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Transmission Waveform Analysis for Active Ultrasound Fish Monitoring Systems

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***Abstract*—This paper proposes the performance analysis of different transmission waveforms employed for fish monitoring by active ultrasound systems. The obtained results are analyzed both qualitatively and quantitatively in terms of frame rate, Signal-to-Noise Ratio and resolution at the reception.**

I. Introduction

Generally, in dams or weirs (natural or artificial), hydro power plants have a certain impact on the water ecosystems especially for fish (migratory species) and aquatic organisms. Many fish species migrate on more or less extended areas, such as the wild salmon and eels which migrate several thousand of kilometers during their life cycle.

The ecological continuity concept is defined as the possibility of free movement of animals (especially fish) and a free sediment transport. Considering the European regulation (European Water Frame Directive, 2000/60/CE), ecological continuity is a key criterion for fulfillment of the objectives of the regulation in rivers. Among the environmental risk mitigation measures, fish passes and downstream bypass are of increasing importance for the restoration of free passage for fish and other aquatic species in rivers.

Bypass channels provide a way to completely circumvent the undesired barrier to fish migration. It is designed to match any side channel of the main river system both in form and function. Bypass channels mainly used to small scale barriers such as low head weirs (< 2 m), where the height difference between up and downstream does not lead to an overly long bypass section. More technical details can be found in [1].

Fish passes represent a range of in-channel structures designed to facilitate the upstream and downstream movement of fish and other aquatic fauna. Fish passes are applied to watercourses where natural (or human) obstructions such as dams, weirs, or culverts prevent or interfere with fish migration. Such fish passage problems can occur at almost any site where the water level difference between upstream and downstream of the structure is higher than about 0.5 m [2]. An extensive presentation of French fish passes types can be found in [3]. Fig. 1 illustrates the downstream wild salmon fish pass from the Poutes dam, Auvergne-Rhône-Alpes region, France.

One can note that, due to the fact that efforts to re-establish free movement for migrating fish began with the construction of upstream fish passage facilities, downstream fish passage technology is less advanced in present state of the art [4]. Such devices are often the only way to make it possible for aquatic fauna to pass obstacles that block their up and down river journey. Efficiency of these structures can be quantified in situ by various methods, such as trapping [5], telemetry [6] or video counting [7].

(a)

(b)

Fig. 1. Poutes dam, Auvergne-Rhône-Alpes region, France: (a) example of downstream wild salmon fish pass, (b) example of smolts (young salmons) migrating downstream on the Allier river ©ONEMA.

More recently, it has been shown in [8] that an active ultrasound fish monitoring system can efficiently and continuously contribute to detect, quantify or identify in the water column the fish species. This paper proposes the analysis of different transmission waveforms employed for fish monitoring by active ultrasound systems. The results are analyzed in terms of "in situ" experiments on a smolt fish pass.

II. Active Ultrasound Fish Monitoring System

This paper illustrates an example of active ultrasound wild salmon monitoring system which can be installed on mountainous rivers. The current system was developed in collaboration between the GIPSA-lab, the EDF R&D and the SIGINTEC company. It is composed of several acoustic barriers as illustrated in Fig. 2. Each salmon passage will obstruct the acoustic propagation channel between the emitter and the receiver, which makes possible fish monitoring. Each acoustic barrier acts as a conventional immersed wideband ultrasound system in bistatic configuration [8].

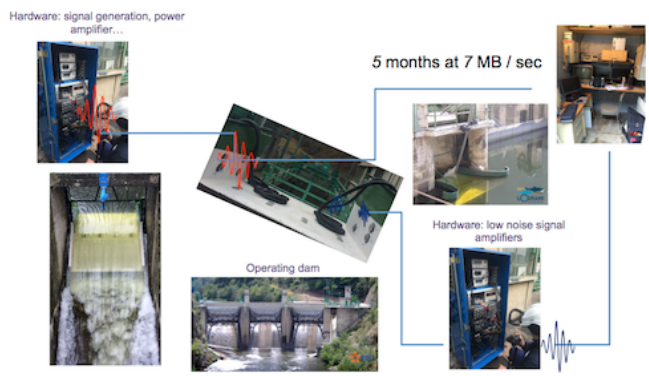

Fig. 2. Active ultrasound wild salmon monitoring system in bistatic configuration.

