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The Seasoar, an undulating towed vehicle, samples the upper ocean for oceanographic parameters such as temperature, conductivity, pressure and fluorescence. Basic engineering parameters of the vehicle are not routinely measured. We therefore developed an instrument package that measures roll and pitch of the vehicle, wing angle, impeller turns, and pressure. Data collected during the Subduction 2 cruise in March of 1992 are used to describe Seasoar's behavior under typical conditions. Attempts to increase the maximum profiling depth by deploying additional faired and unfaired cable are described as well.

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Monitoring the Flight of the Seasoar

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Abstract

The Seasoar, an undulating towed vehicle, samples the upper ocean for oceanographic parameters such as temperature, conductivity, pressure and fluorescence. Basic engineering parameters of the vehicle are not routinely measured. We therefore developed an instrument package that measures roll and pitch of the vehicle, wing angle, impeller turns, and pressure. Data collected during the Subduction 2 cruise in March of 1992 are used to describe Seasoar's behavior under typical conditions. Attempts to increase the maximum profiling depth by deploying additional faired and unfaired cable are described as well.

1 Introduction

The Seasoar is an undulating airplane-like vehicle towed behind a research vessel at speeds of approximately 8 knots (Figure 1). The system was developed at the Institute of Oceanographic Sciences/Wormley (IOS) in England in the 1960s, and is marketed with few changes by Chelsea Instruments Ltd., London (Dessureault, 1976; Collins, Pollard and Pu, 1983). Its vertical range extends from the surface down to 300 - 500 meters depth, depending on the specifics of the system. Onboard instruments measure oceanographic parameters such as temperature, conductivity, pressure and fluorescence. It is used extensively by research groups for upper ocean profiling in the world's oceans.

The system utilizes an analog servocontrol loop in which the wing angle of the vehicle is controlled by the difference between the observed pressure and a synthetic reference control signal. Based on this difference, the Seasoar deck unit generates a current signal that sets a valve in the hydraulic unit to either extend or retract the hydraulic ram. The ram is coupled to the wings, and rotates them into diving or climbing positions. Power to the ram is supplied by a water driven impeller connected to a hydraulic unit.

Basic engineering parameters such as wing angle and attitude of the vehicle are not routinely measured, so that one is essentially flying blind. This is particularly bothersome when the performance of the vehicle deteriorates, as it occurred on our Subduction 1 cruise in May of 1991 (Bahr 1991). To learn more about the behavior of Seasoar, an engineering unit was developed and added to the system for the Subduction 2 cruise in March of 1992. It supplied measurements of vehicle roll, pitch, wing angle, impeller turns, and pressure. Together with cable tension, valve current, and control voltage, these parameters were displayed in real time, and recorded for subsequent analysis.

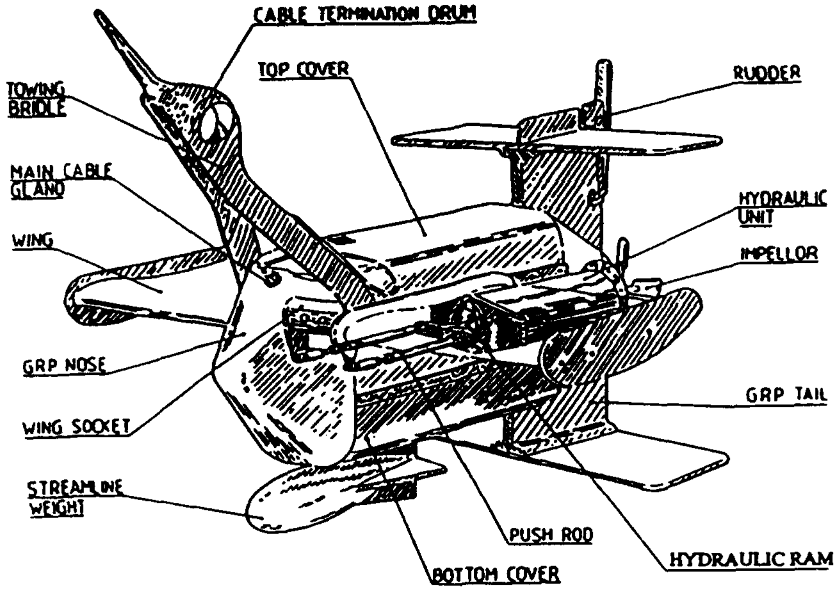

Figure 1: The Seasoar vehicle.

2 The engineering unit

To monitor parameters not normally measured in the Seasoar, we built an instrument based on the Onset Computer Tattletale model 4A controller to monitor the Seasoar while underway. Time, roll, pitch, ambient pressure, wing angle and impeller revolutions were telemetered via EIA 232 at 1200 baud over the 1000 meter cable to a shipboard display and logging personal computer. A Tattletale BASIC (TTBASIC) program scanned the sensors, applied calibration constants and made scaling adjustments, then telemetered the data at a 2.5 Hertz rate .

Time was logged with one second resolution from the Tattletale's real time clock using the TTBASIC RTIME command and remained accurate within a second over the two week period. The roll, pitch, pressure and wing angle DC signals were multiplexed with the 4A's 12-bit D/A converter.

The attitude of the Seasoar fish in the roll and pitch axes was sensed with Lucas AccuStar tilt sensors used in the ratiometric configuration. They were scaled for a range of +/- 40° with resolution of 0.1°. The plots show that pitch went over-range at the beginning of each Seasoar climb (pitch greater than 40°).

Pressure was measured with a Transmetrics P21L transducer which provides 0 to 5 volts DC output over the 0 to 2000 psi range of the sensor. The Tattletale program scaled the signals to decibars with one decibar resolution. Pressure in decibars and meters in depth are very nearly equal so decibars and meters are sometimes used interchangeably in this discussion.

A hydraulic ram is used to pivot a shaft on which the fixed wing of the Seasoar is constructed. A linear potentiometer was used to measure the displacement of the ram and this quantity was called wing angle. The sensor pressure housing flooded with sea water during the initial deployment. Attempts to repair the pot were successful but an internal fixed resistor failed early in the second deployment. Some data were obtained but it's use should be considered very qualitative.

