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Noise characteristics of the Kirby Morgan 37 surface-supplied diving helmet under simulated diving conditions

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ABSTRACT:
Divers are exposed to noise from a variety of sources, including their breathing apparatus. Furthermore, there is a significant body of information that suggests divers are susceptible to hearing loss that worsens faster than the general population. This study measured the noise characteristics of a commonly used diving helmet, the Kirby Morgan 37 (Kirby Morgan Dive Systems, Inc., Santa Maria, CA) under simulated diving conditions that included variations in depth, breathing rate, and breathing gas. Depth was varied from 0 to 165 feet sea water (fsw) and breathing rates were varied from 22.5 to 90 liters per minute (lpm). Air and an 80% helium/20% oxygen mixture (heliox) were considered as diving gases. Measured noise levels increased with increases in both diving depth and breathing rate. Using heliox as the breathing gas produced lower noise levels than air under the same conditions. It was observed that the spectral characteristics of inhalation and exhalation were considerably different due to different flow paths through the apparatus. Exhalation produced mostly low frequency noise (below 600 Hz), while inhalation was responsible for most of the noise between 600 Hz and 20 kHz. https://doi.org/10.1121/10.0008904

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I. INTRODUCTION

Divers are routinely exposed to noise from a variety of sources, including their breathing apparatus, communications system, ambient dive site sources, and underwater tools. There is significant evidence in the literature showing that divers are at risk of hearing damage. Anthony *et al.* (2010) collected the results of several investigations and categorized them into retrospective and prospective studies. Retrospective studies compared hearing loss with diving history, while prospective studies examined the same individuals before and after periods of significant diving. Overall, multiple studies were identified that found hearing among divers worsened more quickly than the general population (Zannini *et al.*, 1976; Edmonds and Freeman, 1985; Molvaer and Lehmann, 1985; Molvaer and Albrektsen, 1990; Johnston and Pethybridge, 1994; Zulkaflay *et al.*, 1996; Skogstad *et al.*, 1999; Haraguchi *et al.*, 1999; Skogstad *et al.*, 2000; Skogstad *et al.*, 2005; Ross *et al.*, 2007).

Breathing apparatuses provide significant contributions to overall noise levels, which may exceed occupational limits on noise exposure (Reimers and Summitt, 1973; Parvin *et al.*, 1994; Anthony *et al.*, 1994; Occupational Safety and Health Administration, 1999; OSHA 1910.95, 1971). The primary breathing apparatus noise contributors are inhalation flow noise through the demand regulator and exhalation exhaust bubbles. Korenbaum *et al.* (2016) and Radford *et al.* (2005) showed that breathing noise in scuba and rebreather devices was periodic with variations in frequency spectrum and intensity during inhalation and exhalation. However, Korenbaum *et al.* (2016) attributed the more powerful broader frequency bands to exhalation bubble noise, while Radford *et al.* (2005) attributed these zones to inhalation gas flow through the demand regulator. Both noted that overall noise from closed-circuit rebreather devices was lower than scuba devices due to reductions in bubble production. Radford *et al.* (2005) determined that the noise reductions in rebreathers occurred at lower frequencies, supporting their determination that the lower-frequency zones were the exhalation periods. Donskoy *et al.* (2008) also measured scuba system noise and modeled flow through the first-stage pressure regulator, concluding that the significant pressure drop across the regulator during inhalation is the primary broadband noise contributor.

With regard to mitigating diver noise hazards, there exists significant differences in the type of apparatus used. Specifically, whether the diver's ears are "wet" or "dry" is important. When using a mask that does not cover the ears, water can fill the auditory canal and contact the tympanic membrane. However, when diving with an enclosed helmet breathing apparatus, the diver's head is surrounded by gas and the ears are consequently "dry". In the wet situation, sound can more easily transfer to the body and generate hearing through bone conduction. Hearing can occur by

