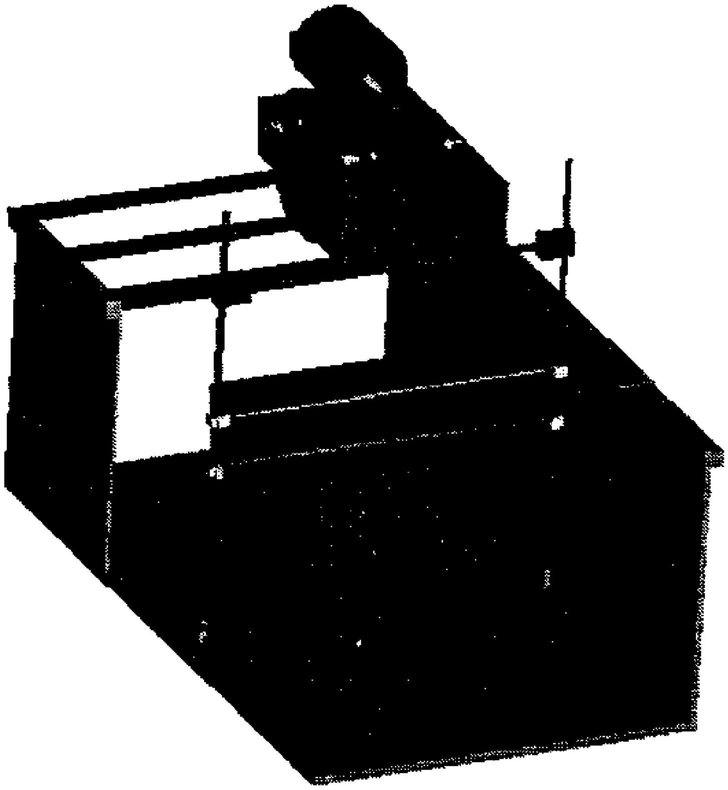
Wave Generation System

UNH Tech 797 - Ocean Projects



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Chad A. Turmelle - Project Leader
Brian Lamb
Ronald S. Regnier
Advisor: Dr. M. Robinson Swift

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Abstract

A wave train generation system was designed, fabricated and incorporated into an existing flume tank at the Center for Ocean Engineering at the University of New Hampshire. Specifications for the system include the generation of uniform, periodic water waves, 1 to 3 inches in amplitude at frequencies of 0.5 to 4 Hz., while resulting in minimal flow disturbance and/or turbulence. In addition, the system should be capable of complete installation and removal without draining the tank

A unique solution was found in the form of a ventilated flap-style wave maker with hinge mounts at the bottom of the tank. The flap face consists of a series of hinged flaps which open upon retreat and close upon advancement. This design allows flow to pass generally unobstructed while still retaining wave generation capabilities. The device is powered by an electric motor that rotates a flywheel. This, in turn, is connected to a push rod that drives the multiple vent frame.

The device proved capable of creating, periodic, waves with 0.25 to 2.25 inch amplitude. The frequency of these waves ranged from 1 to 3 Hz. However, the waves were not uniform, often containing a distinct secondary wave. Limitations were found with the action of the hinged flaps at high flume tank velocities. Overall, the system performs within design specifications and enhances the flume tank model tests.

Introduction

Purpose:

The Center for Ocean Engineering at the University of New Hampshire (UNH) has been involved with the development and design of oil spill management and cleanup technologies for much of the last decade. Some prototype testing takes place in a four foot wide, three foot high, 40 foot long flume tank. The tank generates flow rates of up to 0.9 m/s and has a transparent side for experiment observation. To investigate failure modes of oil containment booms in a more realistic environment it was determined that a wave generating device was a necessary addition. With the new dimension of waves added to the model tests, a wider range of experiments could be performed on models to enhance the full scale prototype construction. The challenge was to develop a device capable of generating uniform, sinusoidal waves with one to three inch amplitudes over a range of frequencies.

Flume Tank Description:

The circulating flume tank at the University of New Hampshire is located in the Jere A. Chase Ocean Engineering Laboratory. The tank measures 48 inches high, 46 inches wide and 40 feet long with an open top and one transparent side. Shown in Figure 1 is a horizontal partition that runs the length of the tank approximately one foot from the bottom. This divides the tank into two stages. Two 20 horsepower electric motors, located outside the tank, drive propellers located at one end of the lower stage that drive the water. The flow proceeds to the opposite end of the tank before encountering turning vanes which redirect it 180 degrees into the upper stage. The water then passes through flow straighteners before continuing to the test section. Once through the test section, the flow is again redirected back to the lower stage to repeat the cycle.

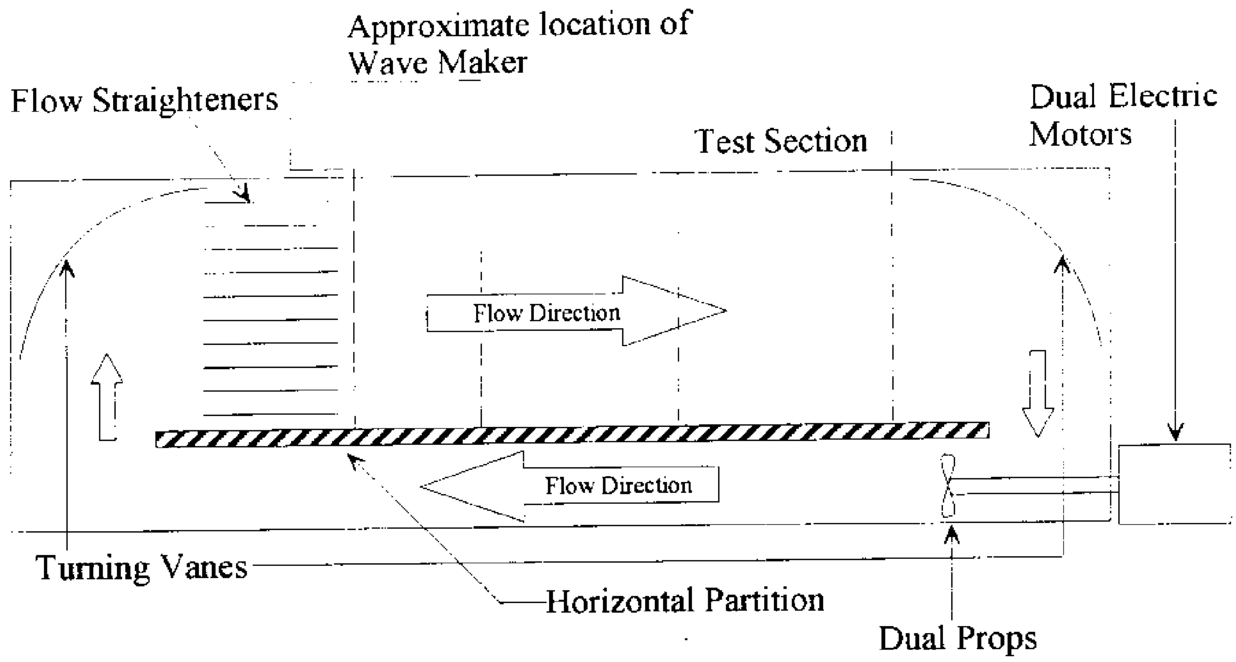


Figure 1: Schematic of Flume Tank

Previous Work:

Before conceptualization, a thorough search was conducted to uncover previous work performed in flume tank wave generation. The University of New Hampshire library system proved to contain no relevant information on the subject.

An extensive literature and World Wide Web search produced evidence of only two previous attempts. The first consisted of a fixed object in the water column that resembled a high pitch air foil (McPherson,1998). This foil pushes the water down; rising after it clears the foil, the water forms a crest and trough system. This wave system design is limited by its inability to vary wave characteristics without physically changing the foil shape or interchanging the foil.

The second yielded a device designed and fabricated by Skyner (1992) at the University of Edinburgh, Scotland, UK. in partial fulfillment of his doctoral requirements. His method involved using water jets to inject flow underneath the paddle of a standard wave tank. The excess water added from the injection was drained at the opposite end of the tank. Though Skyner had significant success with his system it was not a solution that was applicable to UNH's flume tank.

Design Goals:

The primary design goal was to generate small amplitude periodic waves in a flow field generated by the flume tank. The waves must propagate in the direction of the water flow. Optimally, the wave generation system is to operate with minimal interference with the water circulation. A subsequent goal was to construct the device in such a way that it could be easily removed from the tank

Approach:

In an initial series of meetings, the group conceptualized several unique, potential solutions to the problem. Wave maker theory was investigated and this, along with theory of fluid mechanics was used to develop these concepts while ruling others out. Through process of elimination, the field of possible devices was narrowed to three, and prototypes were constructed of each of these. These hand powered prototypes were evaluated in a smaller, shallow flume. From this series of tests the final design was chosen.

Next, details of the mechanical design were addressed. Computational kinematic analysis was performed as well as force and stress analysis. From this, dimensions and positioning of the device was determined. Commercially available parts were sought but seldom found, therefore most components were fabricated from stock materials..

Testing of linkages and the motor drive was performed as components were assembled. The flume was then filled and operated for final wave generation experiments. Quantitative measurements were conducted with a wave staff and accompanying software.

Design Alternatives

Several designs potentially capable of wave generation were conceptualized. Each one was evaluated for effectiveness, feasibility and cost. Below are the design concepts considered, with a brief description:

1) Rotating Ellipse:

This design consists of a rotating elliptical cylinder suspended over the tank, as shown in Figure 2. The cylinder would impinge the water surface twice on each rotation. This would create reciprocal crests and troughs from each interaction with the water surface. The rotation speed of the cylinder was required to be great enough to produce a linear velocity at the outer edge that would exceed the flow velocity of the tank. The height of the cylinder relative to the water surface would be variable as would the rotation speed such that the operator could obtain the desired wave amplitude and frequency. This design would be inexpensive and easy to implement.

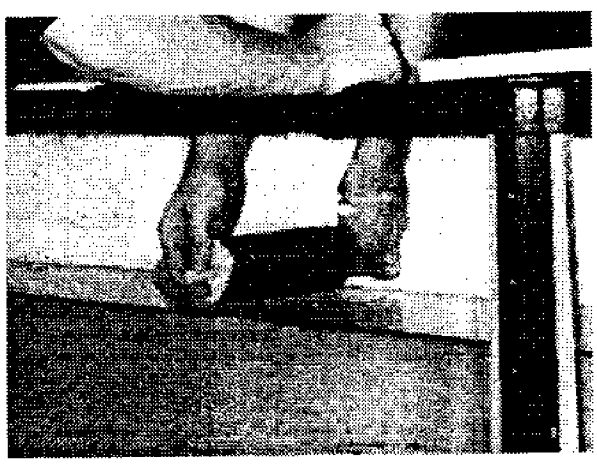


Figure 2: Picture of Rotating Ellipse

2) Belt Driven Paddle:

A conveyer belt with elliptical paddles attached, would be suspended horizontally above and parallel to the tank. As the belt rotates on pulleys, the paddles would break the water surface pushing water ahead and leaving a trough in the same manner as the rotating cylinder. This concept is a more complex version of the rotating ellipse.

3) Undulating Flap:

A sectioned and hinged flap, laid horizontal to the water surface, would undulate to coerce the water surface into the shape of a wave, as shown in Figure 3. The flap consisted of three sections, each oscillating semi-independently to reproduce the motion of a dolphin tail. Frequency and amplitude of the oscillations would be independently variable to obtain the desired wave pattern. Due to its complexity this design could be both expensive and difficult to implement.

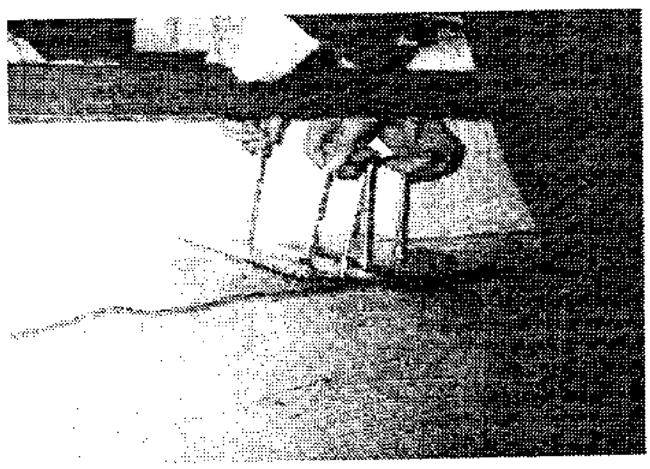


Figure 3: Undulating Flap

4) Vented Paddle:

A vented paddle is mounted on the bottom of the flume tank, as illustrated in Figure 4. The paddle is similar to a flap-style wave generator but instead of a solid paddle, it would consist of a series of horizontal doors. These doors, or flaps, swing open on the backstroke to allow the flow of water to pass. The doors close at the start of the forward stroke to create a uniform paddle surface. Its frame is driven at the top of an external frame by a push-rod and rotating disk assembly. As with the hinged flap, frequency and amplitude of the paddle motion would be independently variable to obtain the desired wave pattern.

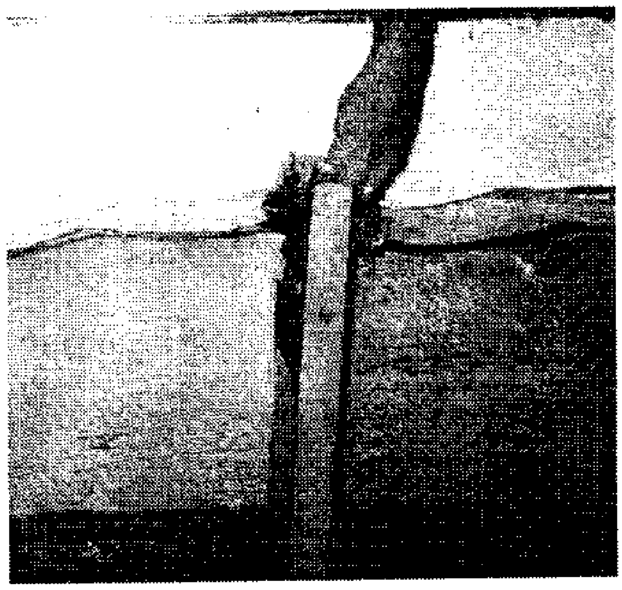


Figure 4: Vented Paddle

5) Hydrofoil:

A hydrofoil suspended at the water surface depresses the water as it flows underneath, as shown in Figure 5. The water rising behind the foil produces a crest and trough system. This design was the simplest but was believed to only work for high velocity flow fields. The flow generated by the UNH flume tank has a low velocity rendering this design unusable.

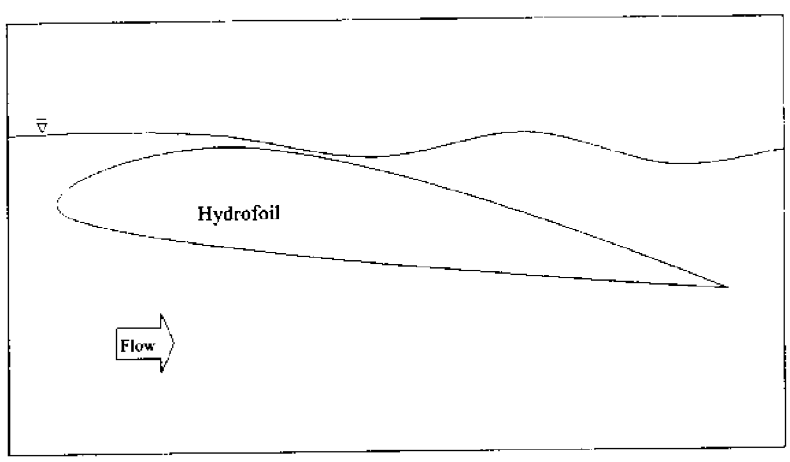


Figure 5: Schematic of Hydrofoil

Among the aforementioned designs, 3 concepts progressed to the prototype stage: The rotating ellipse, the undulating flap, and the vented paddle. Others were ruled out either due to complexity, similarity or unlikely hood to achieve the design goals. The prototypes were small hand held, hand powered mechanisms, constructed with low cost, readily available materials i.e., duct tape, plexiglass, scrap lumber, etc..

Qualitative tests were conducted in a 10 inch wide flume tank at the Geo-Fluids laboratory at UNH. Figures 2, 3 and 4 show pictures of the actual tests being performed. Through 2 tests the vented paddle prototype produced the most significant deep water waves at all amplitudes and frequencies. It accomplished this through a range of flow velocities. In a group council with Dr. Swift and team members, the test results were evaluated and a general consensus was obtained. The ventilated paddle was found to have the most potential, and it was decided to pursue this as the final design.

Design Description

Major Components:

The selected design is a direct descendant of a flap-style wave generator with some modifications. When used in a conventional wave basin (without flow), a large wall, or flap, is hinged at the bottom of a tank of stationary water. The motion of the hinged wall fits the velocity profile of a small wave that has its largest velocity at the top, and smallest at the bottom. The wall is then forced to rotate about its hinges sinusoidally creating reciprocal crests and troughs with each advancement and retraction. These have typically been driven by hydraulics, however, mechanical elements have also been employed.

The wave generation team's solution has several modifications from the basin style design. An external frame was created and hinged at the bottom of the tank (as shown in Figure 6). Detailed drawings of parts used in the construction of the wave generation system along with assembled drawings are shown in Appendix A The center of the frame is filled by a series of flaps. These flaps are hung from hinges and are able to open and close without mechanical interference. Along the uppermost part of the frame is an unhinged flap. It is not meant to be submersed, but instead to catch the turbulent "spillage" that could tend to develop under forcing. Below the unhinged flap and starting a few inches above water level, when the vents are vertical, is a series of two to three other flaps that can extend a maximum of 14 inches below the surface. The final design of flaps, number, size and configuration is to be optimized through testing. This design allows the flaps to shut while advancing, effectively creating a solid wall, and forcing a wave crest. Upon retraction, the doors open, allowing water to flow through the wall with minimized drag and turbulence.

