Underwater and in-air sounds from a small hovercraft

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I. INTRODUCTION

Northstar Island is an artificial gravel island built for oil production by BP Exploration (Alaska) in nearshore waters of the Alaskan Beaufort Sea. Most of the sound emanating from the island operation is not produced on the island itself, which is relatively quiet, but by the vessels connected to the Northstar operation (Blackwell and Greene, submitted). The predominant sound sources are crew boats in particular, but also tugs, self-propelled barges, oil spill response vessels, and the vessel from which the hovercraft measurements were made. Vessel sounds are of concern because of potential disturbance to marine mammals (Richardson *et al.*, 1995), especially bowhead whales.

During the summer of 2003, BP tested a relatively small, diesel-powered hovercraft to ferry crew and supplie between the mainland and Northstar Island. Along with other advantages, it was anticipated that the hovercraft would produce less underwater sound than the crew boat.

The main objectives of this study are to characterize the sounds of this hovercraft in water and air by determining received levels, spectral characteristics, and transmission loss through both media, and to compare the findings with sounds from conventional vessels of approximately the same size.

II. METHODS

Underwater and airborne recordings were obtained on 8 August 2003 near Prudhoe Bay (Beaufort Sea), Alaska. The recording site was between the mainland and Northstar Island at a location 5.2 km north of the crew boat dock at West Dock. The recording vessel's position was 70° 26.48′ N, 148° 34.28′ W, and water depth was 7.3 m.

A. Acoustic equipment

The omnidirectional sensors included two hydrophones and a microphone, all calibrated. The hydrophones were model 6050C by International Transducer Corporation (ITC) and included a low-noise preamplifier next to the sensor and a 30-m cable. The hydrophone cables were attached with cable ties to a fairing to minimize strumming. Prior to recording, the hydrophone signals were amplified with an adjustable-gain postamplifier. The omnidirectional microphone was a G.R.A.S. Sound and Vibration $\frac{1}{2}$-in. prepolarized free field microphone model 40AE with an ICP preamplifier model TMS426C01 and a windscreen. Prior to recording, the microphone signals were amplified with an adjustable-gain postamplifier.

Hydrophone and microphone signals were recorded simultaneously on three channels of a SONY model PC208Ax instrumentation-quality digital audiotape (DAT) recorder. The sampling rate was 24 kHz, providing a frequency response that was nearly flat from <4 to 10 000 Hz on all channels. Both types of sensors were calibrated from 4 to 20 000 Hz. Quantization was 16 bits, providing a dynamic range of >80 dB between an overloaded signal and the instrumentation noise. A memo channel on the tape recorder was used for voice announcements, and the date and time were recorded automatically.

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Recordings were obtained using the Alaska Clean Seas (ACS) vessel *Mikkelsen Bay* of length 12.8 m as a recording platform. After selecting a recording location that satisfied our acoustic needs as well as logistical and safety concerns, the *Mikkelsen Bay* was anchored, all engines and sound-generating devices were shut down, and the hydrophone string was lowered into the water with the two hydrophones at depths of 1 and 7 m. A microphone was positioned on the deck of the vessel, ~2 m above water level, with an unob-

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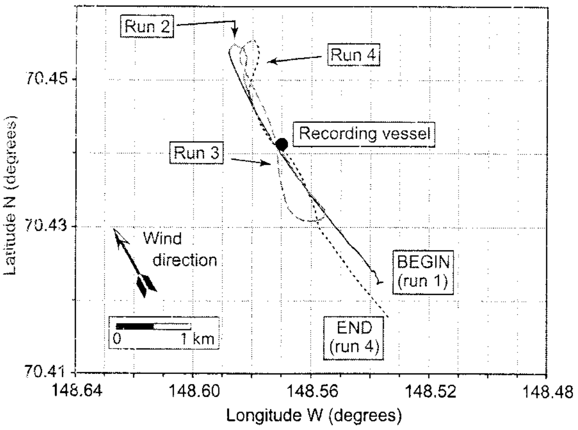

FIG. 1. Track of the hovercraft during its four passes near the recording vessel, shown as a filled circle. During the recordings the hovercraft was traveling on the same path as the wind, which was from the south-southeast.

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The hovercraft, shown in Fig. 2, was a Griffon 2000TD (length 11.9 m, width 4.8 m), capable of carrying 20 passengers at high speeds over a variety of surfaces. Its top speed with full payload was said to be 35 knots (18 m/s) in ideal conditions, i.e., calm water, no wind, and 15 °C ambient temperature. It was both lifted and propelled by a single Deutz air-cooled 355 hp (265 kW) diesel engine (BF8L513LC), running at a maximum speed of 2100 rpm. The 12-bladed lift fan turned at a maximum of 2100 rpm, as it was coupled directly to the engine; its blade rate was therefore 420 Hz. The thrust propeller had 4 blades with variable

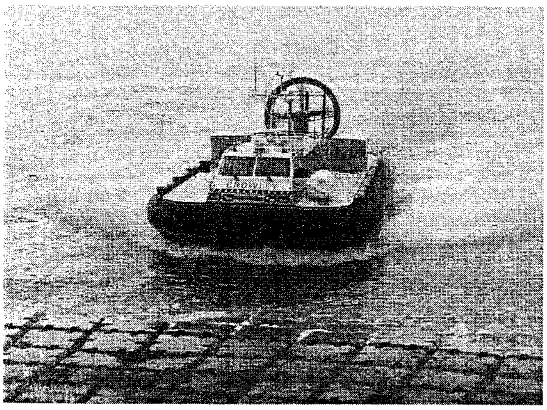

FIG. 2. Griffon 2000TD hovercraft landing on the slope protection mat at Northstar Island's southeastern shore.

pitch. The pulley ratio between engine and propeller was 1.52 (70 to 46) so at an engine rpm of 2100 the propeller rpm was 1380 and the blade rate was 92 Hz. According to the manufacturer's specifications, maximum recommended wind speed for normal operations was 30 knots or 15 m/s (Force 7 Beaufort), and maximum recommended wave height was 1 m.

C. Signal analysis

1. Underwater sounds

The recorded, digitized hydrophone signals were transferred as time series to a computer hard drive for processing. They were then equalized and calibrated in units of sound-pressure with flat frequency response over the data bandwidth (10–10 000 Hz). Analysis was done using MATLAB (The MathWorks, Natick, MA) routines and custom programs for analysis of both transient and continuous signals. For each recording, a sound-pressure time series (waveform) was inspected to help select samples for further analysis.

To assess variability in broadband levels during a fly-by of the hovercraft, acoustic recordings were partitioned into overlapping segments of length 0.25 s. Computing the mean square pressure of each segment yielded the broadband sound pressure level (SPL) for that segment. Each analysis segment was shifted in time by 0.1 s from the previous segment. This process produced a time series representing the fluctuation in broadband SPLs during the hovercraft's very rapid passage in front of the recording vessel.

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Spectral composition was examined by calculating the sound-pressure spectral density by Fourier analysis, using the Blackman-Harris minimum three-term window (Harris, 1978). A signal section of length 1.5 s was selected at the maximum broadband value on each run, i.e., at or near the CPA. Two 1-s segments overlapped by 50% were analyzed. This resulted in 1-Hz bin separation and 1.7-Hz bin resolution. One-third-octave band levels were derived from the narrow-band spectral densities by summing the mean square pressures in all frequency cells between the lower and upper frequency limits for the one-third-octave band in question. Proportional amounts were taken from the end cells as appropriate.

