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Wave Interactions and Energy Cascade

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Wave Interactions and Energy Cascade

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May 2022

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University of Arkansas

Abstract

Structural engineers design buildings and their components to withstand code-specified wind loads. The ASCE 7-16 manual sets the standards for calculating wind loads in the U.S. Depending on the velocity of wind, deflections may occur as wind passes through the building. The pressure reported from ASCE are based on wind tunnel measurements. The peak pressure from ASCE 7 is much less than what is measured from the field for a low-rise building. As an alternative economic tool, Computer modeling has been developed to help with this dilemma. Methods based on computational fluid dynamics (CFD) are used to calculate velocities and peak pressures of wind. CFD can help visualize the invisible and predict fluid motion. Because of this, CFD has the potential to become a more cost-effective tool; saving time and money (Atencio, 2021).

A CFD program (pb3d2.exe) is used to compute velocities and pressures at every point in the domain. A visualization software (TECPLOT) is then used to visualize the change in u, v, w velocities and pressure in time and space. The behavior of velocity and pressure without a building in the computational domain is investigated. The u-velocity for each timestep is recorded and a frequency vs. time plot is created using a visualization software (MATLAB). Using both visualization software's, energy cascade is investigated. To investigate energy cascade, symmetric and asymmetric waves vary in grid size, time step, wavelength and amplitude in the x, y, and z directions. These results can help with the development of more efficient inflow turbulence generators without much loss of energy.

Acknowledgment

I would like to thank my research advisor Dr. R. Panneer Selvam, for giving me the opportunity to do research and provide invaluable guidance throughout this thesis experience. I would also like to thank my advisory committee member, Dr. Eric Fernstrom for his support and cooperation. Lastly, I would like to thank my family and friends for their constant support and encouragement throughout my four years at the University of Arkansas.

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Chapter 1: Introduction

1.1 Overview

Strong winds from thunderstorms, downbursts, hurricanes, and tornadoes can devastate large geographical areas which can affect many people. To avoid structural collapse, a building must absorb wind forces safely and have enough strength to resist the applied loads from the wind. For this to happen, a building must be designed for design level winds, if not, the property damage and the risk of injury or death significantly increases. One of the most famous cases of wind load failure was the Tacoma Narrows Bridge failure. Because of its disproportionate depth-to-width ratio, the bridge was vulnerable to high-speed winds resulting in it collapsing due to wind. To avoid catastrophic failures like this one, understanding wind forces on buildings can be extremely valuable.

One way to understand wind forces on buildings is to use field measurement methods to find velocities and pressures. Because field measurement methods are expensive and unpredictable, numerical methods like computational fluid dynamics (CFD) procedures are used. CFD can provide velocities and pressures at a specific point in time in a computational domain (Selvam, 2020). Using a CFD computer model, an engineer can simulate different conditions giving a better understanding of flow changes in time.

The ASCE 7-16 manual sets the standards for calculating wind loads. According to ASCE 7-16, a building can be classified by its geographical location and surroundings, importance factor, and geometrical shape and characteristics. Once the building has been classified, one of three methods for calculating wind pressure on a structure can be used. Those three methods are the simplified method used for low rise, symmetrical, completely enclosed, and rigid buildings, the analytical method used for flexible buildings, and the wind tunnel method used for irregular shaped buildings subjected to unusual conditions. Even though CFD analysis is not an approach used in ASCE to determine wind loads, it is still a powerful tool used to gain insight into wind flow behavior around the building (Giraldo, 2021). As

CFD programs advance, the programs will have the ability to provide a more detailed analysis of wind effects and will help designers and engineers make design decisions earlier in the design process.

Current inflow turbulence generators lose their energy at the building location compared to what is given at the input. This process of losing energy may be called energy cascade, which is further explained in Chapter 2. This is reported by Mansouri et al. (2021) by comparing the velocity spectrum at the inlet and at the building location without building.

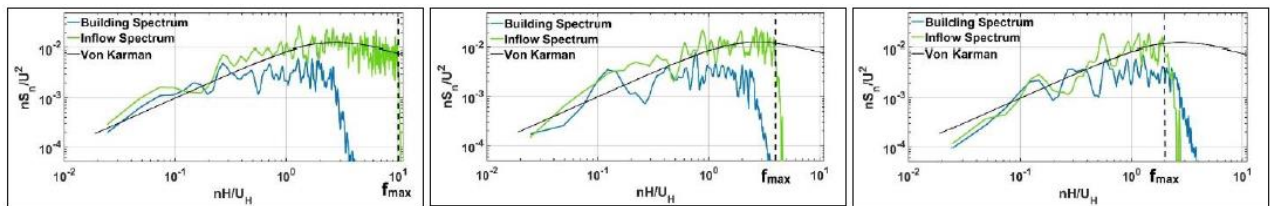


Figure 1.1: Velocity spectrum at the inlet and building location without building for various f_{max} using $H/16$ grid (a) $f_{max}=10$ (b) $f_{max}=4$ and (c) $f_{max}=2$ (Mansouri et al., 2021)

In this work, an attempt is made to study the interactions of sine waves with different parameters and see which one has energy cascade and which one does not.

1.2 Research Objectives

- Investigate one or more wave interactions to see when there is energy cascade and when there is no energy cascade in a computational domain without a building.

Chapter 2: Background

For this thesis work, the Navier-Stokes (NS) Equations reported in Selvam (2021-class notes) are solved using finite difference method. The detail of solution and solver are reported in Selvam (1997). For turbulence modeling large eddy simulation is used. The CFD program used in this work is pb3d2.exe (the 3 means periodic boundary 3D program and the 2 means second version). All three directions periodic boundary is used. The input for the program is provided in pb3d-i.txt file. The detail of preparing input for the program is discussed in Section 3.1. When the program is run, the program gives velocity (u, v, w) and pressure p for all the grid points for all the time steps. The program writes the following data files:

Pb3d-o.plt writes for each time step: time, U, V, W, p & total KE (kinetic energy). The middle of the domain grid point is taken for monitoring.

Pb3d-p.plt For all the grid points u, v, w, & p are recorded for TECPLOT viewing at the last time step.

Wlet.txt Only U velocity for each time step is recorded for wavelet analysis using MATLAB.

2.1 TECPLOT

TECPLOT 360 is a visualization tool that improves the understanding of computational fluid dynamics. The program can produce XY, 2D, and 3D plots. Using the program 'pb3d-o.plt', the TECPLOT software creates u, v, w & p 2D and 3D plots.

2.2 MATLAB

MATLAB or 'Matrix Laboratory' is a programming language that is used to simulate matrices. A program is created to perform repetitive tasks. Using a text file called 'wlet.txt', MATLAB creates a frequency vs. time graph. Looking at the graph, amplitude is shown as color and any dissipation of frequency can be defined as energy cascade.

2.3 Turbulence

When considering flow, it can be laminar, turbulent, or somewhere in between. Laminar flow is smooth and travels the same path as the rest of its particles. Turbulent flow is an irregular motion of air resulting from eddies and vertical currents (Turbulence). An eddy is a gust or whirl of wind that appears in turbulent flow. This can be any kind of turbulent motion such as a vortex. Turbulence is composed of different sized eddies. As speed, V , increases, transition to turbulence will occur. For example, if you stir a cup of water then stir a cup of honey, the honey has a higher viscosity than water resisting the transition to turbulence. The result is the honey remains laminar while the water is turbulent (Princeton). Laminar and turbulent flow in terms of wind can be seen in Figure 2.3.

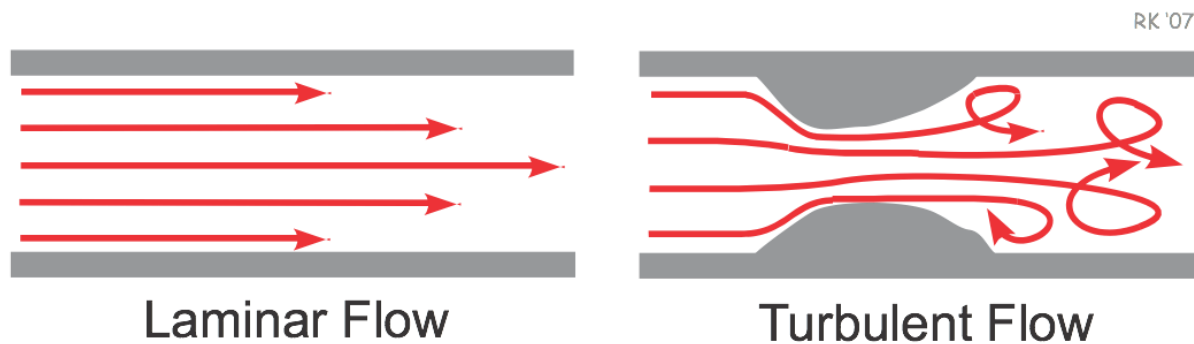


Figure 2.3: laminar vs turbulent flow (Turbulent flow)

Reynolds number is dimensionless and is used to determine whether a flow is laminar or turbulent. Osborne Reynolds used systematic experiments and determined that if the Reynolds number was less than approximately 2300, the flow was laminar, and above this value, the flow was turbulent (Princeton). The equation for Reynolds number for a pipe is below.

$$R_e = \frac{Vd}{\nu}$$

Equation 2.1

Where V is the fluid speed, d is the orifice diameter, and ν is the kinematic viscosity (Kouropoulos, 2014).

2.4 Energy Cascade

Energy cascade is when energy in the wind is reduced from one place to another. Large eddies take energy from the mean flow via the Reynolds stresses and feed it down a cascade of progressively smaller eddies; at the end of the cascade, the smallest eddies dissipate the kinetic energy into thermal energy (EC1, 2022). Over time large eddies break down into smaller eddies resulting in those smaller eddies breaking down into even smaller eddies. Once the eddies reach a significantly small scale, the Reynolds number becomes significantly small as well. This creates a steady eddy motion but will soon dissipate and destroy the eddy at the end of the energy cascade. In Figure 2.4 below, the eddies transfer energy from large to small scales, allowing the energy to move around and dissipate.

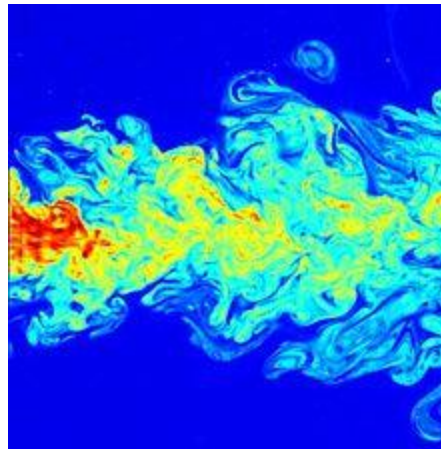


Figure 2.4: Example of Energy Cascade (*Energy cascade*)

Chapter 3: Numerical Models

The program pb3d2.exe, solves the NS equations in time. For the initial condition of the waves, the following equations are used:

$$U=U_m+\sum a_{xi}\sin(k_{xi}(x-Umt)+k_{yj}y+k_{zk}z) \quad \text{Equation 3.1}$$

$$V=\sum a_{yj}\sin(k_{xi}(x-Umt)+k_{yj}y+k_{zk}z) \quad \text{Equation 3.2}$$

$$W=\sum a_{zk}\sin(k_{xi}(x-Umt)+k_{yj}y+k_{zk}z) \quad \text{Equation 3.3}$$

In the above equations, U, V and W are velocities in the x, y and z direction. U_m is the mean velocity, k_x , k_y and k_z are wave numbers and a_x , a_y and a_z are amplitudes. Here the wave number is calculated as $k=2\pi/L$, where L is the wavelength. For the initial condition of the flow $t=0$ is used. Here the subscript 'i' denotes the particular wave. So more than one wave can be used in the above equations.

