

UEK Drag Force Calculations and Project Review

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OVERVIEW

The purpose of this report is to provide an analysis of the dynamic forces expected to be imposed on the Underwater Electric Kite (UEK) during deployment offshore south Florida in the Florida Current, and provide a general review of the overall system design. The procedures, assumptions, and conditions used in determining these forces are discussed along with discussion on system stability and issues that may affect operations when deployed.

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BACKGROUND

The Underwater Electric Kite (UEK) is a device designed to extract energy from the flow of the Florida Current, and convert this energy into useable electric power. The design of the UEK requires the unit to remain in the highest water velocity region of the Florida Current in order to extract the maximum amount of energy. This requirement exposes the unit to large drag forces, as well as other dynamic forces resulting from the flow of water around and through the unit.

In order to properly design and model the UEK system, certain parameters must be determined. These include the predicted drag and lift forces on the unit, a reasonable approximation of the drag coefficient, and a range of conditions and forces to which the system may be exposed. With this basic information, the rest of the system (mooring cables, anchor systems, control systems) may be reviewed and analyzed prior to advanced design and installation.

The specific tasks are indicated in the following sections, along with the analysis and results of each task.

Task 1. Establish the principal forces acting on the UEK and determine approximate drag coefficient. Describe methods of calculation and coefficient determination.

The UEK is a fairly unique shape as far as submerged objects are concerned, and as such very little information on such shapes regarding hydrodynamic forces exists. The UEK may be analyzed using various assumptions and methods, however, with each providing an estimate of forces on the unit. A series of methods were used to determine an approximate drag coefficient for the UEK in the velocity fields expected at the deployment site.

CONDITIONS AT DEPLOYMENT SITE

The predicted conditions at the UEK deployment site are vital for the determination of forces on the unit. The proposed deployment site is about 10.5 miles offshore Dania Beach, Florida in approximately 950 ft of water. The actual UEK operating depth is approximately 100 ft deep, near the core of the Florida Current. The Florida Current is the portion of the Gulf Stream that connects the Loop Current in the eastern Gulf of Mexico to the Gulf Stream as it proceeds into the open Atlantic Ocean beyond Cape Hatteras, NC. The Florida Current flows through the Straits of Florida, a curving conduit that joins the Gulf of Mexico and Caribbean to the Atlantic Ocean. The Florida Current passes closet to shore between Miami and Palm Beach, with the

closest approach occurring off Dania Beach, near the proposed deployment site. While direct current measurements in the core of the Florida Current off Dania Beach are not available, data from Miami and Palm Beach were used to estimate water velocities at the deployment site (Table 1).

Flow Condition	Cm/sec	Ft/sec	Knots
Average	171	5.61	3.32
Minimum	31	1.01	0.58
Low Range	129	4.22	2.50
High Range	213	6.98	4.13

Table 1
Estimated Water Velocities at UEK Deployment Site
30 m depth (100 ft)

It must be noted that these are predicted conditions, and the flow in the proposed deployment area has been known to reverse or essentially stall for a short period of time due to large frontal eddies. While not directly relevant to this analysis, these phenomena could have significant implications regarding the UEK mooring design.

In addition to water velocity, other required parameters include water temperature and salinity. The estimated water temperature at the deployment site is approximately 72° F (22°C) with salinity between 35 and 36 parts per thousand (ppt). These values provide two other required water properties, the density and kinematic viscosity, with values of 1.987 slugs/ft³ and 1.0816 x 10⁻⁵ ft²/s, respectively.

UEK CHARACTERISTICS

The UEK is essentially a large, oblong shape with its largest surface area exposed normal to the flow, thereby providing the largest area of drag (Figure 1). Within this area, two 20 ft diameter turbines are mounted to facilitate maximum flow exposure. The total projected area of the UEK normal to the flow is 730 square feet, with a total width of 40.16 ft and height of 22 ft. The UEK has a width to height ratio normal to the flow of 1.825.

Each turbine consists of 7 blades, with a projected area of about 26.5 ft² per blade. The blades are twisted to maximize flow and thrust, yet may be approximated as a curved vane with a 54° incline above the horizontal. The turbines are free to rotate in the current, thereby generating electric power via connected generators. While free to move, the blades still provide some resistance to flow and therefore contribute to the overall UEK drag force.

The overall projection of the UEK to the flow is best approximated as a large flat plate, with the same projected area and width to height ratio. This flat plate method provides a starting point that provides the maximum resistance to flow, and therefore the theoretical maximum drag force. This method also neglects the reduction in overall drag afforded by the water passing through the turbine blades. Several tables and graphs are available for flow around a flat plate normal to flow, and these provide a drag coefficient based upon Reynolds number.

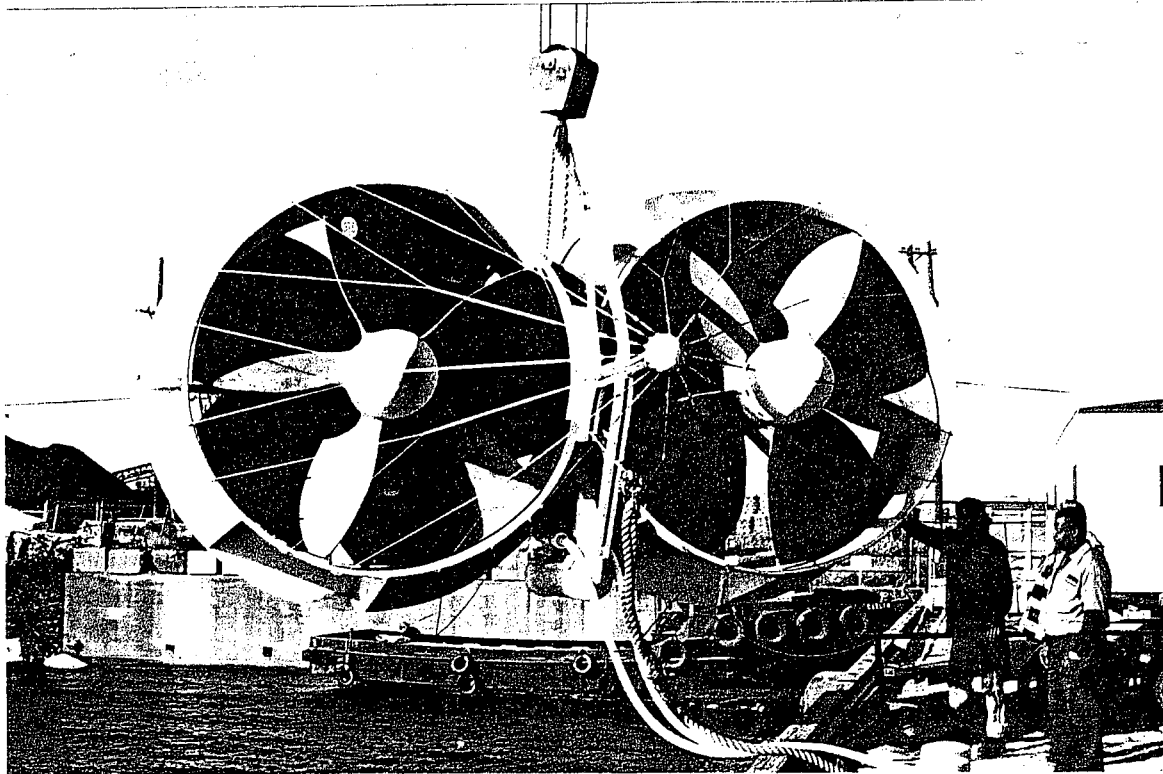


Figure 1
UEK (10 ft Diameter Blades, 5 Blades per Turbine Shown)

