Future towed arrays - operational drivers and technology solutions

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Abstract — Towed array sonars provide a key capability in the suite of ASW sensors employed by undersea assets. The array lengths achievable and stand-off distance from platforms provide an advantage over other types of sonar in terms of the signal to noise ratio for detecting and classifying contacts of interest. This paper identifies the drivers for future towed arrays and explores technology solutions that could enable towed array sonar to provide the capability edge in the 21st Century.

1 Introduction

Towed arrays are a primary sensor for ASW acoustic detection and classification. They are used extensively by submarine and ASW surface combatants as part of their armoury of tools against the submarine threat. As the nature of ASW evolves, the design and technology incorporated into future ASW towed arrays will also need to adapt. This paper examines the drivers behind the shift in ASW and explores the technology space that may provide leading edge for future capability.

The scope of towed arrays that this paper considers includes submarine towed arrays optimised for use on nuclear and conventional submarines, towed arrays for use on ASW unmanned surface and underwater vehicles.

2 What does the future hold for towed array design?

The future trends for ASW towed array technology will be driven by the often conflicting requirements to maintain performance against evolving threat capability that is both effective and affordable. Trends in the operational landscape including submarine evolution, development in autonomous systems and the ever present drive for cost effectiveness are discussed below.

2.1 Submarine evolution

Advanced submarines are getting quieter. The latest generation of nuclear submarines are continuing the trend for signature control with the effect of reducing radiated noise signatures [1]. This reduces the level of the signal available for target detection.

Furthermore the number of countries operating nuclear submarines is expanding, as is the number and capability of conventional submarines, and less capable, but still effective coastal and midget submarines. The growing number of advanced submarine threats in a wide variety of geographical environments indicates an evolved sensing capability is needed.

2.2 Maritime Autonomous Systems and sensors for ASW

Recent advancement in autonomous systems and technology is opening up a plethora of new ASW capability opportunities and threats, including concepts that involve the use of a towed array sensor on an unmanned underwater or surface vessel in order to support mission objectives.

The use of towed arrays on autonomous systems has been studied to show how effective this type of capability can be. Modelling of the utility of towed array sonar from unmanned surface vehicles has indicated that towed sonars are more effective than dipping sonars in ASW missions due to the towed sonar's greater detection range and the need for dipping sonar to be stationary whilst operating [2].

Maritime Autonomous Systems are available in a wide variety of designs with a range of characteristics. The systems components relevant to this analysis are the vehicle and sensor combination. Example vehicles and their characteristic of relevance to towed arrays are presented below.

2.2.1 Autonomous Underwater Vehicles

AUVs are characterised by the vehicle's ability to operate fully submerged without requiring input from human operators once its mission us underway. Autonomy is of particular importance for underwater vehicles for ASW due to the difficultly of achieving reliable and timely long range communications.

Key issues for towed array operation with AUVs include:

- Propulsion – sufficient thrust to overcome drag forces.
- Depth – AUVs can operate at much greater depths than manned platforms. Towed array systems must be able to survive these depths to have utility over the full depth capability.
- Payload power and energy storage – power on AUVs is a precious commodity. The power

consumption of the towed array and associated sonar processing must be optimised.

- Platform integration and autonomous array handling – clip on arrays, or a potential need for autonomous handling systems.
- The need for autonomous operation and constrained communications means that false alarm rates must be minimised.

Example AUV's which may be suited for towed array operations include:

- **SeaCat** (Atlas Elektronik) is medium size vehicle. Its modular design means it is configurable for different mission types. Maximum speed is greater than 6 kts, with typical operating speeds between 2 and 4 kts. Its endurance is up to 20 hours at 3 kts speed [3].
- **Autosub** (National Oceanography Centre) is a family of AUVs. Autosub is 7 m long and 900 mm diameter. It has a range of 500 km and 6 days endurance [4]. The smaller 'Autosub Long Range' vehicle has a depth rating of 6,000 m and an endurance of up to 6 months and range of 6,000 km [5] travelling at low speed.
- **Echo Voyager** (Boeing) is a long range Extra Large Unmanned Undersea Vehicle (XLUUV) which is capable of operating over extended periods without human intervention with a range of up to 12,000 km [6].
- **Nautilus 100 Eel** is a futuristic concept developed by the Future NEST initiative from the UK Naval Engineering Science and Technology forum. The sensors in this concept "could travel hundreds of miles in near silence using an eel-like sine wave propulsion motion, disguising themselves as a marine lifeform to an enemy's sensors" [7]. This concept is included to illustrate a possible future outcome for autonomous vehicle design that may require a sensing capability currently delivered by towed arrays.