Impeller revolutions were measured by a

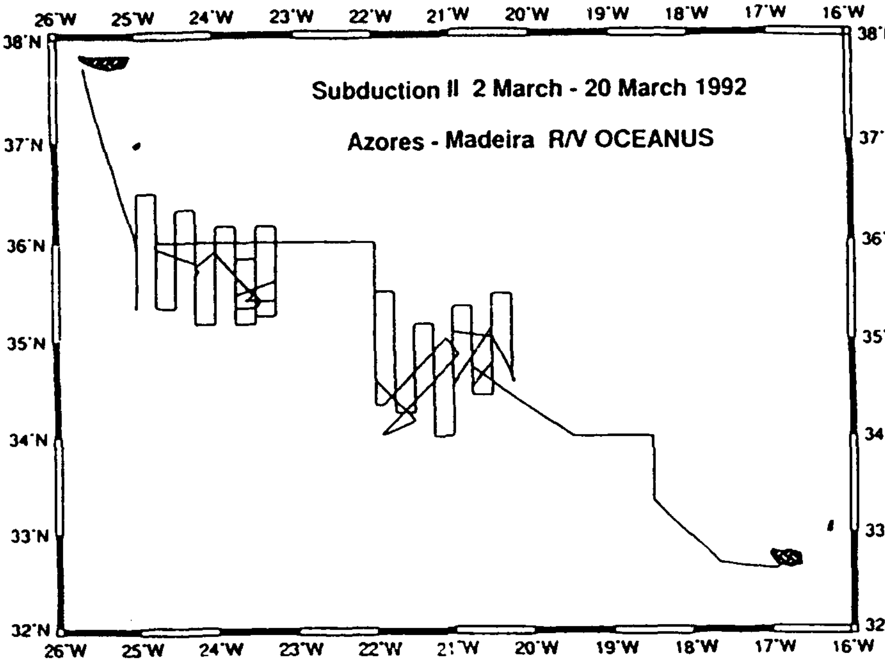

Figure 2: Subduction 2 cruise track.

magneto-diode which detected the passage of magnets installed on each of the six blades. The resulting pulses were counted by the TTBASIC COUNT command, an interrupt routine which runs in background and counts input pulses as they occur. The program computed and telemetered the running average of 10 record scans.

In the shipboard lab the Seasoar controller functions from the deck unit were converted with a Keithley/Metrabyte DAS-8 analog to digital converter package installed in an acquisition PC. Seasoar valve current; command, and the cable tension signals were merged with the ASCII data from the Tattletale on the PC. A Quick-BASC program further scaled and displayed the data and stored the information on the PC disk to be subsequently compressed and archived on tape.

The roll and pitch attitude sensors and the pressure transducer were assembled with the Tattletale and its related electronics in a 4 inch diameter pressure housing. A 15 volt battery pack was included to power the self-contained unit which was mounted in the center of the underwater fish below the wing axis. The engineering unit consumes 25 milliamps and will run for a typical month-long cruise on the battery pack. If desired, the program can be stopped to conserve power while the Seasoar is on deck; the current then drops to seven milliamps.

3 The cruise

The data shown here were collected in March of 1992 during the Subduction 2 cruise onboard the RV Oceanus (Figure 2; Rudnick and Bahr, 1992). After some checks on deck including turning the wings etc., Seasoar was first launched on March 2. However, when all cable was deployed and seasoaring was attempted, the vehicle did not respond to either up– or down–wing commands. After its recovery, the problem was determined to be the hydraulic unit. With a spare unit installed, two 4–day surveys were completed without further problems. The last ten hours of the second deployment were available for various engineering tests. These tests included modifications of the control box