The Reynolds number expresses in nondimensional form a ratio between inertia forces and viscous forces on the fluid particles flowing around an object. The effects of Reynolds number of the flow about, and the resultant forces on, a body depend on the body shape. The shape for the UEK uses the flat plate analogy, taking the height as the characteristic dimension. The Reynolds number (Re) for a particular flow may be calculated by the equation

$$Re = V_0 d / \nu$$

where d is the characteristic dimension (height in this case), V_0 is the water velocity, and ν is the kinematic viscosity. One key use of the Reynolds number is to determine which type of flow an object experiences, whether it is laminar (smooth) or turbulent. Turbulent flow is often preferred in design since the layer adjacent to the body becomes infused with high-velocity, high-momentum fluid particles, which tend to disrupt pressure drag and reduce overall drag forces. This change is usually triggered at $Re > 10^5$. The range of Re for the UEK deployment from minimum to maximum water velocities is 2.05×10^6 to 1.42×10^7 , with an average velocity Re of 1.14×10^7 , indicating turbulent flow for all estimated water velocities.

FLAT PLATE METHOD

The UEK appears to the flow as a flat plate, yet unlike the flat plate flow passes through the turbines to the rear side of the unit. This is a fundamental difference in determining drag based on the flat plate analysis, because of the difference in pressure between the front and rear sides of

the UEK and flat plate. In the case of a flat plate, the pressure distribution on the front side is positive relative to the pressure on the rear side, due to the differences in flow across the front surface and away from the rear surface (Figure 2).

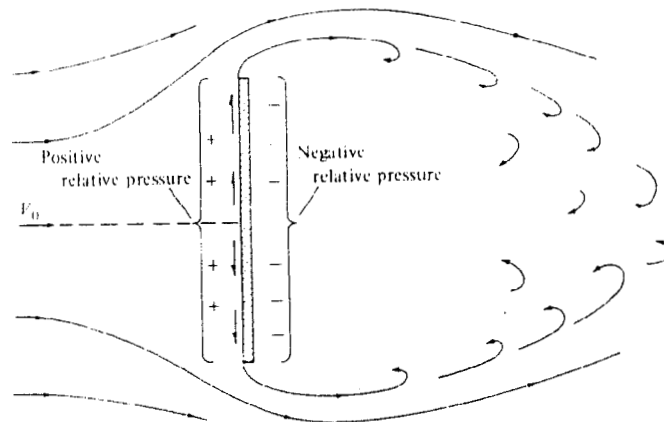


Figure 2
Flow Past a Flat Plate

This pressure difference is similar to that across the surface of an airfoil, where the difference in flow velocities creates lift on the foil. In the case of the flat plate, the pressure force only acts parallel to the flow, and therefore contributes totally to the drag of the plate.

A similar effect is experienced by the UEK, although due to the flow of water through the drag “surface” the pressure difference between the front and rear of the UEK is not as great as that of the plate, and therefore the drag force is not as large. The use of the flat plate method, however, is an effective way to estimate the theoretical maximum drag force the UEK may experience with no regards to the turbine blades and passage of water. The total drag of a plate normal to the flow, or the UEK in this case, is given by

$$F_D = 0.5\rho C_D V_0^2 A_p$$

where A_p is the projected area, V_0 is the water velocity, ρ is the water density, and C_D is the drag coefficient. This drag coefficient is dependent on the Reynolds number, and published values of C_D are available (Figure 3 and 4).

Type of Body	Length Ratio	Re	C_D
 Rectangular plate	$l/b = 1$	$>10^4$	1.18
	$l/b = 5$	$>10^4$	1.20
	$l/b = 10$	$>10^4$	1.30
	$l/b = 20$	$>10^4$	1.50
	$l/b = \infty$	$>10^4$	1.98

Figure 3
Approximate Value of C_D for Rectangular Plate

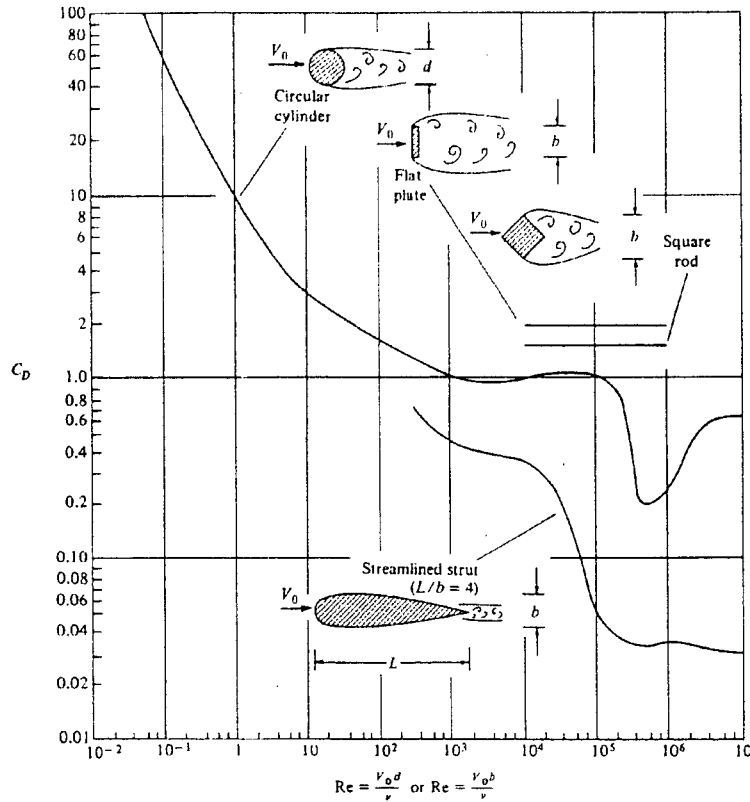


Figure 4

C_D versus Re for Various Bodies

The drag coefficient for a flat plate at $RE > 10^4$ and a length to height ratio of 1 is between 1.18 and 1.20; a value of 1.19 was used for this analysis.

Using the above equation and $C_D = 1.19$ the UEK drag force ranged from 880 lbs at the lowest velocity to 42,048 lbs at 6.98 ft/s. It must be noted, however, that a small change in drag coefficient C_D can lead to significant differences in estimated drag, in some cases several thousand pounds for the UEK. For the purpose of this flat plate "worst case" estimation, however, the choice of 1.19 is appropriate.