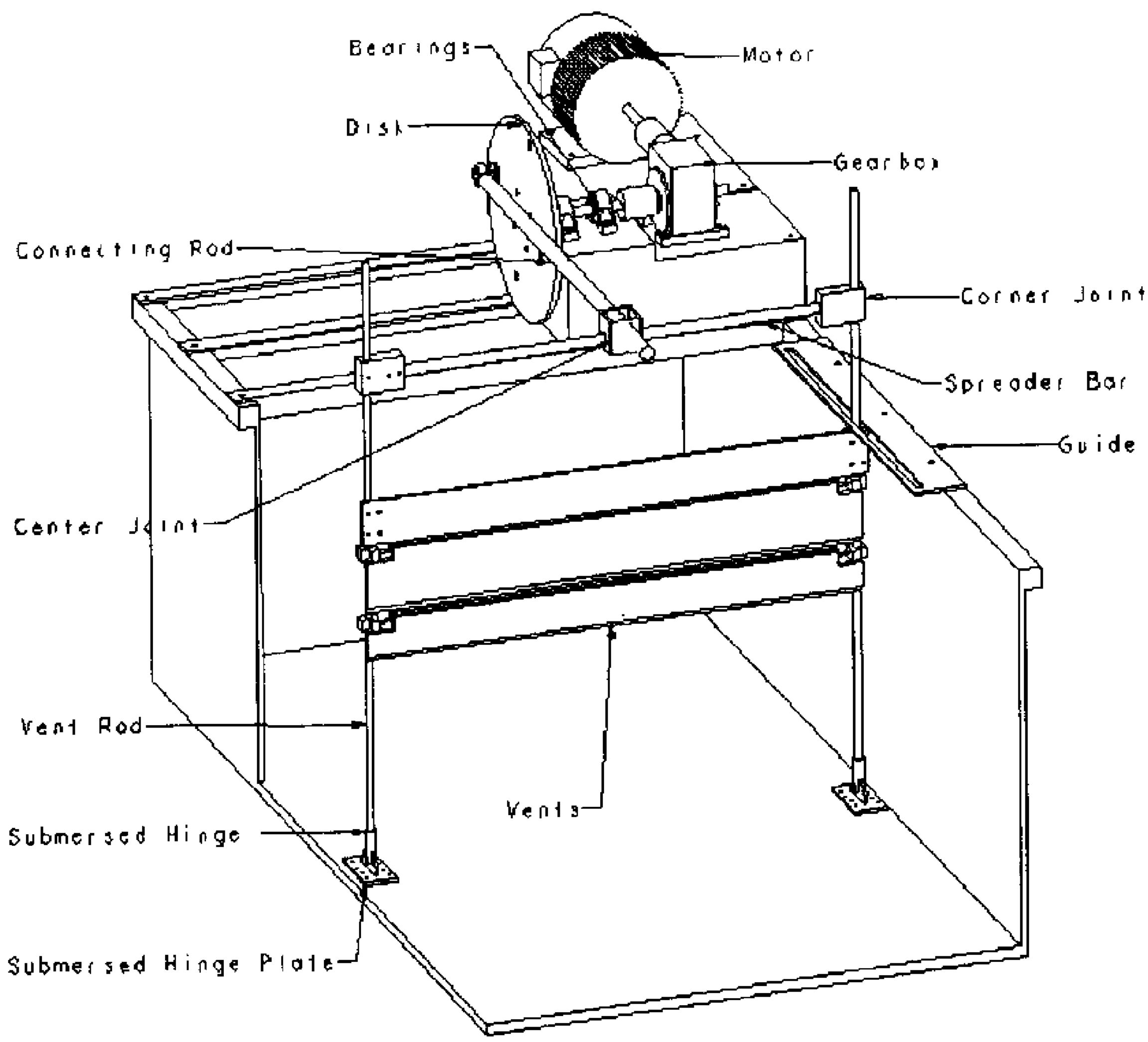


Figure 6: Drawing of design for wave generation system

The flap-style method of wave generation depends upon the retraction of the wall to create the troughs equally as much as it depends on the advancement of the wall to create a crest. We have consciously not included a retraction as a part of the wave forcing knowing that it will diminish the effectiveness of the device. This is necessary to adhere to the design requirement of allowing flow through the tank.

With access to a 3-phase induction motor at no cost, it was decided to pursue a mechanical drive over a hydraulic drive. The sinusoidal motion of the wall is generated by using a connecting rod attached to a 20 inch rotating disk with its axis of rotation perpendicular to the desired motion of the vents (see Figure 6). The disk will then be indirectly driven by the induction motor which is controlled by an open loop frequency controller. This can be used to control the period of the waves created. There is a series of connection holes on the disk located at several radii to provide adjustments for different amplitude waves.

Power Train:

The power train of the wave generation system is an electric 3 phase induction motor rated to 10 hp at 3500 rpm . The motor output is reduced through a 30:1 gear which turns the driving mechanism of the wave maker, the disk.

The reason this motor was chosen to be used was primarily due to the fact that it was obtained at no cost to the project. This was important due to the fact that it is expensive to purchase an electric motor with high torque at low revolutions per minute (rpm). Since high torque was a necessity for the wave maker, it was decided that the funds budgeted for an electric motor could be better used for a speed reducer gearbox. Using the motor specifications along with the power requirements of the system, a 30:1 gear reduction was chosen which increases torque at low output speeds.

The electric motor is controlled by a open loop frequency controller. The user inputs a frequency into the controller, then a voltage is sent to the electric motor to drive it at the desired frequency. The controller is capable of being run from 0 to 60 hertz., which is also true for the motor.

A platform was created and mounted to the top of the flume tank. This platform serves as a base for mounting the motor and gearbox rigidly to the tank. The electric motor was oriented such that the output shaft of the electric motor is parallel with the long axis of the tank (see Figure 7). The gear box and the motor are joined by a Lovejoy spider coupling. This type of coupling has a hard plastic insert between the two steel parts of the coupling that allows for limited misalignments.

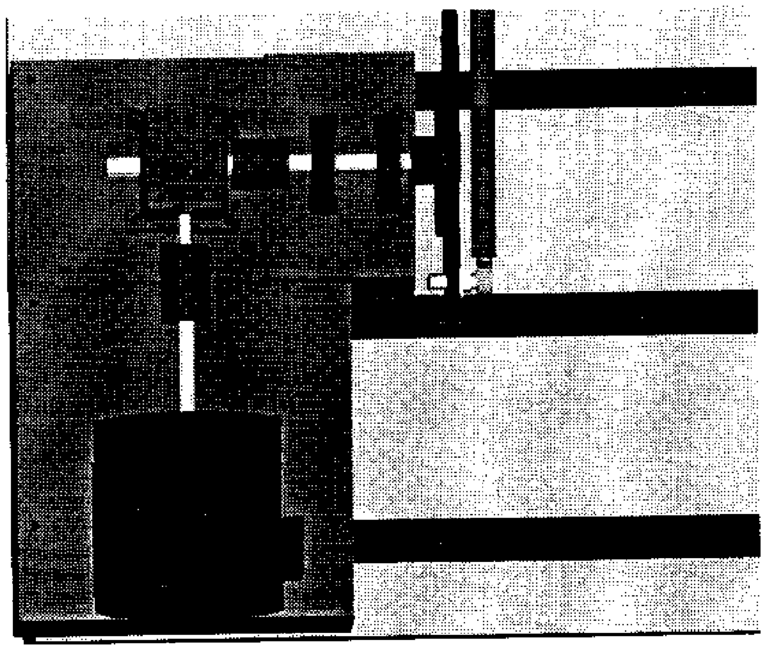
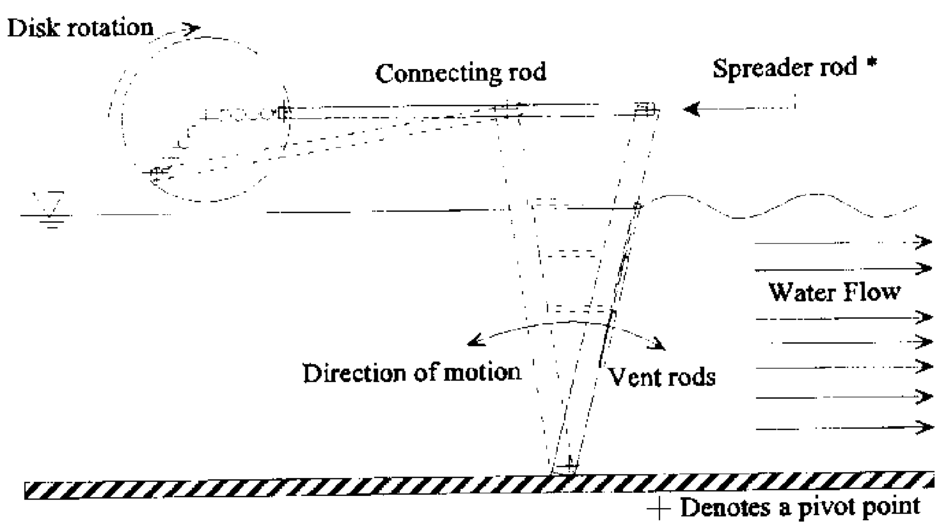


Figure 7: Drawing of Power Train

The gear reducer has two output shafts that are perpendicular to the input shaft. This 90 degree turn orients the shaft perpendicular to the flow of water in the tank. The shaft is then attached to another Lovejoy coupling. Connected to the opposite end of the coupling is a short drive shaft. This shaft is held in place through the use of two radial steel ball bearings. This small section of shaft is needed so that the disk mounted on the drive shaft is directly in the center of the tank.

Drive Linkage:

The driving mechanism for the wave generation system is powered by the motor and gear reducer discussed previously. The driving mechanism consists of four main components. They are the disk, connecting rod, spreader rod and the vent rods (locations in Figure 8). The key features of the driving mechanism are the disk and the vent rods. However, the connecting rod, spreader rod and related joints also have a distinct and specific purpose.



* Spreader rod axis perpendicular to paper

Figure 8: Schematic of Drive Linkage

The driving mechanism was analyzed using a kinematic and dynamic analysis described in Appendix B. To complete this analysis, a certain condition and assumption was made. The condition was that the pivot point, located at the top of the vent rod, be placed at the same height as the center of rotation of the disk. This condition was maintained throughout construction and testing. The assumption was made that the mechanism was constrained to two dimensions. This is valid because the mechanism is in fact constrained to two dimensional motion by the axis of its hinges. The only movements out of this dimension is deformation and vibration, both of which were neglected for the analysis.

The analysis yielded the angular velocity of the vent rods as a function of time. This is of value for the calculation of the linear velocity of the vent rod. The velocity of the vent rod is given by

$$Vel. = \omega \cdot r \qquad [1]$$

where ω = angular velocity and r = radius. With the above formula and the kinematic and dynamic analysis, the velocity at the vent rod air-water interface could be found. This value determines the velocity the vent rod must have to generate waves at any flume tank water velocity. Having obtained the linear velocity at the air/water interface, the physical parameters of the wave generation system could be designed to match the desired linear velocity. Calculations were performed in Appendix C.

Detailed descriptions of the driving linkage components are given below:

1) Disk & Coupling:

The disk component (see Figure 8) of the drive mechanism is made of half inch thick aluminum and has a diameter of 20 inches. Located on the disk are five 3/4 inch holes with varying radii of 5 to 9 inches with 1 inch increments. The disk is connected to a coupling (see Figure 9) by four 3/4-16 bolts and nuts. The disk and coupling are attached to a drive shaft which is turned by the output of the gearbox.

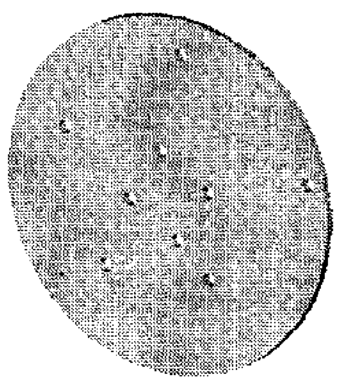


Figure 8: Disk

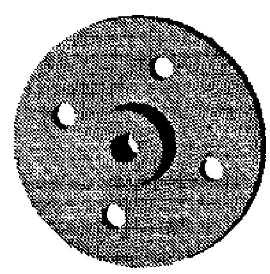
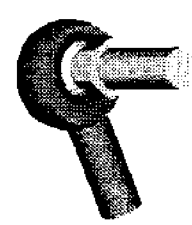


Figure 9: Coupling

2) Ball Joint:

The ball joint connects the disk to the connecting rod. It allows for free rotation and misalignments. (see Figure 10).

Figure 10: Ball Joint



3) Connecting Rod:

The connecting rod is made of 1.25 inch diameter stainless steel rod that is 3.5 feet in length. On one end of the rod is 3/4-16 threaded female connector, 2.5 inches deep This is so that the ball joint (described above) that connects the disk to the connecting rod can be attached.

Frame:

The frame is the backbone that provides the support for the ventilated flaps and is configured to be driven at its top and hinged at its bottom. By design, the entire frame can be totally removed from the tank with the exception of two parts, the submerged hinge and hinge plate. Detailed descriptions of the frame components are given below:

1) Spreader Rod:

The spreader rod is made of one inch diameter stainless steel rod that is 41 inches long. The connecting and spreader rods are interfaced with the center joint (described below). This intersection point, as specified, is at the same height as the center of rotation of the disk.

2) Vent Rods:

The vent rods are made of 5/8 inches in diameter stainless steel rod that is 4.5 feet long. One end of each rod has male 5/8-11 to screw into the submerged hinge (described below).

3) Center Joint:

The center joint (see Figure 11) is the joint that interfaces the connecting rod to the spreader rod and allows for rotation about the spreader rod axis. It is constructed of three inch steel box beam. The box beam has two 1.25 inch diameter holes drilled through the two different planes of the solid faced stock. A 3 inch, oil impregnated, brass bushing is press fit into one of these openings to alleviate friction on the spreader rod. The connector rod and the spreader rod are held in place by two collars that are placed on either side of the center joint.

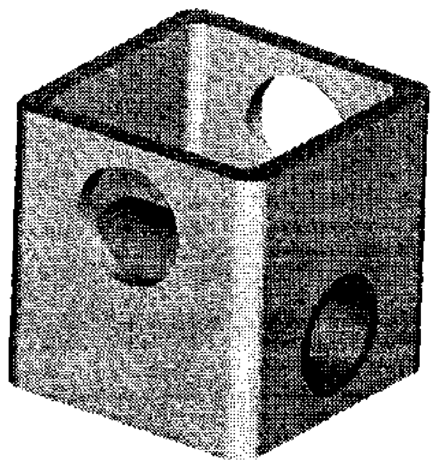
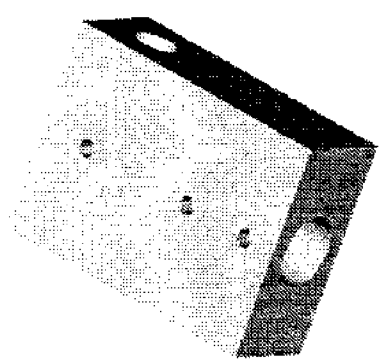


Figure 11: Center Joint

4) Corner Joints:

The corner joints (see Figure 12) connect the spreader rod to the vent rods. They are made of aluminum blocks, 4 x 3 x 1.5 inches, with two large bore holes drilled into the material. In one side there is a one inch diameter hole in which the spreader rod is inserted and held by two set screws. Another 5/8 inch diameter opening through the block allows the vent rod to slide completely through. The vent rod is held in place with a set screw and by two collars that are placed on top and bottom of the joint.

Figure 12: Corner Joint



5) Submerged Hinge and Hinge Plate:

The submerged hinge (see Figure 13) is made of one inch diameter stainless steel rod whose overall length is 3 inches. The vent rod screws into the hinge and is secured to the hinge plate (see Figure 14) with a clevis pin. The dimensions of the hinge plate are 3 x 6 inches, 1/4 inch thick, on the base with a 1.75 inch piece of the same material welded to the lower plate.

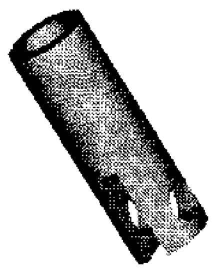


Figure 13: Submerged Hinge

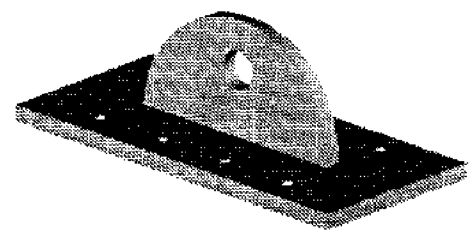


Figure 14: Submerged Hinge Plate

Once the driving linkage and frame was assembled, it was noticed that the device was not rigidly constrained to the two designed dimensions. It was observed that when in motion, the linkage would shift from side to side. As a remedy, two guides (see Figure 15) were constructed of 1/4 inch thick aluminum plates. The plates have a 11/16 inch slot cut into them for the 5/8 inch diameter vent rods to pass through. The plates were mounted to the upper outside frame of the flume tank. The guides completely remedy the rigidity problem.

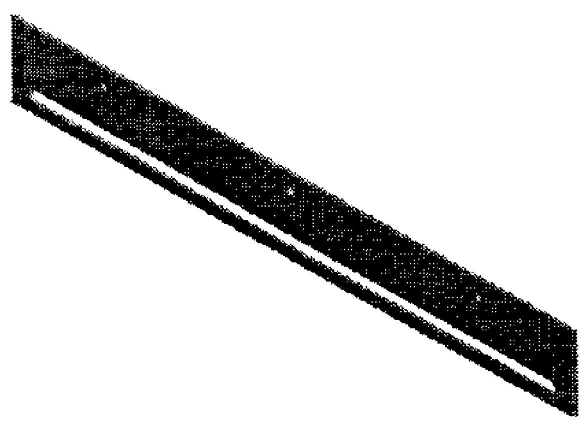


Figure15: Frame Guide

Ventilated Flaps:

The essence of the wave generation system lies in the design of the ventilated flaps. The flaps are a series of long, thin doors that are hinged at the top and span the frame. Most of the major design requirements are met by the shape and function of these flaps.

The first and foremost design requirement is the ability to coerce the water into a wave while simultaneously allowing flow of water through the tank. This is accomplished by creating a series of flaps (see Figure 16) that extend into the upper part of the flow field and are mounted on the frame. The flaps that are in contact or submerged in the water are hinged. The hinges consist of a 0.25 inch diameter and 2 inch deep hole drilled into either side of a cut away corner section of each flap. In each hole are two compression springs that supply tension to a 1/4 inch diameter, 2 inch long pin that is mated to a spindle in the vent bracket, The spindles are mounted on the vent rods using set screws. This allows the flaps to close, by the force of the water, when the frame is advancing and open upon retreat, thus meeting the most important design requirement. This also meets another design requirement of ease of assembly/disassembly. To install or remove, the cotter pins are simply pulled back compressing the springs and allowing the pins to be removed from the spindle. When this is done the flap easily lifts out.

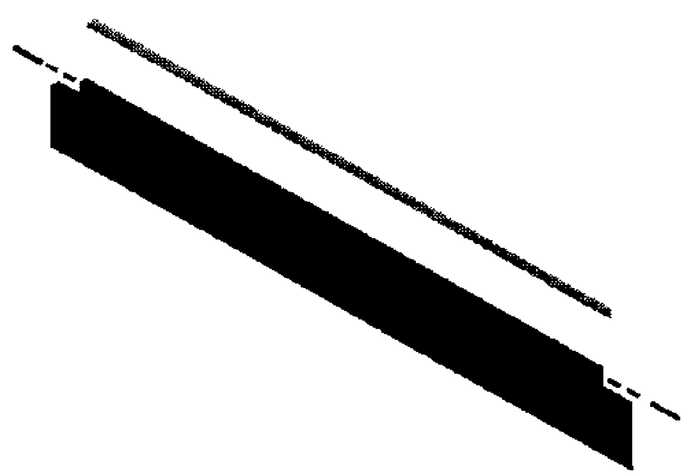


Figure 16: Ventilated Flap Assembly

The final layout consists of one 6 inch high flap, that is partially submerged (approximately 2 inches out of the water, depending on water depth) and another 4 inches high fully submerged. There is another 4 inch high PVC section located above the 6 inch flap that is used as a splash guard. This layout was attained experimentally. It was found if the vents extended any farther under the surface of the water that the motion of the frame was not sufficient to result in a contribution from the lower vents.. The splash guard was found to be a necessity to prevent water from washing over the top of the 6 inch flap.