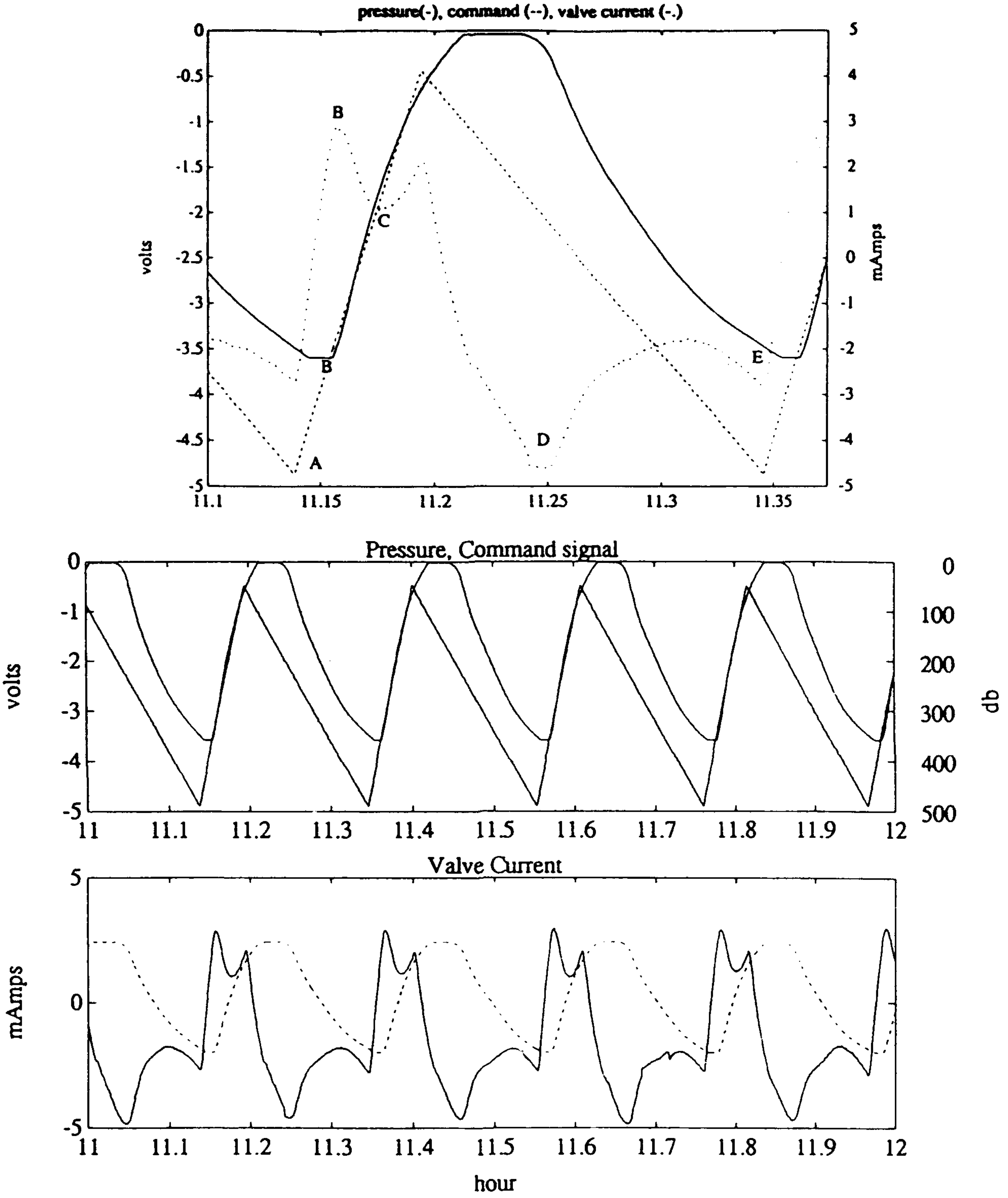

Figure 3: Top: Pressure (solid), command (dashed) and valve current (dash-dot) for one dive cycle. Symbols "A" to "E" are referenced in the text. Middle: 1 hour time series of pressure and command signal. Bottom: 1 hour time series of valve current; pressure (dashed) is included as reference.

circuitry and attempts to increase the profiling depth.

4 The dive cycle

In this section, a typical dive cycle of the Seasoar is described in detail. Two types of figures will be used: vertical profiles, in which 11 hours of continuous measurements are displayed as function of pressure, and time series of a 1-hour subset. Separate profiles may be given for the dive and the climb segments of the Seasoar path. The data were collected on March 13 during the second deployment.

4.1 Pressure, command signal, and valve current

The command signal generated by the Seasoar controller is a saw–tooth pattern which represents an ideal trajectory for the Seasoar. Its shape is set manually by specifying the dive rate, climb rate, and the maximum and minimum depth with dials on the Seasoar deck unit. The DC level of the command curve can be moved vertically by adjusting the bias. The difference between the command signal and pressure measured inside the vehicle is the loop following error, and the the Seasoar deck generates a corresponding current signal. This current, called valve current, sets the valve in the hydraulic unit to either extend or retract the hydraulic unit's piston, which will move the wings into up-wing or down-wing positions at a rate proportional to valve current. Positive valve current corresponds to up-wing, negative to down-wing angles. A feedback loop is thus formed, in which the pitch of the wings is continually adjusted as the vehicle attempts to alter its depth until the output from the pressure transducer matches the command signal (Seasoar manual). Loop gain can be adjusted with a front panel control potentiometer. Under stable conditions of the servo loop, pressure never catches up to the command signal, but rather a balance between the two is reached.

In a typical dive cycle, the command signal (COM) leads pressure voltage (PV), and thus reaches the deep turning point prior to PV (Figure 3, top; point A). With Seasoar continuing to dive, COM now ascends (decreases) and quickly overtakes PV. The valve current (VC) shows a corresponding sharp rise from negative to positive current. The maximum is reached when Seasoar turns around at the deep extremum of its path (point B). The vehicle ascends somewhat more quickly than the command signal, so that PV catches up with COM, resulting in a relative minimum in VC (point C). A second maximum in VC is reached when the Seasoar slows its climb near the surface. VC drops sharply once COM goes through its surface turn. It changes to down–wing current before Seasoar reaches the surface, and the down–wing signal continues to increase until Seasoar starts to dive (point D). The surface extremum of negative VC is smoother in shape than the maximum in positive, up–wing VC at the deep turning point because of the slower turning of the vehicle near the surface.

Variations of the typical scenario described above include a less pronounced drop between the two surface peaks of VC (point C), when the climb rate of the Seasoar corresponds more closely to the slope of the command signal. Further, we found that the relative extremum in negative VC just prior to its steep rise to up–wing current (point E) may be reduced or missing. We typically used a setting for the command signal descent rate that was slightly less than the descent rate of the vehicle. Thus, Seasoar would catch up with COM during its dive, reducing PV-COM and thus VC. It would typically slow its descent, however, as it approached maximum depth, which widened the gap between COM and PV causing in down–wing (negative) VC to increase again. At one instance during the engineering tests, the command curve was further ahead of pressure. PV,