MOMENTUM METHOD

Another method of estimating the UEK drag forces is by looking at the forces on the blades themselves and then adding the drag from the rest of the unit. This blade analysis utilizes the conservation of momentum principle, which states that (from Newton's second law) the summation of all external forces on a system is equal to the rate of change of momentum of that system, $\sum F = d(\text{momentum})/dt$. In fluid mechanics, the basic form of the equation applies when there is a uniform velocity in the streams crossing the control surface, as long as the control surface delineates the body of interest. The momentum equation is commonly used in the determination of the force exerted on a piece of equipment, such as a nozzle or bend in a pipe, given a certain discharge and pressure. In the case of the UEK, an individual blade may be taken as the body of interest, and the volume of water passing over it as the mass in the control volume. The mass flow rate, m , is used in this method, and is defined as

$$m = \rho A_p V_0$$

where ρ is water density, A_p is the projected blade area (about 26.5 ft²), and V_0 is the water velocity.

Two methods may be used, one which simply assumes the flow strikes the blade and water flows in both directions along the blade, and the second which conserves all of the fluid throughout the change in flow direction. Both methods will be used and the results compared. The contributing drag from the rest of the structure, approximately 346 ft², was determined using the flat plate method and C_D of 1.19, for a maximum non-momentum drag force of 19,759 lbs.

The first momentum method is similar to the projected area drag calculation method. The method assumes frictionless flow along the surface, the flow strikes a surface inclined at some angle θ , and the only force on the surface is normal to the surface (Figure 5).

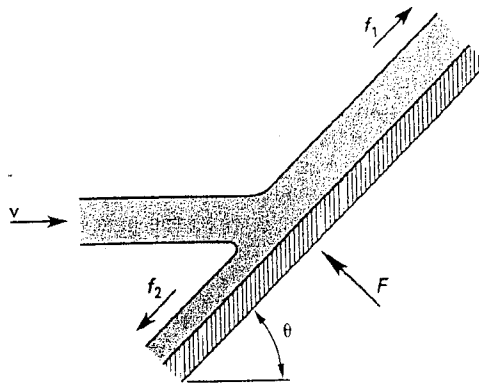


Figure 5
Flow Striking an Inclined Surface

The force perpendicular to the surface is found by

$$F = mV_0 \sin\theta$$

The force in the direction of flow, i.e. drag force, is given by

$$F_D = mV_0 \sin\theta / \sin\theta, \text{ or simply } F_D = mV_0$$

which is also equal to

$$F_D = \rho A_p V_0^2$$

which is the familiar drag force equation without the drag coefficient, C_D . By assuming frictionless flow, and accounting for the pressure drag by maintaining constant flow, the need for

the drag coefficient is eliminated. This provides a method of determining drag while accounting for the blade effect, which was not possible in the flat plate method due to the pressure issues.

So, using the inclined surface method, the UEK drag forces in the direction of flow ranged from 53 lbs per blade at the minimum velocity to 2,565 lbs at 6.98 ft/s, with a drag force of 1,657 lbs per blade at the average water velocity. Multiplying these blade drag values by 14 blades, the resulting UEK drag from blades range from 742 lbs to 35,910 lbs, with an average drag of 23,198 lbs. Adding the non-blade drag force, the maximum drag force is estimated at 55,669 lbs.

The second method assumes a fixed vane that effectively changes the direction of the entire flow, which results in two reactions. The x-direction reaction contributes to the drag, while the y-direction reaction is countered and cancelled by the reactions on the other blades (Figure 6).

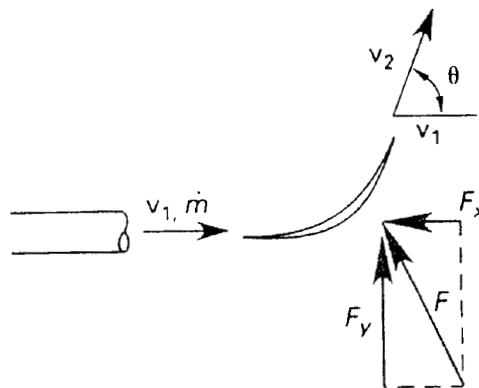


Figure 6
Flow Striking a Vane

Once again the mass flow rate, m , is used, and the assumption is made that the flow is constant. The UEK vane angle is approximated at $\theta = 54^\circ$ above the horizontal. Since two components of the reaction force are used, the change in velocity for both directions is found by

$$\Delta V_x = V_2 \cos \theta - V_1 \quad \text{and} \quad \Delta V_y = V_2 \sin \theta$$

The reaction forces are then found from the mass flow rate and the change in velocity,

$$F_x = m \Delta V_x \quad \text{and} \quad F_y = m \Delta V_y$$

The F_x force contributes to the drag force, while the F_y force is exerted outwards from the hub of the turbine, along the blade at an angle of θ degrees. This is countered by the outward force from the other blades arranged around the hub, and is therefore cancelled. This method is more analytical in that it accounts for the entire flow and all of the forces associated with the redirection of the flow.

Using this method, the blade drag forces ranged from 22 lbs to 1,057 lbs per blade; with an average flow drag of 683 lbs per blade. Again multiplying by 14 blades, the total drag for this

method ranges from 308 lbs to 14,798 lbs, with an average flow value of 9,562 lbs drag. Adding the non-blade drag force, the maximum drag force is estimated at 34,557 lbs.

Please note that in both momentum methods, the fluid rotation, or vorticity, was not considered. Due to the unique and complicated nature of the water flow through this turbine, and the lack of either methods or empirical data dealing with such a configuration, the rotational effects were assumed negligible. The turbine symmetry, however, will most likely result in cancellation of vorticity effects in a fashion similar to the opposing y-forces indicated in the vane method.

CONCLUSIONS AND RECOMMENDATIONS

The various methods used to determine the approximate drag forces on the UEK during deployment resulted in different values, ranging from about 35,000 to as much as 56,000 lbs in the maximum anticipated current field. While each method approaches the problem from a different perspective, they all indicate that the drag forces on the UEK will be substantial, and as such the entire system must be designed to carry the loads.

The largest calculated drag force resulted from the first momentum method, which used both momentum change and flat plate resistance for various parts of the turbine. This method resulted in a drag force of 55,669 lbs at a flow velocity of 6.98 ft/s, or 4.13 kts. This value, 55,669 lbs, should be used, along with an appropriate safety factor, in all system designs.

The most basic approach, that of the flat plate method, predicted UEK drag force at 42,048 pounds for the highest flow. This force was determined using a drag coefficient of 1.19, based upon a Reynolds number of 2.05×10^6 , indicating turbulent flow through the turbine. While the UEK is not exactly analogous to the flat plate, the flow behavior should at least resemble flat plate flow. The difference between this result and the maximum drag force is most likely due to differences in the flow characteristics through the turbine blades and the inability of the flat plate method to account for this flow.

The second momentum method, calculating momentum changes across a stationary vane, resulted in the lowest predicted drag force, 34,557 lbs. The reason for the lower value is likely due to the cancellation of the momentum y-component, which is deflected out at approximately 54 degrees radially, with the forces around the turbine essentially canceling each other. The only remaining drag forces are those parallel to the water flow, essentially the force multiplied by cosine of 54 degrees. Intuitively, this force seems quite low, given the size of the UEK and the relatively high water velocity passing through and around the unit. This value is not recommended for use in the design process, and should only be used for comparison with actual drag measurements obtained during field testing.

