

Fish Sound Characterization Using Multifractal Detrended Fluctuation Analysis

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The present work involves application of a nonlinear method, multifractal detrended fluctuation analysis (MFDFA) to describe fish sound data recorded from the open water of two major estuarine systems. Applying MFDFA, the second order Hurst exponent $h(q = 2)$ values are found to be 1.10 ± 0.03 and 1.43 ± 0.02 for fish families Batrachoididae (common name: Toadfish) and Sciaenidae (common name: croakers, drums) respectively. The generalized Hurst exponent $h(q)$ related width parameters $\Delta h(q)$ are found to be 1.05 ± 0.08 and 0.94 ± 0.06 , respectively for Toadfish and Sciaenidae vocalizations, implying greater heterogeneity and multifractal characteristics. The results suggest that the Sciaenidae fish calls are smoother in comparison with the Batrachoididae. Clustering of multifractal spectrum related parameters with respect to the Toadfish and Sciaenidae vocalization characteristics are observed in this analyses.

Keywords: Fish sound; Batrachoididae; Sciaenidae; Nonlinear technique; MFDFA.

1. Introduction

Many fish family uses vocal signal during their activities and produce sounds using sonic muscles that vibrate the swimbladder or rubbing of bony elements (stridulation) [1]. The passive acoustic data recording using an autonomous system with wideband hydrophones are imperative for fish sound data recording [2]. In this study, we analyzed fish vocalizations recorded using a passive acoustic device from the shallow water locations of two major estuarine systems. Fish sound identification under captive conditions and related difficulties are not unknown [3]. The tank dimension, maintenance of oxygen level and effect of chronic aquarium noise exposure to fish health within the tank are major hindrances to study the fish behavior under captive environment. Therefore, in recent years *in situ* passive acoustic data recordings and analyses became increasingly popular [4].

In general, the temporal and spectral characteristics of fish calls such as oscillogram, spectrogram, and peak sound level of the power spectral density (PSD) (Table 1a) allow fish family identification [5]. The power spectrum encompasses several dominant frequencies, which presumably represent major oscillation modes in the fish sound, but the amplitudes of these modes may vary in a complex manner [6]. The animal vocalizations are frequently characterized by two basic parameters, namely, the dominant and peak frequency [7]. Colson et al. [8] compared the peak frequency derived from the fish vocalization. However, the peak frequency is found to be fluctuating, which may be ascribable to the phase couplings observed across temporal scales in the fish call train [9], for example the Toadfish and Sciaenidae studied here [Fig. 1(a, b)]. The insets in panels (a) and (b) show temporal variation of the local Hurst exponent H_t in call signals. The computation of H_t is advantageous to identify the time instant of structural changes within the time series [10]. Although the spectrogram analyses of fish calls indicate phase couplings [Fig. 1(e, f)] with several dominant frequencies (ranging between 0.1 – 2.5 kHz and 0.5 – 1.5 kHz for Toadfish and Sciaenidae calls respectively), this phase coupling behavior complicates the detection of the peak frequencies of the PSDs. This makes spectrogram analyses and related peak frequency estimation inadequate for describing all statistical features of fish calls [9]. This phase coupling behavior calls for the application of alternative higher-order statistical techniques including bispectral and Multifractal Detrended Fluctuation Analysis (MFDFA). Moreover, the power spectral density based analyses are not effective for such nonlinear signals [11] due to the presence of large fluctuations, especially at high-frequencies and the use of a nonlinear technique to characterize recorded fish sound data [12] is a necessity. Previous studies have reported such complexities in seahorse (*Hippocampus Kuda*) feeding clicks due to nonlinearities in the sound production system [6, 9].

The nonlinear phenomena in animal vocalizations are common, and now being used to understand the bioacoustics observations including family description [13]. Therefore, the application of nonlinear signal processing techniques is important to describe complexities of animal vocalizations, and have been hypothesized to take an important role in individual identification. Multifractal system [14, 15], is a generalization of a fractal system in which a single scaling exponent is not enough to describe its dynamics. Instead, a continuous spectrum of exponents (so-called singularity spectrum) is needed. The MFDFA was first conceived by Kantelhardt et al. [16]. This method has been applied to study the multifractal scaling behavior in feeding clicks of seahorse (*Hippocampus Kuda*) [9]. Accordingly, in this work, the MFDFA is used to evaluate its effectiveness in distinguishing two fish family vocalizations (Toadfish and Sciaenidae).

