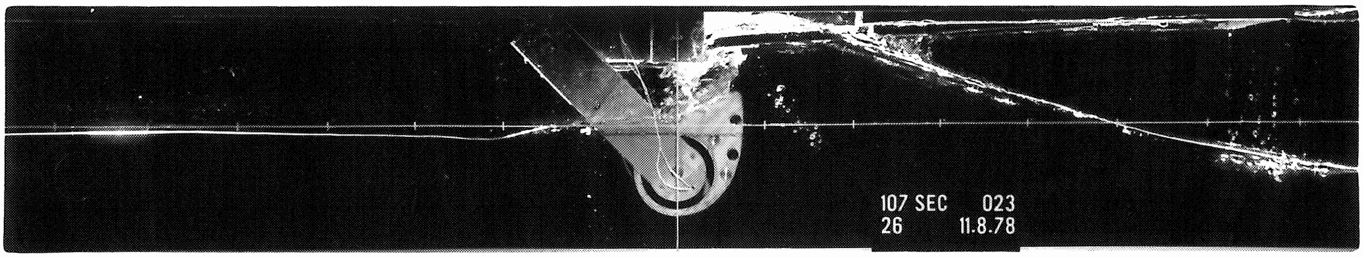
PHOTO 9a | scale 1/150 | RIGID Axis small time step (cf Ph10)

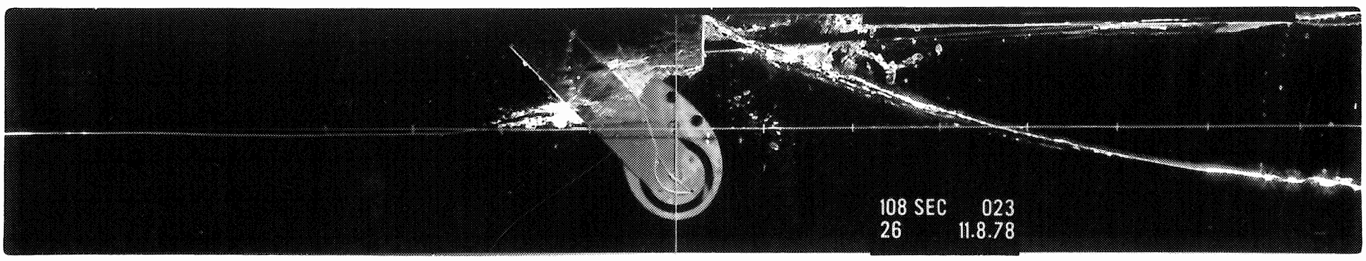




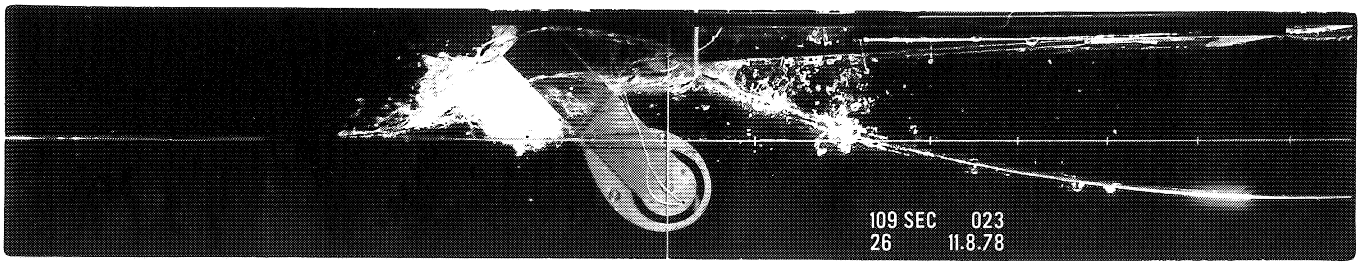


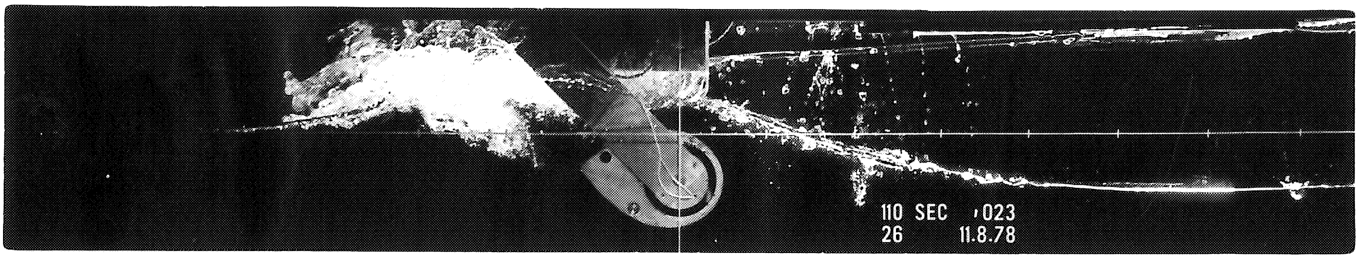


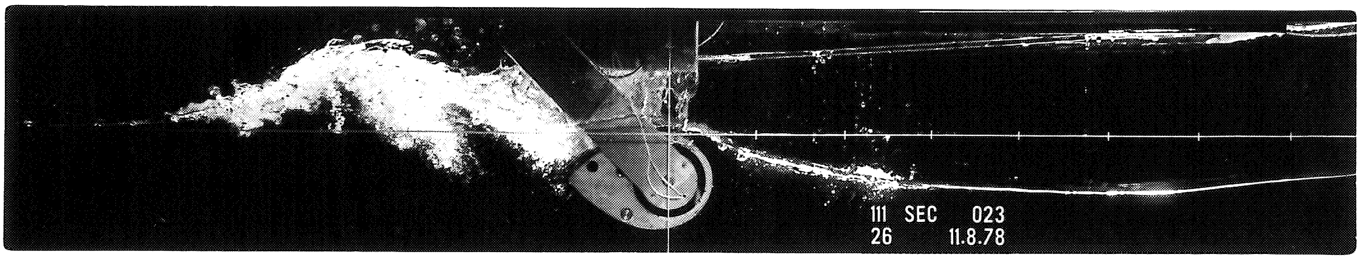


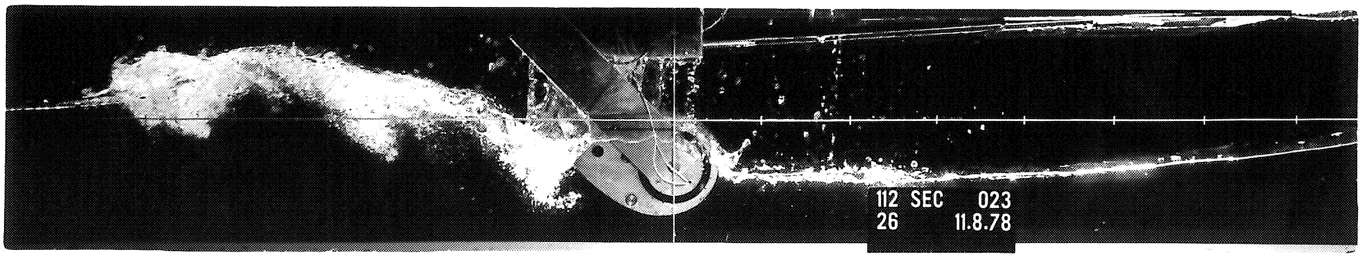


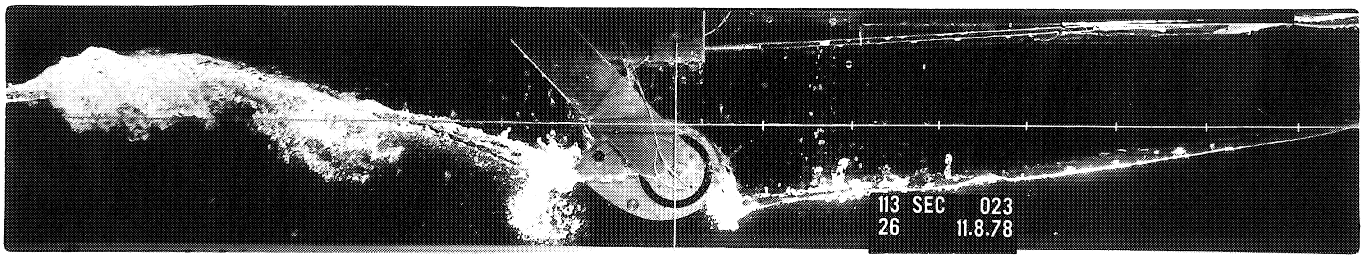
~~Electrical Stiffness Density~~ HEAVE SURGE	RIGID	Duck Damping (MNm/rad/s/m) 0	~~Torque Limit (MNm/m)~~	Time Step (sec) 1	position 0m	PHOTO 9b