In regards to a drag coefficient for the UEK, given the range of predicted flow velocities at the deployment site, the best approximation is found using the drag force from the momentum method and the projected area of the flat plate method. The flow is turbulent at all predicted velocities, and in a turbulent flow domain, form drag is more significant than viscous drag. Using the momentum drag force in the basic drag force equation, $F_D = 0.5\rho C_D V_0^2 A_p$, an equivalent drag coefficient that would yield the same value is 1.58. This coefficient value is

based upon form drag measurements and the value of the highest calculated drag force, and as such should be used in all modeling and simulation efforts. Since most cable modeling programs use basic drag equations as part of their algorithms, this coefficient is most appropriate, and should yield the most conservative values. It must be stressed that in the design of at-sea systems, conservatism is not only prudent, but also oftentimes essential for success.

Task 2. Review overall design and provide comments.

The UEK device and its associated mooring and support systems pose a daunting engineering challenge, and involve a wide range of issues that must be considered. Any one issue could be sufficient to cause total system failure, or at least significant downtime and expensive repairs. Many of these issues have been identified, and the purpose of this task is to review the overall system from a global perspective, as opposed to a component-level viewpoint. Such global issues include types of models and simulations that should be conducted, mooring system design, issues related to system degradation, and actual deployment, maintenance, and recovery of the system at sea. This review is based upon past experiences in the field of ocean engineering and first-hand knowledge from actual projects at sea. Information on the existing system has been gleaned from drawing packages, project descriptions, SPIR progress reports, and numerous conversations with project personnel (George O'Sullivan, Bob DeMilia).

SUPPORT VESSEL

The most important issue regarding the actual deployment of the UEK is the choice of support vessel, and the assurance that the vessel can handle not only the UEK, but also the myriad of other equipment required for deployment, and the ability to operate in the core of the Florida Current. Similar large structures have been deployed in the waters off south Florida, some ending with success and others with abject failure. Causes have ranged from a lack of understanding regarding oceanographic and bottom conditions to blatant disregard for such factors in pursuit of the objective. The deployment site is subject to high currents, heavy seas, and uncommonly strong winds during most of the year, all driven by the presence of vast amounts of energy-rich, warm ocean water carried by the Florida Current. These factors can conspire to seriously impact at-sea operations.

The size of support equipment required to handle objects such as the UEK also require an adequate platform to operate safely. While the UEK will be submerged at or near the surface during transit to the site and during deployment, the system will experience considerable drag forces and probable shock loads while exposed to wave action, and will transmit these loads to the handling equipment. The use of undersized equipment or support vessel would pose significant risk to the UEK, deck personal, the vessel itself, and the project overall. An adequate weight handling system, ideally a crane, adequate deck space, dynamic positioning capability, and sufficient stability to work in the range of sea states is essential. An ROV is also required for connecting to the shore cable, and any required site preparation work. Again, the ROV must be capable of operating in large currents and dynamic conditions.

Other issues more specific to the UEK system include the types of computer models that should be run during design, the mooring system, and modifications to the UEK itself to improve

performance. The UEK system is basically a subsurface mooring system consisting of an anchor system, mooring line, ballast vessel, and the UEK. While straightforward conceptually, the actual deployment of such a system is subject to a wide range of forces, including drag, lift, cable stress and strain, corrosion, biofouling, and mechanical fatigue. Each factor must be addressed to prevent total system failure. Of these factors only one, mechanical fatigue, will not be addressed in this report. Since this factor is primarily associated with the actual turbine generator system (blades, shafts, etc.), this analysis is left to the UEK designers. The other factors are ocean-dependent, and will be discussed.

MODELING AND SIMULATION

The deployed system configuration should be modeled and simulated prior to advanced design to determine approximate loads that may be imposed on the system. Experience has shown that since the advent of computer modeling, significant time and funds have been saved by the use of computer simulation prior to deployment. Factors such as cable drag and lift, strumming, and line tension become increasingly important with longer lengths and higher currents. Body drag is also important, as well as surface interactions. While the UEK is designed to reside at approximately 100 ft below the surface, during deployment, recovery, and large storm events, surface wave effects could occur. This periodic forcing could increase system loads beyond design limits if not considered during the design phase.

The recommended simulation program is SEADYN, a finite-element computer program that allows user-defined cable systems to be modeled dynamically. The output is organized into coordinates, velocities, and tensions for each element and node in the model. This program has proven very effective for numerous Navy and civilian projects, and has been verified through actual at-sea testing.

MOORING SYSTEM

The mooring system must be designed to resist all forces acting upon it, during normal conditions as well as extreme events. The proposed mooring configuration described in the October 25, 2001 Progress Report shows the UEK and ballast vessel moored in 902 ft (275 m) of water on a 2952 ft (900 m). The scope of this mooring design is 3.2 to one (line length to depth). Most mooring designs use a minimum of 5 to 1 scope for drag embedment type anchors. Shorter scopes are possible with other types of anchors (pile, deadweight, and direct-embedment), but associated costs increase significantly, especially in deep water. Bottom composition is also important to the effectiveness of the anchor, and must be determined prior to anchor type selection. The bottom type in the deployment area is typically a sand-silt mixture covering more consolidated materials. Drag embedment anchors have been used successfully in the area, and provided enough scope, would be an economical and functional solution if designed properly.

The mooring line must be capable of holding the ballast vessel, UEK and itself in the current, and also be capable of resisting corrosion, strumming, and biofouling. The mooring cable should be independent of the electrical cable, unless the electrical cable is specifically designed to function as a load-bearing cable. The cyclic forces experienced by the mooring cable would eventually fatigue the electrical cable conductors to failure, and could also damage any

connectors or splices along the suspended length. Instead, the electrical cable should have its own strength member, capable of supporting the cable and preventing any extreme loads. This strengthened cable could then be married to the mooring cable from the surface to the seafloor, with sufficient slack to prevent force transmission between the two. This bundle of cables will change the drag characteristics of the mooring, however, and should be accounted for in the design.

The ballast vessel connection to both the mooring line and the electrical cable needs to be specified. The attachment connection should be capable of resisting torque and line twisting, as well as vertical and horizontal motions. As the flow varies and the ballast vessel depth is adjusted, the fleet angle, or angle the mooring line tends from the ballast vessel, will change, and this change must be compensated for. The UEK tether connection point must also be designed, so that the tether and electrical cable transition effectively to the UEK.

The ballast vessel adjustment system, which appears to consist of a submersible winch system, needs to be defined in much greater detail prior to any serious mooring system designs. The size, buoyancy, reserve buoyancy, power system, winch system, and anchoring system for the ballast vessel need to be specified. Unlike the anchor system for the mooring, the ballast vessel mooring will not have the benefit of scope or fleet angle, and must resist a force perpendicular to the seafloor. This precludes the use of a drag-embedment anchor, and necessitates the use of a pile, deadweight, or direct-embedment anchor. As mentioned earlier, these anchors require much more effort to properly install, and become increasingly difficult as the water depth increases.