For a given computational region with lengths XL, YL and ZL in the x, y and z directions, the largest wavelength accommodated in a given direction is XL or YL or ZL. For a given sine wave with wavelength L, a minimum of 10 points are needed. Accordingly, the number of points in the x, y and z directions (IM, JM and KM) need to be chosen based on the smallest wavelength used in the equation.

In preparing data, the one requirement that is satisfied should be the continuity equation. This can be taken care of by:

$$a_x k_x + a_y k_y + a_z k_z = 2\pi(a_x/L_x + a_y/L_y + a_z/L_z) = 0.0 \quad \text{Equation 3.4}$$

In this work the computational region is considered with equal length in all the three directions ($XL=YL=ZL$).

Input Data:

41, 41, 41, 0.025, 40.0, 1.E-5, 2.0, 2.0, 2.0, 1
2.0 2.0 2.0 0.1 -0.05 -0.05

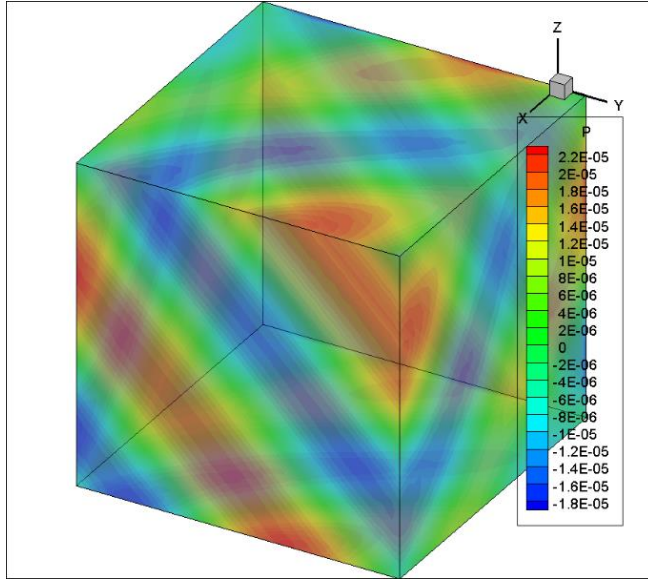


Figure 3.1: 3D symmetric continuous figure with equal lengths in all three directions

3.1 Symmetric, Asymmetric and Inconsistent Waves

Symmetric waves are the ones that have the same wavelength in all the directions and the amplitudes satisfy the continuity equations. If more than one wave is considered, the wavelengths should be proportional. The largest wavelength will be $XL=YL=ZL=L$. The other wavelengths should be $L_{xn}=L_x/n$ where n is an integer.

Asymmetric waves are the ones that don't have the property of $L_x=L_y=L_z$. But these waves also satisfy the continuity equations.

Inconsistent waves are the ones which do not satisfy the continuity equation. These waves may be symmetric or asymmetric and may have energy cascade, but they are not investigated in this study.

3.2 Preparation of Input Data File pb3d-i.txt.

The input file pb3d-i.txt is run with the pb3d2.exe program. The program gives the output files pb3d-o.plt and pb3d-p.plt.

Within the “pb3d-i.txt” file, grid size, time step, wavelength and amplitude can be altered to get different wave interactions. This file consists of 2 lines which are described below.

Line 1: IM, JM, KM, DTT, TTIME, VISC, XL3, YL3, ZL3, NWAVE

IM:	# of points in x-direction
JM:	# of points in y-direction
KM:	# of points in z-direction
DTT:	Time step
TTIME:	Total time to run the computer program
VISC:	Reynolds number
XL3:	Length of domain in x-direction
YL3:	Length of domain in y-direction
ZL3:	Length of domain in z-direction
NWAVE:	# of waves to be considered

Line 2: (WLEN (I, J), I=1, 3), (UTM (I, J), I=1, 3)

WLEN:	Wavelength in x, y, z direction
UTM:	Amplitude in x, y, z direction

3.3 Data Preparation

Once the variables are defined, different wave interactions are programmed. Starting with line 1, the number of points in the x (IM), y (JM), and z (KM) direction determine the grid size. For this thesis, three different grid sizes are used, 41x41x41, 51x51x51, and 61x61x61. To determine the total number of grid points, IM x JM x KM are multiplied. For example, a 41x41x41 grid size has a total of 68,921 grid points within the program.

TTIME is calculated by subtracting 1 from the grid size. The value for TTIME for a 41x41x41 grid size is calculated below.

$$TTIME = 41 \text{ grid size} - 1 = 40$$

Equation 3.1

The time step (DTT) is an interval of time in which the equations are solved. The time step varies depending on the grid size. To find the DTT, the equations are listed below.

$$DTT < \frac{h}{u_{max}} \quad \text{Equation 3.2}$$

Where,

$$h = \frac{XL3}{(IM-1)} \quad \text{Equation 3.3}$$

and,

$$u_{max} = 1.5 \quad \text{Equation 3.4}$$

For example, if a 41x41x41 grid is being used and the TTIME is 40, the DTT would be:

$$DTT < \frac{2}{\frac{(41-1)}{1.5}} = 0.033, \quad \text{Equation 3.5}$$

A good DTT to use for a 41x41x41 grid is 0.025 since $0.025 < 0.033$.

The viscosity (VISC) or Reynolds number remains constant throughout the program at 1.E(-5). The length of the domain in the x (XL3), y (YL3), and z (ZL3) also remains constant at 2. The number of waves considered (NWAVE), wavelengths (WLEN), and amplitudes (UTM) are determined in line 2.

Continuing to line 2, a wave can be identified as either symmetric or asymmetric. A symmetric wave has the same wavelengths in the x, y, and z directions while asymmetric waves have different wavelengths in the x, y, and z direction. An example of a symmetric wave in the x, y, and z direction = 2, 2, 2. An example of an asymmetric wave in the x, y, z direction = 2, 1, 0.67. The amplitude (UTM) must be less than 0.1 in the y, and z directions and equal to 0.1 in the x-direction. The wavelengths and amplitudes are needed to satisfy the continuity equation. For a wave to be continuous, it must satisfy the continuity equation. The continuity equation is calculated below.

$$2\pi*(ax/Lx + ay/Ly + az/Lz) = 0 \quad \text{Equation 3.6}$$

For this study, the data is prepared using continuous waves. The wave can either be symmetric or asymmetric. To satisfy the continuity equation, wavelengths and amplitudes in the x, y, and z direction are used. For example, a 41x41x41 asymmetric single wave interaction, has a wavelength in the x, y, and z direction equal to 2.0, 1.0, and 0.67. Since the amplitude in the x-direction is equal to 0.1, the amplitude in the y, and z direction must be -0.01 and -0.0268 to satisfy the continuity equation. Now that the grid size, wavelengths, and amplitudes have been found the input data can be created. The input data is written in pb3d-i.text in order to run the pb3d-p.plt program in TECPLOT. The input data is written below. In Figure 3.2, the flow is from input to output face. The pressure contour at the end of 40s is shown. There you can see the energy cascade. In Figure 3.3, the TTIME is changed to 0.1s. There you can see no energy cascade.

Input Data:

```
41,41,41,0.025,40.0,1.E-5,2.0,2.0,2.0,1
2.0 1.0 0.67 0.1 -0.01 -0.0268
```

Input Data:

```
41,41,41,0.025,0.10,1.E-5,2.0,2.0,2.0,1
2.0 1.0 0.67 0.1 -0.01 -0.0268
```

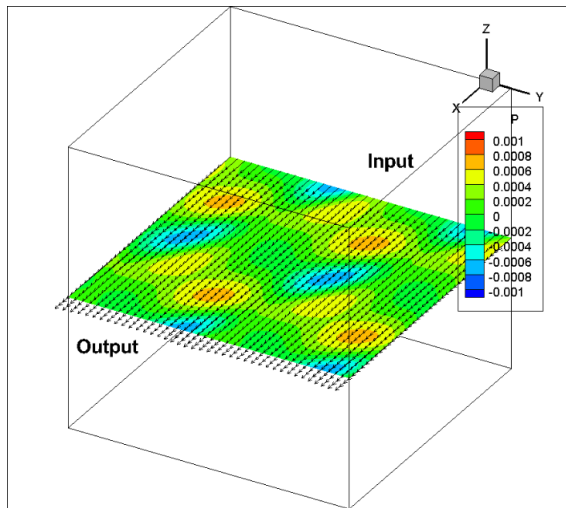


Figure 3.2: Asymmetric single wave

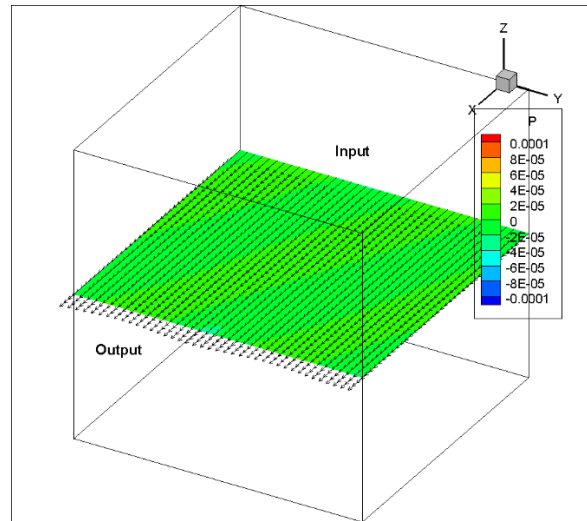


Figure 3.2: Asymmetric single wave: no energy cascade

Chapter 4: Results and Discussion

All computations are done without a building. Here, symmetric waves are compared to asymmetric waves. Using the CFD computation, u , v , w velocities and peak pressures are obtained. For this thesis, grid size, time step, wavelength, and amplitude vary to see if energy cascade occurs. Figures and comparisons are explained in the following sections.

4.1 Single Wave

The velocity and pressure without the building are plotted for single wave interactions to see if energy cascade occurs. Figure 4.1-1 through Figure 4.1-3 shows the pressure, velocity, and frequency for a symmetric single wave interaction. Figure 4.1-4 through 4.1-9 shows the pressure, velocity, and frequency for an asymmetric single wave interaction.

