The Journal of Undergraduate Research

Volume 7 *Journal of Undergraduate Research, Volume 7: 2009* | Article 4

2009

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ABSTRACT

The experiments discussed in this paper describe the turbulent fluid pressures in breaking waves. Before actual data measurements could be made, the instruments used were put through various tests to determine their ability to capture accurate data. These tests were both static and dynamic in nature. Following the tests on the pressure measurement system, waves were produced such that they were breaking at the instrument panel. Wave height, subsurface pressure, and three components of velocity were measured at this point. Using MATLAB to produce plots, waves that produce strong turbulence were isolated and their respective pressures, as well as theoretical and measured velocity heads were observed.

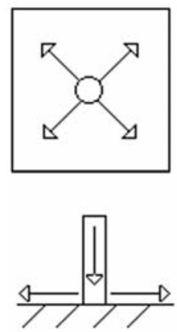

Figure 1. Water jet which could be produced by a turbulence structure

INTRODUCTION

Extensive work has been performed on the velocity characteristics of breaking waves and the subsurface pressures of non-breaking regular waves. However, there exists little to no research on the subsurface pressures of breaking waves. The purpose of determining these pressures would be to determine the actual forces that act on sediment particles. Ting (2006) has shown that breaking waves produce large-scale organized flow structures (coherent structures) that impinge on the bed, as shown in figure 1. The purpose of this study is to determine whether coherent structures can produce large fluid pressures at the base of the water column.

A set of instruments was assembled to measure both the velocity and subsurface pressures of breaking waves. Fluid pressure was measured using a pitot tube connected to a Validyne model P55 pressure transducer. Wave elevations were measured using resistance type wave gages, and fluid velocities were measured using a three-component acoustic Doppler velocimeter (ADV). Control and data acquisition of the various instruments were conducted using a data acquisition board, LabVIEW™, and a PC computer. The sampling frequencies were 50 Hz for the pressure and elevation measurements and 25 Hz for the velocity data.

The pressure transducer and resistance wave gages require calibration in order to ensure that the data taken will be accurate. The pressure transducer was calibrated by taking voltage readings at known differential pressures, and fitting a linear regression to the data. In the same manner, the resistance wave gages were calibrated by moving the staff up and down in the water surface at known depths and taking voltage readings, also creating a line of best fit. This linear regression becomes the calibration curve which is applied to voltages taken during the tests.

The experiments were conducted in a 25-m-long, 0.9-m-wide, and 0.75-m-deep open channel flume. The channel slope can be adjusted from 0.25% adverse to 3.0% positive by a system of synchronized jacks. A constant slope of 2% was used in this study.

The flume is equipped with a piston type wave generator from DHI Water and Environment. The wave generator is mounted on a frame that allows for adjustment of the attitude of the wave paddle so that it will be plumb at any 0.5% channel slope increment between 0% and 3%. A false bottom, 1 m long and 0.89 m wide, was placed underneath the wave paddle to keep the floor level in the area of wave generation.

A profile view of the experimental apparatus is shown in Figure 2, and a profile view of the instrument setup is shown in Figure 3.

The water depth at generation for all wave conditions was 0.298 m.

Before collecting any data on breaking waves, the pressure transducer was tested for the measurement of both static and dynamic pressure. The static tests were completed to simply ensure that calibrations were correct and to verify that the measurement system was working properly, while the dynamic tests determined the ability of the transducer to pick up a dynamic signal and any system response that may be present.

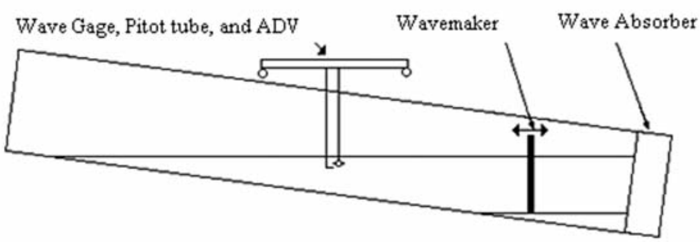

Figure 2
Profile view of the experimental setup

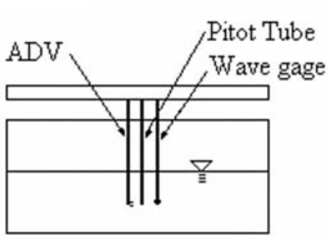

Figure 3
Sectional view of the flume displaying the instrument

Following the testing of the pressure measurement system, solitary, spilling breaking waves were produced, and the pressure, velocity, and water surface elevation were measured at both the center of the water column and bed of the flume. The measured velocity data was used to search for coherent structures (see Ting, 2006).

