VCU
VIRGINIA COMMONWEALTH UNIVERSITY

Virginia Commonwealth University
VCU Scholars Compass

Biology Publications

Dept. of Biology

2007

Stream ambient noise, spectrum and propagation of sounds in the goby Padogobius martensii: Sound pressure and particle velocity

Marco Lugli
Universitá di Parma

Michael L. Fine
Virginia Commonwealth University, mfine@vcu.edu

Follow this and additional works at: http://scholarscompass.vcu.edu/biol_pubs

Part of the Acoustics, Dynamics, and Controls Commons, Biology Commons, and the Marine Biology Commons

Stream ambient noise, spectrum and propagation of sounds in the goby *Padogobius martensii*: Sound pressure and particle velocity[a]

Marco Lugli[b]

Dipartimento di Biologia Evolutiva e Funzionale, Universitá di Parma, Italy

Michael L. Fine

Department of Biology, Virginia Commonwealth University, Richmond, Virginia 23284-2012

The most sensitive hearing and peak frequencies of courtship calls of the stream goby, *Padogobius martensii*, fall within a quiet window at around 100 Hz in the ambient noise spectrum. Acoustic pressure was previously measured although *Padogobius* likely responds to particle motion. In this study a combination pressure (p) and particle velocity (u) detector was utilized to describe ambient noise of the habitat, the characteristics of the goby's sounds and their attenuation with distance. The ambient noise (AN) spectrum is generally similar for p and u (including the quiet window at noisy locations), although the energy distribution of u spectrum is shifted up by 50–100 Hz. The energy distribution of the goby's sounds is similar for p and u spectra of the Tonal sound, whereas the pulse-train sound exhibits larger $p–u$ differences. Transmission loss was high for sound p and u: energy decays 6–10 dB/10 cm, and sound p/u ratio does not change with distance from the source in the nearfield. The measurement of particle velocity of stream AN and *P. martensii* sounds indicates that this species is well adapted to communicate acoustically in a complex noisy shallow-water environment. © *2007 Acoustical Society of America.*
[DOI: 10.1121/1.2783113]

I. INTRODUCTION

Acoustic pressure and particle velocity are physically related components of sound (Morse Uno Ingard, 1968; Michelsen, 1983). Pressure p is a scalar, i.e., its magnitude at a given point is the same regardless of the orientation of an (omnidirectional) receiver to the sound source. Particle displacement and its derivatives, particle velocity u and acceleration, are vectors, and their magnitude is maximal along the propagation axis of the sound.

In the far field several lengths from the source and in absence of reflecting boundaries, the front of an acoustic wave is approximately planar, and p and u are in phase; their ratio (p/u) is proportional to the product of the water density (ρ) and sound velocity (c) in the medium (Michelsen, 1983). In the near field well below one wave length to the source, particle velocity predominates over pressure, and the phase difference between the two quantities changes with distance. Further, the magnitude of p/u increases with propagation distance for simple sound sources, i.e., a pure tone produced by a monopole, dipole or quadrupole source (Kalmijn, 1988). Velocity depends on factors such as the geometry and frequency response of the source and the presence of nearby reflecting boundaries (Michelsen, 1983; Rogers and Cox, 1988). Excluding simple sound sources under ideal condi-

tions, the relationship between the two quantities becomes quite complex and unpredictable in the near field. To our knowledge there are no theoretical or empirical studies describing the p/u amplitude and phase changes with propagation distance for acoustic frequencies below the cutoff frequency, i.e., under very shallow water conditions.

Many sonic fishes live in shallow waters (near the shore of the sea or lakes, in small rivers, ponds, etc.) and emit low frequency acoustic signals (i.e., with long wavelengths) intended for receivers at short distances. For example the wavelength of a 100 Hz sound would be approximately 15 m. Thus, acoustic communication in many teleosts occurs mainly or exclusively in the near field, and many fishes that communicate at close distance are primarily or exclusively particle-motion sensitive species (reviewed in Popper and Fay, 1973).

Sensing particle velocity in water for military purposes such as submarine detection has long been performed using a geophone in sonobuoys. However, particle displacement of fish sounds has been rarely reported in the fish literature. Horch and Salmon (1973) measured both acoustic pressure and particle displacement components of the sound in the squirrelfish, *Myripristis violaceus*. Using separate sensors, an omnidirectional hydrophone for p and a bidirectional geophone for u, they found similar spectral energy distribution and attenuation levels for both components. Simultaneous characterization of the scalar and vectorial quantities of the same sound was not performed. The recent development of a $p–u$ probe for underwater measurements allows simulta-

---

neous measurement of both parameters along a single axis at the same point in the acoustic field. Bastyr *et al.* (1999) discussed the advantages of a $p-u$ probe over other methods that employ the finite differencing technique (i.e., $p-p$ or $u-u$ probes) for accurate intensity measurements in complex acoustic fields.

The Italian freshwater goby, *Padogobius martensii*, is a bottom-dwelling species whose acoustic behavior has been investigated thoroughly (Torricelli and Romani, 1986; Lugli *et al.*, 1997). This small goby (maximum size: 9 cm total length (TL)) lives in small stony streams and rivers. Individual adult males defend a hollow under a large stone. During the breeding season (March–July), males court ripe females to attract them to the nest hollow for mating (Torricelli *et al.*, 1986; Lugli *et al.*, 1992), after which the male cares for the eggs. The nest hollow has one or, most often, two openings.

Courting males produce two sound types (Lugli *et al.*, 1995). The tonal sound, typical of early courtship, is made of rapidly repeated pulses (sound duration: <0.5 s, pulse rate: 150–200 pulses/s (pps); Torricelli *et al.*, 1990). The pulse-train sound, emitted only when the female enters the nest hollow, is a short train of low-frequency pulses repeated at a lower rate (around 50 pps, Lugli *et al.*, 1995). Pulse-train sounds are often combined with a short tonal sound to form complex "spawning sounds" (Lugli *et al.*, 1995). Female *P. martensii* are silent during courtship and spawning (Torricelli *et al.*, 1986). The sound-producing mechanism is unknown.

Lugli and Fine (2003) measured ambient noise (AN) and sound propagation in a small stony stream inhabited by this species. They found a quiet window around 100 Hz in the noise spectrum at many noisy sites (e.g., near small waterfalls, riffles, etc.). The window lies between low-frequency turbulent noise and higher-frequency noise from bubbles associated with breaking water (see Franz, 1959). The quiet window is also present in another stony river inhabited by the goby *Gobius nigricans* (Lugli and Fine, 2003), and similar windows are a recurrent feature of the AN spectrum also of Austrian rivers and streams (Amoser, 2007). Lugli and Fine (2003) found sound propagation in the stream was limited to only a few decimeters from the source because of low water depths (15–50 cm). Lugli *et al.* (2003) also found a match between stream AN, sound frequency spectrum and hearing sensitivity of the goby. The main frequencies of the sound, and the most sensitive frequencies of the goby audiogram, fit within the low-frequency window/notch of the noise spectrum.These studies utilized acoustic pressure, but the goby is likely sensitive to particle motion. Its small oval-shaped gas bladder is not involved in sound production or hearing, i.e., bladder deflation does not affect sound level and spectrum or hearing range and sensitivity (Lugli *et al.*, 2003). Therefore, measurement of particle velocity for both the stream AN and *P. martensii* sounds is essential to obtain a realistic picture of their relationship and to validate conclusions about communication.

Here we measure pressure and particle velocity of stream AN and *P. martensii* sounds with the $p-u$ sensor to reexamine the relationship between the noise spectrum of the stream and the communication frequencies of the goby. Additionally, we measure propagation of *P. martensii* sounds to investigate the relationship between acoustic pressure and particle velocity close to the sound source in a complex near-field environment. Results will be relevant to the understanding of the fish acoustic communication in the presence of high AN levels and short-range sound propagation.

II. MATERIALS AND METHODS

The freshwater goby, *P. martensii*, inhabits Stream Stirone, a small hill stream in Northern Italy (Lugli *et al.*, 1992). The study site is a 2.5 km stretch of the stream with a stony bottom, water depths usually <30 cm, and low water current (under non-flood conditions). Quiet areas alternate with small waterfalls, rapids, riffles, places with high water turbulence, where water breaks the surface and clouds of air bubbles form underwater. The goby population is widespread at both quiet and noisy areas (Lugli *et al.*, 1992).

A. Ambient noise measurements

AN was measured at five representative noisy sites near small waterfalls and rapids. Although adjacent to noise sources, the probe was placed in locations with no or modest underwater flow to minimize flow induced noise (McConnell, 2003) and self-induced turbulent pressure fluctuations by the probe and mounting support (Morse Uno Ingard, 1968). AN was also measured at two quiet sites away from the waterfalls for comparison. A single noise recording was made at each location for approximately 1 min. The AN spectrum shows only minor changes with sample duration (Lugli and Fine, 2003), being remarkably stable over time (M. Lugli, 2003).