The continuity equation is satisfied for all figures. Figure 4.1-1 shows a symmetric single wave interaction with a grid size of $41 \times 41 \times 41$. There is no energy cascade present. For Figure 4.1-2 and Figure 4.1-3, the grid size is increased to $51 \times 51 \times 51$ and $61 \times 61 \times 61$. Both of these figures show no energy cascade. Figure 4.1-4 shows an asymmetric single wave interaction with a grid size of $41 \times 41 \times 41$. There is slight energy cascade that spans the whole length of the timeline. As the grid size increases for Figure 4.1-5 and 4.1-6, the energy cascade continues to span the whole length of the timeline and increases towards the end of the timeline. Figure 4.1-7 shows an asymmetric single wave interaction with a grid size of $41 \times 41 \times 41$. Energy cascade spans the whole length of the timeline. For Figure 4.1-8 the grid size is increased to $51 \times 51 \times 51$. The energy cascade increases across the timeline and the wave starts to dissipate at 0.8 minutes. The grid size is increased one last time to $61 \times 61 \times 61$ for Figure 4.1-9. The wave starts to dissipate at 1.2 minutes, at this time energy cascade starts to spike to a frequency of about 3 Hz.

Input data:

41, 41, 41, 0.025, 40.0, 1.E-5, 2.0, 2.0, 2.0, 1
2.0 2.0 2.0 0.1 -0.05 -0.05

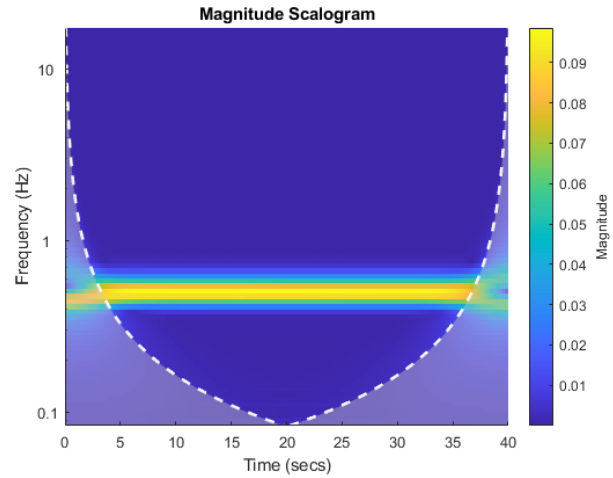
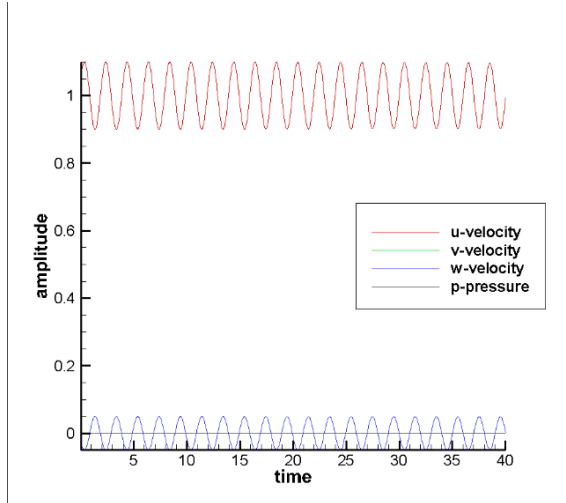


Figure 4.1-1: 41x41x41 Symmetric single wave

Input data:

51, 51, 51, 0.020, 50.0, 1.E-5, 2.0, 2.0, 2.0, 1
2.0 2.0 2.0 0.1 -0.05 -0.05

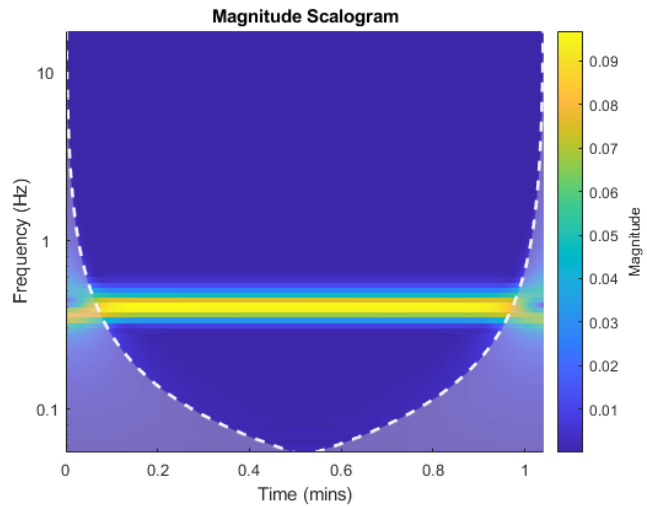
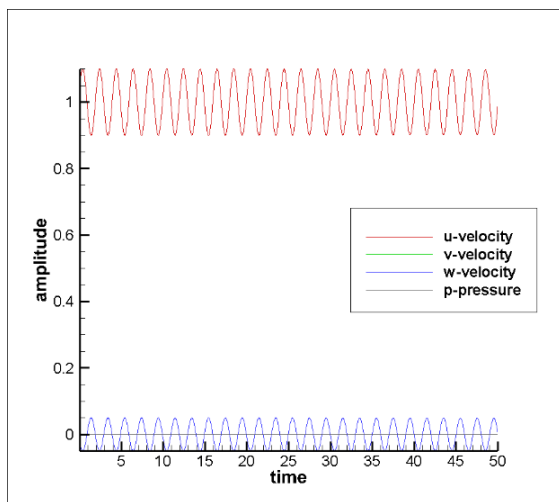


Figure 4.1-2: 51x51x51 Symmetric single wave

Input data:

61, 61, 61, 0.015, 60.0, 1.E-5, 2.0, 2.0, 2.0, 1
2.0 2.0 2.0 0.1 -0.05 -0.05

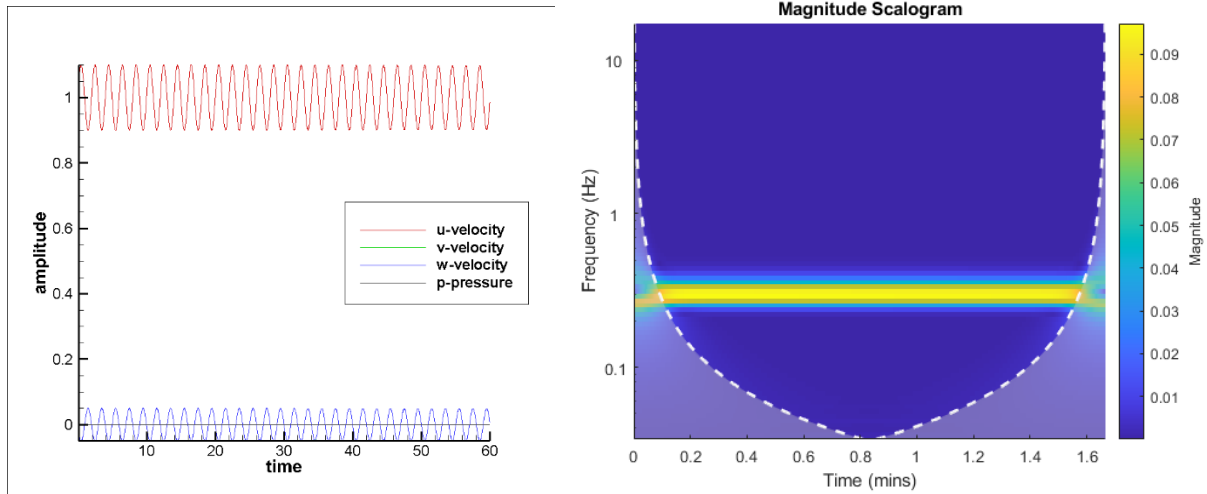


Figure 4.1-3: 61x61x61 Symmetric single wave

Input data:

41,41,41,0.025,40.0,1.E-5,2.0,2.0,2.0,1
2.0 1.0 1.0 0.1 -0.02 -0.03

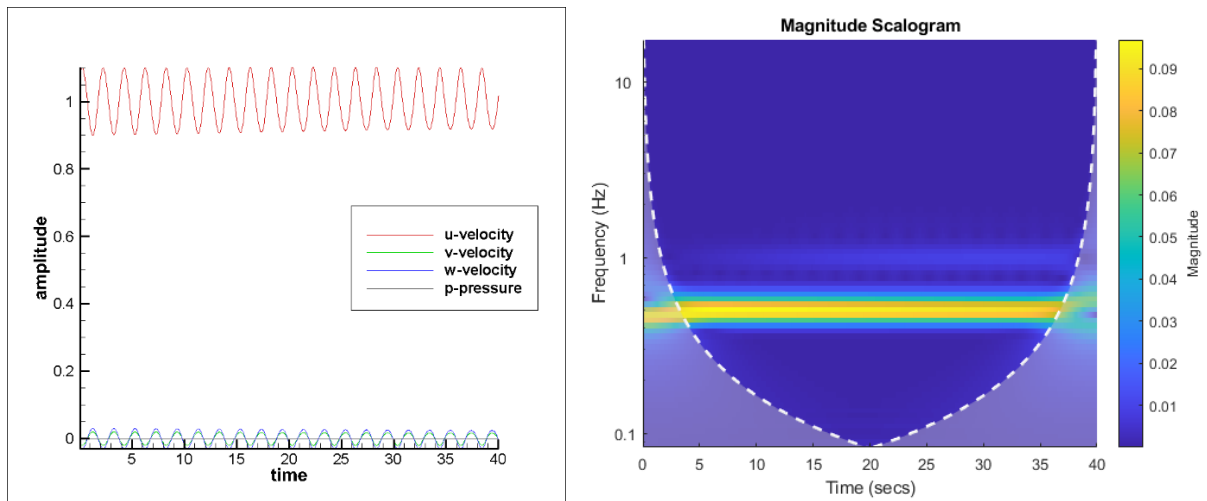


Figure 4.1-4: 41x41x41 Asymmetric single wave

Input data:

51,51,51,0.020,50.0,1.E-5,2.0,2.0,2.0,1
2.0 1.0 1.0 0.1 -0.02 -0.03

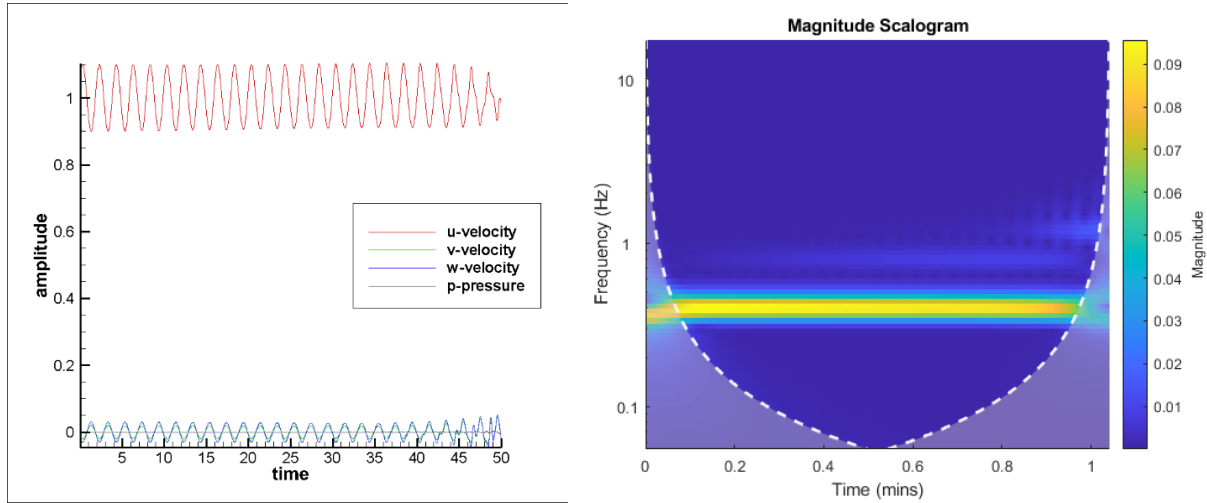


Figure 4.1-5: 51x51x51 Asymmetric single wave

Input data:

61,61,61,0.015,60.0,1.E-5,2.0,2.0,2.0,1
2.0 1.0 1.0 0.1 -0.02 -0.03

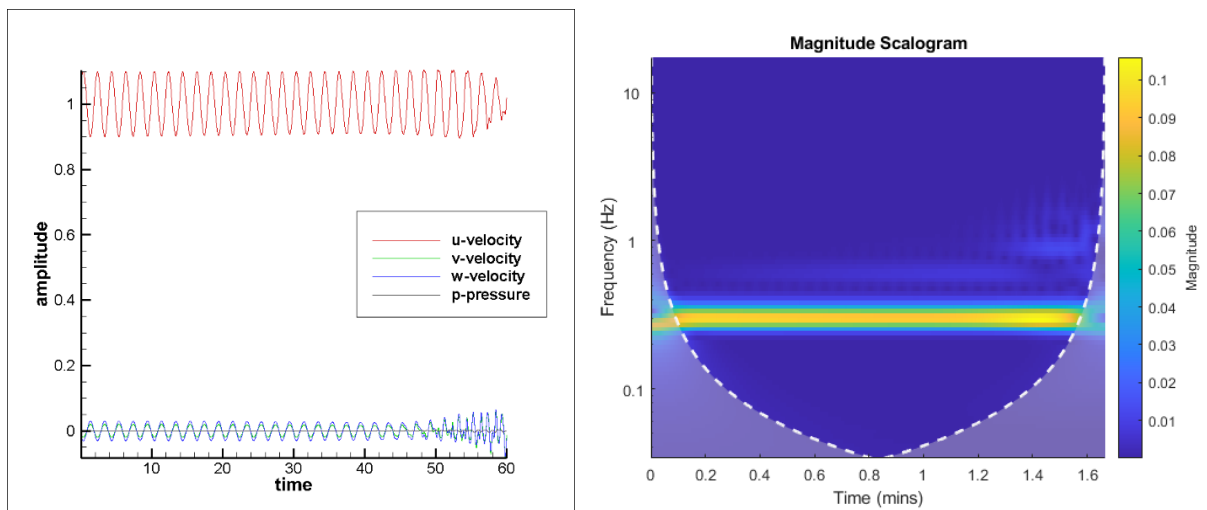


Figure 4.1-6: 61x61x61 Asymmetric single wave

Input Data:

41,41,41,0.025,40.0,1.E-5,2.0,2.0,2.0,1
2.0 1.0 0.67 0.1 -0.01 -0.0268

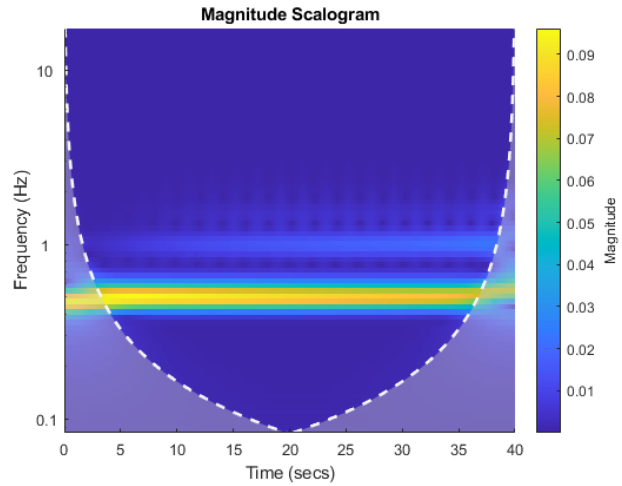
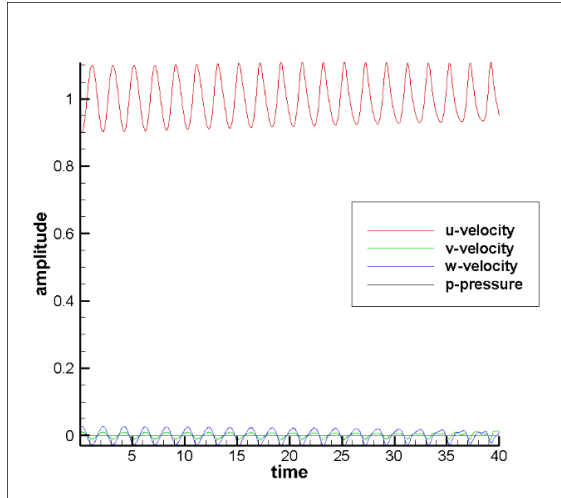


Figure 4.1-7: 41x41x41 Asymmetric single wave

Input Data:

51,51,51,0.020,50.0,1.E-5,2.0,2.0,2.0,1
2.0 1.0 0.67 0.1 -0.01 -0.0268

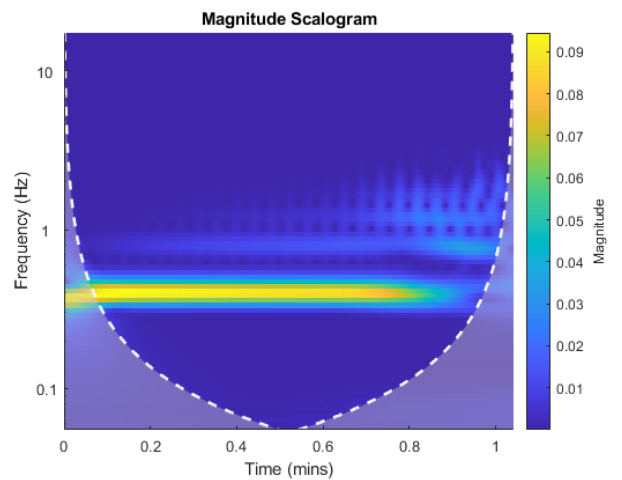
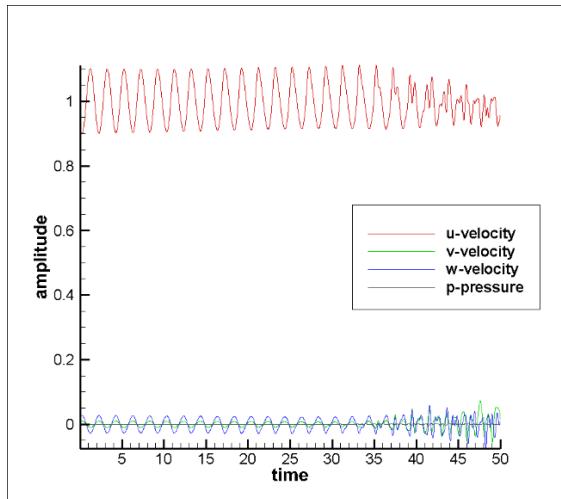


Figure 4.1-8: 41x41x41 Asymmetric single wave

Input Data:

61,61,61,0.015,60.0,1.E-5,2.0,2.0,2.0,1
2.0 1.0 0.67 0.1 -0.01 -0.0268

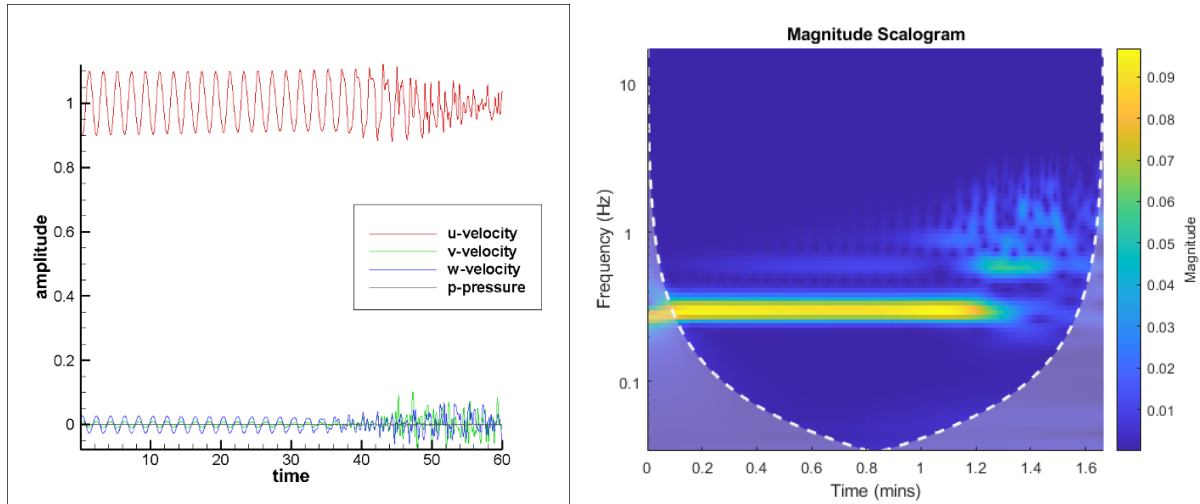


Figure 4.1-9: 41x41x41 Asymmetric single wave

4.2 Two Waves

The velocity and pressure without the building are plotted for two wave interaction to see if energy cascade occurs. Figure 4.2-1 through Figure 4.2-4 shows the pressure, velocity, and frequency for a symmetric two wave interaction. Figure 4.1-5 through Figure 4.2-7 shows the pressure, velocity, and frequency for one symmetric and one asymmetric two wave interaction. Figure 4.1-8 through Figure 4.2-10 shows the pressure, velocity, and frequency for asymmetric two wave interaction.