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[a)] Also at: Department of Ocean and Mechanical Engineering, Florida Atlantic University, 777 Glades Road, Boca Raton, FL 33431, USA. Electronic mail: Tye.Langston@Navy.mil excitation of the cochlear, with little involvement from the outer ear and tympanic membrane (Montague and Strickland, 1961; Norman *et al.*, 1971; Hollien and Feinstein, 1975; Anthony *et al.*, 2010). The tympanic membrane has been shown to play some role in underwater "wet" hearing, although sound is coupled less effectively underwater and therefore, plays a lesser role (Smith, 1969, 1985; Parvin and Nedwell, 1993). A wet-ear–specific auditory threshold curve and noise weighting scale have been defined to account for the differences in underwater sound (Parvin *et al.*, 1993; Parvin and Nedwell, 1995).

In a "dry" ear situation, such as in a diving helmet, bone conduction conversely plays a lesser role and the majority of sound is heard through the hyperbaric gas eardrum pathway (Parvin *et al.*, 1994; Anthony *et al.*, 2010). Thus, dry helmet noise exposure hazards can be evaluated using similar methodology to occupational noise hazard assessments on land. However, there are environmental differences when diving that affect sound propagation through the air, including: variations in pressure, gas density, and gas compositions. Divers may use various non-air gas mixtures, such as nitrox (nitrogen and oxygen), heliox (helium and oxygen), trimix (nitrogen, helium, and oxygen), or hydreliox (hydrogen, helium, and oxygen), which may further vary in their individual compositions.

Previous studies have investigated the hearing effects of different breathing gases and hyperbaric pressure changes. In terms of pressure variations, the reported results are mixed. Fluur and Adolfson (1966) reported increasing hearing impairment at 500 Hz and 3–5 kHz with increasing depth using air as the breathing gas. Thomas *et al.* (1974) and Thomas *et al.* (1979) found increasing hearing deficits with increasing depth using heliox as the breathing gas. However, they also identified increases in hearing sensitivity at 2 and 6 kHz. Conversely, other investigators have found no changes in diver hearing following long saturation dives, in which divers can remain submerged for extended periods by allowing the inert components of their breathing gas to equalize partial pressures with their tissues. Mendel *et al.* (2000) evaluated divers during saturation dives to 1000 feet sea water (fsw), while O'Reilly *et al.* (1977) evaluated divers after a 24 d saturation dive to 610 fsw. Waterman and Smith (1970) examined the effects of different breathing gases on hearing at standard temperature and pressure, finding no changes. Considering these studies, Anthony *et al.* (2010) recommended the application of land-based occupational noise limits to helmet diving, regardless of pressure or breathing gas.

Enclosed diving helmets are reported to generate significant diver noise exposure. Using air, internal helmet sound pressure levels have been reported as high as 103, 104, and 106 dB(A) for different helmet types, depths, and breathing rates (Reimers and Summitt, 1973; Parvin *et al.*, 1994; Anthony *et al.*, 1994). When using heliox, Reimers and Summitt (1973) reported a maximum sound pressure level of 116 dB(A) for the Mark V model dive helmet (Dive Lab Inc., Panama City, FL). Evans *et al.* (2007) also performed manned noise evaluations in three different diving helmet types [Diving System International (DSI) SuperLite (SL) 17B (Diving Systems International., Santa Maria, CA) Kirby Morgan SL-17K (Kirby Morgan Dive Systems, Inc., Santa Maria, CA) and Divex "Dirty Harry" (Divex Ltd., Aberdeen, Scotland)], under various ventilation rates, although they did not apply hyperbaric depth simulation. The maximum sound pressure levels were 93, 95, and 97 dB(A) respectively, under maximum ventilation conditions up to approximately 120 liters per minute (lpm). Furthermore, they found that communications needed to exceed background levels by approximately 15 dB to be audible, which exacerbates the problem. From these studies, it is apparent that noise levels increase with depth, breathing rate, and communications.