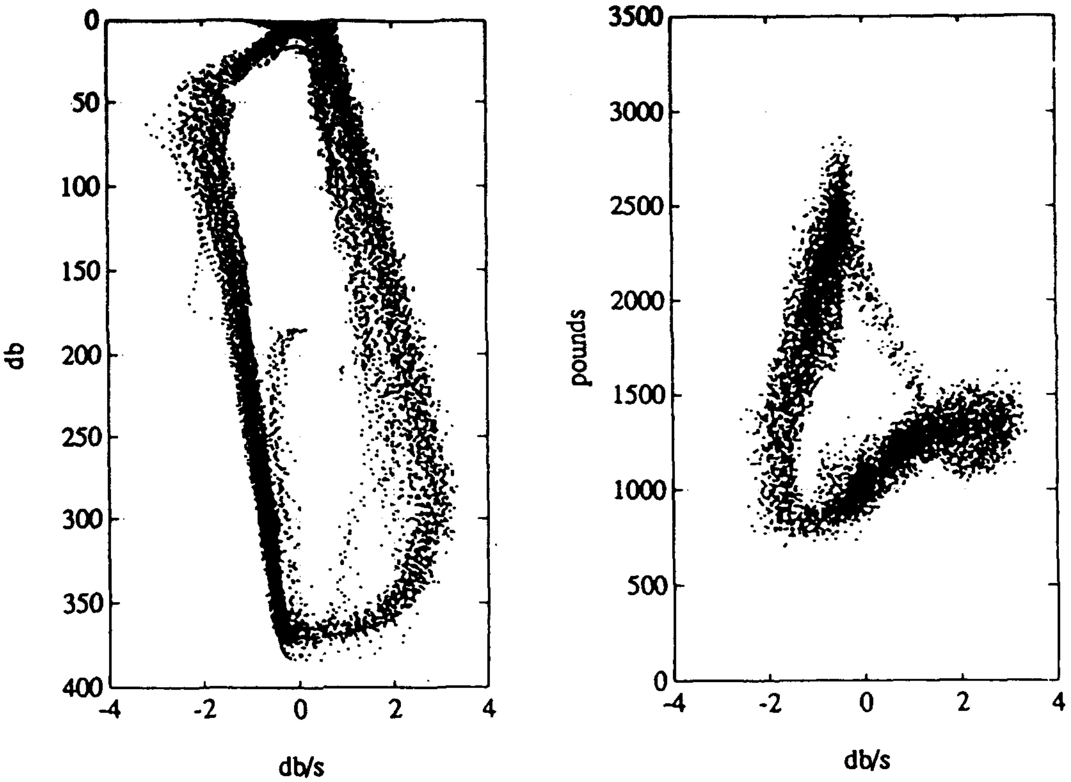

Figure 4: Left: Profile of dive (negative) and climb rate (positive). Right: cable tension versus climb rate.

with a larger gap to cover, did not catch up to COM, and Seasoar's descent rate remained steep. Once the settings for COM were changed to a smaller descent rate, and the minimum in VC re-appeared. At the time, the settings were changed to a reduced descent rate and shortly thereafter to a deeper bottom depth to deepen Seasoar's relatively shallow dives (less than 350m). In hindsight, it would have been interesting to see what would have happened if only the maximum depth of COM had been changed.

4.2 Dive rate, cable tension and impeller turns

Dive rate typically remains within ± 3 m/s (Figure 4, top and 5, top). However, we have seen dive rates of up to 6 m/s during some of the less regular seasoaring on our earlier Subduction 1 cruise. On this cruise, there were a few cases of similarly high dive rates during the engineering tests.

As expected, cable tension rises as the Seasoar dives (Figure 6 and 5, middle). For about 600 meters of faired cable deployed, tension ranges between 1000 and 2600 pounds, with occasional spikes of up to 3000 pounds. Tension at large depths averages closer to 3000 pounds when 750 meter of faired cable is deployed.

Immediately following the maximum at Seasoar's deep turning point, tension drops rapidly. It then decreases on the climb towards the surface. Surprisingly, though, the minimum is not reached until after Seasoar starts to dive again, typically around 30m. The dive rate may have already reached 1 m/s at this time (Figure 4, bottom). From here on, tension increases at first swiftly, then more moderately towards the nadir of the dive cycle.

Impeller rotation rates are generally stable, and average around 160 rpm (Figure 5, bottom

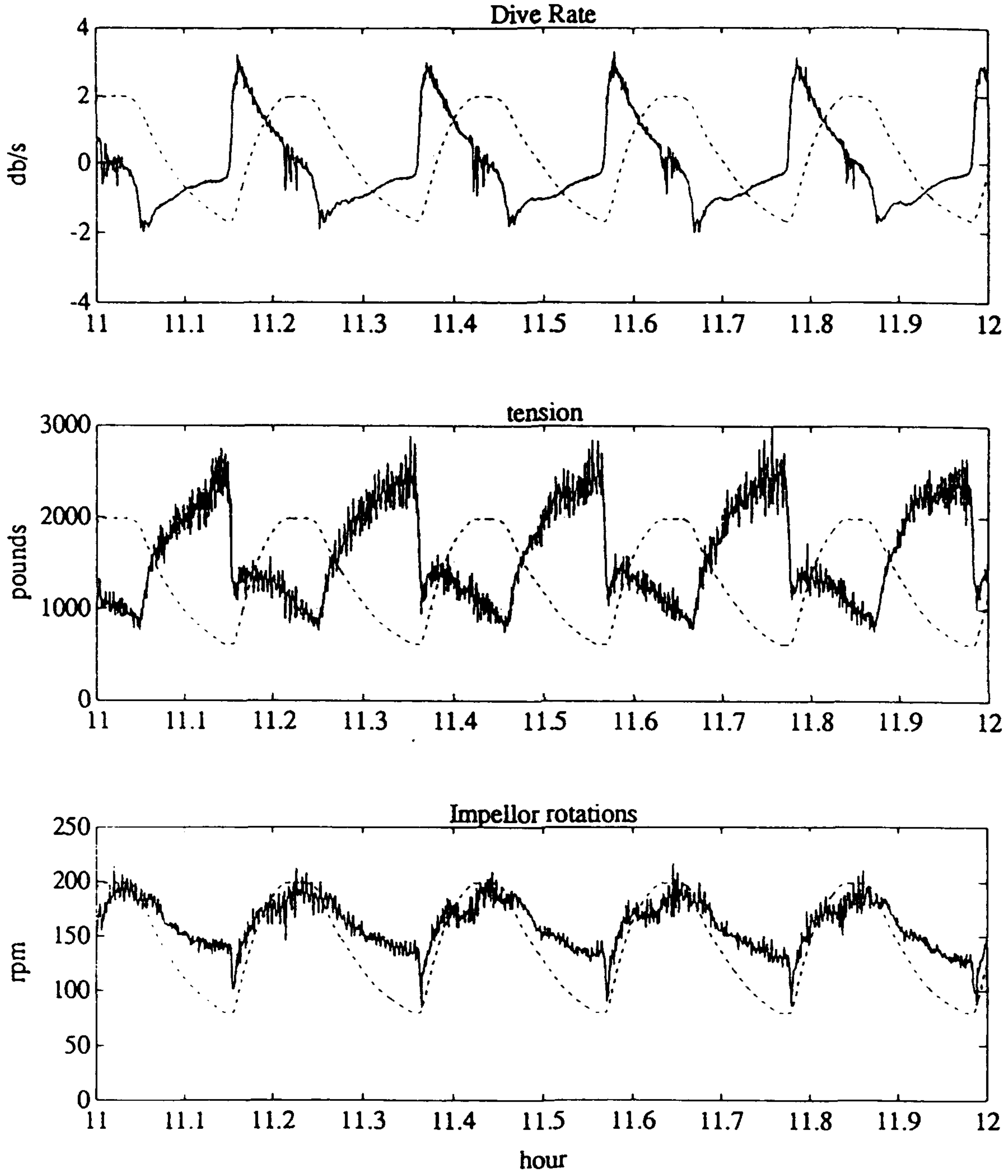

Figure 5: Time series of dive rate (top), cable tension (middle), and impeller rotations (bottom); pressure (dashed) is included as reference.