Toadfish produce sounds by contracting its fast intrinsic sonic muscles attached to large areas of the swimbladder. Sounds include boatwhistles (produced by rapid, sustained sonic muscle contraction), and grunts (agonistics sounds) [17]. The members of the Batrachoididae family such as *Colletteichthys occidentalis* are usually called Toadfishes [18], which have been reported in the Arabian Sea. Sciaenidae is a family of fishes commonly called drums or croakers. Sciaenidae have extrinsic sonic muscles originate on other muscles which are superficially attached to the swimbladder. Sciaenidae sounds range from pulsed to tonal produced by a rapid contraction of the sonic musculature. Both the fish family produces sound using sonic muscles that vibrate the swimbladder. There is a long history of many elegant studies of fish sound generation involving neural, muscular and hormonal mechanisms [19].

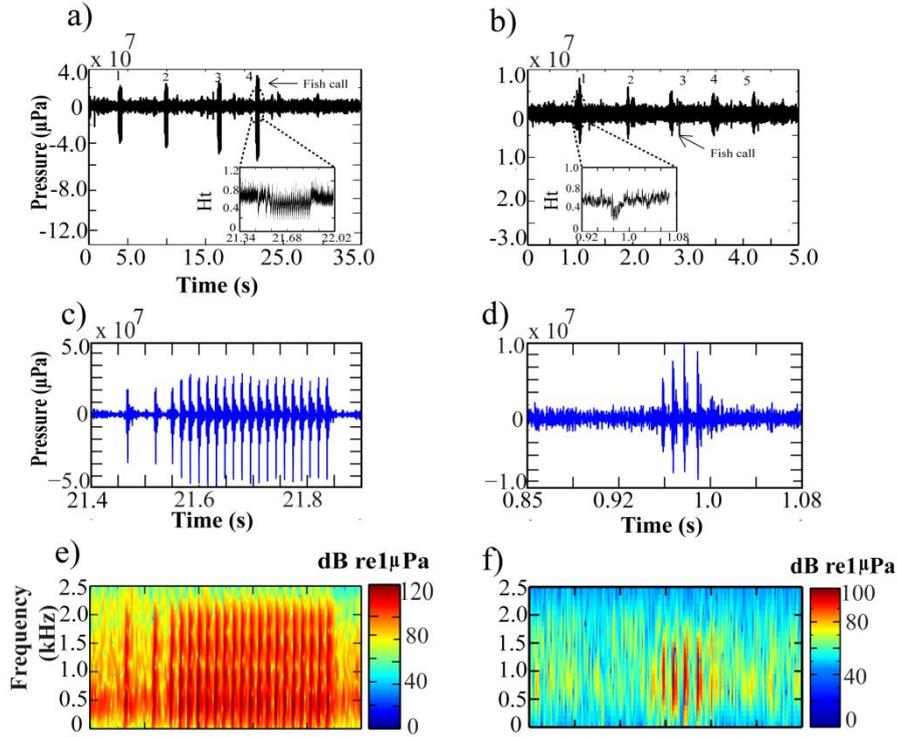


Fig. 1. (Color online) Example oscillogram of Toadfish and Sciaenidae are depicted in panel (a) and (b). The inset in panels shows an example for temporal variation of the local Hurst exponent H_t in the respective fish calls, highlighting the time instant of structural changes. The spectrogram analyses show phase couplings in the signal (c and d) with several dominant frequencies ranging between: (e) 0.1 – 2.5 kHz for Toadfish and (f) 0.5 – 1.5 kHz for Sciaenidae (see introduction section for more details).

In this communication, sec. 2 (materials and methods) describes *in situ* recording of sound data using passive acoustic devices, and identification of fish family involving the MF DFA based signal processing. Results and discussion (sec.3) provides interpretation of the multifractal spectrum related parameters, followed by concluding remarks in sec.4.

2. Materials and Methods

2.1. Study Locations

Present study utilizes passive acoustics data acquired from two shallow and littoral environments in Goa, India: i) off *Britona* near *Chorao Island* in the Mandovi estuary (latitude: $15^{\circ} 30.587'$ N; longitude: $73^{\circ} 50.730'$ E), and ii) the *Grande Island* in the Zuari estuary (latitude: $15^{\circ} 20.16'$ N; longitude: $73^{\circ} 45.277'$ E), two major estuarine systems in Goa, India [20]. The Toadfish sounds were recorded off *Chorao Island* at 7m water depth. The Sciaenidae sounds were recorded off *Grande Island* at 20m water depth.