EXPERIMENTAL PROCEDURE AND RESULTS

Table 1
Characteristics of wave trains for testing the dynamic characteristics of the pressure measurement system

Wave Period (s)	Amplitude (m)	Measurement Depth (m)
0.5	0.02	0.011
0.5	0.04	0.011
0.5	0.06	0.011
0.5	0.02	0.142
0.5	0.04	0.142
0.5	0.06	0.142
1.0	0.04	0.010
1.0	0.04	0.075
1.0	0.04	0.211
1.0	0.08	0.010
1.0	0.08	0.075
1.0	0.08	0.211
2.0	0.02	0.011
2.0	0.04	0.011
2.0	0.06	0.011
2.0	0.08	0.011
2.0	0.02	0.142
2.0	0.04	0.142
2.0	0.06	0.142
3.0	0.02	0.011
3.0	0.04	0.011
3.0	0.06	0.011
3.0	0.02	0.142
3.0	0.04	0.142
3.0	0.06	0.142
4.0	0.02	0.011
4.0	0.04	0.011
4.0	0.06	0.011
4.0	0.02	0.142
4.0	0.04	0.142
4.0	0.06	0.142

Pressure System

Static Tests

Static tests performed on the transducer included simple measurements of differential pressure using two vertical tubes filled with water. The depths of each tube were measured with a yardstick, whose results were compared to the pressure output. The second static test incorporated the actual still water depth and the pressure measurement while the Pitot tube was submerged in the flume. The wave tank was drained, and at four centimeter increments, the draining was stopped to take measurements. Water depth was measured using a resistance wave gage and point gage, along with the subsurface pressure in order to determine whether the Pitot tube was sufficient to measure pressure changes in the wave tank.

Dynamic Tests

A considerable amount of theoretical work has been performed on the subject of the dynamic response characteristics of pressure transducers. In spite of this, in order to best determine the characteristics of the specific system that was used in this experiment, a series of tests were performed.

These tests used small amplitude wave theory with different periods, wavelengths, and amplitudes to calculate the subsurface pressure at various heights within the water column. These calculated pressures were compared to experimental data which was measured at the corresponding height by the pressure transducer.

A total of 25 cases of differing wave amplitudes, periods, and measurement depths were completed. A summary of the test conditions are shown in Table 1. In all of

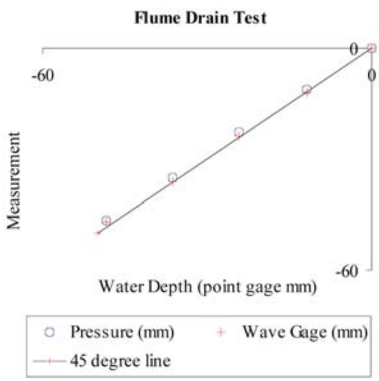

Figure 4. Results of the flume draining test.

these tests, the waves were allowed sufficient time (at least five minutes) to reach steady state oscillation.

Results and Discussion

The data taken from the resistance wage gage, and pressure transducer from the flume draining test were plotted using Microsoft Excel relative to point gage depth along with a 45 degree line, and are shown in Figure 4. The accuracy of the pressure measurements to that of the wave gage and 45 degree line indicates that the transducer used is working properly and can successfully measure the still water depth within the flume

The importance of determining the dynamic characteristics of the pressure measurement used can best be explained in the following quote:

> "The extraneous pneumatic circuitry will have frequency characteristics of its own, affecting system response. When liquid pressures are measured, the effective sprung mass of the system will necessarily include some portion of the liquid mass. In addition, the elasticity of any connecting tubing will act to change the overall spring constant. Connecting tubing and unavoidable cavities in the pneumatic or hydraulic circuitry introduce losses and phase lags, causing differences between measured and applied pressures."
>
> -Beckwith, et al. 1982

The measured data were phase-averaged over 2000 data points. This corresponds to a different number of successive waves depending on the individual wave periods. Theoretical subsurface pressures were determined using linear wave theory (Dean and Dalrymple, 1984). These physical variables are shown in figure 5.