2.2.2 Autonomous & Unmanned Surface Vehicles

Many of the factors to consider for surface vessels are similar to the AUV case, but the different characteristics of USVs and their operation may drive a different set of solutions.

Key issues for towed array operation with USVs include:

- High speed operation – The maximum speed of unmanned surface vehicles range from the very slow to fast (40 kts without payload). A robust towed array is required to survive high speed operation and consideration must be given to impact of speed on sonar performance.
- Payload power and energy storage – USVs may have better access to stored energy (e.g. batteries, fuel) and / or energy harvesting capability (e.g. solar) in order to power sensor systems for longer.
- Active sonar – A USV is less likely to be used as a covert platform than an AUV. Therefore an inclusion of a towed active sonar system from a USV becomes an attractive ASW capability.

Example USV's which may be suited for towed array operations include:

- **Wave Glider** (Liquid Robotics) is a wave and solar powered USV consisting of a surface float and an underwater 'sub' [8]. Wave Glider is capable of speeds up to 3 kts and has a long endurance and an average continuous power of up to 20 W.
- **ARCIMS** (Atlas Elektronik UK) is an 11 m long USV in service with Navies worldwide, including the Royal Navy. It offers fully autonomous capability and has a maximum speed without a payload of 40 kts. An ASW mission module for ARCIMS has been developed, which includes an advanced triplet towed array receiver [9].
- **Sea Hunter** (Office of Naval Research) is a Medium Displacement USV developed as part of the DARPA ASW Continuous Trail Unmanned Vessel (ACTUA) programme. Sea Hunter is 40 m long and has a top speed of 27 kts [10]. Range is up to 10,000 nm at 12 kts with an endurance of 30 to 90 days [11].

The diversity in the type and capability of platforms that will be used for future ASW will also drive an equivalent level of diversity in the design of towed arrays to provide the acoustic sensing capability.

2.3 Cost effectiveness

Cost is always a key driver in the development and acquisition of new capability and this will be the case for future towed arrays development. This is not only driven by the unit price of a towed array sensor itself, but also the cost factors related to availability, reliability and pan DLOD (Defence Lines of Development) considerations that provide an operational capability. New towed array technology and designs must address this as well as providing an appropriate acoustic specification.

Alternative lifecycles and models of ownership should be investigated. This could be particularly beneficial with unmanned systems, where there is a chance a towed array may be damaged. In the unmanned Battlespace, it is expected that there may be many more unmanned systems than current ASW assets in the fleet. It is therefore worth considering the model of a 'consumable' sensor that is more cost effective to replace rather than maintain and refurbish. Whilst intended for extended mission (potentially multiple missions i.e. not a single use sensor), the benefits of a maintenance free replaceable sensor could reduce design complexity and allow for improved obsolesce management and logistics.

Manned platforms will continue to demand the most effective towed arrays to provide the necessary capability. A focus on cost effectiveness for manned platforms should therefore be on reducing the whole life cost of towed array ownership through improving availability and reducing the impact on platform and combat system.

3 Design trade-offs

Towed array design involves a trade-off between a number of often competing design factors and ultimately becomes a compromise. This outcome of the design trade-off can be very different depending on the array's intended use. This section provides an analysis of the factors involved in this trade off and identifies broad solution categories to guide future development strategies.

Figure 1 - Key design factors for towed arrays

Key design factors include:

- The directivity of a towed array is defined by the length of its acoustic aperture. The longer the acoustic aperture, the greater the directivity index and hence gain of the array. The greater the directivity the more able the sensor is to detect targets in the presence of noise.

- The drag forces on the array define the longitudinal strength that the array needs to survive. Drag increases with diameter, length and speed. The greater the drag, the stronger the strength members need to be which normally leads to larger array diameter.

- Flow noise increases with speed and reduces as array diameter increases. High flow noise levels will limit the acoustic performance of the sensor.

- Platform impact in terms of mass and volume for array stowage and handling system increases with array length and diameter. Drag and array power consumption also has an impact on the platform vessel.

- Power consumption of the array increases with the number of channels, which is a function of design frequency, length and nesting arrangement.

- The buoyancy of the array is affected by the density of the components within it. A lighter than water fluid fill is usually used to compensate for the more dense components. Normally a towed array is designed to be neutrally buoyant. The buoyancy headroom reduces with diameter and/or component (channel) density.

