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3aUWb1. A towable combustive sound source for ocean surveys and ocean acoustics experiments  
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The Combustive Sound Source (CSS) is a broadband impulsive sound source that generates a wide bandwidth underwater acoustic signal, similar to explosives and airguns, yet allows for a reduced and controllable acoustic output, suitable for meeting modern environmental regulations. The source consists of a submersible combustion chamber filled with electrolytically-generated hydrogen and oxygen ignited via spark. Upon ignition, the combustive mixture is converted into high temperature water vapor and the ensuing bubble activity radiates broadband acoustic energy. CSS has previously been used in the water column from stationary platforms, and has been deployed on the bottom to generate seismic interface waves. We now report the successful implementation of a self-contained CSS system deployed in a tow body. No hazardous gas is ever stored on board the ship, as it is produced in situ while at depth. The system can produce high amplitude acoustic pulses while being stably towed behind a ship with an electro-mechanical cable. Discussion will focus on the functionality, capability and expandability of the system. [Work supported by ONR.]

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A TOWABLE COMBUSTIVE SOUND SOURCE
FOR OCEAN SURVEYS AND OCEAN ACOUSTICS EXPERIMENTS

The Combustive Sound Source (CSS) is a broadband impulsive sound source that generates a wide bandwidth underwater acoustic signal, similar to explosives and airguns, yet allows for a reduced and controllable acoustic output, suitable for meeting modern environmental regulations. The source consists of a submersible combustion chamber filled with electrolytically-generated hydrogen and oxygen ignited via spark. Upon ignition, the combustive mixture is converted into high temperature water vapor and the ensuing bubble activity radiates broadband acoustic energy. More detailed information about the device and basic operation can be found in Refs. 1 and 2. CSS has previously been used in the water column from stationary platforms, and has been deployed on the bottom to generate seismic interface waves [3-4]. The system can also produce high amplitude acoustic pulses while being stably towed behind a ship with an electro-mechanical cable. This paper describes the successful implementation of a self-contained CSS system deployed in a tow body at the Lake Glendora test facility in Sullivan, IN. The following sections give a description of the device and the test set up, provide the test results, and comment on the robustness of the associated hardware.

Description of CSS Towbody

This towable body not only serves as a housing for the three essential CSS components: the submersible combustion chamber, the gas delivery system, and the ignition system, but it also serves as a finned, streamlined body which can be trimmed to stably tow with minimal drag. As a system, these components allow users to produce high amplitude acoustic pulses while being stably towed behind a ship with an electro-mechanical cable. Theses acoustic pulses are similar to the signals produced by airguns and explosives, yet the CSS Towbody allows users to reduce and control the acoustic output to comply with modern environmental regulations. Another added feature of the system is that no hazardous gases or explosives are transported or stored on board the ship, as all hazardous gas is produced in situ while at depth. This section further describes the main components and operation of the CSS Towbody.

Towbody

As previously mentioned, the towbody is a finned, streamline body which serves as the housing for the CSS components during towed events. An underwater photograph of the towbody is provided in Fig. 1. The streamlined shape is formed from a hemispherical nose cone, a cylindrical body, and a tapered conical tail primarily comprised of an aluminum skeleton whereby aluminum skins are fastened to form the outer shell. The towbody is free flooding, and is not intended to prevent other components from getting wet. Adjustable fins are integrated into the tail cone, which allow users to trim the device as needed for varying tow conditions. The horizontal fins can be pitched up or down, and the vertical fins can be extended in the towbody’s axial direction via a fin extender (not shown in Fig. 1). A rotating tow bail is integrated into the top of the cylindrical body, which provides both a lifting and tow point during transportation.

Combustion Chamber

The combustion chamber is one of the three essential components needed to successfully fire a CSS event. For this test the combustion chamber was fabricated by welding a hollow conical chamber on top of an open-ended, hollow cylinder. The conical portion of the chamber is open to the water and used to entrap gas below the water surface during the combustion process. The cylindrical portion of the chamber is used to minimize gas spillage during the filling process and to contain the resultant bubble activity after combustion. The need for the cylindrical skirt was deemed necessary since the chamber was to be mounted inside the towbody.