Table 1(a). Details of fish calls and corresponding peak frequencies.

Duration of deployment	Deployment depth (m)	Fish type	Water Temperature (°C)	Total number of calls	Individual call duration (s)	Number of pulses per call	Peak frequency (Hz)
13-14 March 2014	5	Batrachoididae (Toadfish)	29.0° to 30.45°	600	0.25 - 0.60	10-38	470±52
10-11 March 2016	10	Sciaenidae	29.20° to 29.65°	940	0.04 - 0.10	4-10	700±54

2.2. Song Meter

Modern autonomous underwater acoustic recorders, the Song Meter systems (www.wildlifeacoustics.com) (SM2M+) were used for the experiments conducted to acquire fish sound data. The recording systems were secured in the middle of the mooring line for data acquisition. The data was recorded with sampling frequencies of 44100 and 96000 Hz, respectively for deployments off *Chorao Island* and *Grande Islands*. The Song Meter hydrophones (standard acoustic type) possess bandwidth of 2-48000 Hz. The Song Meters were scheduled to record sounds for 60 and 120 sec duration at every 15 minutes interval for *Chorao* and *Grande Island* locations respectively. The Song Meter systems were calibrated at ESSO-National Institute of Ocean Technology (NIOT) calibration facility (<http://www.niot.res.in/ATF/>).

2.3. Fish Sound Identification

The spectral characteristics of fish calls were calculated by applying spectrogram and PSD analyses. Individual call details of both fish families are given in Table 1a. The PSD analysis for peak frequency estimation was performed with the Hanning window length (256), overlap (128), and nfft (1024). For fish family identification, we determined call parameters (i.e. call duration, the number of pulses, peak frequency) and compared with the published data available (Table 1a).

2.4. Noise Removal for MFDFA

The extraction of noise-free fish sound is needed before applying the MFDFA. The presence of background noise in the MFDFA analyses can generate spurious and erroneous multifractality [10]. For MFDFA analyses, we have used band-pass filtering to individual fish calls [Fig. 1 (c, d)], which involves the use of a four-pole Butterworth filter within the frequency bands: 100 to 2000 Hz. This band was chosen based on published frequency ranges of most fish calls so that we can focus on the dominant sound sources within each band [21]. To identify the start- and end-points of the individual fish call, an enhancement of the contrast between signal and background noise in the data stream is important.

We perform noise level reduction by multiplying the time series x_k with ratios of its corresponding absolutes $|x_k|$ to the maximum absolute value $[x_k |x_k|/\max|x_k|]$. Subsequently, Hilbert transform based envelope detection procedure [22] was utilized to identify the time duration of the detected signal. After identifying the time window, the corresponding amplitude values of each fish sound were extracted from the data stream. The extracted individual fish sounds were subject to the MFDFA.

The fish sound may exhibit a broad power spectrum with many subsidiary peaks. The phase coupling behavior complicates the detection of peak frequencies in the data. This can be corroborated by the spectrogram analyses provided [Fig. 1(e, f)]. MFDFA can provide satisfactorily good results when the input signals (fish sounds) are noise-like time series. The time series can be realized as noise like if the Hurst exponent H_t in the standard detrended fluctuation analysis (DFA) varies between 0.2–0.8. The MFDFA can be employed directly in such instances without transforming the signal [10]. The local Hurst exponent H_t values of Toadfish and Sciaenidae analyzed in the present study were restricted within 0.2 to 0.9 [see the inset in Fig. 1(a) and (b)]. Therefore, as suggested by Ihlen [10], the time series does not require any mathematical operation before performing MFDFA. The MFDFA followed herein has several advantages over the standard power spectral density (PSD) analyses. Previous analyses [6] using PSD has focused on the quantification of the single power-law exponent β (i.e. monofractal feature) to study the seahorse clicks. However, results of the further study [9] affirm that the fish sounds are intrinsically complex and require multiple exponents for its characterization.