The ultrasound (US) transducers have been excited using Apex Microtechnology PA107 power amplifiers and the Keysight 33522B arbitrary signal generator. The received signals have been conditioned using Texas Instruments VCA 5807 low noise amplifiers and recorded using synchronous TiePie HS4 oscilloscopes.

III. Transmission Waveforms

First of all, several considerations must be taken into account when setting up the system's pulse repetition frequency (PRF) requirements:

- A larger burst duration at the transmission will induce a better Signal-to-Noise Ratio (SNR) at the reception. By applying appropriate match filtering, the SNR scales with the excitation burst power times the burst duration. Therefore, increasing the burst duration is desirable in terms of SNR.
- Longer burst durations may produce multi-path propagation in confined environments, such as fish passes. Hence, large duration will impose smaller PRF in order to have a sufficiently large waiting time for the multi-path reflexions to go below the desired SNR.
- With rapid moving targets, such as the smolts in a fish pass ($\approx$ 10 m/s), the PRF should be increased in order to be able to observe the fish as many times as possible (increase the frame rate).

These issues were taken into account when selecting the different waveforms to be tested :

1) **Sine-wave**.

$$s_t(t) = sin(2\pi f_0 t + \phi_0), \tag{1}$$

with f_0 the frequency, t the time and $\phi_0 = 0$ the initial phase.

2) **Linear chirp**.

$$s_t(t) = sin\left[2\pi\left(f_0 t + \frac{k}{2}t^2\right) + \phi_0\right], \tag{2}$$

where

$$k = \frac{f_1 - f_0}{T} \tag{3}$$

is the rate of frequency change and T is the sweep time.

3) **Frequency Shift Keying - FSK**.
In FSK [9], the signals transmitted for marks (binary ones) are short sine-wave signals, as described in Eq. 1, with increasing frequency. For spaces (binary zeros), no signal is transmitted. One can note that the duration of each symbol was designed to contain a constant integer number of periods (5 in our case).

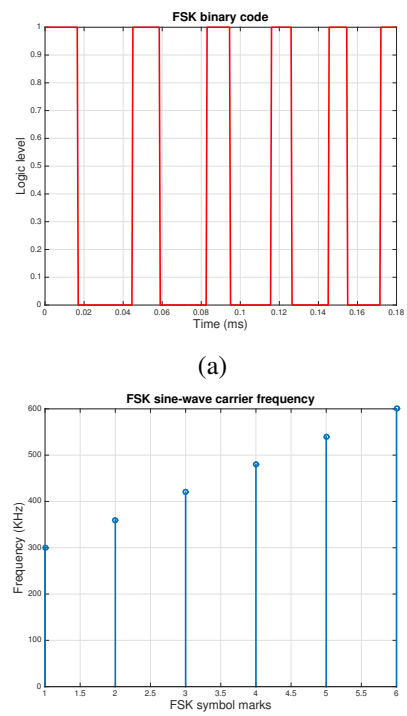

Fig. 3. FSK transmitted waveform parameters: (a) binary symbols and (b) frequency of the sine-wave for each symbol (in chronological order).

4) **FSK with Barker code Phase-Shift Keying - PSK**.
A coded pulse of short length, such as the one from Fig. 3-(a), will have an autocorrelation function consisting of a main lobe at zero time shift and secondary lobes, called sidelobes. The binary code sequences with the highest ratio of aligned correlation (main lobe) to misaligned correlation (sidelobe) are called Barker codes [10]. We have adopted here the 2-bit Barker code from Fig. 4 and

we operated a $\phi_0 = \pi$ phase change of the sine-wave for the PSK marks [11]. Note that the symbols have equal duration.