Additionally, the combustion chamber contains several ports and a mounting plate in order to interface with other components in the system. The conical chamber contains three ports equally spaced around the circumference, which allow igniters to be mounted through the side wall to create sparks inside the chamber. The chamber also contains a port near the apex of the cone to allow air to be expelled from the chamber upon its initial submersion, and a port near the bottom of the chamber was added to allow input of the combustive gas mixture. The mounting plate was welded around the chamber, which provides a bolt pattern to secure the chamber within the towbody.
FIGURE 1. An underwater photograph of the Combustive Sound Source Towbody.

Gas Delivery System

The gas delivery system is comprised five electrolytic cells and a submersible pressure vessel containing a power supply. The system is capable of producing a hydrogen-oxygen gas mixture at 15 liter/min. Each of the electrolytic cells is surrounded by a urethane potting compound as a means of waterproofing and electrical isolation. These cells are filled with an electrolytic fluid, potassium-hydroxide, and produce the combustive gas mixture when an electric current is passed through the cells. The cells are powered by an off-the-shelf power supply contained within the submersible pressure vessel (at max power the cells run at 12 volts and 200 amps), and this power supply is powered through the electro-mechanical cable used to tow and power the system.

A unique feature of the gas delivery system is that it is fully submersible and it does not store any appreciable volume of combustive gas. Once the gas is produced in the cell, it is expelled into the combustion chamber through a one-way check valve. Any gas leakage that may occur during the process will simply leak into the water column and bubble to the surface. Thus, use of this system circumvents any need to transport or store hazardous gas on board a ship.

Ignition System

The ignition system serves the purpose of sparking the aforementioned igniters to initiate the combustion process. For this experiment, the ignition system was comprised of electronics mounted in a submersible oil-filled pressure vessel. The primary electronic components in the system are a high voltage capacitor and a spark gap trigger. In order to operate the system, the capacitor is charged to the desire voltage (generally 20 kVolts) and discharged through the spark gap trigger and the igniters upon users command. The high voltage discharge creates a spark inside the combustion chamber, which initiates the combustion process and the resultant bubble activity.
**Sensors**

The CSS Towbody is also equipped with several sensors to monitor the device while in use. The sensors include a depth sensor, submersible video camera, and a reference hydrophone. The submersible video camera is positioned below the combustion chamber, which allows users to visually monitor the gas level inside the chamber. The camera proves quite useful when venting and filling the combustion chamber. The hydrophone can be towed behind the towbody and provides users with an acoustic reference signal near 1 meter from the source. Each sensor is powered through the electro-mechanical tow cable and can be monitored in real time.

**Description of Test**

The experiment was set up to test the stability of the device when towed at various speeds, test the full functionality and robustness of the device, and measure the acoustic output of events while in tow. The experiment was conducted in three phases and completed over a four day testing period. Phase I investigated the stability of the towbody without firing any combustion events. This phase determined any need for trimming (fin adjustment) and ballasting (weights or floats) of the towbody to ensure a horizontal ride with minimal changes in pitch and roll throughout the tow. Phase II investigated the robustness of all mechanical hardware during the combustion events. All events in Phase II were conducted during a stationary deployment, thus no towing was required in this phase. Phase III investigated the robustness and acoustic output of the towbody when firing events while in tow. This phase tested the full functionality of the CSS towbody.

**Phase I**

Phase I investigated the stability of the towbody by monitoring the pitch and roll of the device at tow speeds ranging from 2 to 5 knots for several fin configurations. This phase was purely a tow test, so no combustion events were fired in this phase. In order to monitor the stability and angles of rotation of the towbody a submersible tilt sensor measured the pitch and roll of the towbody at each speed. Each test began with the slowest speed and worked up to the faster speeds. Data was captured and analyzed in real time to ensure that subsequent tow speeds could safely be achieved.

This phase of testing required the use of Lake Glendora’s “Translator” (a double pontoon mobile barge with a large opening in the middle), a stationary barge containing a crane and winch, and an outboard motorboat to push the “Translator”. The general operating procedure was as follows: First the CSS towbody was lowered through the center of the “Translator” by the winch on the stationary barge to a specified depth. The towbody was then removed from the winch and attached to a masterlink on the “Translator”, such that the towbody would hang in the water column. The “Translator” was then moved away from the stationary barge, and it was pushed across the lake by a motorboat at a specified speed. During the tow, users monitored the tilt sensor data to determine the stability and angles of rotation of the towbody. This process was then repeated for multiple fin configurations to allow users the opportunity to gather data for multiple tow conditions.