2.5. MFDFA Technique

In this section, we briefly present the MFDFA technique [16]. In general, the MFDFA comprised of five major steps. The first step involves the subtraction of the mean $\langle x \rangle$ from the fish sound time

series x_k of length N to determine the cumulated data series $Y(i)$. In the second step the resulting profile $Y(i)$ was divided into non overlapping segments $[N_s \equiv \text{int}(N/s)]$ of equal length s , and the local linear trend for each of the segment was calculated in the third step by a least-square fit of the series to determine the variance

$$F^2(s, v) \equiv \frac{1}{s} \sum_{i=1}^s \{Y[(v-1)s + i] - y_v(i)\}^2, \quad (1)$$

for each segment $v = 1, \dots, N_s$. Where $y_v(i)$ is the fitting polynomial in the segment v . In the fourth step, the average over all segments was computed to obtain the q^{th} order fluctuation function

$$F_q(s) \equiv \left\{ \frac{1}{N_s} \sum_{v=1}^{N_s} [F^2(s, v)]^{q/2} \right\}^{1/q}, \quad (2)$$

where the index variable q can take any real value except zero. These fluctuation functions depend on the time scales s for different values of q [-5 to 5]. In fifth step, from the slopes of plot between $\log_2 [F_q(s)]$ and $\log_2 (s)$ for a range of q , we determine the scaling behavior of the fluctuation function.

If the series x_k has long-range power-law correlations, $F_q(s)$ scales with s as

$$F_q(s) \sim s^{h(q)}. \quad (3)$$

The function $h(q)$ is a generalized Hurst exponent. Another way to characterize a multifractal series is the calculation of singularity spectrum $f(\alpha)$, which is related to the classical multifractal scaling exponents $\tau(q)$ via a Legendre transform as $\alpha = \tau'(q)$ and $f(\alpha) = q\alpha - \tau(\alpha)$. Here, α is the singularity strength or Holder exponent, while $f(\alpha)$ denotes the dimension of the subset of the series characterized by α . Referring to Eq. (13) of [16], we can directly relate α and $f(\alpha)$ to $h(q)$ as

$$\alpha = h(q) + q(h'(q)) \text{ and } f(\alpha) = q[\alpha - h(q)] + 1. \quad (4)$$

In a multifractal formalism, the Hurst exponents provide information on the degree of call smoothness (or roughness). We used twenty representative calls from each fish family for the MF DFA. From Table 1(a), the fish call durations are observed to be in the range of 0.25 to 0.6 sec (for Toadfish) and 0.04 to 0.10 sec (for Sciaenidae). With sampling frequencies of 44100 and 96000 Hz used during data acquisition, the average data sample numbers N (within the call duration) of Toadfish and Sciaenidae were 17200 and 12384 respectively. Due to different sampling frequencies used, the data sample numbers extracted for analyses are also different. A local slope computation was necessary [23] to identify the equal scaling range between these two data sets. For local slope computation, we chose suitable segment size (s) from minimum (16) to maximum ($N/4$) i.e., 3121

and 4300 for Sciaenidae and Toadfish respectively. The computed local slopes are found to be reasonably constant up to $s = 256$ for three values of q ($q = -5, q = 0, q = +5$). The range of scales (s) for the computation of $F_q(s)$ presented in this work is chosen within 16 - 256. This range of scaling was then used to calculate the multifractal spectrum with the polynomial order ($m = 1$).

2.6. Generalized Hurst Exponent $h(q)$ and Singularity Spectrum $f(\alpha)$

The understanding of fish sounds using MF DFA is practicable by analyzing the graph of q versus $h(q)$. The fish calls would be a monofractal if $h(q)$ is constant for all values of q [16]. The width of $h(q)$ curve [$\Delta h(q) = h(q)_{max} - h(q)_{min}$] shows a measure of the multifractality and indicates the deviation from monofractal behavior. Similarly, α versus $f(\alpha)$ (multifractal spectrum) can also provide information about the multifractality. If the $f(\alpha)$ curve (i.e. multifractal spectrum) of fish call converges to a single point, it can be a monofractal. The width of $f(\alpha)$ curve [$w = \alpha_2 - \alpha_1$] also underlines a measure of multifractality and indicates the deviation from monofractal behavior. The width w would be small (e.g. background signal) and tend to zero in the case of a monofractal series. The unvarying $h(q)$ reduces $f(\alpha)$ spectrum to a narrow width and considered as monofractal series. We also computed an additional parameter (B) = $\left[\frac{(\alpha_2 - \alpha_0) - (\alpha_0 - \alpha_1)}{(\alpha_2 - \alpha_1)} \right]$, which measures the degree of asymmetry of the multifractal spectrum [24]. 'B' value indicates the dominance of low or high fractal exponents and α_0 denotes maximum singularity. The value of B is zero for symmetric shapes and positive and negative for right or left-skewed shapes respectively. A left-skewed spectrum denotes dominant low fractal exponent distributions, while the right-skewed spectrum implies dominance of high fractal exponents.