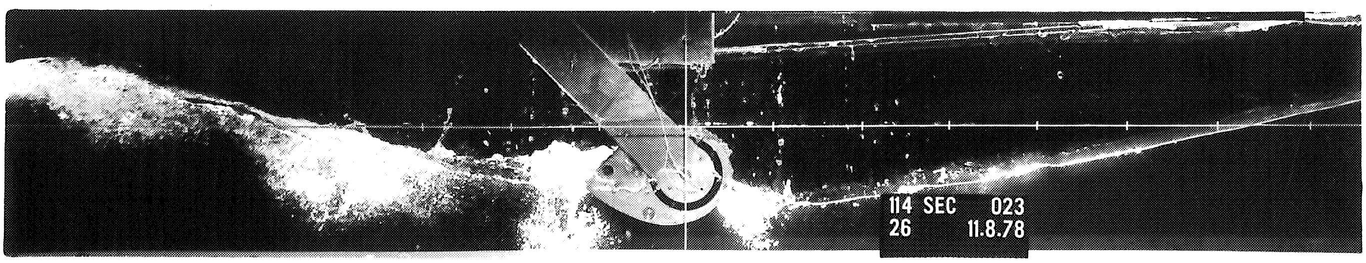
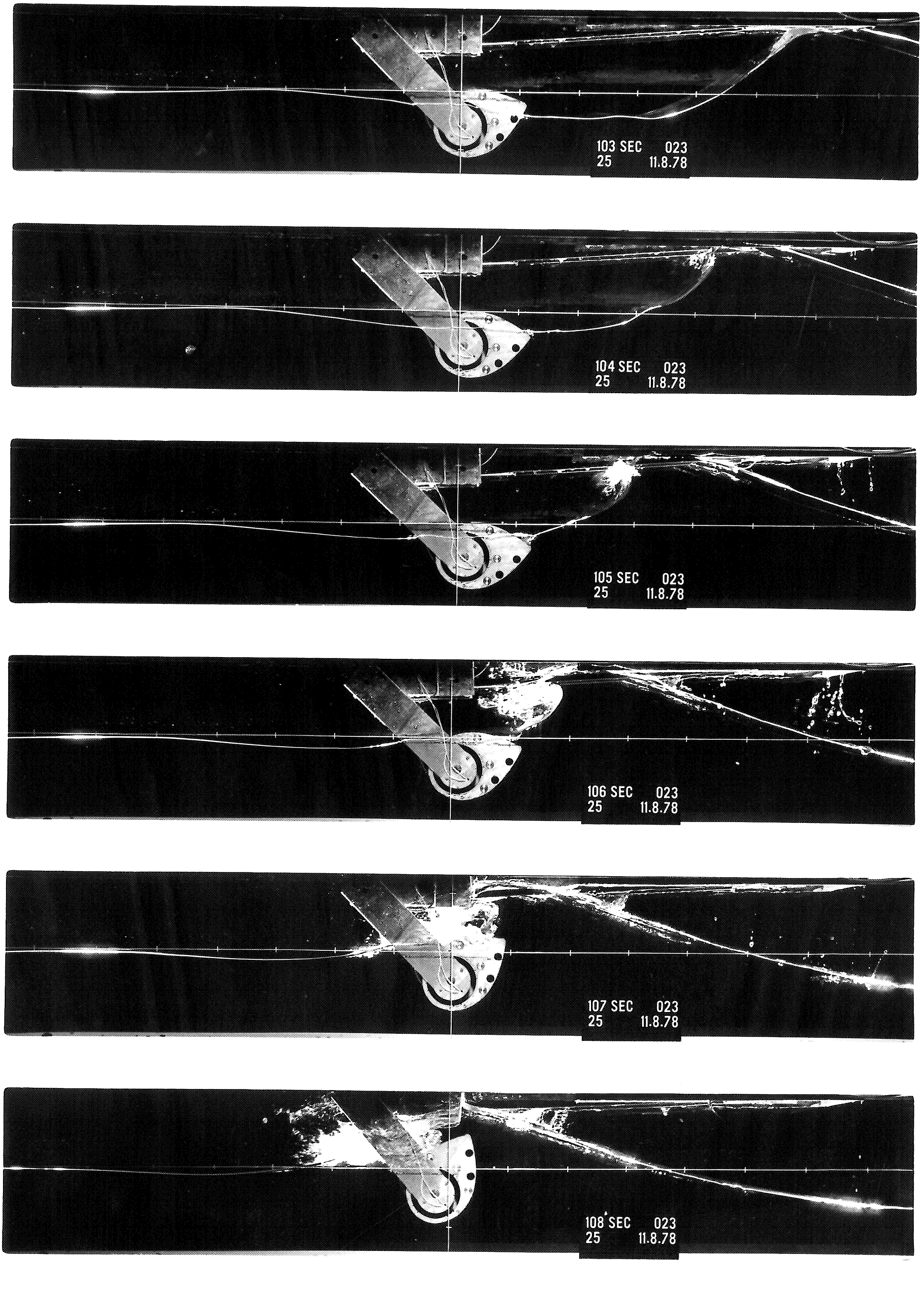


PHOTO 10a | scale 1/150 | COMPLIANT Axis small time step (cf Ph9)



Electrical Stiffness Density	HEAVE ·76MN/M² SURGE ·76MN/M²	Duck Damping (MNm/rad/s/m)	7·7	Torque Limit (MNm/m	3	Time Step (sec)	1	position 0m

