High Performance Synthetic Ropes for Wave and Tidal PTO Applications

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Abstract— **High-performance synthetic ropes (HPSR) offer many benefits in wave and tidal energy applications across all phases of deployment, from installation and operation through decommissioning.**

In these applications, rope performance, demands are typically much higher. Exceedingly high break strengths, long fatigue life, stiffness or compliance, and safety are often required in proposed systems. Through lab-scale testing and ongoing research, performance expectations can be better defined, hence more effectively managed.

Though high-performance synthetic ropes have properties that favour these stricter demands, there are also technical considerations for performance expectations we can require from a rope. With these technological factors, system designers should take a holistic approach to ensure maximum safety, design life, and operational efficiency for a system. This paper explains these considerations and properties of high-performance synthetic ropes, to assure that performance expectations can be achieved.

Keywords— **High performance synthetic ropes, fibre rope, mooring ropes, rope fatigue, offshore lifting, wind energy, wave energy**

I. INTRODUCTION

Global energy trends shifted from biomass to petroleum-based resources starting in the late 1800's when Edwin Drake drilled the first commercial oil well [1]. Since the turn of the 21st century, the realization of major global climate change has fuelled global energy markets to shift from fossil fuels to renewable energy sources. The formation of the Paris Agreement in 2015 has reinforced the migration to renewable energy resources by establishing targeted limits of global temperature rise by limiting greenhouse gas emissions [2].

High performance synthetic ropes (HPSRs) have been used in the oil and gas industries for the past several decades and will play a vital role in the success of renewable energy as technologies are developed. HPSRs are used in the oil and gas industry for vessel mooring, station keeping, seismic activity, anchor lines, installations, towing, and riser pull-ins. These applications demand durable and efficient ropes with predicable service lives. As offshore renewable energy becomes a more viable energy source, HPSR manufacturers are noting increasing demands on the rope used in systems and devices, including requirements for higher strength and higher durability than ropes used in the oil and gas industry today.

While the future of the oil and gas industries remains uncertain, investments in renewable energy sources are on the rise [3]. Global new investment in clean energy has increased five-fold since 2004 [4]. These investments help accelerate technology development and efficiency gain. As wave and tidal energy devices are developed today, the durability and reliability of components is of the upmost importance to prove commercial viability. As an integral component of the system, HPSR properties must be considered during the development phases of renewable energy technology.

This paper will discuss HPSRs as a part of the power take off (PTO) system. The properties of ropes used in the PTO system differ significantly from ropes used in other applications such as mooring or positioning. The primary considerations for HPSRs used for PTO's in wave and tidal applications, are elongation, strength and fatigue properties, such as tension fatigue and cyclic bend over sheave (CBOS). These properties, and how they are defined by standard (or nonstandard, in some cases) test methods, should be clearly understood and considered in engineering the PTO system.

II. HPSR PROPERTIES

HPSR ropes are differentiated from traditional rope by their much higher tenacity than commodity rope forms such as polyester, nylon, or polypropylene [5]. Along with increased tenacity, HPSR ropes are often more durable and stiffer than traditional ropes. High modulus polyethylene (HMPE), aramid, liquid crystal polymer (LCP), and poly(p-phenylene) benzobisoxazole (PBO) fibres are all considered materials for HPSRs, as shown in table 1.

Active spooling is often used for wave and tidal PTO systems. Due to their high strength, low elongation, and durability HPSRs are a common material selection for winchlines used in PTO systems. Point absorbers often rely on a high-strength HPSR to translate the linear displacement of the device to the power-generating device, such as a turbine or hydraulic pump. This means that minimum energy absorption between the buoy and the power-generating device. Because of these demands within the PTO system, the HPSR must have a high load rating, very low stiffness, and withstand aggressive tension fatigue and cyclic bending to achieve the highest efficiency.