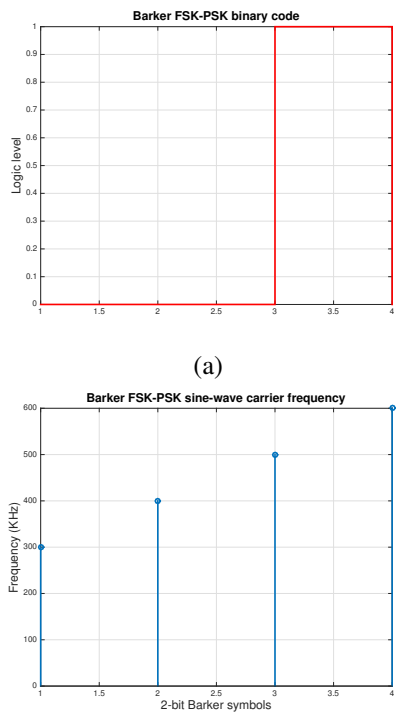

Fig. 4. Barker FSK-PSK transmitted waveform parameters: (a) binary symbols and (b) frequency of the sine-wave for each symbol.

In all cases the square root of a Hamming weighting window is applied to the entire waveform or to each transmitted symbol.

IV. Results and Discussion

The proposed transmitted waveforms are illustrated in Fig. 5 both in time and spectral domains. The PRF for the sine-wave and the linear chirp is the same, the latter having the advantage of spectral diversity (wideband). In order to increase the PRF, the FSK waveform decreases the pulse width, while the waiting time for echo attenuation is kept.

The Barker FSK-PSK waveform is proposing an increase in PRF by a factor 10: almost no waiting time is kept. This means that the received signal have parasite echoes superposed on the main path. At the reception, the Barker FSK-PSK demodulation will help selecting the desired direct path, provided that the SNR is high enough.

Fig. 6 shows an example of received signal for the linear chirp transmitted waveform. The demodulation by normalized cross-correlation (match filtering) is illustrated, also.

After demodulation at the reception, the peak value for each burst is recorded in order to construct the associated time series for fish monitoring. Fig. 7 presents histograms of these time series for the transmitted waveforms without fish passages: the smallest variance is recorded by the linear chirp

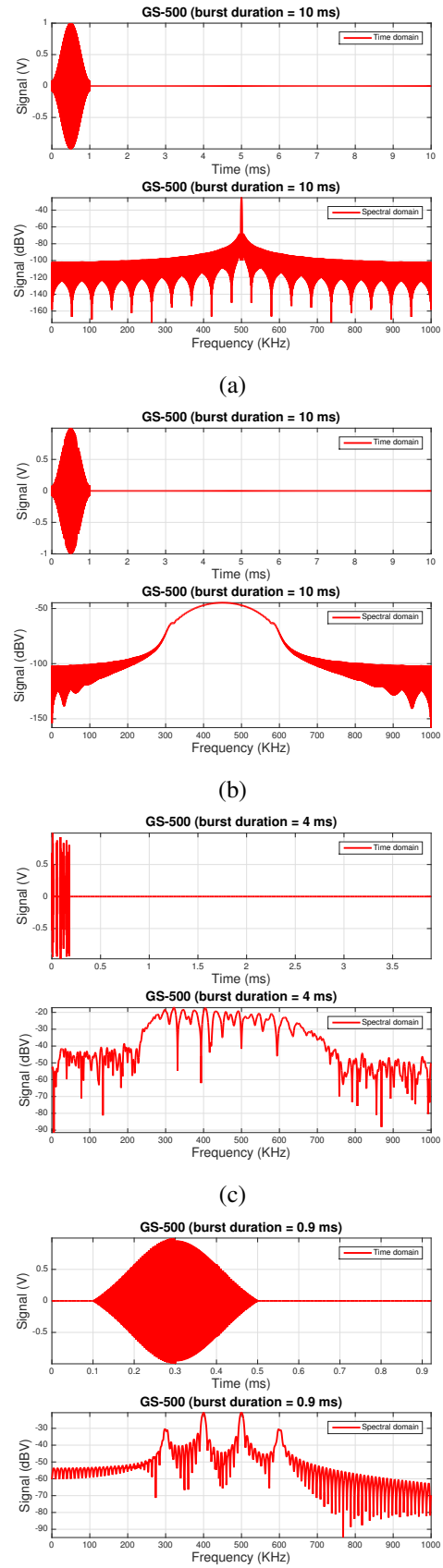

Fig. 5. Transmission waveforms : (a) sine-wave burst, (b) linear chirp burst, (c) FSK burst and (d) Barker FSK-PSK burst.

