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PERFORMANCE ANALYSIS OF AN UNDERWATER WIRE FLYING

PROFILING VEHICLE

BY

LUKE ANDREW LOGAN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

IN

OCEANOGRAPHY

UNIVERSITY OF RHODE ISLAND

MASTER OF YOUR DEGREE THESIS

OF

LUKE ANDREW LOGAN

APPROVED:

Thesis Committee:

Major Professor

Chris Roman

David Ullman

Stephen Licht

Nasser H. Zawia

DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND

ABSTRACT

Profiling the water column from a moving vessel places significant limitations on the achievable spatial resolution of the data collected. Current solutions such as underway CTDs and undulating towed bodies are limited by vessel speed and operational water depths. With an increased focus on submesoscale processes (e.g., stirring, mixing, regulation of thermocline structure, chemical distributions along isopycnals and resolution of hydrothermal plumes), there is a growing need to collect profiles with high vertical and horizontal resolution. A new autonomous profiling vehicle has been developed to address this need. The autonomous wire flying profiling vehicle slides up and down a towed wire in controlled manner using the lift generated from actuated wing foils. Using a depth and velocity controller, the vehicle is capable of maintaining prescribed flight paths over a range of ship speeds and tow depths. The vehicle has achieved glide slopes (ratio of vertical to horizontal speeds) up to 2.5 for tow cables angles between vertical and 45 degrees during field testing. This results in a sample path with more horizontal resolution than otherwise achievable with other underway or undulating systems. This paper presents a summary of the vehicle's capabilities along with field test data from a test cruise to the New England Shelf Break.

ACKNOWLEDGEMENTS

Throughout this thesis I have been afforded the opportunity to study a unique, new technology. With the associated challenges in developing and testing a new technology, I was able to gain considerable knowledge. I am sincerely thankful to my advisor Chris Roman for providing this opportunity for me and helping me significantly along the way. As with the development of any new technology, there are many behind the scenes players that are instrumental to the overall success of the project. For that I thank Dave Casagrande, Todd Gregory and Will Snyder for their efforts. I also wish to express thanks to David Ullman and Stephen Licht for their knowledge and input as committee members.

I am exceptionally grateful for the support of my loving family and so many new and old friends. It is always difficult to move somewhere new and succeed and they helped to ease the process. Their confidence in me kept me pushing toward the finish line. I extend my deepest gratitude to Lauren Schmalzbach. She left the sunny, warm, tropical climate of South Florida to follow me to Rhode Island for my graduate studies. Her unwavering and unequivocal support was nothing short of amazing and I am forever indebted to her for following me on this journey.

PREFACE

Rather than using the traditional division of the thesis into chapters, this thesis is written in "manuscript" style. The abstract, body text, references, tables and figures are all formatted in accordance to the AMS Journal of Atmospheric and Oceanic Technology. Due to formatting restrictions, new sections do not start on new pages and all figures are removed from the body of text and placed at the end of the document. Submission to this journal is expected in the upcoming months.

ABSTRACTii
ACKNOWLEDGEMENTS iii
PREFACE iv
TABLE OF CONTENTSv
LIST OF FIGURES
MANUSCRIPT: Performance Analysis of an Underwater Wire Flying
Profiling Vehicle
1 Introduction
Existing Profiling Vehicles
2 The Wire-Flying Vehicle
Vehicle Dynamics7
3 Profiling Performance
Stall and Angle of Attack13
CTD Data Resolution16
Testing Limitations18
4 Conclusion19
REFERENCES
LIST OF FIGURES
FIGURES

TABLE OF CONTENTS

LIST OF FIGURES

- 2 Colored curves represent idealized performance estimates for a full scale system. Curves are shown for differing body drag coefficients. Scaled model test results are overlaid on the initial predictions. Glide slopes were extracted from all of the steady state slope values achieved during the tests (Roman and Herbert 2011). ..27
- Full scale prototype vehicle. The vehicle is resting in a custom landing cart. The 950 kilogram depressor weight can be seen resting on the ship's deck below the cart (yellow).
- 6 Free body diagram for the wing forces generated during climbing and descending situation. The wing produces a net force F, with lift and drag components relative to the apparent flow velocity. The net force has projections F_{AC} along and F_w perpendicular to the wire. (a) F_{AC} is able to pull the flyer up the cable and there is

- 7 (a) Cable angles plotted for a series of repeating profiles on the WiFly. Cable angles are measured using a US Digital X3M Inclinometer. Upwards motion profiles are in blue and downwards motion profiles are in red. The black line is the calculated average cable profile. This average profile was used for calculating the cable layback during this series of profiles. The cable layback changes as a function of depth (b).