TABLE I
TENACITY OF ROPE MAKING MATERIALS

Product or Manufacturer	Fiber Type	Grade	Tenacity (g/denier)
HPSR Fibres			
Dyneema	HMPE	SK78	40
Spectra	HMPE	S1000	34
Kevlar	Aramid	Kevlar 49	24 [6]
Technora	Aramid	T220	28
Vectran	LCP	T97	23
Zylon®	PBO	High Modulus	42 [7]
Commodity Fibres			
Invista	Nylon 6,6	T728	9.4
Hailide	Polyester	L1005-B	6.5
Cordex	Polypropylene	MFP	5.0

A. *Elongation.*

To assure the maximum amount of energy transfer to the device, high stiffness/low elongation ropes are required. This translates to higher peak loads on the line for a given displacement and thus a higher power output.

HPSR elongation properties fall into two primary categories; constructional elongation and elastic elongation, as seen in Figure 1. Constructional elongation is the initial elongation observed directly after installation and is driven primarily by rope construction. Under tensile load, the rope structure aligns and compacts radially, translating to a longer length rope. This elongation is non-recoverable. It is important to consider constructional elongation if the length of the rope during installation must be the same as the final length. Once the constructional elongation has been removed from the rope, it is considered "bedded-in".

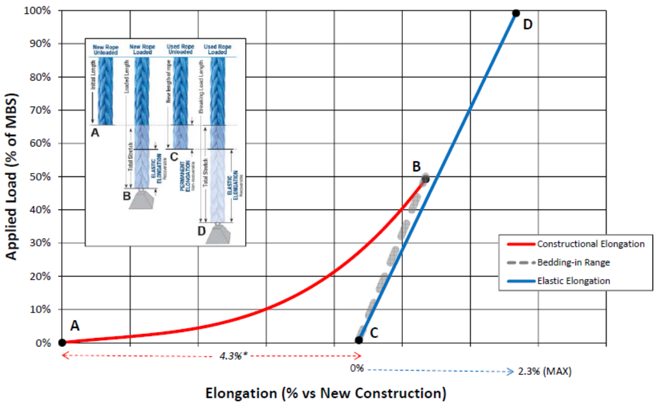

Fig. 1 Typical elongation curve for HMPE rope. The non-recoverable constructional elongation is the section between points A and C and the blue curve shows the recoverable elastic elongation.

Separate from constructional elongation, elastic elongation is the recoverable elongation that occurs after the rope has been bedded-in. Elastic elongation is primarily attributed to the fibre properties of the rope. As seen in Figure 2, the elongation properties of HPSRs are comparable to traditional steel ropes.

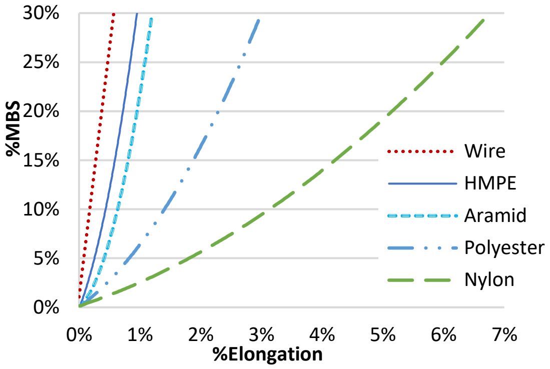

Fig. 2 Elongation response due to loading by fibre type.

B. *Strength.*

As devices progress from prototypes to full scale units, the strength of the HPSR will scale. For some full-scale devices, rope strength requirements may surpass 5000 mT (11 million lbs). With the highest tenacity materials, the present-day manufacturing capabilities are just short of meeting these projected strength requirements. This is one issue rope manufacturers are experiencing with the requirements of HPSRs for wave and tidal devices.

If the strength requirements could be met, the logistics of manufacturing, splicing, transportation and strength verification remain. For these reasons, devices must be engineered to conform to current technology limitations to scale quickly. One consideration is to divide the load between multiple ropes. Though it complicates the system, it allows the possibility to scale the device to commercial levels. If commercial scale success becomes a reality, rope manufacturers will likely need come up with innovative ways to deliver and reach the required breaking strengths associated with wave and tidal energy applications.