Land-based occupational noise limits have been identified that relate sound levels to permissible exposure durations. In the U.S., these limits are dictated by the Occupational Safety and Health Association (OSHA). The permissible exposure durations range from 16 h/day at 85 dB(A) to 15 min at 115 dB(A) (Occupational Safety and Health Administration, 1999; OSHA 1910.95). However, the National Institute for Occupational Safety and Health (NIOSH) found that hearing loss can still occur at the OSHA-required exposure limits (National Institute for Occupational Safety and Health, 1998) and OSHA further requires a Hearing Conservation Program be established when the 8 h exposure is 85 dB(A) or higher (OSHA 1910.95). It is clear that diving helmets could exceed these exposure limits, especially when considering that communications require sound pressure levels approximately 15 dB over the ambient breathing noise (Evans *et al.*, 2007).

One commonly used dive helmet for both Navy and commercial use is the Kirby Morgan 37 (KM37). The KM37 is a surface-supplied helmet breathing apparatus with a composite (fiberglass and carbon fiber) shell. It is typically configured with a SuperFlow 350 (SF350) (Kirby Morgan Dive Systems, Inc., Santa Maria, CA) regulator, a quad valve exhaust system, a defogging/steady flow valve, and a communications system. In this effort, unmanned in-ear noise levels were evaluated for the standard KM37 configuration under a range of simulated diving depths and breathing rates. Both air and an 80% helium/20% oxygen mixture (heliox) were considered for breathing gases.

II. METHODS

Unmanned noise measurements on a KM37 helmet were performed utilizing a specially designed manikin head capable of simultaneously breathing in a dive helmet and capturing in-ear noise measurements. The manikin head, provided by Dive Lab Inc. (Dive Lab Inc., Panama City, FL) is shown in Fig. 1. It has rubber ear simulators and access to the intracranial area for microphone management, as well as a mouth and trachea tube for connection to a breathing machine. The breathing machine sound pressure level at the helmetless manikin ear was not found to significantly change with variations in breathing rates. That is, the measured levels were not contaminated by breathing machine noise.

Diving depths of 0, 66, and 165 fsw were simulated in a hyperbaric chamber (ASTM certified to 1000 fsw with a

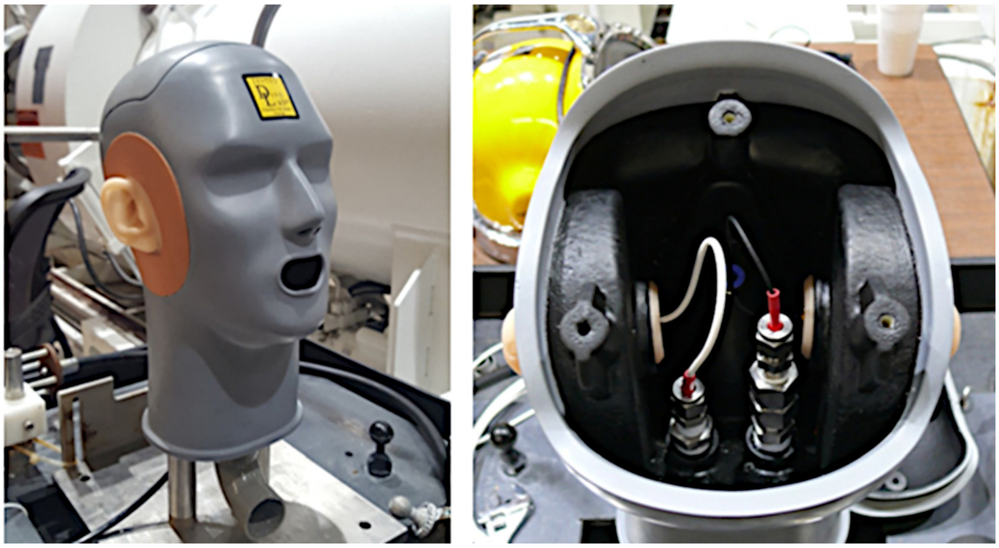

FIG. 1. (Color online) Breathing, hearing manikin head used for noise testing.