$$p = -\rho g z + \rho g \eta K_p(z) \qquad (1)$$

$$K_p(z) = \frac{\cosh(k(h+z))}{\cosh(kh)} \qquad (2)$$

$$k = \frac{2\pi}{L} \qquad (3)$$

Where:
p = subsurface pressure
ρg = unit weight of water
z = depth of measurement from mean water level
η = free surface elevation
$K_p(z)$ = pressure response factor
h = bottom of water column (z=-h)
L = wavelength

The maximum and minimum measured and theoretical pressures were taken from the averaged wave records and plotted relative to each other for each individual wave period. Trendlines were added to the data set, whose slopes show the difference between the measured and theoretical pressures. The characteristics of the trendlines are shown in Table 2, and an example plot is shown in figure 6. The regression coefficients all being above 0.94 show that the data is consistent with what is actually happening in the system. The variability of the slopes of these lines indicates that there are some dynamic characteristics of the pressure measurement system that needs to be accounted for in any future analysis. Because of this calculated phenomenon, a gain function was taken for every data point in each wave period of the phase averaged data. The gain function is defined as:

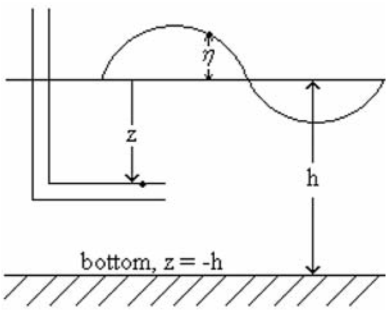

Figure 5. Variables for the subsurface pressures calculations

$$gain = \frac{P_t}{P_m}$$

where Pt is the theoretical pressure, and Pm is the measured pressure. The gain function that was plotted used the average gain of an entire phase averaged wave cycle over all wave heights. The gain was then plotted relative to wave period and is shown in Figure 7. This gain function shows that for wave periods below two seconds, a significant amount of pressure is lost in the system, whether by resonance or the sensitivity of the instrument. This gain function could be used to compensate

Table 2
Theoretical and measured maximum and minimum pressure trendline characteristics

Wave Period	Value	Slope	Intercept	R^2 Value
0.5	Max	0.347	-0.0001	0.941
	Min	0.238	-0.0001	0.995
1	Max	1.097	0.0039	0.975
	Min	0.696	0.0002	0.990
2	Max	0.859	0.0015	0.983
	Min	0.875	-0.0006	0.996
3	Max	0.942	-0.0003	0.992
	Min	1.043	-0.0003	0.998
4	Max	0.850	0.0005	0.953
	Min	1.004	-0.0003	0.950

for system resonance, however, as demonstrated by the maximum and minimum slopes of a given period not being the same (see Table 2), it should not be considered completely accurate. Because of this inconsistency, the pressure transducer should not be used for quantitative analysis, but still could offer benefits to a qualitative study.

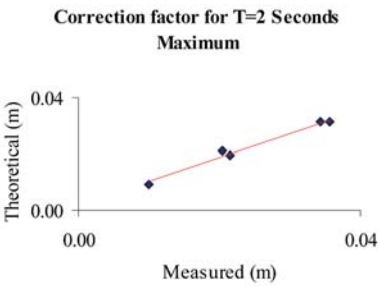

Figure 6. Theoretical and measured maximum pressures for a two second wave period

BREAKING WAVE

Pressure, velocity, and water surface elevation data were taken of a solitary breaking wave of a height 0.22 m at generation in a depth of 0.3 m. The data was taken at an arbitrary location past the breaking point where the local water depth was 0.157 m. These data were taken on two separate days, on day one, the measurement depth (meaning the position of the ADV probe and the top of the Pitot tube from the water surface) was located at 0.151 m and on day two the depth was 0.0701 m. A total of 30 trials for each day were included in data analysis.