The continuity equation is satisfied for all figures. Figure 4.2-1 shows a symmetric two wave interaction with the same wavelengths and amplitudes for both waves and a grid size of 41x41x41. There is one distinct wave, and no energy cascade is present. Figure 4.2-2 shows a symmetric two wave interaction with different wavelengths and amplitudes and a grid size of 41x41x41. There are two distinct waves, and no energy cascade present. For Figure 4.1-3 and Figure 4.1-4, the grid size is increased to

51x51x51 and 61x61x61. Figure 4.1-3 shows two distinct waves. The 2.0 wave starts to dissipate at 0.8 minutes and energy cascade is present. Figure 4.2-4 also shows two distinct waves. The 1.0 wave starts to show signs of dissipation while the 2.0 wave starts to dissipate at 1.2 minutes with an increase of energy cascade. Figure 4.2-5 shows one symmetric and one asymmetric two wave interaction with a grid size of 41x41x41. There are no distinct waves and energy cascade is present across the whole timeline. For Figure 4.2-6 and Figure 4.2-7, the grid size is increased to 51x51x51 and 61x61x61. Both figures show no distinct waves and energy cascade increases across the whole timeline. Figure 4.2-8 shows an asymmetric two wave interaction with a grid size of 41x41x41. The first wave has no energy cascade. The second wave dissipates from 0 seconds to 25 seconds and slight energy cascade is present across the timeline. For Figure 4.2-9 and Figure 4.2-10, the grid size is increased to 51x51x51 and 61x61x61. Figure 4.2-9 shows one distinct wave with potential to dissipate. The second wave is lost to energy cascade. Figure 4.2-10 shows both waves lost to energy cascade. The plots for Figure 4.2-8 through 4.2-10 look inverted and different than the rest of the asymmetric and symmetric plots. This is an anomaly. The subtle difference in data, made the wave reformulate to have $WL=2$ & 1 in the wavelet diagram. Energy cascade then occurs. A systematic study of changing amplitude in one direction, two directions and three directions from one wave to another may shed like on this issue. As an example, if the second wave data would have been: 2.0 1.0 0.67 0.1 -0.2 -0.2. The outcome is unknown, hence future work is needed.

Input Data:

41,41,41,0.025,40.0,1.E-5,2.0,2.0,2.0,2
2.0 2.0 2.0 0.1 -0.05 -0.05
2.0 2.0 2.0 0.1 -0.05 -0.05

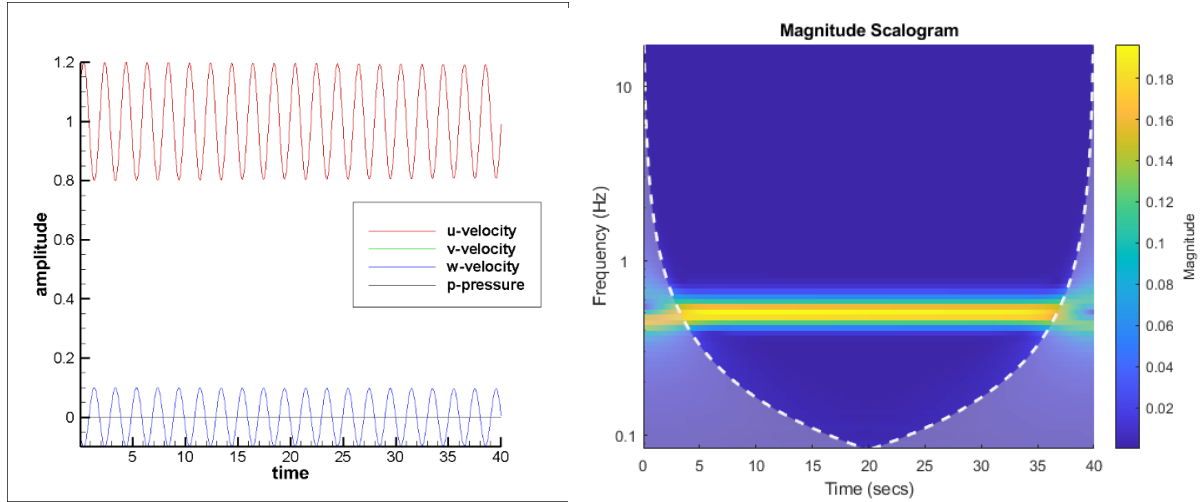


Figure 4.2-1: 41x41x41 Symmetric two waves

Input data:

41,41,41,0.025,40.0,1.E-5,2.0,2.0,2.0,2
2.0 2.0 2.0 0.1 -0.05 -0.05
1.0 1.0 1.0 0.1 -0.05 -0.05

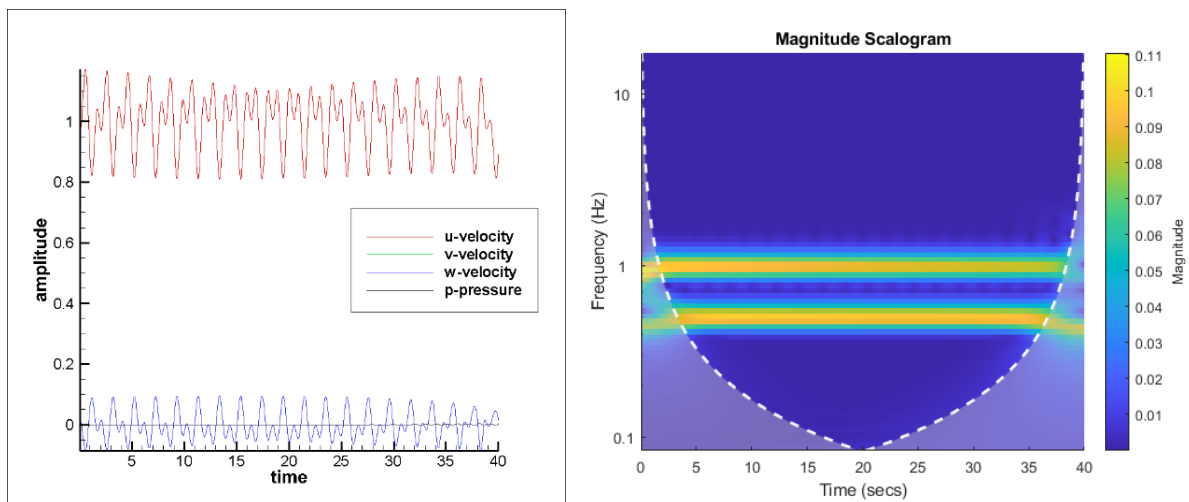


Figure 4.2-2: 41x41x41 Symmetric two waves

Input data:

51,51,51,0.020,50.0,1.E-5,2.0,2.0,2.0,2
 2.0 2.0 2.0 0.1 -0.05 -0.05
 1.0 1.0 1.0 0.1 -0.05 -0.05

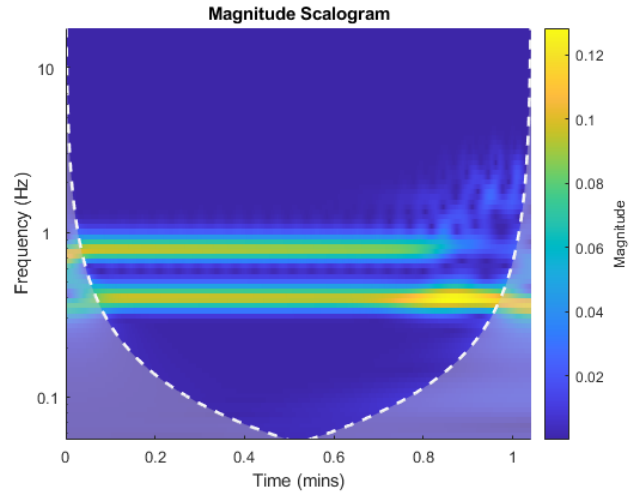
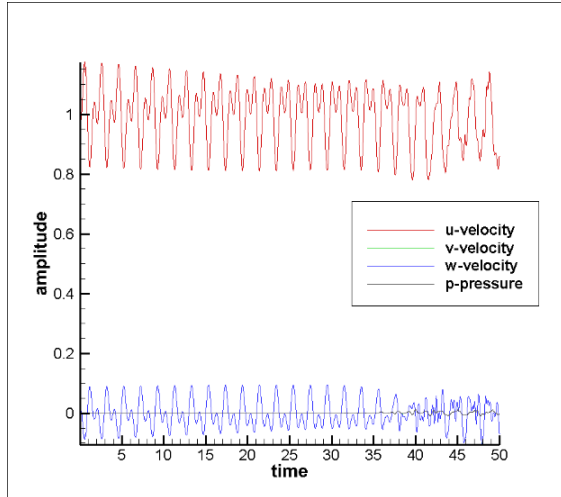


Figure 4.2-3: 51x51x51 Symmetric two waves

Input data:

61,61,61,0.015,60.0,1.E-5,2.0,2.0,2.0,2
 2.0 2.0 2.0 0.1 -0.05 -0.05
 1.0 1.0 1.0 0.1 -0.05 -0.05

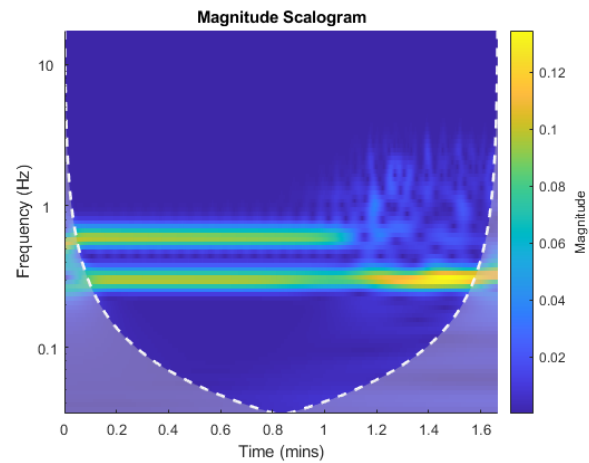
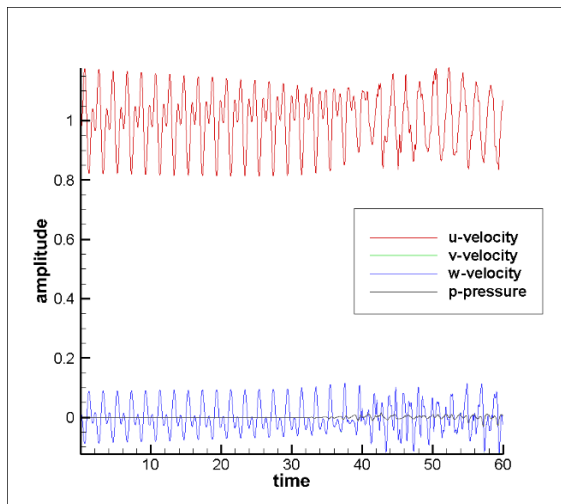


Figure 4.2-4: 61x61x61 Symmetric two waves

Input Data:

41,41,41,0.025,40.0,1.E-5,2.0,2.0,2.0,2
 2.0 2.0 2.0 0.1 -0.05 -0.05
 2.0 1.0 1.0 0.1 -0.02 -0.03

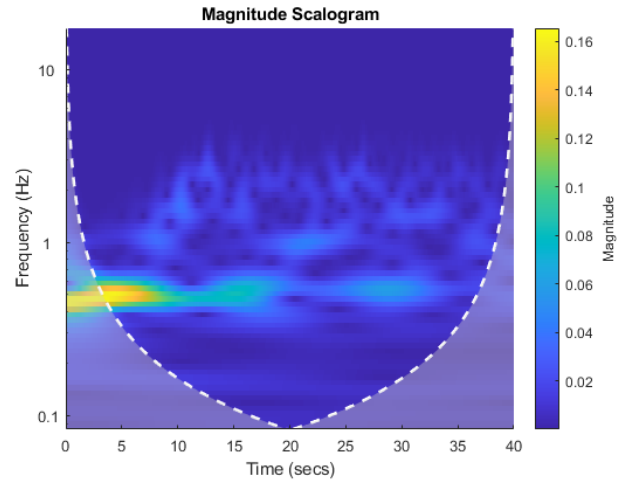
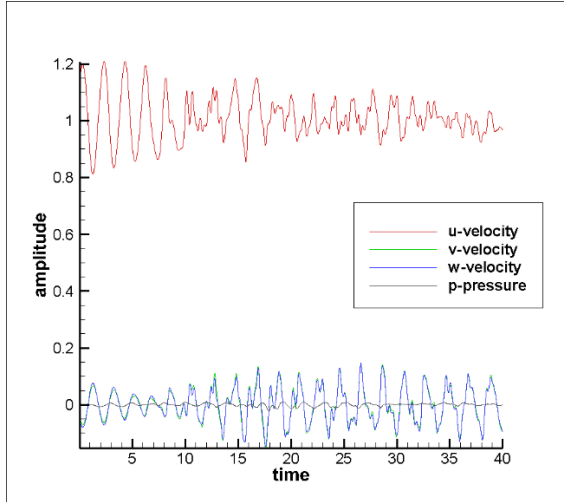


Figure 4.2-5: 41x41x41 One symmetric and one asymmetric two waves

Input Data:

51,51,51,0.020,50.0,1.E-5,2.0,2.0,2.0,2
 2.0 2.0 2.0 0.1 -0.05 -0.05
 2.0 1.0 1.0 0.1 -0.02 -0.03

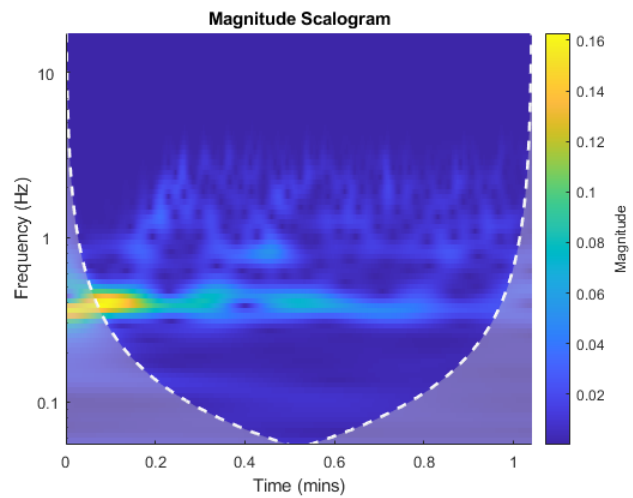
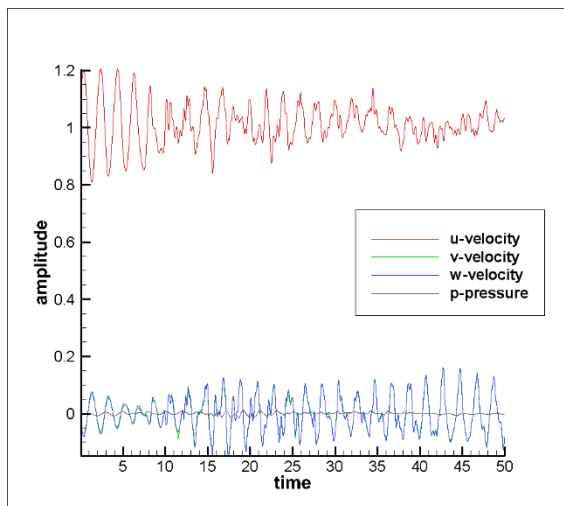


Figure 4.2-6: 51x51x51 One symmetric and one asymmetric two waves

Input Data:

61,61,61,0.015,60.0,1.E-5,2.0,2.0,2.0,2
 2.0 2.0 2.0 0.1 -0.05 -0.05
 2.0 1.0 1.0 0.1 -0.02 -0.03

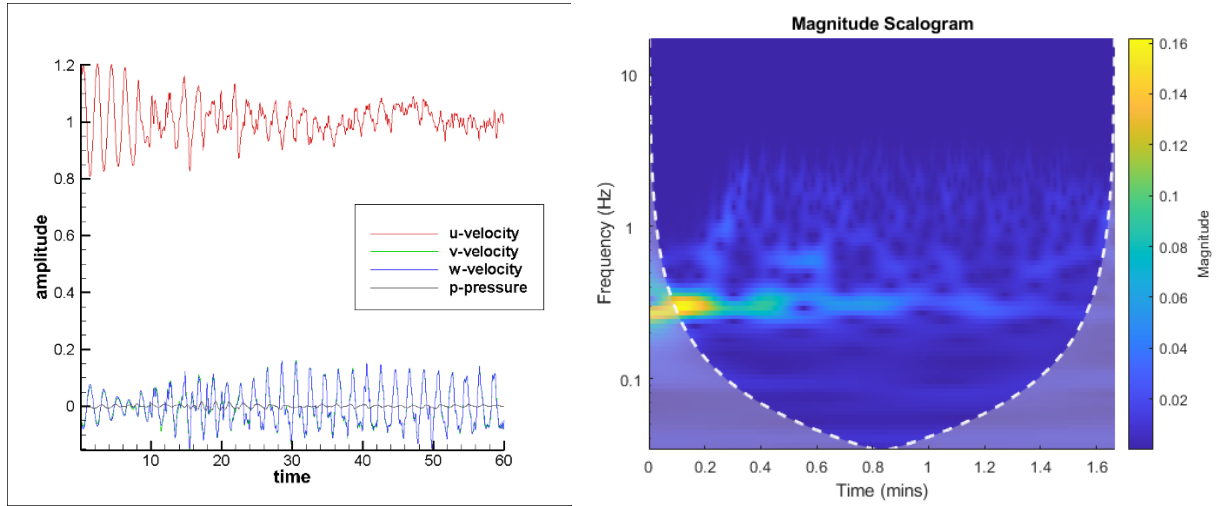


Figure 4.2-7: 61x61x61 One symmetric and one asymmetric two waves

Input Data:

41,41,41,0.025,40.0,1.E-5,2.0,2.0,2.0,2
 2.0 1.0 1.0 0.1 -0.02 -0.03
 2.0 1.0 0.67 0.1 -0.01 -0.0268

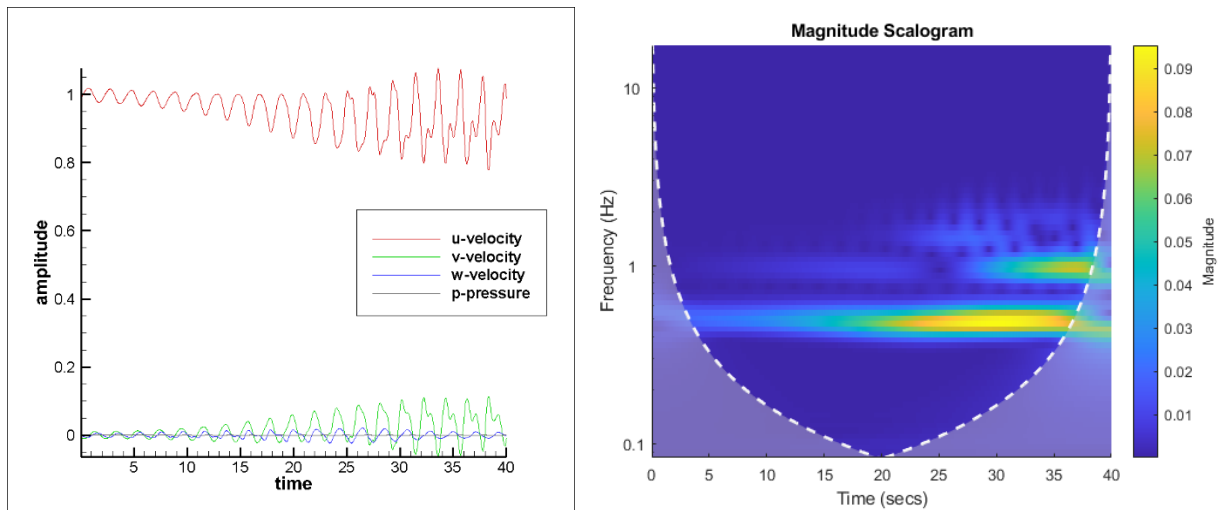


Figure 4.2-8: 41x41x41 Asymmetric two waves

Input Data:

51,51,51,0.020,50.0,1.E-5,2.0,2.0,2.0,2
2.0 1.0 1.0 0.1 -0.02 -0.03
2.0 1.0 0.67 0.1 -0.01 -0.0268

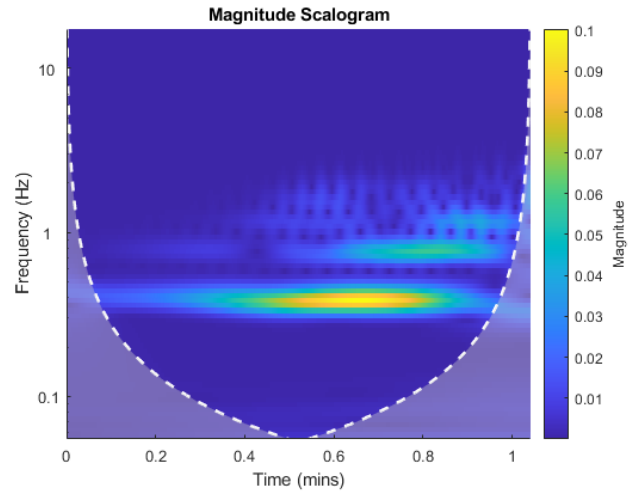
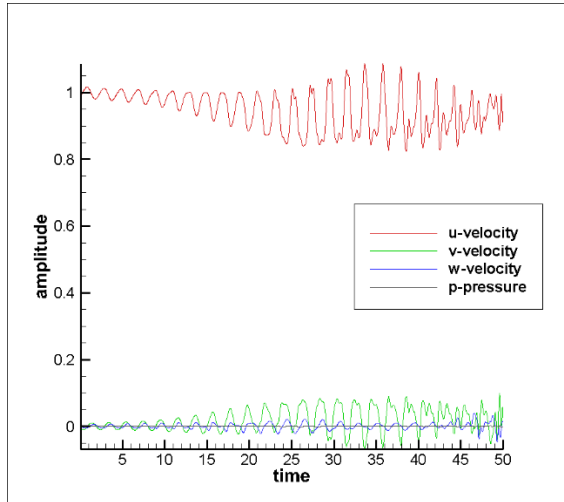