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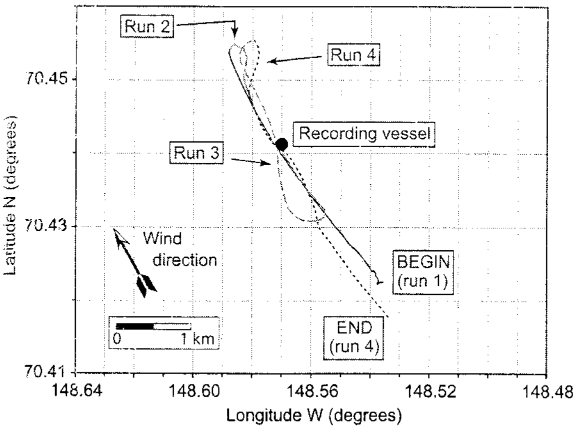

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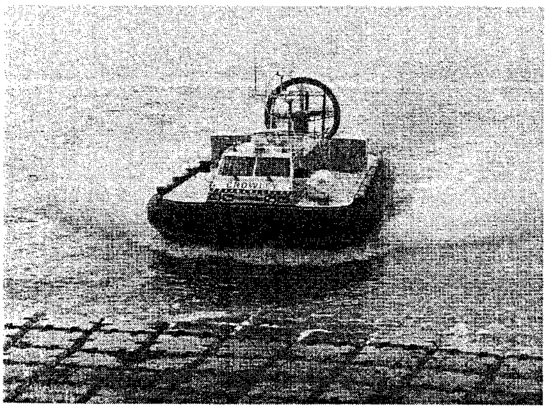

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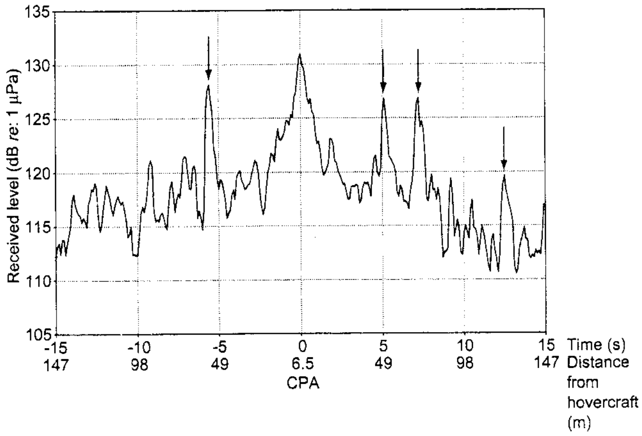


FIG. 3. Broadband (10–10 000 Hz) sound pressure time series for the deep hydrophone during run 4. The x axis shows time, centered on the closest point of approach (CPA), and the corresponding distance from the hovercraft, calculated using the vessel's mean speed during that particular run. Arrows indicate spikes in the sound pressure time series that were caused by waves slapping the recording vessel's hull.

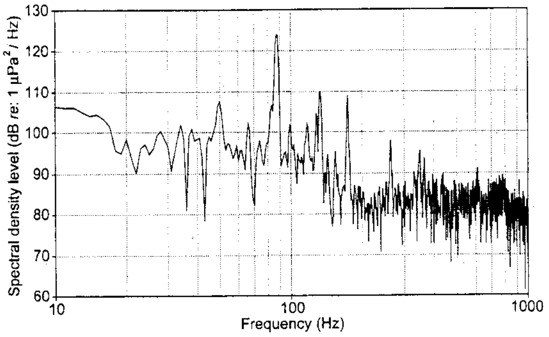


FIG. 4. Sound-pressure density spectrum (10–1000 Hz) for a 1.5-s sample recorded by the deep hydrophone and centered on the maximum broadband value for run 3.

We fitted a simple propagation model to broadband levels received by the microphone in order to develop equations that characterize propagation loss in air:

$$\mathbf{RL}(\text{received level}) = A - B \log(R). \tag{1}$$

In this equation, R is the range in m and the unit for **RL** is dB *re*: 20 μPa. The constant term A is the hypothetical extrapolated level at distance 1 m based on far-field measurements; B is the spreading loss. When applying the model to the data, recordings were included at increasing distances from the sound source until the point at which levels reached a minimum and remained constant (within $\sim\pm 2$ dB). This model is not ideal in that it ignores aspect dependence that is confounded with range dependence. Propagation loss modeling was inappropriate for the underwater data because the signal at all but the closest few meters was too close to background levels.

III. RESULTS

The hovercraft measurements were made during a short window of acceptable weather conditions on 8 August 2003. Wind was from the south-southeast, 5.1 m/s (10 knots) on average with peaks at 5.7 m/s (11 knots), temperature was 5.6 °C, and sea state was 1–2. The hovercraft runs were roughly NNW-SSE, i.e., either with or against the wind (see Fig. 1). The hovercraft was run at or near full throttle on all passes, but sea conditions kept its speed well below the theoretical maximum (35 knots). For runs 1–4, mean travel speed calculated from GPS positions, using straight stretches of the tracks centered on the closest point of approach (CPA) to the recording vessel, were as follows: 11.8 m/s (22.9 knots), 9.9 m/s (19.2 knots), 11.9 m/s (23.1 knots), and 9.8 m/s (19.0 knots), respectively. Runs 1 and 3 were downwind; runs 2 and 4 were upwind.

A. Underwater sounds

Figure 3 shows the broadband (10–10 000 Hz) SPL time series for the deep hydrophone during the fourth pass. Note that sound radiating from the hovercraft is likely to be directional, so that sound levels will vary both as a function of distance and of the aspect of the craft to the receiver. The latter variable was not taken into account in these measurements. Maximum SPLs were 122.5–130.9 dB *re*: 1 μPa for the four passes. The spikes before and after the CPA (indicated by arrows in Fig. 3) are caused by waves slapping on the vessel's hull. The shallow hydrophone data were more contaminated by wave noise than the deep hydrophone data, and the fourth pass did not yield any useable data. Maximum SPLs for the shallow hydrophone were 130.0–132.8 dB *re*: 1 μPa, on average 7.4 dB higher than the deep hydrophone values for the three runs for which both sets of data were available. Background levels on the deep hydrophone (computed over 30-s samples), obtained while the hovercraft was >1 km from the recording vessel or before the hovercraft was on location, were in the range 114–119 dB *re*: 1 μPa.

Sound spectral density levels are plotted in Fig. 4 to examine the tones (narrow spectral peaks) produced by the hovercraft during a fly-by. The largest peak was centered at ~87 Hz, with smaller peaks at harmonics thereof, i.e., 173.5, 260, 346, and 432.5 Hz (Fig. 4). A comparison of spectral lines from different samples during the fly-by showed the expected amount of Doppler shift between approach and retreat.

The thrust propeller was expected to produce sound with a fundamental frequency near 92 Hz. This is based on the nominal 2100 rpm engine rotation rate at full power, the pulley ratio of 1.52 (resulting in a propeller shaft rate of 1382 rpm), and the presence of 4 blades on the propeller [(1382 rpm × 4 blades)/60 = 92 Hz]. The occurrence in the spectra of a strong narrow-band component centered between 86 and 87 Hz, but no strong component centered at 92 Hz, suggests that the actual engine and propeller rotation rates were slightly less (by ~5.5%) than the nominal full-power values. These rotation rates are consistent with the lower speed appropriate to the sea conditions. The presence of narrow-band components centered at 173.5, 260, 346, and 432.5 Hz, which are very close to multiples of 86.5 Hz, strongly suggests that the component near 87 Hz was the fundamental frequency associated with the thrust propeller.

Both the lift fan and the thrust propeller were likely generators of airborne sound, but we expected sounds from the lift fan to be easier to detect on underwater recordings.