- 16 (a) WiFly vehicle profiling between 350 and 600 meters depth. The clump weight depth is represented by the black line. (b) Cable angles were in excess of 50 degrees at top of upwards profiles. (c) Target velocities of 2.0 meters per second upwards and downwards are shown in red with the achieved velocities in blue.(d) Wing angles during profile are shown. The onset of stall is seen at 300

- 19 (a) Sections of upwards movement steady state apparent velocity measurements. Red dots are velocities measured with the vehicle's speed sensor. Blue dots are the calculated based on ADCP measured horizontal velocities for the corresponding depths and times. Not all steady state upwards movement is represented here. (b) Relative errors between the measured and calculated apparent velocities. (c) Histogram showing the distribution of errors. A positive error means the speed sensor measurement is less than the ADCP calculated value. The mean error for the data shown is 5.2.
- **20** Achieved glide slopes calculated using ADCP horizontal velocities in place of the speed sensor velocity measurements. Glide slopes are plotted over the range of tow cable angles. The colorbar corresponds to apparent velocity (m/s) calculated

Manuscript

Performance Analysis of an Underwater Wire Flying Profiling Vehicle

By

Luke Logan¹ and Chris Roman¹

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Journal of Atmospheric and Oceanic Technology

¹ Graduate School of Oceanography, University of Rhode Island, Narragansett, Rhode Island, USA.

Manuscript

Performance Analysis of an Underwater Wire Flying Vehicle

1. Introduction

Ocean processes on smaller horizontal scales are of increasing environmental importance. Scientific research continues to work toward identifying and understanding smaller scale processes in the ocean. As scientific research advances, the technology through which that research is conducted must follow suit. Existing technologies have limited ability to profile the water column with the horizontal and vertical resolution needed to capture many of the relevant spatial scales.

On horizontal scales between 10's of meters to 10's of kilometers, critical ocean processes occur such as stirring and mixing to regulate ocean thermocline structure, chemical distributions, and meridional overturning throughout the water column (Crawford 1986, Schiermeier 2007).

As an example, in the deep ocean the enhancement of vertical mixing over regions of rough topography has been documented via measurements of turbulent dissipation rates (Polzin et al. 1997). This has significant implications for the abyssal stratification and circulation (Jayne et al. 2004). Using traditional microstructure instruments to measure turbulent dissipation rates in the deep ocean is very difficult and time consuming due to the deployment time required for such instruments. Water mass and current formations are also greatly influenced by topography. Evidence of topographic effects extends all the way to surface currents via the curvature of the current flow in response to bottom topography (Knauss 1997). Understanding the linkage between these processes is crucial

to efforts aimed at predicting the consequences of the warming and freshening of highlatitude surface waters to the climate system (Lozier 2012).

Resolving hydrothermal plume structure from seafloor vents has proven to be challenging as well. Hydrothermal plumes typically rise and spread hundreds of meters laterally over the seafloor. As such, dense sampling near then seafloor is required to accurately resolve plume structures. Past studies in water depths deeper than 2000 meters have used tow-yo CTD surveys to resolve plume structures (D'Asaro et al. 1994). This requires slow ship speeds and constant winch operations. Conducting such a survey with sufficient resolution to identify the plume structure is difficult. By decoupling the sampling instrument's motion from the motion of the tow cable, higher resolution sampling and more efficient vertical movement of the instrument can be achieved.

Existing Profiling Vehicles

Current repeat profilers and undulating tow bodies have achieved some success profiling with high vertical and horizontal spatial resolution while underway. Most of these technologies however are limited by vessel speed and operational water depths, and typically leave either the horizontal or vertical under sampled.

The Oceanscience UnderwayCTD is capable of vertical profiling in waters up to 2000 meters deep. This instrument employs a free falling sensor equipped with a Sea-Bird Electronics CTD that is dropped, up to speeds of 4 meters per second, and then reeled back to the ship repeatedly. This method requires a full recovery to the surface after each cast in order to spatially located the instrument and beginning timing the free fall. Thus, the instrument is constrained by the time it takes to complete a vertical cast, which then

impacts the spacing between casts. Additionally, the Underway CTD cannot profile within a specified depth band without recovering the profiler to the surface. Although full profiles may be useful in certain studies, the added time of a full recovery limits the sampling density for studies at depth or near bottom topography.

The EVIA Scanfish is a towed undulating body capable of operating in surface waters up to 500 meters. To operate towed bodies such as the Scanfish, the vessel must maintain a minimum speed to provide sufficient lift to the body. The performance of such undulating bodies is limited by the attached tow cable being fixed to the body. As more cable is paid out, the drag forces on the tow cable increase and it becomes difficult to maintain large vertical profiles without sacrificing horizontal resolution. These large drag forces limit the achievable glides slopes (ratio of vertical to horizontal speeds) to approximately 0.25. In regions of sub-mesoscale frontal boundaries, these instruments under sample the horizontal structure.