The UEK attachment point is specified at the center of drag, although this has not been indicated on drawings to date. The center of drag, due to symmetry, is at the centerline of the unit both vertically and horizontally. A single attachment point, however, may pose problems regarding yaw in the flow. A better approach may be to use a single attachment point at the center, with two stabilizing guy wires running from the main line to the outside edges of the unit from a bridle-type arrangement. This will provide more stability and resistance to undesirable motions. It is also unclear whether the UEK structure can withstand the drag forces, which in cases may exceed 55,000 pounds. Perhaps an onshore pull test should be conducted to verify that the structure could withstand the loads prior to deployment. The applied load should not be the maximum drag force, but should instead include a suitable factor of safety, perhaps a factor of at least 2 times maximum expected load, and perhaps as much as 3 to 5 times.

MATERIALS AND DEGRADATION ISSUES

The materials required for the mooring and anchoring systems must be strong enough to hold the system, and must be capable of performing for long periods of time. While component weight is not as important for ocean-deployed systems, resistance to corrosion, biofouling, and degradation is very important. The use of steels, aluminum, composites, and synthetics are appropriate, although each has its own restrictions regarding use.

Stainless steel mooring lines and fasteners are a good choice for this application, yet attention must be given to the specific failure causes for stainless steels. Stainless steels are susceptible to

pitting and stress corrosion in the absence of sufficient oxygen, and are therefore not suitable for conditions that would deprive them of oxygenated water. Biofouling, or the covering of objects with marine organisms, is one method of depriving stainless steel of oxygen. As the organisms grow on the surface, more and more of the surface is covered until the material is completely encapsulated. Another consequence of this growth is the added surface area and mass in terms of drag. A cable diameter may be increased several times over due to biofouling, with an associated increase in drag, which increases line tension and mooring system loading, potentially overloading the system.

Galvanic corrosion is another factor that could cause problems in the UEK design. Dissimilar metals in seawater tend to establish electric potentials between the metals, with one metal acting as the cathode and the other as the anode. Typically, the anode "sacrifices" itself to the benefit of the cathode, as in the use of zinc anodes to protect steel hull ships. This is notable in the use of two popular marine materials, aluminum and stainless steel. The aluminum acts as the anode, and protects the stainless steel through corrosion and reduction of itself "sacrificially." Mooring lines also tend to create additional corrosion potential due to the flow of water past their surfaces. While not well understood, accelerated corrosion has been observed due to this phenomenon, where insulated materials were still affected due to this dynamic effect. Typically, materials are chosen to minimize these effects, and with proper design, many of these problems can be avoided.

Biofouling is more difficult to eliminate, since the marine organisms do not limit themselves to only metal items, but tend to cling to every surface. The organisms arrive in planktonic form carried by the ocean current, and cling to objects that they encounter. While the high water velocities at the deployment site should reduce initial growth, experience has shown that organisms will still attach to an object in the high flows. Once attached, the organisms cling to the surface and begin to build carbonate structures that are secured to the surface by extremely strong organic adhesives. Some organisms even bore into the surface and physically "anchor" themselves. In addition to interference with moving parts, especially parts that are only operated occasionally such as during deployment or recovery, the organisms add surface area and mass to the structure, increasing drag forces and disrupting flow around and, in the case of the UEK, through the system. This would also happen to the ballast vessel, and could interfere with the depth-adjustment system. Growth could prevent the cables from moving on the drum or prevent the ratchet mechanism from functioning properly.

There are several ways to deal with biofouling, from the use of toxic coatings to periodic cleaning. Several types of antifouling paints and coatings are available, although due to their toxic nature not only to fouling organisms but all marine organisms, they are rapidly becoming prohibited for use. New formulations are being developed, incorporating repellents in the coating, but there is no clear solution to the problem at this time. Another paint-based method is self-fairing or self-leveling paint, which continually erodes their surface layers, thereby shedding any organisms that attempt to attach. This method is also environmentally unfavorable, however, because of the large amounts of materials that could be deposited into the marine environment. This method requires repainting on a more frequent basis than other paint-based methods.

Fiberglass gelcoats are also susceptible to biofouling, with the added problem of coating loss during removal activities. Small sections of gelcoat are lost when the organisms are removed, resulting in a portion of the fiberglass becoming exposed to seawater. Over time, fiberglass composites tend to absorb water, making them heavier and weaker than the original material. Since fiberglass is very difficult to inspect and measure in terms of water absorption, this becomes a larger problem than more conventional materials (steels, aluminum, etc.) The benefits of fiberglass, however, are the immunity to galvanic corrosion and relatively low weight, both in air and in water. Strength is also a benefit, and in some cases the strength of fiberglass is comparable to similar metal structures, with a fraction of the weight. Again, inspection is difficult, and replacement is often the only option if weakness or failure is encountered. Repairs are often not feasible due to degradation of surrounding materials, and the requirement of clean, sold material to insure a good bond.

The only practical method of preventing adverse biofouling effects is routine maintenance, which involves the mechanical removal of growth. In the case of the UEK, this is made more difficult due to the remote site location, logistics of working at the site, the depth of the unit, high currents, and difficulty in cleaning the complex turbine shape. Divers are typically used to clean vessels while in port, however the dangers involved in working offshore in high currents makes such a solution risky at best. The constant risk of becoming swept off the unit and carried away by the current is significant, and even the act of remaining on the UEK to perform useful work becomes almost impossible as currents approach 1.5 kts, much less the 4+ kts expected at the site. Bringing the UEK to the surface for cleaning is an option, but this again involves a support vessel, divers, and the dangers associated with high currents. The UEK must be shut down for the operations, with the associated loss in revenue during down time. The use of a purpose-built ROV system has been suggested, and may be the best solution for this unique application. In the mean time, biofouling must be considered a major factor in the total system design.

DEPLOYMENT, MAINTENANCE, AND RECOVERY

The actual deployment, maintenance, and recovery of the UEK are complex and difficult tasks, yet steps may be taken to streamline the operations. Several issues have been discussed earlier with regards to support vessel, mooring system, and routine maintenance requirements (biofouling). The following discussion relates to the process of putting the system in the water and recovering it for whatever reason, again from a global perspective. Actual details regarding step-by-step operations will not be discussed.

Prior to deployment, the installation site must be established and prepared for the UEK's arrival, ideally well in advance in order to compensate for any unexpected problems that may arise. Cables must be laid to the site, anchor systems and attachment pendants must be installed, and procedures must be tested for connecting the UEK to the underwater infrastructure. The cable end must be laid to the location, either from shore or an offshore junction site, and rigged with a recovery system and enough slack to permit recovery. The anchor system must be installed and set, so that the UEK will not drag the moor and shore cable when installed. The anchor and mooring line must be put in and connected to a temporary support buoy prior to UEK arrival. The ballast vessel anchor system must also be installed and set, and must be ready for reeling

onto the depth-control system equipment. As mentioned earlier, this phase of the installation may be the most challenging, given the type of anchor system that may be required.