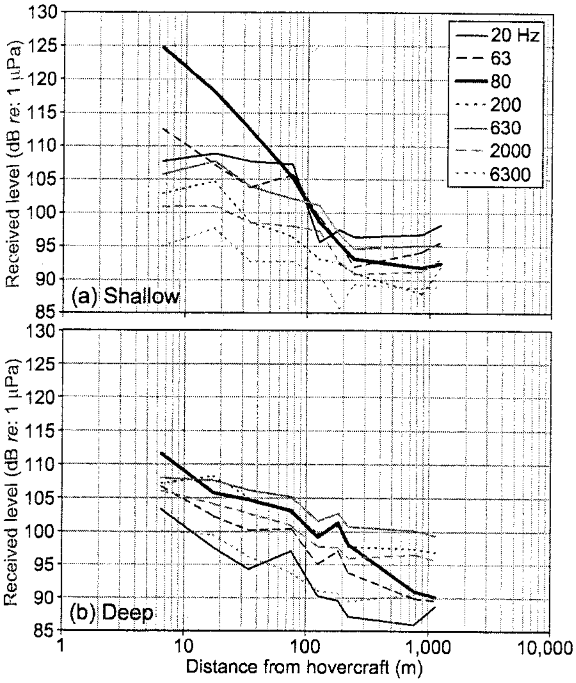


FIG. 5. Mean received levels as a function of mean distance from the hovercraft for seven selected one-third-octave bands and both hydrophones. (a) Shallow hydrophone. (b) Deep hydrophone. The indicated frequencies correspond to the bands' center frequencies.

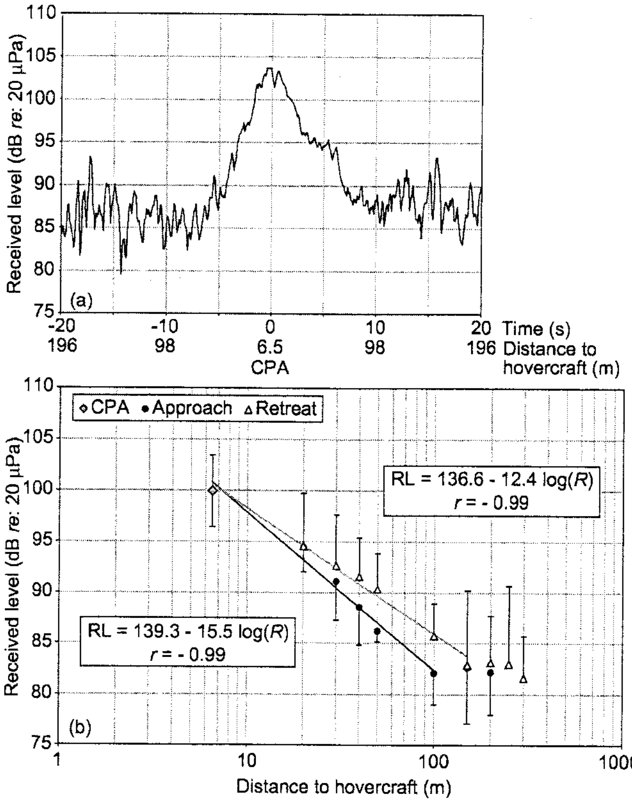


FIG. 6. (a) Broadband (10–10 000 Hz) sound pressure time series for the microphone during run 4. The x axis shows time, centered on the closest point of approach (CPA), and the corresponding distance from the hovercraft, calculated using the vessel's mean speed during that particular run. (b) Mean received broadband (10–10 000 Hz) levels in air ($\pm$ one s.d.) for the hovercraft's approach (filled circles), CPA (gray diamond), and retreat (empty triangles), as a function of distance. The logarithmic spreading loss model (R in m) was applied to both data sets.

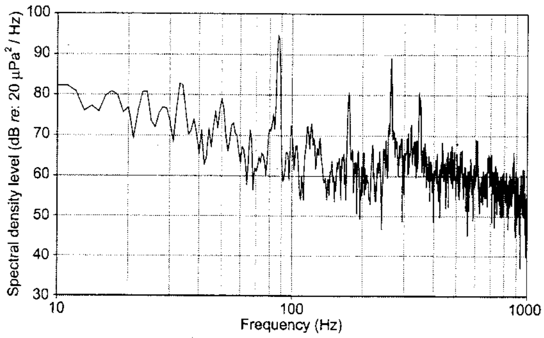
The lift fan was positioned under the hovercraft, close to the water, whereas the thrust propeller was upright on the stern deck (Fig. 2). However, contrary to expectation, lift fan components (i.e., 420 Hz blade rate $-5.5\% = \sim 397$ Hz) were present but small in the underwater sound, even at the CPA.

Figure 5 shows levels of underwater sound for seven selected one-third-octave bands versus distance from the hovercraft for the two hydrophone depths. The one-third-octave band centered at 80 Hz is dominant at close distances on the shallow hydrophone. Levels for this band reach background values much faster on the shallow than on the deep hydrophone, which is what we would expect for an airborne sound source. Another difference in the sounds at the two depths involved the relative levels in the one-third-octave bands centered at 20 and 63 Hz: they contained some of the highest received levels at the shallow depth, but some of the lowest levels at the deeper depth.

B. Airborne sounds

Figure 6(a) shows the broadband (10–10 000 Hz) SPL time series for the microphone during the fourth pass. Maximum SPLs were 97–104 dB *re*: 20 μPa for the four passes (maximum A-weighted levels were 85–97 dBA *re*: 20 μPa). Broadband (10–10 000 Hz) levels of airborne sound as a function of distance from the hovercraft are shown in Fig. 6(b). The logarithmic sound propagation model represented by Eq. (1) was fitted separately to data from the hovercraft's approach and retreat. Spreading loss terms were 15.5 and 12.4 dB/tenfold change in distance, respectively. The effects of aspect and range dependence were confounded in the measurement geometry. This probably accounts for the deviations from expected spherical spreading (20 dB/tenfold change in distance), although other possible causes include atmospheric refraction and near-field effects. The spreading loss coefficient was smaller for the vessel's retreat in all four passes. Background in-air values were in the range 74–80 dB *re*: 20 μPa.

Sound spectral density levels are plotted in Fig. 7 to examine the tones or frequency peaks produced by the hovercraft in air during a fly-by. As seen in the underwater data the spectrum included a large peak at 87 Hz. In addition eight harmonics of this fundamental frequency were found up to ~870 Hz.



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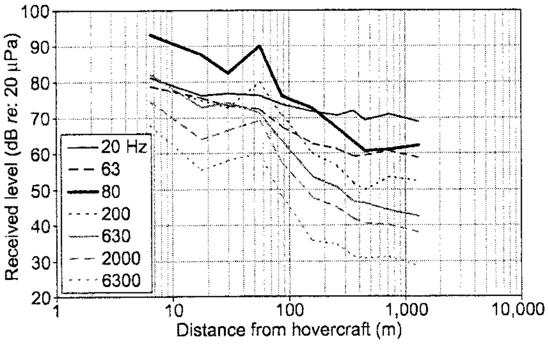

FIG. 8. Mean received levels of airborne sound as a function of mean distance from the hovercraft for seven selected one-third-octave bands. The indicated frequencies correspond to the bands' center frequencies.

The location of the thrust propeller on the stern deck of the hovercraft, in full view of the recording vessel, made it likely that tones produced by this propeller would be identified on the recordings. If we assume that the hovercraft was running somewhat below full power (see Sec. III A), then the peak centered at ~87 Hz very likely represents the thrust propeller's blade rate. Richards and Mead (1968) name the propeller rotational noise (at 80–800 Hz) as the major source of sound from a hovercraft.

Figure 8 shows that the one-third-octave band containing the thrust propeller's blade rate is dominant at close distances. Received one-third-octave levels of airborne sound generally decreased with distance at a higher rate for higher than for lower frequencies. For example, between the CPA (6.5 m) and 1310 m, received levels dropped by 12 dB for the band centered at 20 Hz, and by 39 dB for the band centered at 6300 Hz.