0.1 psi resolution). Sinusoidal breathing patterns were provided with a single cylinder breathing machine at the rates of 0, 22.5, 40, 62.5, 75, and 90 lpm, which are commonly specified for Navy underwater breathing apparatus testing (Navy Experimental Diving Unit, No. 15–01). Evaluations were performed while breathing air at all depths and breathing rates, and on an 80% helium/20% oxygen mixture (heliox) at 165 fsw and all breathing rates. Heliox was only considered at 165 fsw because this represents a typical depth for transitioning from air to heliox in practice (NEDU No. 15–01). Additionally, noise was measured with the defogging steady flow valve fully open and purge valve depressed. Both of these unique scenarios were evaluated at a depth of 0 fsw, breathing air at 40 lpm.

In-helmet sound was recorded with two PCB quarter-inch microphones (model 378A12) (PCB Piezotronics, Depew, NY) with calibrated sensitivities of 0.19407952 and 0.26337687 mV/Pa, and a usable frequency range of 5 Hz to 20 kHz. One microphone was fitted in each of the manikin head's ears. Data from each transducer was recorded using a LMS SCADAS Mobile multi-channel data acquisition system (LMS International, Leuven, Belgium) with a dynamic range of 150 dB, calibrated traceable to National Institute of Standards and Technology (NIST) standards at a sampling rate of 124 kHz. Two test runs were performed for each configuration for at least 30 s, which included multiple inhale–exhale breathing cycles. The average difference was 1.7 dB for data between the two microphones and 0.3 dB between independent test runs. The data reported consist of averages of the test runs and individual sensor data. Microphone data acquired in atypical atmospheric conditions, such as with variations in pressure and gas types, requires data corrections to allow comparison between data taken in different conditions. Changes in gas pressure and density affects sound speed, which in turn, affects impedance. To account for these changes, adjustments were made using the equation

$$dB_{adjusted} = 20 \times log_{10}\left\langle \frac{Z_{Surface}}{Z_{Depth}} \right\rangle, \tag{1}$$

where $dB_{adjusted}$ = the decibel transfer function to subtract from measured levels, Z = impedance = ρc, ρ = gas density, and c = speed of sound.

III. RESULTS

Similar to results reported for other helmet types (Zannini *et al.*, 1976; Edmonds and Freeman, 1985; Molvaer and Lehmann, 1985; Molvaer and Albrektsen, 1990; Johnston and Pethybridge, 1994; Zulkaflay *et al.*, 1996; Skogstad *et al.*, 1999; Haraguchi *et al.*, 1999; Skogstad *et al.*, 2000; Skogstad *et al.*, 2005; Ross *et al.*, 2007), KM37 noise levels were found to increase with both depth and breathing rates. Figure 2 shows the overall sound pressure levels for all breathing conditions tested and Table I provides the values. Figures 3 and 4 independently show the spectral changes as

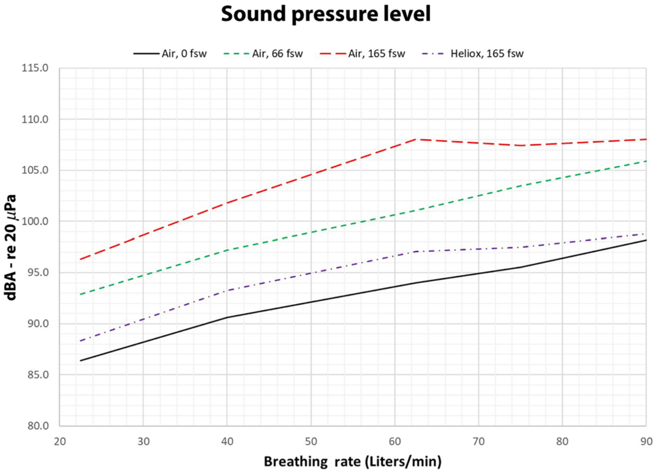

FIG. 2. (Color online) A-weighted helmet sound pressure level as a function of breathing rate, simulated depth, and breathing gas.

TABLE I. A-weighted helmet sound pressure level as a function of breathing rate, simulated depth, and breathing gas.