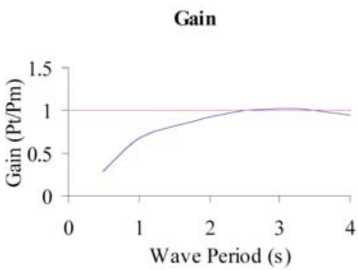

Figure 7. Gain Function relative to wave period

The measured data were ensemble averaged over all the test runs (Ting, 2006). The ensemble averages were subtracted from the original data. The deviations from the mean data were defined as turbulence. The strength of the turbulent kinetic energy can be calculated as $k = \frac{1}{2}(u'^2+v'^2+w'^2)$, where u', v', and w' are the x, y, and z components of the turbulence velocities, respectively. The dynamic pressure produced by the turbulence is related to the turbulence velocity squared. By applying these two parameters (k and w'w'), trials with significant vertical turbulence may be separated from those which do not.

After determining which trials present significant vertical turbulence, the measured pressure characteristics may be compared with theoretical pressures. The theoretical turbulent pressures were calculated using the equation for velocity head $v^2/2g$), where v is the vertical turbulent velocity (w'), and g is the acceleration due to gravity (981 cm/s^2). An approximate value for the measured pressure produced by turbulence was determined by subtracting the theoretical wave-induced dynamic pressure calculated using the wave gage measurement from the measured total subsurface pressure. It should be noted that the resistance wave gages used in this study are not a particularly reliable instrument for determining wave height while there is a matrix of air in the area being measured, which is why this value is only given as an approximation.

Results and Discussion

Following the charts for each of the sixty trials, the most apparent vertical turbulence trial from each of the data sets (middle and bottom of the water column) was taken for further analysis. The middle of the water column experienced a higher amount of turbulence than the bottom of the water column. This is most likely due to dissipation of energy as the turbulence descends. Because of this, both measured and theoretical turbulent velocity head are higher in the middle region of the water column. In all data sets, the theoretical velocity head taken from ADV measurements is much lower than the measured velocity head. The calculated turbulent velocity head does not reach values above 0.25 cm, compared to measured values of ±1 cm. This is most likely due to the effect of the water surface fluctuations. Thus, the data shows that the turbulent pressure is outweighed by the randomness of the free surface deformation occurring in the breaking process. The wave gages show a trend in the oscillating period and to some extent the magnitude of the pressure and wave gage data. This phenomenon may be seen in figure 8, which was taken from the strongest structure at the bottom of the water column. If additional study is to be performed in this area, a more reliable way to measure the elevation head would greatly aide in measuring the actual pressure characteristics of turbulence structures in breaking waves.

CONCLUSIONS

1. The Validyne P500 series pressure transducer attached to a pitot tube is accurate in measuring the still water elevation head of within a wave tank

2. The gain function for wave periods ranging from 0.5 to 4 seconds has been analyzed and plotted for the Validyne P500 series pressure transducer, and shows a significant loss at periods below three seconds, and as accurate results above three seconds. It should also be noted that the trendlines fitted to data suggest that the maximum and minimum values do not both follow the same pattern, so the gain function should only be used as an approximation to true data.

3. Pressure fluctuations produced by the free surface deformation in the breaking process vastly outweighs the dynamic pressure produced by turbulence structures.

4. Resistance wave gage data is not accurate enough to determine the subsurface pressure fluctuations caused by the motion of the free surface. Hence, the dynamic pressure produced by the turbulence structures cannot be determined accurately from the total measured pressure by subtractions.