These design factors are interdependent, with a change to one aspect having an impact on all the others. The design of towed arrays is therefore an exercise in engineering trade-off to find the optimal solution that best balances these factors. Given that the range of platforms for towed array operations is likely to be diverse, an understanding of the fundamental design factors is needed.

The main factors that determine the basic design and form factor of an array include:

- Drag forces experienced, which defines the mechanical strength required, survival speed and influences diameter.

- Mass and volume, which is driven by array diameter and affects the handing system and stowage requirements.

- Flow noise, which determines the range of speed where acoustic performance is sufficient.

Figure 2 illustrates the trade-off that needs to be made between drag, mass and flow when selecting array diameter.

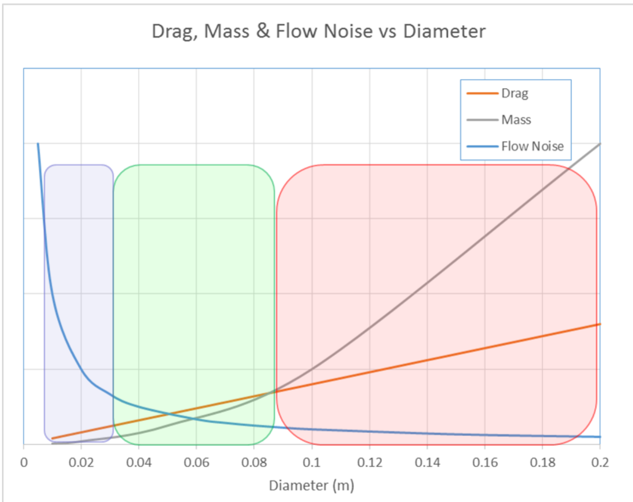

Figure 2 - Trade space for drag [12], flow noise [13] and mass as a function of array diameter

At small diameters, the drag experienced by the array and the array mass is low, however the small diameter array is very susceptible to flow noise, limiting the maximum operational speed at which good sonar performance can be maintained. As diameter increases, the flow noise quickly reduces, however the drag and mass of the array increase. For this trade-off, three design regimes have been identified, illustrated by the blue, green and red zones:

- **Low cost, low speed, limited performance** (Blue zone): very little drag and mass makes lightweight arrays a feasible solution. However, they are fundamentally susceptible to flow noise which is not possible to mitigate through design at very small diameters. Very thin arrays below approximately 30 mm diameter in this design space may have utility but the focus should be on producing them at low cost.

- **Sweet spot for performance versus diameter for capable ASW arrays** (Green zone). Flow noise is much reduced for thin arrays so provide performance at operational speed. Noise can be minimised by implementation of noise reduction design features. Arrays in this category need to be robust to the drag loads experienced at the higher speeds, and handling if reelable. The challenge in this category is to achieve the mechanical robustness and noise performance in as compact an array as possible.

- **Diminishing returns** (Red zone): Beyond this point, reductions in flow noise with increased diameter are negligible and the array becomes large and cumbersome to operate, handle and store.

Figure 3 illustrates the trade-off between flow noise, drag and speed.

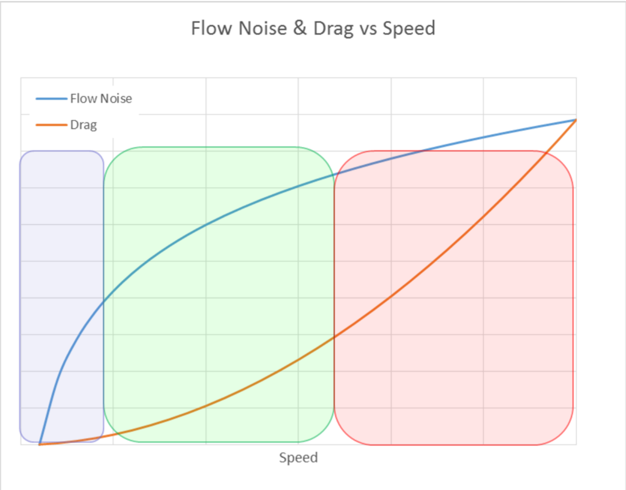

Figure 3 - Trade space for flow noise [12] and drag [13] as a function of speed

Flow noise and drag both increase with speed. Again, three design regimes have been identified:

- **Low speed performance** (Blue) – At low speeds, low levels of drag are experienced. Not much mechanical strength is needed so small diameter arrays with thin strength members are possible. Flow noise at low speed is sufficiently low that it mitigates the poorer flow noise performance of thin diameter arrays.
- **Optimal Operational Performance** (Green): This is the zone of performance where flow noise needs to be a major consideration in array design. This will drive diameter and flow noise reduction design features. Drag is becoming an important factor which the array must be sufficiently strong to withstand.
- **Survival Zone** (Red): The array needs to survive, but will not provide optimal operational performance (e.g. sprint and drift or emergency manoeuvre). Maximum speed causes high drag forces requiring high mechanical strength of the array.

