NAVAL APPLICATIONS OF ELASTOMERS

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ABSTRACT

The fact that rubber can be studied in a state of mechanical equilibrium makes it the most fundamentally interesting polymeric material. Elastomers also find wide application both in industry and the military, due to the unique combination of obtainable properties. This short review describes selected uses of rubber by the U.S. Navy on surface vessels, submarines and aircraft. The emphasis is applications which exploit rubber's capacity for energy transmission, storage and dissipation.

CONTENTS

I. ACOUSTICS

Elastomers for acoustic applications have a long history. This usage includes decouplers, which prevent sound passage, anechoic coatings, which attenuate sound reflections, and acoustic windows, which transmit sound waves. There are several reasons why rubber is the material of choice for underwater acoustics. One of the most important is that the acoustic impedance of rubber can be made to match that of sea water. At a boundary, there is no reflection of sound waves if the acoustic impedance of the two media are equal.[1] The acoustic impedance, analogous to the optical refractive index, is given by the product of the mass density of a material and the speed of sound within it. For low loss materials, the latter quantity is proportional to the square root of the ratio of the density and the modulus (bulk modulus for longitudinal waves, or shear modulus for shear waves).

Obviously, the acoustic impedance and its frequency dependence can be modified over a broad range for rubber, both by polymer selection and compound formulation. Most commercial materials are proprietary, although compilations of acoustic property data are available.[2] For filled rubber, the mechanical response is strongly nonlinear.[3] However, below about 10^{-3} strain amplitude, the dynamic modulus becomes invariant to strain (higher strains are required to observe the Payne effect).[4] Since the deformations arising from transmission of acoustic waves through rubber are quite small (typically, strain amplitudes $\leq 10^{-6}$), acoustic properties can be characterized from conventional, small-strain dynamic mechanical measurements.[5]

Another property that can be realized with rubber is a low attenuation coefficient for longitudinal sound waves. The amplitude of a transmitted wave diminishes exponentially with product of the distance traveled and the attenuation coefficient, the latter a material property. For longitudinal waves (oscillating in the direction of the sound propagation), this attenuation coefficient is proportional to the ratio of the bulk loss modulus to the bulk storage modulus. For elastomers, the relevant loss tangent is usually less than 10^{-3}.[6] Thus, sound waves can be transmitted

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long distances with minimal loss.

When avoiding detection is the objective, sound waves must be attenuated. This is readily accomplished with elastomers by converting the longitudinal sound waves into shear waves ("mode conversion").[7] The attenuation coefficient for shear waves (also referred to as transverse waves) is proportional to the loss tangent for shear deformation, which for elastomers can be on the order of unity. This mode conversion can be achieved in various ways, such as constraining the rubber as a thin film between two rigid surfaces, or by incorporating inclusions such as small glass spheres or gas bubbles. The interfacial rubber in such a confined geometry deforms in a shear (or extensional) mode, which is readily attenuated.

The rubber itself can be formulated to be highly dissipative at the frequencies of interest. As noted above, the Payne effect does not contribute to acoustic loss at ordinary sound pressure levels. In general, maximum energy dissipation occurs when the viscoelastic response of the material falls into the rubber-glass transition zone at the applied frequency and temperature. This transition can occur far above the conventional glass transition temperature. As measured using scanning calorimetry at typical heating rates, T_g corresponds to a deformation time scale of *ca.* 100 seconds. Since the effective activation energy for local motion in polymers is very large (a ten degree temperature change can alter the relaxation time by orders of magnitude), relatively high T_g elastomers are required to obtain a room-temperature rubber-glass transition at acoustic frequencies.[8,9]

Conventional dynamic mechanical testing is often used to predict the material's response to acoustic frequencies, by construction of master curves versus reduced frequency.[2] A caveat in using time-temperature superpositioning of mechanical data to predict acoustic properties is the need to use shift factors determined for local segmental motion (the high frequency end of the transition zone), rather than for the low frequency dynamics (such as the rubber plateau or the viscosity). The local segmental relaxation times change more rapidly with temperature than do the relaxation times for the chain modes.[10-12] This can lead to large errors if shift factors determined from high temperature, low frequency mechanical measurements are applied to acoustic data.[13]