IV. DISCUSSION

The purpose of this paper is to present underwater and in-air sound measurement results for a small hovercraft in use for crew transfer to and from an island-based oil production facility. It might have been desirable to perform a physical acoustics study of the sources of sound on the hovercraft, including the directional effects, but such a study was well beyond the scope of the project. Good reviews of propeller and propfan noise are in Chap. 1 of Hubbard (1995) or Chaps. 9 and 10 in Richards and Mead (1968). These references do not include considerations of underwater sounds.

A. Underwater sounds

Few measurements of underwater sounds from hovercraft have been reported previously, and the limited existing data concern larger hovercraft. Slaney (1975) recorded the sounds from a Bell Voyageur hovercraft; in that study the hydrophone was at 1.8-m depth. The Bell Voyageur was a much larger hovercraft than the Griffon 2000TD used in this study: 20 m long, 11.2 m wide, and with a 23 720 kg payload, as compared to 11.9 m, 4.8 m, and 2268 kg for the Griffon 2000TD. The Bell Voyageur was powered by two marine gas turbines (2 × 1300 hp continuous) that drove two centrifugal lift fans and two propellers. At a horizontal distance of 46 m, received levels in one-third-octave bands centered at 80–630 Hz were ~110 dB *re*: 1 μPa. In our data set, the corresponding values were 97–105 dB (at a hydrophone depth of 1 m). Slaney (1975) also reported a 50–2000 Hz band level of 121 dB *re*: 1 μPa (also at a distance of 46 m), compared to ~111 dB in our data set for the same frequency range.

In another study, Brown (1988) reported broadband (22.5–22 500 Hz) levels of underwater sound generated by an AP.1-88 Hovercraft. Recordings were made with a hydrophone on the bottom in water 6–7 m deep. However, this hovercraft was also considerably larger than the Griffon 2000TD: 25 m long, 10.5 m wide, 7260 kg payload, powered by four diesel engines (two propulsion and two lift engines, at 2 × 500 and 2 × 390 hp continuous, respectively) driving six pairs of lift fans and two propellers. Maximum SPLs, as recorded on the bottom, were 122–126 dB and 117–119 dB *re*: 1 μPa at CPAs of 15 and 30 m, respectively. Brown (1988) presented one-third-octave band data from which we calculated a maximum level of 124 dB *re*: 1 μPa at a distance of 15 m for the 25–8000 Hz band. For that distance and frequency range (with hydrophone depth 7 m), our measured value is 122 dB *re*: 1 μPa, i.e., slightly lower.

In view of the differences in size and engine power between the hovercraft in this study and those studied by Slaney (1975) and Brown (1988), the lower received levels for the Griffon 2000TD are expected. However, large differences would not be expected, as (other factors being equal) a halving of power output would only result in a 3-dB drop in SPL. Similarly, dividing the power output by 5 would result in a 7-dB drop in SPL. If we limit our analysis to the propulsion (thrust) engine horse power, the differences between the vessels seem reasonable: the Bell Voyageur had 7.3 times the Griffon's hp and a 10 dB higher broadband level. The AP.1-88 had 2.8 times the Griffon's hp and a 2.5 dB higher broadband level.

The Griffon 2000TD hovercraft included three interlinked rotating components that might be expected to produce tonal sounds at particular frequencies: the vessel's diesel engine, the 12-bladed lift fan located under the vessel, close to the water, and a 4-bladed thrust propeller positioned vertically on the aft deck. When the hovercraft ran at full power, these sources were all in air. Therefore, we expected SPLs recorded by the shallower hydrophone (depth 1 m) during the fly-bys to be higher than those recorded by the deeper hydrophone (depth 7 m). This turned out to be true at the CPA where the difference was over 7 dB, indicating a rapid loss with depth. The experimental conditions (i.e., sea state) were such that the sounds produced by the hovercraft did not exceed ambient levels by a sufficient amount and duration to model transmission loss usefully.

Compared to the deep hydrophone, the shallow hydrophone recorded higher levels for the one-third-octave band centered at 20 Hz (Fig. 5). This is accounted for by the low-frequency cutoff caused by the shallow water at the recording site (Richardson *et al.*, 1995). The fact that the hovercraft is a sound source in air, where the low-frequency cutoff phenomenon does not apply, explains the presence of a range dependency at such a low frequency.

The distance at which broadband levels reached background values can be estimated by examining one-third-octave band levels (Fig. 5). For the shallow hydrophone [Fig 5(a)] levels for five out of seven bands shown did not decrease beyond 300 m. The exceptions were the bands centered at 80 and 200 Hz. For the deep hydrophone [Fig. 5(b)] the exceptions were the bands centered at 63 and 80 Hz. These exceptions had or were close to having reached their lowest value by a distance of 1 km. Consequently, for the particular set of sea state and water depth found during our recordings, we estimate that underwater sound levels had returned to background values by ~1 km fore and aft of a Griffon 2000TD hovercraft cruising by at full power.

The hovercraft recorded in this study was used as an alternative to conventional crew boats (length 19 m) at Northstar Island. Therefore, we compared levels of underwater sound produced by the hovercraft with conventional propeller-driven crafts of similar sizes. We have no close-up recordings of the Northstar crew boat, but unpublished measurements showed broadband (10–10 000 Hz) levels of 121 dB *re*: 1 μPa at a distance of 1820 m during cruising. A $15\log(R)$ propagation loss [which has been measured for this area, see Blackwell and Greene (submitted)] brings this value to 130.9 dB (the maximum hovercraft value at 6.5 m for the deep hydrophone) at a distance of ~400 m. Greene (1985) reported source levels of 156 dB *re*: 1 μPa-m for the 90-Hz tone of a 16-m crew boat. Buck and Chalfant (1972) reported source levels of 166 dB *re*: 1 μPa-m for a 37-Hz tone produced by a 25-m tug pulling an empty barge. In the two latter studies the broadband levels can only be higher than the values reported here. Thus, despite the paucity of comparable underwater measurements it is clear that conventional vessels of approximately the same size as the Griffon 2000TD hovercraft have higher source levels than the hovercraft. More importantly, because the hovercraft sound source is in air, it does not propagate well horizontally through the water. Consequently the amount of time that the two types of craft will be audible underwater while passing by a stationary underwater listener is on the order of 20–60 times longer for a conventional propeller-driven vessel.

Blackwell *et al.* (2004) also monitored underwater sounds from Northstar using an autonomous recorder located 550 m from the island. Broadband (10–500 Hz) sound levels were averaged for 1 min every 4.3 min. Whereas crew changes at the island by the crew boats raised broadband levels ~600 m away by ~15 dB, those by the hovercraft did not cause a noticeable change in broadband levels at that distance.

In conclusion, the Griffon 2000TD hovercraft was considerably quieter underwater than conventional vessels of comparable sizes. A hovercraft is therefore an attractive alternative when there is concern about the levels or the duration of vessel sounds produced underwater.

B. Airborne sounds

Maximum broadband values at the CPA were 97–104 dB *re*: 20 μPa or 85–97 dBA *re*: 20 μPa. For comparison, this corresponds to the sounds of a blender at the operator's position, or the cockpit of a light aircraft in the compilation of common airborne sounds by Kinsler *et al.* (2000). In one of the rare publications on hovercraft sounds in air, Lovesey (1972) reports maximum broadband SPLs for five types of hovercraft at a distance of 152 m during maneuvering in a terminal area. These were 94, 94, 95, 85, and 69 dBA for SRN2, SRN3, SRN5, SRN4, and VT1 hovercraft, respectively (the SRN2, 3, and 5 hovercraft were early models not optimized for reduced noise). The values for the SRN hovercraft are all higher than those recorded for the Griffon 2000TD, whereas the maximum value recorded for the VT1 is comparable. However, the hovercraft reported on by Lovesey (1972) were 3–80 times heavier than the Griffon 2000TD and had 2.5–38 times the horsepower. In addition, they were maneuvering, not flying by at full power as during our measurements. The Griffon 2000TD's specifications sheet states that the external noise level is less than 90 dBA at 150 ft (46 m). This statement is supported by our measurements (not shown).