Once the items have been put in, the ballast vessel should be brought to the site first and installed. Its systems will require specially trained personnel, due to the hazards of working in an enclosed space at sea, in high currents, and with relatively unproven systems. The danger of premature flooding or sinking must be planned for and the personnel working on the vessel must be trained in dealing with such emergencies. The ROV will most likely be required to rig the vessel's lifting line(s) from the seafloor to the surface, and may be required in the event a line is lost or dropped prematurely. All of these contingencies must be described and detailed in the operations plan.

After the ballast vessel is in place, the UEK will be towed out to the site and attached to a tether from the ballast vessel. The electrical cabling, married to the mooring line, will also be connected to the generators. There must be a method of securing the turbine blades during deployment while personnel are working on the unit. Again, personnel will most likely be on the unit making connections and securing lines, and will be exposed to the same hazards as the ballast vessel installation. Once the UEK is secured and connected, the support vessel will stand off during system tests in case recovery is required. If all goes well, the shore will then command the system to descend to operating depth and begin operations.

Routine maintenance would involve biofouling cleaning, turbine lubricant changes, or other inherent maintenance items. Due to the high currents and unit depth, the best method of accessing the UEK will be to bring it to the surface. The ballast vessel and its depth-control system would accomplish this task. A support vessel would be required, but it should not need to be as large as the vessel used for installation. Instead a medium-sized dive boat could be used for servicing the UEK. Ideally the UEK would have access hatches and other devices to simplify planned maintenance tasks, to minimize time required on site and to reduce personnel exposure to the environmental conditions. Modular systems and quick-disconnect fittings for fluid changes and other maintenance would be extremely useful. Personnel restraint systems or attachment points would help reduce worker risk, and improve task efficiency. A strong mooring point for the support vessel would also facilitate better operations. Besides the mooring line attachment point, no other strong point presently exists on the UEK.

UEK recovery would entail disconnecting the unit from the ballast vessel, and either replacing the UEK with a surrogate buoy to hold the tether and electrical cable, or remove the tether and electrical cable from the system along with the unit. In the event the ballast vessel required removal, both the vessel and the UEK would be removed, and a buoy installed in their place to hold the mooring line and electrical cable. A surrogate buoy of sufficient size and design for the high current environment would be required, and should be available on site in the event of an immediate recovery. Storage for such a buoy would also have to be arranged in the vicinity. A large support ship, similar in size to the deployment vessel, would be required, along with an ROV in the event the mooring or cables were lost. The UEK would be removed in the reverse order it was installed; with the support vessel removing the unit from the mooring system and towing the unit back to port. Again, personnel would be involved, so due care would be required in regards to contingency and operational planning.

CONCLUSIONS AND RECOMMENDATIONS

The UEK installation is a complex and formidable task, and it involves a significantly amount of design and engineering in addition to that of the UEK itself to be successful. The deployment site remoteness, oceanographic conditions, and sheer size of the equipment and associated loads on the system provide a great challenge. Even the smallest creatures in the sea pose a potential problem, yet with careful and thoughtful designs and planning it will be a success. There are many issues to consider, and may different ways to address them, yet in the end the "one best way" will end in a successful installation. A computer model is recommended, which will provide a large portion of the information needed for the mooring design. More details are needed on the ballast vessel depth control system, as well as the vessel's dimensions, construction, and physical characteristics. The UEK is scheduled for testing in late 2002, and the information gained will greatly assist in the final system design. The issues of corrosion and biofouling must be dealt with, but other aspects of the design must be completed first. This is a very interesting project, and should prove to be very educational and gratifying to all who participate.

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UEK Follow-on System Analysis

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OVERVIEW

The purpose of this report is to provide follow-on analysis of the various forces expected to be imposed on the Underwater Electric Kite (UEK) during deployment offshore south Florida in the Florida Current, and provide recommendations on methods of mooring and stabilization. The procedures, assumptions, and conditions used in this analysis are based upon information provided by Abacus Controls, as well as calculations made during this investigation.

This report was developed under contract with Abacus Controls, Inc., PO Number 37763.

BACKGROUND

The Underwater Electric Kite (UEK) is a device designed to extract energy from the flow of water through its turbine, and convert this energy into useable electric power. The test deployment location for the UEK is the Florida Current, offshore south Florida. The design of the UEK requires the unit to remain in the highest water velocity region of the Florida Current in order to extract the maximum amount of energy. This requirement exposes the unit to large drag forces, as well as other dynamic forces resulting from the flow of water around and through the unit.

These forces, as well as a general overview of issues relative to UEK deployment and operation, were discussed in a previous report. Based upon that report and other design work pursuant to actual UEK construction, additional analysis and discussion was requested by Abacus Controls.

The specific tasks are indicated in the following section, along with analysis and results of each task.

Task 1. Review attachment point design, drawings, and strength calculations based upon maximum design loads from previous analysis.

The UEK is a fairly unique shape as far as submerged objects are concerned, and as such very little information regarding hydrodynamic forces exists. The UEK has been analyzed using various assumptions and methods, and a worst-case drag load was determined. At a water velocity of 4 knots (6.98 ft/s), the maximum drag force on the UEK was calculated at approximately 100,000 pounds. This maximum load was used for all new calculations in this report. Loads used in the calculations provided as supporting information should be available from the source engineer, JTD Incorporated.

The UEK attachment point is composed of two Type 316 stainless steel (SS) plates held together with 20 1-12 UNF SS bolts, and is located at the joint between the turbine housings. The joint is comprised of two 0.75" thick fiberglass sections made of S500 glass (35% glass with vinyl ester resin). The actual fiberglass lay-up is slightly thicker than the material specifications, with a layer thickness of 0.078" vice 0.016" in the specification. This results in a lower laminate strength, since there is approximately 5

times less glass in the laminate to carry the load ($0.016/0.078 \approx 1/5$). A conservative value of 10 ksi tensile strength plus a safety factor was used in the provided load calculations. Load calculations were also made for this report, as explained below.

The attachment point could experience several types of failure, and each method was investigated. The attachment could fail by bolt shearing, where the bolts fail due to the shear forces imposed by the attachment bracket. The fiberglass material at the joint and between the SS plates could fail in tension, essentially tearing out from between the plates and around the bolts, and finally the stainless steel plates themselves could fail in tension, particularly at the point of smallest cross-section.

The attachment design, which uses two SS plates and 20 one-inch SS bolts, effectively shares the drag load (100 kips) between the bolts, all which are in double shear. The load is also distributed across 10 fiberglass cross-sections with regards to fiberglass loading. The load in the SS plate is shared by the top and bottom plates, which while of different thickness, are assumed to be one plate at the critical point of smallest cross-section.