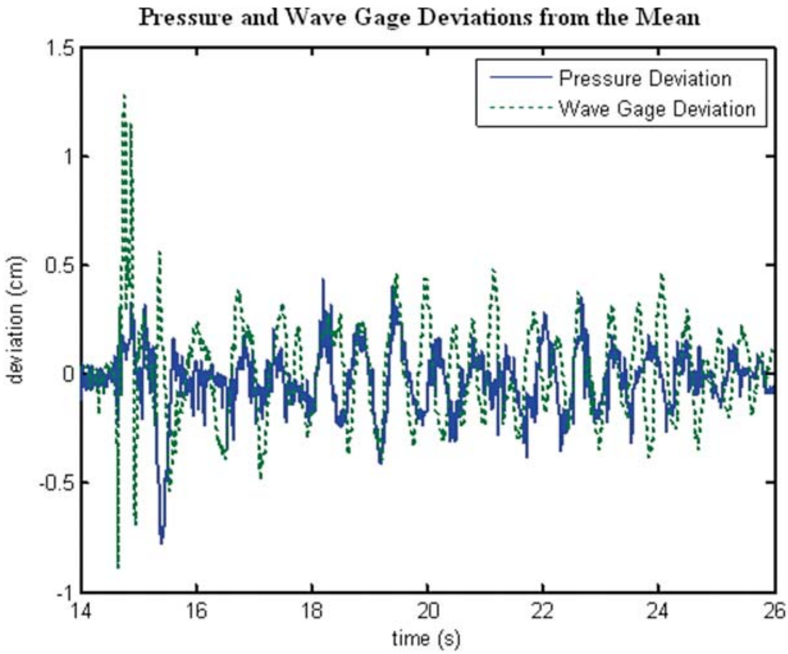

Figure 8. Comparison of pressure measurements and water surface elevation deviations from the mean

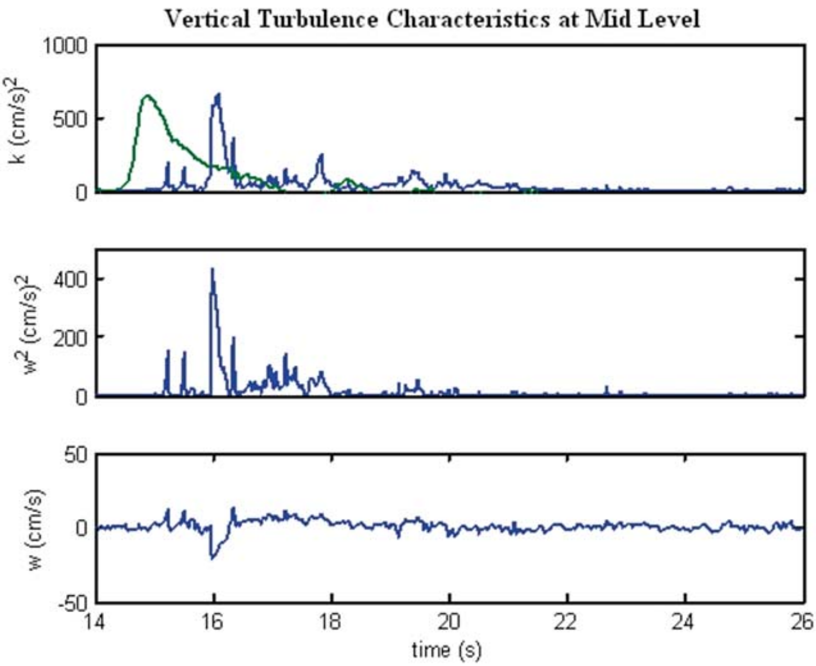

Figure 9. Strongest measured turbulent velocities in the middle of the water column

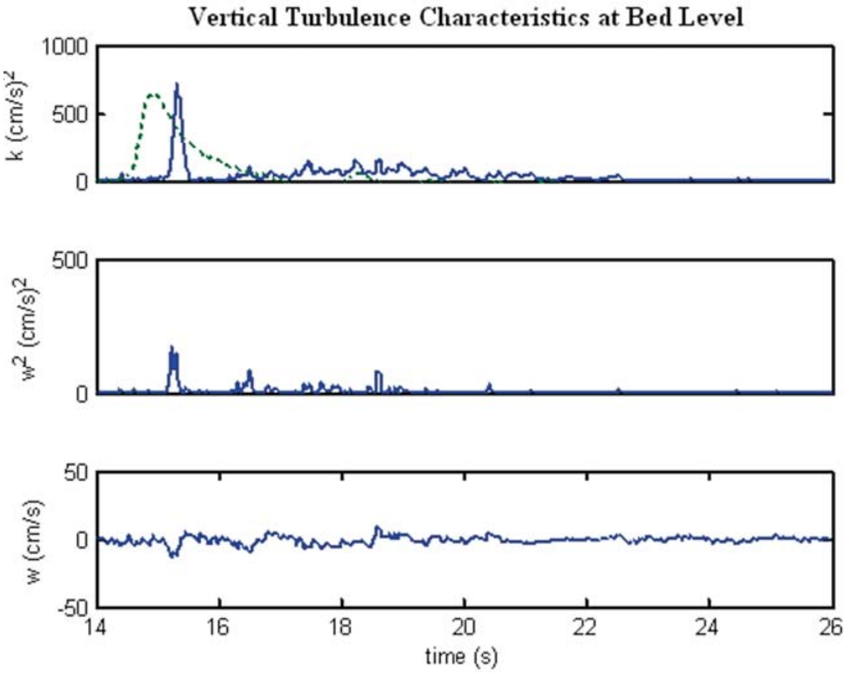

Figure 10. Strongest measured turbulent velocities at the base of the water column