AN was measured with an underwater acoustic pressure-velocity probe (Mk.2, Acoustech©; outer ∅: 4.3 cm) containing two built-in units: a piezoelectric, omni-directional hydrophone (sensitivity: −203.1 dB re:1 V/μPa) to measure acoustic pressure (p), and a bidirectional geophone (sensitivity: 10.5 V/m/s) to measure particle velocity (u) along one axis. The geophone has resonance peaks at 17 and 28 Hz. The response of both sensors is almost flat (hydrophone: ±1 dB; geophone: ±1 V) between 60 and 800 Hz. The probe was connected to an external, battery powered two-channel preamplifier (Acoustech@). Separate output jacks of the pre-amplifier for pressure and velocity were connected respectively to a portable Digital Audio Tape (DAT) recorder (Casio DA-7, sampling rate: 48 kHz). The probe was mounted on an iron support anchored to the stream bottom (Fig. 1). The support holds the outside of the unit rigidly, and the inner core containing the sensors is neutrally buoyant and free to register acoustic pressure and particle velocity. The distance between the top of the probe (mounted on its supporting harware) and the bottom substrate was about 9 cm. The probe's main axis was aligned toward the noise source like waterfalls or parallel to the stream axis at quiet sites. Additionally, three orthogonal measurements were made at two sites with minimal underwater flow that were adjacent to noisy sites: facing the stream axis (x), perpendicular (y), and vertical (z). Location 1 was a quiet pool below a small waterfall (water depth 28 cm). Location 2 was a riffle with low
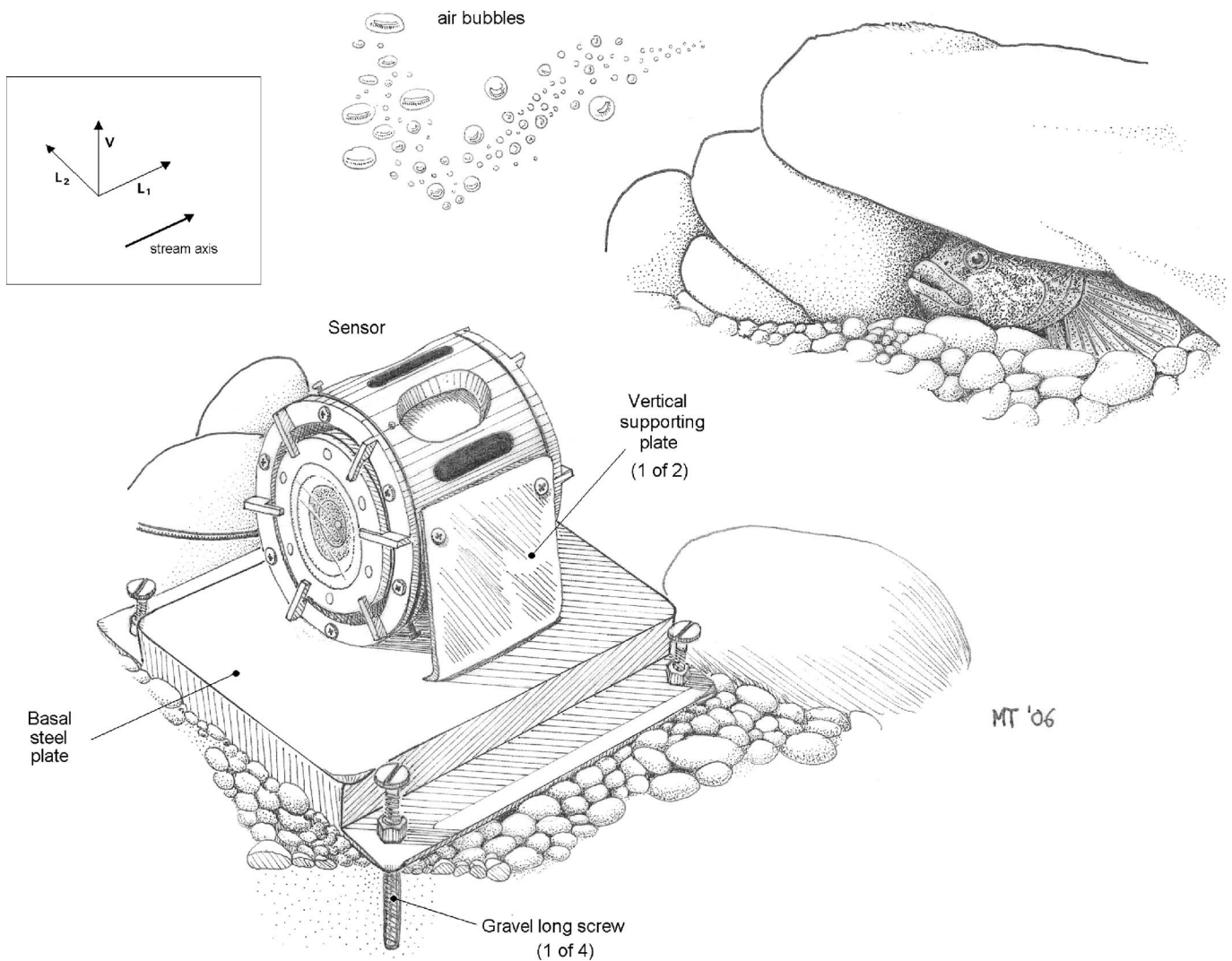
FIG. 1. Schematic of the $p-u$ probe and the mounting hardware, anchored to the stream bottom. For the measurements along three orthogonal directions (L_1, L_2, and V) (respectively x, y, and z) at two nonturbulent locations (see also Fig. 2) the mounting harware and the probe were oriented parallel to the stream axis (L_1), perpendicular to it (L_2), and vertical axis (V).

current and places of gas-bubble release (water depth of 26 cm). Therefore, these data exhibit differences from AN at noisy sites and are treated separately (see below).

Noise recordings were stored on a PC (sampling rate 44,100 Hz), and analyzed with AVISOFT$^{©}$ software. Recordings were band-pass filtered between 50 Hz - 1 kHz to avoid the geophone's two resonance peaks and capture frequencies important for acoustic communication (Lugli *et al.*, 1995; Lugli and Fine, 2003; Lugli *et al.*, 2003). The AN spectrum was determined for each location following Lugli and Fine (2003). Three noise segments of approximately 700 ms were randomly selected from the 1-min recording. Each segment was analyzed for the pressure spectrum level (the sound energy in 1 Hz bands of noise, dB re : 1 $\mu Pa^2/Hz$) and particle velocity spectrum level [the sound energy in 1 Hz bands of noise, dB re : 1 $(cm/s)^2$]. Levels from the continuous spectra were measured at 50 Hz intervals from 50 to 900 Hz, using the power spectrum function of AVISOFT$^{©}$. Decibel values referenced to 1 V were converted to absolute measurements using the calibration factors for all components of the measuring system (i.e., probe sensitivity, gain of

the preamplifier, gain of the DAT recorder). Data from the three noise segments were averaged to compute the AN pressure and particle velocity spectrum level curves.