C. *Fatigue*

Rope durability can be defined through many modes of wear, but typically boils down to abrasion resistance. With each passing wave, the mooring and PTO ropes are subjected to repeated loading and, in some cases, repeated dynamic bending. This repetitive motion causes a scissoring effect on the strands of the rope. As the strands move relative to one another, material is abraded, wearing away material, which reduces the strength of the rope.

Mooring ropes and PTO ropes alike face cyclic tension fatigue with each wave cycle. Tension fatigue may be a concern for long deployments or when low safety factors are used. HPSRs outperform nylon, polyester, and steel wire ropes in tension fatigue, as seen in Figure 3.

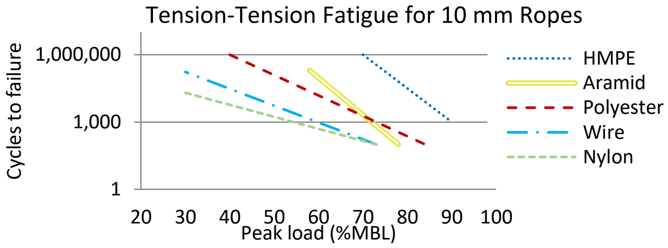

Fig. 3 Tension fatigue characteristics by fibre type [8].

Similar to the repeated motion of tension fatigue, CBOS is a concern in any scenario where a rope repeatedly bends over a sheave. CBOS is particularly a concern for wave energy devices, which experience 8 to 12 second wave cycles. This translates to 2.5 to 4 million bend cycles per year if the rope is used to translate linear displacement to angular displacement. At this time, there is no commercially available rope technology that can economically achieve more than 200,000 CBOS cycles. Improvements to CBOS life can be made by using advanced coatings, modifying the rope construction, and appropriate fibre selection/blending. Aside from rope technology improvements, CBOS life is improved by oversizing the rope and sheave and by providing a way to cool the rope as it passes over a sheave, typically with water.

Two major design parameters will affect the durability of the rope in CBOS applications; applied load and severity of the bend. As the safety factor and sheave diameter are increased, the cycles to failure is also increased. Life factor, defined by the product of rope safety factor and ratio of sheave diameter to rope diameter (Figure 4), is often used to normalize the two parameters. For example a safety factor of 5 and a D/d of 12, the lift factor will be 60. Life factors of 150 or more are often required for offshore applications using active heave compensation. For wave and tidal applications facing cyclic bend fatigue, life factors of 200+ should be considered.

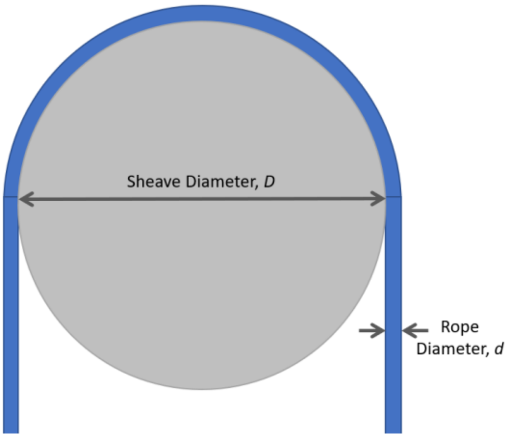

Fig. 4 D/d is defined by the sheave diameter, D, divided by rope diameter, d.

III. HPSR Guidance for Wave and Tidal Devices

Most inquiries from wave and tidal energy developers needing ropes for PTO systems require ropes with performance attributes that exceed current rope capabilities. Additionally, for many specifications, standard test methods do not exist. The gap between rope requirements and how they are defined against a standard furthers the challenges with rope procurement.

As shown in Table II, for some specifications, there are several applicable standards, whereas other specifications do not have any associated standards. Each of these cases may cause confusion in the design phase and purchasing process.