PHOTO 10b

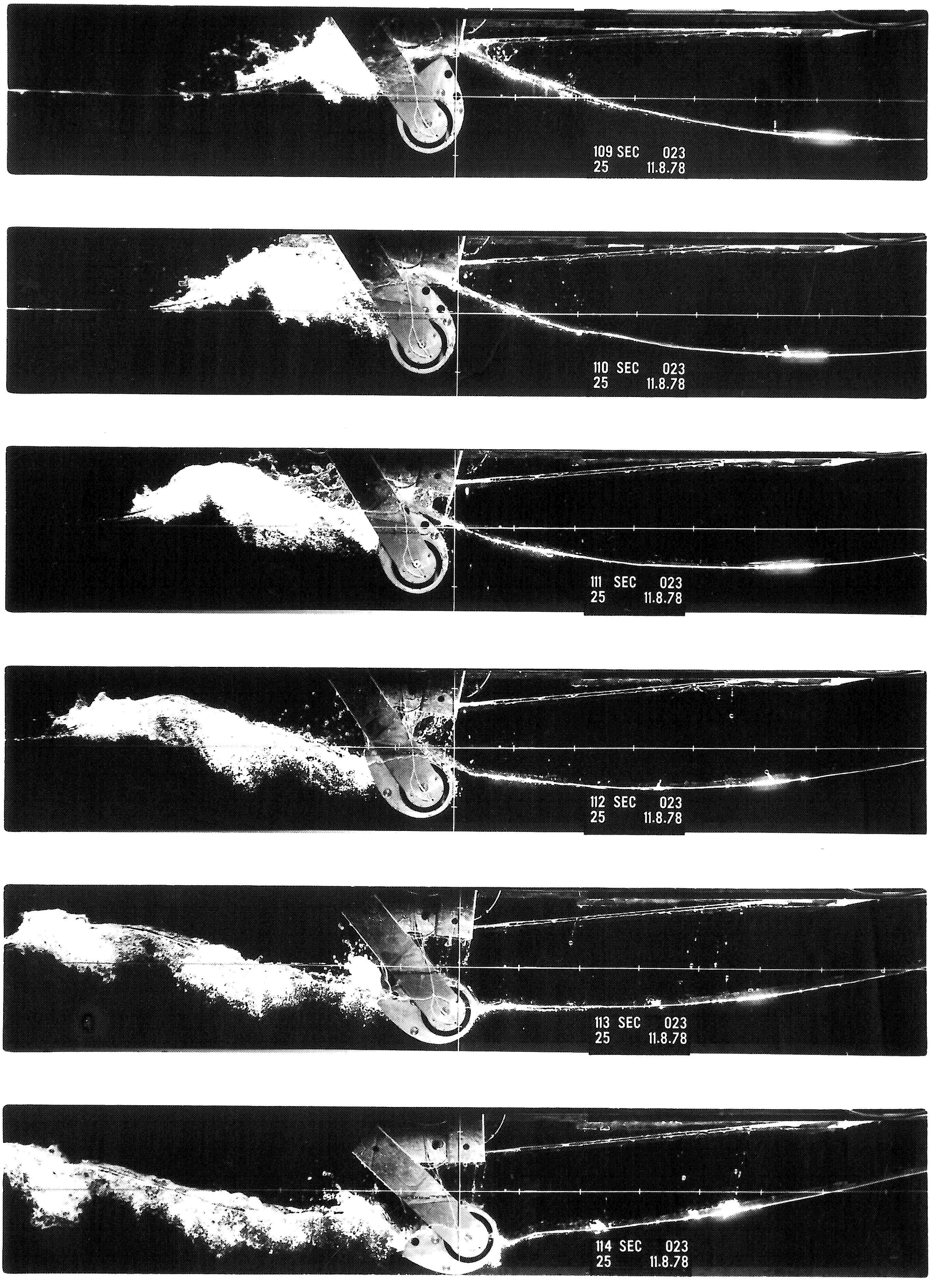
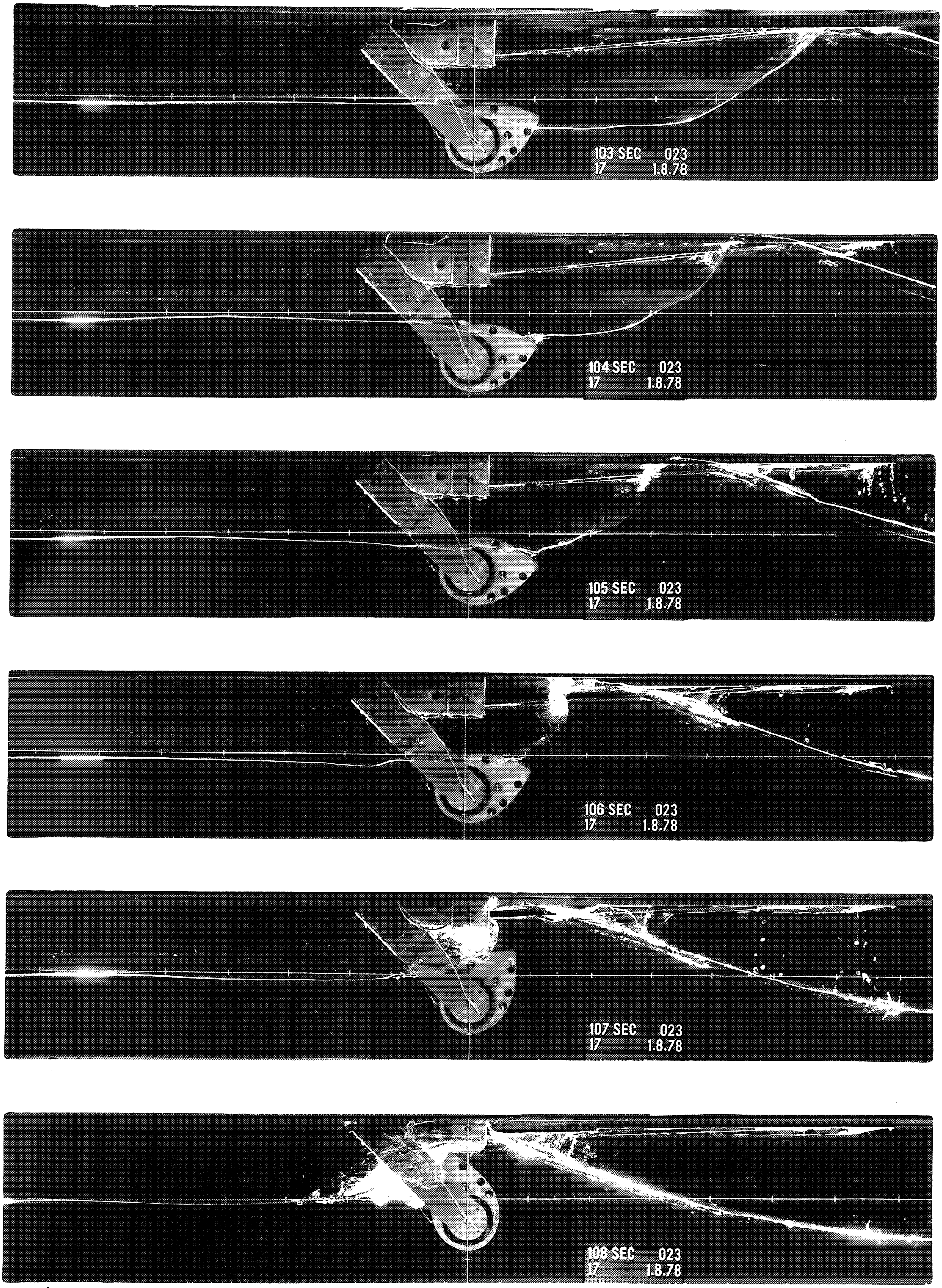


PHOTO 11a | scale 1/150 | COMPLIANT in HEAVE, RIGID in SURGE (cf 12)



Electrical Stiffness Density	HEAVE ·76 M N/M² SURGE RIGID	Duck Damping (MNm/rad/s/m)	7·7	Torque Limit (MNm/m	1	Time Step (sec)	1	position m