4 Towed array solutions

Solutions for towed arrays from current and future ASW platforms are discussed below. These solutions range from mature proven designs through to concepts that require technology development to achieve.

4.1 Submarine & ASW Frigate towed array

Capable towed arrays for submarine and surface ship ASW systems should be targeted at the 'sweet spot' green zone illustrated in figure 2. The design challenge here is to optimise acoustic performance (noise and directivity) in a package that minimises platform impact, through minimising the diameter to reduce both drag and towed array handling size and mass.

AEUK have developed a Thin Line Array that provides an advanced sensing capability that has been configured to fit into a small space making it ideal for use by submarines, whilst delivering all the advantages of more conventional larger systems.

The AEUK Thin Line Array is neutrally buoyant, submarine winchable. It has a high survival speed, low sensor and self-noise, is capable of achieving long acoustic apertures and has a high channel count. In the design of the array, traditional design preconceptions were discarded and a new mechanical design produced enabling the diameter reduction and excellent acoustic performance**Error! Reference source not found.** that extends the boundaries of what was traditionally possible.

The array is designed around reliability improvement principles and a common module concept which means that all acoustic modules are the same, rather than being specialised for different frequency bands. This enables efficiencies in logistics (e.g. spares) to be realised and provides individual acoustic channel access throughout the array which can be exploited to optimise the sonar processing.

4.2 Towed array for unmanned systems

There is a wide variety of unmanned vessels that could be considered for use with an ASW towed array sensor. For the purposes of towed array operation, they can be categorised into 2 broad classes of 'small / slow' and 'high speed / large payload' autonomous systems.

4.2.1 Small / slow vessels

Small and / or slow vessels are limited in the available thrust for towing, which will limit the length of array able to be towed, and the speed at which it is towed. Depending on the size and design of vehicle, the majority of the available thrust may be required to propel the vehicle at operational speed. The remaining thrust available to overcome the drag force of the array will limit the maximum speed. However, running at this speed would run the propulsion system at full capacity and reduce platform endurance. It is therefore likely that optimal operational speed will be somewhat slower at approximately half this speed. Operations for small and slow vehicles are contained within the blue zones of Figure 2 and Figure 3.

For slow speed operation, the array does not need to withstand high drag loads so the array can be designed with thin and lightweight strength members enabling small diameters. At low speeds, flow noise is not a dominant noise source, so acoustic performance can be achieved with small diameter arrays. The key issues are diameter reduction (for reduced drag and payload space), power consumption and cost.

The future solution for these vessels therefore should be driven towards something very simple and affordable and such as the consumable array concept. This may not scale to longer lengths or higher speeds, but may provide a very cost effective sensing system in certain scenarios.

4.2.2 High speed or large payload vehicles

Autonomous systems with large payload capacity or high speed capability (e.g. ARCIMS, Sea Hunter, Echo Voyager) have sufficient thrust and endurance to tow long aperture arrays, potentially at high speed (for surface vessels). Where investment in capable vehicles has been made, an investment in capable, low noise and high gain arrays is also justified. There are a number of potential towed array solutions for this class of vessel.

High Capability Thin Line Array – An array with a diameter of 50 mm or less would occupy the 'green zone' of capability. The AEUK Thin Line Array is an example of this type of array. This array has the mechanical strength to withstand the greatest survival speeds and the acoustic engineering to provide sonar performance at high operational speeds. The array is reliable and reelable, which are both important factors for both manned and autonomous sensing systems.

Very Thin line array - The next towed array concept is a cheaper and thinner towed array design that provides a significant reduction in array mass, drag and platform impact whilst retaining a capability for a long array to survive high speeds. Acoustic performance would be retained at medium speeds, but would be degraded at high operational speeds compared to the high capability thin line array. This type of array is suited to medium speed surveillance or use in a 'sprint and drift' mode. An array with a diameter less than 30 mm would feasibly achieve this acoustic performance. The factor limiting further reduction in diameter is the mechanical strength needed to survive high speeds and / or long apertures. A towed array needs to withstand large drag forces for tow speeds above 15 kts. This is achievable with a design that utilises the latest in lightweight high tensile materials combined with high performance array fabrication expertise. Survival tow speeds in excess of the maximum payload speeds for ARCIMS and SEA HUNTER are achievable. This type of array occupies the capable end of the spectrum represented by the blue zones in figures 2 and 3 and would also be suitable for use on slower vessels for surveillance and situational awareness.

