2018 EAGE ANNUAL
80TH CONFERENCE + EXHIBITION
COPENHAGEN | DENMARK

SailWing™ | Stable Marine Source Control

INTRODUCTION

A novel segmented-foil diverter (SFD) design with the added functionality of being able to remotely control the magnitude of lift that is generated by the diverter is introduced. This capability offers numerous advantages for application to seismic source arrays to stabilize geometry and control positioning. Additionally, the flexible segmented-foil concept provides improved logistics for vessels of opportunity, allows for closer passes around obstructions, and improves operational efficiency while simultaneously reducing back deck HSE risk. A selection of results is presented from a recent sea trial in which one of the source subarrays was fitted with an SFD, complete with a remotely controlled actuator to control the amount of lift being generated. Once the active feedback control capability was engaged, results successfully demonstrated the improvement that was achieved to separation stability during unsteady towing conditions.

THEORY OF OPERATION

Figure 1 provides a plan view of a dual source configuration, with the starboard side source utilizing a conventional diverter (paravane) with its dedicated tow rope and inter-connecting taglines, and the port side source utilizing SFDs (one SFD dedicated to each of the three subarrays). The physical size of the paravane required to spread the three starboard side subarrays to their required lateral offsets is a function of the length of the tagline connecting it to the outboard subarray, and the lift-to-drag efficiency of the particular paravane design being used. The lift required from the paravane must be sufficient to satisfy the force and moment balances associated with the following list of hydrodynamic forces:

a) The drag of each subarray at its assigned lateral offset position
b) The drag and spreading forces generated by the three subarray umbilical cables
c) The drag of all the interconnecting taglines
d) The drag and spreading force of the rope required to tow the paravane from the vessel
e) The paravane's own parasitic drag

As the length of the tagline from the outboard subarray to the paravane increases, the lift demanded from the paravane must also increase due to:

a) The increase in lateral moment arm between the vessel and the drag vector of the paravane
b) The increase in drag of the longer connecting tagline
c) The increase in drag and spreading force of the longer tow rope required to reach the paravane at its wider lateral offset
d) The increase in spreading force required for the paravane's tow rope as its sweep angle increases with increasing lateral offset from vessel to paravane

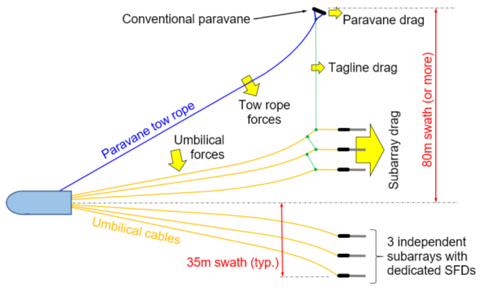

Figure 1 Paravane vs SFD Configurations

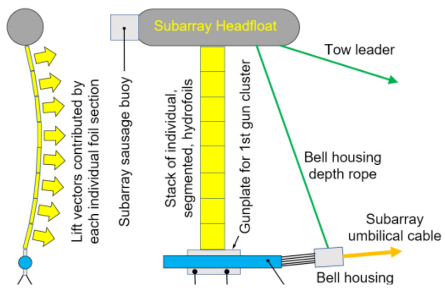

Figure 2 Elevation Views of the SFD

The aspect ratio (height/width) of the paravane is also an important factor in determining its lift-to-drag efficiency. Typical source paravanes have an aspect ratio of unity or less, such that lift-to-drag efficiency is often on the order of 2:1. A poor lift-to-drag ratio has a direct impact on how large the paravane must be just to overcome the moment created by its own parasitic drag at its required lateral offset.

Figure 2 presents the SFD concept, whereby a stack of segmented foil sections is attached directly to the subarray itself, typically connected between the headfloat at the surface, and the first gun plate at the bottom. The advantages of this design, compared to the conventional rigging of Figure 1, are:

a) The SFD applies lift directly to the subarray itself, thus eliminating the long moment arm associated with the conventional paravane's connecting tagline
b) The stack of airfoil sections will generally have an aspect ratio in excess of 10:1, compared to 1:1 for a conventional source paravane

In addition to the above two stated advantages of the SFD, a third important feature of this design is that its lift output can be controlled to provide positioning stability for the subarray. Figure 3a presents a cross-section of the asymmetric foil design used for the stack of SFD foils shown in Figure 2 (note the relatively flat profile on the bottom of the foil compared to the slightly cambered top surface). Also note that there is a conduit (thru-hole) provided both in the nose and the tail of the foil cross-section. The nose conduit has been positioned well forward of the foil's maximum thickness cross-section. Thus, when a forward rope is threaded through the nose conduits of a stack of SFD foils and brought under tension in a flow field, the moment coefficient Cm associated with the foil design (due to its asymmetric cross-section) will cause the foil to rotate to an equilibrium angle of attack, as per Figure 3b. Note that with the forward pivot point positioned as shown, the associated moment coefficient will cause the foil to assume a negative angle of attack (i.e. the cambered side becomes the pressure side of the foil rather than the suction side).