B. Sound measurements

Spectrum shape, level and propagation of *P. martensii* sounds were also measured using the $p-u$ probe. To avoid corruption of sound measurements by AN, recordings utilized nests far from sources of elevated AN levels in places with low water current. Sound production was elicited by presenting territorial males with a ripe, conspecific female inside a small plastic-mesh cage, in front of the nest entrance. Males produced courtship sounds [i.e., tonal, pulse-train, and complex sounds, (Lugli *et al.*, 1995)]. The sensor was anchored to the substrate facing the nest entrance and the female, and multiple sounds were recorded. Five males were recorded with the probe approximately 10 cm from the nest entrance, and three were also recorded at 20, and 40 cm (the exact distance depended upon positioning the sensor because of bottom complexity). The male was then netted and
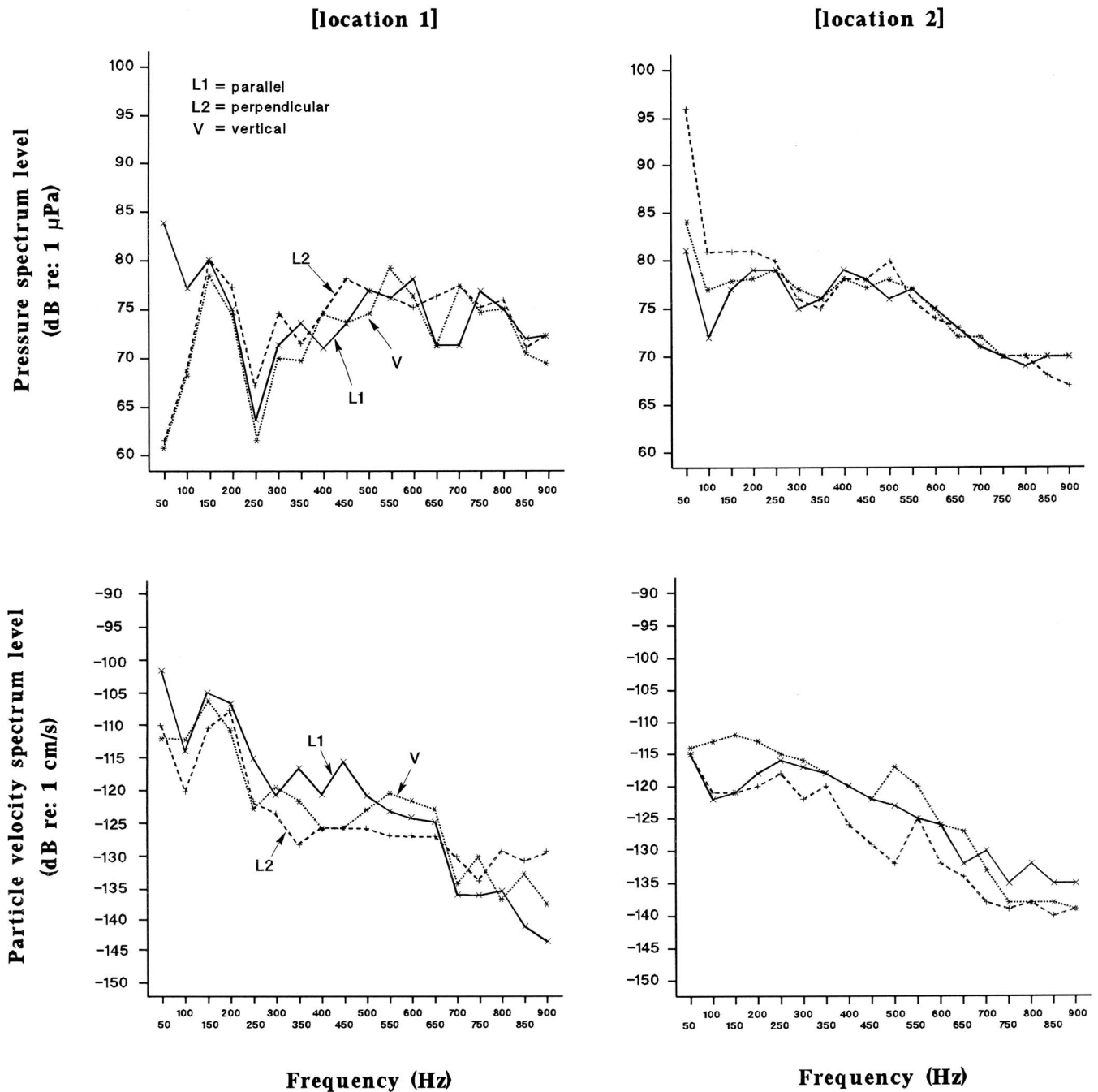
FIG. 2. Pressure (top) and particle velocity spectra (bottom) of the ambient noise at two nonturbulent locations close to sites of gas-bubble formation, measured with the sensor positioned in each of the three orthogonal directions: L_1, L_2, and V (respectively x, y, and z). Pressure levels above 100 Hz are similar in the x−y−z plane, whereas velocity levels are more variable. However, in the lower part of the spectrum (i.e., at 100 Hz and below), noise level variability in the three directions is larger for pressure.

measured for total length (mm), and water temperature was measured.

Pressure and velocity spectra and amplitudes were determined for 5 sounds with the best signal-to-noise (S/N) ratio in the pressure modality for each male at 10 cm from the nest. Twenty-five sounds (see the following) were high-pass filtered at 50 Hz and analyzed (FFT length: 512 Hz, bandwidth: 15 Hz, Hamming window). The frequency spectrum of the *P. martensii* sounds resolves into few (tonal sound) to many (pulse-train sound) harmonic bands between 50 and 900 Hz (Lugli *et al.*, 1995, 2003). To compare the level and

frequency distribution of the *P. martensii* sound spectrum with stream AN spectrum, the continuous *p* and *u* spectra of each sound were partitioned into seventeen 50 Hz frequency bands. Each band was examined for the presence of harmonics. Amplitude and peak (=center) frequency of all harmonics were measured, i.e., a harmonic band with peak frequency at 320 Hz was assigned to the 300–350 Hz class. Amplitudes were converted to absolute dB_{rms} (re:1 μPa, pressure mode; re:1 cm/s, velocity mode) (bandwidth: 10 Hz, Hamming window) using the calibration factors for all components of the measuring system. Sound spectra were

determined for 25 sounds (12 tonal and 13 pulse-train sounds), and mean p and u spectra were obtained by averaging the frequency and amplitude within each frequency band.

Sound propagation was examined by measuring the amplitude of the fundamental frequency (i.e., the pulse repetition rate of the sound; Watkins, 1967; Torricelli *et al.*, 1990) and higher harmonics, as the logarithmic root mean square pressure (SPL re : 1 μPa) or particle velocity (SL re : 1 cm/s) converted to absolute dB$_{rms}$ (bandwidth: 10 Hz, Hamming window). Only tonal sounds were used for the analysis as pulse-train sounds were not consistently present at each distance. Levels of at least five sounds from each male at each distance were averaged to determine the transmission loss of p and u. Our measurements are an estimate of transmission loss as they do not control for variation in call level. However, call levels in a single recording typically vary by 1–4 dB standard deviations (s.d.), which is considerably less than the propagation losses observed in the field (around 20 dB/20 cm, Lugli and Fine, 2003; Fig. 9, present paper).

C. Statistical analysis

Noise spectra from the five locations, tested with Kendall's concordance test (Siegel and Castellan, 1988), demonstrated significant concordance (see Lugli and Fine, 2003 for details) and therefore averaged within each frequency band to compute mean AN spectra for p and u. Similarly, the mean spectrum of sounds of individual males was calculated to determine if differences occurred in spectral shape. Finally, the magnitude (i.e., the real part) of the p/u ratio was calculated for frequencies of both AN spectra and sounds (see Sec. III for details). A preliminary analysis of the phase relationships between p and u showed the $p–u$ shift was around $-90°$ (the theoretical near-field value) for most sound and noise frequencies. These relationships will be considered in a forthcoming paper.

Mean p and u spectra for each individual were calculated by measuring the amplitude of the peak frequency (if present) in each 50 Hz band and averaging regardless of sound type. Not every frequency band contained significant sound energy (i.e., >3 dB above the background noise), and therefore, the number of sounds used to calculate means was usually less than the number of sounds analyzed. Mean sound spectra for p and u across males were concordant, and therefore all sounds recorded in a given modality were pooled, and the mean sound spectra for p and u were calculated regardless of sound type. The *P. martensii* sound spectrum is not affected by male size (Torricelli *et al.*, 1990).

III. RESULTS

A. Spectral characteristics of the stream ambient noise

AN spectra in the x–y–z plane for acoustic pressure (p) and particle velocity (u) exhibit similarities in shape and level at two nonturbulent locations (Fig. 2). Above 100 Hz, p levels are relatively similar in the three orthogonal directions, whereas corresponding u levels are more variable. At 50 and 100 Hz however, pressure is more variable. The p and u spectra vary considerably at location 1 but are more
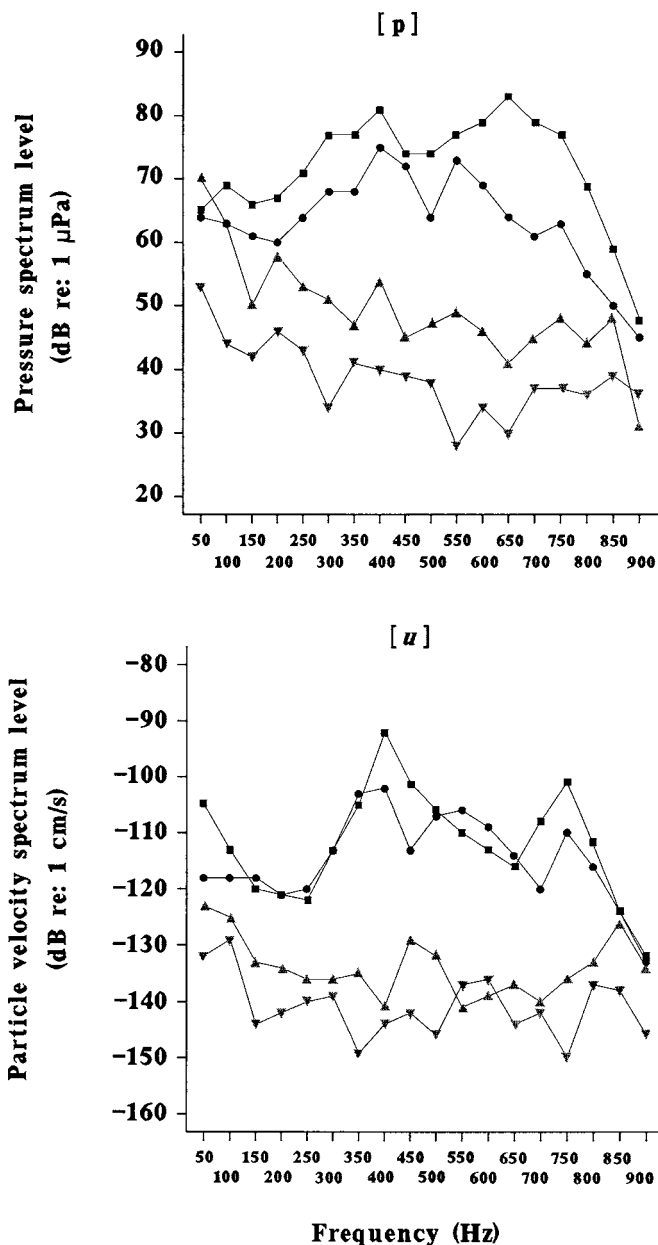

FIG. 3. The pressure spectrum (top) and the particle velocity spectrum (bottom) of the ambient noise at two noisy locations and two quiet locations (a given location is identified by the same symbol on the pressure and velocity spectra; triangles: quiet locations). Notice the region of lower noise levels at frequencies below 250 Hz is more marked on the velocity than on the pressure spectrum at the two noisy locations (i.e., the quiet window, Lugli and Fine, 2003, see also Fig. 4).

similar at location 2. At location 2 p and u spectra of bubble noise (i.e., frequencies above 100 Hz) peak around 250 Hz, except for the vertical u spectrum, which peaks at 150 Hz. Thereafter, noise levels fall off with increasing frequency for both spectra although the u slope is greater ($\sim$9–13 dB for p and u, respectively, between 400 and 800 Hz), i.e., the magnitude of p/u increases with frequency (Fig. 5, top graph).

