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CARBON NANOTUBE ELASTIC ENERGY STORAGE AS A POWER SOURCE FOR TORPEDO PROPULSION

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Abstract- *Speed and range are two of the most important parameters determining the effectiveness of torpedo as a weapon. While the first parameter, speed, requires a high level of propulsive power, the latter, range, requires a high amount of energy stored within the limited weight and space available in the torpedo. This requires both high power and energy levels per weight and volume. The purpose of this paper is to propose a new energy source - carbon nanotube elastic energy storage. Carbon nanotubes, with their high modulus of elasticity, high strength and strain endurance within the elastic limit, constitute a media that is capable to store large amounts of energy per volume and per weight, capable of delivering mechanical energy directly. Since carbon nanotube springs provide a completely air independent and high energy density storage media, they are considered to be a perfect energy source for torpedoes, as well as autonomous underwater vehicles (AUV's), remotely operated vehicles (ROV's) and even for small submarines.*
Keywords: *Carbon nanotubes, elastic energy, Young modulus of elasticity, strain, energy storage, torpedo propulsion*

1. INTRODUCTİON

Torpedo propulsion has been one of the important challenges of naval engineering since the development of modern torpedo in late 19th century. Speed, range and stealth are the main parameters required from the torpedo propulsion system. Speed and range are conflicting requirements, since the first one requires a high time rate of energy consumption, i.e., power, and the latter a high reserve of energy. In addition to speed and range requirements, the propulsion system has to occupy a small limited volume and preferably should not leave any visible or instrumentably audible trace.

The classical method of torpedo propulsion has been the use of heat engines, fueled by liquid hydrocarbon fuels and using high pressure air as the oxidant, driven either by turbines or by reciprocating engines. More recent systems involve the use of high performance batteries and heat engines energized by self-decomposing chemicals (for example, hydrogen peroxide), monopropellant fuels (such as Otto fuel) and light metal (such as Lithium) oxidation. Each system has its own merits and drawbacks. The conversion of chemical and/or heat energy into mechanical energy involves inefficiencies, with penalties related to speed and range, as well as exhaust gases betraying the stealth of the torpedo.

Another requirement that a torpedo should posess is reuseability- a torpedo is launched with an exercise head and later recovered several times during its lifecycle, until the day comes it is fired with a warhead or it is decomissioned. Each time after recovery, it is reconditioned and prepared for the next launch.

The purpose of this paper is to propose a system to yield mechanical energy for the propulsor directly: Mechanical energy stored in an elastic media. The mechanical energy stored per unit volume in an elastic media under stress is given by the equation:

$$u = \frac{1}{2} E\varepsilon^2 \qquad (1)$$

where E is the Young's modulus of elasticity, ε is the strain. The most promising media for such future applications is the carbon nanotube (CNT). In the following paragraphs, the utilization of this energy reserve for torpedo propulsion shall be discussed.

2. CARBON NANOTUBES AS ELASTİC ENERGY STORAGE MEDİA

CNT's are basically graphene sheets (hexagonally connected carbon atoms) rolled into a form of tubes, resembling chicken wires rolled up in cylindical forms. The tubes can be of single-walled carbon nanotube (SWNT) (with one sheet rolled) or multi-walled carbon nanotube (MWNT) type (two or more sheets rolled coaxially).

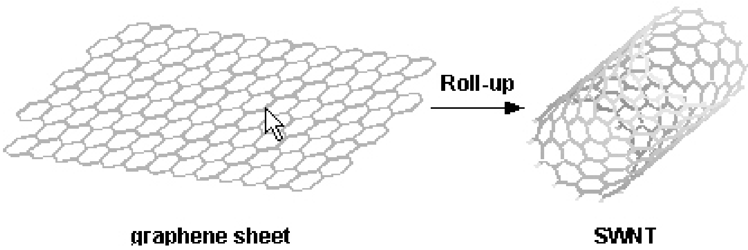

Figure 1. Relation between graphene sheets and SWNT's

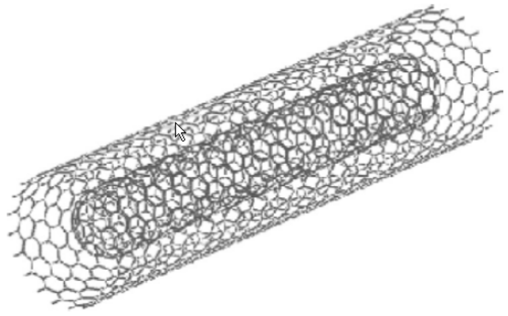

Figure 2. A MWNT (dual tube CNT)