The force on each bolt is then

$$F_{\text{bolt}} = F_{\text{drag}} / 20 = 100 \text{ kips} / 20 = 5 \text{ kips}$$

The stress area of each 1-12 UNF SS bolt is 0.663 in^2 , so the stress in each bolt is

$$\sigma_{\text{bolt}} = F_{\text{bolt}} / A_{\text{stress}} = 7.5 \text{ ksi}$$

The bolts are in double shear, however, so the shear stress on each bolt is only half, or 3.75 ksi. The shear strength of the bolt is found from its yield strength, 35 ksi, resulting in an allowable shear stress of 10.6 ksi. The safety factor for each bolt is

$$SF = \sigma_{\text{allowable}} / \sigma_{\text{bolt}} = 10.6 / 3.75 = 2.8$$

This value is slightly less than the factor of 4 provided, yet still indicates the adequacy of the attachment bracket bolts under these maximum conditions.

The cross-sectional area of the fiberglass at the joint, taking the section width at 5.5" (same as stainless plate) is

$$A_{\text{fiber}} = (5.5'' \times 1.5'') - 2(\pi / 4 \text{ in}^2) = 5.25 \text{ in}^2$$

The stress at the fiberglass section is then

$$\sigma_{\text{fiber}} = (100 \text{ kips} / 10 \text{ sections}) / A_{\text{fiber}} = 2 \text{ ksi per section}$$

Since the as-built fiberglass laminate contains only 1/5 of the specified glass, the strength is only 1/5 of the specified strength, which is 128 ksi. This results in an as-built tensile strength of 25.6 ksi. Since the laminate strength decreases as the load is applied at an

angle away from the warp direction, the strength was further reduced to 12.8 ksi, and 10 ksi was the strength used for calculations, as provided.

Using the stress and tensile strength of the fiberglass, the safety factor is

$$SF = \sigma_{\text{tensile}} / \sigma_{\text{fiber}} = 10 \text{ ksi} / 2 \text{ ksi} = 5$$

which is quite satisfactory for this application, and very conservative.

Finally, the stainless steel plate of the bracket itself has a minimum cross-sectional area when assembled of 6.875 in², and a tensile load of 100 kips. The tensile yield strength of the plate is given as 35 ksi. The stress and safety factor for the attachment plates is

$$\sigma_{\text{plates}} = 100 \text{ kips} / 6.875 \text{ in}^2 = 14.54 \text{ ksi}$$

$$SF = 35 \text{ ksi} / 14.54 \text{ ksi} = 2.4$$

Which is almost half of the provided safety factor of 4.5. Perhaps a difference in maximum load is used is the reason for the discrepancy.

The conclusion is that the attachment point design seems adequate to restrain the UEK at the maximum expected water velocity, 4 knots (6.98 ft/s) at a drag force of 100,000 pounds. The initial water tests should be monitored closely, however, in the event the drag forces exceed these design values.

Task 2. Describe relationship between difference in turbine performance with drag and degree of yaw with respect to current direction.

The UEK is composed of two counter-rotating turbines that generate electricity as they are rotated by water passing over them. Ideally, the power from each turbine is the same, and the loads and power output is balanced. In the event that one turbine does not perform as well as the other, however, the resulting difference in rotation could induce a change in orientation with the water direction, possibly causing the UEK to yaw and behave unpredictably.

The UEK drag calculations were based upon a variety of analytical methods, each with assumptions based upon water flow across, through, and around the turbines. Each resulted in a range of drag forces, yet they all assumed both turbines would perform identically. The new question is what would happen if one turbine either slowed or stopped relative to the other in a high current.

The most effective way to determine what this would do to the system's stability is to use a combination of the energy method and the forces from the momentum method. Based upon previous discussions and the earlier drag report, the energy extracted from the water results in a drag force in addition to the basic drag caused by a resistance to water flow. The UEK is estimated to produce 120 kilowatts (KW), or 60 KW per turbine. The unit

generates 180 horsepower (HP) based upon various efficiencies, with a corresponding output of 90 HP per turbine. This may be converted into a drag force by multiplying by 550 ft-lbs/sec per horsepower and dividing by the water velocity, so each turbine at this power generation level would experience

$$F_{\text{drag}} = (90 \text{ HP} \times 550) / 6.98 \text{ ft/s} \approx 7,100 \text{ lbs of drag}$$

So, if one turbine stopped or began to turn freely, as in the case of a damaged gearbox, a net moment would be imposed on the UEK of

$$M_{\text{UEK}} = F_{\text{drag}} \times 10 \text{ ft (distance from center of turbine to attachment point)} = 71,000 \text{ ft-lbs}$$

This is in addition to the steady-state drag of the momentum method, approximately 100,000 pounds at the maximum water velocity. The relationship may be stated as a differential, such that

$$M_{\text{UEK}} = [(\Delta\text{HP} \times 550) / V_{\text{max}}] \times 10 \text{ ft}$$

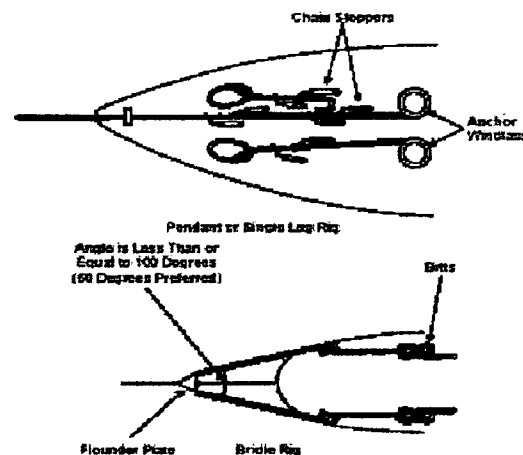
This relationship indicates that only the difference in horsepower will cause an inequality in the drag force and induced moment about the center attachment point, with the maximum at ΔHP equal to the maximum per turbine output.

Another way to estimate this moment is to assume that one turbine is totally open, allowing the water to pass through with no interference, and have the other turbine completely closed. This would result in larger moments, but is less reasonable based upon the UEK geometry. The extracted power method seems to be the best basic approximation at this point, considering the lack of quantitative drag measurements. Once sea trials have been conducted, this relationship can be refined.

Task 3. Explain and provide information regarding method of mooring line attachment, to include both single pendent and bridle configurations.

Task 2 leads into this task, which discusses the various methods of attaching the UEK to its mooring line. Two basic approaches are available; a single pendent attachment and a bridle arrangement (Figure 1).

The single pendent rig is the simplest and most straightforward and is generally used for open ocean towing of ships with fine bows, sonar domes, bulbous bows or when the tow is most stable in this configuration. The advantage of the pendent rig is its ease of connection. There is little, if any,



likelihood of the pendent fouling on the structure of the UEK. If the tow is not stable in this configuration, however, the single pendent rig is not capable of stabilizing the tow. The tow tends to rotate about the single attachment point, and under extreme conditions, erratic motions could lead to mooring failure.

The bridle rig is characterized by a two-legged bridle instead of a single pendent. According to the Navy Towing Manual, the length of each bridle leg should be approximately equal to the beam of the towed vessel, or about 60 degrees at each vertex. The fitting at the apex of the bridle is usually a flounder plate with the two bridle legs connected at its base and the apex usually connected to the tow hawser, or mooring line in this case. The bridle rig, by definition, uses two off-centerline fairleads. As a consequence, if the tow does not track directly astern of the tow vessel or mooring line, there may be an off-center dynamic load. This load, while tending to be self-correcting, unbalances the loads on each bridle leg. Therefore, each bridle leg must be of full towline strength (Figure 2).