At quiet locations, AN levels for both p and u are higher at low frequencies and decrease slowly and irregularly with frequency although the u curve is somewhat flatter (Fig. 3). At noisy locations, both spectra feature a quiet window (see also Fig. 2) below 300 Hz, increased levels in the
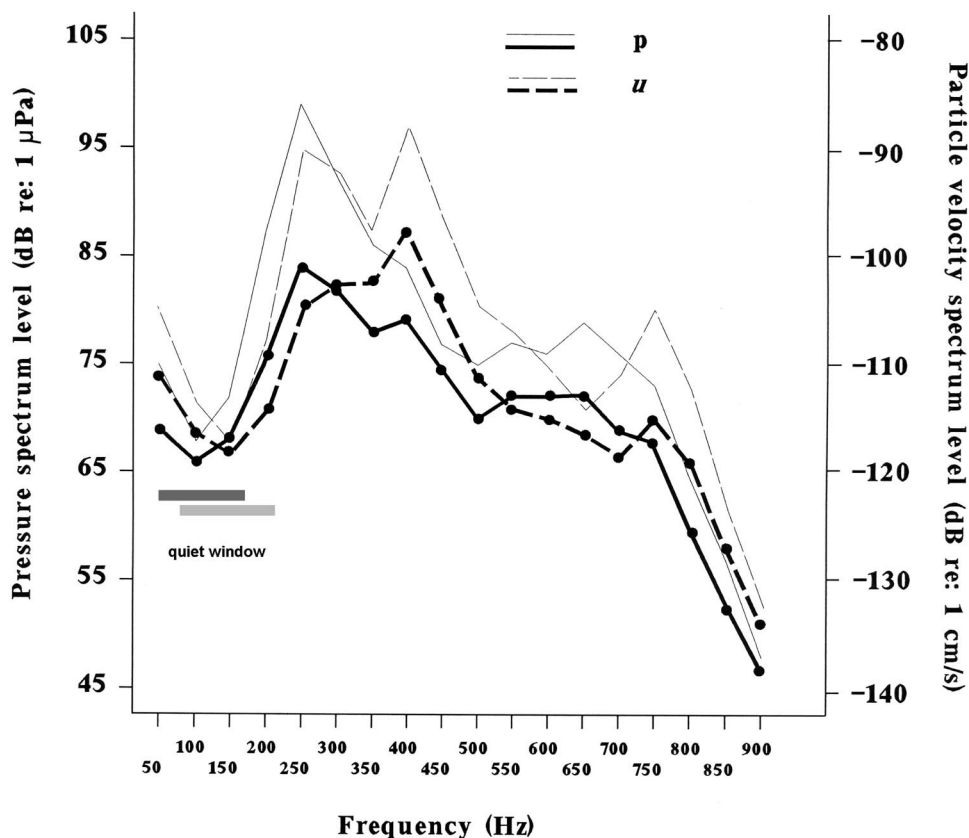
FIG. 4. Mean (thick lines) +1 s.d. (thin lines) pressure spectrum levels (left Y axis) and particle velocity spectrum levels (right Y axis) of Stream Stirone AN (noisy locations, $n=5$). The presence of lower spectrum levels at around 100 Hz (i.e. the quiet window, Lugli and Fine, 2003) is clear in both pressure (dark-gray horizontal bar) and velocity (light-gray horizontal bar) spectra. However the quiet window for particle velocity is displaced by 50 Hz, and maximal levels about 150 Hz toward higher frequencies.

300–700 Hz band, and decreasing levels at higher frequencies. U spectra however, have a wider window that is 10–15 dB deeper. Although p and u spectra appear similar, some peaks exhibit differences in amplitude and frequency. For instance, in Fig. 3 (square symbols), both exhibit peaks at 400 Hz, but a second peak occurs at 650 Hz for p and 750 for u.

Shifts between the p and u components are also apparent in the mean AN spectrum (Fig. 4). The quiet window exhibits its minimal variability in both p and u spectra, although the u window is displaced from 150 to 200 Hz.

The magnitude of p/u at noisy locations (Fig. 5, bottom graph) exhibits peaks between 200 and 300 Hz and between 600 and 700 Hz, and the mean value (Fig. 5, bottom graph: thick line) peaks at 200 and 650 Hz, the two peaks reflecting the $p-u$ shift of individual AN spectra (Fig. 3) and of the mean spectrum (Fig. 4), respectively.

B. Spectral characteristics of *P. martensii* sounds

Tonal ($n=12$) and pulse-train sounds ($n=13$) have similar levels and generally similar energy distributions for p and u. In the tonal sound from male #4 (Fig. 6, top) both the p and u spectra have four harmonic bands between 180 and 800 Hz, with the largest band at the fundamental frequency of 180 Hz. The pressure peaks are distributed relatively equally between bands, but the second harmonic of the u spectrum is almost absent. The u waveform of the tonal sound in Fig. 6 builds up more slowly and decays more quickly, although this response was not present in all signals.

Differences between p and u spectra are greater in the multiharmonic pulse-train sound than in the tonal sound (Fig.

6, bottom). The fundamental frequency (around 100 Hz) is the dominant p band, but the second harmonic (220 Hz) is larger in the u spectrum. Pressure exhibits a harmonic series of three decreasing bands and a second set of peaks with a maximum at about 500 Hz, which then exponentially decays to around 800 Hz (Fig. 6, bottom). Most of the energy in the u spectrum is concentrated in the lower half of the spectrum (i.e., below 400 Hz), with a secondary component between 700 and 900 Hz. The greater energy at lower frequencies on the u spectrum of the pulse-train sound is determined by the longer period components of u sound pulses (Fig. 7). The pulse waveform differs considerably between p and u oscillograms, with the single pulses barely distinguishable in the u sound (Fig. 7: male #4).

Mean spectrum shape of the tonal sound (Fig. 8, top) is similar for p and u: energy is concentrated within a narrow band around 150 Hz and a wider band around 500 Hz. However, the position of the peak frequency within these bands differs between the spectra. The u spectrum also contains more energy at higher frequencies ($>$600 Hz), where the p spectrum drops off. The mean p and u spectra of the pulse-train sound exhibit greater differences than for the tonal sound (Fig. 8, bottom). As in the tonal sound spectra, both spectra of the pulse-train sound exhibit a low frequency maximum around 100 Hz, and a secondary peak at middle frequencies. However, both peaks are shifted toward lower frequency bands in the u spectrum, particularly the secondary one. In the p spectrum of the pulse-train sound, energy is concentrated within a single low frequency band (from 100 to 150 Hz), and the secondary peak is distributed over a broader frequency band, than in the u spectrum. Finally,

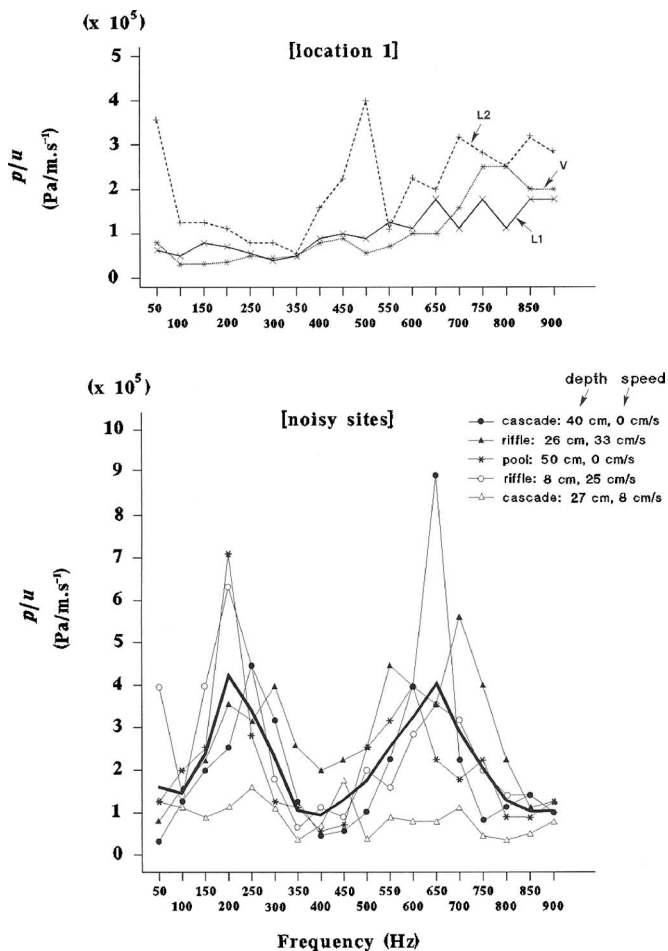M. Lugli and M. L. Fine: Pressure–velocity measurements in the stream

FIG. 5. Relationship of the magnitude of p/u to frequency in the three orthogonal directions at location 1 (top graph), and along an axis of AN propagation at the five noisy locations (bottom graph; CASCADE: probe in a riffle close to a cascade; RIFFLE: probe in a riffle close to places of bubble noise release; POOL: probe in a pool located below a small waterfall). The mean p/u ratio curve of the five locations (bottom graph: thick line) was computed by averaging the five values of p/u at each frequency. P/u ratios were computed by converting decibel levels of pressure and velocity into original units and computing the ratio as Pascals per meter per second.

pressure falls off above 600 Hz, whereas velocity varies by only about 3 dB from 500 to 900 Hz. Notice spectra shape of tonal and pulse-train sounds are more similar for p than u.