2. The Wire-Flying Vehicle

A concept for a new wire-flying profiling vehicle (WiFly Profiler) was presented in Roman and Herbert 2011. The WiFly vehicle is an autonomous profiling vehicle that is able to fly up and down a towed cable in a controlled manner using the lift created by wing foils. The wings provide a low power method of propulsion by using the free stream velocity of the wire moving through the water. The wing lift is translated to motion along the tow cable without the need to pull the cable with the vehicle. Figure 1 shows a schematic of the WiFly vehicle operating behind a ship. By sliding along the cable rather than being fixed to the cable, several advantages can be gained when compared with the previously mentioned systems. In allowing the vehicle to move independently the drag forces on the cable and the vehicle are decoupled and thus the vehicle is not depth limited. Also, without the attached cable, all of the lifting force generated by the wings is able to generate motion along the cable without needing to overcome the cable dynamics. Performance of the WiFly is evaluated by examining the achieved glide slopes of the vehicle. The glide slope is the ratio of the vertical velocity of the vehicle over the horizontal through water velocity of the vehicle. Prior scale model tests in a tow tank have proven the WiFly concept (Roman and Herbert 2011). From these tests, glide slopes of up to 0.7, were achieved at tow cable angles as large as 45 degrees (Figure 2). Flow simulations were used to hydro-dynamically optimize the WiFly body and wing foil shapes (Amaral 2013).

A model representation of the WiFly Profiler is shown in Figure 3 and the full scale prototype vehicle is shown in Figure 4. The vehicle has a total dry weight of 90

kilograms and an in-water weight of -2 kilograms. The internal structure of the vehicle is aluminum. The exterior shell of the vehicle is comprised of a combination of syntactic foam, machined plastic and 3-D printed plastic pieces. The wings are molded urethane with internal aluminum struts and shafts. Wing movement is controlled via an Animatics SmartMotor SM17205D coupled through a gear train. The vehicle slides along a standard 0.322 inch diameter CTD steel cable with two custom spring mounted, hard plastic rolling wheels. The wheels were designed in a manner so as to minimize friction with the cable and to isolate the vehicle from vibrations resulting from cable strum. At the end of the cable, a 950 kilogram depressor weight is attached to keep the cable tight. Additionally, the depressor weight provides housing for a depth sensor and a WHOI Micromodem. Communications are sent acoustically between the depressor weight and the vehicle and then transmitted up the CTD cable to the ship. This link provides periodic real-time status updates to the operator and allows for control messages to be relayed during operation to adjust the vehicle's profiling behavior. In addition, subsets of data can be transmitted to view vehicle performance and environmental conditions.

For environmental sensing, the vehicle is equipped with a Seabird Electronic 49 FastCat CTD Sensor. It is a pumped sensor that measures the conductivity, temperature and pressure.. The WiFly is also equipped with a WETLabs ECO Puck flourometer that measures turbidity and chlorophyll, and an Aanderra Optode sensor which measures oxygen concentration. Additionally, the tail of the vehicle is designed to measure the apparent flow of water past the vehicle. The tail is able to freely swivel up and down to align with the apparent flow. A rate propeller at the end of tail freely spins as the flow hits it. The rotation of the propeller is then converted to an apparent velocity of the vehicle through a linear conversion factor. Inside the vehicle's electronics housing, a US Digial X3M Inclinometer is mounted providing orientation data. The vehicle is powered by four lithium ion batteries providing an endurance of 24-36 hours, depending on load.

Due to the autonomous nature of the WiFly, an on-board control system is necessary to control the vehicle and perform pre-set or acoustically updated profiling tasks. The control system is a linear Proportional Integral Derivative (PID) control system to control depth or velocity. The system uses measurements of the vehicle's depth, tilt and speed through the water. Wing angles are adjusted continuously, within limits, to achieve the desired depth or vertical velocity. The wings can also be set to fixed angles if preferred.

The desired profiling behavior is setup in a mission file prior to each deployment. The missions are broken into small legs, each with prescribed up and down profiling rates and depth limits. While underway, the acoustic modem can be used to modify the mission by adding legs, stopping legs, or issuing an abort. All science data collected during each mission along with a number of vehicle control parameters are logged and stored on board the vehicle and then downloaded post-dive.

Vehicle Dynamics

Figure 5 illustrates the all the measurable and calculated vehicle parameters on the vehicle. The apparent velocity relative to the surrounding water (V_a) , flyer vertical velocity (V_z) , wire angle (θ_c) , and wing angle (θ_w) are measured in real time. The wire velocity (V_{wire}) relative to the water can be determined from horizontal velocities measured with an Acoustic Doppler Current Profiler (ADCP) and can be used in post

dive analysis. From these measured quantities, the angle of apparent velocity (θ_a), along cable velocity (V_{AC}), horizontal velocity of the flyer relative to water (V_{FH}), and angle of attack (AOA) can all be calculated using the relations below.