Depth (fsw)	Sound pressure level (dB – re: 20 μPa)				
	Breathing Rate (lpm)				
	22.5	40	62.5	75	90
0 (air)	86	91	94	96	98
66 (air)	93	97	101	104	106
165 (air)	96	102	108	108	108
165 (heliox)	88	93	97	98	99

functions of depth (constant 40 lpm breathing rate) and breathing rates (constant 66 fsw depth), respectively, using air as the breathing gas. Figure 5 shows the spectral changes using heliox at different breathing rates (heliox was only evaluated at 165 fsw due to typical operational usage). Figure 6 shows the spectral content in the independent free-flow cases of breathing with the defogging steady flow valve fully open and purge valve depressed. In addition, Fig. 7 provides a spectrogram graph to highlight the temporal frequency variations between inhalation and exhalation.

IV. DISCUSSION

There is a significant number of studies, both retrospective and prospective, that indicate divers are susceptible to hearing impairment (Zannini *et al.*, 1976; Edmonds and Freeman, 1985; Molvaer and Lehmann, 1985; Molvaer and Albrektsen, 1990; Johnston and Pethybridge, 1994; Zulkaflay *et al.*, 1996; Haraguchi *et al.*, 1999; Skogstad *et al.*, 1999; Skogstad *et al.*, 2000; Skogstad *et al.*, 2005; Ross *et al.*, 2007; Anthony *et al.*, 2010). Noise may originate externally from tools and ambient sources, but the breathing apparatus and communications system are significant contributors.

In this effort, the internal "in-ear" noise generated by a Kirby Morgan 37 dive helmet was evaluated under a variety of breathing rate, breathing gas, and depth conditions.

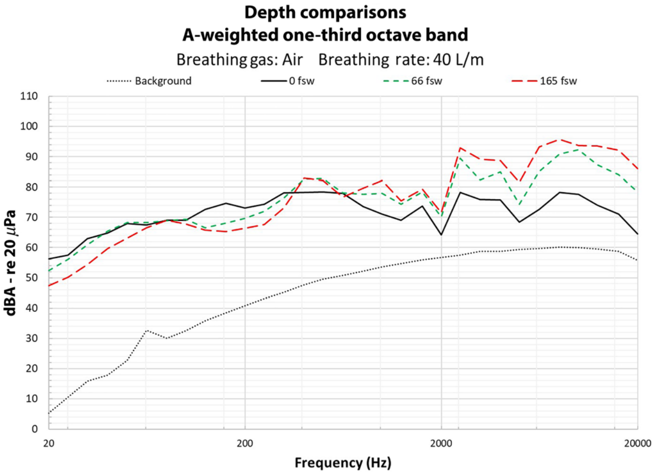

FIG. 3. (Color online) A-weighted one-third octave band sound pressure levels as a function of simulated depth (40 lpm, air).

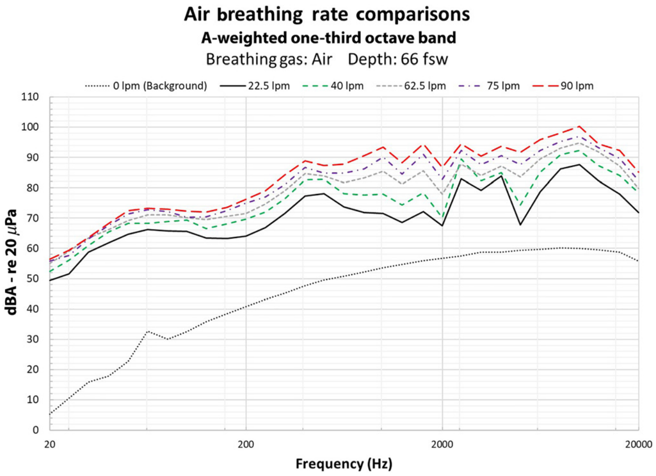

FIG. 4. (Color online) A-weighted one-third octave band sound pressure levels as a function of breathing rate (66 fsw, air).