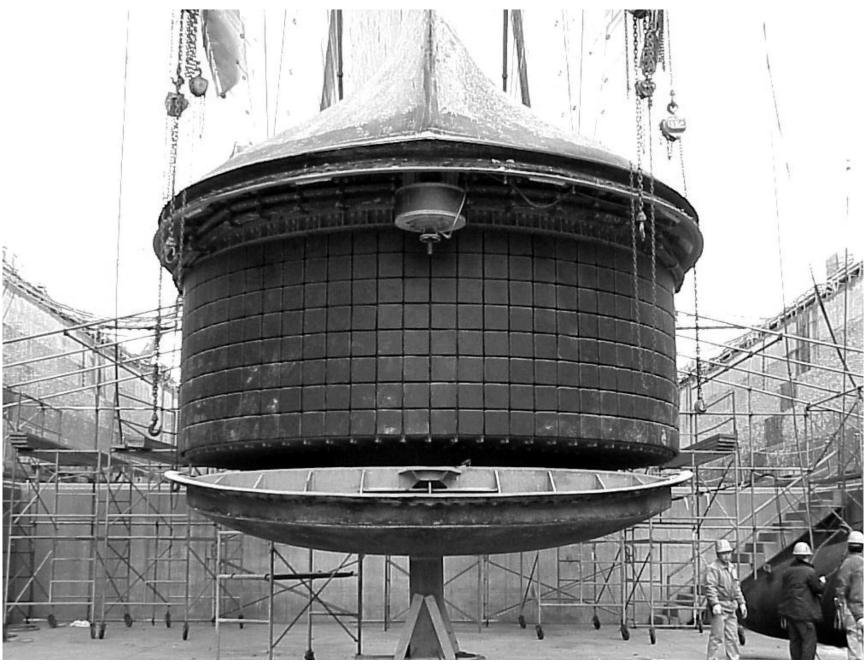

FIG. 1. — Sonar transducer showing outer rubber coating.
This assembly is located inside the rubber dome structure when mounted on the ship.

The various techniques outlined above are employed in the quieting of naval vessels. An example is the elastomeric coating of submarines used to avoid detection. By appropriate design of the rubber's acoustic impedance, the main echo of any impinging sonar is amplified (constructive interference) and directed away from the source. Diffuse echoes, as well as internal noise, are attenuated by a combination of proper formulating of the rubber and from the geometry of the coating layer itself.

FIG. 2. — The guided missile destroyer *USS Cole*, being returned to the United States after the terrorist attack in Yemen. Despite the damage to the hull, as well as the severe jostling when mounted on a Norwegian transport vessel (top), the bow dome (seen in lower photograph, hanging off the edge of the transport) remained functional. After repairs that included replacement of 550 tons of exterior steel plating, the Cole returned to sea duty 18 months later.

Although sound enables their detection, it also provides underwater “vision” to sea vessels. The sonic transducer on ships is covered with rubber (Figure 1), and contained in a steel-reinforced rubber dome, whose primary purpose is protection of the transducer. This function of the sonar dome was exemplified by the bombing of the *USS Cole*. Subsequent x-ray examination revealed the dome to have survived intact, despite substantial damage to the ship itself (Figure 2). The sonar dome must efficiently transmit the acoustic energy, and not significantly disrupt the flow of seawater around the vessel. Initial domes were made of steel. These had obvious problems, such as poor sound transmission, susceptibility to corrosion, and the need for internal supports, which obstructed the sound. The first prototype rubber dome was installed in 1965, with actual production beginning in 1972.

Sonar bow domes (Figure 3) are reputed to be the largest molded rubber article in the world. They weigh 8,600 kg, with a 11 m length, 6.4 m width, and standing almost 2.5 m high. The rubber wall thickness varies, up to a maximum of 20 cm. The construction involves manual lay-up of multiple steel-cord reinforced polychloroprene plies. The steel cords are necessary to provide structural rigidity. To avoid interference with acoustic performance, the spacing of the cords must be less than the wavelength of sound (*e.g.*, 1.5 m at 1 kHz). The rubber itself has minimal absorption over the sonar frequencies. The dome is constructed as two separate halves, which are then molded together in a large autoclave. The bow dome is inflated with *ca.* 95,000 liters of water, to an internal pressure of 240 kPa. Its location below the baseline of the ship minimizes hydrodynamic resistance.

FIG. 3. — Rubber sonar dome mounted to bow of ship.

Since their introduction over 30 years ago, various improvements to the design of rubber sonar domes have been made, greatly increasing the expected lifetime. In the late 1970’s, some domes began exhibiting a failure mode similar to that seen a few years earlier in radial tires on automobiles. Water migration into the structure caused corrosion of the steel cords, resulting in dome failures while at sea. Blockage of the migration pathways rectified this problem. Current sonar domes have a long lifetime, some remaining in service for over twenty years without mishap.

A single, spliceless ("monolithic") dome was constructed in 1992, and has been in use since that time. Recently, rigid composite domes, comprised of a rubber/plastic laminate, are being investigated as a replacement for steel-cord reinforced keel domes (Figure 4). A prototype composite keel dome has been in sea trails since 1997 on a destroyer surface ship. Composite domes using fiberglass and polychloroprene have been employed on naval submarines for almost two decades.