The flap material was chosen from a myriad of design requirements. A necessity of the design is that the density of the material be low enough so that upon retreat the flaps will not inhibit flow. Yet if the density is too low, upon advancement the flaps may never close. Furthermore, the material must have a modulus of elasticity that can withstand the bending moment of the wave creation. It was decided that 0.5 in wide PVC (Poly Vinyl Chloride) was the optimal choice with a density that was below steels but not as low as to be buoyant. Using standard beam deflection calculations, with forces predicted from wave theory the PVC vent was expected to deflect 0.001 inch under the maximum loading situation (See Appendix D).

To enhance the performance further, two design features were added. To aid in the stiffness of the flaps, aluminum L-braces were installed along the top edges. To facilitate the speed of closure of the flaps, the lower (leading when extended) edge is angled to 45 degrees. Without this, there is a significant resultant force resisting the closure of the flaps, with it, the flap slices through the water like a fin.

Testing and Evaluation

The wave generation system was tested varying three different parameters: radius, flume velocity, and motor control frequency. The full range of operating abilities was tested using these three parameters. The radius was varied from five inches to nine inches, in increments of one inch. The flume velocity was run from zero to 0.3 m/s, in increments of 0.15 m/s. The motor control frequency was varied from 15 Hz to 45 Hz, which correlates to a wave flap frequency of 0.5 Hz to 1.5 Hz. The goal of these tests was to determine the optimal range of operation for a given flume tank velocity.

The results of a total of 46 tests are shown in Appendix F. A summary of these results is in Table 1. For each combination of variables, a wave form and power spectrum were plotted. The wave form was measured by a wave staff and the data was collected by LABTECH Notebook, a data acquisition software program. From these plots, the amplitude of the wave and frequency content could be determined. The resolution of the power spectrum plots is limited to 0.5 Hz due to the limitations of the Fast Fourier Transform (FFT) performed by LABTECH Notebook.

The plots indicate that the wave generation system creates a periodic waveform. The waves created varied in amplitude from 0.25 inches to 2.25 inches, and in frequency from 1 Hz to 3 Hz. Two examples of waveforms and their respective power spectrums are shown in Figure 17 and 18. Figure 17 correlates to a disk radius of 5 inches, flume speed of zero m/s and a wave flap frequency of 1.167 Hz. Figure 18 correlates to a disk radius of 6 inches, flume speed of 0.152 m/s and wave flap frequency of 0.833 Hz.

One important observation was made during the testing. The spider coupling used to connect the disk to the drive shaft is not stiff enough for the rotating mass of the system. When the connecting rod changes the direction of motion, the momentum of the system also shifts, creating a hitch in the action of the system. This phenomena is particularly noticeable when the disk radius is set large.

Table 1: Summary of Testing Results

Flume velocity = 0.0 m/sec

Radius (in)	Motor control freq. (Hz)	Wave flap freq. (Hz)	Amplitude (in)	Wave freq. (Hz)	Period (sec)	Comments
5	15	0.50	0.5	1	1	double peak
5	25	0.83	1	1.5	0.67	double peak, constant
5	35	1.17	1	1	1	
6	15	0.50	0.5	1	1	wo small then one large peak
6	25	0.83	1.5	1.5	0.67	double peak, second larger
6	35	1.17	1	1	1	
7	15	0.50	0.5	1	1	wo small then one large peak
7	25	0.83	1.5	1.5	0.67	double peak, second larger
7	35	1.17	1.75	1	1	varing amplitude
8	15	0.50	0.75	1	1	double peak
8	25	0.83	1.5	1	1	aring amplitude, double peak
8	35	1.17	1.75	1	1	varing amplitude
9	15	0.50	0.75	1	1	double peak, second larger
9	25	0.83	2	1	1	large then small peak
9	35	1.17	2.25	1	1	varing amplitude

Flume velocity = 0.152 m/sec

Radius (in)	Motor control freq. (Hz)	Wave flap freq. (Hz)	Amplitude (in)	Wave freq. (Hz)	Period (sec)	Comments
5	25	0.83	0.5	1.5	0.67	noisy, double peak
5	35	1.17	0.75	1	1	nosiy, double peak
5	45	1.50	0.75	1.5	0.67	
5	55	1.83	1	2	0.50	varing amplitude
6	25	0.83	1	1.5	0.67	nosiy, double peak
6	35	1.17	0.5	1	1.00	noisy
6	45	1.50	indiscernible	indiscernible	indiscernible	extreme noise
7	15	0.50	0.5	1	1.00	nosiy
7	25	0.83	1	1.5	0.67	noisy, double peak
7	35	1.17	1	1	1.00	double peak, second larger
7	45	1.50	1.25	1.5	0.67	
8	15	0.50	0.5	1	1	noisy, double peak
8	25	0.83	0.75	1	1	large peak and small peak
8	35	1.17	1.5	1	1	noisy, random wave
9	15	0.50	0.75	1	1	noisy
9	25	0.83	1.5	1.5	0.67	
9	35	1.17	1.5	1	1	noisy, random wave

Flume velocity = 0.304 m/sec

Radius (in)	Motor control freq. (Hz)	Wave flap freq. (Hz)	Amplitude (in)	Wave freq. (Hz)	Period (sec)	Comments
5	25	0.83	0.25	2	0.50	noisy, random wave
5	35	1.17	0.25	1	1.00	noisy
5	45	1.50	0.5	1.5	0.67	noisy
6	25	0.83	0.5	1.5	0.67	noisy
6	35	1.17	0.75	1	1.00	
6	45	1.50	0.5	1.5	0.67	noisy
7	25	0.83	0.5	1.75	0.57	
7	35	1.17	1.5	1	1	noisy, double peak
7	45	1.50	0.5	3	0.33	nosiy, high frequency
8	25	0.83	1	1.5	0.67	double peak, second larger
8	35	1.17	1.5	1	1.00	
9	15	0.50	0.25	1.5	0.67	noisy
9	25	0.83	1.5	1.5	0.67	double peak, second larger
9	35	1.17	1.5	1	1	noisy, double peak

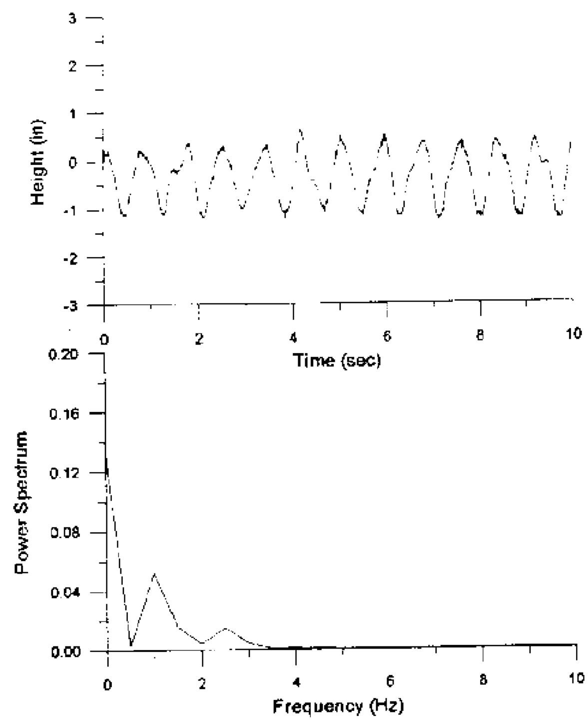


Figure 17: Representative Wave Data 1

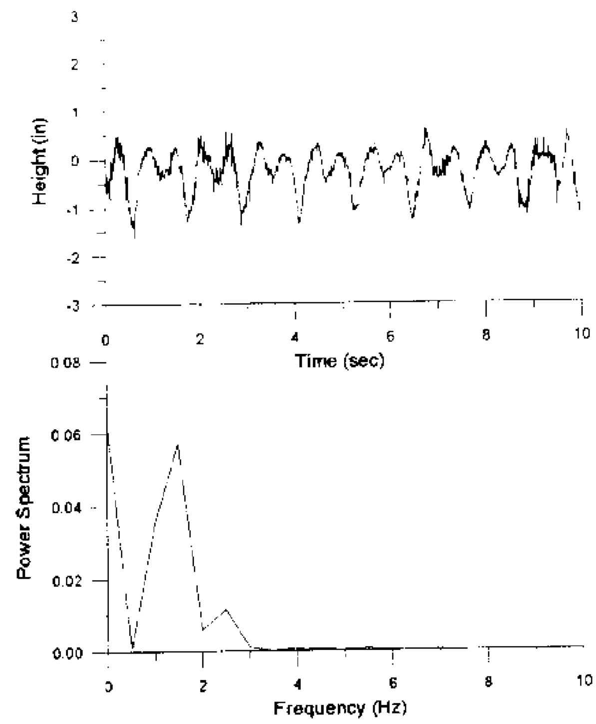


Figure 18: Representative Wave Data 2

Budget and Finances

Sea Grant funding guidelines recommend that project budgets not exceed $2000.00. It was, therefore, the Wave Generation group's goal to remain within these guidelines. As shown in Appendix E, the bulk of the project expenses involved construction materials. Many of these were obtained through a distribution warehouse: McMaster-Carr. It was thought that although costs might be slightly higher by obtaining materials in this way, the time saved in locating the necessary components would be significantly more valuable. An active record of all expenses was kept from the project outset and several purchases were returned when a less expensive alternative was developed. Most of the component fabrication was completed by the group members utilizing the machine shop facilities at UNH. Work that was beyond the group's capabilities i.e. welding and high voltage wiring, was contracted to local enterprises. Small miscellaneous purchases were also made at local merchants. Final project cost is determined to be $1917.33. This represents a under-budget margin of 4.13 percent.

Table 2: Expenses

Item	Cost
Conduit and Wiring	$560.00
Right Angle Reduction Gear	$221.75
Stainless Steel Rods	$253.62
Aluminum Plate	$144.09
Poly - Vinyl Chloride (Sheet)	$104.16
Aluminum Disc	$ 85.00
Other - See Appendix E	$511.81
Total	**$1917.33**

Discussion

Performance:

The wave generation system proved capable of creating periodic waves. The amplitudes and frequencies were comparable to the desired values of 1 to 3 inch amplitude and 0.5 to 4 Hz frequency. Examples of two specific waveform shapes and power spectra are shown in Figure 17 and 18. Figure 17 represents a combination of settings that produces a uniform periodic wave, as desired, with a high frequency content around one frequency, approximately 0.5 Hz. This example is reflective of the strengths of the design. Figure 18, in contrast, demonstrates the system has irregularities.

A distinct secondary wave presents itself along with the primary wave in Figure 18. The secondary wave form is hypothesized to be a result of a reflection off the flow straighteners located directly behind the wave generation system. Another irregularity which could lead to the secondary wave is the action of the ventilated flaps. Under all operating conditions, there is a significant lag in the timing of when the frame begins advancing to when the flaps close. At high flume tank velocities the vents do not close regardless of input frequency. Both conditions could be a result of the lack of system intervention to actuate the flaps.

Despite the evidence of system irregularities, the results are suitable for the testing purposes for which the design was intended. With the addition of the wave generation system, oil spill collection boom models can be tested in conditions that contain more variables encountered by full scale booms elevating the existing research capabilities of the University of New Hampshire in this field.

Future Considerations:

Several areas are open for the improvement and advancement of the wave generation system. The most obvious area in need of improvement results from the observations of the action of the flaps. At slow to medium flume tank velocity, the flaps open and close according to design, with a noticeable delay. At the highest flume velocities, the flaps remained open, never closing to create a wave crest. Mechanical actuation of the flaps is a feasible improvement. If they can be induced to close at the advent of the frame advancement and opened upon retraction, it is believed that system performance could be enhanced and expanded to a greater range of flume tank velocities.

An alternative to controlling the ventilated flaps mechanically would be to alter the velocity profile of the frame at the extreme range of the stroke. A higher frame velocity at the beginning and end of the stroke would force the flaps to shut and open with less lag. A suggestion to accomplish this would be to alter the driving path of the connecting rod from circular to elliptical. This could be done by creating a track that the connecting rod would be mounted to in the shape of an ellipse that is driven by a variable length linkage attached to the motor.

A simple design improvement could be made by replacing the Lovejoy coupling between the disk and the drive shaft with a rigid coupling. The existing coupling is designed to allow for misalignments by using a rubber star to join the mating shafts. This rubber compresses and expands with the alternating rotational loads and produces a significant hitch in the action of the wave maker. This improvement help alleviate noise and possibly even help reduce the secondary waveform.

One last alternative can be addressed by repositioning the flaps such that they open about a vertical axis instead of horizontal. This would facilitate the simultaneous closure of the flaps by subjecting each one to the same fluid behavior and linear velocity. Furthermore, implementation of a mechanical flap closing actuator would be significantly easier due to an exposed end of each flap above the water's surface. Thirdly, this orientation would allow for shorter flaps, which would ameliorate flap deflection.

References

Coyne, P.M. (1995) "Development of a Fast Current Oil Containment Barrier" Thesis submitted to the University of New Hampshire, Durham NH in fulfillment of a Masters Degree.

Dean, D.G., and R.A.Dalrymple, *Water Wave Mechanics for Engineers and Scientists*, World Scientific., London, England 1991.

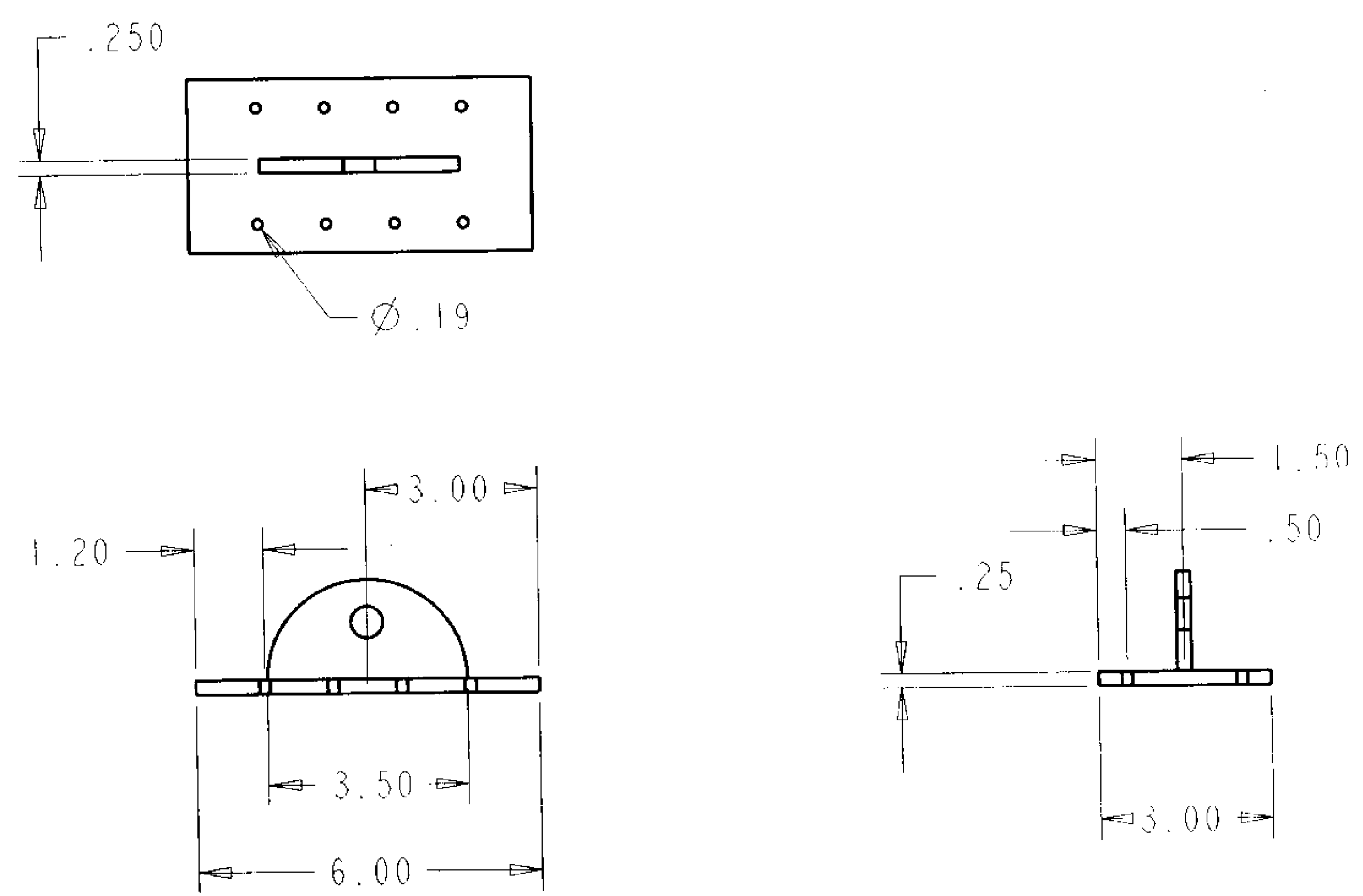
Doane, C.W. (1994) "An Open-Channel Flume for the Study of Two-Dimensional Oil Containment Boom Models in Fast Current" Thesis submitted to the University of New Hampshire, Durham NH in fulfillment of a Masters Degree

MacPherson, Donald (1998) Personal interview.

Skyner, D.J.(1992) "The Mechanics of Extreme Water Waves" Thesis submitted to the University of Edinburgh, in fulfillment of a Doctor of Philosophy. (Located at www.mech.ed.ac.uk)

Sorensen, Robert M., *Basic Wave Mechanics: For Coastal and Ocean Engineers*, John Wiley & Sons, Inc., New York, New York 1993.