Figure 4.2-9: 51x51x51 Asymmetric two waves

Input Data:

61,61,61,0.015,60.0,1.E-5,2.0,2.0,2.0,2
2.0 1.0 1.0 0.1 -0.02 -0.03
2.0 1.0 0.67 0.1 -0.01 -0.0268

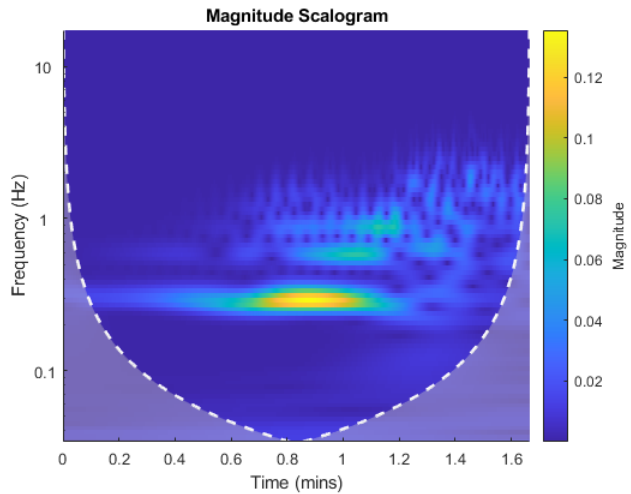
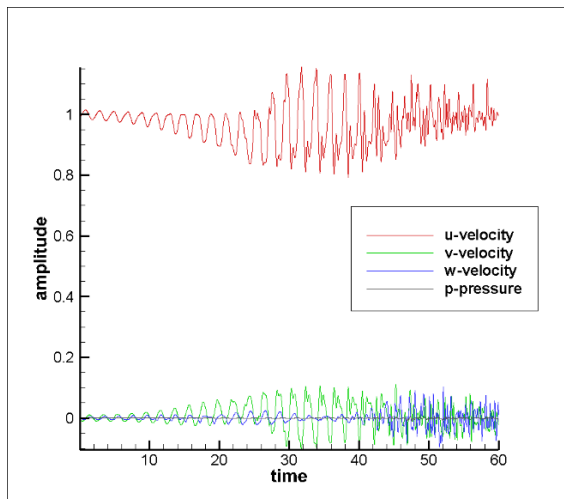


Figure 4.2-10: 61x61x61 Asymmetric two waves

4.3 Three Waves

The velocity and pressure without the building are plotted for three wave interactions to see if energy cascade occurs. Figure 4.3-1 through Figure 4.2-4 shows the pressure, velocity, and frequency for a symmetric three wave interaction. Figure 4.3-5 through Figure 4.2-7 shows the pressure, velocity, and frequency for an asymmetric three wave interaction.

The continuity equation is satisfied for all figures. Figure 4.3-1 shows a symmetric three wave interaction with the same wavelengths and amplitudes for all three waves and grid size of 41x41x41. There is one distinct wave, and no energy cascade is present. Figure 4.3-2 shows the symmetric three wave interaction with different wavelengths and amplitudes for all three waves and a grid size 41x41x41. Here the 1.0 wavelength is distinct but is in the process of dissipating. Both the 2.0 and 0.67 wavelengths have a slight distinct wave from 0 seconds to 10 seconds. Energy cascade takes over the rest of the waves. Figure 4.3-3 and Figure 4.3-4, the grid size was increased to 51x51x51 and 61x61x61. Figure 4.3-3 shows three distinct waves from 0 seconds to 0.2 seconds. Energy cascade takes over the rest of the waves. Figure 4.3-4 shows three distinct waves from 0 seconds to 0.4 seconds. Energy cascade increases and stretches across the whole timeline. Figure 4.3-5 shows an asymmetric three wave interaction with a grid size of 41x41x41. There is one distinct wave from 0 seconds to 10 seconds. Energy cascade takes over the rest of the waves. For Figure 4.3-6 and Figure 4.3-7, the grid size is increased to 51x51x51 and 61x61x61. Figure 4.3-6 shows one distinct wave from 0 seconds to 0.2 seconds. Energy cascade stretches across the whole timeline. Figure 4.3-7 shows one distinct wave from 0 seconds to 0.6 seconds. Energy cascade increases and stretches across the whole timeline.

Input Data:

```
41,41,41,0.025,40.0,1.E-5,2.0,2.0,2.0,3
2.0 2.0 2.0 0.1 -0.05 -0.05
2.0 2.0 2.0 0.1 -0.05 -0.05
2.0 2.0 2.0 0.1 -0.05 -0.05
```

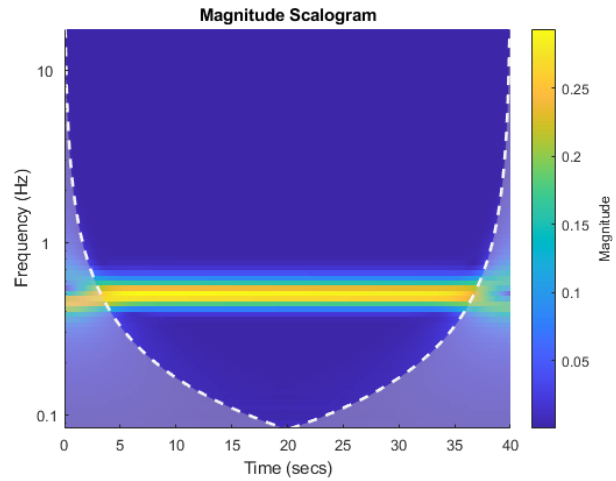
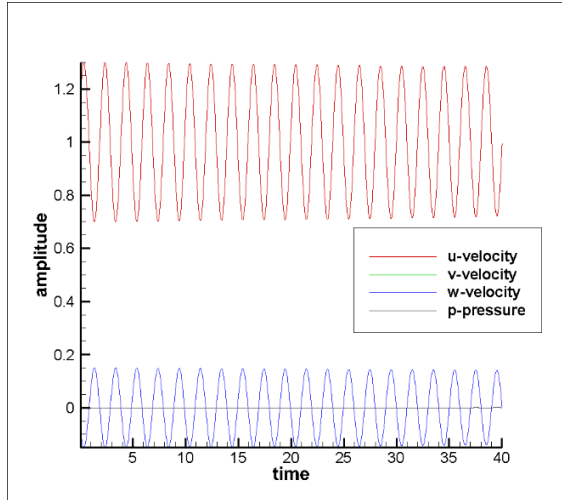


Figure 4.3-1: 41x41x41 Symmetric three waves

Input Data:

```
41,41,41,0.025,40.0,1.E-5,2.0,2.0,2.0,3
2.0 2.0 2.0 0.1 -0.05 -0.05
1.0 1.0 1.0 0.1 -0.05 -0.05
0.67 0.67 0.67 0.1 -0.05 -0.05
```

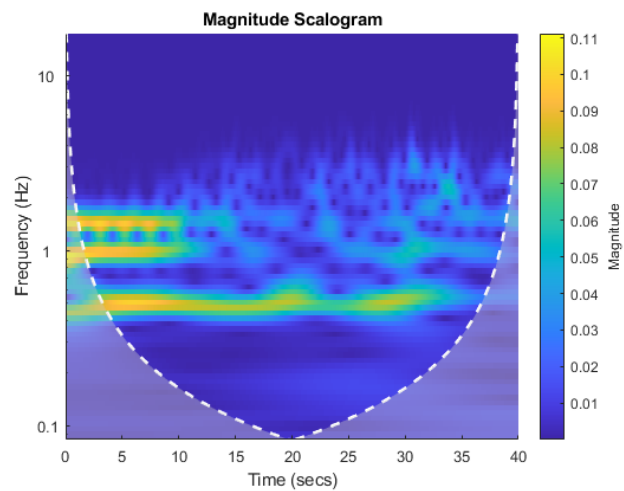
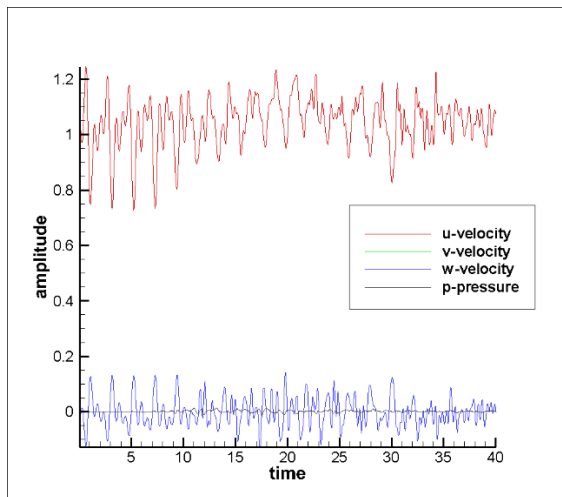


Figure 4.3-2: 41x41x41 Symmetric three waves

Input Data:

```
51,51,51,0.020,50.0,1.E-5,2.0,2.0,2.0,3
2.0 2.0 2.0 0.1 -0.05 -0.05
1.0 1.0 1.0 0.1 -0.05 -0.05
0.67 0.67 0.67 0.1 -0.05 -0.05
```

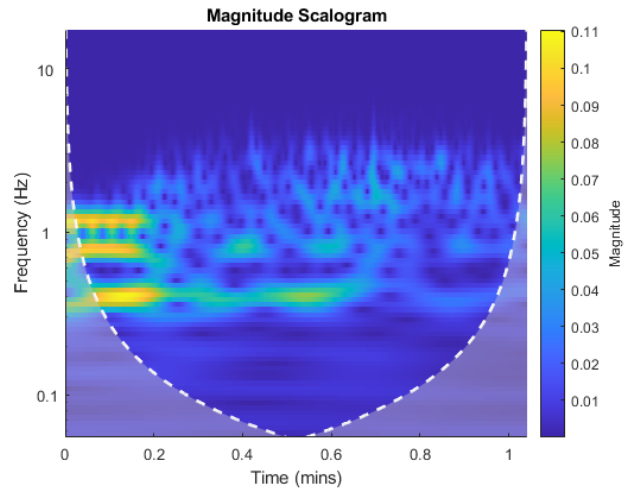
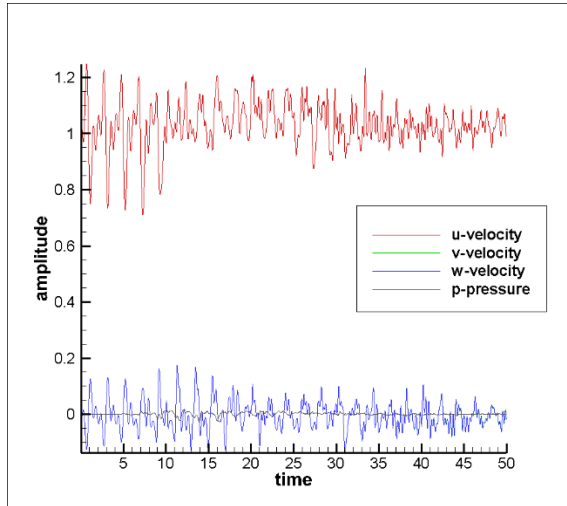