The hovercraft's spectral composition in air was very similar to that underwater, with a peak at ~87 Hz accounted for by the thrust propeller's blade rate. Consequently, the one-third-octave bands centered at 80 Hz (and 160 Hz, not shown) showed marked increases, relative to neighboring bands, at all recorded distances. Slaney (1975) reported similar peaks in the one-third-octave bands centered at 100 and 200 Hz. Eight harmonics to the fundamental 87 Hz frequency were detected in the spectrum. In comparison, Wheeler and Donno (1966) detected up to 14 harmonics of this rotational noise on the SRN5 hovercraft.

Because all the hovercraft's sound sources (engine, lift fan, and propeller) were located in air during cruising, the craft was detectable in air out to distances exceeding the maximum distances where it would be detectable underwater. Mean broadband values in air reached a minimum and then remained constant at ~100 m and 150 m during approach and retreat, respectively [Fig. 6(b)]. However, there was a large amount of variation in background sound during the recording. In addition, many organisms are able to hear tones at levels below ambient—for example, the acoustics crew could clearly hear the hovercraft in air at distances of more than 400 m. Levels for three of the seven selected one-third-octave bands shown in Fig. 8 were still decreasing 1 km from the hovercraft, but only slightly. It is therefore reasonable to state that airborne broadband levels reached background values less than 2 km from the hovercraft for the conditions existing during our measurements.

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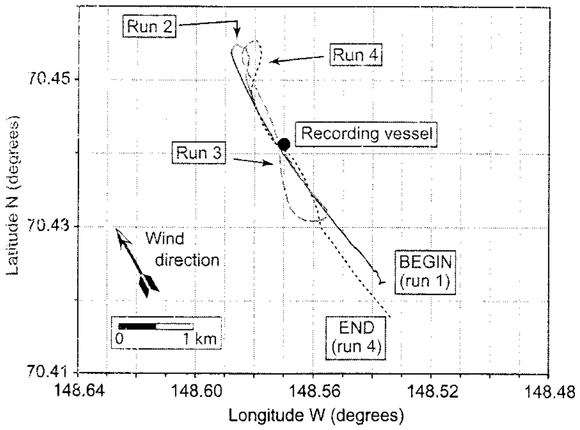

FIG. 1. Track of the hovercraft during its four passes near the recording vessel, shown as a filled circle. During the recordings the hovercraft was traveling on the same path as the wind, which was from the south-southeast.

structed path to the sound source at all times. The hovercraft was asked to drive by the recording vessel at full speed four different times, as shown in Fig. 1. A hand-held GPS (Garmin model 12XL), placed on the bridge of the hovercraft, logged its position every 5 s. During the nearby portion of the fly-by, the hovercraft's distance from the recording vessel was called out (and recorded) every few seconds by an observer on the *Mikkelsen Bay* using a laser rangefinder (Bushnell model # 20-0880). Wind speed, wind direction, and temperature were recorded over a period of 4 min with a Kestrel 2000 Pocket Thermo Wind meter (Nielsen Kellerman, Chester, PA 19013), and wave height (sea state) was estimated. A total of 27 min of boat-based recordings were obtained.

The hovercraft, shown in Fig. 2, was a Griffon 2000TD (length 11.9 m, width 4.8 m), capable of carrying 20 passengers at high speeds over a variety of surfaces. Its top speed with full payload was said to be 35 knots (18 m/s) in ideal conditions, i.e., calm water, no wind, and 15 °C ambient temperature. It was both lifted and propelled by a single Deutz air-cooled 355 hp (265 kW) diesel engine (BF8L513LC), running at a maximum speed of 2100 rpm. The 12-bladed lift fan turned at a maximum of 2100 rpm, as it was coupled directly to the engine; its blade rate was therefore 420 Hz. The thrust propeller had 4 blades with variable pitch. The pulley ratio between engine and propeller was 1.52 (70 to 46) so at an engine rpm of 2100 the propeller rpm was 1380 and the blade rate was 92 Hz. According to the manufacturer's specifications, maximum recommended wind speed for normal operations was 30 knots or 15 m/s (Force 7 Beaufort), and maximum recommended wave height was 1 m.

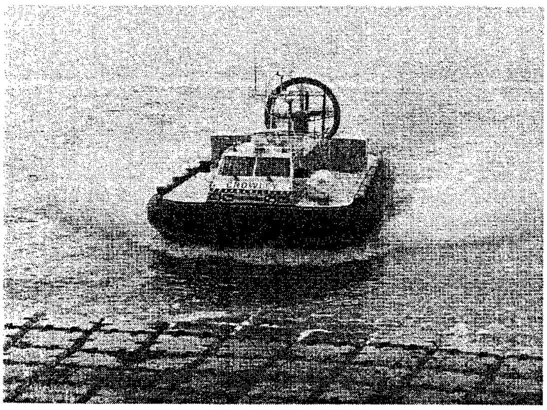

FIG. 2. Griffon 2000TD hovercraft landing on the slope protection mat at Northstar Island's southeastern shore.

C. Signal analysis

1. Underwater sounds

The recorded, digitized hydrophone signals were transferred as time series to a computer hard drive for processing. They were then equalized and calibrated in units of sound-pressure with flat frequency response over the data bandwidth (10–10 000 Hz). Analysis was done using MATLAB (The MathWorks, Natick, MA) routines and custom programs for analysis of both transient and continuous signals. For each recording, a sound-pressure time series (waveform) was inspected to help select samples for further analysis.

To assess variability in broadband levels during a fly-by of the hovercraft, acoustic recordings were partitioned into overlapping segments of length 0.25 s. Computing the mean square pressure of each segment yielded the broadband sound pressure level (SPL) for that segment. Each analysis segment was shifted in time by 0.1 s from the previous segment. This process produced a time series representing the fluctuation in broadband SPLs during the hovercraft's very rapid passage in front of the recording vessel.

Background levels (10–10 000 Hz) were obtained by computing the mean square pressure of 30-s segments, while the hovercraft was at least 1 km away or before the start of the experiment.

Spectral composition was examined by calculating the sound-pressure spectral density by Fourier analysis, using the Blackman-Harris minimum three-term window (Harris, 1978). A signal section of length 1.5 s was selected at the maximum broadband value on each run, i.e., at or near the CPA. Two 1-s segments overlapped by 50% were analyzed. This resulted in 1-Hz bin separation and 1.7-Hz bin resolution. One-third-octave band levels were derived from the narrow-band spectral densities by summing the mean square pressures in all frequency cells between the lower and upper frequency limits for the one-third-octave band in question. Proportional amounts were taken from the end cells as appropriate.

Distances from the hydrophones to the hovercraft were calculated based on a combination of GPS positions, rangefinder distances, and the travel speed of the hovercraft.

2. Airborne sounds

Microphone data were transcribed to disk files and analyzed in the same way as the hydrophone data. Microphone data were unweighted and are expressed in dB *re*: 20 μPa. To allow comparisons with published data for various sound sources, a few values were A-weighted and are expressed in dBA *re*: 20 μPa.