Triplet Receive Array - For use as an active receiver, a triplet receive array is an attractive solution for autonomous systems. The directional nature of triplet arrays improve the array's gain and hence it's detection performance and also enable unambiguous bearing resolution which will be of great value in autonomous ASW detection and localisation. As part of the ARCIMS ASW system, AEUK have developed a new triplet array receiver for autonomous ASW.

5 Technology of the future

Technology development that are may contribute to addressing the design drivers to achieve the concepts above include:

Connectorless towed arrays – Underwater connectors can be expensive, heavy and bulky and can introduce failure modes into the system. Removal of complex interconnects for power and telemetry at inter-module connections and through the tow cable transmission path could offer a more simple and robust system enabling more efficient manufacture and greater reliability availability. The technology to achieve this could be based on developments of Near Field Communication (NFC) from consumer electronics. NFC provides low power communications over short distances with very short set-up times, however the current data rates of less than 1 Mb/s are only sufficient to support a low number of channels, approximately 8, depending on sample frequency. High bandwidth NFC prototypes have achieved data rates of 6.78 Mb/s [14], which may be sufficient for short to medium length arrays, depending on number of channels and data bandwidth. Further developments in this technology will be needed to support the data rates for arrays with more channels, which may be driven by developments in ultra-high definition digital video formats, which have data rates approaching those of high channel towed array sonars.

Wireless Power Transfer is now common place in consumer mobile devices and electric vehicles and may offer a method of transferring power between array modules without a physical electrical connection [15]. The challenge for a towed array will be achieving the power transfer required with the envelope of the towed array and managing the impact of electromagnetic emissions and heat on the sensor electronics.

Integrated telemetry strength members – Buoyancy and space are two of the major constraints in array design. Strength members and electronic wiring are both significant factors that contribute to the mass and component count. The concept of integrated telemetry strength members combines the function of these components and allows the transmission of data and power through the strength members. This removes the need for additional electronics wiring looms which add weight and complexity to the array.

Adaptive buoyancy control – Methods to automatically alter the buoyancy of the array during use will provide greater control (and hence performance) especially in slow speed operation and / or for UUVs, enable the array to operate at a different depth to the towing platform. It will provide advantages by being able to adapt to different environmental conditions (temperature, salinity etc…) and simplify the manufacture processing be reducing the need to tune the mass of the each array to achieve neutral buoyancy.

Fibre optic sensing – During the early 2000's fibre optic sensors for towed arrays were heralded as being the likely sensing technology to dominate the towed array market in future decades, resulting in longer arrays with more hydrophones [16]. To date, this technology has not materialised into an in-service capability due to limitations on sensor performance and complexity of the inboard interrogator equipment. New research and fabrication methods offer the potential for improved performance and a micro-diameter single fibre array. Such an array could be very long, deployed from a compact spool from within even a small vehicle.

Advanced shape estimation – New developments in inertial measurement units, are expected to provide opportunity to more accurately determine the position of the array and the sensors within it. Research is progress in the field of quantum gyros with a demonstration of a 3-axis quantum accelerator planned in 2019 by Imperial College London and the National Physical Laboratory [17]. Super-precision in sensing the shape of the array will enable processing enhancements to maximise the performance of the array.

Energy harvesting - The motion of towed arrays in the water offers potential opportunity to harvest energy to power the array. It may be possible to replace the rope tail or drogue, which intentionally causes drag, with an energy recovery device create the drag needed and create energy as a by-product. Additionally, the array itself could incorporate a mechanism to harvest energy from array flex and movement. An energy harvesting capability could enable a long endurance battery powered sensor with no need for the platform to provide power to the array, thus extending platform endurance.

6 Conclusions

The design of towed array sensors for ASW is being driven by submarine evolution, the advent of autonomous systems and the constant drive for through life cost effectiveness.

The diversity in future towed array platforms, ranging from large manned warships and submarines through to small autonomous systems will drive diversity in the range of sensor solutions. This will allow the right balance in cost and capability to be struck for each application.

Technologies being developed in fields such as consumer electronics and quantum sensing form opportunities to offer key enablers needed to satisfy the future demands for ASW acoustic sensing. If they can be successfully brought through into towed array development, they will help achieve a new era of cost-effective towed array sensing capability for the future manned and unmanned systems.

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