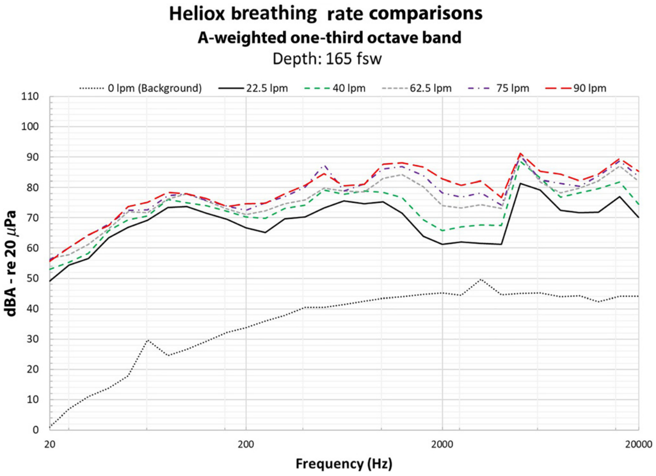

FIG. 5. (Color online) A-weighted one-third octave band sound pressure levels as a function of breathing rate (165 fsw, heliox).

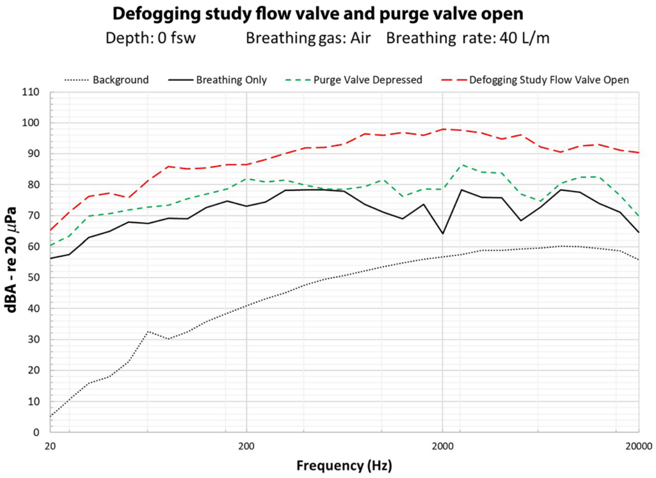

FIG. 6. (Color online) A-weighted one-third octave band sound pressure level with defogging steady flow and purge valves open (0 fsw, air).

Similar to results reported for other dive helmets (Reimers and Summitt, 1973; Parvin *et al.*, 1994; Anthony *et al.*, 1994; Evans *et al.*, 2007), this evaluation determined that the Kirby Morgan 37 dive helmet produces noise levels that could exceed occupational limits under certain conditions and dive durations. Noise levels ranging from 86 to 109 dBA were measured in this effort. OSHA defines an acceptable work day limit as 85 dBA and reduces allowable exposure time with noise level. Exposure to noise at 115 dBA is considered acceptable for no longer than 15 min (Occupational Safety and Health Administration, 1999; OSHA 1910.95). As these limits are a function of both noise level and exposure time, it is important to consider dive durations to protect divers from hearing damage when diving with the KM37. Furthermore, it must also be considered that communications systems require approximately 15 dB over the helmet noise to be effective (Evans *et al.*, 2007).

Noise levels were found to increase with both breathing rate and simulated diving depth. On average, sound pressure level consistently increased by approximately 11 dB between the lowest and highest breathing rates (22.5 and 90 lpm, respectively), independent of pressure. Similarly, sound pressure levels also increased by approximately 11 dB with depth increases from 0 to 165 fsw, independent of breathing rate. The breathing rate SPL increases can be explained simply through the fact that higher breathing rates required higher flowrates through the breathing apparatus, therefore, increasing flow noise within the regulator (Morse and Ingard, 1968). This increase is seen largely at higher frequencies. And consequently, the SPL at lower frequencies, which was dominated by bubble noise, increased due to additional volumes of exhaled gas.