FIG. 4. — Composite rubber/reinforced plastic keel dome.

An acoustic application related to sonar rubber domes is the use of active sonar for detection of submarines and surface ships. Advances in quieting of naval vessels by the former Soviet Union, as well as the use of diesel electric submarines by third-world navies, has reduced the utility of passive sonar. However, active sonar does not rely on "hearing" nearby vessels, and thus is immune to sound-quieting efforts. Since the attenuation coefficient for sound waves is inversely proportional to the wavelength, low frequency (100-1000 Hz) active sonar can provide long-range detection. However, the longer wavelength reduces the obtainable resolution, meaning less discrimination among undersea objects.

Low frequency active sonar transducers are typically towed behind a surface vessel, emitting sound waves which can exceed 200 decibels at the source. The potential to induce hearing loss in marine animals[14-16] has necessitated extensive testing of the biological effect of exposure to low frequency sound. Although a ship using active sonar reveals its location, the improved detection capabilities, especially in shallow water (littoral operation), provided by this technique makes it the most important anti-submarine warfare development in a generation.[17]

A role for elastomers in this application, especially castable rubbers such as polyurethanes, is as a thick outer casing on the towed transducer, functioning analogously to the sonar domes on ships. The amount of acoustic information obtained using active sonar is enormous. Detection and classification of submarines in the complex acoustic environment of shallow water requires sophisticated mathematical algorithms for processing the acoustic data. Since any influence of the rubber on the transmitted sound must be accounted for, accurate characterization of the acoustic properties of the rubber is necessary. For low frequencies especially, this is a demanding experimental task.[13]

Related to acoustic applications is the use of elastomers for vibration damping, such as in shock and motor mounts. An example of this is the thrust reducer on submarines (Figure 5), which decouples the hull from propeller vibrations. Natural rubber, renowned for its outstanding dynamic properties, is used as an insert between the steel and polyethylene rings. Adhesion and resistance to fluids, such as hydrocarbon oil spills, are critical issues. Elastomeric bearing are used in the propeller shafts of the V-22 Osprey tilt-rotor aircraft. This is an innovative aeronautical design,[18] with 43% by weight of its structure comprised of fiber-reinforced plastic. The latter's radar absorption qualities are a major advantage for military aircraft.

FIG. 5. — Thrust reducer to decouple the propeller from the submarine. The natural rubber is sandwiched between the steel ring and an outer layer of polyethylene.

II. AIRCRAFT TIRES

Generally, aircraft tires differ from automotive passenger tires in two respects. Due to the extensive use of retreading, about 85% of aircraft tires are bias ply, rather than radial design.[19] And because of the high temperatures attained during takeoff and landing (exceeding 100 °C), aircraft tires, including the treads, are based primarily on natural rubber.

Although military aircraft tires perform a similar function to their commercial counterparts, the demands imposed on the former can be more severe. The wear of tires is due to frictional forces, arising from sliding at the road-tread interface. In automotive tires, cornering maneuvers, and to a lesser extent braking, are the primary causes of tread wear.[20] A similar situation exists for aircraft using land-based runways – about 70% of tread wear is ascribed to braking. Typically, tire treads on such aircraft might last on the order of 100 landing cycles.

The situation for carrier-based aircraft is quite different. Tire treads typically wear out 2 to 3 times sooner than their land-based counterparts. Ironically, this reduced lifetime has little to do with the extreme acceleration of launching or the rapid deceleration of carrier landings. (For example, during launch, an F/A-18 Hornet attains a speed of 165 miles per hour within a space of 250 feet.) The acceleration relies on steam-assisted catapulting, while landings utilize arresting wires rather than relying on tire friction (Figure 6). Thus, the contribution to tread wear is minimal for both cases. An additional factor is that carrier launches and landings take place with the ship turned into the wind, which adds (or subtracts) to the relative speed, putting less demand on the tires.

FIG. 6. — An F-18 Hornet about to catch a wire upon landing on the flight deck of the USS Abraham Lincoln.

The high wear rate of carrier-based aircraft tires is due to the maneuvering on the deck required to position the plane. Rollout and alignment prior to launch and straightening after arrestment impose severe cornering forces on the tires. The scuffing of the rubber on the non-skid deck governs the tread lifetime. This wear rate depends on the nature of the deck surface being used, although these are always high in friction in order to minimize skidding. A worst-case example was during the 1991 war in the Persian Gulf. Make-shift plates were used for a landing deck, with a surface so abrasive that tire treads wore out after only 4 to 5 landing cycles.

