The Design Documentation for Analog Front End

HU3910: Russian Dragon
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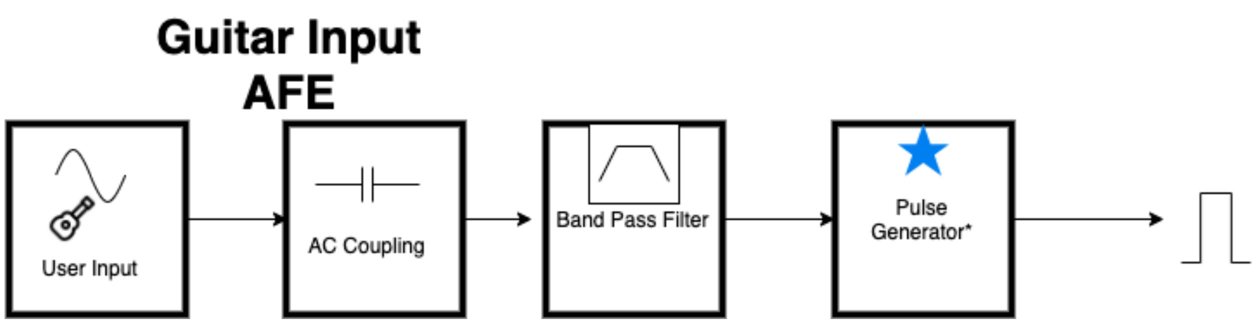
1. Goal

The goal is to digitize the guitar's sinusoidal input. In other words, turn the sinewave into a simple digital high-low transition that uses falling edge to signal the guitar's picking of a string.

2. Design

The block diagram is shown below, which shows a general design approach It contains various functional blocks including:

1. AC coupling (later changed to high-impedance input buffer);
2. bandpass filtering for audio signals(left out for future group);
3. and a pulse generator (feedback controlled sample and hold circuit with decay);
4. Not shown in block diagram, but there is also a 5V dual-rail power regulator circuit.



Schematics

AFE Schematic and 5V Dual-Rail Power Regulator Schematic are attached in appendix. Notice some components in AFE schematic requires +/-5V dual-rail supply, and one component requires 3.3V supply (from arduino).

The AFE schematic shows a feedback controlled sample and hold circuit with decay. The input buffer (module U1A) gives needed high input impedance (will be addressed more in challenge section).

The buffered input then goes into transistor switch (module CD4007UBE), which is used as an inverter and NMOS switch, this is the “sampling” of the sample and hold with decay. The switch is controlled by a hysteresis comparator (module U1C), which turns high after input cross above a preset threshold(in this case 200mV) and consequently opens the switch to “hold” the input. The “hold” with decay (module R1, R2 & C2) constitutes a dead-zone, during which the AFE is disabled from listening to the guitar input, the duration of this dead-zone can be adjusted by changing R1,R2 and C2. In this schematic, the “held” signal (since the hysteresis comparator triggers at 200mV, thus one can assume this signal to have a typical value of 200mV) of 200mV decays to 100ms in approximately 50ms. When this “held” signal reach below 100mV, it will trigger hysteresis and consequently closes the switch, and enable AFE to listen to guitar’s input again. This sample and hold with decay (the dead-zone) is critical because guitar resonates and such resonating signal attenuates slowly over time (this problem will be discussed more in challenge section).

The hysteresis comparator (module U1C) has thresholds: VH = 200mV, and VL = 100mV. These values can be set with reference voltage and resistors values as noted in schematic.

The feedback loop from the hysteresis output to the sampling NMOS switch (CD4007UBE) consists of large resistor (R5) to eliminate excess gate current, as well as a diode (D1) to act as a level shifter. This level shifter is very critical because the hysteresis outputs +4.02V and -3.6V due to the comparator runs on +/-5V dual-rail supply, but in order to give a digital high/low (+3.3V/0V) signal for the arduino, the sampling switch (CD4007UBE) runs on 3.3V and GND provided from arduino. Thus, a negative voltage from the hysteresis comparator will cause incorrect body bias inside CD4007UBE. Therefore it is critical to implement this D1 diode to convert negative voltage to approximately 0V.

3. Challenges

During the development of this AFE, various challenges presented themselves, some of which were came up with solutions but others just documented here and left unsolved, so good luck to whoever's reading this!