PHOTO 11b

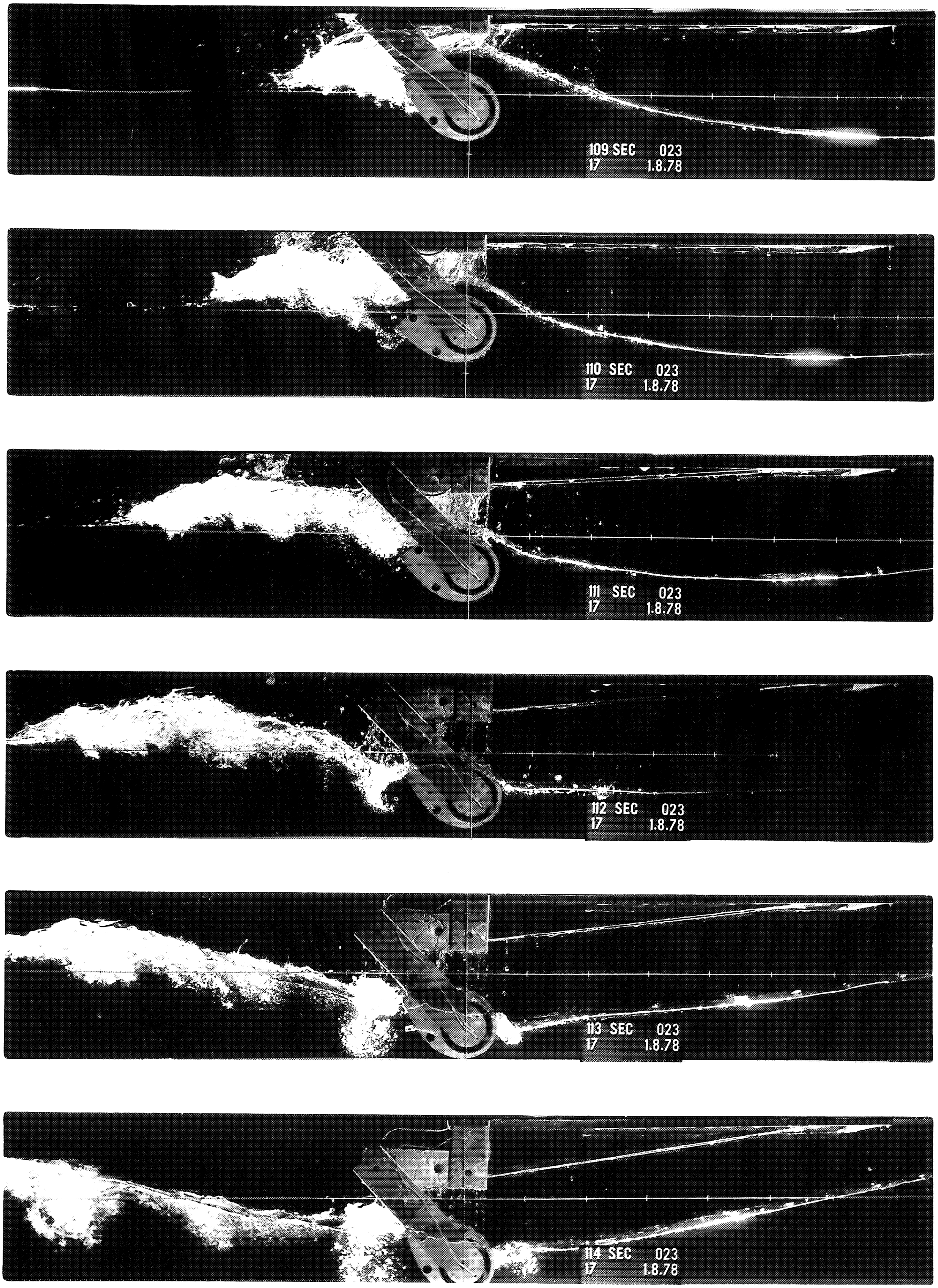
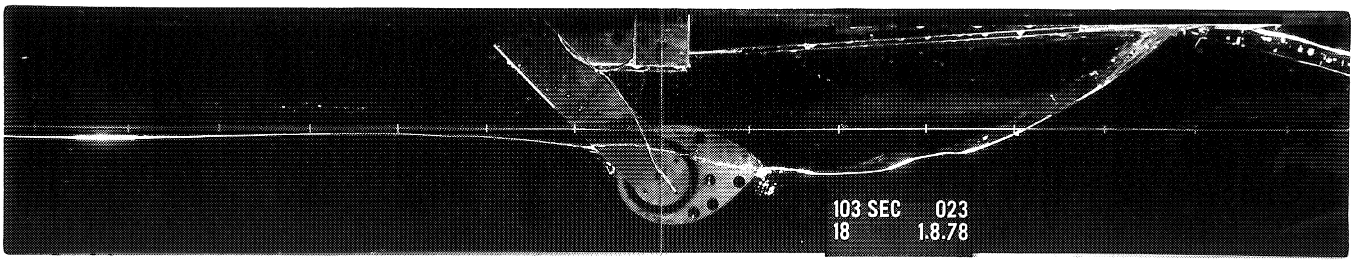
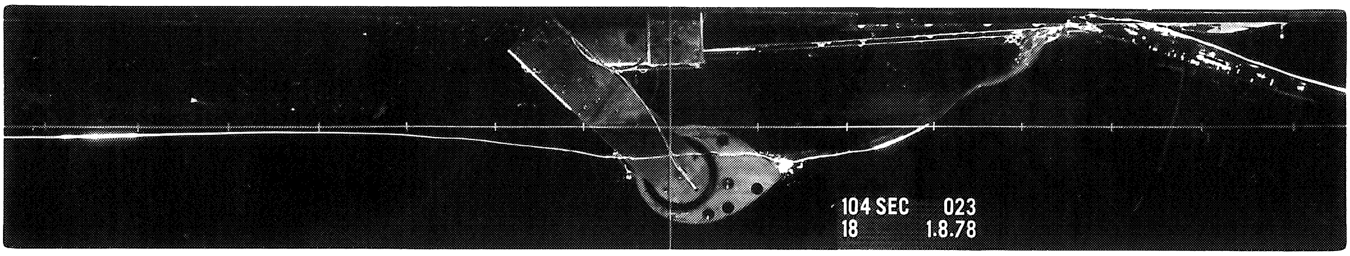
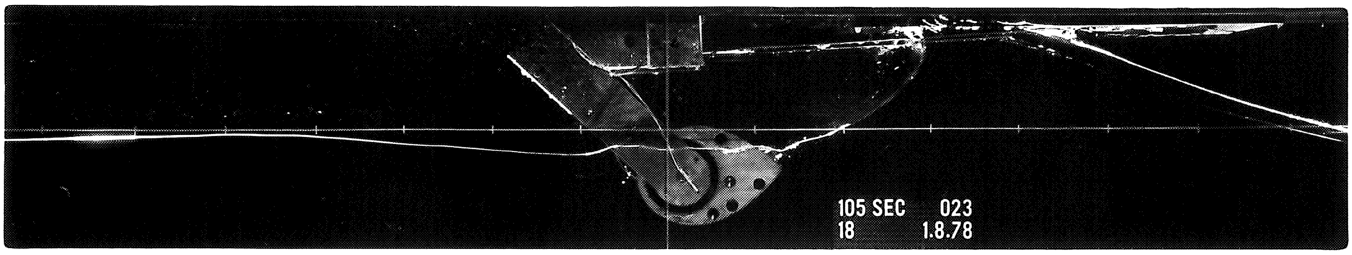
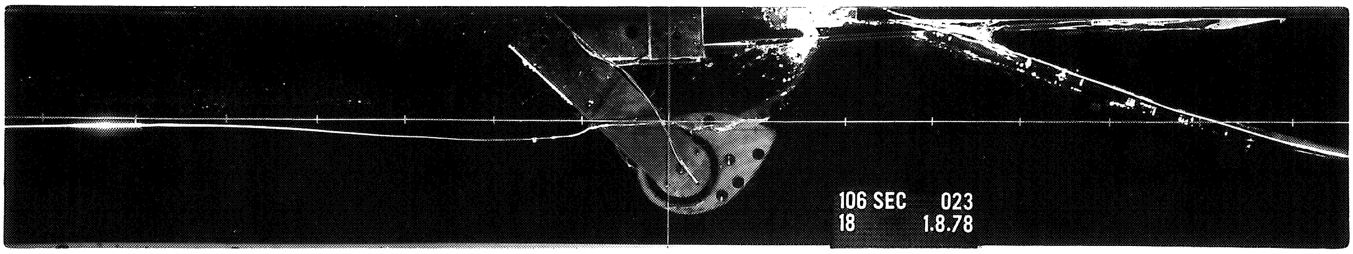


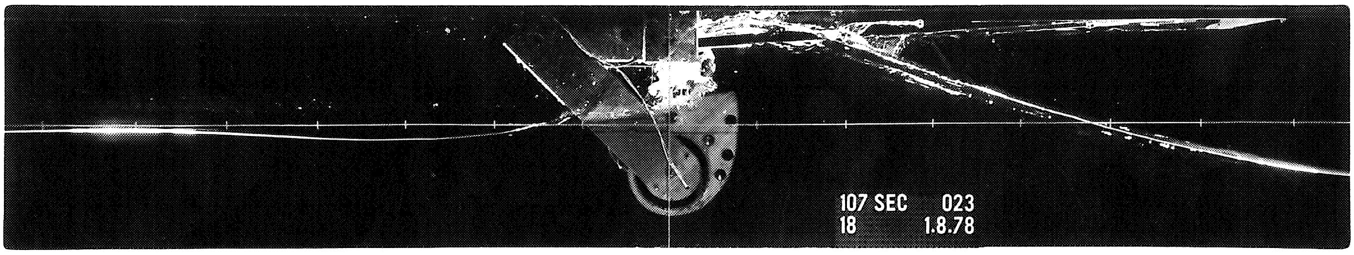
PHOTO 12a | scale 1/150 | COMPLIANT in SURGE, RIGID in HEAVE (cf11)