Figure 4.3-3: 51x51x51 Symmetric three waves

Input Data:

```
61,61,61,0.015,60.0,1.E-5,2.0,2.0,2.0,3
2.0 2.0 2.0 0.1 -0.05 -0.05
1.0 1.0 1.0 0.1 -0.05 -0.05
0.67 0.67 0.67 0.1 -0.05 -0.05
```

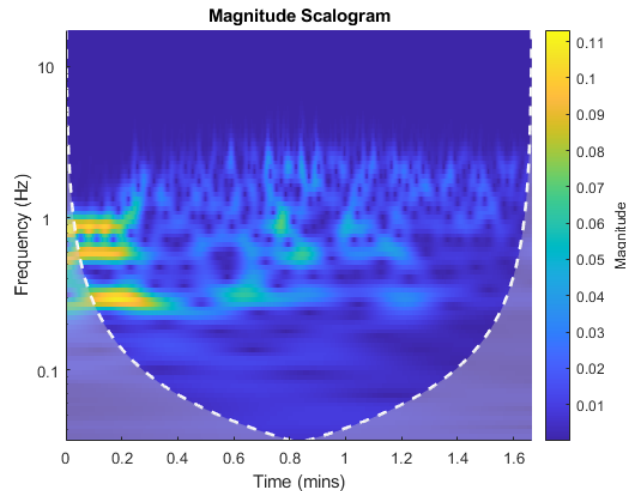
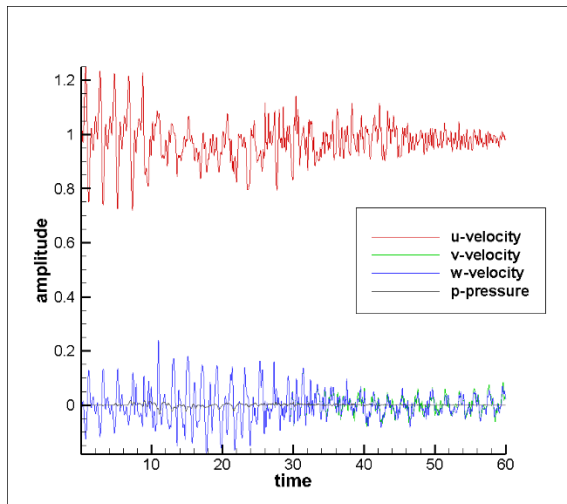


Figure 4.3-4: 61x61x61 Symmetric three waves

Input Data:

```
41,41,41,0.025,40.0,1.E-5,2.0,2.0,2.0,3
2.0 1.0 1.0 0.1 -0.02 -0.03
2.0 1.0 0.67 0.1 -0.01 -0.0268
2.0 2.0 1.0 0.1 -0.05 -0.025
```

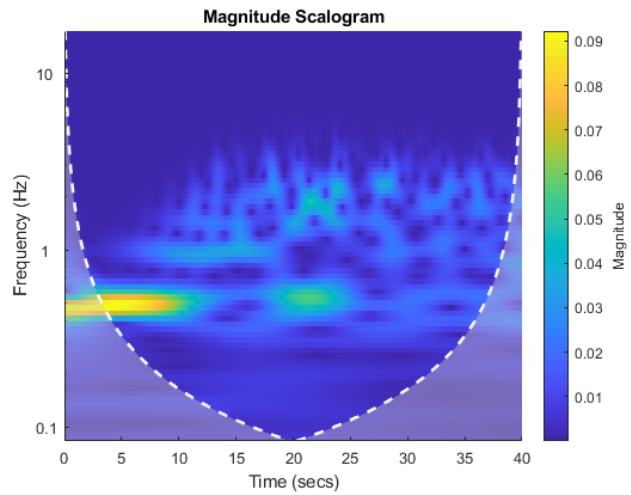
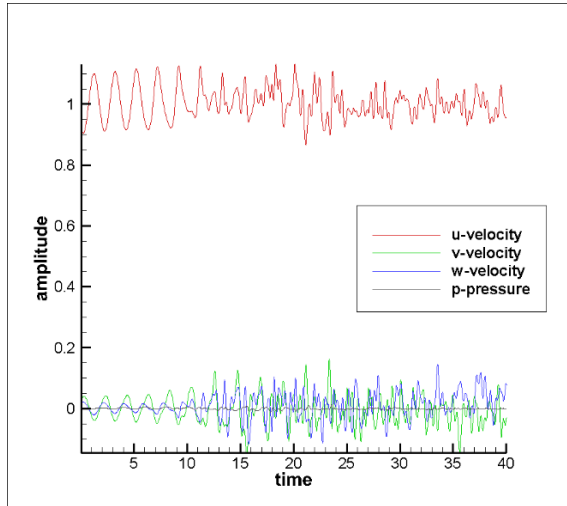


Figure 4.3-5: 41x41x41 Asymmetric three waves

Input Data:

```
51,51,51,0.020,50.0,1.E-5,2.0,2.0,2.0,3
2.0 1.0 1.0 0.1 -0.02 -0.03
2.0 1.0 0.67 0.1 -0.01 -0.0268
2.0 2.0 1.0 0.1 -0.05 -0.025
```

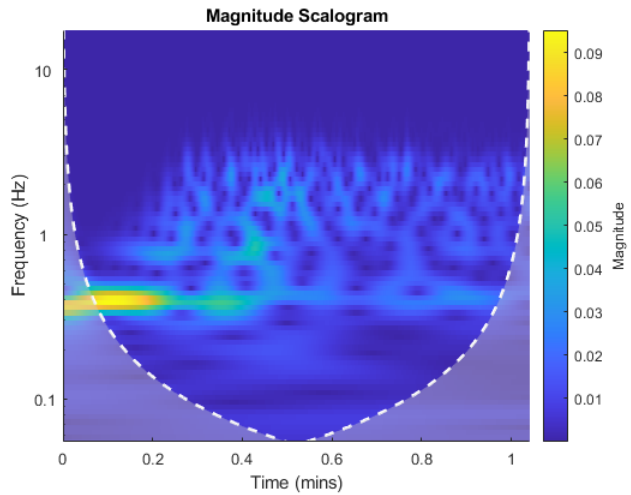
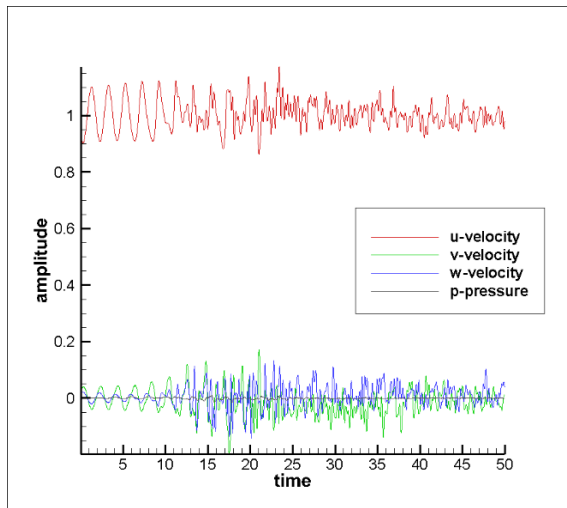


Figure 4.3-6: 51x51x51 Asymmetric three waves

Input Data:

```
61,61,61,0.015,60.0,1.E-5,2.0,2.0,2.0,3  
2.0 1.0 1.0 0.1 -0.02 -0.03  
2.0 1.0 0.67 0.1 -0.01 -0.0268  
2.0 2.0 1.0 0.1 -0.05 -0.025
```

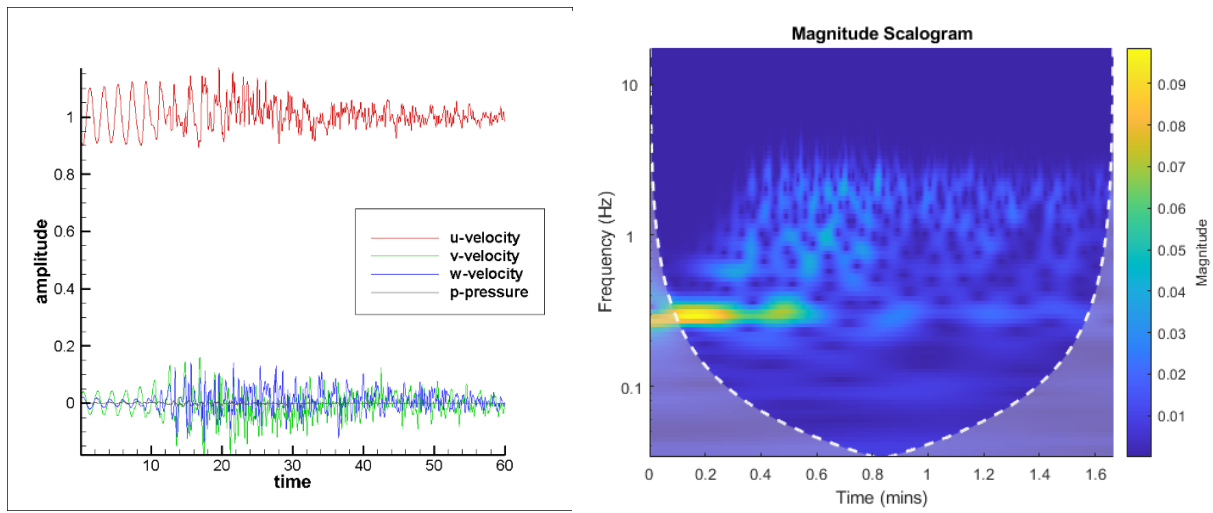


Figure 4.3-7: 61x61x61 Asymmetric three waves

Chapter 5: Conclusion

The behavior of pressure and velocity using TECPLOT and a frequency vs. time graph using MATLAB are investigated to see which wave interactions have energy cascade. The pressure, velocity, and frequency are calculated without a building in the computational domain. The effect of grid size, wavelength and amplitude in the x, y and z directions are investigated in this wave interaction study. From the study conducted one could show that for certain waves, there is no energy cascade and then for other waves there is energy cascade.

Some conclusions that can be drawn from the testing reported in this thesis are:

1. Symmetric waves do not have energy cascade with single waves.
2. Symmetric waves do not have energy cascade with multiple waves when the wavelengths and amplitudes are the same for each wave.
3. Asymmetric wave interactions have energy cascade with single or multiple waves when the wavelengths and amplitudes are different for each wave.
4. There are situations where symmetric multiple waves have energy cascade. This could be due to not having enough grid resolution for smaller wavelengths. At this time, it is hard to conclude due to a need for more data. Further research is needed.

Using this study one can develop more efficient inflow turbulence generators without much loss of energy. For future work, more investigations of wave interactions need to be performed to confirm the conclusions from this thesis. Also, further research needs to be done to investigate inconsistent waves and their effect on energy cascade.

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