Appendix A -
Drawings of System



Tolerances: X.X ±.1 X.XX ±.01 X.XXX ±.001	Figure A-1: Submerged Hinge Plate
	Material: Stainless Steel
Scale: .333	

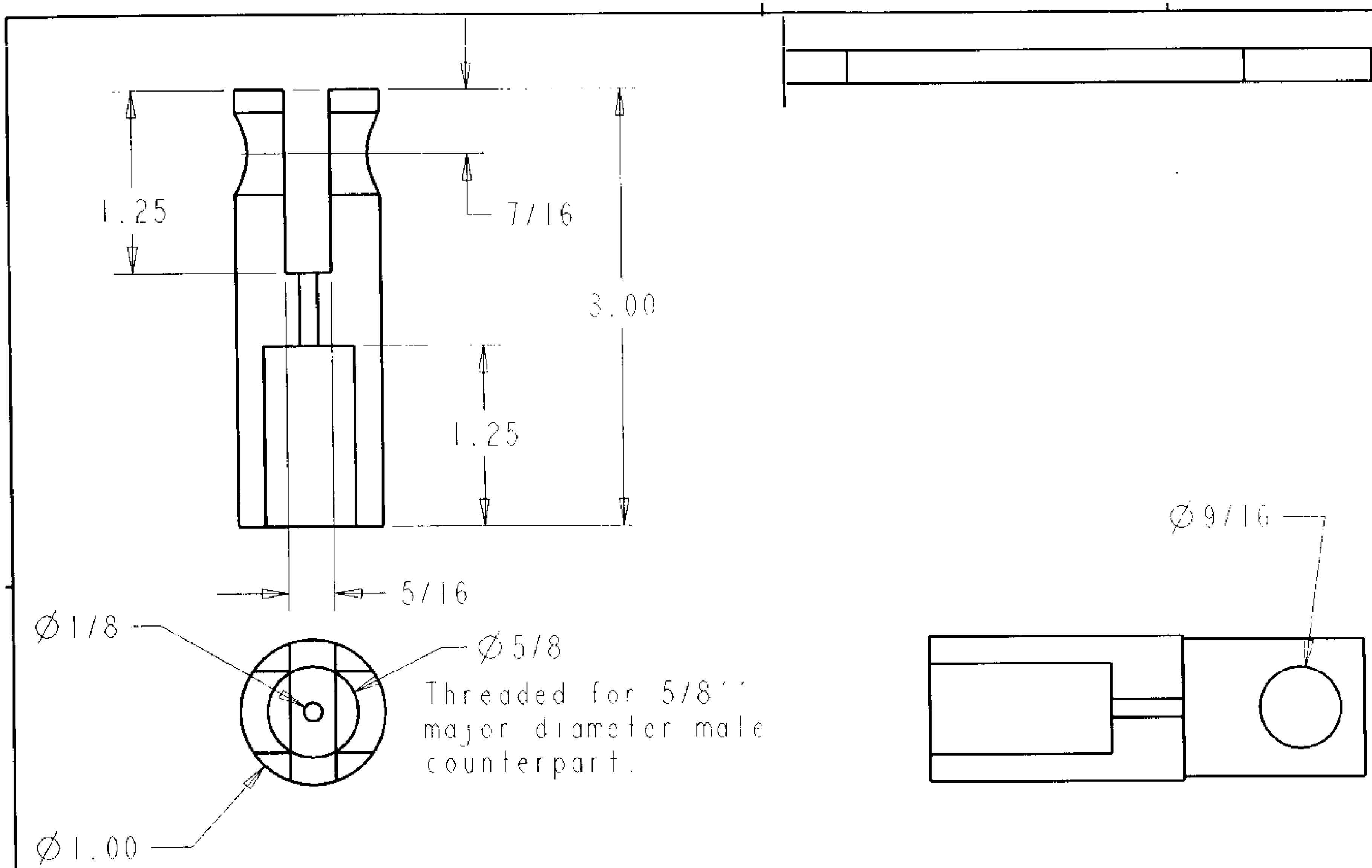


Figure A-2: Submerged Hinge

Material: Stainless Steel

Scale: 1.0

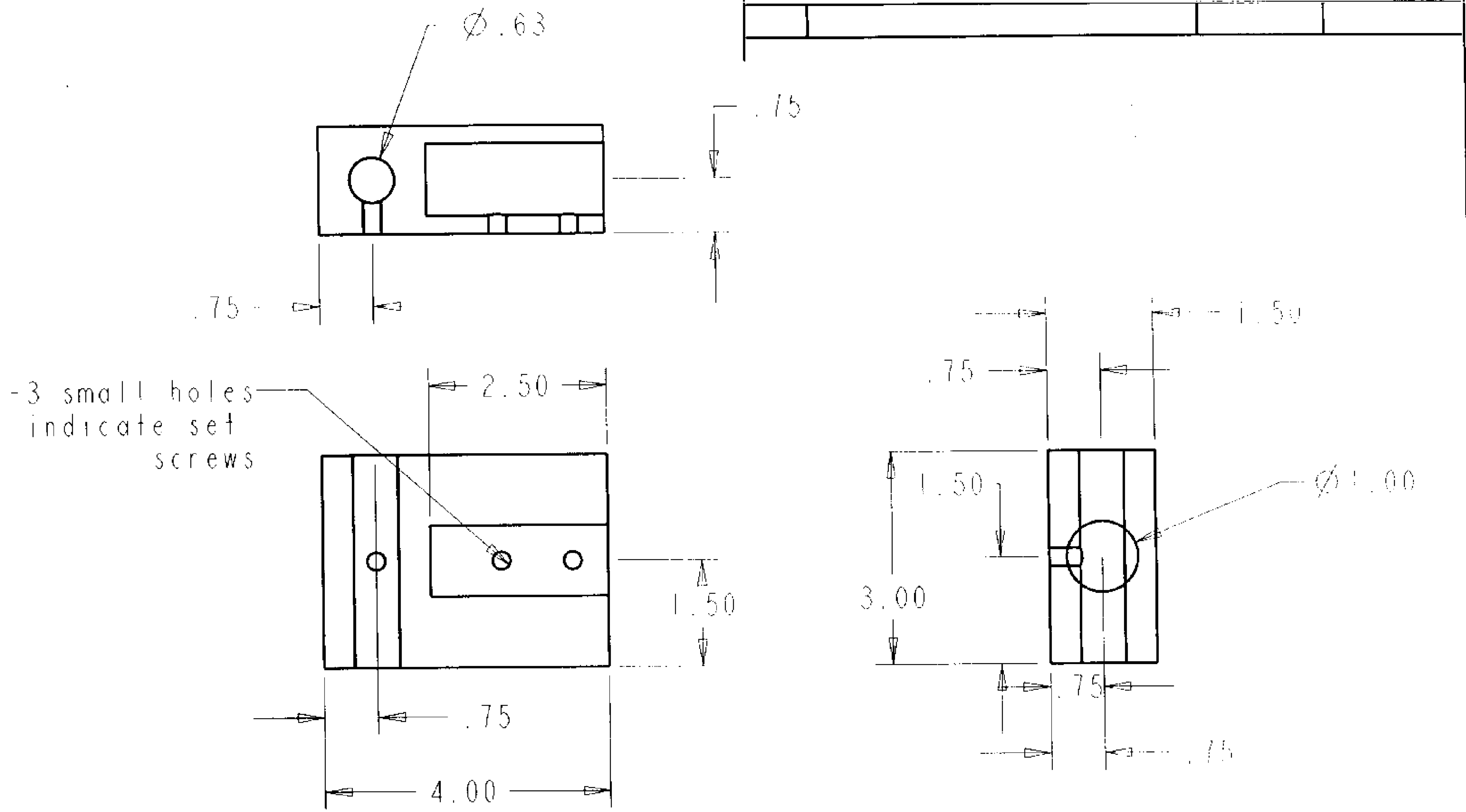


Figure A 3: Corner Joint

Material: Aluminum

Scale: .5

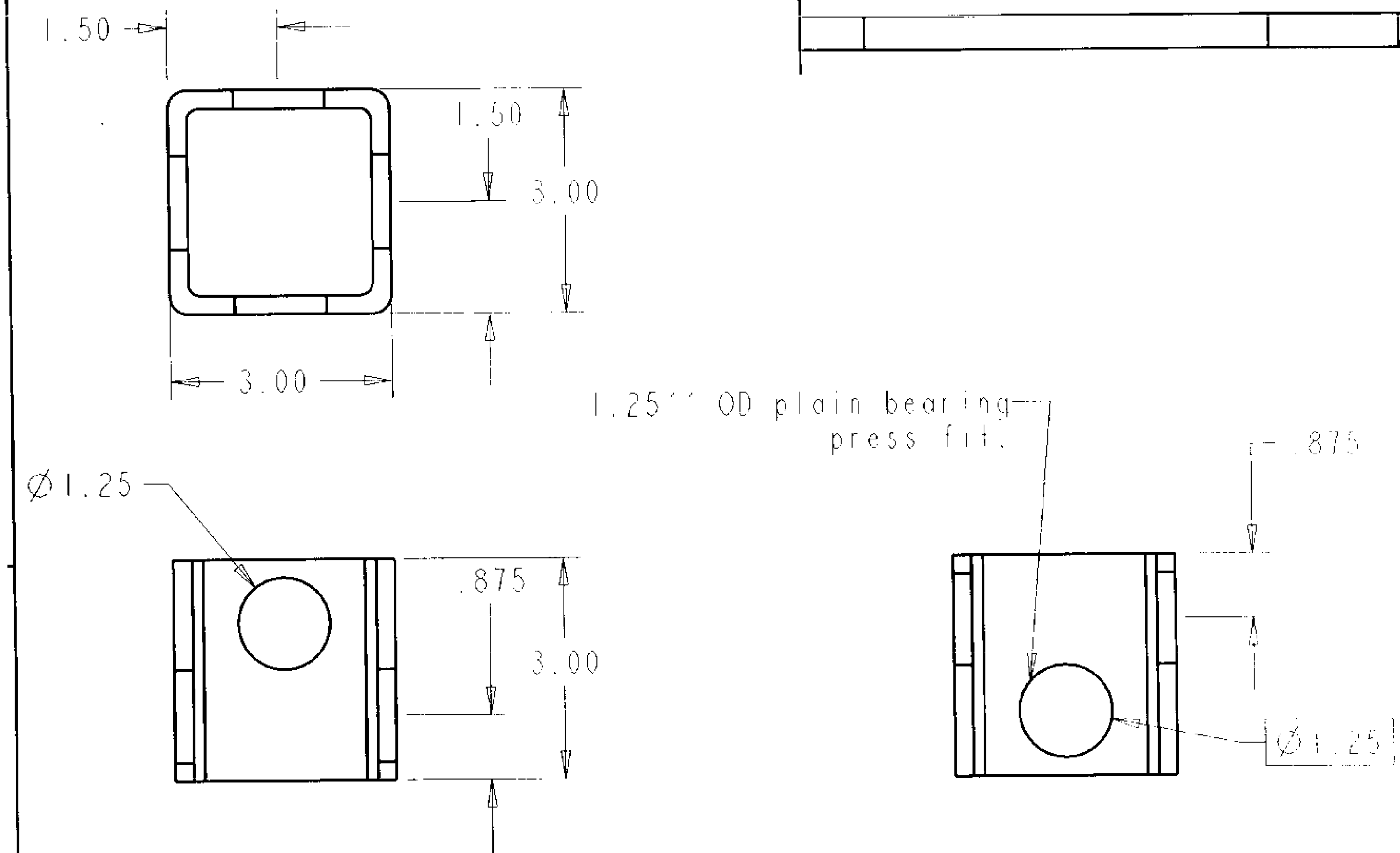


Figure A-4: Center Joint

Material: Steel

Scale: .5

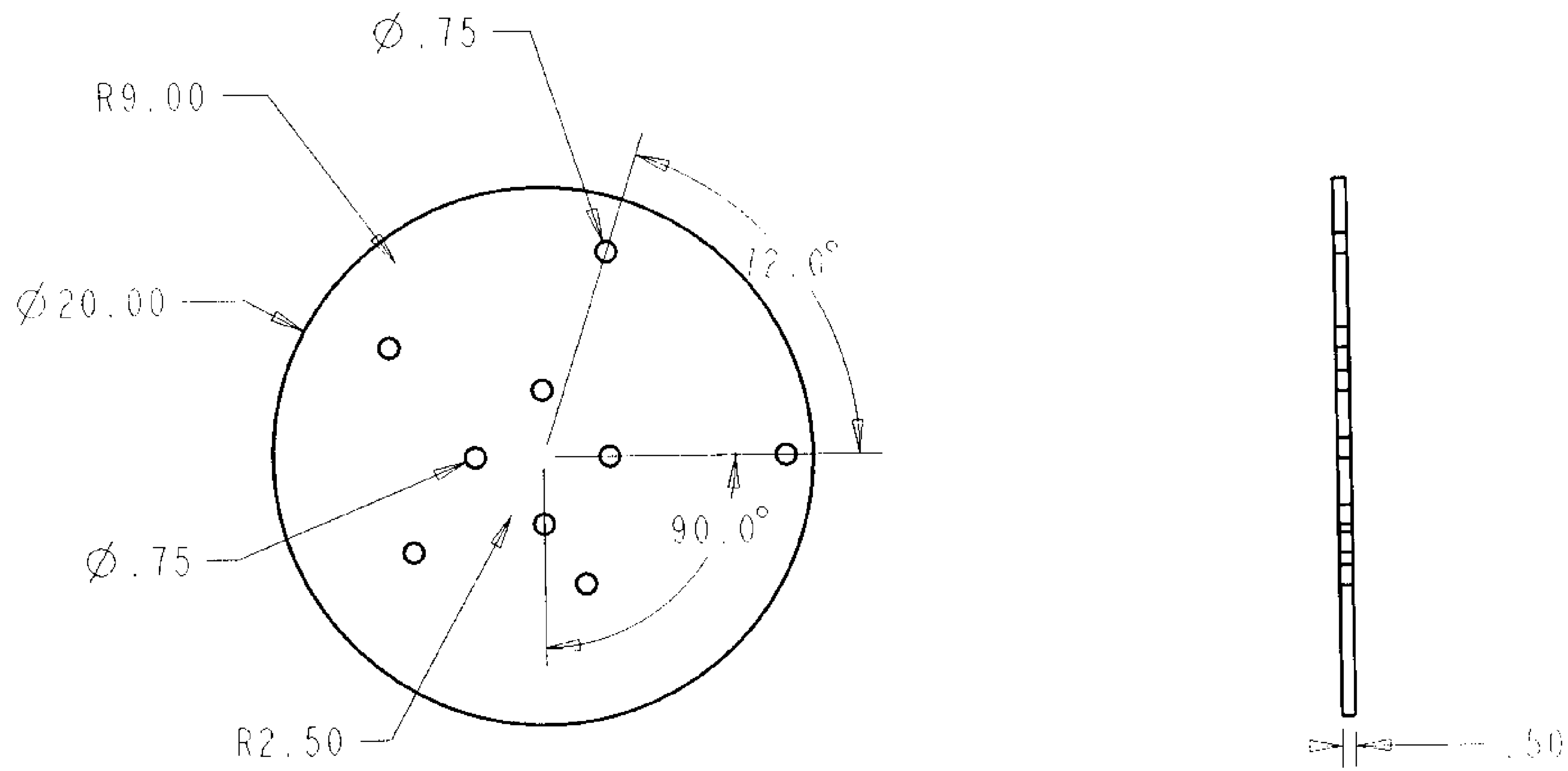


Figure A-5: Disk

Material: Aluminum

SCALE 0.150

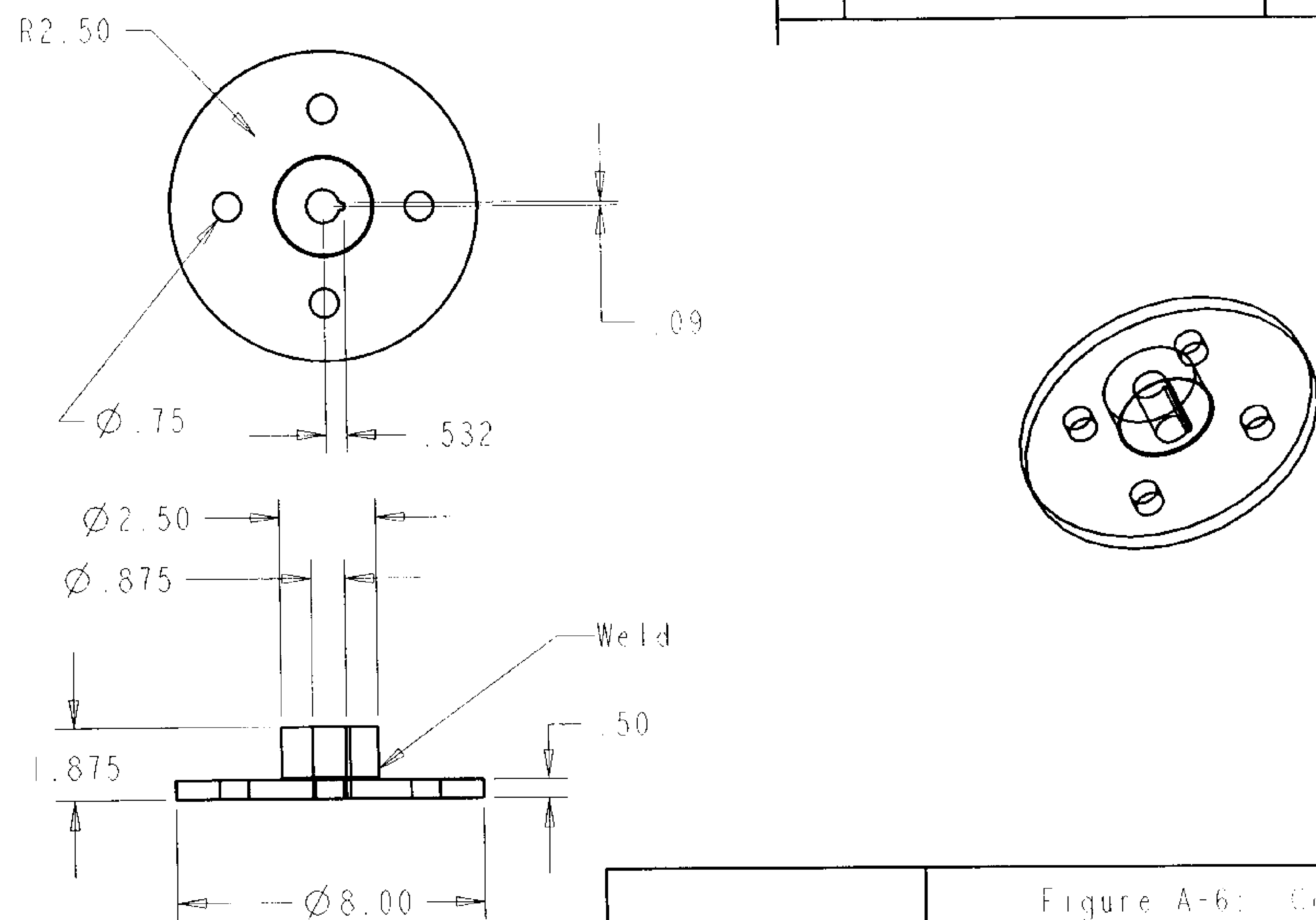


Figure A-6: Coupling

Material: Steel

Scale: .25

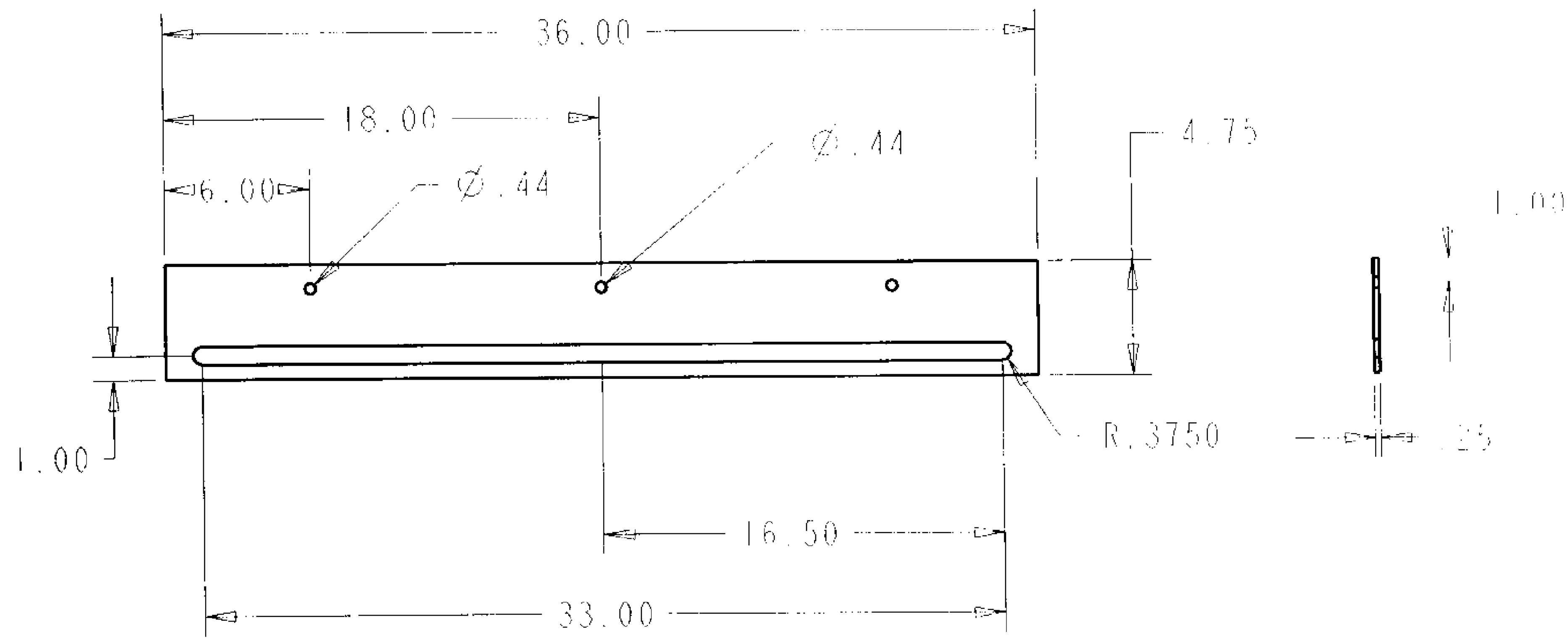


	Figure A-7: Frame Guide
	Material: Aluminum
SCALE 0.150	

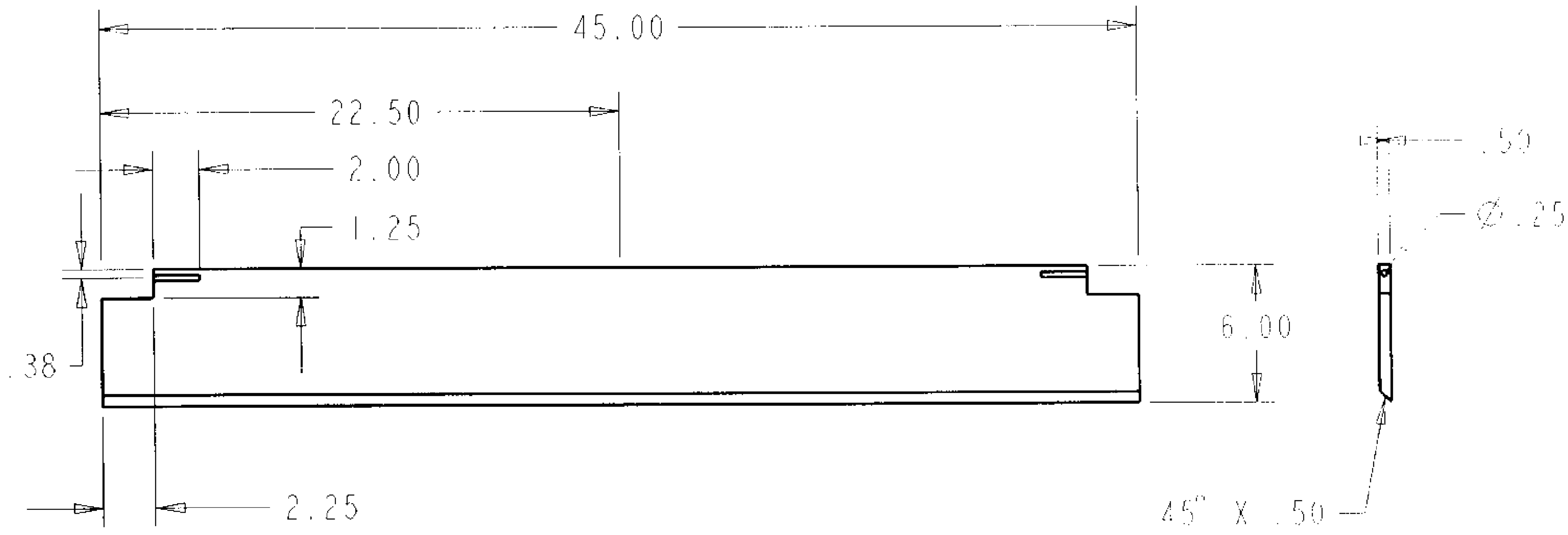


Figure A-8: Upper Vent

Material: PVC

SCALE 0.150

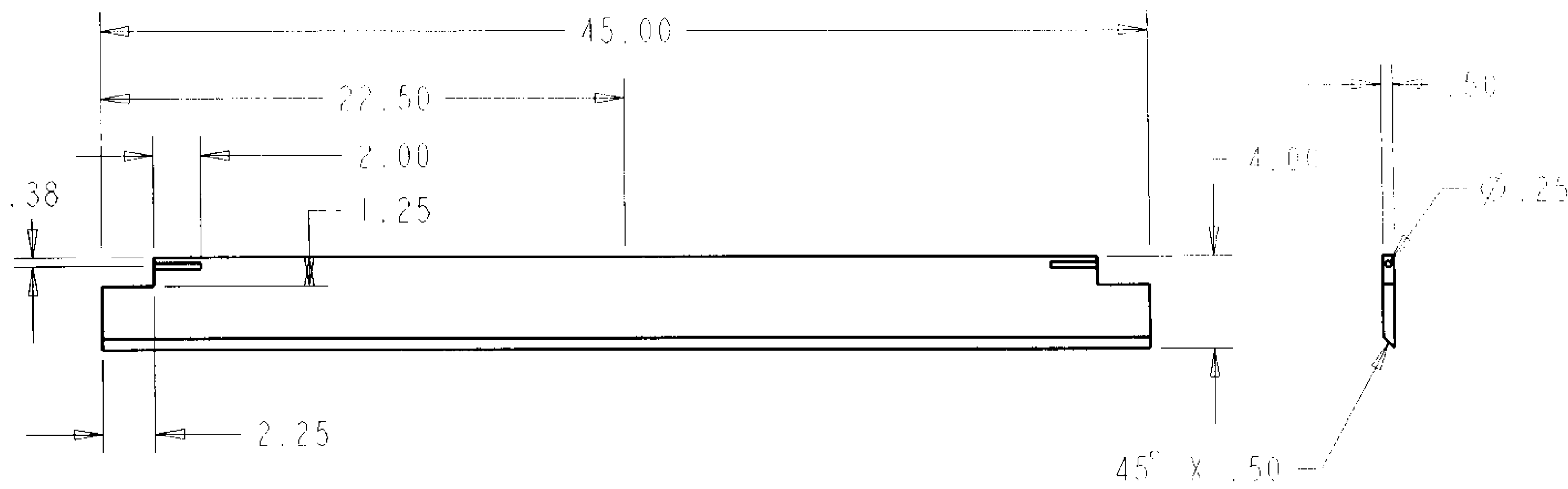
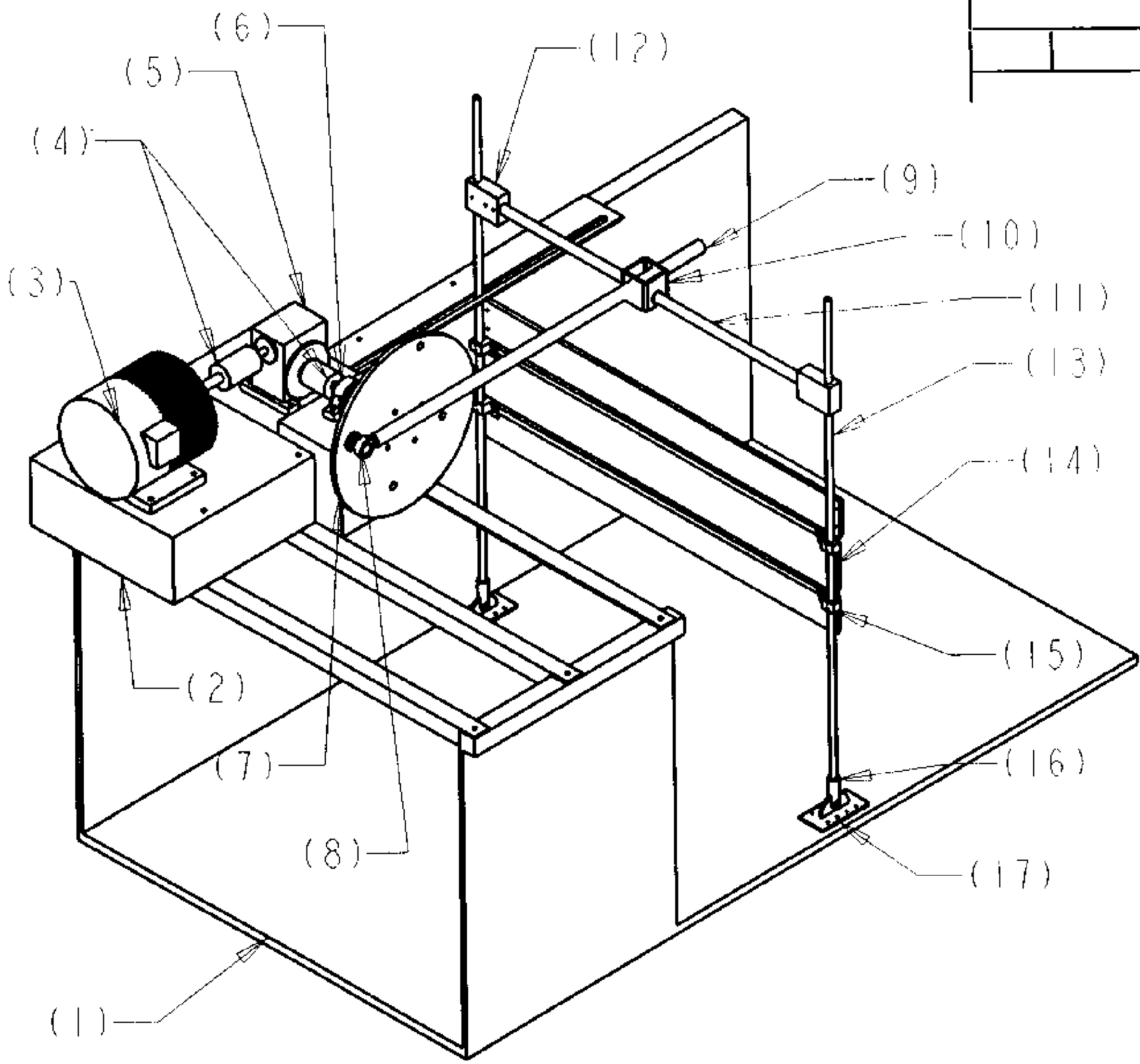


Figure A-9: Lower Vent

Material: PVC

SCALE 0.150



Parts List:
1) Tank
2) Mount
3) Motor
4) Lovejoy couplings
5) Gearbox
6) Bearing
7) Disk
8) Ball Joint
9) Connecting rod
10) Center joint
11) Spreader bar
12) Cornerjoint
13) Vent rod
14) Vents
14) Vent Brackets
15) Submersed hinge
16) Submersed hinge plates
**) Disk coupling not visible

Figure A-10: Assembly Parts

SCALE 0.060

Appendix B -
Kinematic and Dynamic Analysis

APPENDIX B: Kinematic and Dynamic Analysis

NOTE: superscript (') denotes vector, otherwise value is a magnitude

Range of motion for disk $\theta := 0 \cdot deg, 1 \cdot deg .. 360 \cdot deg$

(See diagram on following page for variable locations)

Radius of Disk: $r_1 := 5 \cdot in$

$r_1 = 0.127 \cdot m$

Horizontal distance from the motor center to the lowest hinge joint. $x_o := -.75 \cdot m$

Height of vent rod:

$y_o := r_1 + 2 \cdot in + 35.75 \cdot in$ $y_o = 42.75 \cdot in$

$y_o = 1.086 \cdot m$

r'_o is the vector that describes the base of vent rod to the center of the disk

$$r'_o(\theta) := \begin{bmatrix} x_o \\ y_o \\ 0 \end{bmatrix}$$

r'_1 is the vector that describes the motion of the disk

$$r'_1(\theta) := \begin{bmatrix} \cos(\theta) \\ \sin(\theta) \\ 0 \end{bmatrix} \cdot r_1$$