TABLE II
Common Rope Specifications and Standards

Specification	**Definition**	**Units**	**Applicable Standards and Guidelines**
Break Strength	The maximum force applied to a rope in a tensile test carried out to rupture. [9]	Force	ASTM D4268, ISO 2307, CI 1500, OCIMF Guidelines for the Purchasing and Testing of SPM Hawsers
Elongation	The ratio of the extension of the rope under an applied load to the unloaded length of the rope [5].	Δ Distance/ Distance	API RP 2SM, OCIMF Guidelines for the Purchasing and Testing of SPM Hawsers
Linear Density	The mass per unit length of fiber, yarn or rope [5].	Mass/ Distance	ASTM D4268, ISO 2307,
Stiffness	Ratio of change in force to change in stain under a specified load range [10]	Δ Force/ Δ Strain	DNV-OS-E303, API RP 2SM
Dynamic Stiffness	Peak stiffness, observed during storm conditions at peak load magnitudes and peak load rates [10]	Δ Force/ Δ Strain	DNV-OS-E303
Cyclic Fatigue	Fatigue caused by repeated bending over a curved surface such as a drum of sheave	Cycles to Failure (CTF)	No industry standards (CI guideline draft in progress)
Tension Fatigue	Fatigue caused by repeated tensioning of the rope in a straight configuration.	CTF, TCLL	API RP 2SM, OCIMF Guidelines for the Purchasing and Testing of SPM Hawsers
Abrasion Resistance	Resistance to damage when subjected to a contact surface [5].	N/A	No industry standard exists
UV Resistance	No universal definition	No universal definition	No industry standard exists correlating lab data with field performance

The developer should recognize which standard should be used to define the rope specification. In cases where no test methods exist, the performance requirements must be carefully examined to determine the appropriate testing to validate a rope for use. For example, abrasion resistance is often required in applications which require the rope to pass through a fairlead, however there are no existing standard test methods established to measure the abrasion resistance of a rope. Abrasion resistance is currently only defined by independent testing, often tailored to the conditions of the intended application, such as roller diameter, material, and finish. On the other hand, some rope properties can be defined by a number of accepted test methods. For example, ISO 2307 break strength may be different from the CI 1500 break strength, due to differences in cycling the rope prior to breaking. The preference for test method is usually defined by the developer's reference guideline or standard, such as those defined by class societies or committees (i.e. DNV, ABS, BV, MERiFIC), however some guidelines and standards use their own standards, such as API test methods.

Most guidance notes and regulations on HPSRs for offshore applications have been developed by the oil and gas industry. Though these guidelines lay a good foundation for HPSRs used in wave and tidal energy devices, in many cases the guidelines are not directly applicable. Some wave and energy device guidelines look toward an independent third party to set the pass/fail criteria for the mooring systems [11], however very few third party organizations have specific guidelines for HPSR mooring rope design criteria for wave and tidal device applications.

IV. HOLISTIC SYSTEM DESIGN

During the development phase of a wave energy device, careful consideration must be given to the limitations of the selected rope. Though HPSRs are a common rope selection for demanding applications, wave and tidal devices have much different operational conditions than traditional rope applications.

Samson has worked with AquaHarmonics and CalWave, both recipients of the Wave Energy Prize in 2016, to advance technology in wave PTO design. As with most wave energy inquiries, the companies both had early designs that demanded more from the state-of-the-art HPSR. In a preliminary feasibility study, CalWave encountered the challenge of millions of CBOS cycles in a 20-year design life. Samson worked with CalWave early in the design phase to quantify the specific risks and identified alternative solutions that address feasibility within the existing rope technology. By engaging with rope manufacturers early on, both companies were able to make the necessary system adjustments with minimal impact to the project budget and met performance expectations.

Involvement of primary component manufacturers early in the design process can help clarify some otherwise overlooked design elements. With limited technical guidance for developers, this step is even more important for understanding the technical limitations of each component.

V. CONCLUSIONS

As wave and tidal technology climbs the technology readiness scale, the supporting technology for these devices must grow to adapt to the changing energy landscape. Though HPSRs boast many positive performance attributes for wave and tidal energy devices, some shortfalls still exist.

By understanding the technical limitations of HPSRs and how HPSR specifications are defined through testing methods and standards, manufacturers and developers can collaborate to bridge the gap for commercially viable devices. Through this holistic design approach, both development timeline and cost can be greatly reduced and better managed.

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