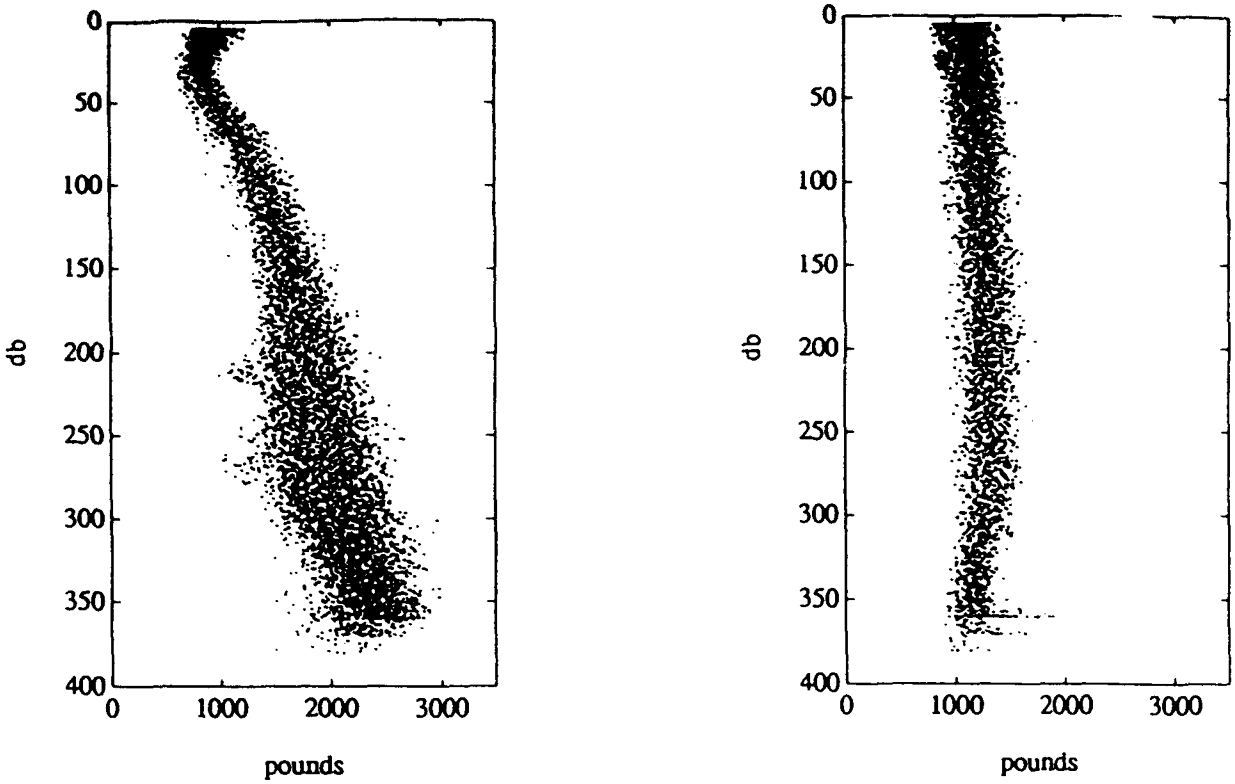

Figure 6: Profile of cable tension, during dive (left) and climb (right).

and Figure 7). The signal varies with depth by about 25%, with rotation rates reduced at depth and highest near the surface. A short term reduction, particularly pronounced in the one hour of data shown in figure 5, coincides with the drop in cable tension at the nadir of the Seasoar path. It may be caused by a brief slowing of the vehicle when it first turns upwards towards the ship.

4.3 Pitch and roll

The pitch of the Seasoar displayed a pattern that repeated itself consistently over subsequent dive cycles (Figures 8 and 9). In a typical cycle, the vehicle arrives at the surface with a small upward angle. It continues to turn slowly downward through level while it remains at the surface, and slowly starts to dive again once the nose points down a few degrees.

The dive then gets quickly underway with pitch decreasing sharply downwards and dive

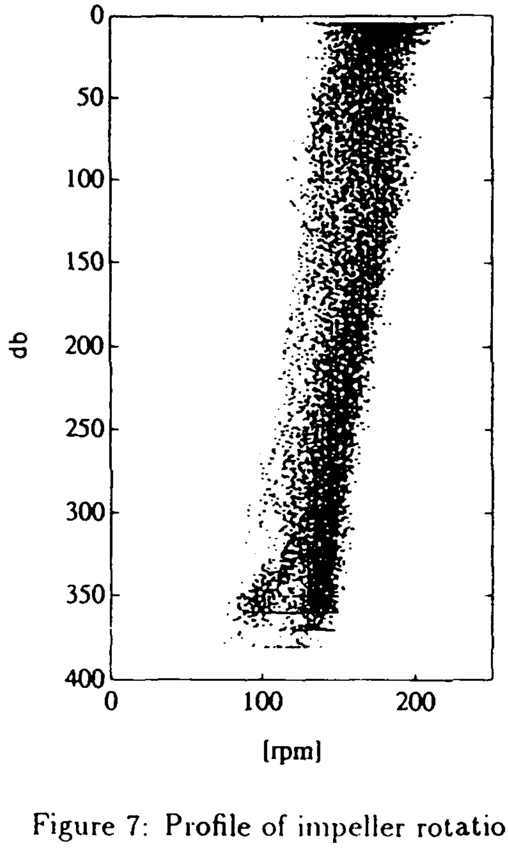

Figure 7: Profile of impeller rotation.

rate increasing to maximum values. The change in pitch abruptly stops at approximately -20°, which is typically reached around 60 meters depth. From here on, the Seasoar remains pointed downwards throughout the rest of the descent. The subsequent climb starts with an abrupt rise in pitch that often exceeds 40°, the limit of our instrument system at the time. As the vehicle ascends, the upward angle decreases at first rapidly, then more slowly as the vehicle approaches the surface.