r'_3 denotes the vent rod

$r_3 := y_o$ $r'_3 := r_3$ $r_3 = 42.75 \cdot in$

$r_3 = 1.086 \cdot m$

r_n denotes the horizontal distance the separates the center of disk and the pivot for the vent rod

$r_n := x_o$ $r_n = -29.528 \cdot in$

$r_n = -0.75 \cdot m$

r_2 denotes the vector the connects the disk to the top of the vent rod

$r_2 := \sqrt{r_1^2 + r_n^2}$ $r'_2 := r_2$ $r_2 = 2.496 \cdot ft$

$r_2 = 0.761 \cdot m$

$r_2 = 29.948 \cdot in$

$r'_d(\theta) := r'_o(\theta) + r'_1(\theta)$ $r_{d\_unit}(\theta) := \dfrac{r'_d(\theta)}{\left|r'_d(\theta)\right|}$

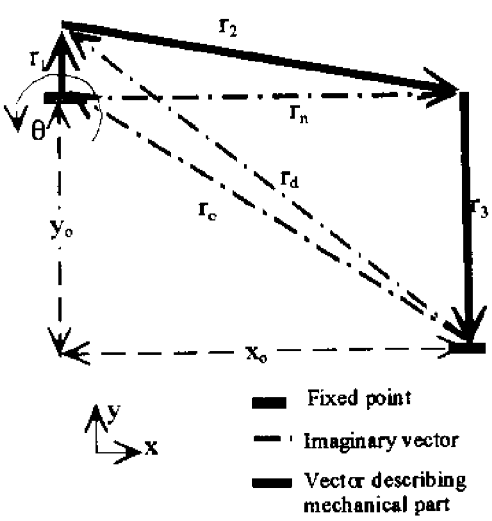


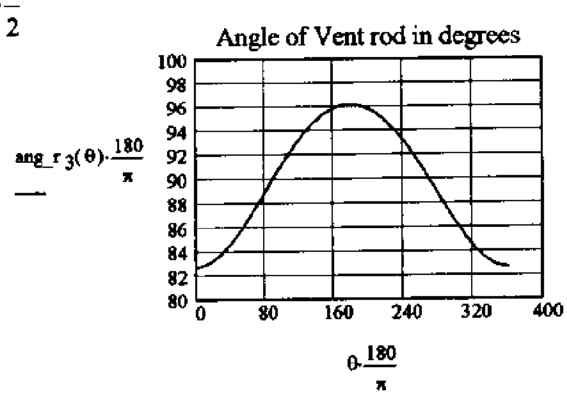
Figure B-1: Vector Diagram for Variables

$$k := \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \qquad a(\theta) := \frac{r_3^{\,2} - r_2^{\,2} + \left(\left|r'_d(\theta)\right|\right)^2}{2\cdot\left|r'_d(\theta)\right|}$$

$$r'_2(\theta) := \sqrt{r_3^{\,2} - a(\theta)^2}\cdot\left(r_{d\_unit}(\theta) \times k\right) + r_{d\_unit}(\theta)\cdot\left(a(\theta) - \left|r'_d(\theta)\right|\right)$$

$$r'_3(\theta) := -\sqrt{r_3^{\,2} - a(\theta)^2}\cdot\left(r_{d\_unit}(\theta) \times k\right) - a(\theta)\cdot r_{d\_unit}(\theta)$$

$$ang\_r_3(\theta) := \begin{cases} \operatorname{atan}\left(\dfrac{r'_3(\theta)_1}{r'_3(\theta)_0}\right) + 180\cdot deg & \text{if } \dfrac{\pi}{2} < \theta < 3\cdot\dfrac{\pi}{2} \\ \operatorname{atan}\left(\dfrac{r'_3(\theta)_1}{r'_3(\theta)_0}\right) & \text{otherwise} \end{cases}$$



$Hz := 2\cdot\pi\cdot\frac{rad}{sec}$

ω_1 denotes the angular velocity of the disk

$\omega_1 := 0.8\cdot Hz$ $\qquad \omega_1 = 5.027\,\frac{rad}{sec}$ $\qquad \omega'_1 = \omega_1$

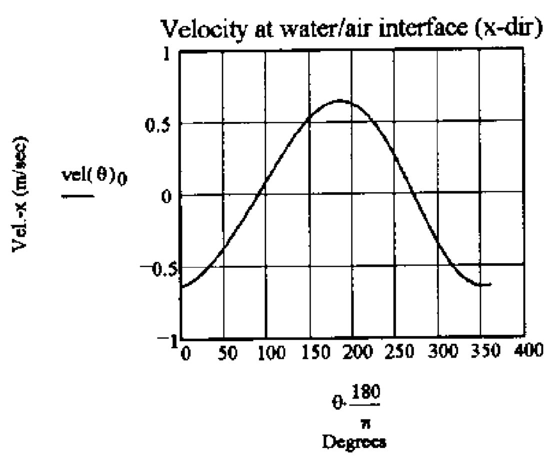
$$\omega'_1\cdot r'_1(\theta)_1 + \omega'_2\cdot r_2(\theta)_1 + \omega'_3\cdot r_3(\theta)_1 = 0$$

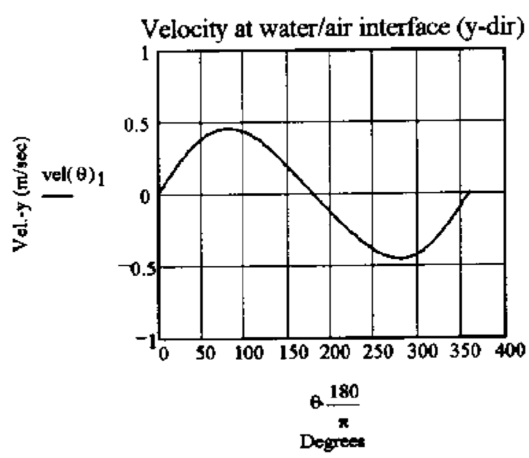
$$\omega'_1\cdot r'_1(\theta)_0 + \omega'_2\cdot r_2(\theta)_0 + \omega'_3\cdot r_3(\theta)_0 = 0$$

$$C(\theta) := \begin{pmatrix} r'_2(\theta)_1 & r'_3(\theta)_1 \\ r'_2(\theta)_0 & r'_3(\theta)_0 \end{pmatrix} \qquad b(\theta) := \begin{pmatrix} -\omega'_1\cdot r'_1(\theta)_1 \\ -\omega'_1\cdot r'_1(\theta)_0 \end{pmatrix}$$