C. Propagation of sound pressure and particle velocity in the stream

The two nests were located over a stony bottom with low current speed and maximum water depth of 11 cm (male #1, total length=80 mm, water temperature: 27.8 °C) and 21 cm (male #4, total length=88 mm, water temperature: 26.7 °C) respectively. The tonal sound generally exhibits a large transmission loss at all frequencies for p and u (Fig. 9; exception: 400 Hz for u sounds recorded at 10 cm from male #1). Attenuation of the fundamental frequency was 6–7 dB/10 cm for p, and 7–10 dB/10 cm for u. P losses are similar to those previously recorded for this species [8 dB/10 cm from 5 to 45 cm (Lugli and Fine, 2003)]. Attenuation of p and u for other frequencies is similar to those determined for the fundamental frequency. Notice in male #1 an increase of 4 dB between 10 and 20 cm for 400 Hz for u,

whereas p decreases. The magnitude of p/u for the fundamental frequency (ranging from 100 000 to 150 000 Pa/m/s for male #1 and 50 000 to 100 000 Pa/m/s for male #4) is independent of distance from the nest (Kruskal-Wallis tests: $t=3.44$, NS, male #1; $t=0.09$, NS, male #4).

D. Relationship between sound and ambient noise spectrum

The dominant frequencies of *P. martensii* sound occur within the quiet window for both p and u (Fig. 10). Both p and u levels of the sound mean spectrum peak between 100 and 150 Hz, the band with lowest AN levels for p and u in the fish's hearing range, which extends to about 700 Hz (Lugli and Fine, 2003; Lugli *et al.*, 2003). Maximal S/N ratio within the quiet window is similar (i.e., about 10 dB) for pressure and velocity. A secondary, broad p peak around 500 Hz simultaneously occurs with a drop off in the AN spectrum, which peaks at 250 Hz. The presence of a secondary peak around 450 Hz in the call's u spectrum is less clear. In addition, this peak is only 50 Hz higher than the noise peak at 400 Hz. However, this peak is considerably above the noise in the quiet u spectrum (Fig. 3) and could provide information under quiet conditions.

IV. DISCUSSION

A. Noise

Previous work demonstrates that acoustic pressure in the AN spectrum is concentrated between 300 and 700 Hz, and a quiet region exists around 100 Hz in AN spectra from most noisy sites, i.e., pools below small waterfalls, small rapids, riffles, etc. (Lugli and Fine, 2003). The window is a recurrent and stable feature of the stream AN at such places and has recently been reported in Austrian rivers and streams (Amoser, 2007). The current study demonstrates the quiet window is also present in velocity spectra at noisy but not quiet locations, and in some cases can be deeper for the u than the p spectrum (Fig. 3). Noisy sites are characterized by high water turbulence and formation of air bubbles (Lugli and Fine, 2003). Water flowing around submerged objects (and the sensor) generates noise at the lowest frequencies (i.e., below 10–20 Hz; Strasberg, 1979), and this flow-induced noise may corrupt noise measurements at higher frequencies relevant to goby communication. We minimized this effect by placing the sensor in areas with low or no water current. Therefore, most of the noise energy between 50 Hz and 1 kHz is from nearby turbulence and bubble sources. Lugli and Fine (2003) argued that the low-frequency notch/window in the AN pressure spectrum results from the combined effect of the turbulence noise falling off above infrasonic frequencies and the presence of bubble noise above 200 Hz.

Shapes of the mean p and u AN spectra at noisy sites are generally similar although the u spectrum is shifted up 50–100 Hz (i.e., a minor $p–u$ mismatch). The magnitude of the p/u ratio of the AN spectrum at noisy sites exhibits a frequency-dependent pattern consistent with the $p–u$ mismatch of the mean spectrum. The reason for the shift at turbulent sites is unclear. This pattern is not present in the x,
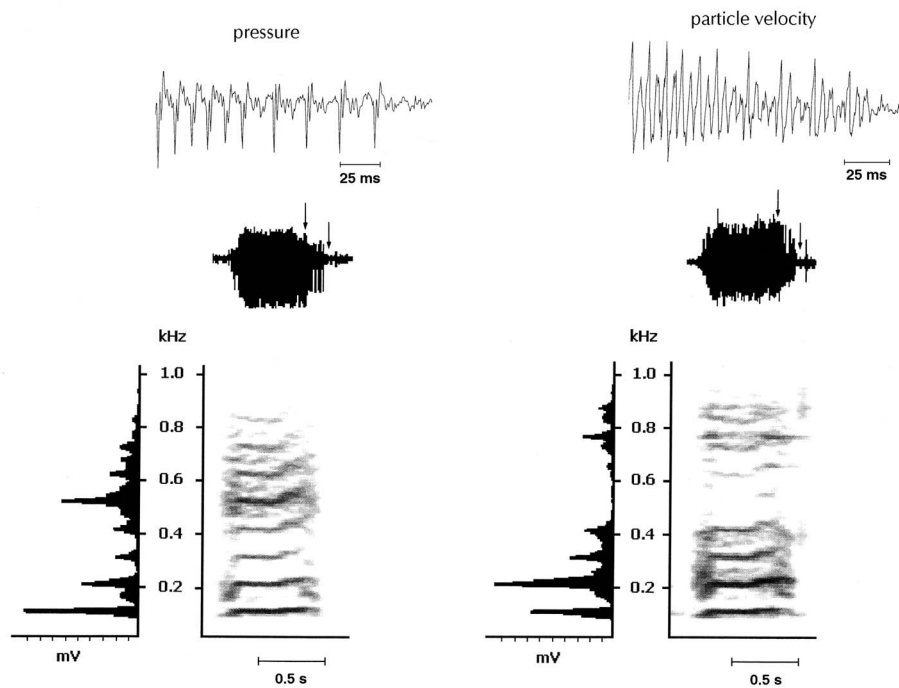
(A)
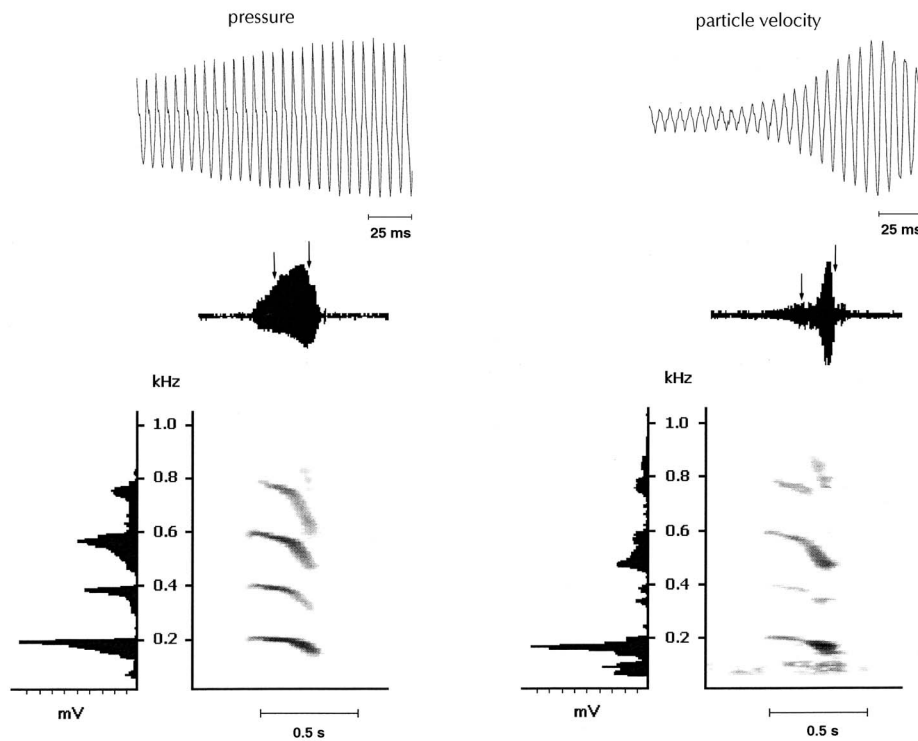
FIG. 6. Spectrogram (bottom-right, FFT=512 points, Hamming window), power spectrum (bottom-left half of panel, amplitude on a linear scale of 100 mV/division, arbitrary units), envelope (trace above the spectrogram), and oscillogram of a 150 ms section of the sound (top trace), of a representative (A) tonal sound (male #4) and (B) pulse-train sound (male #2) of *P. martensii*, recorded as pressure (left) and particle velocity (right). The expanded waveforms illustrate the portion of the sound between the two arrows. (A) Tonal sound: the pressure and particle velocity envelopes differ, but the tonal structure is clear in both cases. Notice sound energy is concentrated at the fundamental harmonic (about 200 Hz) in both spectra. The signal at about 100 Hz in the velocity sonogram is background noise. (B) Pulse-train sound: the oscillograms illustrate the end of the sound. The pulse-train waveform differs for pressure and particle velocity. Like the tonal sound, the velocity spectrum of the pulse-train sound has relatively more energy concentrated at the lower harmonics.