**Phase II**

Phase II investigated the robustness of all components contained within the towbody system during the combustion events. All testing in this phase occurred during stationary deployments, thus no towing was necessary. This phase tested the functionality of the system without being towed, including the gas delivery system and the ignition system, at a range of depths in the water column.

The general operating procedure for Phase II proceeded as follows: The towbody was lowered to the desired depth by a crane and winch on a stationary barge. Once at depth, users turned on the gas delivery system, which filled the combustion chamber with hydrogen and oxygen gas. After the chamber was filled with the combustive gas mixture, a capacitor in the ignition system was charged. Users then verified that all surrounding personnel were ready for the combustion event to occur. Upon verification, the gas was ignited and the combustion event ensued. This process was repeated at a range of depths. Hydrophones were not used in this phase, but an underwater camera was used to visually monitor the submersed system throughout testing.
Phase III

Phase III combined the processes of Phases I and II in order to test the full functionality of the CSS towbody while in tow. This phase had the same operating procedure as Phase I in terms of deployment, retrieval, and towing the system. However, in addition to monitoring the tilt sensor users followed the operating procedures of Phase II during the tow. A five channel, vertical hydrophone array was utilized in this phase to monitor the acoustic output of the combustion events while in tow.

Test Results

Six different tow configurations were tested in Phase I of the experiment. All of the tow configurations tested contained 250 lbs. of ballast weight in the nose of the tow body without any use of ballast floats. Each configuration can be differentiated by the adjustment angle of the horizontal tail fins and the use (or absence) of the vertical fin extender. The six tow configurations tested in this experiment are described as follows: (1) no vertical fin extension, 0° horizontal fin adjustment; (2) no vertical fin extension, 20° horizontal fin adjustment; (3) no vertical fin extension, 30° horizontal fin adjustment; (4) with vertical fin extension, 20° horizontal fin adjustment; (5) with vertical fin extension, 25° horizontal fin adjustment; and (6) with vertical fin extension, 30° horizontal fin adjustment.

Although pitch and roll were found to change as a function of speed, each of the configurations were found to be quite stable for any maintained speed, up to 5 knots. Figure 2 shows an example case from a 2 knot tow, whereby the pitch and roll angles remain relatively stable. Here it is seen that pitch and roll angles do fluctuate during the tow, but these fluctuations are within ±1° of the mean value observed over the 200 second tow. Fluctuations of pitch and roll angles remained on this order of magnitude throughout the test for each tow configuration at any single maintained speed. (i.e. The towbody never violently shook or underwent gross movements.) However, this is not to say that the pitch and roll angle did not change as a function of tow speed or from one tow configuration to the next. Tables 1 and 2, respectively, give the mean values of the pitch and roll angles recorded for each tow configuration at tow speeds ranging from 2 to 5 knots. Here it is seen that the pitch angle of the horizontal fins and use of the extended vertical fin both affect how the towbody ride while in tow.

![Figure 2](image-url)  
*Figure 2.* Pitch and roll angles recorded for a constant 2 knot tow during the 2012 Lake Glendora experiment.
As described in the previous section, the acoustic signature of CSS events fired while in tow were recorded on a five channel array. These events contained approximately 60 STP liters and were fired at a depth of approximately 10 meters. The five hydrophone elements were evenly spaced in 2 meter increments between 6 and 14 meters. Figure 3 shows the time series and spectra produced by an event recorded on the center channel of the hydrophone array (the element at 10 meters) along with a CSS event fired from a stationary platform. Due to the position of the CSS and hydrophone array, all the acoustic data presented in this report contains multi-path signals from the direct and reflected paths.

### TABLE 1. Mean values of pitch angle (degrees) observed for each tow configuration at tow speeds ranging from 2 to 5 knots.