$\omega(\theta) := C(\theta)^{(-1)}\cdot b(\theta)$ $\qquad$ water_height := 30·in

vel(θ) := ω(θ)·water_height





Appendix C -
Water Velocity Wave Calculations

Appendix C: Water Velocity Wave Calculations

Definitions:

$T \equiv period$ $\quad \sigma \equiv \frac{2\cdot\pi}{T} \equiv radian\_frequency$ $\quad f \equiv \frac{1}{T} \equiv frequency$ $\quad f \equiv \frac{\sigma}{2\cdot\pi}$

$L \equiv wavelength$ $\quad K \equiv \frac{2\cdot\pi}{L} \equiv wavenumber$ $\quad C \equiv \frac{L}{T} \equiv phase\_velocity$

Constants: $h := 30\cdot in$ $\quad z := 0\cdot in$

$x := 0\cdot m$ $\quad knots := .51444\cdot\frac{m}{sec}$

$t := 0\cdot sec$

Water Velocity:

$F_V \equiv Flume\_water\_velocity$ $\quad F_V := 0\cdot\frac{m}{sec}$ $\quad F_V = 0 \cdot knots$

$i := 0..100$ Amplitude goes with i

$$Amp_i := \left(0.1 + \frac{i}{100}\cdot 3\right)\cdot in \qquad H_i := Amp_i\cdot 2$$

$j := 0..200$ Period goes with j

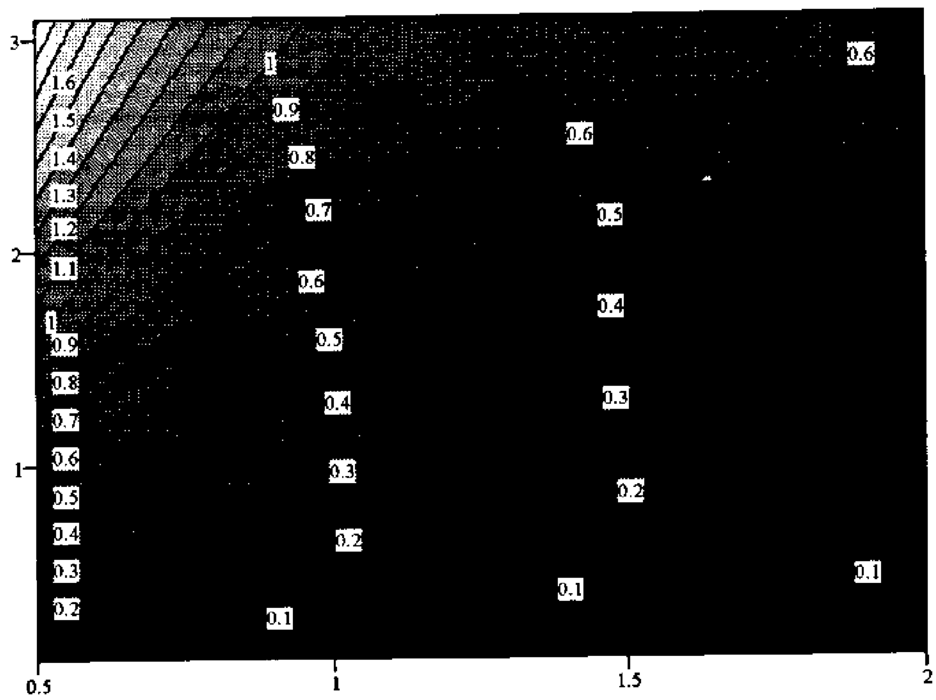
$$T_j := \left(.5 + \frac{j}{200}\cdot 1.5\right)\cdot sec \qquad \sigma_j := \frac{2\cdot\pi}{T_j}$$

$L := \frac{2\cdot\pi}{1\cdot in}$ needed for root solve block

$$K_j := root\left[\left[\left(\sigma_j\right)^2 - g\cdot L\cdot \tanh(L\cdot h)\right], L\right]$$

$$L_j := \frac{2\cdot\pi}{K_j}$$

$$u_{j,i} := \left[\frac{H_i}{2}\cdot\left(\frac{g\cdot K_j}{\sigma_j}\right)\cdot\frac{\cosh\left[K_j\cdot(h+z)\right]}{\cosh\left(K_j\cdot h\right)}\cdot\cos\left(K_j\cdot x - \sigma_j\cdot t\right)\right] + F_V$$



Choosing desired Amplitude and Period:

$Amp := 2 \cdot in$ $\quad T := .5 \cdot sec$ $\quad F_v := 0.0 \cdot \frac{m}{sec}$

$H := Amp \cdot 2$ $\quad \sigma := \frac{2 \cdot \pi}{T}$

$L := \frac{2 \cdot \pi}{1 \cdot in}$ **needed for root solve block**

$$K := root\left[\left[(\sigma)^2 - g \cdot L \cdot \tanh(L \cdot h)\right], L\right]$$

$$L := \frac{2 \cdot \pi}{K}$$

$$u := \left[\frac{H}{2} \cdot \left(\frac{g \cdot K}{\sigma}\right) \cdot \frac{\cosh(K \cdot (h + z))}{\cosh(K \cdot h)} \cdot \cos(K \cdot x - \sigma \cdot t)\right] + F_v$$

$u = 0.638 \cdot \frac{m}{sec}$

$u = 1.241 \cdot knots$

Appendix D -
Force and Deflection

Appendix D: Force and Deflection

Force on Vents

$\lambda := 0.152 \cdot m$ Wavelength

$C := \frac{1 \cdot m}{sec}$ Wavespeed

$\rho := 998 \cdot \frac{kg}{m^3}$ Water Density

$k := \frac{2 \cdot \pi}{\lambda}$ Wave Number

$E := \frac{\rho \cdot g \cdot H^2}{8}$ Energy per unit Area

$b := 1.168 \cdot m$ Tank Width

$h := 0.737 \cdot m$ Average Water Height

$H := 0.102 \cdot m$ Wave Height

$V_{max} := 1.5 \cdot \frac{m}{sec}$ Linear Paddle Velocity

$C_g := \frac{C}{2} \cdot \left(1 + \frac{2 \cdot k \cdot h}{\sinh(2 \cdot k \cdot h)}\right)$ Wave Group Velocity

$Power_{ave} := E \cdot C_g \cdot b$ Average Power Transmitted by Wavetrain

$Power_{paddle} = \frac{F_{max} \cdot V_{max}}{2}$ Power input to Paddle

$F_{max} := \frac{6 \cdot E \cdot C_g \cdot b}{V_{max}}$

Force on Paddle Surface

$F_{max} = 29.733 \cdot newton$

Deflection of Vents

$L := 1.143 \cdot m$ Length of Vent

$E_{pvc} := 3.3 \cdot 10^{9} \cdot Pa$ Young's Modulus of Elasticity for Poly-Vinal Chloride

$b_{vent} := 0.013 \cdot m$ Thickness of Vent

$h_{vent} := 0.152 \cdot m$ Height of Vent

$$I := \frac{b_{vent} \cdot h_{vent}^{3}}{12}$$ Moment of Area

$$\delta_{max} := \frac{5 \cdot F_{max} \cdot L^{3}}{384 \cdot E_{pvc} \cdot I}$$

Maximum Delfection of Vent

$\delta_{max} = 4.605 \cdot 10^{-5} \cdot m$

Appendix E -
Expenses

Appendix E: Expenses

Table E-1

Account	Description	Quantity	Cost per unit ($)	Cost ($)
Samuri Electric Co.	Conduit and Wiring	N/A	N/A	560.00
McMaster - Carr	Right Angle Reduction Gear	1	221.75	221.75
	1-1/4" Stainless Rod	1	108.82	108.82
	Aluminium Plate - 0.5 x 18" x18"	1	103.59	103.59
	0.5" PVC - 48" x 48" sheet	1	104.16	104.16
	5/8" Stainless Steel Rod	2	34.45	68.90
	Radial Ball Bearings - 7/8" shaft	2	29.15	58.30
	Stainless Steel Rod - 1"dia. x 3 feet	1	44.73	44.73
	2 Piece Stainless Collor	4	7.35	29.40
	7/8" Steel Shaft - 3/16" keyway	1	27.5	27.50
	3/4 - 16 Bolts	4	5.12	20.48
	Shaft Collars	2	9.34	18.68
	Ball Joint Rod End - w/ 3/4-16 stud	1	17.82	17.82
	Compression Springs	2	7.67	15.34
	3 Piece Spider Coupling - 5/8 ' Bore	1	13.76	13.76
	3 Piece Spider Coupling - 1" bore	1	13.76	13.76
	Set Screw Collars	2	5.65	11.30
	Stainless Steel Nuts	5	8.10	8.10
	2 Piece Aluminum Collar	2	3.97	7.94
	Stainless Steel Rod	1	5.88	5.88
	Bushing	1	5.43	5.43
	Clevis Pin -0.5" dia.	2	2.63	5.26

continued

Custom Welding Inc.	20" Aluminium Disc	1	85.00	85.00
	1" x 6' Stainless Steel Rod	1	75.00	75.00
	Hinge Plate	2	30.00	60.00
	18" x 18" Aluminium Plate	1	40.50	40.50
	Coupling	1	30.00	30.00
Filion Lumber	4" x 4" x 8' Treated Lumber (3)	N/A	N/A	58.00
Houghton Hardware	Bolts, Nuts, Washers, etc.			
	Threaded Rod, Nuts, Washers	N/A	N/A	32.57
Brooks Pharmacy	Film Developing	3 Rolls	9.49	28.47
			Sub Total	1880.44
			Shipping	36.89
			Total	**1917.33**

Appendix F -
Waves Generated

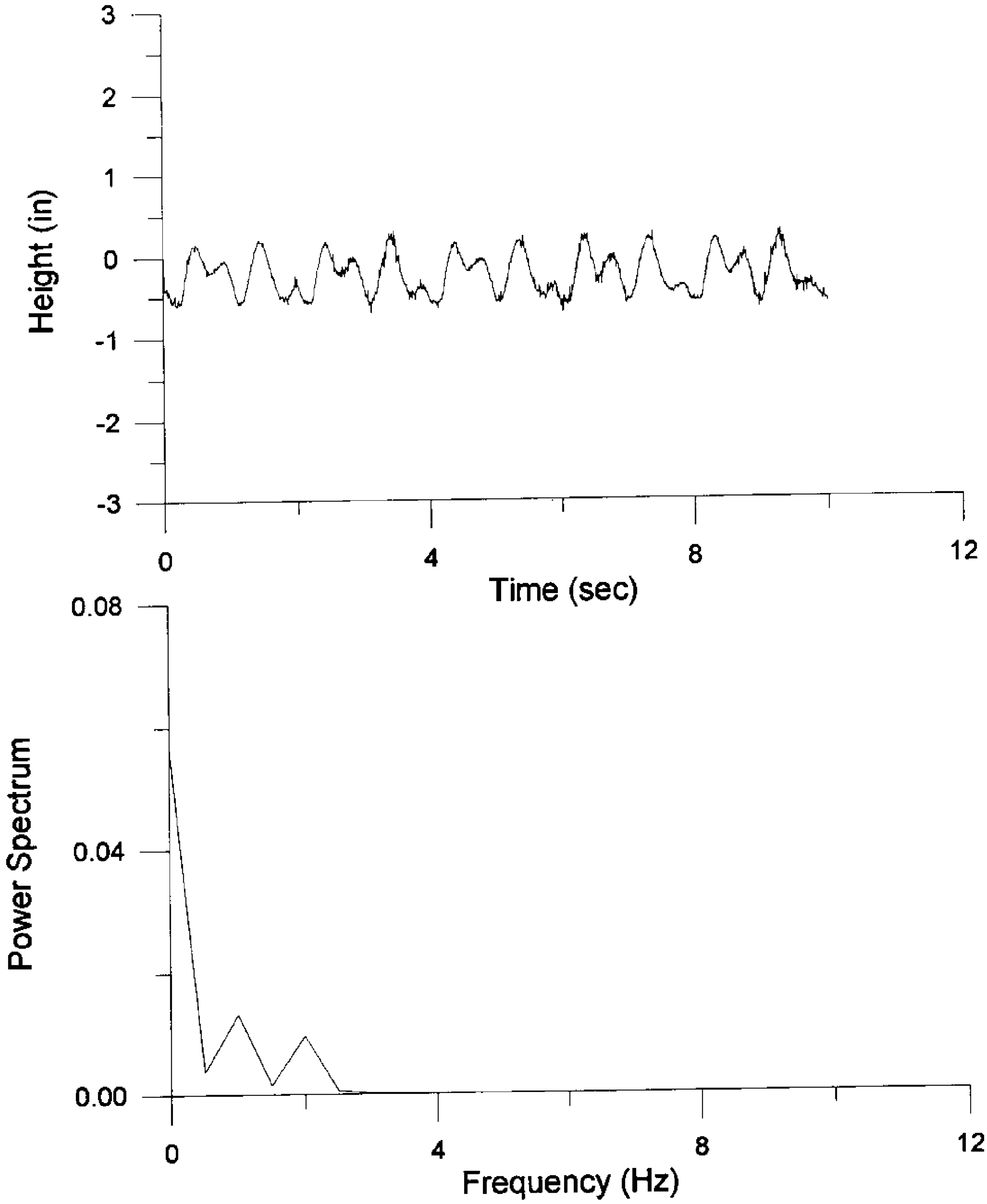


Figure F-1: Plots of wave profile and power spectrum. Radius = 5 inches; flume speed = 0.0 m/sec; wave flap frequency = 0.5 Hz.

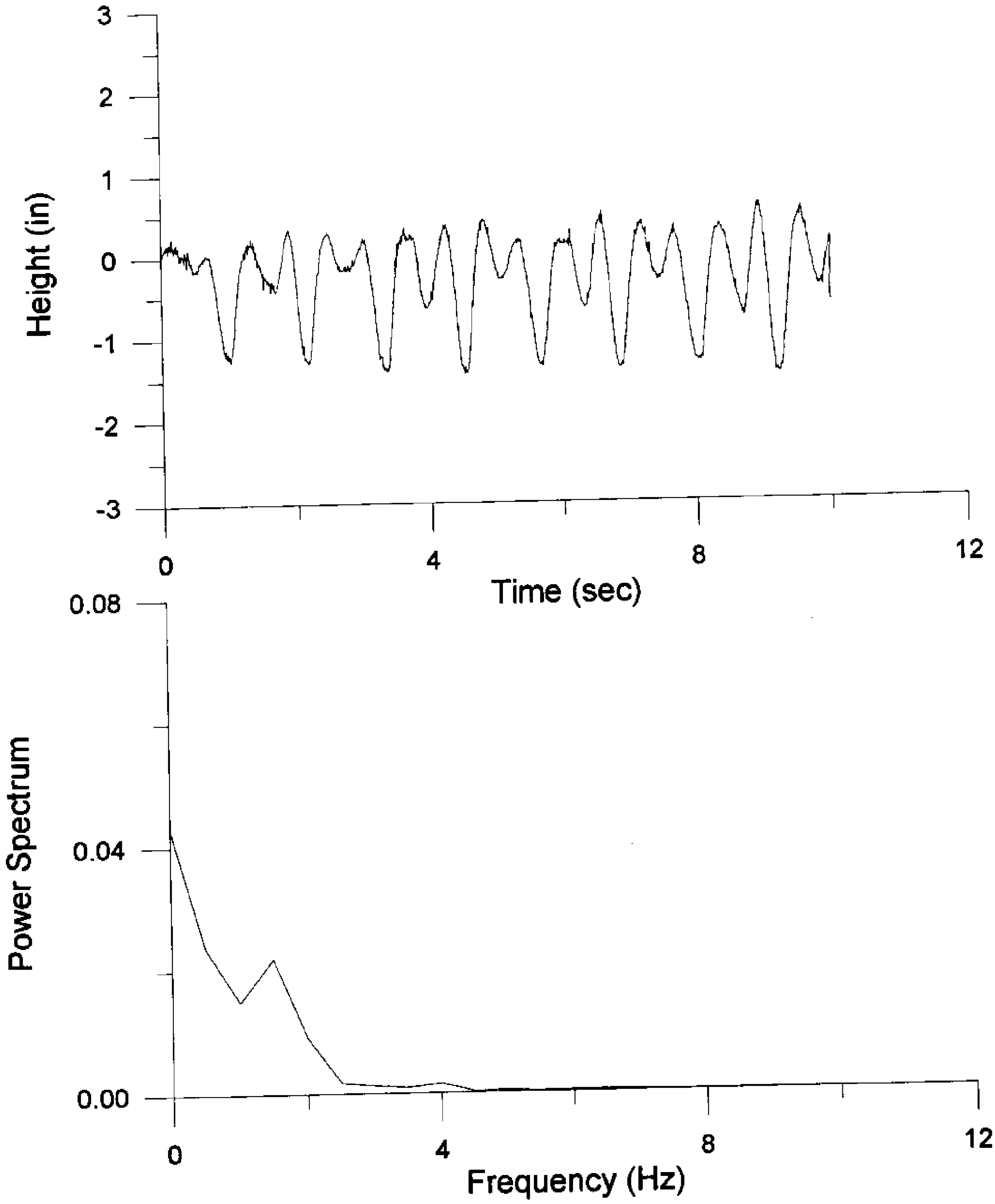


Figure F-2: Plots of wave profile and power spectrum. Radius = 5 inches; flume speed = 0.0 m/sec; wave flap frequency = 0.833 Hz.