Although less well defined, roll exhibited a repeatable pattern as well (Figure 8. Its range, however, was smaller, aside from occasional large rolls on the ascent. In the composite dive cycle (Figure 9) Seasoar usually displays a peculiar roll as it first descends from the surface with the initially large dive rate. Below 100 db or so, the vehicle levels out as the dive continues. The surface roll is mirrored at the initial climb after the deep turning point, though smaller in amplitude. The vehicle remains tilted by about 5° during the remaining climb. We do not have an explanation for either the rolls at the extreme ends of the dive path, or the 5° tilt on the climb. Imperfect alignment of the tilt sensors probably caused some of the large pitch to couple into the roll axis at initial dive and climb times.

4.4 Surface turning

One motive for making the engineering measurements was the frustration of not knowing what caused Seasoar's deteriorating performance towards the end of our previous cruise. During the last deployment of the Subduction 1 cruise in May of 1991, the vehicle started to show the tendency to stall at the surface. At first, it could be coaxed into diving by manually providing a short period of up-wing valve current, followed by a strong down-wing signal. According to one theory, a heavy dragging tail kept the wings at a nearly neutral angle of attack to the flow even in maximum down-wing position. The wing-up signal supposedly straightened the vehicle out before sending the down-wing current. Finally, however, Seasoar would get stuck at about 75 meters, responding to neither up- nor down-wing signals. In these situations, a brief reduction in ship speed was the only measure that led to a (swift) dive as it began to sink from lack of towing.

Because of the good performance of Seasoar during Subduction 2, the engineering data collected on this cruise provided little help in identifying the cause of the previous surface stuckness. They did, however, provide a background against which one can evaluate future difficulties. In a typical surface turning, the zero-crossing of pitch approximately coincides with the apex of the Seasoar path (Figure 10,top). The following descent begins slowly, but changes to a swift dive once pitch increases to angles between 5° to 10°. Downward valve current, which has continued to grow during this period, now reaches its maximum and starts to decrease as pressure catches up with the command signal.

The surface turning at the very end of the cruise was not as swift as before. During the last few dive cycles, the vehicle remained near the surface for up to 8 minutes (Figure 10, bottom). Despite large downward valve current, the vehicle turned downwards only very slowly, and the dive rate remained low. It was not until pitch had reached about −5° that the dive fully began. At this point, however, both pitch and dive rate increased quickly. These dives occurred at a time when various experiments were performed, including deploying additional faired and unfaired cable. At first we suspected that the reduced performance was related to these experiments. Since returning from the cruise, however, we learned that the hydraulic unit developed a problem sometime before it arrived back in Woods Hole. When tested here in the lab, it was unable to move the wings. The unit may have already been damaged during the last hours of the cruise, and may have not been strong enough to rotate the wings.

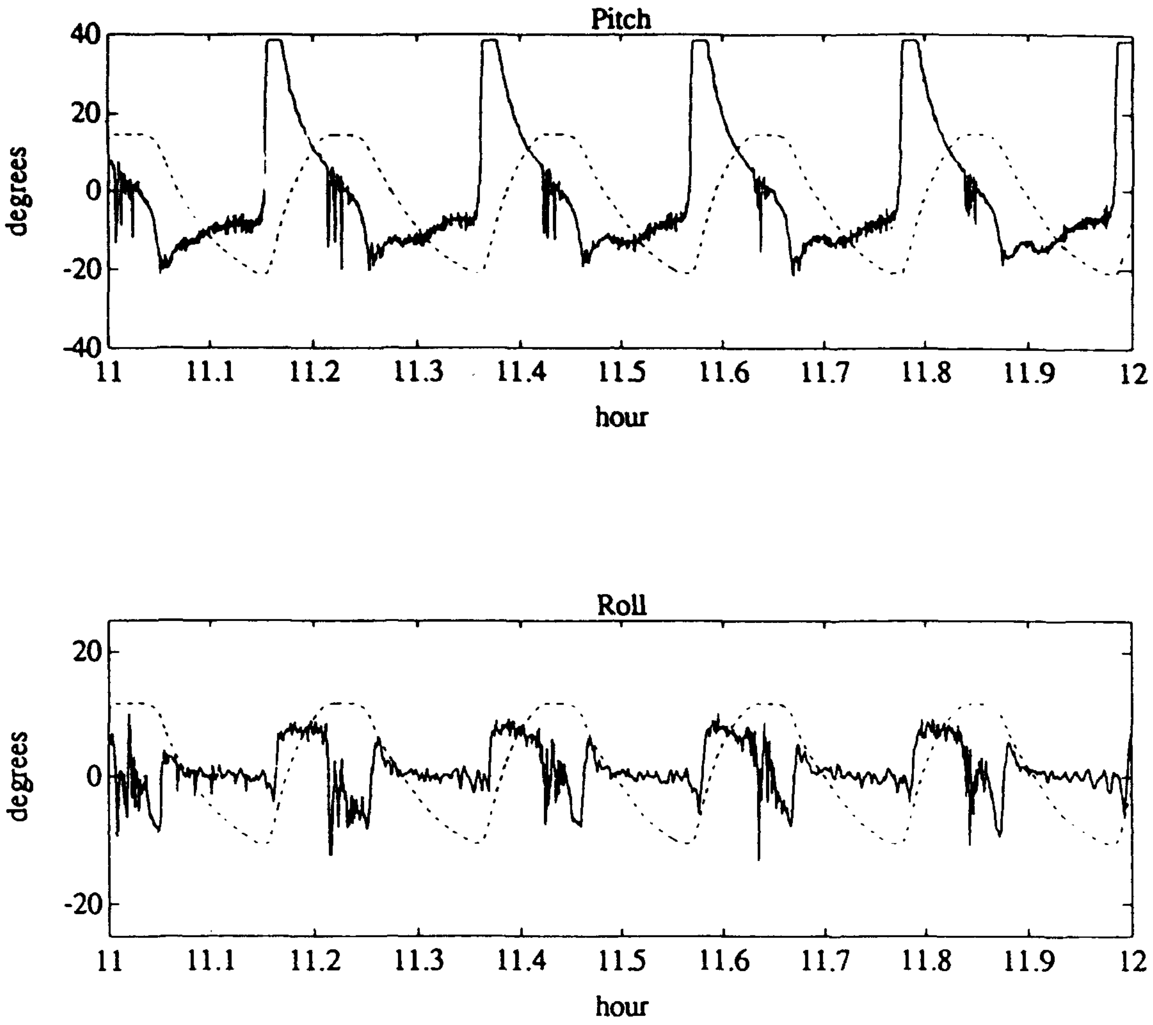

Figure 8: Time series of pitch (top), and roll (bottom); pressure (dashed) is included as reference.

