ECE 5760: Laboratory 3

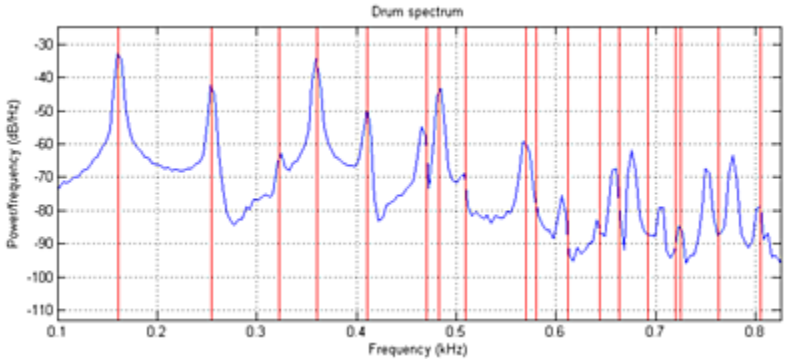
Multiprocessor Drum Synthesis.

Introduction.

For this exercise, you will simulate the 2D wave equation on a square mesh in realtime to produce drum-like sounds.
This year we will add a nonlinear effect related to the instantaneous tension in the mesh.

Procedure:

Read *Study Notes on Numerical Solutions of the Wave Equation with the Finite Difference Method*. The main result you will need to simulate is equation 2.18.
A matlab program gives a sequential version of the algorithm and plots the Fourier modes of the drum. Another version is tuned to middle C (261 Hz). You can see in the figure below that the simulated sound spectrum (blue) matches the theoretical drum modes (red) up to about mode 8 or 9 (see *Physical modeling with a 2D waveguide mesh* for details) . The theoretical square drum mode frequencies follow the ratio sequence:
`sqrt(m+n) where m,n=1,2,3,...`
Where the first term (`sqrt(2)`) corresponds to the fundamental mode of the drum. The first few modes are `sqrt(2), sqrt(5), 2*sqrt(2), sqrt(10), sqrt(13), sqrt(17), sqrt3*sqrt(2).`



Modifying the boundary conditions, damping, wave speed, drum size, and distrubution of input energy can modifiy the sound of the simulation from drum-like, to chime-like, to gong-like or bell-like. You can modify the program further to include frequency-dependent damping and other effects. This version simluates a long, thin bar struck at one end.

Adding tension modulation allows pitch bending observed in a real drum after a large amplitude input. The large amplitude means that the membrane is stretched more, and therefore the speed of propagation (and therefore pitch) is increased. This matlab code produces an exagerated pitch effect with initial high amplitude. See also PHYSICALLY-BASED SYNTHESIS OF NONLINEAR CIRCULAR MEMBRANES equation 10.

You will probably want to read

- *IMPLEMENTATION OF FINITE DIFFERENCE SCHEMES FOR THE WAVE EQUATION ON FPGA*
- *PARALLEL IMPLEMENTATION OF FINITE DIFFERENCE SCHEMES FOR THE PLATE EQUATION ON A FPGA-BASED MULTI-PROCESSOR ARRAY*
- Time Domain Numerical Simulation for Transient Wave Equations on Reconfigurable Coprocessor Platform
- Design Methodology for Real-Time FPGA-Based Sound Synthesis

for ideas on parallelization.

Also read documentation on incremental compilation. Some compile times may be *very* long.
To avoid long compile read Using ModelSim to test node computations
You may want to read the Evans and Sutherland HDL guide, chapter 9, for info on using generate statement.

The hardware audio interface is a Wolfson WM8731 codec which is controlled by an I2C interface.
This hardware is hidden behind Altera IP called the University Audio Core for Qsys.
An example using the audio core is near the bottom of the Avalon Bus master page.

Cyclone5 handbook describing available hardware, **but here is a summary**.