(B)

y, and *z* spectra at two nonturbulent sites (locations 1 and 2). At location 1 the p/u ratio increases with frequency regardless of sensor orientation. Theoretically, pressure–velocity ratios should increase with frequency in the nearfield of simple noise sources (Siler, 1969; Kalmijn, 1988). Simple theoretical predictions, however, may not apply to complex sources of underwater bubble noise which may interact de-structively, as well as constructively, and whose energy at lower frequencies decays rapidly because of the very shallow depths (see the following). The ratio measured at noisy locations does not increase linearly with frequency but exhibits a remarkably similar pattern suggesting the presence of environment-specific relationships between *p* and *u* ambient noise close to the source.

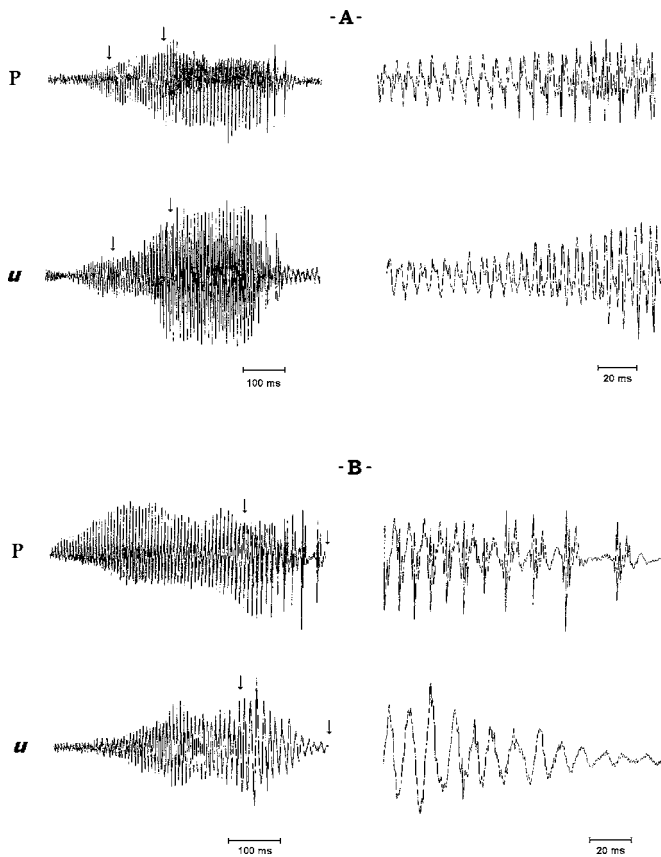M. Lugli and M. L. Fine: Pressure–velocity measurements in the stream

FIG. 7. Two examples of a pulse-train sound (A: male #2, recording distance of 10 cm; B: male #4, recording distance of 8 cm) illustrating the waveform of the sound (left) and an expanded portion of it (right) between the two arrows for acoustic pressure (p) and particle velocity (u). Notice the sound by male #2 is different from the selection in Fig. 6 (bottom).

B. Sounds

All male *P. martensii* emitted tonal and pulse-train sounds to a caged ripe female near the nest opening. Sounds were recorded while the male was inside the nest (a hollow underneath a flat stone), a situation typical for courtship sound production in this species (Lugli *et al.*, 1997). Spectral characteristics of pressure for tonal and pulse-train sounds were similar to those determined in earlier studies (e.g., Lugli *et al.*, 1997; Lugli and Fine, 2003), i.e., the sound energy is concentrated at the fundamental frequency [=pulse repetition rate (Watkins, 1967; Torricelli *et al.*, 1990)] around 200 Hz (tonal sound), or at the lower harmonics at around 100 Hz (pulse-train sound). Laboratory recordings of *P. martensii* courtship sounds indicate little or no energy above 0.5 kHz in either sound (e.g., Lugli *et al.*, 1997). In this study however, both types of sound had notable energy above 500 Hz (likely due to the higher recording temperature in the stream; M. Lugli, private communication), allowing us to compare pressure and particle velocity over a broader frequency range. Most energy in p and u spectra of both sounds is still below 200 Hz. The frequency distribution is similar for p and u spectra of the tonal sound, but the pulse-train sound exhibits larger differences between spectra. In several pulse-train sounds, some frequencies in the p spectrum are missing from the u spectrum, and vice-versa (Fig. 6).

Because of the complexity of the acoustic environment,

reasons for these differences are speculative. Position of the emitter might affect radiation of directional and nondirectional components of the sound field. Additionally, the acoustics of the nest, a hollow under a flat stone, might affect sound propagation. Laboratory experiments indicate the nest may amplify pressure (M. Lugli, private communication). Perhaps sound is reflected from the back of the nest hollow resulting in constructive interference. Additionally, some of the sound energy could propagate through the substrate as in other bottom-dwelling species such as the mottled sculpin (A. Whang and J. Janssen, 1994) and other gobiids (Janssen, private communication). This effect however, is likely minimized in a rock-lined stream compared to a sandy or muddy bottom.

A gas bladder may change the directional properties of the sound through scattering, even if it is not involved in sound generation. Barimo and Fine (1998) found a directional field that matched the heart-shaped swim bladder in the oyster toadfish in which the swim bladder is the acoustic radiator. For the goby passive effects of the swim bladder would likely dominate at the resonant frequency of the bladder's gas cavity, and it is unlikely that the small bladder in *P. martensii* would exert large effects at various frequencies. Possible filtering effects of stones and gravel surrounding the fish nest (rocks: density approximately 2–3 times the water density) could attenuate and/or change directionality of some frequencies, thereby accounting for differences in the p and u spectra. The amplitude and frequency spectrum of croaker sounds (acoustic pressure) was not affected by enclosing a hydrophone within a terra cotta drainage tile (Barimo and Fine, 1998). However, particle velocity is more likely to be affected by stone barriers. Still, given the long wavelength of goby sounds, it is unlikely that rock positions would dramatically affect low frequency propagation, and we suggest that p and u are affected separately by destructive and constructive interference.

The tonal sound has a simpler acoustic structure than the pulse-train sound, and acoustic differences in waveform between p and u spectra are less pronounced in the tonal sound. Although both sounds attenuate rapidly, the tonal sounds has features that may allow longer distance propagation than the pulse-train sound, which is only emitted when the female is in the male's nest. For instance, the tonal sound is frequency (=pulse-rate) modulated, a feature common to acoustic signals used for long-range communication among birds and mammals (Wiley and Richards, 1982).

C. Transmission loss

Far from the sound source (i.e., in the far-field) pressure and particle velocity are in phase and decay slowly with distance from the source; furthermore, the p/u ratio is constant for all frequencies and noise-source types, being equal to the product of the density of the medium times the sound velocity (Michelsen, 1983; Rogers and Cox, 1988), i.e., the acoustic impedance of the medium, which is about 1.4 $\times 10^6$ Pa/m/s in freshwater (sound velocity: 1430 m/s;
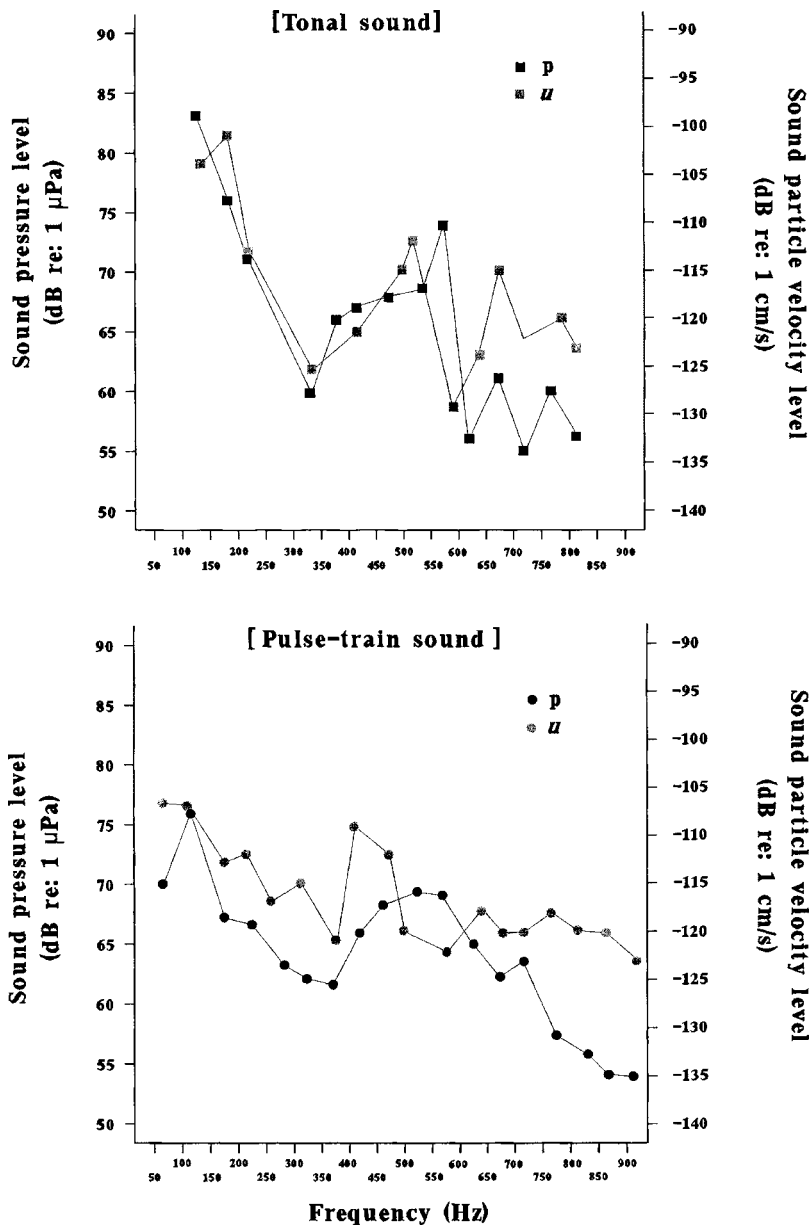
FIG. 8. Mean spectrum of the tonal sound (top, $n=12$) and the pulse-train sound (bottom, $n=13$) of male *P. martensii*. Acoustic pressure (black symbols), particle velocity (light symbols).