III. NEW TECHNOLOGY

Elastomers play a critical role in emerging naval technologies. Rubber can store a substantial quantity of energy, which may be recovered very quickly. The Navy has exploited this concept in developing a torpedo launching system, in which an elastomer functions as a mechanical capacitor. Prior to its internal propulsion mechanism taking over, a torpedo must be ejected from the submarine. This is a demanding task. For example, the Mark 48 torpedo, weighing 1600 kg, must achieve an exit speed of 50 km/hr in 1 sec. Conventionally, this is done using an air turbine or ram pump. The elastomeric ejection system employs a 1,400 kg, two-meter diameter rubber disk (Figure 7). Due to the need for durability and low hysteresis, the material is natural rubber, deproteinized to minimize water absorption,[21] with a semi-EV cure system.[22,23] A small recharge pump inflates the disk with water drawn from the ocean. A biaxial strain of about 100% is attained in the rubber, which yields 2,400 horsepower (1800 kwatts). Opening of a slide valve collapses the rubber disk, forcing water into the torpedo tube to effect the launching.

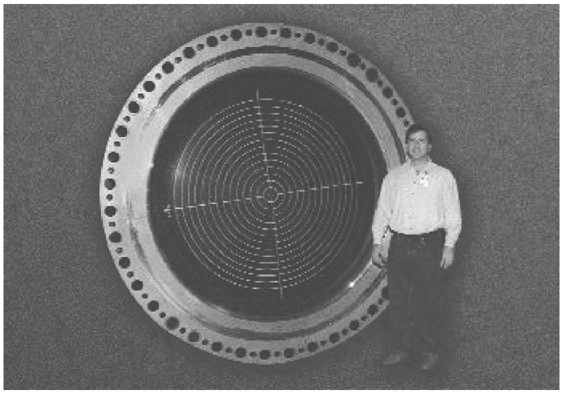

FIG. 7. — Disk prototype for elastomeric ejection system.

The advantages of an elastomeric torpedo launcher include a reduction in cost and complexity, as well as superior acoustic performance. The elastomeric disk is situated in the seawater, outside the pressure hull behind the outer hull, opening up additional space with the submarine. Full-scale prototypes have been successfully tested, and currently the elastomeric ejection system is under consideration for installation in future *Virginia*-class submarines.[24]

Another potential naval application of rubber is in the Mobil Offshore Base (MOB). MOB, or “artificial beach”, would be the largest floating structure ever built – a self-powered, mile-long open-sea platform.[25,26] Intended to be deployed in international waters in proximity to areas of military interest, MOB would house 70 acres of enclosed storage space, and also serve as a runway for fixed-wing aircraft. The size and functions of the MOB platform make it unique compared to other floating structures (Figure 8).

FIG. 8. — Illustration of Mobile Offshore Base concept (from McDermott Technology, Inc.; used with permission). The rubber connectors would be located between each of the five detachable modules.

The eventual design for the MOB has yet to be decided, with various concepts being investigated. The platform could be a single, continuous elastic hull, or involve as many as five individual modules, connected by hinges or elastic connectors. A critical aspect of the design is the response of the runway structure to ocean-wave induced dynamics over its one mile length. The base must support fixed wing cargo planes operating up to sea state 6 (15 foot waves and wind speeds of 35 miles per hour). The platform itself must survive all sea states, including hurricanes and typhoons (50 foot waves and wind speeds exceeding 100 miles per hour).

A modular approach offers important advantages, such as redundancy. The connectors between modules, and a method to control positioning, are the critical feasibility aspects of a modular approach. The assembly must be rigid enough to minimize relative motion between modules in order to provide a useable flight deck, but also be sufficiently compliant to reduce stresses generated over its length by ocean waves. Various connections methods are under consideration. One promising approach employs 5 meter long elastomeric conical connectors between the modules.[27] Elastomers offer the ability to tailor both the frequency response and the damping behavior of the connector. Advantage is taken of a conical geometry and the inherent damping afforded by rubber to control yaw motions, enhancing MOB maneuverability.

The technical feasibility of the MOB concept has been established and currently the program is under assessment by the Defense Department and Congress. Potential off-shoots of the floating platform technology, such off-shore airports, are also being explored.

IV. ACKNOWLEDGEMENT

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tion and complexity. By way of comparison, the B26 Marauder medium bomber, developed in 1940, experienced 15 non-combat crashes during its first three years (many of these due to tire failures), acquiring the nickname "Widowmaker". Nevertheless, 5157 Marauders were built, and these were very successful during World War II combat, achieving the lowest loss rate of any American aircraft in the European theater.

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