SPL increases with depth were only observed above approximately 600 Hz (Fig. 3), which is the approximate frequency cutoff for the exhalation bubble noise contribution (Fig. 7). This suggests that the higher-frequency regulator inhalation noise increases with depth, but the lower-frequency exhalation bubble noise does not. The inhalation noise increases can be explained by the increases in gas density. While breathing rates affect inhalation noise by changing the volume of gas passing through the regulator, depth changes the gas mass. Both of these factors lead to higher Reynold's numbers and therefore, more turbulence and noise. Breathing gases are at higher pressure at depth to match ambient helmet pressure and consequently, more mass must pass through the regulator passages at any given breathing rate and inhalation volume.

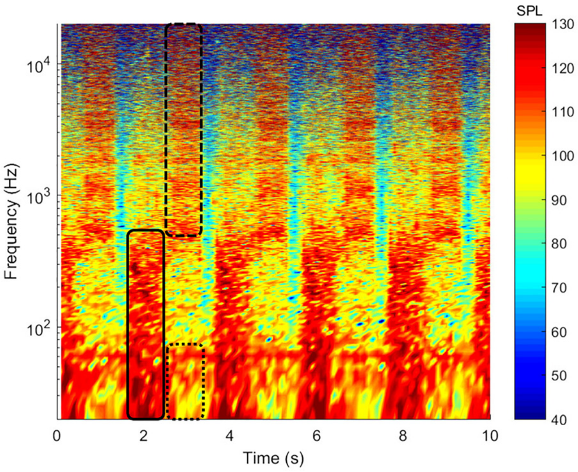

FIG. 7. (Color online) Spectrogram showing frequency-dependent differences between breath-in versus breath-out.

But with the lung tidal volume remaining constant, the volume of bubbles at a given breathing rate remains unchanged regardless of depth, and although the gas within the bubbles is denser, its average density is in equilibrium with the surrounding seawater. As discussed by Prosperetti (1988), and Longuet-Higgins (1990), bubble noise is primarily a result of shape oscillation. In this case, newly formed bubbles released from the helmet exhaust were observed to be irregularly shaped and would be expected to oscillate in shape until a spherical equilibrium was reached. The exhaust bubbles were noticeably large and, as mentioned in Prosperetti (1988), larger bubbles have been observed to split, which would also result in shape oscillation of the resultant aspherical bubbles.

Changing the breathing gas from air to heliox also affected noise levels, with heliox noise levels being approximately 9 dBA lower than air at the same depth (165 fsw) and breathing rates. As heliox is a lower density gas than air, flow noise through the regulator passages would be expected to be lower due to lower Reynolds numbers in all conditions.

While the SPL continued increasing through all breathing rates at 0 and 66 fsw, it appeared to level off beyond the breathing rate of 62.5 lpm at 165 fsw depth with both air and heliox. It is noted that these scenarios represent the most demanding conditions for the breathing machine (highest pressure and densest gasses), and it is possible that this leveling off effect may indicate a performance limitation where the machine was not capable of delivering its full programmed flow rates. Heliox, being the lower density gas, would be expected to have a lesser effect as the Fig. 2 data shows.

The sound properties of inhalation versus exhalation are very different for the KM37 due to the different gas flow paths, as shown in Fig. 7. During inhalation, breathing gas is drawn into the helmet through the SF350 regulator and higher-frequency flow noise is generated. But during exhalation, lower-frequency bubble noise dominates as the gas is exhaled to the surrounding water through the helmet exhaust valves and whisker wings. Most of the spectral contribution from inhalation was seen above 600 Hz up to the upper range of human hearing (∼16 kHz) while exhalation was dominated by lower-frequency bubble noise below 600 Hz.

V. CONCLUSION

The KM37 helmet breathing apparatus, like other helmets that have been evaluated by others, can produce significant sound pressure levels, which vary depending on breathing rate and depths in which it is used. As there is a significant body of literature pointing to diver hearing impairment, it is important to plan dive durations to consider these factors and assure exposures are limited to within the applicable occupational safety guidelines. Furthermore, the understanding of how hyperbaric sound affects human hearing is still subject to debate and continued evaluation is warranted.

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