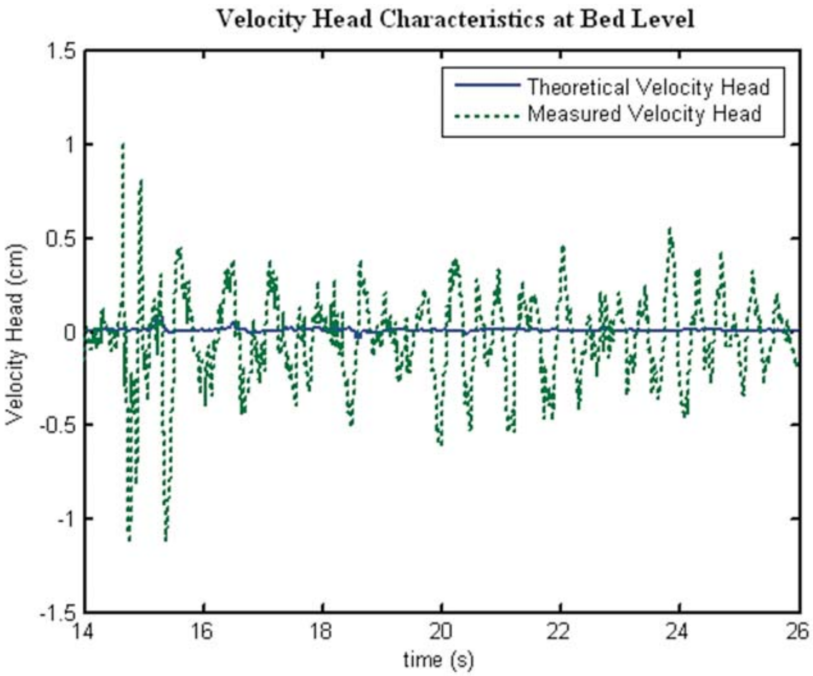

Figure 11. Theoretical and measured velocity head at the base of the water column

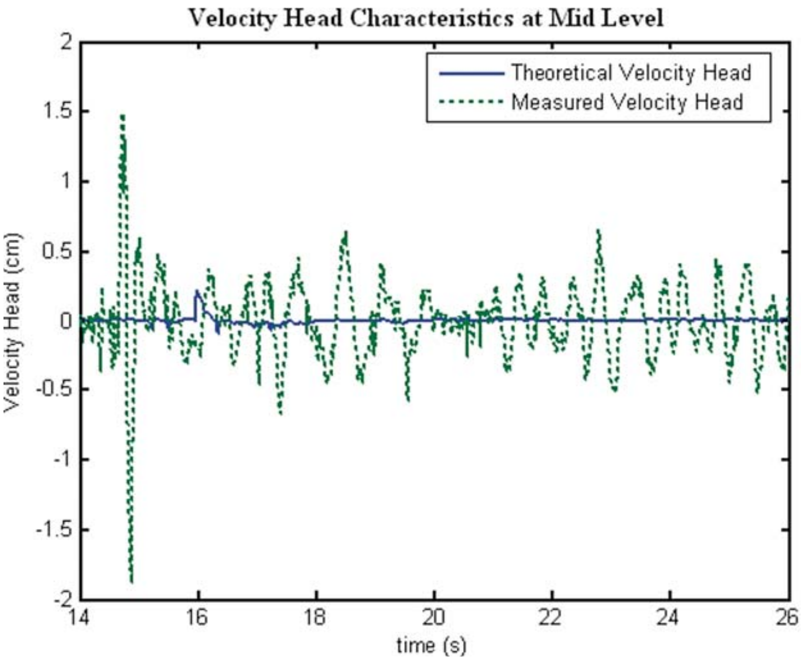

Figure 12. Theoretical and measured velocity head in the middle of the water column

ACKNOWLDGEMENTS

This study was funded by the National Science Foundation (NSF) through Grant OCE-0525676. The support of NSF is gratefully acknowledged. I would also like to thank Dr. Francis Ting for his guidance in this research opportunity.

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