3. Results and Discussion

3.1. Fish Call Identification

Notably, the characteristics of Toadfish representative call train (Fig. 1a), single call (Fig. 1c), and related spectrogram (Fig. 1e) off *Britona* location are found to be matching well with the archived Toadfish sound (*.wav format) available at the Discovery of Sound in the Sea (DOSITS) website (www.dosits.org). Given the call interval of ~5 sec (Fig. 1a), the recorded call duration and number of pulses per call are observed to be 0.25-0.60 sec and 10-38 respectively (Table 1a), indicating Toadfish boatwhistle sound [25]. The PSD analyses of individual calls show a peak frequency of 470 ± 52 Hz in comparison with the DOSITS archives (450 Hz). Fish sounds are usually not sharply tuned, therefore the difference in amplitude at different peak frequency is quite likely due to the potential addition of spurious variability in the dataset. Call pattern (Fig. 1b) from the *Grande Island*

location and the spectrogram of a single call confirms Sciaenidae sound (Fig. 1f) [5, 26]. The PSD analyses of individual call show a peak frequency of 700 ± 54 Hz. The call duration and number of pulses per call for Sciaenidae are observed to be 0.04-0.10 sec and 4-11 respectively (Table 1a).

3.2. Application of MF DFA

The log-log plots of $F_q(s)$ versus s and corresponding regression slopes for the Toadfish (Fig. 2a) and Sciaenidae (Fig. 2b) are q -dependent (between -5 to 5), indicating multifractality and scaling behavior. The second order Hurst exponent account for the overall root-mean-square (RMS) fluctuation in the data [9]. The average $h(q=2)$ values for Toadfish and Sciaenidae are found to be 1.10 ± 0.03 and 1.43 ± 0.02 respectively (Table 1b). Mean values of the estimated parameters are presented along with the standard deviation in the table. Low standard deviation value suggests that the data points are closed to mean values. Similar lower values of the estimated MF DFA parameters are also depicted [27]. The $\Delta h(q)$ values can be used to describe the multifractality of representative fish calls (Fig. 2c). We observe greater multifractality [i.e. higher $\Delta h(q)$] for Toadfish (1.05 ± 0.08) in comparison with Sciaenidae (0.94 ± 0.06) fish sounds. The shape parameters estimated from the $f(\alpha)$ singularity spectrum also corroborates with this interpretation. The w values of Toadfish and Sciaenidae show a higher degree of multifractality (Fig. 2d). w values are significant for both Toadfish (1.55 ± 0.08) and Sciaenidae (1.20 ± 0.09) (Table. 1b). The estimated B values for Sciaenidae and Toadfish are positive, highlighting right-skewed multifractal spectrum. In comparison, the Sciaenidae possess higher B values (0.65 ± 0.08), indicating high fractal exponents dominating the distribution as compared to Toadfish sound (0.22 ± 0.07) (Fig. 3a).

The origin of multifractality in a time-series needs to be validated. Two basic sources of multifractality in the time-series are (i) multifractality due to long-range correlations of the small and large fluctuations and (ii) multifractality due to broad probability density function [16, 28]. Therefore, there is a need to verify the multifractality of fish calls analyzed in this study. The shuffled series for the individual call pattern are generated by applying a shuffling procedure [29] that eliminates long-range correlations in the data. The Δh_q values computed with these shuffled series are 0.16 ± 0.03 and 0.16 ± 0.05 , respectively, for Toadfish and Sciaenidae (Table 1b). Similarly, the estimated average w for Toadfish and Sciaenidae are (0.32 ± 0.06) and (0.17 ± 0.05) respectively (Table 1b). The validation process indicates that the shuffled series of fish calls show monofractal behavior. The $h(q=2)$ values of shuffled series are found to be 0.51 ± 0.01 for both the fish family representative calls (Fig. 3c; Table 1b). The origin of multifractality in a time-series can be attributed to broad probability density function if $h(q)$ values does not change with the shuffling procedure,

i.e. $[h_{original}(q) = h_{shuffled}(q)]$. In this study, applying the shuffling and surrogate procedures to both the fish sound, we found that the recorded fish sounds (Toadfish and Sciaenidae) exhibit long-range correlation because the magnitudes of $h(q)$ and $h_{shuffled}(q)$ show significant differences (Fig. 2c) [9, 16].