water density: 1000 kg/m^3). In this study recordings were conducted close to the sound source (i.e., in the extreme near field) and near the air–water–bottom interfaces at shallow depths (<40 cm). Therefore biologically relevant sound frequencies (50–700 Hz, Lugli *et al.*, 2003) will not propagate (Urik, 1983). Transmission loss is high for pressure and velocity at all frequencies, and the observed values (i.e., 6–10 dB/10 cm) are much larger than expected from spherical spreading in an acoustic free field, 6 dB loss per distance doubled, equivalent to a decay of $1/r$, $r=$source distance >1 m (Urik, 1983). Considering the shallow depths and cylindrical spreading of 3 dB/DD, attenuation is even more striking.

There is a tendency for p and u transmission loss to decrease at higher frequencies. The high, frequency-dependent attenuation can be predicted using the waveguide model analogy for sound transmission in small tanks with low water depths (Akamatsu *et al.*, 2002): a sound frequency below the cutoff within a circular tank whose diameter is larger than its depth. The energy of, e.g., a 200 Hz tone will be reduced by 20 dB every 15 cm for water depth of 20 cm and 22 dB for a water depth of 30 cm. Slightly longer distances are obtained for higher harmonics (e.g., a 400 Hz tone). Thus, our propagation measurements are consistent with theoretical predictions for frequencies traveling below the cutoff in very shallow bounded bodies of water.

The magnitude of the p/u ratio for the fundamental frequency of the tonal sound (around 200 Hz) does not change with distance from the source in the near field, and the ratios are 10-fold lower than the theoretical value for the free-field situation (see Fig. 9). Again, this result is reasonable considering that sound energy decreases rapidly below the cutoff, and particle displacement predominates over sound pressure in the near field. Note Rogers and Cox (1988) caution that the p/u ratio is not a meaningful quantity in nonfree-field situations, and we use it here to permit simple comparisons

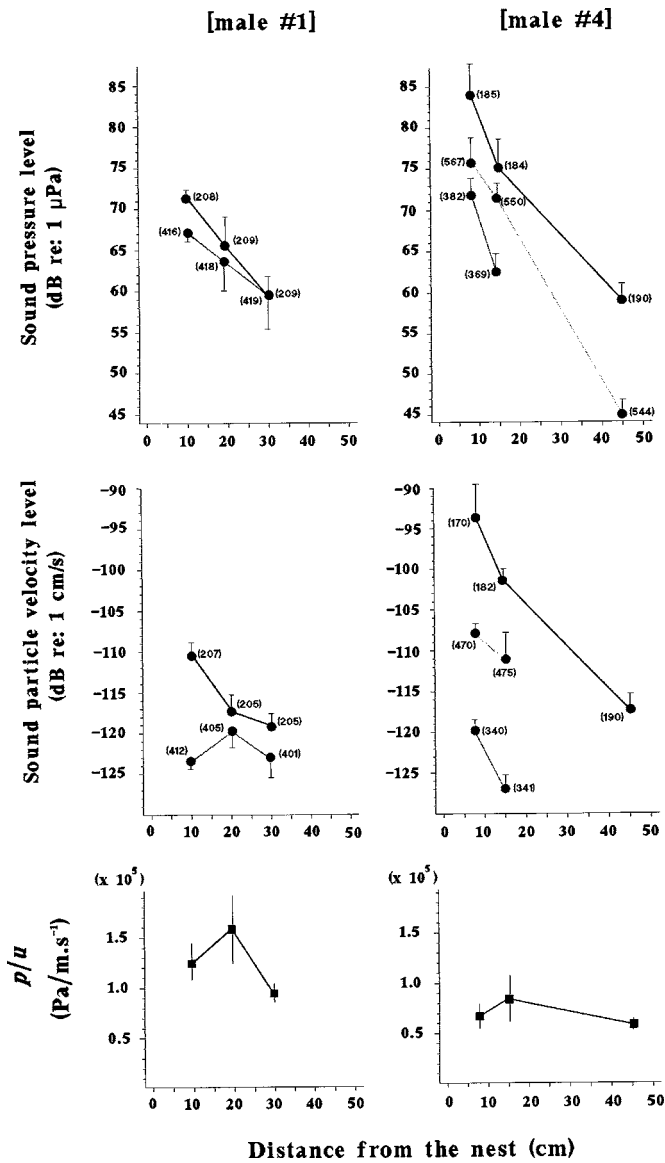M. Lugli and M. L. Fine: Pressure–velocity measurements in the stream

FIG. 9. Transmission loss (mean +1 s.d.) with distance (cm) for the fundamental frequency and higher harmonics of sounds by two males, recorded as pressure (top) and particle velocity (middle), and p/u ratios of the fundamental frequency (bottom). Sounds were emitted by the male at the nest entrance. Mean levels for pressure (dB re:1 μPa) and velocity (dB re:1 cm/s) of each harmonic were calculated from five sounds at each distance. Differences in fundamental frequency (and higher harmonics) between the two males are explained by water temperature (Torricelli *et al.*, 1990). Changes in the mean value of the p/u ratio with distance were determined for the fundamental frequency of sounds of the two males. P/u ratios were computed by converting decibel levels of pressure and velocity into original units and computing the ratio as Pascals per meters per second.

D. Relationships between sound and AN spectrum: Implications for acoustic communication and hearing in noise

By fitting the main sound frequencies into the quiet region, *P. martensii* increases the S/N ratio for the perception of sound under high AN levels, regardless of the physical stimulus used for detection (i.e., pressure or velocity). Maximum auditory sensitivity of *P. martensii* occurs between 70 and 150 Hz, i.e., within the quiet window, and thresholds are above 105 dB (re:1 μPa). Thus SPL of *P. martensii* sounds recorded 10 cm from the nest (see Fig. 10, top) should be
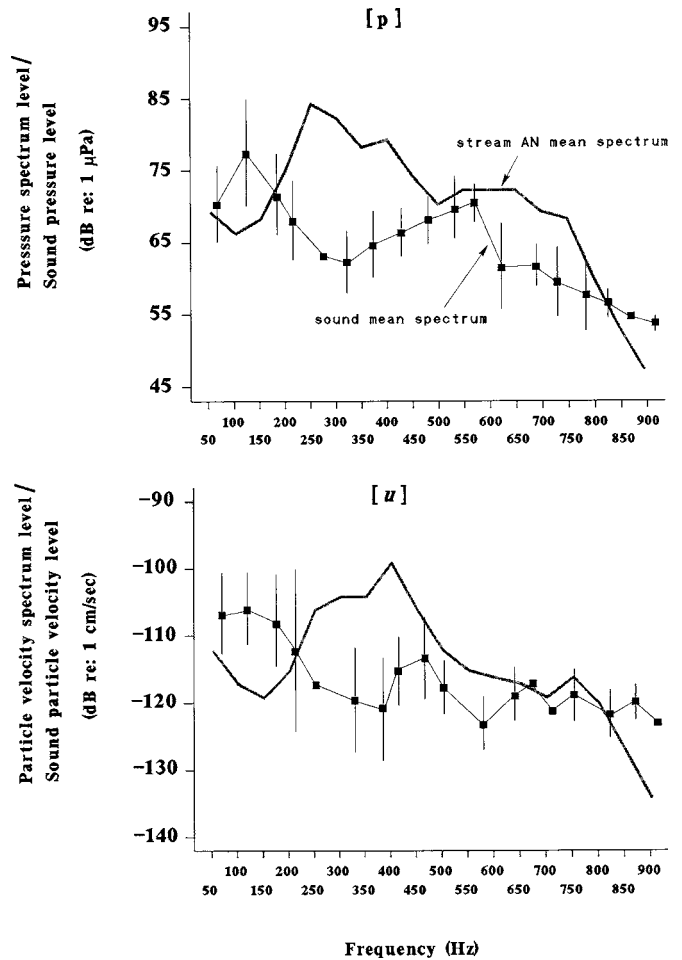

FIG. 10. The relationship between *P. martensii* mean sound spectrum (10 cm from the calling male) and the stream mean AN spectrum for sound pressure (top) and particle velocity (bottom). Mean spectrum was calculated using 30 sounds by 5 males recorded at quiet sites of the stream (i.e., far from sources of elevated AN levels, see Sec. II). Square symbols without standard error bar indicate mean values computed using $n < 3$ sounds. The AN mean spectra for pressure and particle velocity are those reported in Fig. 4.

audible only within several centimeters of the emitter. Yet, laboratory experiments indicate both sexes respond to courtship sound playback at typical levels through a speaker placed 30 cm from the test fish (Lugli *et al.*, 1996, 2004). The stream goby is likely a velocity sensitive species, and a complete understanding of signal/AN matching must also consider velocity sensitivity.