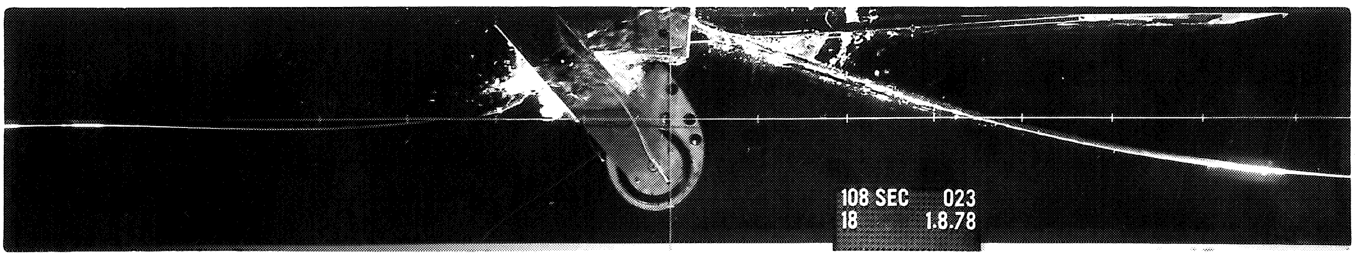












Electrical Stiffness Density	HEAVE RIGID SURGE ·76 MN/M^2	Duck Damping (MNm/rad/s/m)	7·7	Torque Limit (MNm/m)	1	Time Step (sec)	1	position m

PHOTO 12b

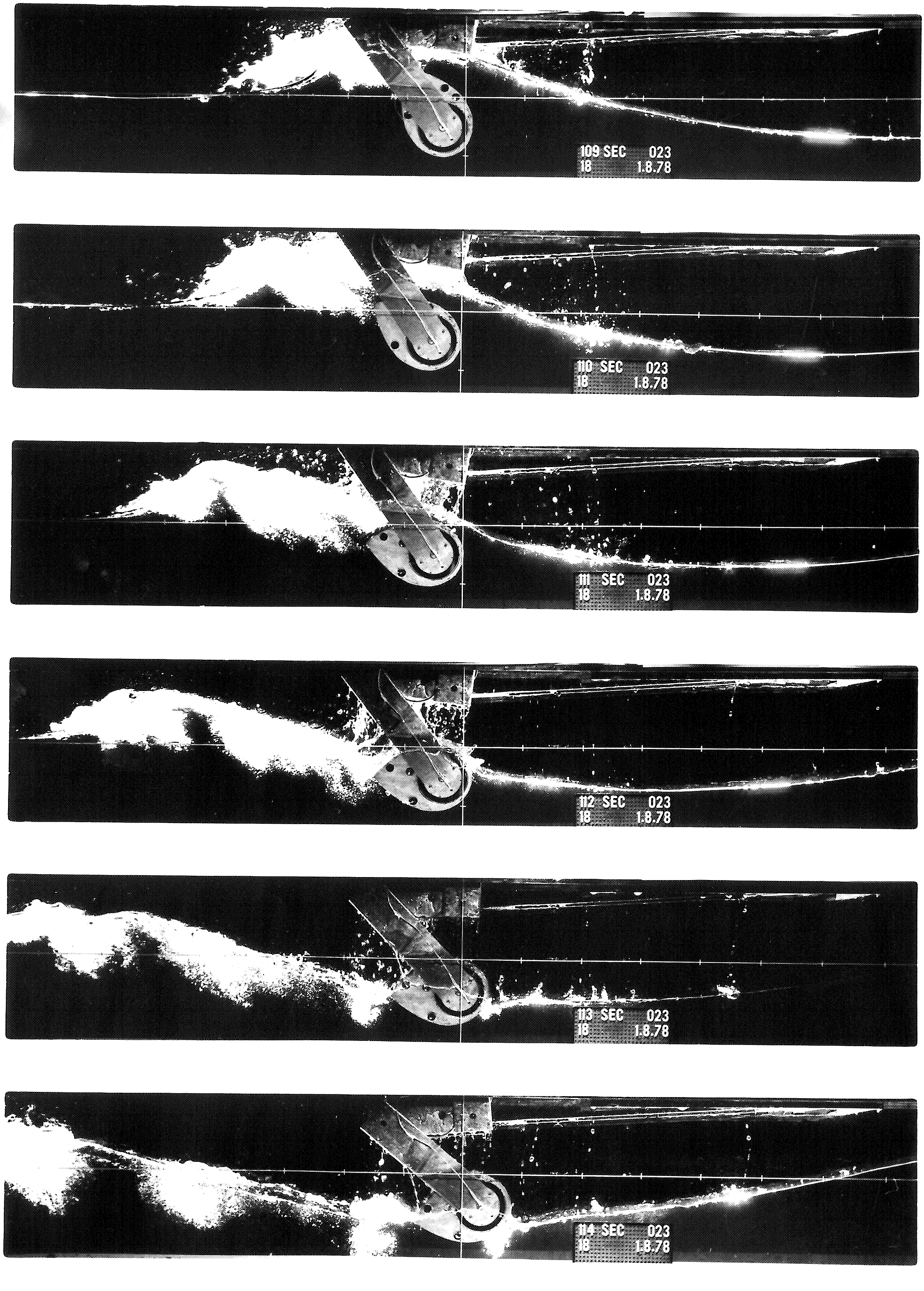
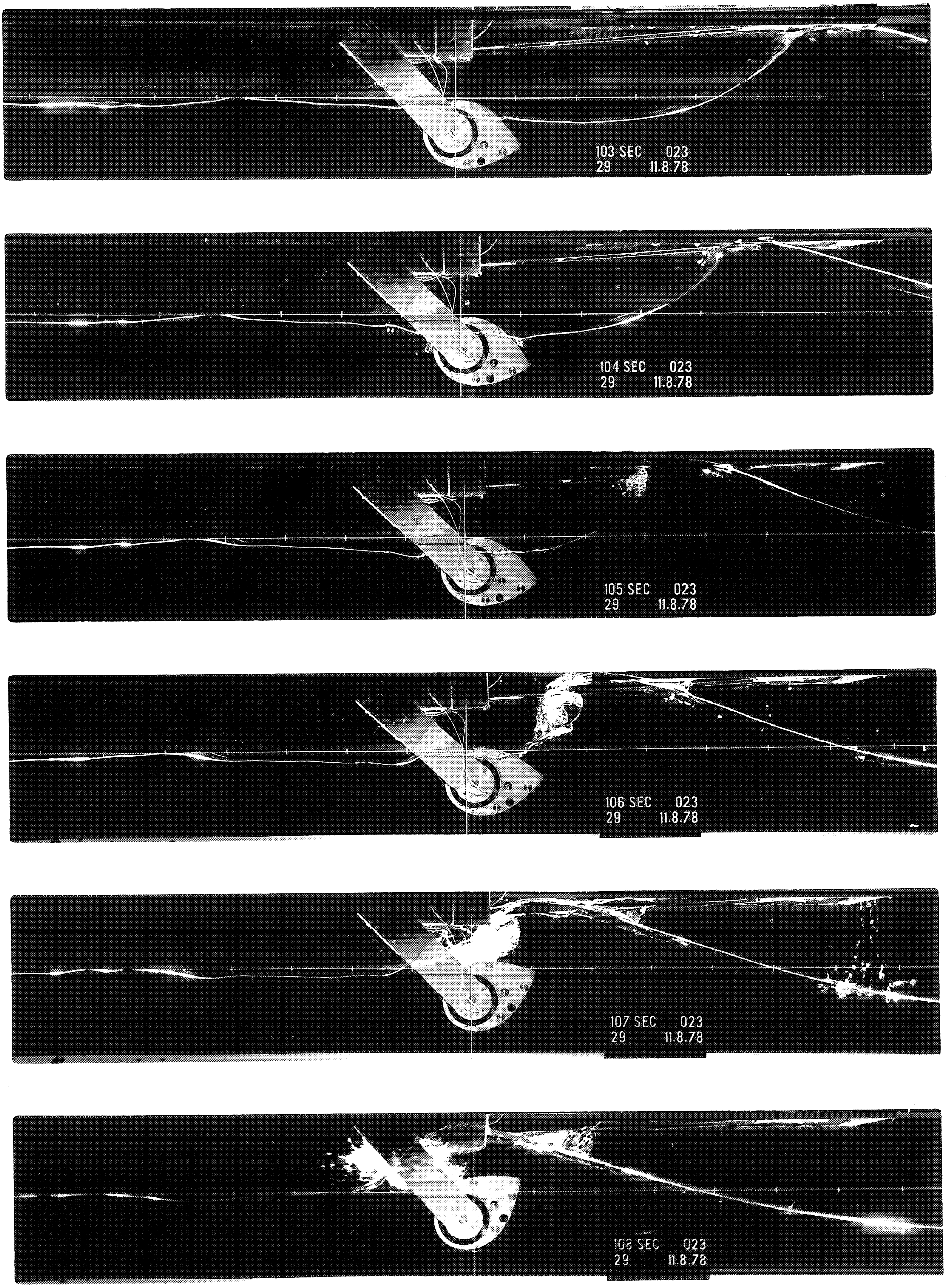
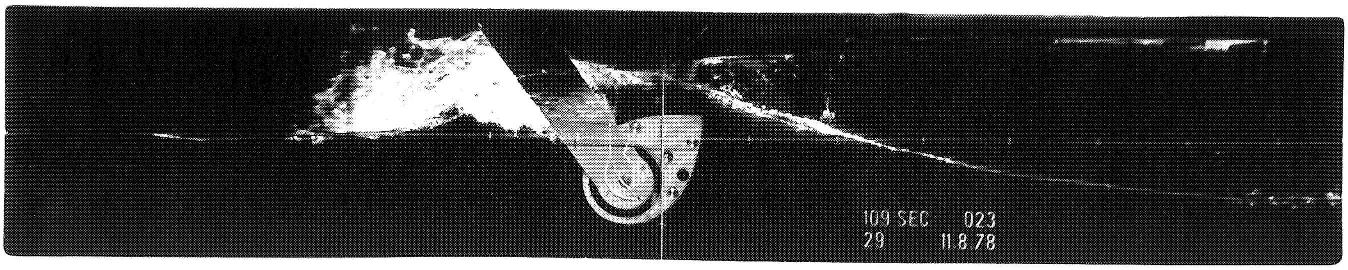
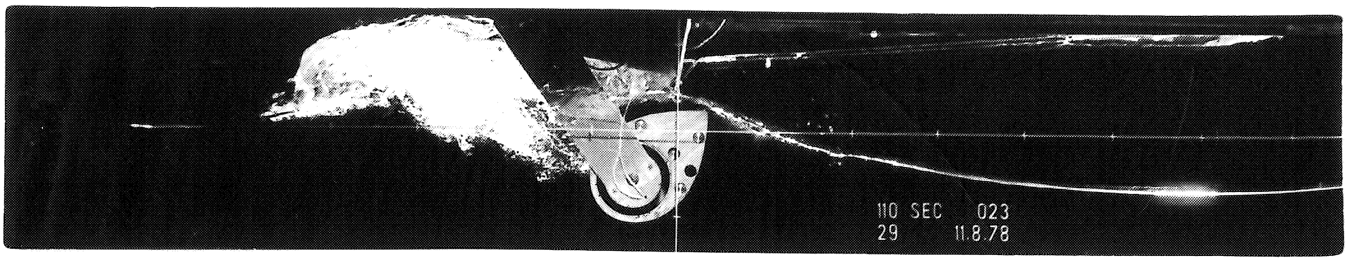