Since their discovery in 1991, their properties have made them candidates of a large number of applications within a large spectrum, such as semiconductor electronic components, superconductive electrical elements, batteries, fuel cell components, ultra-strong composite materials, solar cells, ultra-capacitors, hydrogen storage media, membrane technology and even medical applications. Laboratory experiments have indicated that the modulus of elasticity of SWNT's of about 1 TPa and that they can be linearly strained up to 6% [1], which make them excellent candidates for elastic energy storage. More recently, Zhang et al [2] have reported a Young's modulus of elasticity for triple-walled CNT's of 1.34 TPa, tensile strength of 200 GPa and breaking strain of 17.5%, also an excellent fatigue resistance. Those figures place CNT materials stronger than the naturally existing hardest material-diamond. Unfortunately, due to the voids within and between individual CNT's, the modulus of elasticity shall be significantly lower. The mechanical properties of CNT's are presented in Table 1 below[3]. Steel is also included for comparison.

Table 1. Mechanical properties of CNT's

	Young's Modulus (GPa)	Tensile Strength (GPa)	Density (g/cm^3)
MWNT	1200	~150	2.6
SWNT	1054	75	1.3
SWNT bundle	563	~150	1.3
Graphite (in plane)	350	2.5	2.6
Steel	208	0.4	7.8

A study of the various aspects of using CNT's as a means of mechanical energy storage has been made by Hill[3]. The comparison of CNT's with other energy storage media is given in the Ragone plot below, where the obvious advantage of CNT energy storage is obvious [2]:

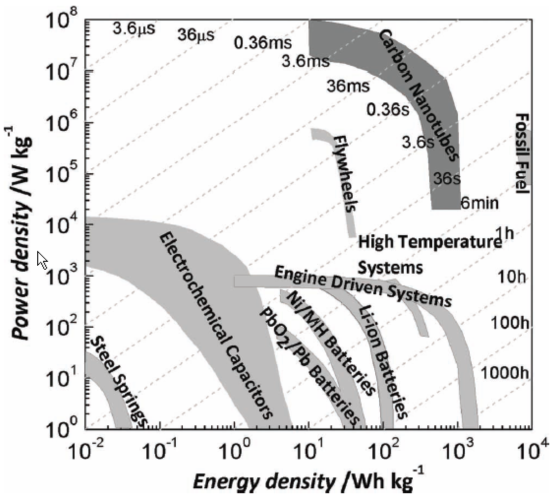

Figure 3. Ragone plot comparing various modes of energy storage[2]

3. CNT ELASTİC ENERGY STORAGE FOR TORPEDO PROPULSİON

In order to produce CNT springs, it shall be necessary to produce strands of CNT's, either SWCNT or MWCNT type. The springs can operate both in compressive or tensile mode. Since very high forces shall be involved, the springs should be placed into sufficiently strong supporting structures. Therefore, the density and space requirements of supporting structures also play an important part in the study of the feasibility of CNT springs. The stresses and strains on the supporting structures should also be taken into account. However, as shall be outlined later in this paper, a self supporting CNT system is proposed. Also, a power takeoff system should be devised and as shall be outlined below, equipped with a control system for a constant power output through the takeoff system. An additional system for re-loading and locking the spring before each launch is also required.

For a spring material of volume V_s, assumed to be constant during compression, potential energy U stored within the spring shall be:

$$U = \frac{1}{2} V_s E \varepsilon^2 \quad (2)$$

The power yielded by the release of potential energy stored in the spring is:

$$P_s = \frac{dU}{dt} = V_s E \varepsilon \dot{\varepsilon} \quad (3)$$

where the dot over the symbol denotes time rate of change. The power from the spring should be transmitted to the propulsors. The energy delivered to the propulsor shaft is related to the external resistance by the relation:

$$P_D = \frac{P_E}{\eta_P} \quad (4)$$

where η_p is the propulsive coefficient, equal to the product of propulsor's open water, hull, relative rotative and transmission and P_E is the effective power of the torpedo, equal to:

$$P_E = \frac{1}{2} \rho_W v_t^3 S C_T \quad (5)$$

where ρ_w is the density of seawater, v_t is the speed of torpedo, S is the wetted surface area of the torpedo, including the rudders and the propulsor assembly, and C_T is the coefficient of resistance. Setting the power from the spring equal to the power delivered to the propulsor, the speed of the torpedo shall be:

$$v_t = \left[\frac{2\eta_P V_s E \varepsilon \dot{\varepsilon}}{\rho_w S C_T} \right]^{\frac{1}{3}} \quad (6)$$

As can be seen, in order to obtain a constant speed, the product ($\varepsilon\dot{\varepsilon}$) should be kept constant, i.e., the more energy is released during the course of the torpedo, the rate of release of spring should be increased by a control system.