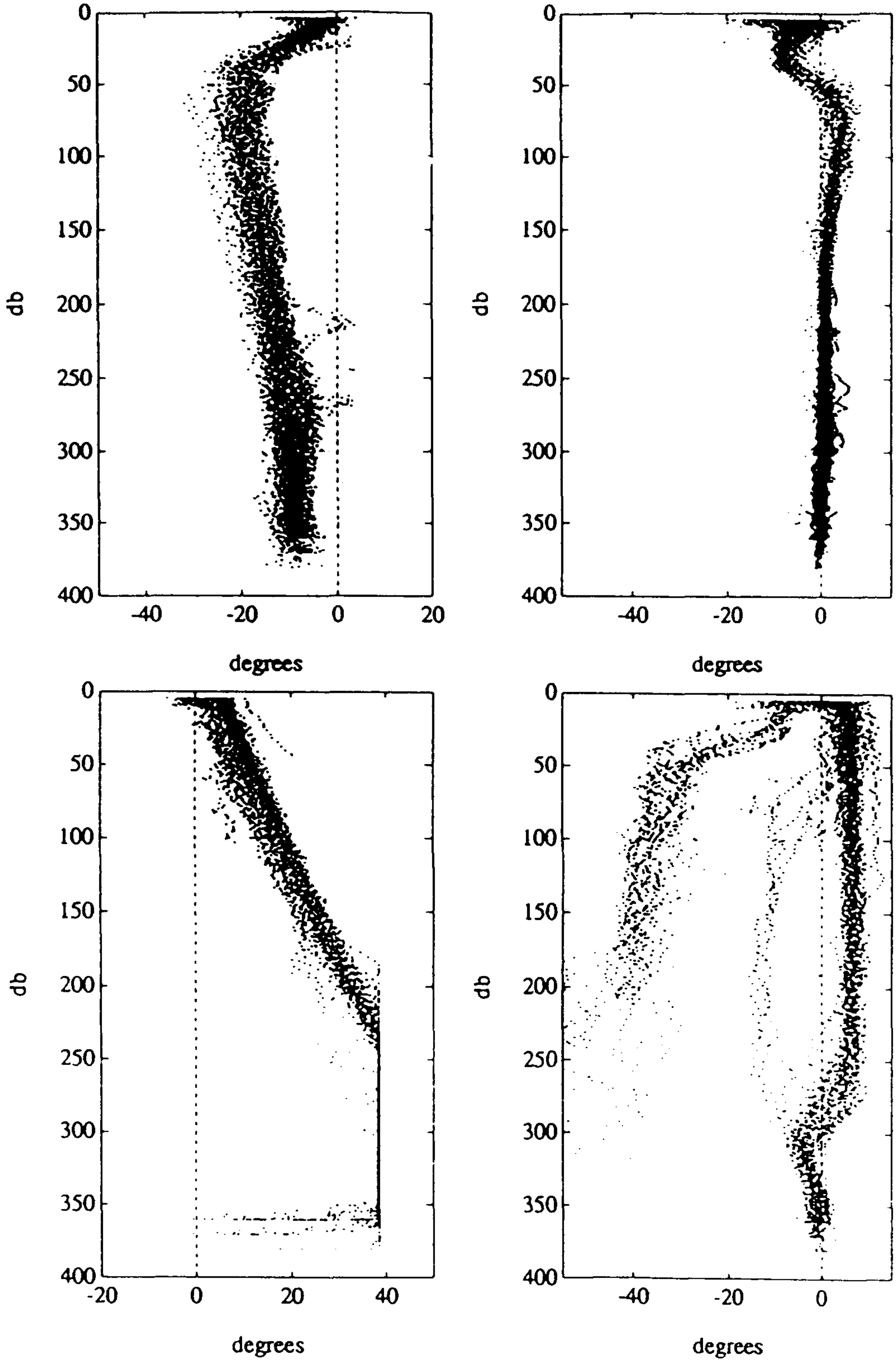

Figure 9: Left: Profile of pitch during dive (top) and climb (bottom). Right: Profile of roll during dive (top) and climb (bottom).

5 Extending Seasoar's depth range

During Subduction 1 in 1991, about 550 meters of the Seasoar cable were faired. Maximum profiling depths were somewhat variable, but typically ranged between 350 and 400 meters. Dive cycles were completed in approximately 13 minutes. Using a new, larger winch with 750 meters of faired cable, Pat Gwilliam from IOS was able to extend the profiling depth to 500 meters (Gwilliam, 1991). As a drawback, the time period required to complete a dive cycle increased to about 20 minutes. For a ship speed of 8 knots, this reduces the horizontal resolution from 3.2 km to 5 km.

Before our cruise in '92, the amount of faired cable of the WHOI system was extended to 780 meters. Several modifications had to be made in order to spool additional faired cable onto the existing Seasoar winch. The winch is laid out for two wraps, with separators for the bottom layer designed for unfaired cable. With faired cable now on the bottom wrap as well, precautions had to be made to prevent the fairing from damage. One sheet of Surlyn foam was placed over half of the winch drum to prevent the plastic fairing from being sheared by the cable separators. Once the first layer was wound onto the winch, a second layer of Surlyn foam was placed over the faired portion before the second cable layer was spooled on. Side cheeks were welded onto the drum to prevent the now raised second layer from spilling. A support bar at the back side of the winch had to be moved to allow clearance for the drum with its increased diameter to rotate freely.