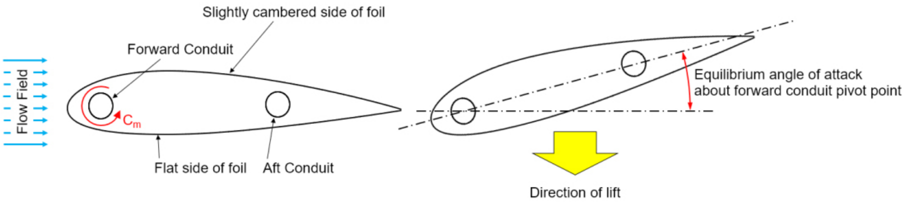

Figure 3a and 3b SFD hydrofoil, with forward and aft rope conduits. At right is the response of the foil when subjected to a flow field and allowed to pivot about the forward conduit rope.

In the absence of a rope threaded through the aft conduit holes, the foil stack will assume a minimum angle of attack and begin generating lift in the direction indicated in Figure 3b. This characteristic allows the SFD to self-orient upon deployment and begin moving the subarray in its intended direction as the umbilical cable is paid out from the vessel. In practice, the aft conduit rope will be present during a deployment, but will initially be longer than the forward conduit rope such that it remains slack (and hence equivalent to being absent altogether).

To increase the amount of lift being generated by the SFD, an actuator can be attached to one end of the forward conduit rope to control its length, relative to the length of the aft conduit rope. As the forward rope is lengthened, it eventually becomes longer than the aft rope, at which point the pivot location for the foil becomes the aft rope, allowing the nose of the foil to increase its angle of attack, thereby generating more lift.

OPERATIONAL ADVANTAGES

Conventional paravanes used for air source geometry separation are large, typically in the 1000-2000 kg range with a foil area of 5-10 m^2. They are required to provide enough lateral lift to separate all subarrays on one side of a seismic vessel via interconnecting taglines between the paravane and each adjacent subarray. The handling equipment for these paravanes includes launch and recovery davits, tow winches, and overboarding sheaves, all requiring high load certifications. By comparison, an SFD distributes the subarray lift requirements proportionately between all source strings, meaning that the SFD itself can be fabricated from light duty materials. The foils of an SFD are made of polyurethane with a summed foil area of 2-3 m^2 and a weight of 80-120 kg depending on the foil stack height. During launch and recovery operations, the foil stack simply expands or collapses as it follows the subarray down or up the stern gun chute. The reduction in HSE risk due to simplification of the deployment procedure and the elimination of unnecessary equipment is profound.

Line changes with conventional paravanes are typically 15-30 minutes in length in order to maintain sufficient forward water velocity past the inboard paravane so as to not stall or collapse the configuration. Conversely, subarrays equipped with SFD's have proven to be un-stallable. Whether in flume tank or field testing, an SFD can be brought to a dead stop in the water, and after resuming forward velocity, it will return to its nominal lateral position. This means that line changes can be very fast, with the limiting condition not being the SFD, but rather the bending of the umbilicals around the stern of the vessel, and the ability of the vessel to stabilize on a new line heading. In multiple sea trials, sub five-minute line changes have been achievable with turning radii of 200m or less.

Segmented foils can also be towed fast. Due to the low drag forces imparted by segmented foils, the limitation on speed is determined by the umbilical tension itself. Field test speeds of more than 7 knots have been achieved while maintaining very acceptable tensile loads on the umbilical and subarray.

GEOPHYSICAL ADVANTAGES

Source geometry stability is an important requirement in seismic surveys to maintain a consistent acoustic output and array response. Natural variations from ocean currents and surface waves make maintaining a stable source array and multi-source separation difficult, especially for fixed towing arrangements. By distributing the lift mechanisms and providing active control to individual subarrays, sea-condition variability can be overcome, yielding better overall source geometry. In addition to maintaining source geometry, the actively controlled SFD can steer individual subarrays or sources to desired locations for more consistent 4D baseline surveys, better matching of 4D monitor surveys, or improving coverage.

Another important advantage for OBS or undershoot surveys is a reduced offset from vessel to obstruction. Because the SFD is attached directly to the subarray itself, as opposed to a conventional paravane at some fixed lateral offset (as per Figure 1 above), gunboat approaches around platforms and other obstructions can be reduced, improving near-offset coverage.

CONTROL & STABILITY

Many source boats today control the path of the source simply by controlling the path of the vessel. The time spent correcting a source back to its desired lateral offset can be greatly reduced by applying the restoring force directly to the point being controlled. This is intuitive as the connections between the boat and the source are long and flexible, and each dynamic element has its own inertia.