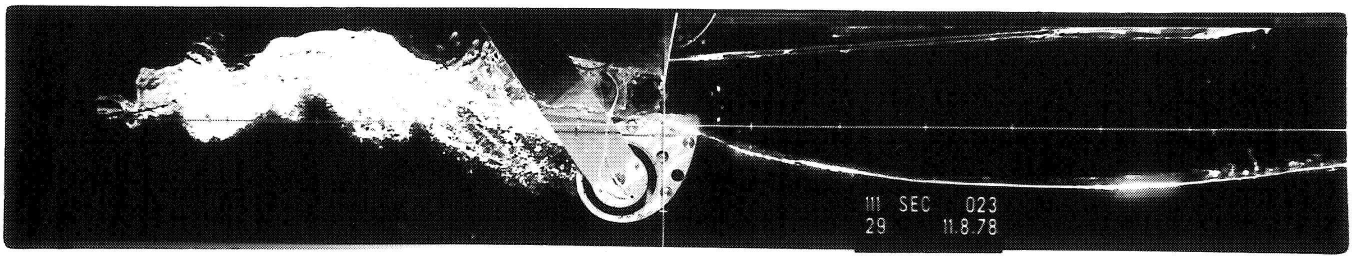
PHOTO 13 a | scale 1/150 | NOSE-DOWN attitude (extra ballast)

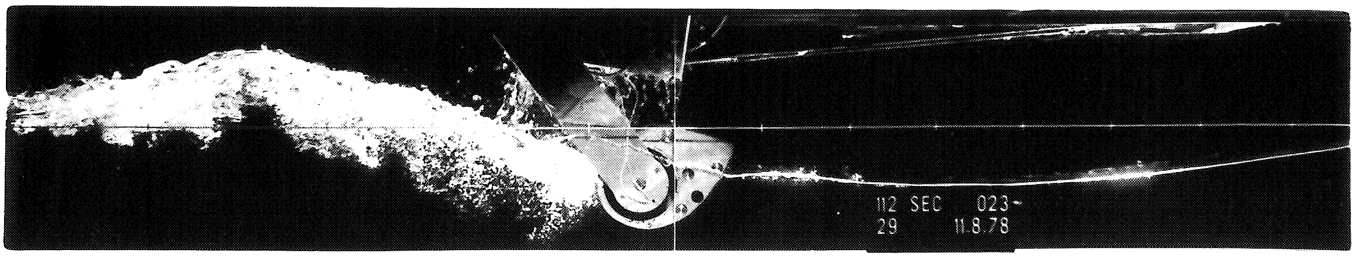


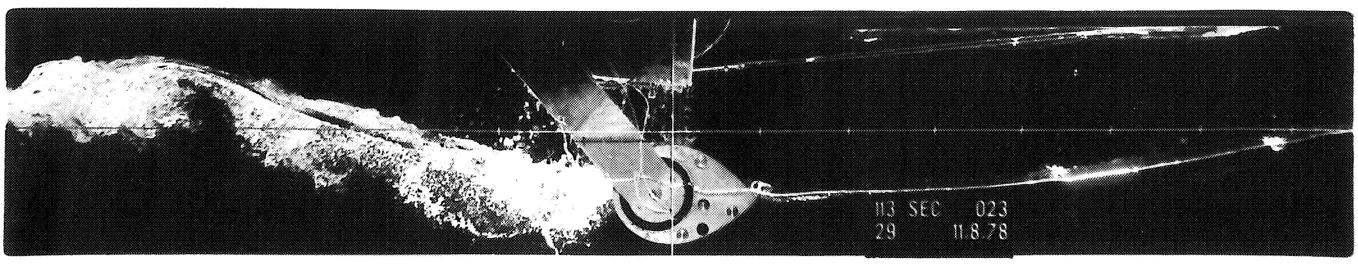
Electrical Stiffness Density HEAVE ·76MN/M² SURGE ·76MN/M²	Duck Damping (MNm/rad/s/m) 7·7	Torque Limit (MNm/m) 3	Time Step (sec) 1	position 0m	PHOTO 13 b