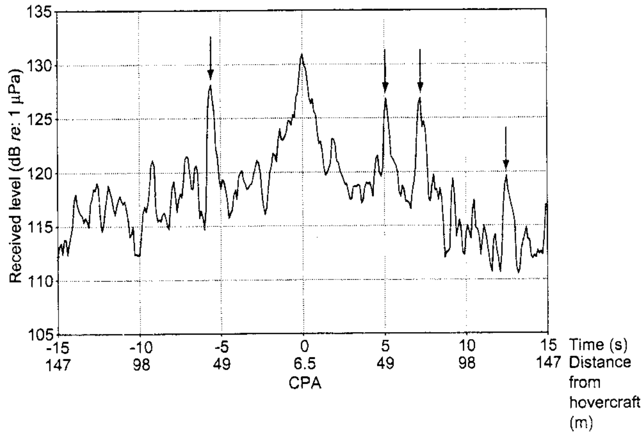

FIG. 3. Broadband (10–10 000 Hz) sound pressure time series for the deep hydrophone during run 4. The x axis shows time, centered on the closest point of approach (CPA), and the corresponding distance from the hovercraft, calculated using the vessel's mean speed during that particular run. Arrows indicate spikes in the sound pressure time series that were caused by waves slapping the recording vessel's hull.

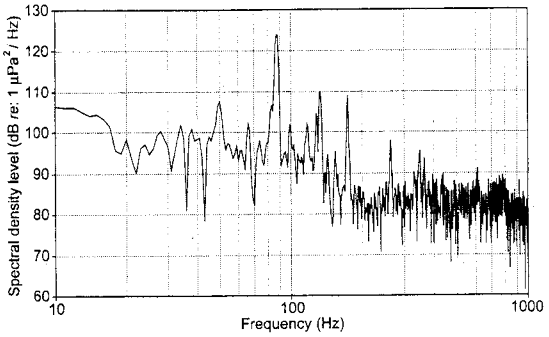

FIG. 4. Sound-pressure density spectrum (10–1000 Hz) for a 1.5-s sample recorded by the deep hydrophone and centered on the maximum broadband value for run 3.

We fitted a simple propagation model to broadband levels received by the microphone in order to develop equations that characterize propagation loss in air:

$$\mathbf{RL}(\text{received level}) = A - B\log(R). \tag{1}$$

In this equation, R is the range in m and the unit for **RL** is dB *re*: 20 μPa. The constant term A is the hypothetical extrapolated level at distance 1 m based on far-field measurements; B is the spreading loss. When applying the model to the data, recordings were included at increasing distances from the sound source until the point at which levels reached a minimum and remained constant (within $\sim\pm 2$ dB). This model is not ideal in that it ignores aspect dependence that is confounded with range dependence. Propagation loss modeling was inappropriate for the underwater data because the signal at all but the closest few meters was too close to background levels.

III. RESULTS

The hovercraft measurements were made during a short window of acceptable weather conditions on 8 August 2003. Wind was from the south-southeast, 5.1 m/s (10 knots) on average with peaks at 5.7 m/s (11 knots), temperature was 5.6 °C, and sea state was 1–2. The hovercraft runs were roughly NNW-SSE, i.e., either with or against the wind (see Fig. 1). The hovercraft was run at or near full throttle on all passes, but sea conditions kept its speed well below the theoretical maximum (35 knots). For runs 1–4, mean travel speed calculated from GPS positions, using straight stretches of the tracks centered on the closest point of approach (CPA) to the recording vessel, were as follows: 11.8 m/s (22.9 knots), 9.9 m/s (19.2 knots), 11.9 m/s (23.1 knots), and 9.8 m/s (19.0 knots), respectively. Runs 1 and 3 were downwind; runs 2 and 4 were upwind.

A. Underwater sounds

Figure 3 shows the broadband (10–10 000 Hz) SPL time series for the deep hydrophone during the fourth pass. Note that sound radiating from the hovercraft is likely to be directional, so that sound levels will vary both as a function of distance and of the aspect of the craft to the receiver. The latter variable was not taken into account in these measurements. Maximum SPLs were 122.5–130.9 dB *re*: 1 μPa for the four passes. The spikes before and after the CPA (indicated by arrows in Fig. 3) are caused by waves slapping on the vessel's hull. The shallow hydrophone data were more contaminated by wave noise than the deep hydrophone data, and the fourth pass did not yield any useable data. Maximum SPLs for the shallow hydrophone were 130.0–132.8 dB *re*: 1 μPa, on average 7.4 dB higher than the deep hydrophone values for the three runs for which both sets of data were available. Background levels on the deep hydrophone (computed over 30-s samples), obtained while the hovercraft was >1 km from the recording vessel or before the hovercraft was on location, were in the range 114–119 dB *re*: 1 μPa.

Sound spectral density levels are plotted in Fig. 4 to examine the tones (narrow spectral peaks) produced by the hovercraft during a fly-by. The largest peak was centered at ~87 Hz, with smaller peaks at harmonics thereof, i.e., 173.5, 260, 346, and 432.5 Hz (Fig. 4). A comparison of spectral lines from different samples during the fly-by showed the expected amount of Doppler shift between approach and retreat.

The thrust propeller was expected to produce sound with a fundamental frequency near 92 Hz. This is based on the nominal 2100 rpm engine rotation rate at full power, the pulley ratio of 1.52 (resulting in a propeller shaft rate of 1382 rpm), and the presence of 4 blades on the propeller [(1382 rpm × 4 blades)/60 = 92 Hz]. The occurrence in the spectra of a strong narrow-band component centered between 86 and 87 Hz, but no strong component centered at 92 Hz, suggests that the actual engine and propeller rotation rates were slightly less (by ~5.5%) than the nominal full-power values. These rotation rates are consistent with the lower speed appropriate to the sea conditions. The presence of narrow-band components centered at 173.5, 260, 346, and 432.5 Hz, which are very close to multiples of 86.5 Hz, strongly suggests that the component near 87 Hz was the fundamental frequency associated with the thrust propeller.

Both the lift fan and the thrust propeller were likely generators of airborne sound, but we expected sounds from the lift fan to be easier to detect on underwater recordings.

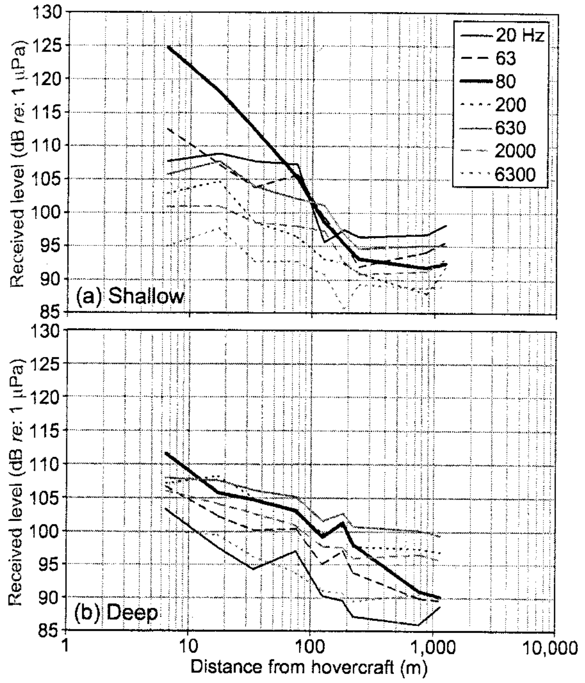

FIG. 5. Mean received levels as a function of mean distance from the hovercraft for seven selected one-third-octave bands and both hydrophones. (a) Shallow hydrophone. (b) Deep hydrophone. The indicated frequencies correspond to the bands' center frequencies.