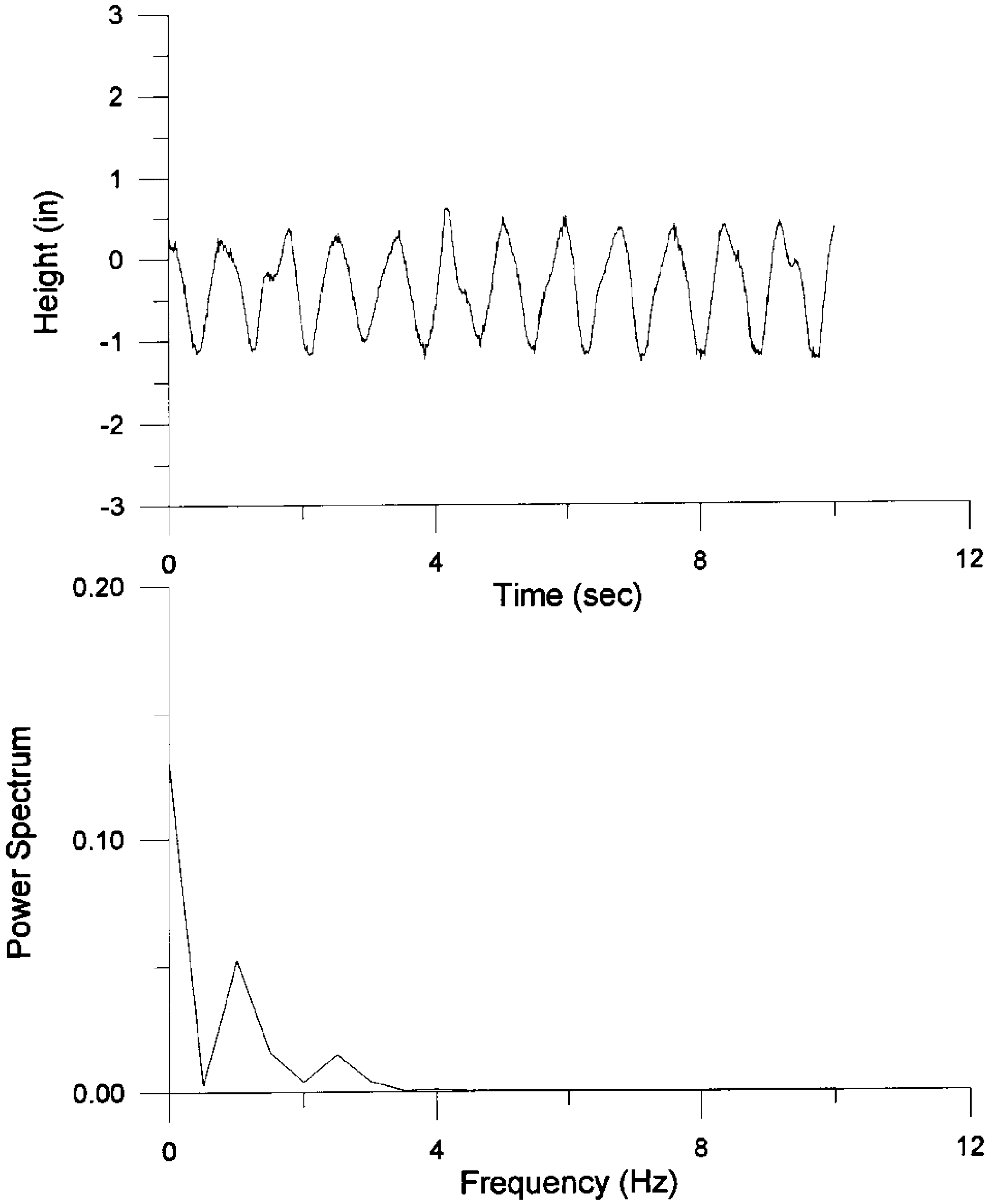


Figure F-3: Plots of wave profile and power spectrum. Radius = 5 inches; flume speed = 0.0 m/sec; wave flap frequency = 1.167 Hz.

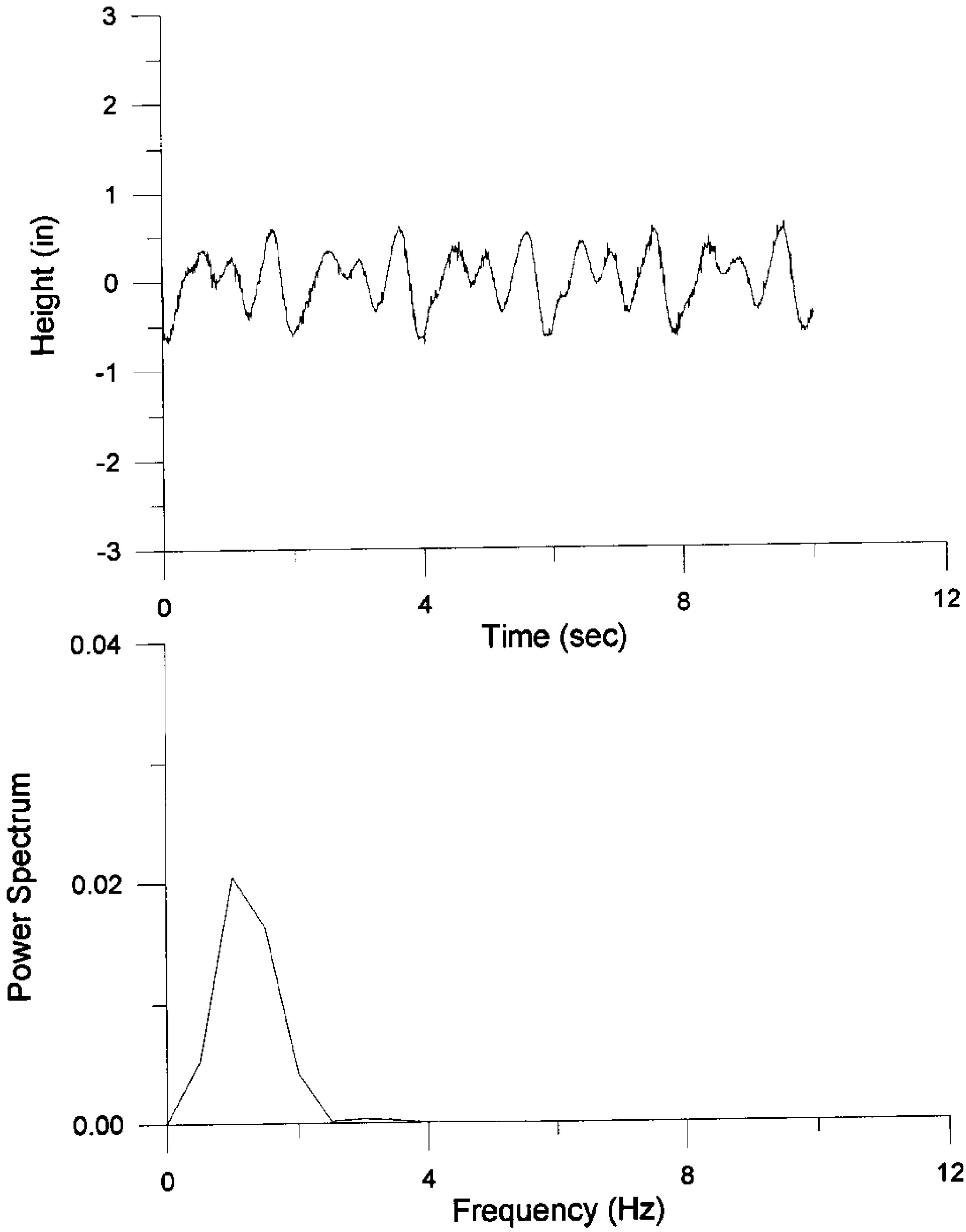


Figure F-4: Plots of wave profile and power spectrum. Radius = 6 inches; flume speed = 0.0 m/sec; wave flap frequency = 0.5 Hz.

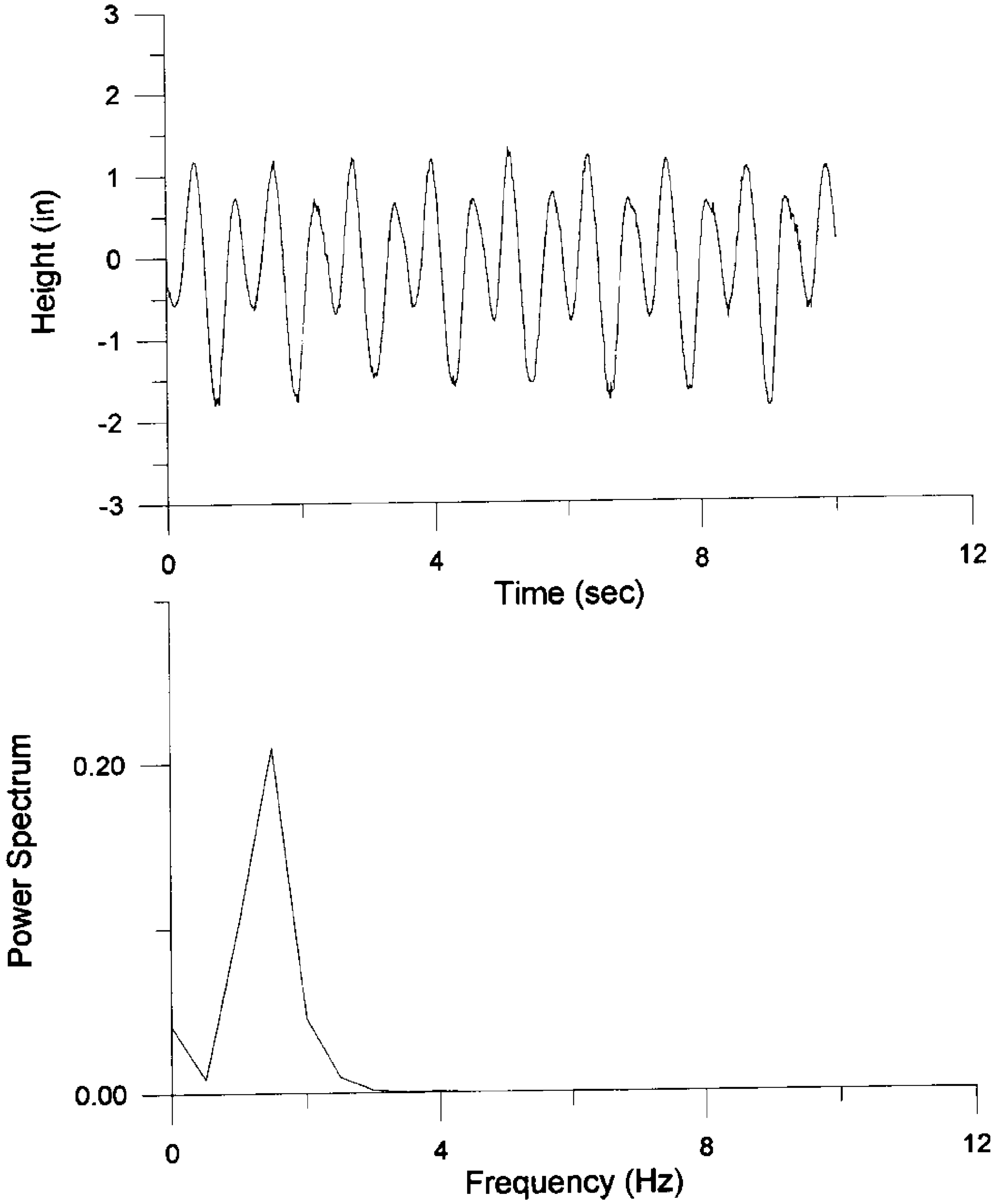


Figure F-5: Plots of wave profile and power spectrum. Radius = 6 inches; flume speed = 0.0 m/sec; wave flap frequency = 0.833 Hz.

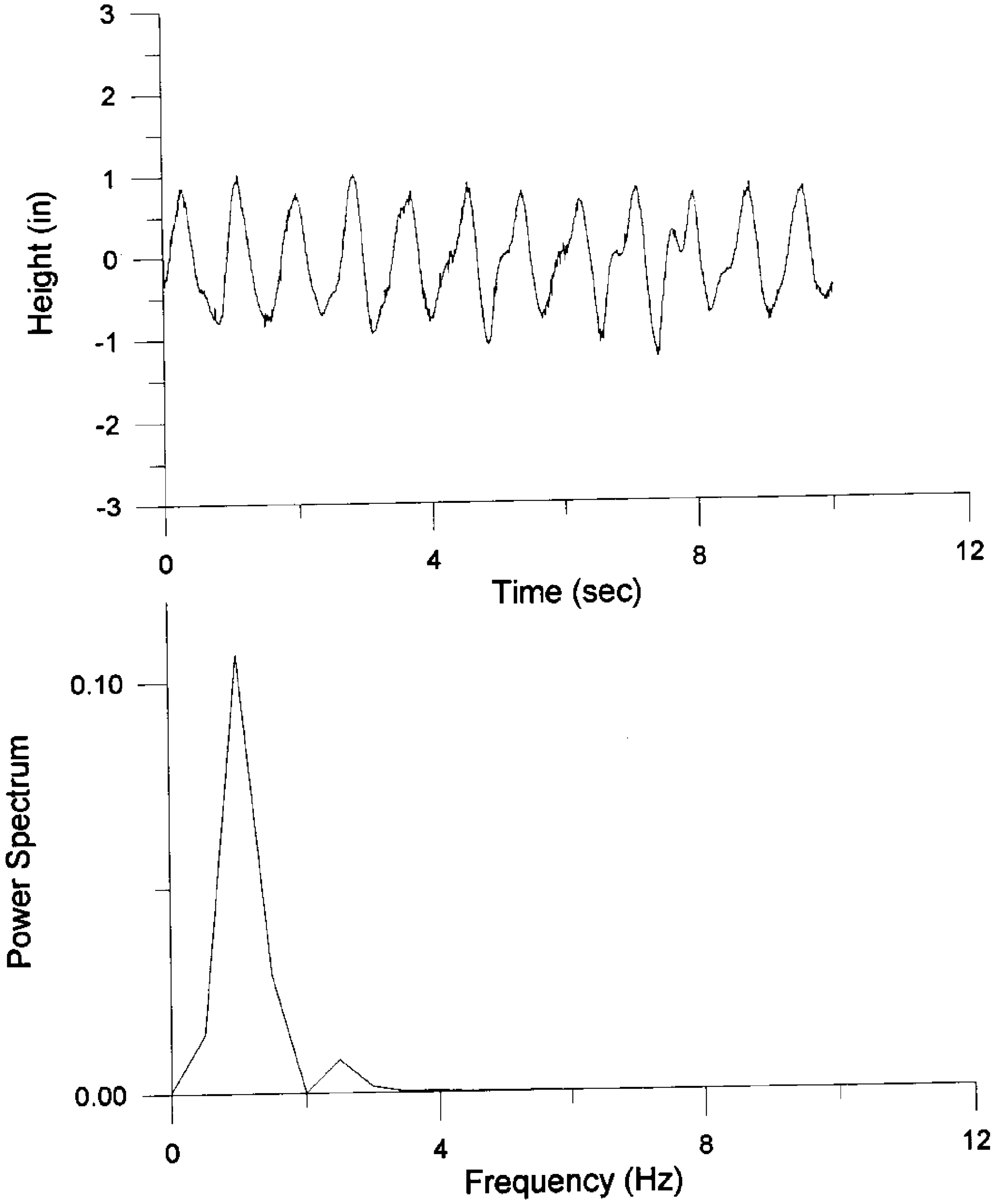


Figure F-6: Plots of wave profile and power spectrum. Radius = 6 inches; flume speed = 0.0 m/sec; wave flap frequency = 1.167 Hz.

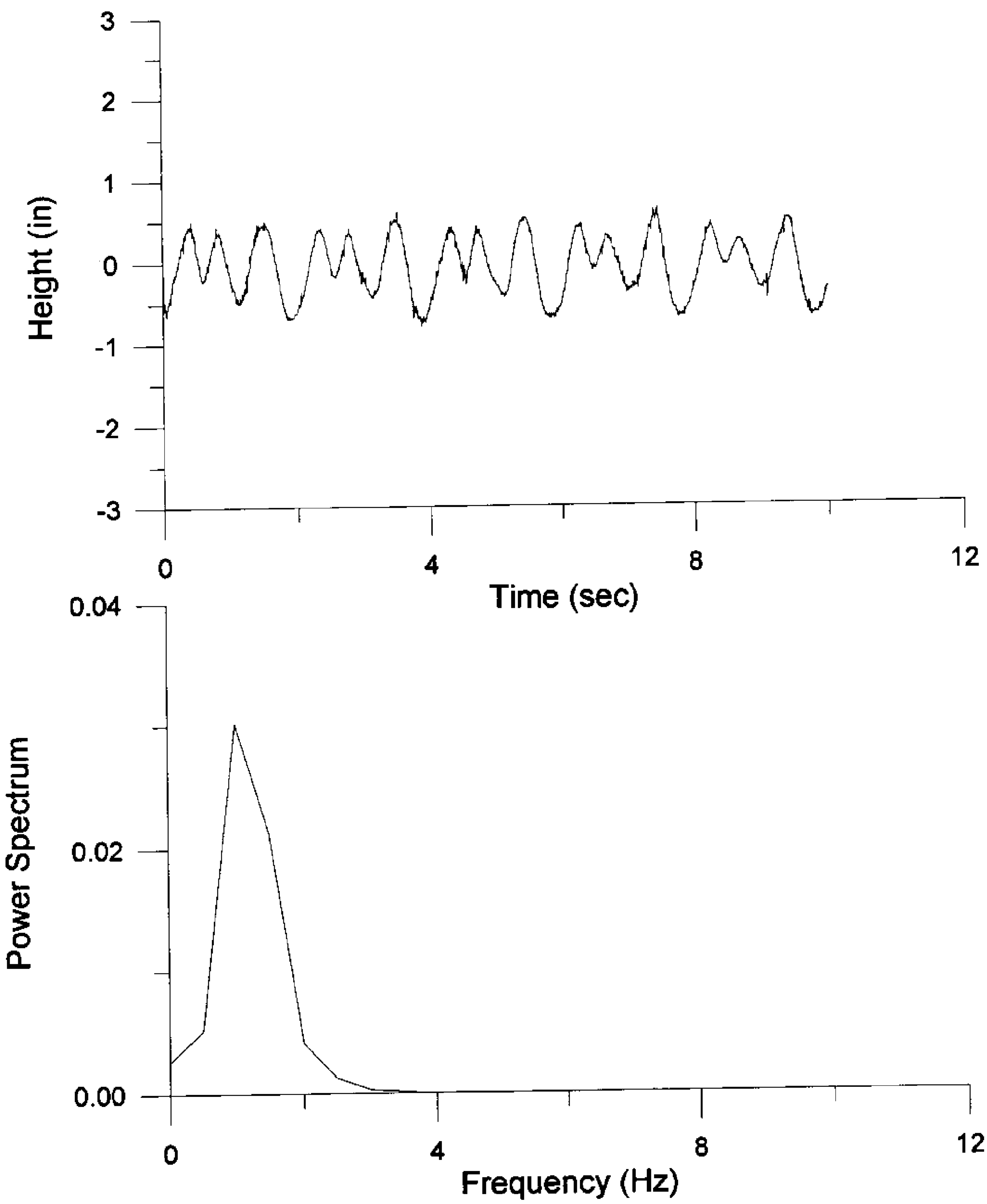


Figure F-7: Plots of wave profile and power spectrum. Radius = 7 inches; flume speed = 0.0 m/sec; wave flap frequency = 0.5 Hz.