<table>
<thead>
<tr>
<th>Speed (knots)</th>
<th>No Ext Fin 0° Horz Fin</th>
<th>No Ext Fin 20° Horz Fin</th>
<th>No Ext Fin 30° Horz Fin</th>
<th>With Ext Fin 30° Horz Fin</th>
<th>With Ext Fin 20° Horz Fin</th>
<th>With Ext Fin 25° Horz Fin</th>
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<td></td>
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<td>13°</td>
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</tbody>
</table>

### TABLE 2. Mean values of roll angle (degrees) observed for each tow configuration at tow speeds ranging from 2 to 5 knots.

<table>
<thead>
<tr>
<th>Speed (knots)</th>
<th>No Ext Fin 0° Horz Fin</th>
<th>No Ext Fin 20° Horz Fin</th>
<th>No Ext Fin 30° Horz Fin</th>
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### Apparatus Robustness

The objectives of the experiment were to investigate how the device towed, record the acoustic output, and determine the robustness of all associated hardware throughout operation. In order for the CSS Towbody to be a viable towed body source, it must be capable of withstanding the rigors of usage over prolonged periods of time. This section addresses the robustness of the device and describes how the main components performed during testing.

The CSS Towbody proved to be quite robust throughout testing in Phase I. During this phase the device was towed over 50 times in various configurations and speeds up to 5 knots. This phase also required that the device be surfaced and submerged many times between tows. The device was inspected upon each surfacing, and none of the components were found to be compromised during Phase I.

Phase II of testing began to show some areas of concern that must be addressed in future versions of the device. The primary area of concern that became apparent during Phase II was the underwater shock isolators used to mount the combustion chamber within the towbody skeleton. The shock isolators were found to extend and compress far beyond their rated limit until they begin to yield and tear apart, which caused the combustion chamber to collide with the inner skeletal frame of the towbody. The failure of these isolators lead to damage of the combustion chamber mounting plate, combustion chamber mounting braces, and the skeletal ribs of the towbody. Furthermore, all bolted connections related to mounting the combustion chamber to the towbody frame were found to be loosened after only a small number of CSS events.
Although there were signs of damage found in Phase II of testing, the overall functionality of the CSS Towbody remained intact. The other components within the towbody remained operational and did not show signs of damage. Furthermore, previously troublesome components such as the igniters (spark plugs designed by ARL) that have been found to break in previous designs were found to withstand the rigors of this test. Thus, at the end of Phase II the CSS Towbody was noticeably damaged but still operable.

![Diagram of CSS event comparison](image)

**Figure 3.** Comparison of CSS event fired from stationary platform (150 STP liters) to CSS event fired while in tow at 2 knots during 2012 Lake Glendora experiment (60 STP liters).

The shock isolators and associated hardware continued to show signs of severe stress and damage during testing in Phase III; however, it was a failure in the combustion chamber that ultimately led to the end of the experiment. A hole was blown through a weld near the apex of the combustion chamber, which compromised the chamber such that it could not contain gas while submerged. Due to the fact that the combustion chamber could not contain the gas and there were no spare combustion chambers, the test was ended after this event. Upon later inspection of the weld area, it was determined that some slag or flux had contaminated the weld, which prevented a full penetration weld during fabrication. This weak spot in the weld led to a failure in the combustion chamber, and ultimately ended the experiment.
Conclusions

The results of the 2012 Lake Glendora experiment highlighted some areas of success and some areas that need to be improved in the CSS Towbody. The device was successful in firing events while in tow, but components such as the shock isolators must be further investigated to ensure long term success. Another highlight of the test was that many new components added to the system turned out to be quite successful, including the towbody shell and the submersible gas delivery system. This section concludes this report by commenting on successful components of the device and by making recommendations for some of the areas of concern.

Phase I of testing showed that the CSS Towbody can be stably towed at speeds up to 5 knots. Use of the vertical fin extender is recommended as it consistently reduced the roll angle during tows, especially near 5 knots. Phase II showed that more work was needed to improve how the combustion chamber is mounted in the towbody. Potential solutions could include hanging the combustion chamber from straps, using a smaller combustion chamber, or adding heavy duty compliant bumpers between the combustion chamber and the towbody skeleton. Phase III proved that the CSS can successfully fire events while in tow, but it also pointed out that the combustion chamber must be sufficiently welded and inspected before rigorous testing. It is recommended that the steel combustion chamber be welded to AWS (American Welding Society) structural welding code D1.1 and that the welds, especially near the apex of the chamber, are inspected to ensure a full penetration weld.

REFERENCES