Noisy sites will impair sound detection. In the quiet region, levels at 10 cm from the nest exceed spectrum levels by 10 dB, or less, for both pressure and velocity. A 10 dB S/N ratio for p is below the minimum (generally 15–25 dB for frequencies below 1 kHz) required by teleosts for detection of tone signals under masking conditions (e.g., Popper and Fay, 1973; Fay and Megela-Simmons, 1999). Goby sounds however, are composed of multiple frequencies and thus will excite more auditory neurons than a tone of a single frequency. Torricelli *et al.* (1986) found that courting males leave the nest and approach ripe females using visual displays and courtship sounds to entice them back to the nest. Communication over truly short distances may be all that is required in this species although communication will be fa-

cilitated under noisy conditions by the quiet window. Detection distances would of course increase in quiet regions.

E. Pressure versus particle motion measurements: suggestions for future studies on fish bioacoustics

P and *u* components of stream AN and for fish sounds may, or may not, track each other for single measurements although mean spectra are more similar. The presence of the low-frequency quiet window is clear in both *p* and *u* AN spectra as is the concentration of the energy at the fundamental in *p* and *u* spectra of the tonal sound. Therefore SPL pressure measurements, either for environmental noise or sounds emitted by a particle-sensitive teleost are likely relevant for characterization of the dominant frequencies used for communication in the *u* dimension. However, the peak values of particle velocity may be under- or overestimated on the pressure spectrum. These conclusions are drawn for frequencies below the cutoff (i.e., under conditions of non propagation of the sound wave). Further investigations are needed to validate them in the case of a propagating sound wave.

ACKNOWLEDGMENTS

Akamatsu, T., Okumura, T., Novarini, N., and Yan, H. Y. (**2002**). "Empirical refinements applicable to the recording of fish sounds in small tanks," J. Acoust. Soc. Am. **112**, 3073–3082.

Amoser, S. (**2007**). "Acoustic communication in fishes: Influence of the habitat on sound detection," Thesis Dissertation, University of Vienna, Vienna, Austria.

Barimo, J. F., and Fine, M. L. (**1998**). "Relationship of swim-bladder shape to the directionality pattern of underwater sound in the oyster toadfish," Can. J. Zool. **76**, 134–143.

Bastyr, K. J., Lauchle, G. C., and Mc Connell, J. A. (**1999**). "Development of a velocity underwater acoustic intensity sensor," J. Acoust. Soc. Am. **106**, 3178–3188.

Fay, R. R., and Megela-Simmons, A. (**1999**). "The sense of hearing in fishes and anphibians," in *Comparative Hearing: Fish and Anphibians*, edited by R. R. Fay and A. N. Popper (Springer, New York), pp. 269–318.

Franz, G. J. (**1959**). "Splashes as sources of sound in liquids," J. Acoust. Soc. Am. **31**, 1080–1096.

Horch, K., and Salmon, M. (**1973**). "Adaptations to the acoustic environment by the Squirrelfishes *Myripristis violaceus* and *M. Pralinius*," Mar. Behav. and Physiol. **2**, 121–139.

Kalmijn, Ad. J. (**1988**). "Hydrodynamic and acoustic field detection," in *Sensory Biology of Aquatic Animals*, edited by J. Atema, R. R. Fay, A. N. Popper, and W. N. Tavolga (Springer, New York), pp. 83–130.

Lugli, M., Bobbio, L., Torricelli, P., and Gandolfi, G. (**1992**). "Breeding ecology and male spawning success in two hill-stream populations of the freshwater goby, *Padogobius martensii*," Environ. Biol. Fishes **35**, 37–48.

Lugli, M., and Fine, M. L. (**2003**). "Acoustic communication in two freshwater gobies: ambient noise and short-range propagation in shallow streams," J. Acoust. Soc. Am. **114**, 512–521.

Lugli, M., Pavan, G., and Torricelli, P. (**1996**). "The importance of breeding vocalizations for mate attraction in a freshwater goby with composite sound repertoire," Ethol. Ecol. Evol. **8**, 343–351.

Lugli, M., Pavan, G., and Torricelli, P. (**2004**). "The response of the male freshwater goby to natural and synthetic male courtship sound playback following exposure to different female sexual stimuli," Ethol. Ecol. Evol. **16**, 55–70.

Lugli, M., Pavan, G., Torricelli, P., and Bobbio, L. (**1995**). "Spawning vocalizations in male freshwater gobies (Pisces, Gobiidae)," Environ. Biol. Fishes **43**, 219–231.

Lugli, M., Torricelli, P., Pavan, G., and Mainardi, D. (**1997**). "Sound production during courtship and spawning in freshwater gobies (Pisces, Gobiidae)," Mar. Freshw. Behav. Physiol. **29**, 109–126.

Lugli, M., Yan, H. Y., and Fine, M. (**2003**). "Acoustic communication in two freshwater gobies: The relationship between ambient noise, hearing thresholds and sound spectrum," J. Comp. Physiol. [A] **189**, 309–320.

McConnell, A. J. (**2003**). "Analysis of a compliantly suspended acoustic velocity sensor," J. Acoust. Soc. Am. **113**, 1395–1405.

Michelsen, A. (**1983**). "Biophysical basis of sound communication," in *Bioacoustics: A Comparative Approach*, edited by B. Lewis (Academic, London), pp. 3–38.

Morse, P. M., and Uno Ingard, K. (**1968**). *Theoretical Acoustics* (Princeton University Press, Princeton, NJ).

Popper, A. N., and Fay, R. R. (**1973**). "Sound detection and processing by teleost fishes: A critical review," J. Acoust. Soc. Am. **53**, 1515–1529.

Rogers, P. H., and Cox, M. (**1988**). "Underwater sounds as a biological stimulus," in *Sensory Biology of Aquatic Animals*, edited by J. Atema, R. R. Fay, A. N. Popper, and W. N. Tavolga (Springer, New York), pp. 131–149.

Siegel, S. and Castellan, N. J., Jr. (**1988**). *Nonparametric Statistics for the Behavioral Sciences* (McGraw–Hill, New York).

Siler, W. (**1969**). "Near- and farfields in a marine environment," J. Acoust. Soc. Am. **46**, 483–484.

Strasberg, M. (**1979**). "Nonacoustic noise interface in measurements of infrasonic ambient noise," J. Acoust. Soc. Am. **66**, 1487–1493.

Torricelli, P., and Romani, R. (**1986**). "Sound production in the Italian freshwater goby, *Padogobius martensii*," Copeia **1**, 213–216.

Torricelli, P., Lugli, M., and Gandolfi, G. (**1986**). "A quantitative analysis of the occurrence of visual and acoustic displays during the courtship in the freshwater goby, *Padogobius martensi* (Gunther, 1861) (Pisces, Gobiidae)," Boll. Zool. **53**, 85–89.

Torricelli, P., Lugli, M., and Pavan, G. (**1990**). "Analysis of sounds produced by male *Padogobius martensi* (Pisces, Gobiidae) and factors affecting their structural properties," Bioacoustics **2**, 261–275.

Urick, R. J. (**1983**). *Principles of Underwater Sound* (Peninsula Publishing, Los Altos, CA).

Watkins, W. A. (**1967**). "The harmonic interval: fact or artifact in spectral analysis of pulse trains," in *Marine Bio-Acoustics*, edited by W. N. Tavolga (Pergamon, New York), vol. **2**, pp. 15–43.

Whang, A., and Janssen, J. (**1994**). "Sound production through the substrate during reproduction in the mottled sculpin, *Cottus bairdi* (Cottidae)," Envir. Biol. Fish. **40**, 141–148.

Wiley, R. H., and Richards, D. G. (**1982**). "Adaptations for acoustic communication in birds: sound transmission and signal detection," in *Acoustic Communication in Birds*, edited by D. E. Kroodsma and E. H. Miller (Academic, New York), Vol. **1**, pp. 131–278.