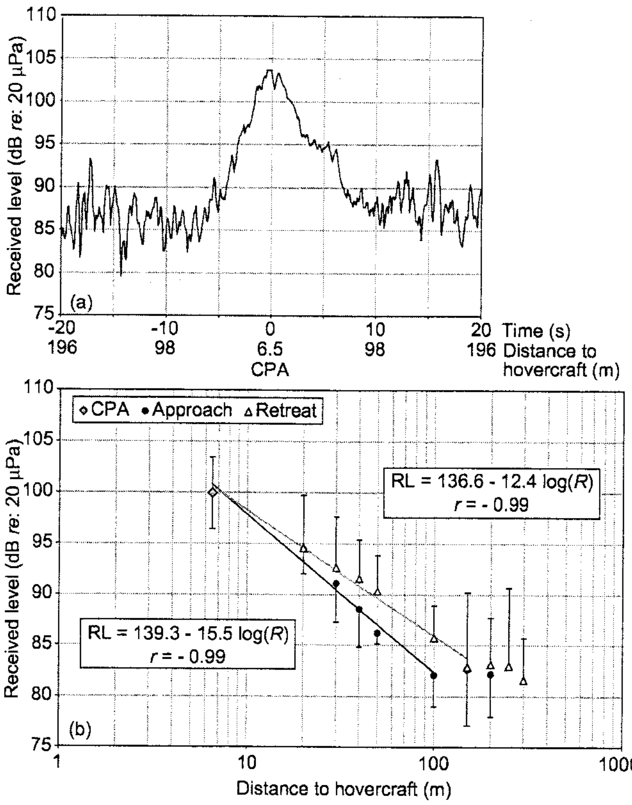

FIG. 6. (a) Broadband (10–10 000 Hz) sound pressure time series for the microphone during run 4. The x axis shows time, centered on the closest point of approach (CPA), and the corresponding distance from the hovercraft, calculated using the vessel's mean speed during that particular run. (b) Mean received broadband (10–10 000 Hz) levels in air (± one s.d.) for the hovercraft's approach (filled circles), CPA (gray diamond), and retreat (empty triangles), as a function of distance. The logarithmic spreading loss model (R in m) was applied to both data sets.

The lift fan was positioned under the hovercraft, close to the water, whereas the thrust propeller was upright on the stern deck (Fig. 2). However, contrary to expectation, lift fan components (i.e., 420 Hz blade rate $-5.5\% = \sim 397$ Hz) were present but small in the underwater sound, even at the CPA.

Figure 5 shows levels of underwater sound for seven selected one-third-octave bands versus distance from the hovercraft for the two hydrophone depths. The one-third-octave band centered at 80 Hz is dominant at close distances on the shallow hydrophone. Levels for this band reach background values much faster on the shallow than on the deep hydrophone, which is what we would expect for an airborne sound source. Another difference in the sounds at the two depths involved the relative levels in the one-third-octave bands centered at 20 and 63 Hz: they contained some of the highest received levels at the shallow depth, but some of the lowest levels at the deeper depth.

B. Airborne sounds

Figure 6(a) shows the broadband (10–10 000 Hz) SPL time series for the microphone during the fourth pass. Maximum SPLs were 97–104 dB *re*: 20 μPa for the four passes (maximum A-weighted levels were 85–97 dBA *re*: 20 μPa). Broadband (10–10 000 Hz) levels of airborne sound as a function of distance from the hovercraft are shown in Fig. 6(b). The logarithmic sound propagation model represented by Eq. (1) was fitted separately to data from the hovercraft's approach and retreat. Spreading loss terms were 15.5 and 12.4 dB/tenfold change in distance, respectively. The effects of aspect and range dependence were confounded in the measurement geometry. This probably accounts for the deviations from expected spherical spreading (20 dB/tenfold change in distance), although other possible causes include atmospheric refraction and near-field effects. The spreading loss coefficient was smaller for the vessel's retreat in all four passes. Background in-air values were in the range 74–80 dB *re*: 20 μPa.

Sound spectral density levels are plotted in Fig. 7 to examine the tones or frequency peaks produced by the hovercraft in air during a fly-by. As seen in the underwater data the spectrum included a large peak at 87 Hz. In addition eight harmonics of this fundamental frequency were found up to ~870 Hz.

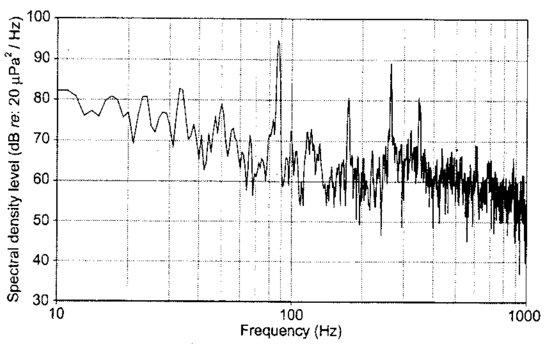

FIG. 7. Sound-pressure density spectrum (10–1000 Hz) for a 1.5-s sample recorded by the microphone and centered on the maximum broadband value for run 3.

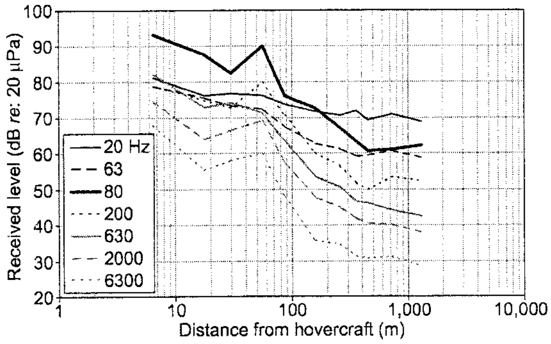

FIG. 8. Mean received levels of airborne sound as a function of mean distance from the hovercraft for seven selected one-third-octave bands. The indicated frequencies correspond to the bands' center frequencies.

The location of the thrust propeller on the stern deck of the hovercraft, in full view of the recording vessel, made it likely that tones produced by this propeller would be identified on the recordings. If we assume that the hovercraft was running somewhat below full power (see Sec. III A), then the peak centered at ~87 Hz very likely represents the thrust propeller's blade rate. Richards and Mead (1968) name the propeller rotational noise (at 80–800 Hz) as the major source of sound from a hovercraft.

Figure 8 shows that the one-third-octave band containing the thrust propeller's blade rate is dominant at close distances. Received one-third-octave levels of airborne sound generally decreased with distance at a higher rate for higher than for lower frequencies. For example, between the CPA (6.5 m) and 1310 m, received levels dropped by 12 dB for the band centered at 20 Hz, and by 39 dB for the band centered at 6300 Hz.

IV. DISCUSSION

The purpose of this paper is to present underwater and in-air sound measurement results for a small hovercraft in use for crew transfer to and from an island-based oil production facility. It might have been desirable to perform a physical acoustics study of the sources of sound on the hovercraft, including the directional effects, but such a study was well beyond the scope of the project. Good reviews of propeller and propfan noise are in Chap. 1 of Hubbard (1995) or Chaps. 9 and 10 in Richards and Mead (1968). These references do not include considerations of underwater sounds.

A. Underwater sounds

Few measurements of underwater sounds from hovercraft have been reported previously, and the limited existing data concern larger hovercraft. Slaney (1975) recorded the sounds from a Bell Voyageur hovercraft; in that study the hydrophone was at 1.8-m depth. The Bell Voyageur was a much larger hovercraft than the Griffon 2000TD used in this study: 20 m long, 11.2 m wide, and with a 23 720 kg payload, as compared to 11.9 m, 4.8 m, and 2268 kg for the Griffon 2000TD. The Bell Voyageur was powered by two marine gas turbines (2 × 1300 hp continuous) that drove two centrifugal lift fans and two propellers. At a horizontal distance of 46 m, received levels in one-third-octave bands centered at 80–630 Hz were ~110 dB *re*: 1 μPa. In our data set, the corresponding values were 97–105 dB (at a hydrophone depth of 1 m). Slaney (1975) also reported a 50–2000 Hz band level of 121 dB *re*: 1 μPa (also at a distance of 46 m), compared to ~111 dB in our data set for the same frequency range.

