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# Power Switching Noise Removal in Sensitive Doppler Applications

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***Abstract*— The velocity profile of fluids flowing in industrial pipes can be detected by pulsed-wave Ultrasound Doppler, where bursts of ultrasounds with frequency in the range 300 kHz-10 MHz are transmitted every pulse repetition interval. To detect the weak echoes present in attenuating fluids and/or large pipes highly sensitive front-ends (gain ~50dB) are employed. These are sensitive to the noise produced by power switching regulators, whose working frequency is within the input working bandwidth. EMI filters and spread-spectrum modulation help, but unacceptable artefacts can still be present in the Doppler spectrum. This work proposes an adaptive method that, based on a mathematical model of the noise, is capable of concentrating the switching noise in the low-frequency region of the Doppler spectrum, which is eliminated by the clutter filter together with the echoes from still or slow-moving targets (e.g. pipe walls). Experiments with a Doppler system show the effectiveness of the method.**

***Keywords*— *Power switching noise; Spread spectrum; Doppler investigation; FPGA; Velocity profile.***

## I. INTRODUCTION

Rheological characterization of fluids flowing in industrial pipes can be obtained by measuring the velocity profile of the fluid through pulsed-wave Ultrasound Doppler [1][2]. Bursts of ultrasounds of frequency $F_{Tx}$ in the range 300 kHz -10 MHz are transmitted every Pulse Repetition Interval (PRI), and the echoes from each depth are processed to detect the Doppler shift [3]. However, industrial fluids and suspensions can be quite attenuating in the frequency range of interest, and pipes diameters can be of several cm. The echoes can be very weak, and their detection requires the use of highly sensitive front-ends with gains over 50dB. This makes the Doppler system quite sensitive to noise, like that produced by its own power switching regulators, whose typical working frequency is within the input bandwidth. EMI filters and spread-spectrum modulation help [4], but unacceptable artefacts can still be present in the Doppler spectrum.

This work proposes an adaptive method that, based on a mathematical model of the noise, is capable of concentrating the noise in the low-frequency region of the Doppler spectrum, where it is eliminated by the clutter filter normally present in every Doppler system [5]. The method basically tunes the switching frequency of the power modules to the characteristic of the Doppler investigation, in particular the PRI temporal length. Experiments carried out in a Doppler system for rheological fluids characterization show the method effectiveness.

## II. METHOD

Starting from the desired Doppler acquisition settings (e.g. PRI, $F_{Tx}$, etc), the parameters of the switching frequency modulation are tuned to moves the noise in the rejected bandwidth of the clutter filter. In particular the minimum and maximum frequencies $F_m$ and $F_M$ of a triangular modulation of rate $F_{FM}$, are calculated based on a mathematical model of the noise. The algorithm was implemented in the FPGA of a research system for Doppler measurements in industrial fluids [6]. The FPGA automatically recalculates the modulation parameters whenever the acquisition settings are updated, and synchronizes the switching regulator accordingly.

### *A. Switching Power Noise Model*

Details of the model of the noise produced by a power switcher can be found in [7], here the mathematical basics are reported for reader convenience.

Most of the spread spectrum techniques employ a triangular frequency modulation, where the switching frequency $f_{SW}$ features a triangular trend in time between the lower and upper frequencies $F_m$ and $F_M$, respectively:

$$f_{SW}(t) = F_m + (F_M - F_m) \cdot \mathrm{TRI}(F_{FM} \cdot t) \tag{1}$$

Here TRI($x$) is a triangular periodic function of period 1 and area 1, and $F_{FM}$ is the frequency of the triangular modulation. In case of spread spectrum applied to clock generation the modulation frequency is typically a small percentage of the clock frequency (e.g. 1%); however, for power switcher, higher modulation value can be used: a variation around ±10% of the nominal switching frequency is reasonable.

For the purposes of this work, the noise produced by the power switcher can be approximated by a sequence of rectangular disturbs, which repeats every switching period. Being RECT(t) a periodic rectangular function of period 1, area 1 and arbitrary duty cycle δ, the noise can be analytically modelled as [7]:

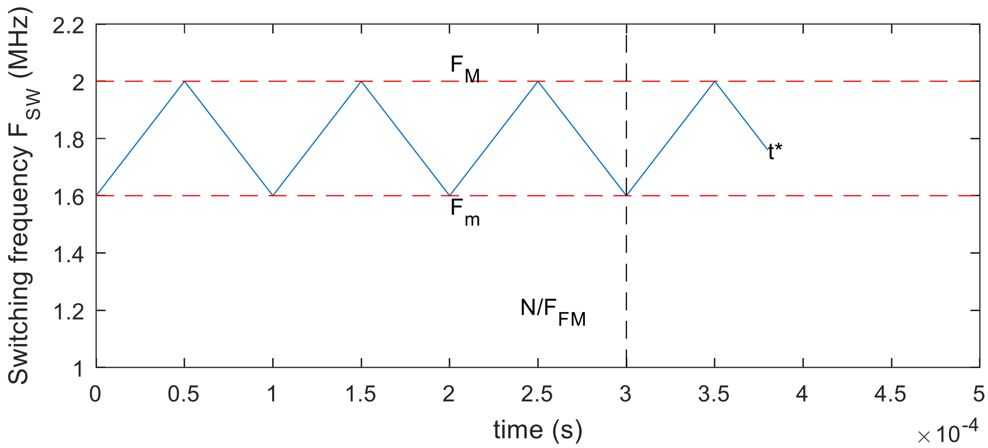


Figure. 1. Example of switching frequency triangular modulated with with $F_M$=2.0 MHz, $F_m$=1.6 MHz, $F_{FM}$= 10 kHz.

$$\mathrm{RECT}\big(\emptyset(t)\big) \tag{2}$$

where:

$$\emptyset(t) = \int_0^t [F_m + (F_M - F_m)\cdot \mathrm{TRI}(F_{FM}\cdot\delta)]d\delta \tag{3}$$

Figure 1 shows an example of switching frequency trend in time, obtained with $F_M$=2.0 MHz, $F_m$=1.6 MHz, $F_{FM}$= 10 kHz. In this example, at the instant $t^*$=0.38ms, the frequency completed $N$=3 cycles of period $^1/_{F_{SW}}$, while the last cycle still incomplete. From this example (3) can be rewritten like:

$$\emptyset(t) = \frac{N}{F_{FM}}\left(\frac{1}{2}F_M + \frac{1}{2}F_m\right) + \\ + \int_{\frac{N}{F_{FM}}}^{t} [F_m + (F_M - F_m)\cdot \mathrm{TRI}(F_{FM}\cdot\delta)]d\delta \tag{4}$$

where the first addend corresponds to the integral (3) calculated over the integer frequency modulation periods $N$ (e.g. 0<t<3ms in the example of Figure 1), and the second addend accounts for the remaining part (3ms<t<t* in Figure 1).

### B. Synchronization strategy

The switching noise is cancelled when [7]:

$$\mathrm{RECT}[\emptyset(n_a\cdot T_{Pri})] = \mathrm{RECT}[\emptyset(n_b\cdot T_{Pri})] \\ \forall\, n_a, n_b \in \mathcal{N} \tag{5}$$

i.e. when switching noise repeats periodically so that the PRI employed in the Doppler investigation includes an integer number of noise repetitions. This is achieved when $T_{Pri}$ is a multiple of the frequency modulation period and the phase (4), at the end of each PRI, is an integer number:

$$T_{Pri} = \frac{N}{F_{Mod}}; \qquad N \in \mathcal{N} \tag{6}$$

$$\emptyset(T_{Pri}) = K_\emptyset \qquad K_\emptyset \in \mathcal{N} \tag{7}$$

In particular (7) grants that the last switching period of the PRI terminates completely in the PRI. Using (7) in (4) the following constraint among parameters is given:

$$\frac{N}{F_{FM}}\left(\frac{1}{2}F_M + \frac{1}{2}F_m\right) = K_\emptyset; \quad K_\emptyset \in \mathcal{N} \tag{8}$$

In summary, if $T_{Pri}$ is the PRI period suitable for the given Doppler investigation, the power switcher should be synchronized by using:

1) a frequency modulation $F_{FM}$ that verifies (6);
2) minimum and maximum switching frequencies $F_m$ and $F_M$ that verifies (8).

If this can be accomplished, the switching noise is cancelled. However other constraints should be satisfied. For example, the $F_m$, $F_M$ and $F_{FM}$ that verifies (6) and (8) should be in the working range of the electronics. Moreover, since the switching frequency is typically generated by dividing a given master clock, not all values are synthesizable.