Challenge Associated with Guitar Input Amplitude:

First, why do we need to know the amplitude? Because it has to be known in order for us to set the threshold values for hysteresis comparators, which gives the digitized output pulses. SO YEAH, pretty damn important.

The guitar input is a combination of sinusoids of various frequencies, and it's a tricky business to generalize the amplitude of its input. The input amplitude varies. What happens when amplitude varies? Well, when the amplitude is too large for too long, it triggers falses pulses and disable the device from correctly identifying consequential picking of strings.

Through experiments we realized that its amplitude depends on these factors:

1. the picking strength;
2. Which one of the six strings;
3. Which fret of that string;
4. Resonation of multiple pickings;
5. gain knob.

Based on observation, the player's strength is the most critical factor that determines the amplitude, it causes the guitar to resonate at peaks of tens of mV up to 400+ mV. That is a huge variance!

Does that mean if the player maintains the playing strength constant, then the problem is solved? Unfortunately, NO. The truth is that even when picked at the same strength, each string vibrates at not only different frequencies but of different amplitudes. This is possibly due to the difference in thicknesses and tightnesses of the strings, or maybe even the material and shape of the guitar that cause some frequencies to resonate better than others. We didn't have time to document this, but maybe you should! It will help refining the product. We roughly note the amplitude in the decreasing order, when played at the same strength:

1. String 2 has the largest amplitude and resonates for the longest time before decaying;
2. String 1 & 3 come after, of similar amplitude but different decaying characteristics;
3. String 4 & 5 smaller amplitude.
4. String 6, so small!!! Even if you try to break the string, the amplitude just won't match those of other strings, sadly.

What about Frets? They only change the pitch so we don't have to worry right? That's what we thought, but unfortunately, the world is not perfect. Like we said before, the shape and material of the guitar might cause some frequencies to vibrate better than others, therefore causing discrepancies in input amplitudes when playing different frets.

Now, the real annoying part. When the guitar is resonating a previous picking, and a new string is picked (this is fundamental of guitar playing), the two signals will stack up to double or even triple the input amplitude (imagine more than two strings picked at the same time, YIKES!). It messes up everything. However, you cannot tell the player to stop the vibration of a previous string before playing the next, because that is just ridiculous! That's not how you play a guitar. So what can we do? Hmmm… excellent question… Good luck!

Finally, guitars that have aux jack output generally have a gain control knob to adjust the gain. This is the least concerning factor that affects the amplitude, on the contrary, it is one way we can use to help us obtain the correct amplitude.

So obviously, this problem is not solved, but rather discussed. It seems that an universal generalization of the input amplitude cannot be realized due to these many variants. So we suggest to you, yes you the future group, to design an automatic gain control (adaptive gain control) that detects the peak and sets a variable gain that will amplify the input signals to have always a fixed peak amplitude.

Challenge Associated with Input Impedance

The input of the guitar is a small sinusoid. This is a problem because originally, as shown in block diagram, there is an AC coupling stage. This stage is necessary to get rid of any unwanted DC offset. However, capacitor's low impedance at high frequency acts as a short. As a result, when playing higher pitches the input amplitude is attenuated.

We addressed this issue by replacing AC coupling with a buffer to obtain high-input impedance. However, this approach forgoes the ac coupling. In reality, AUX cable is metals with body of mass, capable of storing charges thus having parasitic capacitance. There are non-ideality in the circuit that leaks current into the AUX cable, causing a DC offset drift over time. Currently, we use a short wire to reset the DC offset of the input through AUX cable.

However, we suggest you come up with better design that have both high-input-impedance as well as AC coupling.

Challenge Associated with Sample and Hold with Decay

Why do we need decay? Without such decay being implemented, the output will be fuzzy and comparator will trigger multiple edges. This decay allows the guitar's signal to attenuate during the sample and hold decay period, so when the FE is ready to listen to another pick, the guitar's signal won't be so large that it triggers additional pulses.