$$\theta_a = \cos^{-1}(\frac{V_z}{V_a}) \tag{1}$$

$$V_{AC} = \frac{V_z}{\cos(\theta_c)} \tag{2}$$

$$AOA = \theta_w - \theta_a \tag{3}$$

$$V_{FH} = V_{AC} \sin(\theta_c) \tag{4}$$

Additionally, using V_{Wire} a total speed through the water (V_{TOTAL}) can be calculated independently of the vehicle's speed sensor. This total speed should be equal to the apparent velocity. Comparing the two velocities provides a validation of the speed sensor.

$$V_{TOTAL} = V_a = \sqrt{(V_{FH} + V_{Wire})^2 + V_z^2}$$
 (5)

Another important parameter in defining performance guidelines is stall. Stall is defined as a reduction in the lift coefficient generated by a wing as the angle of attack increases (Crane 1997). There is typically a critical angle of attack for a wing foil, beyond which stall occurs. Most studies conducted to determine the critical angle of attack suggest an angle of near 15 degrees. The exact angle varies depending the specific wing shape and the Reynolds number.

The shape of the full scale body and wing were selected based on a study of drag coefficients over a range of scale model body sections (Amaral 2013). It was predicted that a lower drag vehicle will be able to obtain higher glide slopes across a range of tow

cable angles. The current shape was selected to have low drag over a range of flow angles between 0 and 50 degrees.

While climbing and descending the tow cable, the WiFly vehicle will experience different forces generated by the wings. As the cable angle is increased, generating lift in the direction of motion becomes increasingly difficult. Figure 6a shows a schematic of the forces acting on the vehicle during a climbing scenario at a 30 degree cable angle. The primary lifting force (L) acts perpendicular to the apparent flow. This generates a resultant force (F) that is acting to pull the vehicle and tow cable back and a force (F_{AC}) propelling the vehicle along the tow cable. Figure 6b shows a schematic of the forces acting on the vehicle during a descending scenario at a 30 degree cable angle. Again, the primary lifting force acts perpendicular to the apparent flow generating a resultant force that is directed more along the tow cable in this situation. There is very little force being applied perpendicular to the tow cable. As the cable angles are increased the lifting forces are diminished in the direction of motion and the vehicle's ability to climb or descend the tow cable decreases. At extreme high cable angles, F_{AC} will diminish to the point where it can no longer propel the vehicle along the cable. The behavior of such an event will mimic a stall in that the vehicle will stop climbing or descending and experience a drop in V_Z . However, in this scenario the wings are functioning properly and stall has not occurred. Additionally, the forces acting on the tow cable have the potential to alter the cable's shape.

To account for the shape of the cable it is necessary to calculate a layback distance to properly locate the vehicle behind the ship. The shape of the cable will change as a function of depth with the ship speed and horizontal speed of the cable. Repeated profiles yielded similar cable angle measurements for both upwards and downwards motion (Figure 7). When a sufficiently heavy clump weight is fixed to the cable, the forces from the vehicle acting on the cable are not sufficient enough to alter the shape of the tow cable between upwards and downwards profiles. Using the cable angle at a given depth and the difference in depth from the previous data point, an average cable profile can be calculated. From the top of the cable profile, a horizontal layback distance was then calculated for each depth. A sample cable layback shape can be seen in Figure 7b. GPS coordinates were then corrected with this offset. Figure 8 shows the change in vehicle profile when correcting for layback.

3. Profiling Performance

To evaluate the flyer concept, the vehicle was tested aboard the R/V Endeavor during November 2013 at the Rhode Island Shelf Break (Figure 9). The profiling performance was tested by conducting multiple dives at depths ranging from 10 to 800 meters. The test results are summarized in the following sections.

To validate the glide slope predictions, initial missions were conducted with the vehicle stepping through a series of wing angles at various ship speeds and wire angles. A sample section of data from such a test is shown in Figure 10. Different ascent and decent rates were achieved as the wing angle was varied. Vertical speeds reached 3.7 meters per second moving upwards and 2.3 meters per second in the downward direction for a mean ship speed of 1.5 meters per second.

Data from a small section of a velocity profile plotted against the along track distance is shown in Figure 11. During this scenario, the vertical velocity was being regulated via the control system by continuously adjusting the wing angle. Figure 11b shows the cable angles varying between 0 and 45 degrees during profiles between 200 and 360 meters. Figure 11c shows the vehicle can achieve desired profile velocities of 2.2 and -2.0 meters per second after some settling time. Conservative tuning of the controller resulted in the lag in time to achieve the upward velocities (Figure 11c). It is likely this issue can be resolved with better control design. The settling time in the downward direction is caused by a reduction in apparent velocity and possible downward lift (Figure 12). The steepness of the WiFly trajectory during downwards motion compared to upwards motion is due to the layback of the cable behind the ship. Apparent velocities during downwards movement are less than during upwards movement (Figure 12). This is due to the shape of the cable. As the vehicle moves downwards, the cable is both moving forward through the water while extending further away from the ship. Additionally, it is more difficult to generate sufficient lift during downwards movement.