## III. FPGA Implementation

The method was implemented in the FPGA of the research system [6]. In particular the FPGA of the Cyclone III family [8] (Altera-Intel, Santa Clara, CA USA) was modified to accommodate a signal synthesizer for producing the synchronism pulses towards the switching power section, and a suitable code was added to the NIOS II soft processor, already integrated in the FPGA of the board. Figure 2 shows the basic architecture. The user sets the desired $T_{Pri}$ and the processor calculates the $F_m$, $F_M$, $F_{FM}$ parameters so that all the constraints are verified starting from the 100 MHz system clock. If this is not possible, the $T_{Pri}$ is slightly modified to accommodate the constraints. The parameters are programmed in the internal signal generator that produces synchronously the power

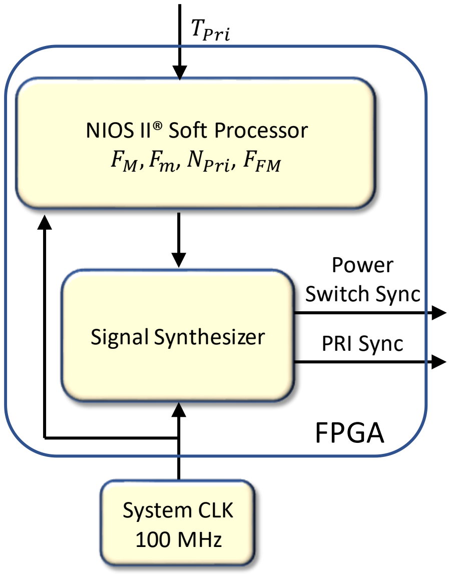


Figure 2. Implementation of the proposed method in the FPGA of the Doppler system.

switcher and the PRI synchronism. The PRI synchronism feeds the Doppler section of the board and it is used to start all of the operations normally executed in each PRI. The circuit dedicated to synchronization is implemented in the FPGA fabric of the Cyclone III FPGA of the system with 97 ALUT and 34 registers only. Time closure was achieved for 100 MHz clock. The code implemented in the soft processor did not require further resources, since the processor was already present in the system.

## IV. Experiments and Results

### *A. Analisys of power switching noise on RF signal*

In this experiment, to maximize the susceptibility to noise, the input of the system was left open, disconnected from the transducer, and the gain of the input analog amplifier was set to its maximum of 55dB. RF data was acquired by programming the switching frequency in 3 modalities: fixed at 2.0 MHz; triangular modulation without synchronization to Doppler parameters; triangular modulation with synchronization. The parameters used are listed in Table I. The acquired RF signals were processed in Matlab (The Mathworks, Natick, MA). Their spectra are reported in Figure 3 for the 0.3-5 MHz frequency range. In all the panels the background noise of the system is visible and grows from the 0db (reference) at low frequency up to about 5dB. In the top panel, where the switching frequency is not modulated, the noise harmonics at 2 and 4 MHz are clearly visible. Triangle modulation, as expected, greatly reduce the noise amplitude, like visible in middle and bottom panels of Figure 3. In these panels the noise signature is similar, since the proposed method does not produce significant differences in the RF signal.

TABLE I. Implementation Parameters

| Parameter | Fixed freq | Modulation not synchronized | Modulation synchronized |
|---|---|---|---|
| $F_M$(MHz) | 2.0 MHz | 2.0000 | 1.5944 |
| $F_m$(MHz) | 2.0 MHz | 1.6000 | 2.0140 |
| $F_{FM}$ (kHz) | - | 14.0003 | 13.9860 |
| $T_{Pri}$ (μs) | 142.860 | 142.860 | 143.000 |
| $F_{Tx}$(MHz) | 3.8 | 3.8 | 3.8 |
| CLK (MHz) | 100 | 100 | 100 |