For the vessel alone to correct the path of the source laterally, it first must change its own heading. There is an inertial lag in getting the vessel to a new heading. Once established on the new heading, the offset error is reduced by the sine of the heading change times the vessel speed. Once the desired offset is reached, the vessel would need to turn back to its original heading. Bringing the offset error to zero requires very precise timing. If the operator or control system does not properly account for ship and towing system dynamics, the offset will either overshoot or undershoot the desired offset, thus requiring another subsequent correction. Variability in speed, umbilical payout, and sea currents are all additional factors in this relationship. It is well known that the response time of closed-loop control systems are limited by the response times of the systems being controlled. While closed-loop feedback controls can automatically correct for errors, one could expect that an error might require considerable time to re-establish equilibrium at a low value.

The SFD allows for manipulation of the head of the source directly, and hence has much less associated delay in response time. If the correcting force can be applied and modulated directly at the head of the source string, it immediately moves in the desired direction without needing to wait for the vessel to turn and transit to a new offset. As the vessel needs to be connected to the source string, there are physical limits to how much change can be made at the source without also bringing the vessel to a new location as well. A control system that can combine SFD manipulation directly applied to the head of the string with vessel steering has a huge advantage in regulating offset in the presence of an external disturbance.

RESULTS

The four graphs presented in Figure 4 present a cross-section of results from a recent sea trial in which a remotely controlled subarray with an actuated SFD was deployed in combination with a reference subarray (i.e. no connecting taglines or diverters, trailing straight aft from the vessel). Figure 4a (top left) presents the displacement length of the hydraulic ram used to control the length of the forward SFD rope (on the right-hand scale), versus the achieved lateral offset (on the left-hand scale) between the 2 subarrays. This initial test established the macro-response of the SFD subarray to maximum excitation (i.e. full dynamic range of the ram displacement, at maximum rate of change of the ram's displacement).

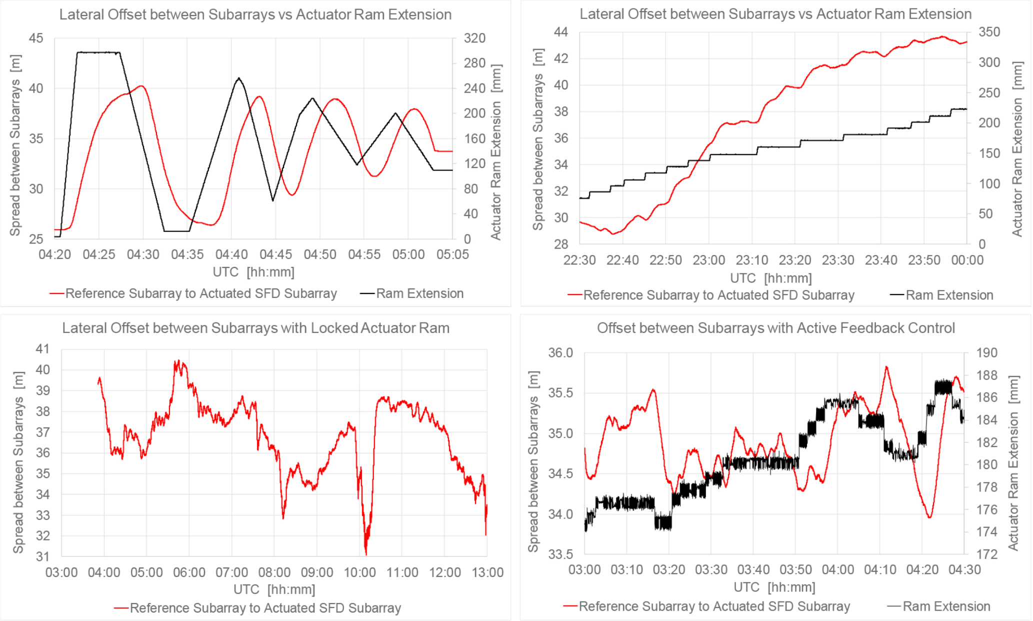

Figure 4a, 4b, 4c and 4d Sample Results from SFD Sea Trial

Figure 4b (top right) presents the short timescale response of the SFD subarray to 10mm increments in ram extension, with 5 to 10 minutes allowed between increments to allow the subarray to approach (or achieve) a new equilibrium lateral offset. Figure 4c (bottom left) presents a 10-hour interval of source towing with the SFD actuator ram locked. During this interval, it can be seen that the lateral offset between the two subarrays varied by up to 9m (peak to peak). Figure 4d (bottom right) presents a 90-minute interval of online towing during which the actuator ram was controlled from the vessel using active feedback control. Here it can be seen that lateral offset variations were reduced to less than 1m (peak to peak). The ram displacement has been overlaid (on the right-hand scale) on top of the offset data (on the left-hand scale).

CONCLUSION

A novel segmented-foil diverter concept has been shown to effectively maintain stable source control using active feedback control. Additionally, this new device has been shown to provide a number of advantages and improvements relating to operational, geophysical, and HSE criteria.

Reference:

Martin, D. [2017] Steerable Fairing String. United States Patent US 9,632,195 B2.