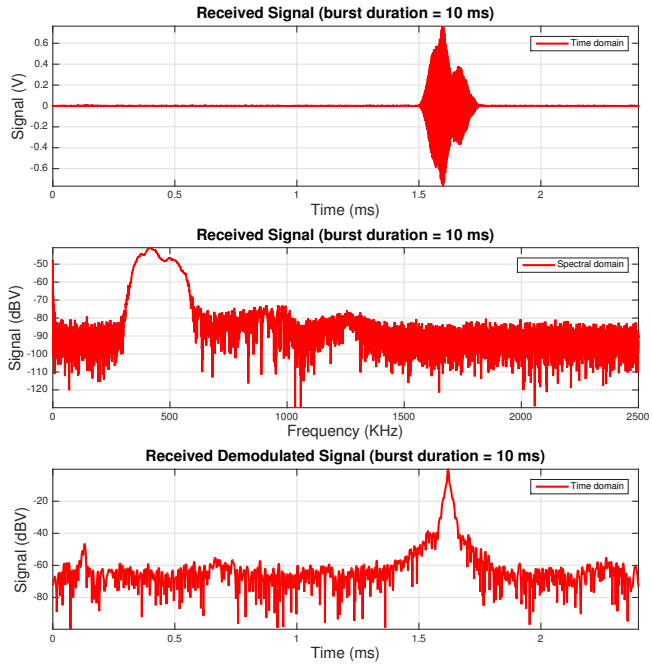

Fig. 6. Linear chirp transmitted waveform: example of received (demodulated) signal.

waveform (closely followed by the sine-wave). Notice that the 95% confidence interval is below ± 0.1 for the Barker FSK-PSK waveform, which is still acceptable in our case.

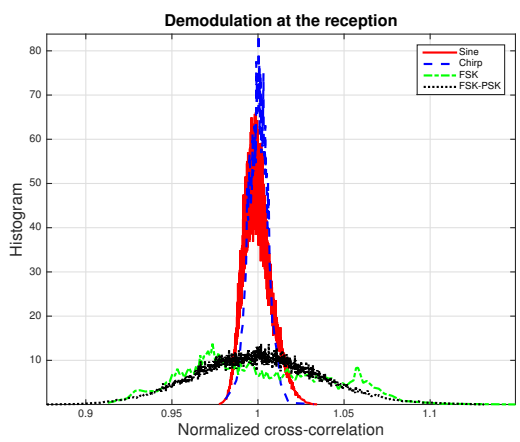

Fig. 7. Demodulated received signal: histograms of the peak value time series for the proposed transmitted waveforms.

Finally, quantitative performance assessment si provided in Table I. We present the recorded SNR value and the obtained resolution at $-3dB$ (δ_{-3dB}) for each of the four transmitted waveforms. It is important to state that the transmission voltage level has been decreased by a factor 3 for the Barker FSK-PSK (as the PSK influence on the ultrasound transducers had not been evaluated prior to the experimentation setup). The sine-wave present the best SNR and the lowest resolution, while the linear chirp seems to be the best compromise (2nd best SNR and best resolution). However, the Barker FSK-PSK waveform is still providing acceptable performances at a frame rate (PRF) 10 times higher, in spite of the multi-path superposition.

TABLE I
QUANTITATIVE PERFORMANCE ASSESSMENT.

Transmission waveform	SNR (dBV)	δ_{-3dB} (ms)
Sine-wave	67.80	0.03
Linear chirp	46.66	0.006
FSK	23.61	0.003
Barker FSK-PSK	18.83	0.004

V. CONCLUSION

This paper proposed a quantification of the impact of the time varying shallow water environment, as the one from a fish pass, on the variance in arrival energy and the distribution of the matched filtered reception. It was shown that a significant increase in the frame rate is obtained by using coded wideband transmission waveforms such as the Barker FSK-PSK. Future studies include identifying reliable ultrasound transducers to support Barker FSK-PSK with higher transmitted power.

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