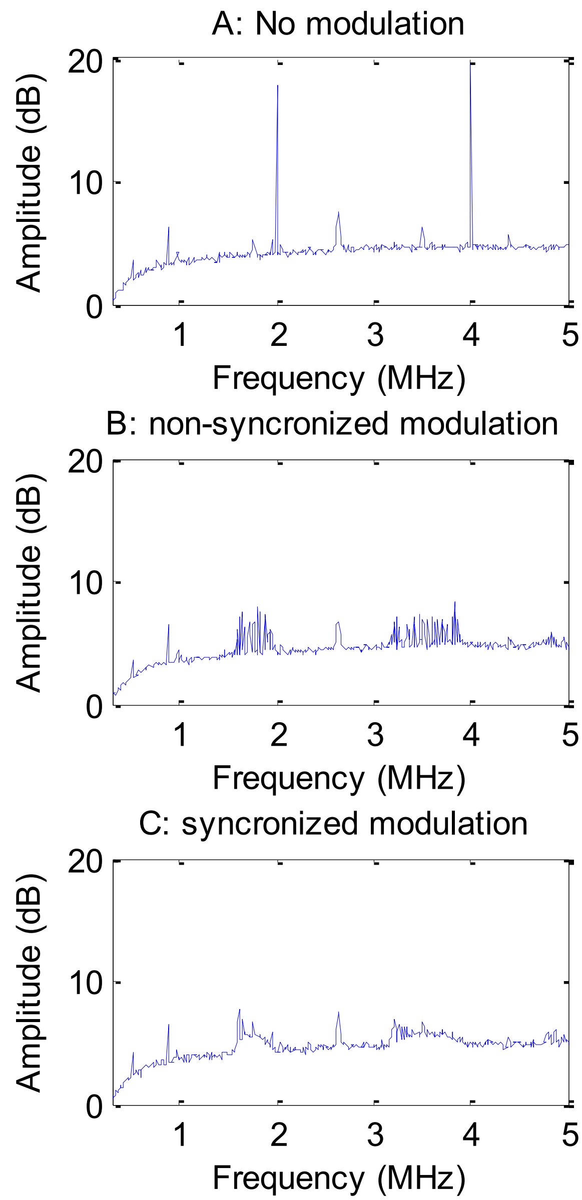


Figure 3. RF spectra measured with: A) power switcher non modulated, B) power switcher with triangular modulation not synchronized to Doppler acquisition, C) power switcher with triangular modulation synchronized to Doppler acquisition

### *B. Analisys of power switching noise on Doppler investigation*

The transducer input of the Doppler system was connected to an electronic emulator of a flow-rig. This tool avoids the use

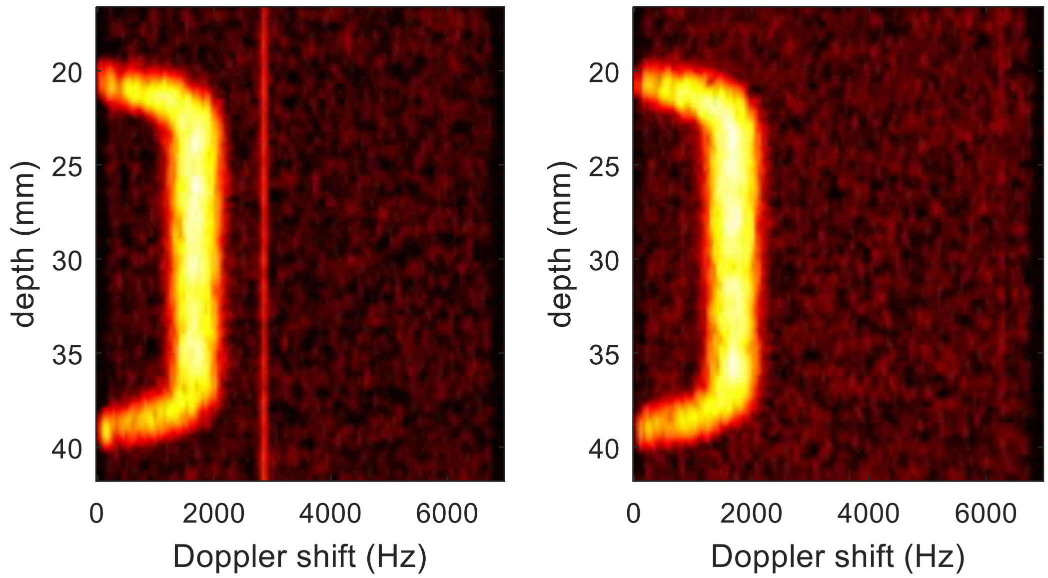


Figure 4. spectral matrices calculated by the Doppler system programmed with the parameters of Table I with the proposed method not applied (left) and applied (right).

of cumbersome flow-rigs by generating an RF signal that, with some limitations, is the same obtained by investigating the real flow in a pipe [9]. The emulator was set for emulating a 20 mm diameter pipe where a non-Newtonian [10] fluid flowed at 60 cm/s. The Doppler system transmitted $F_{Tx}$=3.8 MHz bursts, acquired the signal, processed it through coherent demodulation [11], spectral analysis through FFT [12] or adaptive algorithms [13], and produced the so called 'spectral matrices' that show an intuitive representation of the velocity profile of the fluid [3]. Figure 4 reports the spectral matrixes obtained by triangular modulation of the power switching frequency with the proposed method not applied (left) and applied (right). The parameters are listed in Table I, central and right columns. When the proposed method is not applied, an annoying disturb (vertical red line in Figure 4, left) is clearly visible. The disturb disappears when power switcher are synchronized to Doppler acquisition parameters (Figure 4, right).

## V. Conclusion

In this paper a technique for eliminating the noise produced by switching power suppliers in Doppler applications was presented. In addition to cancelling the artefacts in the Doppler imaging by concentrating the noise in the spectrum region removed by the wall filter, the method applies a triangular frequency modulation which is suitable to reducing noise also in the compatibility tests performed for EMI compliance [14].

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