In another study, Brown (1988) reported broadband (22.5–22 500 Hz) levels of underwater sound generated by an AP.1-88 Hovercraft. Recordings were made with a hydrophone on the bottom in water 6–7 m deep. However, this hovercraft was also considerably larger than the Griffon 2000TD: 25 m long, 10.5 m wide, 7260 kg payload, powered by four diesel engines (two propulsion and two lift engines, at 2 × 500 and 2 × 390 hp continuous, respectively) driving six pairs of lift fans and two propellers. Maximum SPLs, as recorded on the bottom, were 122–126 dB and 117–119 dB *re*: 1 μPa at CPAs of 15 and 30 m, respectively. Brown (1988) presented one-third-octave band data from which we calculated a maximum level of 124 dB *re*: 1 μPa at a distance of 15 m for the 25–8000 Hz band. For that distance and frequency range (with hydrophone depth 7 m), our measured value is 122 dB *re*: 1 μPa, i.e., slightly lower.

In view of the differences in size and engine power between the hovercraft in this study and those studied by Slaney (1975) and Brown (1988), the lower received levels for the Griffon 2000TD are expected. However, large differences would not be expected, as (other factors being equal) a halving of power output would only result in a 3-dB drop in SPL. Similarly, dividing the power output by 5 would result in a 7-dB drop in SPL. If we limit our analysis to the propulsion (thrust) engine horse power, the differences between the vessels seem reasonable: the Bell Voyageur had 7.3 times the Griffon's hp and a 10 dB higher broadband level. The AP.1-88 had 2.8 times the Griffon's hp and a 2.5 dB higher broadband level.

The Griffon 2000TD hovercraft included three interlinked rotating components that might be expected to produce tonal sounds at particular frequencies: the vessel's diesel engine, the 12-bladed lift fan located under the vessel, close to the water, and a 4-bladed thrust propeller positioned vertically on the aft deck. When the hovercraft ran at full power, these sources were all in air. Therefore, we expected SPLs recorded by the shallower hydrophone (depth 1 m) during the fly-bys to be higher than those recorded by the deeper hydrophone (depth 7 m). This turned out to be true at the CPA where the difference was over 7 dB, indicating a rapid loss with depth. The experimental conditions (i.e., sea state) were such that the sounds produced by the hovercraft did not exceed ambient levels by a sufficient amount and duration to model transmission loss usefully.

Compared to the deep hydrophone, the shallow hydrophone recorded higher levels for the one-third-octave band centered at 20 Hz (Fig. 5). This is accounted for by the low-frequency cutoff caused by the shallow water at the recording site (Richardson *et al.*, 1995). The fact that the hovercraft is a sound source in air, where the low-frequency cutoff phenomenon does not apply, explains the presence of a range dependency at such a low frequency.

The distance at which broadband levels reached background values can be estimated by examining one-third-octave band levels (Fig. 5). For the shallow hydrophone [Fig 5(a)] levels for five out of seven bands shown did not decrease beyond 300 m. The exceptions were the bands centered at 80 and 200 Hz. For the deep hydrophone [Fig. 5(b)] the exceptions were the bands centered at 63 and 80 Hz. These exceptions had or were close to having reached their lowest value by a distance of 1 km. Consequently, for the particular set of sea state and water depth found during our recordings, we estimate that underwater sound levels had returned to background values by ~1 km fore and aft of a Griffon 2000TD hovercraft cruising by at full power.

The hovercraft recorded in this study was used as an alternative to conventional crew boats (length 19 m) at Northstar Island. Therefore, we compared levels of underwater sound produced by the hovercraft with conventional propeller-driven crafts of similar sizes. We have no close-up recordings of the Northstar crew boat, but unpublished measurements showed broadband (10–10 000 Hz) levels of 121 dB *re*: 1 μPa at a distance of 1820 m during cruising. A $15\log(R)$ propagation loss [which has been measured for this area, see Blackwell and Greene (submitted)] brings this value to 130.9 dB (the maximum hovercraft value at 6.5 m for the deep hydrophone) at a distance of ~400 m. Greene (1985) reported source levels of 156 dB *re*: 1 μPa-m for the 90-Hz tone of a 16-m crew boat. Buck and Chalfant (1972) reported source levels of 166 dB *re*: 1 μPa-m for a 37-Hz tone produced by a 25-m tug pulling an empty barge. In the two latter studies the broadband levels can only be higher than the values reported here. Thus, despite the paucity of comparable underwater measurements it is clear that conventional vessels of approximately the same size as the Griffon 2000TD hovercraft have higher source levels than the hovercraft. More importantly, because the hovercraft sound source is in air, it does not propagate well horizontally through the water. Consequently the amount of time that the two types of craft will be audible underwater while passing by a stationary underwater listener is on the order of 20–60 times longer for a conventional propeller-driven vessel.

Blackwell *et al.* (2004) also monitored underwater sounds from Northstar using an autonomous recorder located 550 m from the island. Broadband (10–500 Hz) sound levels were averaged for 1 min every 4.3 min. Whereas crew changes at the island by the crew boats raised broadband levels ~600 m away by ~15 dB, those by the hovercraft did not cause a noticeable change in broadband levels at that distance.

In conclusion, the Griffon 2000TD hovercraft was considerably quieter underwater than conventional vessels of comparable sizes. A hovercraft is therefore an attractive alternative when there is concern about the levels or the duration of vessel sounds produced underwater.

B. Airborne sounds

Maximum broadband values at the CPA were 97–104 dB *re*: 20 μPa or 85–97 dBA *re*: 20 μPa. For comparison, this corresponds to the sounds of a blender at the operator's position, or the cockpit of a light aircraft in the compilation of common airborne sounds by Kinsler *et al.* (2000). In one of the rare publications on hovercraft sounds in air, Lovesey (1972) reports maximum broadband SPLs for five types of hovercraft at a distance of 152 m during maneuvering in a terminal area. These were 94, 94, 95, 85, and 69 dBA for SRN2, SRN3, SRN5, SRN4, and VT1 hovercraft, respectively (the SRN2, 3, and 5 hovercraft were early models not optimized for reduced noise). The values for the SRN hovercraft are all higher than those recorded for the Griffon 2000TD, whereas the maximum value recorded for the VT1 is comparable. However, the hovercraft reported on by Lovesey (1972) were 3–80 times heavier than the Griffon 2000TD and had 2.5–38 times the horsepower. In addition, they were maneuvering, not flying by at full power as during our measurements. The Griffon 2000TD's specifications sheet states that the external noise level is less than 90 dBA at 150 ft (46 m). This statement is supported by our measurements (not shown).

The hovercraft's spectral composition in air was very similar to that underwater, with a peak at ~87 Hz accounted for by the thrust propeller's blade rate. Consequently, the one-third-octave bands centered at 80 Hz (and 160 Hz, not shown) showed marked increases, relative to neighboring bands, at all recorded distances. Slaney (1975) reported similar peaks in the one-third-octave bands centered at 100 and 200 Hz. Eight harmonics to the fundamental 87 Hz frequency were detected in the spectrum. In comparison, Wheeler and Donno (1966) detected up to 14 harmonics of this rotational noise on the SRN5 hovercraft.

Because all the hovercraft's sound sources (engine, lift fan, and propeller) were located in air during cruising, the craft was detectable in air out to distances exceeding the maximum distances where it would be detectable underwater. Mean broadband values in air reached a minimum and then remained constant at ~100 m and 150 m during approach and retreat, respectively [Fig. 6(b)]. However, there was a large amount of variation in background sound during the recording. In addition, many organisms are able to hear tones at levels below ambient—for example, the acoustics crew could clearly hear the hovercraft in air at distances of more than 400 m. Levels for three of the seven selected one-third-octave bands shown in Fig. 8 were still decreasing 1 km from the hovercraft, but only slightly. It is therefore reasonable to state that airborne broadband levels reached background values less than 2 km from the hovercraft for the conditions existing during our measurements.

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