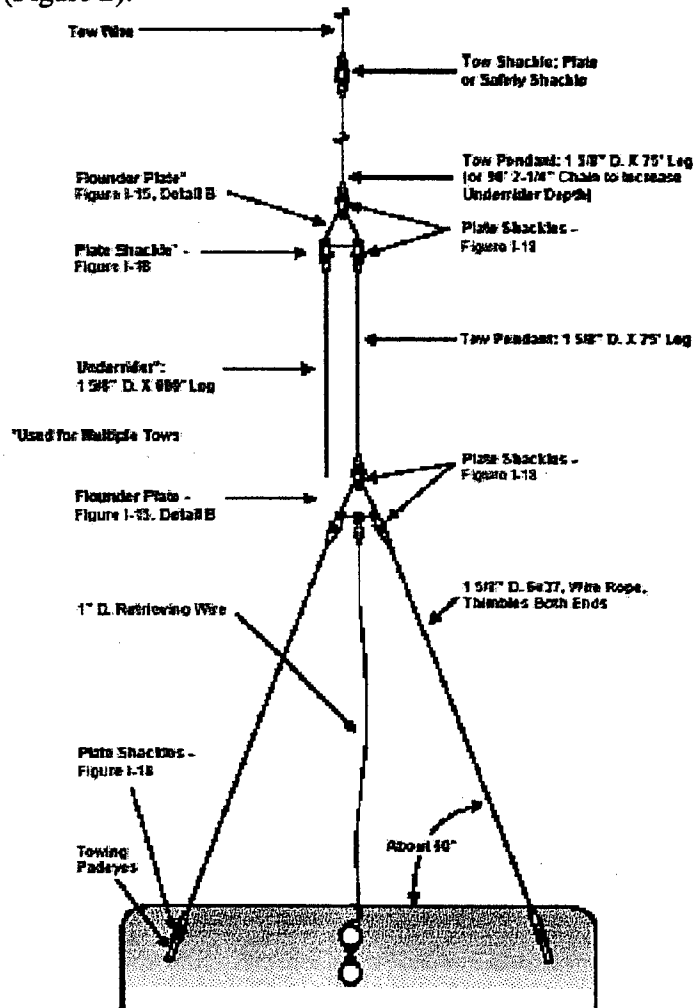


Figure 2 – Example of Wire Bridle with Wire Pendent

Another consequence of the bridle rig is the load imposed on the UEK. As shown in Figure 3, the bridle forces generate considerable compressive forces on the UEK, forces the UEK does not appear to be designed to withstand.

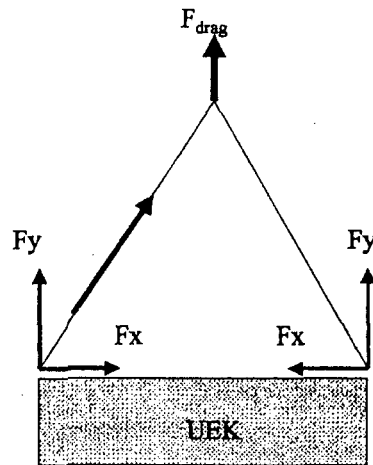


Figure 3 – Bridle Forces

The reactions on the UEK are found by determining the components of the bridle leg tension and bridle angle θ , which is related to the drag/mooring force by

$$T_{\text{bridle}} = F_{\text{drag}} / (2\sin\theta)$$

The F_y reaction is basically one-half F_{drag} , and the F_x reaction is $T\cos\theta$. Since there are two bridle legs, the compressive force on the UEK structure is $2T\cos\theta$, or $F_{\text{drag}}\cot\theta$. Using the 60° bridle angle suggested by the Navy Towing Manual and a 100,000 pound drag force, the compressive load on the UEK would be 57,700 pounds. This compression would most likely damage the UEK structure, or at least affect its performance.

The most feasible mooring arrangement appears to be a combination of the single pendent rig connected to the attachment bracket analyzed in **Task 1**, and a bridle arrangement to counteract the possible drag imbalance described in **Task 2**. In this configuration, the main mooring line would connect to the UEK at the attachment bracket, while two smaller bridle legs would attach to the UEK at the ends of the bearing supports. In the event of an imbalance, the bridle legs would act as springs, effectively countering the induced moment and retaining a perpendicular orientation to the flow.

In order to counter the imbalance-caused moment, the bridle legs must be sized such that they will not exceed their maximum strength while resisting the moment. When required, the bridle leg acts like a spring in that it stretches according to the deflection equation

$$\Delta = (T \times l) / (A \times E)$$

where Δ is elongation in inches, T is cable tension, l is cable length, A is cable cross-sectional area, and E is the cable modulus of elasticity. This equation may be arranged to determine the restoring force available for a known stretch, indicated by the magnitude of the cable tension T . For example, if the UEK were to experience a one degree twist from perpendicular, the force required to stretch the bridle cable the equivalent distance, $10 \text{ ft} \times \sin(1^\circ) \approx 0.17 \text{ ft} = 2.04''$, would be about 56,000 pounds for a 3/8" wire rope! Obviously the wire rope would fail long before it reached this value, but throughout the elongation up to failure it would continuously resist the moment. This shows the importance of understanding the predicted loads and the need to properly size all of the UEK mooring components.

Using the estimated maximum moment from **Task 2**, $M_{\text{UEK}} = 71,000 \text{ ft-lbs}$, the size cable and deflection required to resist this moment is required, along with the compressive forces on the UEK structure, and the safety factor at the maximum cable tension. The actual F_y component of the bridle leg is simply equal to the difference in drag forces, or 7,100 pounds from **Task 2**. Assuming again the 60° bridle angle and attachment at the turbine center, the bridle tension would need to be

$$T_{\text{bridle}} = F_y / \sin(60^\circ) \approx 8,200 \text{ pounds}$$

This would result in a deflection of 0.61" for 3/8" wire rope at a safety factor of 1.6 (13.1/8.2), and only 0.086" for 1" wire rope with a safety factor of about 11 (90/8.2).

This result indicates that for the projected moment on the UEK from a turbine failure or unbalanced load, a main mooring cable supplemented by two smaller bridle lines could ensure the stability and orientation of the UEK. Again, these values are all based upon a large number of assumptions, and until real test data is collected, these are only educated estimates of the UEK behavior.

CONCLUSIONS AND RECOMMENDATIONS

The results of this report indicate the UEK attachment bracket is sufficient supporting the drag forces on the system, and there are sufficient safety factors for each mode of potential failure. The drag imbalance section determined that while there is a definite imbalance and induced moment on the system, it is not very large, even at the maximum water velocity, yet is significant enough to warrant attention. The combination single pendent / bridle rig appears to be the best method of restraining the UEK, while also providing a method of self-correction during times of turbine imbalance. While all of these results indicate the system will perform in an actual deployment, only real in-water testing and analysis of the results can insure ultimate success. It can not be stressed enough how important actual test data is for such a unique system, and without that information all of the detailed deign work is only a best estimation of the actual behavior.

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