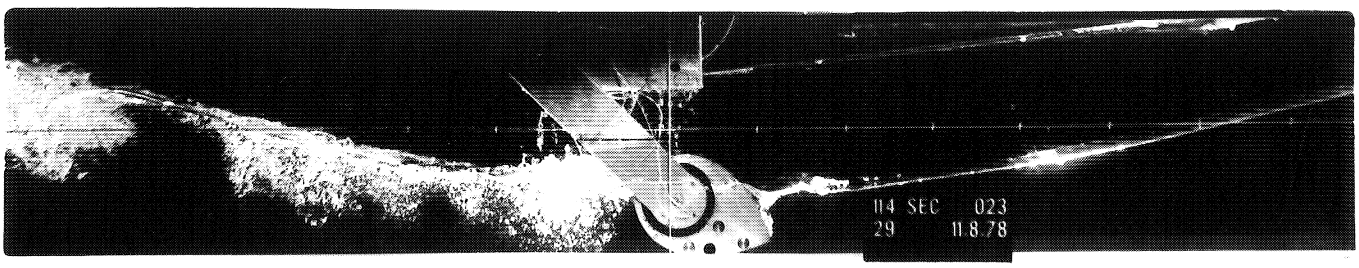
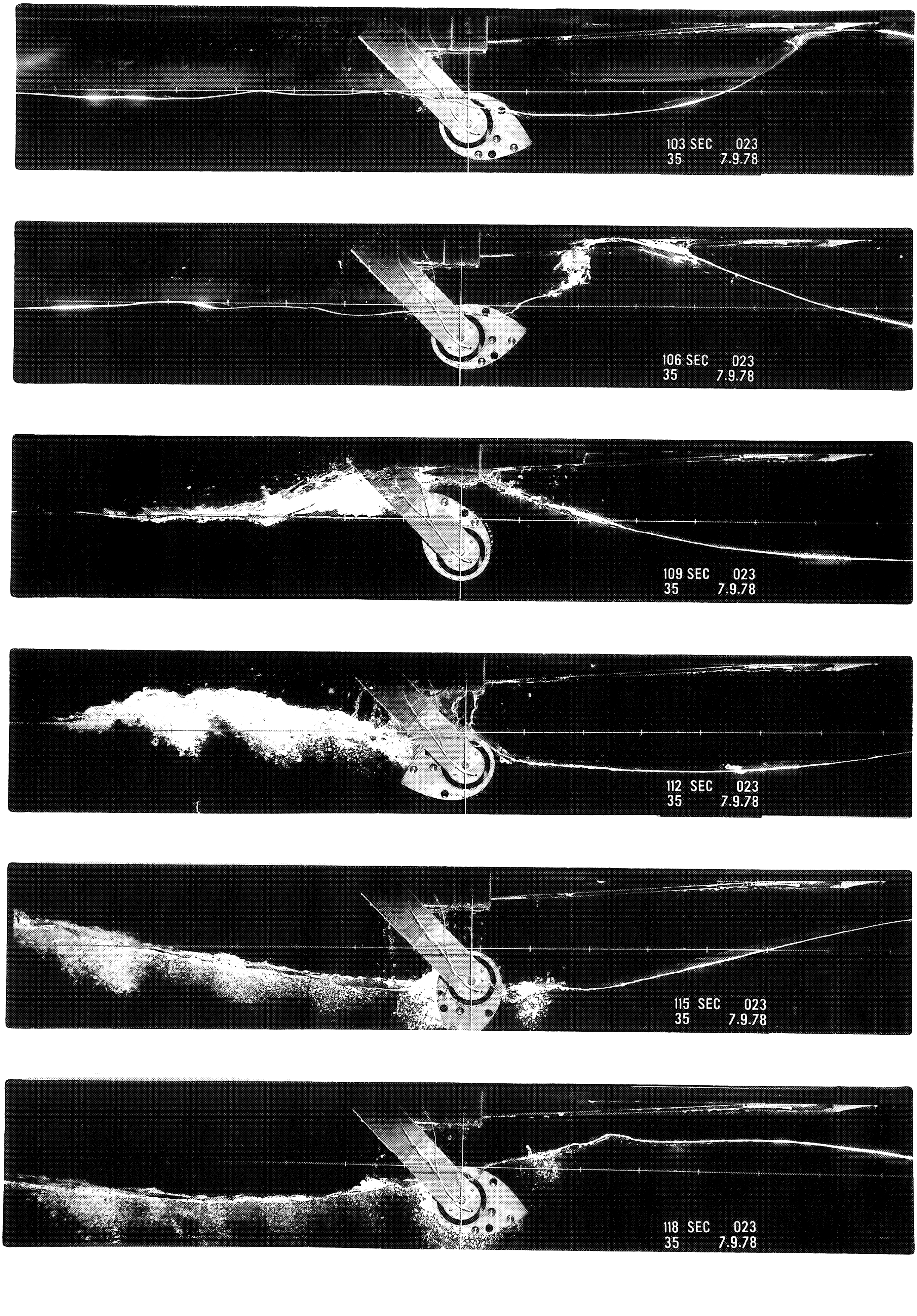
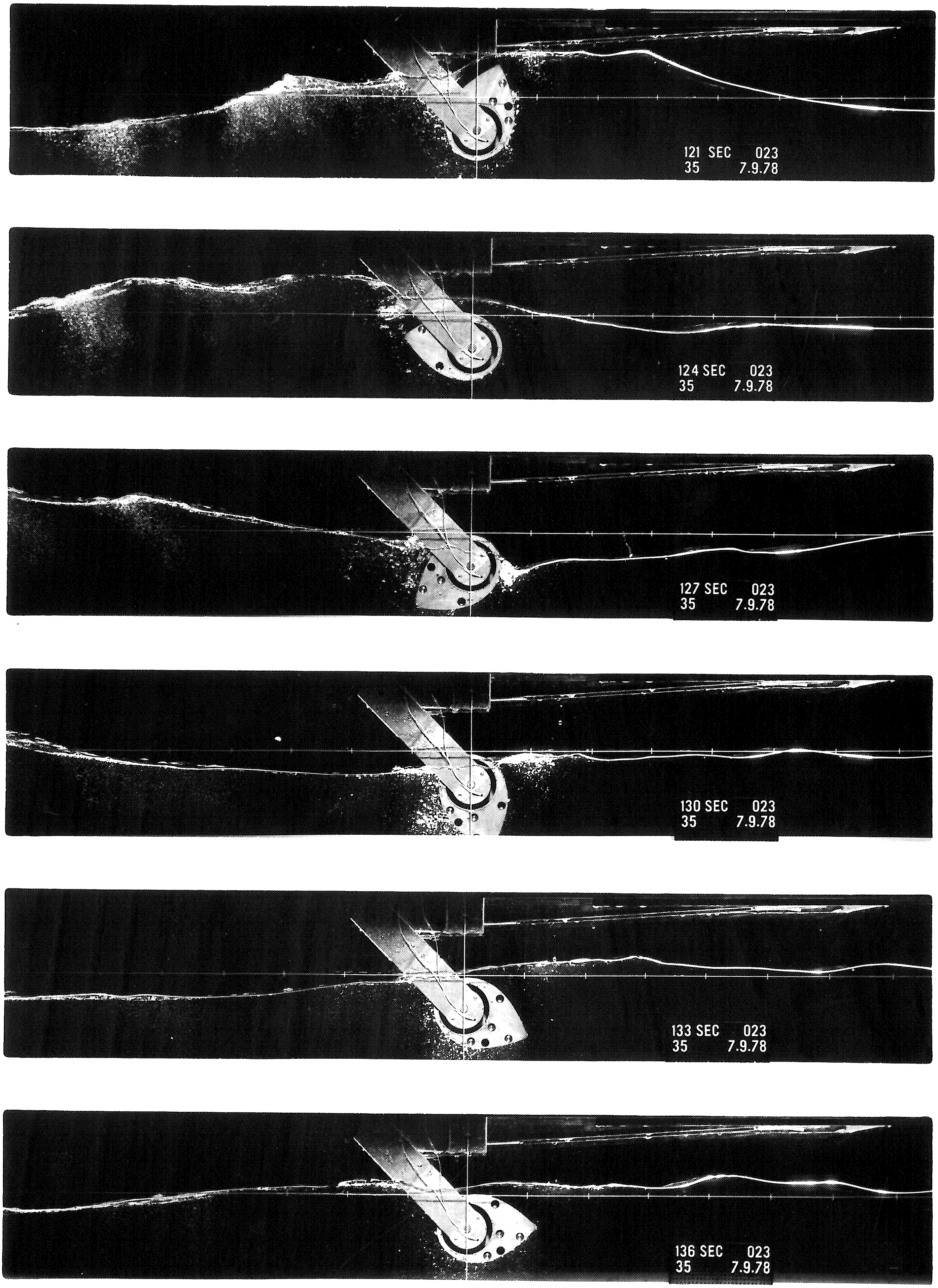


PHOTO 14 a | scale 1/150 | DOUBLE LOOP With NOSE DOWN ballast & RIGID AXIS



Electrical Stiffness Density	HEAVE SURGE	RIGID	Duck Damping (MNm/rad/s/m)	0	Torque Limit (MNm/m)		Time Step (sec)	3	position	0m