Data from a hold depth scenario at 10 meters is shown in Figure 13. During this time the clump weight was being lowered and the tow cable was passing through the vehicle as it held depth. As a result, the cable angle began to increase. The ship speed increased and the vehicle began to experience an increase in apparent velocities. The control system was able to adjust the wing position accordingly and successfully hold the depth.

To assess the overall performance envelope of the vehicle, all steady state sections of the dives were extracted and separated into upwards and downwards segments. The achieved glide slopes were calculated from these data. Segments with incomplete data or significant variations in ascent or decent rates were not considered. Additionally, data near the transition from an upward motion to a downward motion and vice versa were removed. Under these steady state conditions, the vehicle achieved glides slopes ranging from 0.1 to 3.0 while climbing over a range of tow cable angles between 0 and 55 degrees. Glide slopes ranging from -0.1 to -3.0 were achieved while diving over the same range of tow cable angles.

The results for steady state, upward motion glide slopes are shown in Figure 14. For cable angles less than 20 degrees, the achieved glide slopes are higher than predicted in Figure 2 and there is no clear dependence on along cable velocity. Glide slopes of greater than 1.5 were commonly achieved at along cable speeds less than 2.0 meters per second. As the cable angle was increased, some dependence on along cable velocity

becomes apparent. Faster along cable velocities resulted in higher glide slopes with the fastest velocities coinciding with the boundary of glide slope performance. The glide slope decrease at higher cable angles was as predicted and overlaps with the curves in Figure 2 at high cable angles. As expected, there is a direct relationship between wing angle and glide slope (Figure 14b). Larger wing angles resulted in higher glide slopes across all cable angles.

For downward motion of the vehicle, the glide slopes were calculated separately and are shown in Figure 15. Results are more uniform than expected with along cable velocities of 0.5 to 2.0 meters per second frequently resulting in glide slopes higher than -1.0. Performance at cable angles greater than 40 degrees exceeded the upwards motion glide slopes at the same cable angles. At low cable angles (less than 10 degrees), the WiFly performance was again better than expected. There appears to be no dependency on along cable velocity for achieving specific downward motion glide slopes. Higher wing angles again resulted in higher achieved glide slopes (Figure 15b). It should be noted that these tests cannot be considered exhaustive, but do represent the most common operating scenarios over the entire test cruise. Also, the point density in glide slope plots is due to the fact that some particular profiling missions were run for longer periods of time compared to others.

Stall and Angle of Attack

In order to evaluate the limits of the WiFly vehicle, stall was intentionally induced multiple times. A stall like event at high wing angles is shown in Figure 16 and Figure

17. During this stall event, the vehicle was profiling between 350 and 600 meters depth and the cable angle exceeded 50 degrees. The target velocity was reached early in the ascent and appears to stabilize with a wing angle of 40 degrees (Figure 16c). At 300 meters, a decrease in the vertical and apparent velocity occurs and the angle of attack begins to increase past the point where stall is likely for this wing shape (Figure 17b). The linear control system responds to the reduced velocity by increasing the wing angle to generate more lift, resulting in a further increase in the angle of attack. Although full flow separation from the wing is not discernable, the reduced lift during stall reduces the upwards velocity (V_Z) as the upwards along cable force (F_{AC}) is overcome by increased drag. At the upper depth limit, the vehicle begins a downward segment and recovers from the stall.

Angle of attack was calculated for all dives as in equation (4). By calculating the angle of attack, performance guidelines could be defined for the control system to include angle of attack limitations to enhance vehicle efficiency. A high cable angle vehicle profile is shown in Figure 18. The angle of attack is shown in Figure 18f. Positive angles of attack correspond to upwards motion and negative angles of attack correspond to downwards motion. As the vehicle begins the upwards motion, the wing angle and angle of attack dramatically increase. As the desired velocity is reached, the angle of attack decreases and the vehicle enters steady state flight. In general, this is the more common trend in comparison to Figure 17, with the angle of attack typically less than 15 degrees.

In some instances however, as seen in Figure 17b, the angle of attack is calculated as negative during upwards motion. From the free body diagrams in Figure 6, if upwards

lift is being generated then a negative angle of attack is physically impossible and can be explained if the apparent velocity measurement (V_a) is being under predicted by the speed sensor. An under predicted V_a would result in a smaller calculated horizontal flyer velocity (V_{FH}) and consequently a larger calculated glide slope. In order to evaluate the accuracy of the speed sensor measurements, horizontal flyer velocities were determined independently from shipboard ADCP horizontal velocity measurements. Once an estimate of the horizontal velocity was determined from the ADCP, a new V_{TOTAL} or apparent velocity was calculated using equation (5).