The time endurance T and range R of the torpedo can be found from:

$$T = \frac{U}{P_s} = \left(\frac{\varepsilon}{2\dot{\varepsilon}} \right)_{initial} \quad (7)$$

$$R = v_t T = \left[\frac{\eta_P V_s E \varepsilon \dot{\varepsilon}}{4\rho_w S C_T} \right]^{\frac{1}{3}} \left(\frac{\varepsilon}{\dot{\varepsilon}} \right)_{init} \quad (8)$$

4. A SAMPLE CASE

A hypothetical torpedo, of the non-cavitating high speed type, fitted with a pumpjet is conceived. The main particulars of the torpedo are given as:

Length	5.79 m
Diameter	0.533 m
Volume	1.163 m^3

The energy is stored in a compressive, MWCNT spring mechanism, composed of two concentric cylinders where the external hollow cylinder acts in compression and the internal cylinder acts in tension (Figure 4). The bottom part serves to join the two cylinders and acts as a cylindrical beam spring as well. However, its contribution for energy storage can be safely neglected. In order to optimally exploit the energy storage potential of the inner and externam springs/cylinders, they are to be designed with equal unstrained volumes:

Outer diameter of the outer spring
480 mm
Inner diameter of the outer spring
368 mm
Diameter of the inner spring
308 mm
The lengths of inner and outer springs 1500 mm

Therefore, the total effective volume of the shall be 0.112 m^3. The weight of the inner/outer springs shall be 290 kg.

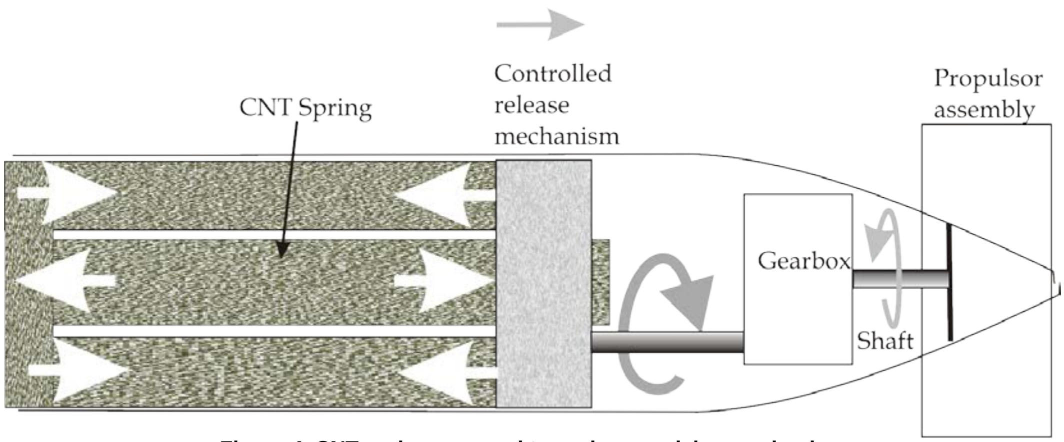

Figure 4. CNT spring powered torpedo propulsive mechanism

The resistance characteristics of the torpedo were calculated using the standard method outlined by Heller [4]. Adopting a propulsive efficiency of 0.65, power delivered to the propulsor shaft shall be 750 kW. Assuming an energy storage capacity of 5 × 10^2 W.h/kg and a corresponding power storage capacity of 2 × 10^4 W.h/kg per Ragone plot (Zhang et al, [2], also Figure 2 of this paper), the system shall be able to provide the required power. The time endurance shall be 697 seconds, and with a constant speed of 60 knots, this will translate to a range of 21500 metres.

5. CONCLUSİONS

It has been discussed and shown that the newly discovered CNT technology gives a good alternative for torpedo propulsion. However, the same concept can be exploited for the propulsion of remotely operated underwater vehicles (ROV) and autonomous underwater vehicles (AUV), and even for the air-independent propulsion of submarines. However, there are challenges related to the design and production of CNT springs, support mechanisms, release mechanisms, loading (compression) schemes, all to be solved by the engineering communities.

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