Table 1(b). MFDA parameters calculated for original fish sound, shuffled, and surrogate data.

Time series type	$h(q=2)$	Δh_q	W	B	H	β	γ
Batrachoididae (Toadfish)	1.10±0.03	1.0 5±0.0 8	1.55±0.08	0.22±0.07	0.10±0.05	1.20±0.08	-0.20±0.09
Batrachoididae (Toadfish) Shuffled	0.51±0.01	0.1 6±0.0 3	0.32±0.06	0.25±0.05	0.51±0.01	0.02±0.03	0.98±0.02
Batrachoididae (Toadfish) Surrogate	1.07±0.04	0.8 0±0.0 7	1.10±0.08	0.33±0.09	0.07±0.04	1.14±0.06	-0.14±0.09
Sciaenidae	1.43±0.02	0.9 4±0.0 6	1.20±0.09	0.65±0.08	0.43±0.02	1.86±0.04	-0.86±0.04
Sciaenidae Shuffled	0.51±0.01	0.1 6±0.0 5	0.17±0.05	0.25±0.08	0.51±0.01	0.02±0.02	0.98±0.02
Sciaenidae Surrogate	1.38±0.02	0.8 4±0.0 8	1.14±0.09	0.44±0.08	0.38±0.03	1.76±0.04	-0.76±0.05

3.3. Characterization of Fish Sound Data Using MFDA

Fig. 3(b-d) presents scatter plots of $\Delta h(q)$, W , and B with respect to the call duration (s) of two families, showing clustering pattern. For a non-stationary time series, the $h(q=2)$ values are greater than unity [27] as observed in both fish families (Table 1b). In that case, the relation between $h(q=2)$ and Hurst exponent (H) is given by $[H = h(q=2) - 1]$. Accordingly, the Hurst exponent (H) is found to be 0.10 ± 0.08 for Toadfish and 0.43 ± 0.02 for Sciaenidae sounds, indicating anti-persistence Hurst exponent $H < 0.5$. Under such condition, the autocorrelation exponent γ and power spectrum scaling β can be estimated using the relation: $[\gamma = -2H]$ and $[\beta = 2H + 1]$. As shown in Table 1(b), for Toadfish, β and γ are 1.20 ± 0.08 and -0.20 ± 0.09 respectively. Similarly, for Sciaenidae β and γ are 1.86 ± 0.04 and -0.86 ± 0.04 respectively. These suggest that both Toadfish and Sciaenidae fish sounds

are long-range anti-correlated time series [30, 31]. Also, a higher β value for Sciaenidae indicates the series is comparatively smooth.

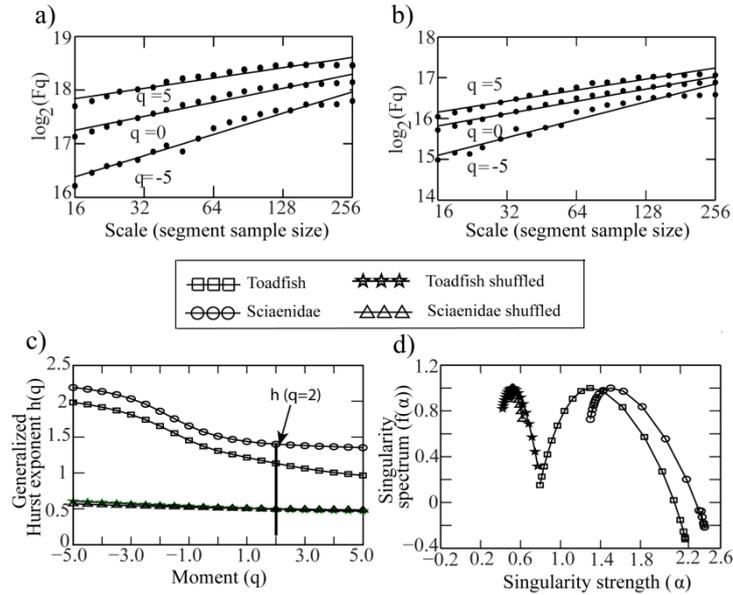


Fig. 2 Panels (a) and (b) represent log-log plot of the fluctuation function $F_q(s)$ versus scale s for Toadfish and Sciaenidae respectively. Panel (c) and (d) depict generalized Hurst exponent $h(q)$ curve and singularity spectrum for a representative call of Toadfish, Sciaenidae, and corresponding shuffled signals.