Figure 19a shows measured apparent velocities for sections of upwards steady state data. Data were taken from sections of larger profiles separate in time. Corresponding horizontal flyer velocities were determined from the ADCP data and are plotted for comparison. Figure 19b shows the percent error between the sensor and ADCP calculated apparent velocities. For this section of data, the mean error is 5.2 % (Figure 19c). This suggests that on average, the speed sensor is under predicting the apparent velocity measurement by about 5% when compared to the ADCP data. Over the entire set of steady state data used in determining glide slopes, there are times where the speed either under predicts apparent velocity such as in Figure 19 or over predicts apparent velocity. Over prediction seems more prevalent at higher cable angles (Figure 19b). As such, new apparent velocities were calculated using the ADCP data for all steady state data used in the previous glide slope plots.

Figure 20 shows the achieved glide slopes calculated using ADCP horizontal velocities. Figure 20a shows data from steady state, upwards motion corresponding to the data in Figure 14. The ADCP horizontal velocities result in lower calculated glide

slopes. The max glide slope during upwards motion was 2.4. However, the achieved glide slopes now are more represented of the prediction curves in Figure 2. At all three cable angles where the model was tested $(15^{\circ}, 30^{\circ}, \text{and } 45^{\circ})$ the vehicle achieved higher glide slopes than predicted. Additionally, a stronger correlation with apparent velocity is noticeable, with the highest apparent velocities located along the edge of performance of the vehicle. Figure 20b shows data from steady state downwards motion corresponding to the data in Figure 15. Again, using ADCP horizontal velocities results in lower calculated glide slopes. The max glide slope during downwards motion was -2.0. Results are uniform with along cable velocities of less than 1.5 meters per second resulting in glide slopes of -1.5 over cable angles from 0 degrees to 35 degrees. At high cable angles, performance was better than expected.

CTD Data Resolution

Subsections of CTD temperature measurements taken along an east/west transect near 39.8 degrees N latitude are shown in Figure 21. The top plot shows data from the WiFly and the bottom plot shows data from the free fall Oceanscience UnderwayCTD. During this section, the WiFly was profiling at constant target velocities of 2.0 meters per second between 10 and 210 meters depth. Ship speed was held at approximately 2.0 meters per second during deployments of both instruments. The data have been corrected for cable layback distance with longitude positions representing the data measurement location, not the ship location. From the direct comparison, it can be seen that over an equal distance

(between the dashed lines) the WiFly performs a total of 30 up or down profiles. The UnderwayCTD performs 12 down profiles; up profiles do not provide useful data.

Subsections of CTD temperatures taken along a north/south transect are shown in Figure 22. The top plot shows data from the towed Underway CTD. The profiles reach a maximum depth of approximately 300 meters. The bottom plot is data from a deeper section of profiled with the WiFly. The data in this plot are comparable in geographical location to the data contained within the black box in the top plot. The WiFly was profiling at target velocities of 2.2 meters per second between 200 and 360 meters depth. Over this section, the WiFly was able to perform 30 up or down profiles. The Underway CTD performed 6 down profiles and was limited to a maximum depth of 300 meters.

Figure 23 is a section of deep profiling with the WiFly vehicle. The vehicle was profiling between depth of 450 and 660 meters. Ship speed was approximately 1.5 meters per second. During this dive the WiFly achieved target vertical velocities of 2.4 meters per second during upwards motion and –2.5 meters per second downwards. This operating depth is deeper than both the UnderwayCTD and the Scanfish instruments achieved during the test cruise. It should be noted that for the 3 depth banded profiles (Figure 21, 22, and 23) presented here, the achievable sampling resolution remained constant independent of the operating depth. This is not possible with the UnderwayCTD or the Scanfish.

Testing Limitations

Although field tests were successful in proving the WiFly concept, there existed several limitations. These tests were designed to test the WiFly's performance under a wide range of wing angles and velocities. In order to achieve this, the control system employed on the vehicle was designed to be linear in repsonse. However, this frequently resulted in a slow response to the desired velocity seen in Figures 11c, 16c and 18c. Additionally, the lack of a stall limiter sometimes allowed for a stall to occur unintentionally during testing, resulting in decreased performance or an aborted profile. When large amounts of cable are towed, the cable layback shape can be dramatic. This can result in a significant offset distance between the recorded position and the actual position of the vehicle behind the ship. The layback correction can account for this but it is very difficult to independently verify that the interpreted tilt measurements are predicting the actual cable shape at any given depth.

4. Conclusion

Oceanographic research is continuing to press toward understanding and identifying smaller scale processes. The need for an efficient method to sample the water column with both vertical and horizontal resolution in order to aid in this quest has become more apparent. This paper has outlined the results from field testing of a new autonomous wire-flying profiling vehicle designed to address this need.

Field testing has validated the wire flying concept as a novel and efficient means to sample the water column. Comparable existing technologies are limited by vessel speed and deployment depth resulting in achievable glide slopes typically less than 0.25. The WiFly vehicle was able to consistently achieve glide slopes from 0.1 to 2.0 over a range of cable angles and water depths. Additionally, the WiFly was able to traverse the tow cable at controlled vertical speeds between 1.0 and 3.0 meters per second from shallow water down to 800 meters depth. The vehicle was able to follow control commands and maintain steady state flight for extended periods of upwards and downwards motion. Furthermore, the WiFly was able to increase the profiling spacing by a factor of three or more when directly compared with the Oceanscience UnderwayCTD.