PHOTO 14 b



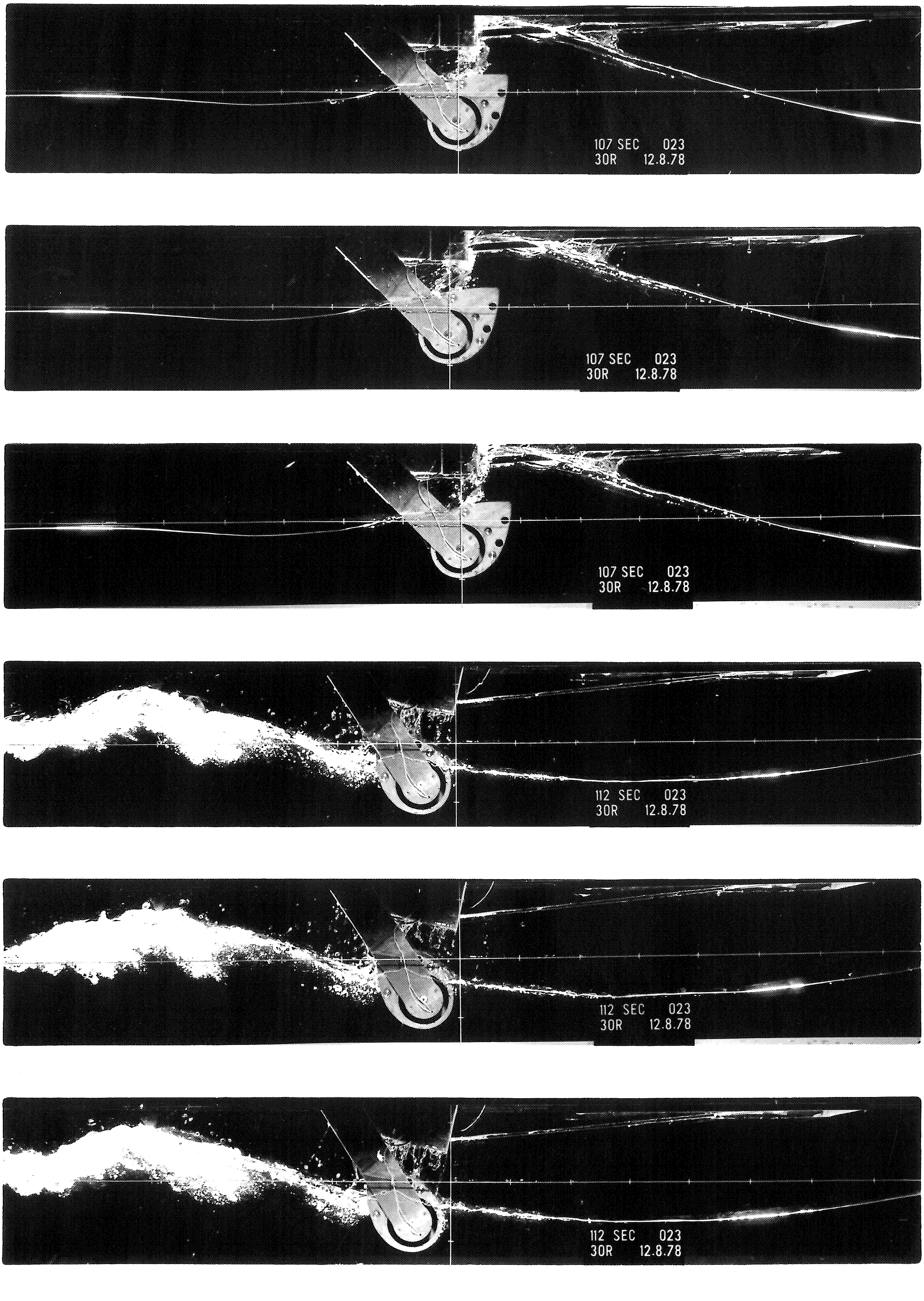
REPEATABILITY

Photograph 15

Three photographs of different waves were taken at 107 and at 112 seconds and are printed together for comparison.

The forwardmost position (graph 1 and photograph 5) showed the poorest repeatability and the wettest conditions for the operator.

PHOTO 15 | scale 1/150 | REPEATABILITY 3 Separate photos taken at 2 different time steps



TAILPIECE

Big Wave In The Wide Tank

Photograph 16 shows a "bullseye" wave in the wide tank. Wavefronts with angles chosen in linear increments up to 60^{o} (relative to the line of wavemakers) converge towards a focus, chosen in this case to lie along the line of the glass. The secret again lies in choosing the starting phases of each component so as to provide superimposition of crests at the correct time and place. We emphasize that this is a regular monochromatic wave in deep water. The period is 1 second, the water depth 1.2m and the distance between the tick marks 20cms. We believe that short-crested wave tests will reveal new problems in ship safety. After experiments with these waves we are not surprised to learn that 1 to 2% of all ships are lost every year. A detached observer would have to conclude that proposals to transport passengers and cargo on the surface of the sea are non-credible.

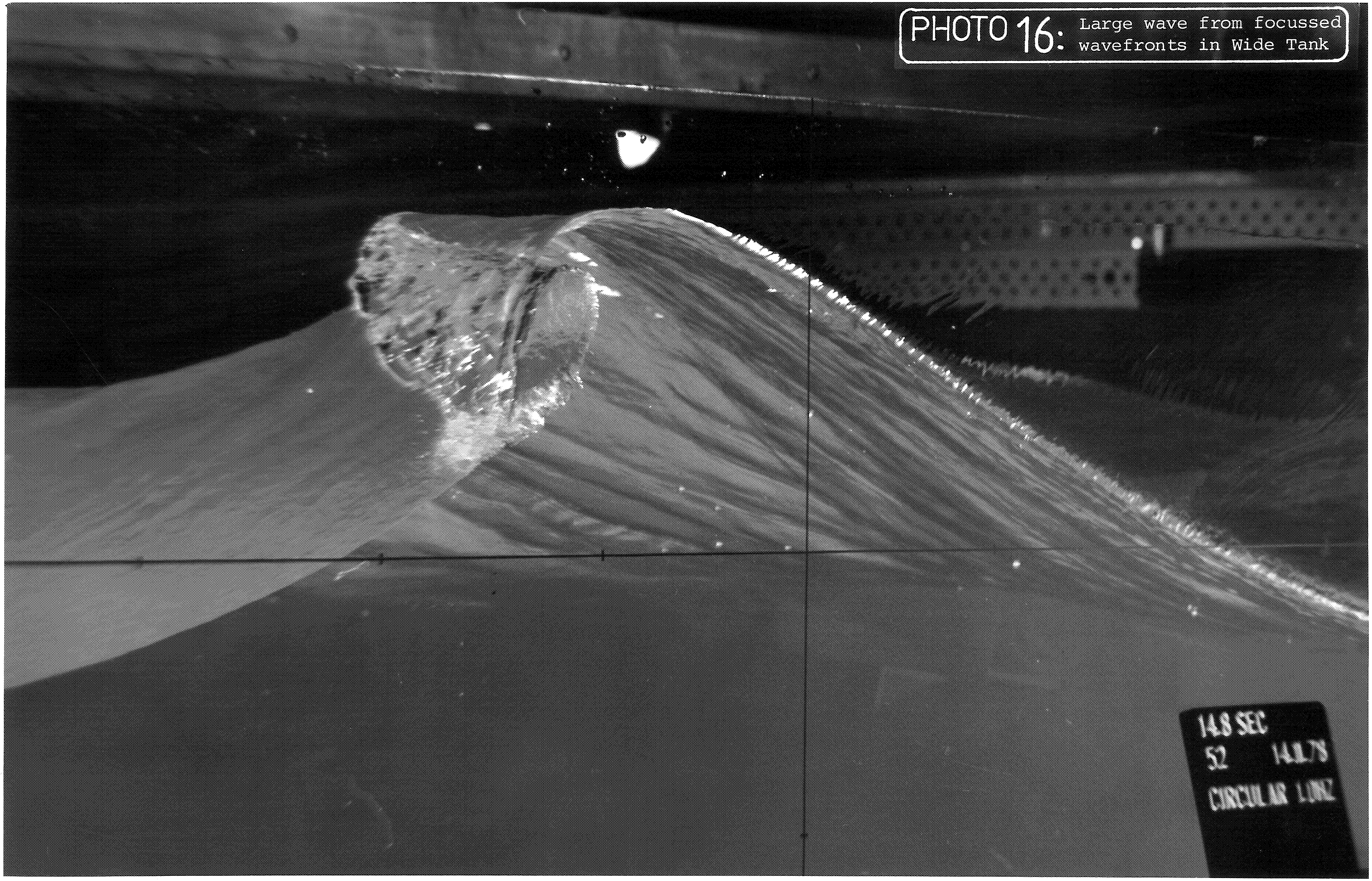


PHOTO 16: Large wave from focussed wavefronts in Wide Tank

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