During Subduction 2, horizontal resolution had priority over increased depth. Therefore only 600 meters of faired cable were deployed during most of the cruise. Seasoar flew very reliably between the surface and about 350 meters in periods of about 12 minutes. At 8 knots, this corresponds to approximately 3 km between successive surfacings. During the last 12 hours of the cruise, set aside for engineering tests, 780 meters of faired cable were deployed. Over a few cycles, the profiling depth increased to 430 meters. The time period increased as well to 17 minutes. The maximum depth increased further to 450 meters when an additional 150 meters of unfaired cable was deployed. It became more difficult, however, to reach the surface, so that the deeper bottom depth does not represent a true increase of the profiling range. Furthermore, the time to complete a dive cycle was increased to 20 minutes in order to keep cable tension below 3000 pounds.

6 Dither

The valve current generated by the original deck unit was probably not dithered as specified in the Seasoar manual. We found the actual circuit to be missing a ground (common) connection as shown in the schematic diagrams. As part of the engineering tests, we added the ground connection, thus the dither. We were unable to show the effect of added dither on the flight characteristics of Seasoar, partly because the vehicle flew already very well without it. It was our impression at the time, however, that Seasoar was more responsive to the controls when dither was included.

7 Conclusions

The addition of an engineering unit to the Seasoar system provided us with a valuable tool to monitor the flight characteristics of the vehicle under favorable conditions. A picture of a typical dive cycle emerged that showed a consistent cycle in many of the recorded parameters. This picture can be used as a base to evaluate the behavior of the Seasoar in future cruises.

Impeller turns were found to be remarkably constant. This was in contrast to an observation by Pat Gwilliam from IOS (pers. comm.), who

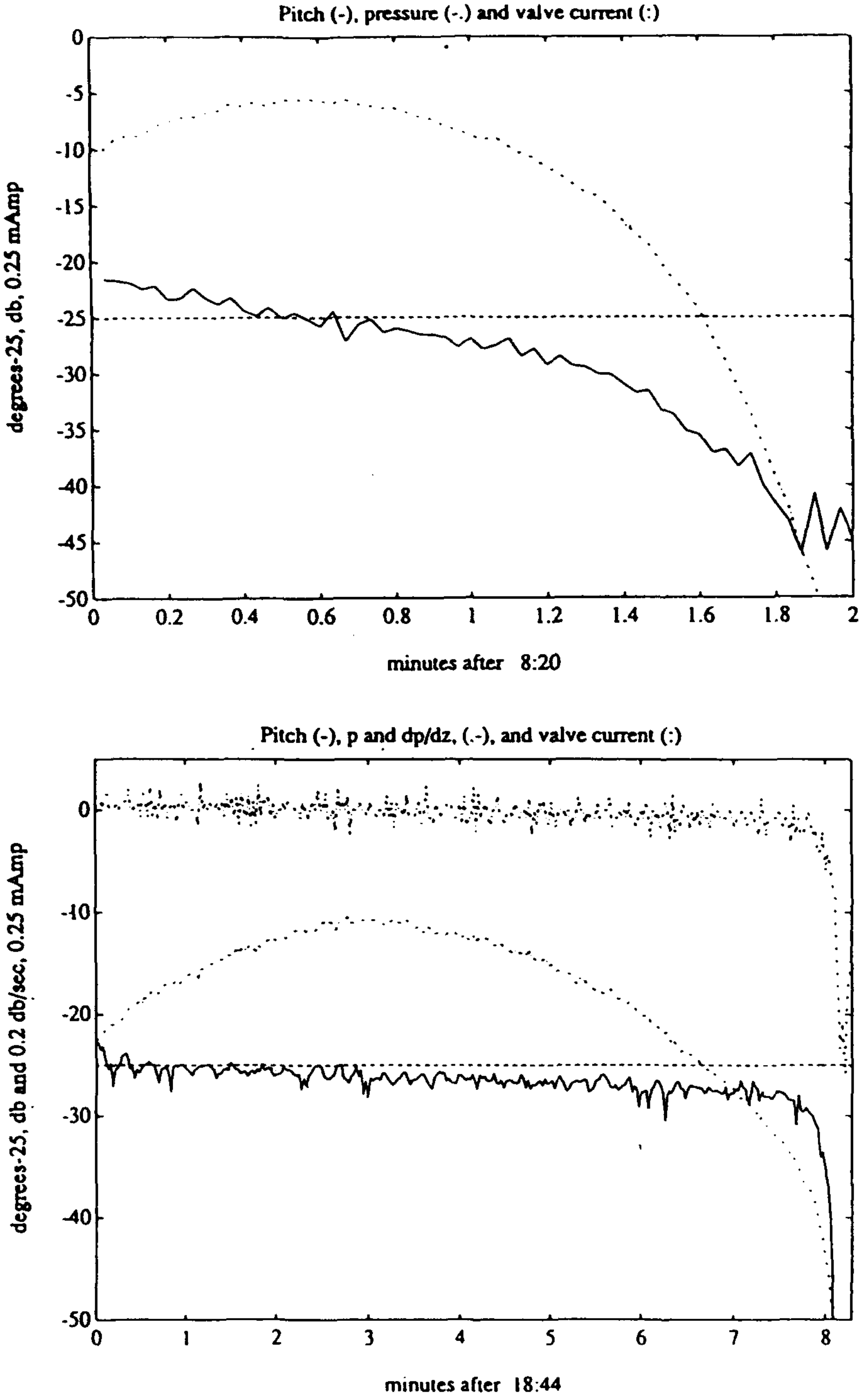

Figure 10: Surface turning. Top: Time series of pitch (solid), pressure (dash-dot) and valve current (dotted) during a typical surface turning. Bottom: similar time series with the addition of dive rate from the end of the cruise. Note the different time spans of the two figures.

had found a sharp reduction of impeller turns near the surface. We had previously speculated that this reduction may have been the reason for the surface sticking we had observed during an earlier cruise. By reducing the power supplied to the hydraulic unit, it would have affected the hydraulic unit's ability to turn the wings. With impeller turns near the surface observed to be high, however, we can not confirm this hypothesis.

We found that the profiling range could be extended when the amount of faired cable was increased. The range did not increase significantly when additional unfaired cable was deployed. The time allocated for the various engineering tests was too short, however, to arrive at quantitative conclusions.

During our upcoming cruise, we will continue to collect the engineering parameters including wing angle. In addition, we will have equipment available that will allow us to test the quality of our hydraulic units.

Acknowledgements

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