Field testing helped to determine the limitations in the WiFly system, which will aid in refining the technology. Better estimation of the angle of attack will greatly improve the vehicle's performance and better predict stall events. The control system employed during testing was not designed to fully optimize the vehicle's performance. A next iteration will certainly improve performance.

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LIST OF FIGURES

- 2 Colored curves represent idealized performance estimates for a full scale system. Curves are shown for differing body drag coefficients. Scaled model test results are overlaid on the initial predictions. Glide slopes were extracted from all of the steady state slope values achieved during the tests (Roman and Herbert 2011). ..27
- Full scale prototype vehicle. The vehicle is resting in a custom landing cart. The 950 kilogram depressor weight can be seen resting on the ship's deck below the cart (yellow).
- 6 Free body diagram for the wing forces generated during climbing and descending situation. The wing produces a net force F, with lift and drag components relative to the apparent flow velocity. The net force has projections F_{AC} along and F_w perpendicular to the wire. (a) F_{AC} is able to pull the flyer up the cable and there is

- 7 (a) Cable angles plotted for a series of repeating profiles on the WiFly. Cable angles are measured using a US Digital X3M Inclinometer. Upwards motion profiles are in blue and downwards motion profiles are in red. The black line is the calculated average cable profile. This average profile was used for calculating the cable layback during this series of profiles. The cable layback changes as a function of depth (b).

- 16 (a) WiFly vehicle profiling between 350 and 600 meters depth. The clump weight depth is represented by the black line. (b) Cable angles were in excess of 50 degrees at top of upwards profiles. (c) Target velocities of 2.0 meters per second upwards and downwards are shown in red with the achieved velocities in blue.(d) Wing angles during profile are shown. The onset of stall is seen at 300

- 19 (a) Sections of upwards movement steady state apparent velocity measurements. Red dots are velocities measured with the vehicle's speed sensor. Blue dots are the calculated based on ADCP measured horizontal velocities for the corresponding depths and times. Not all steady state upwards movement is represented here. (b) Relative errors between the measured and calculated apparent velocities. (c) Histogram showing the distribution of errors. A positive error means the speed sensor measurement is less than the ADCP calculated value. The mean error for the data shown is 5.2.
- Achieved glide slopes calculated using ADCP horizontal velocities in place of the speed sensor velocity measurements. Glide slopes are plotted over the range of tow cable angles. The colorbar corresponds to apparent velocity (m/s) calculated



Figure 1. Schematic of wire-flying profiling vehicle towed behind a ship. A depressor weight is attached to the end of the tow cable to keep the cable tight and provide housing for WHOI acoustic modem and altimeter. The WiFly vehicle moves freely up and down the cable using lift generated from its wing foils. Glide slope is indicated as the ratio of vertical velocity (V_Z) of the WiFly over the horizontal through water velocity (V_{FH}) of the WiFly.



Figure 2. Colored curves represent idealized performance estimates for a full scale system. Curves are shown for differing body drag coefficients. Scaled model test results are overlaid on the initial predictions. Glide slopes were extracted from all of the steady state slope values achieved during the tests (Roman and Herbert 2011).



Figure 3. Components of the WiFly Profiler Vehicle.



Figure 4. Full scale prototype vehicle. The vehicle is resting in a custom landing cart. The 950 kilogram depressor weight can be seen resting on the ship's deck below the cart (yellow).



Figure 5. Schematic of the measured and calculated parameters on the WiFly. Glide slope is indicated as the ratio of vertical to horizontal movement. Angled measurements and calculations are relative to 0 degrees as horizontal.



(a) Climbing scenario free body diagram.



(b) Descending scenario free body diagram.

Figure 6. Free body diagram for the wing forces generated during climbing and descending situation. The wing produces a net force F, with lift and drag components relative to the apparent flow velocity. The net force has projections F_{AC} along and F_w perpendicular to the wire. (a) F_{AC} is able to pull the flyer up the cable and there is no significant force perpendicular to the cable. (b) F_{AC} is pulling down the cable and there is relatively little force perpendicular to the cable.



(a) Cable angle profiles with calculated average



Figure 7. (a) Cable angles plotted for a series of repeating profiles on the WiFly. Cable angles are measured using a US Digital X3M Inclinometer. Upwards motion profiles are in blue and downwards motion profiles are in red. The black line is the calculated average cable profile. This average profile was used for calculating the cable layback during this series of profiles. The cable layback changes as a function of depth (b).



Figure 8. Sample depth profile from WiFly vehicle. The red curve is the raw depth profile with no spatial offset for cable layback distance. The blue curve represents the depth profile with a correction for tow cable layback distance.