Recently, we have seen tremendous improvements in the application of the statistical mechanics particularly to understand biological systems [32]. Long-range correlations appear as a ubiquitous phenomenon. Long-term data of healthy human heartbeats display scale-invariant long-range "anti-correlation" (a tendency to beat faster is balanced by a tendency to beat slower later on). More specifically, appearance of long-range correlations in the healthy and young system and disappearance in the series produced by the aged and diseased system provide better understanding. Interestingly from the present study results, we observed the long-range anti-correlation for Sciaenidae and Toadfish sound. Besides the physiological aspect, we need to understand the detailed sound generation mechanism of these fishes. In general, Toadfish generates few grunting sounds in association with the "boatwhistle" [25]. Grunting sounds are considered as agonistic sound while the "boatwhistle" is known for courtship. A possible reason for observed anti-correlation for Toadfish sound may be related to the hybrid call type.

4. Conclusions

The log-log plots of $F_q(s)$ versus s and corresponding regression slopes for the Toadfish and Sciaenidae are q -dependent (between -5 to 5), indicating multifractality. Toadfish and Sciaenidae

fish indicate scaling behavior and small variance dominates the average $F_q(s)$. Second order generalized Hurst exponent $[h(q = 2)]$ values are found to be 1.10 ± 0.03 and 1.43 ± 0.02 for Toadfish and Sciaenidae respectively. Estimated values suggest that the Sciaenidae fish calls are comparatively smoother than the Toadfish. The average value of the shape parameter $\Delta h(q)$ related to the $h(q)$ spectrum confirms the multifractal character of the Toadfish (1.05 ± 0.08) and Sciaenidae (0.94 ± 0.06). The average value of the W (width of the multifractal spectrum) for both the fish sounds along with the degree of asymmetry (B) parameter also supports our multifractality observation. The high $\Delta h(q)$ and W values for both the fish family signify greater heterogeneity and multifractality.

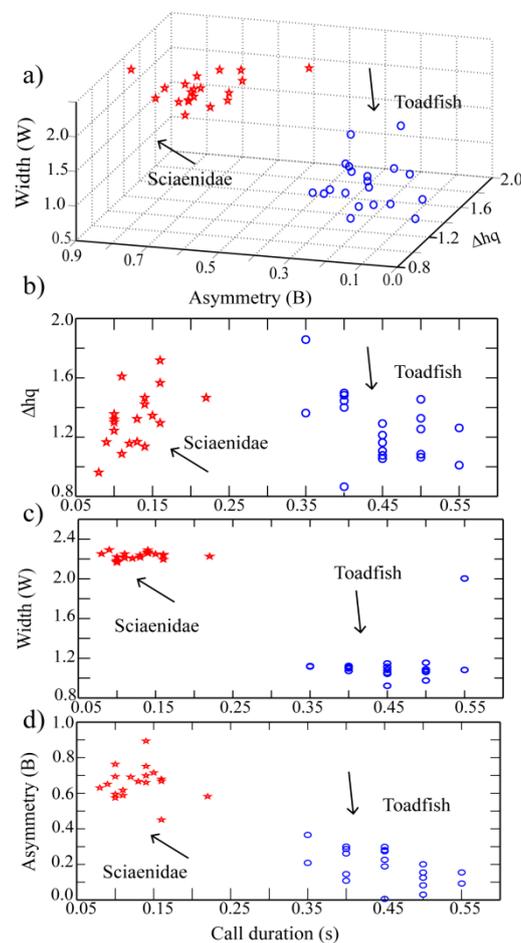


Fig. 3 Scatter plots of a) $\Delta h(q)$, W , and B for Toadfish, Sciaenidae; b) $\Delta h(q)$ versus call duration (s), c) W versus call duration (s), and d) B versus call duration (s). Plots are presented for the estimated parameters using original signals.

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