Using Cyclone5 memory blocks.
Cyclone5 DSP blocks description and arithmetic megafunctions
HDL style -- inferring memory and DSP blocks, and a post from Mohammad
Verilog HDL Synthesis Attributes and Directives
-- RAM-style synthesis parameter
-- MULT-style synthesis parameter

Testing:

1. Simulate one node with four zero-value boundary conditions.
   Result should be simple harmonic motion. Remember that rho<0.5. Start with 0.25.
   Assuming1:17 fixed point, start with initial conditions, $u^n=u^{n-1}$ and amplitude about 1/8 full scale.
2. Simulate about 9 copies of the node, connected as a 3x3 array.
   Listen to output in Matlab.
3. Get generate statement running and simulate 10x10 array for demo in first lab.
   Required Matlab output.
4. Get 10x10 array running using the audio codec on the FPGA for demo in second lab.
   Required audio output with nonlinear rho.
5. Scale up parallel processor to 16x16 or greater.

Student examples running on FPGA:

- 2008: Matt Meister and Cathy Chen wav file.
- 2008: Parker Evans and Jordan Crittenden wav1, wav2
- 2010: Skyler Schneider wav base drum
  with n = 16 ,rho = 0.05, eta = 2e-4, alpha = 0.1, boundaryGain = 0.0, node hit = (8, 8), node probed = (8, 8)
- 2010: Peter Kung and Jsoon Kim, rho bit shifted = 6, 8, 10, 11, 14
- 2010: Kerran Flanigan, Tom Gowing, Jeff Yates, chickencan, glasshit, littlebongo, minibell
- 2011: Jinda Cui and Jiawei Yang, drum, bass drum, bowl
- 2011: Weiqing Li and Luke Ackerman, low, high
- 2011: João Diogo Falcão, growing grid, old MacDonald.
  The growing grid starts at 7*34*4=952 nodes, (#columns*#lines*symmetry), and ends at 254*34*4=34544 nodes. This is with Rho=0.5 and Eta=0.000244.
- 2014 Saisrinivasan Mohankumar, Ackerley Tng, Ankur Thakkar, eta = 0.0002, rho = 0.5 and 0.25, boundary gain =0, Number of nodes = 89x257x2 (rows x colums x symmetry) = 45746 nodes.
  Lower, Higher
- Christine Soong, Mary had a little lamb

Assignment

1. Build a realtime drum solver which produces sound from the audio interface.
   Minimum grid size is 16x16 finite difference grid. The grid should have no more than 4:1 aspect ratio.
   Grid expansion via symmetry does not count for size.

2. The solver should solve the 2d wave equation to produce selectable effects.
   A minimum of three buttons on the DE1-SoC should produce different timbers.
   Timber can be set by boundary condition, eta, rho, tension modulation, or number of nodes.
   At least one timber must include audible nonlinear tension modulation effects.
3. **Part of your grade will be determined by how many nodes** you can solve in realtime at an audio sample rate of 48KHz.
   There should be exactly one computational update of all the drum nodes for each audio sample. Last year the highest number of nodes was around 300,000 on DE1-SoC.
   Each sample that you calculate must be output to the audio codec.
   Each node simulated will require around 10 additions/multiplications. You may be able to use clever shifting schemes to avoid multiplys. Thus the computation rate will be about
   `10*(number of wave equation nodes)*(audio sample frequency)`.
   For a minimal 16x16 grid you will need ~123×10^6 operations/sec. Clearly some parallel processing will be necessary as you go to higher numbers of nodes.
4. You can use fine-grained parallelism or course-grained multiprocessors. You can use HPS or FPGA, or a combination, as you wish.
5. Record the audio output back into matlab to show that your simulation matches drum modes (under the correct boundary conditions, etc).

Be prepared to demo your design to your TA in lab.

Your written lab report should include the sections mentioned in the policy page, and :

- Mathematical considerations (what you actually implemented)
- Your parallelization scheme
- A plot of the power spectrum of your drum sounds for each different timber
- A heavily commented listing of your Verilog design (if you write a bus-master) and GCC code (if you use HPS).