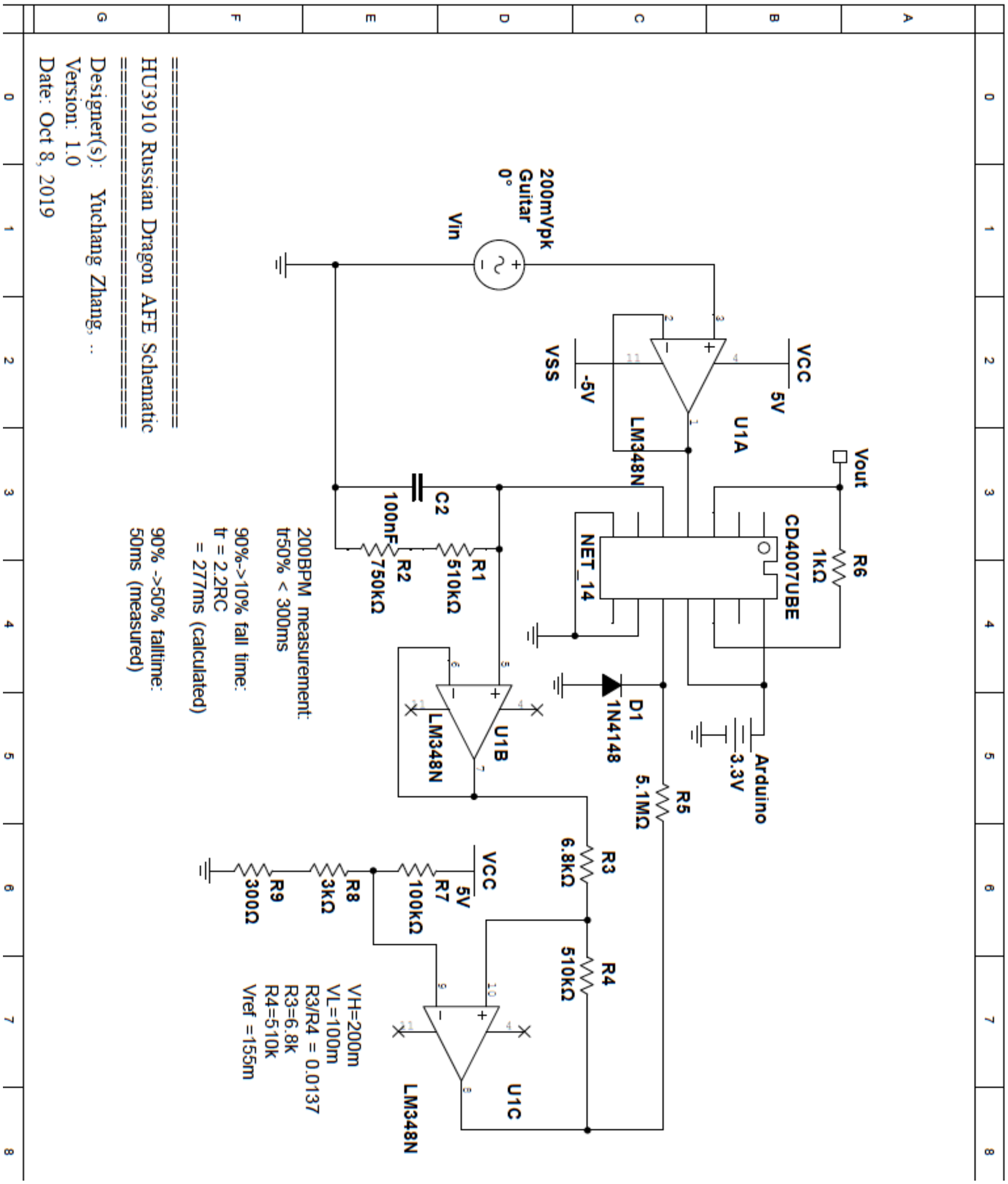
We had difficulty coming up with a good decay time. The tradeoff is that if the decay is too long, then we simply sacrifice the usability of the product at higher BPM, if the decay is too short, the string doesn't get attenuated enough so the output will be triggered multiple times.

We suggest you investigate this tradeoff and finds the optimal decay that enables fast BPM usability and guarantees no false pulses are generated.

4. User Manual

Probe the input signal of the guitar, adjust the gain knob on guitar and play the 3rd string at a strength that gives a peak amplitude between 200mV<peak<350mV. Probe C2, and Vout. Vout gives a falling edge corresponding to the picking of string.

Appendix I -- Pulse Generator Schematic



Appendix II -- 5V Dual-Rail Power Regulator Schematic