Figure 9. Survey area for the research cruise EN-535 aboard the R/V Endeavor. Dives 2-7 conducted by the WiFly profiler are charted in color.



Figure 10. Sample profile data showing a series of incrementing wing angles (θ_w) and vertical velocities. During this time series, the ship speed was 1.5 meters per second. The vehicle depth profile is also plotted for reference. The black line represents the clump weight depth.



Figure 11. Sample velocity controlled profiles. (a) The vehicle profiling between 200 and 350 meters depth. The clump weight depth is represented by the black line. (b) Cable angles were in excess of 35 degrees at top of upwards profiles. (c) The controller target velocities of 2.4 meters per second upwards and 2.0 meters per second downwards are shown in red with achieved velocities in blue. (d) Wing angles (θ_w) during profile are shown.



Figure 12. Sample WiFly vehicle field data. The top plot shows vehicle depth. The bottom plot shows apparent velocity as measured by the WiFly's speed sensor. At the transition from upwards motion to downwards motion, the vehicle experiences a dramatic loss in apparent velocity.



Figure 13. Sample of WiFly vehicle data showing a hold depth profile while the tow cable is being winched outward. Cable angle, wing angle and apparent velocity are also plotted for reference.





Figure 14. (a) Achieved glide slopes during upward motion under steady state conditions. Glide slopes are plotted over the range of tow cable angles. Colorbar values correspond to apparent velocity (m/s) as measured by the speed sensor. Glide slopes are binned by apparent velocity. (b) Achieved glide slopes again and binned according to wing angle (degrees).





Figure 15. (a) Achieved glide slopes during downward motion under steady state conditions. Glide slopes are plotted over the range of tow cable angles. Colorbar values correspond to apparent velocity (m/s) as measured by the speed sensor. Glide slopes are binned by apparent velocity. (b) Achieved glide slopes again and binned according to wing angle (degrees).



Figure 16. (a) WiFly vehicle profiling between 350 and 600 meters depth. The clump weight depth is represented by the black line. (b) Cable angles were in excess of 50 degrees at top of upwards profiles. (c) Target velocities of 2.0 meters per second upwards and downwards are shown in red with the achieved velocities in blue. (d) Wing angles during profile are shown. The onset of stall is seen at 300 meters. The wing angle increased to its upper limit of 50 degrees, but the velocity decayed as the cable angle increases to 55 degrees.



Figure 17. (a) The apparent velocities measured from speed sensor during the profile shown in Figure 16. (b) Angle of attack calculated using the speed sensor. At approximately 300 meters, there is a dramatic increase in angle of attack confirming the stall like behavior.



Figure 18. (a) WiFly vehicle profiling between 450 and 700 meters depth. The clump weight depth is represented by the black line. (b) Cable angles during profile. (c) Target velocities of 2.2 meters per second upwards and 2.5 meters per second downwards are shown in red with achieved velocities in blue. (d) Apparent velocity of WiFly measured from speed sensor. (e) Wing angles during profile are shown. (f) Calculated angles of attack.



(a) Apparent velocity measured from speed sensor plotted with ADCP calculated apparent velocity.



(b) Relative errors (%)

(c) distribution of errors.

Figure 19. (a) Sections of upwards movement steady state apparent velocity measurements. Red dots are velocities measured with the vehicle's speed sensor. Blue dots are the calculated based on ADCP measured horizontal velocities for the corresponding depths and times. Not all steady state upwards movement is represented here. (b) Relative errors between the measured and calculated apparent velocities. (c) Histogram showing the distribution of errors. A positive error means the speed sensor measurement is less than the ADCP calculated value. The mean error for the data shown is 5.2.



Figure 20. Achieved glide slopes calculated using ADCP horizontal velocities in place of the speed sensor velocity measurements. Glide slopes are plotted over the range of tow cable angles. The colorbar corresponds to apparent velocity (m/s) calculated from ADCP data. (a) Achieved glide slopes during upward motion under steady state conditions. (b) Achieved glide slopes downward.



Figure 21. Sample Temperature sections from CTD sensors during EN-535. The top plot is temperature data from Dive 6 with the WiFly vehicle. The bottom plot is temperature data from tow 03 with the Oceanscience UnderwayCTD instrument. The sections between the dash lines are equal along track distance.



Figure 22. Sample Temperature sections from CTD sensors during EN-535. The top plot is temperature data from tow 05 with the Oceanscience UnderwayCTD instrument. The bottom plot is temperature data from Dive 7 with the WiFly vehicle. The vehicle was depth profiling between 190 and 360 meters. The bottom plot represents the section inside the black box on the top plot. The small glitch in the WiFly data at 39.36 Latitude is the vehicle executing a short hold depth behavior between sections of commanded profiles.



Figure 23. Sample Temperature section from WiFly CTD sensor during dive 7 of EN-535. CTD data was collected with a SeaBird Electronics 49 FastCat CTD sensor. The vehicle was depth profiling between 475 and 675 meters.