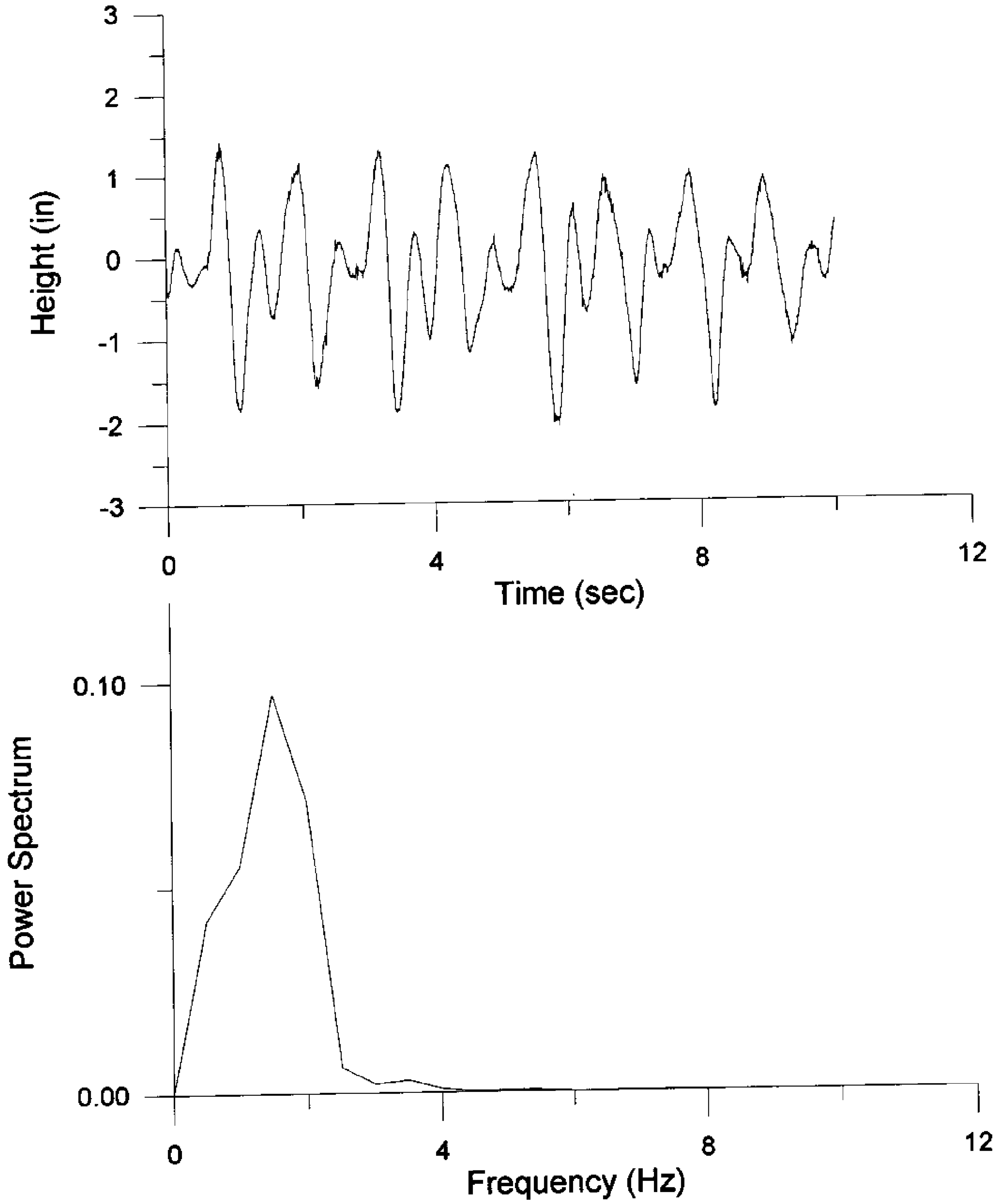


Figure F-8: Plots of wave profile and power spectrum. Radius = 7 inches; flume speed = 0.0 m/sec; wave flap frequency = 0.833 Hz.

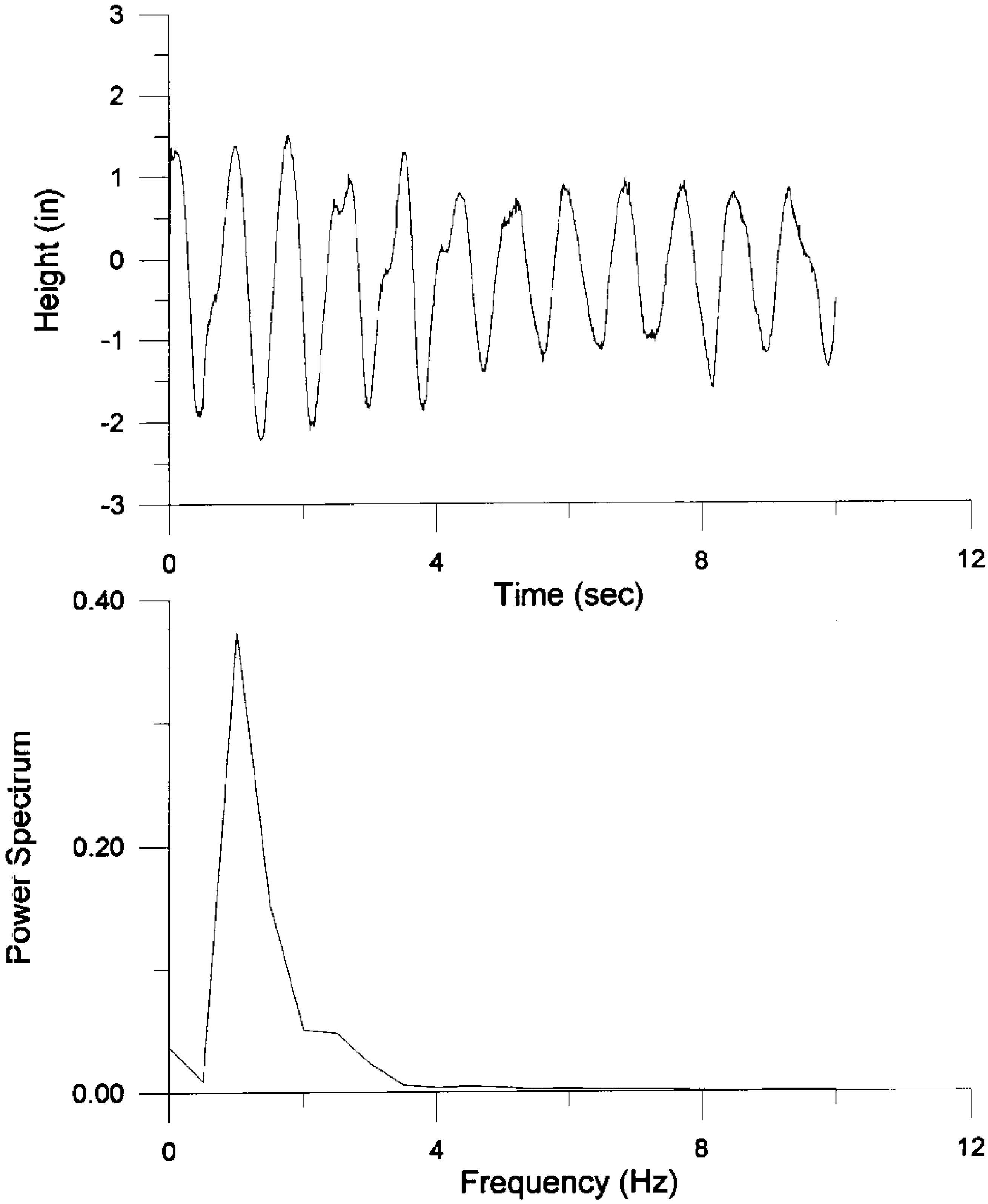


Figure F-9: Plots of wave profile and power spectrum. Radius = 7 inches; flume speed = 0.0 m/sec; wave flap frequency = 1.167 Hz.

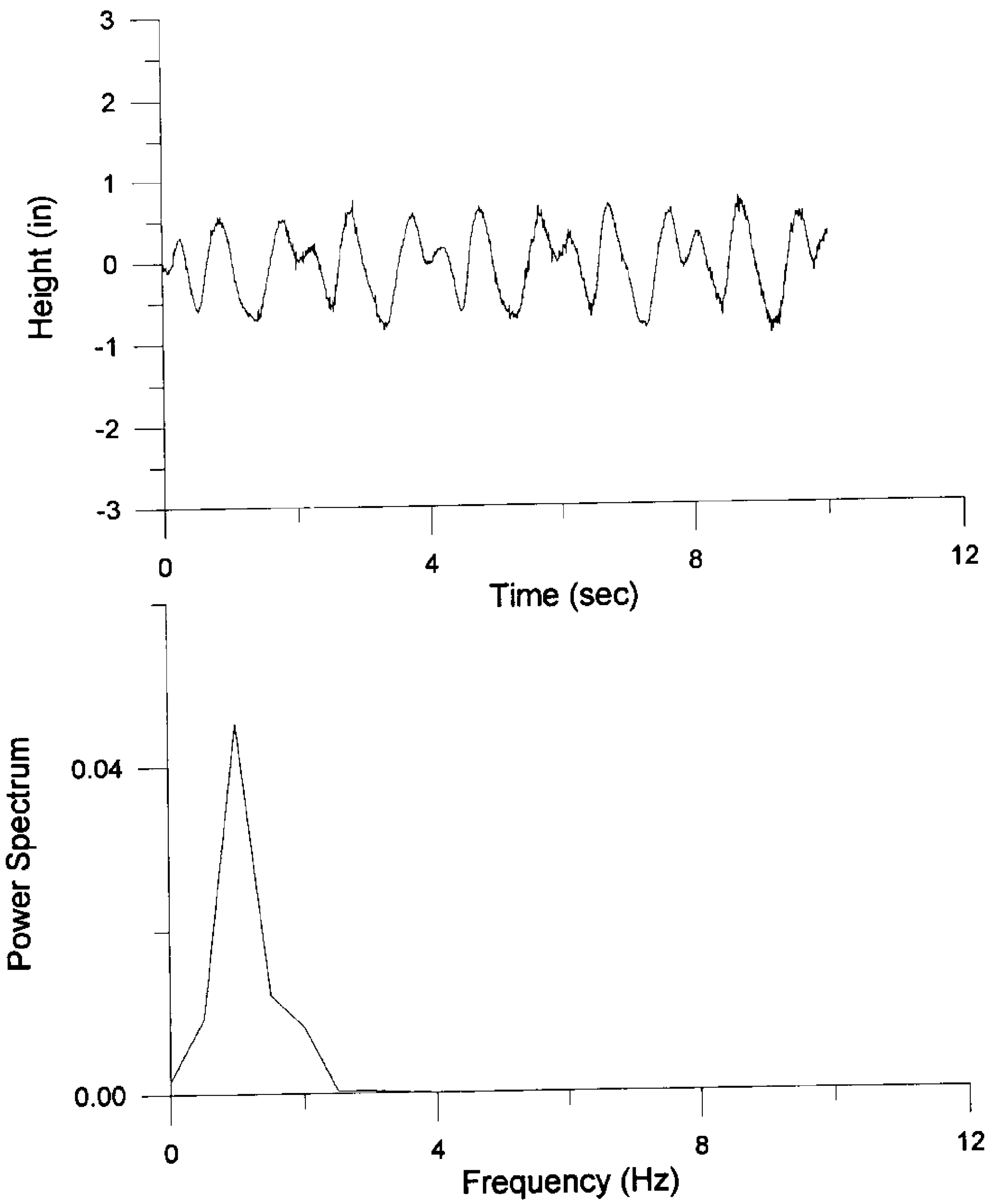


Figure F-10: Plots of wave profile and power spectrum. Radius = 8 inches; flume speed = 0.0 m/sec; wave flap frequency = 0.5 Hz.

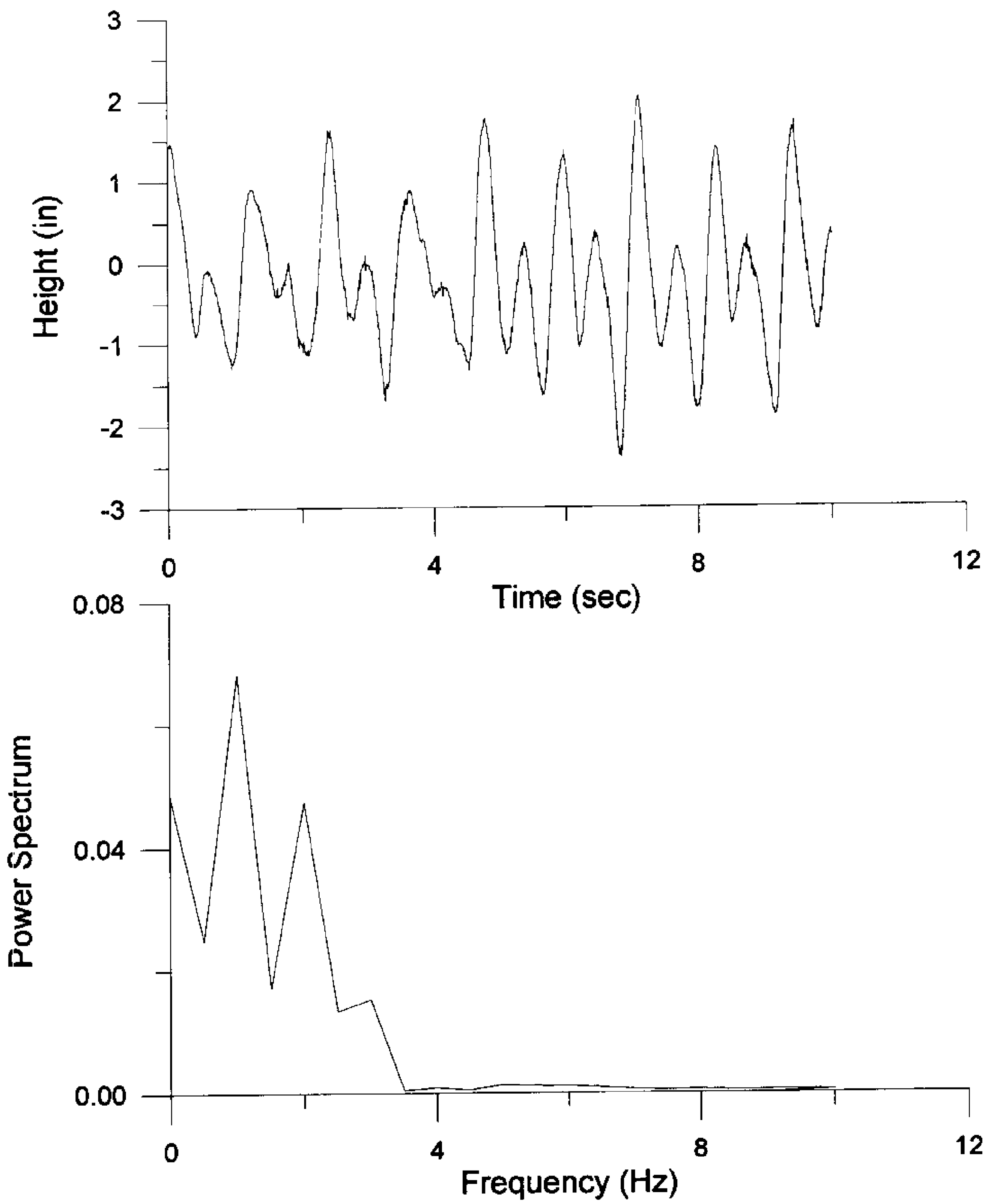


Figure F-11: Plots of wave profile and power spectrum. Radius = 8 inches; flume speed = 0.0 m/sec; wave flap frequency = 0.833 Hz.

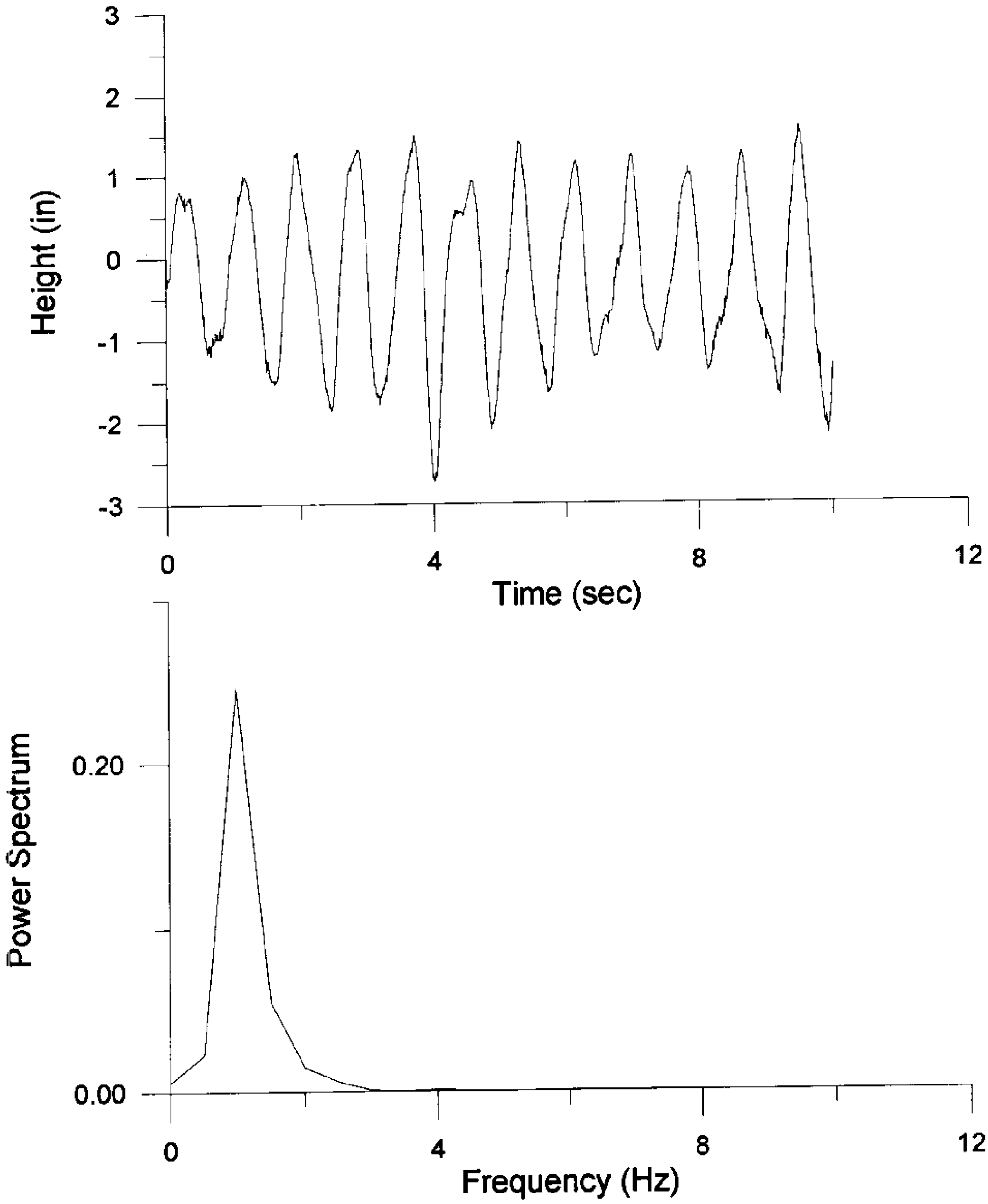


Figure F-12: Plots of wave profile and power spectrum. Radius = 8 inches; flume speed = 0.0 m/sec; wave flap frequency = 1.167 Hz.

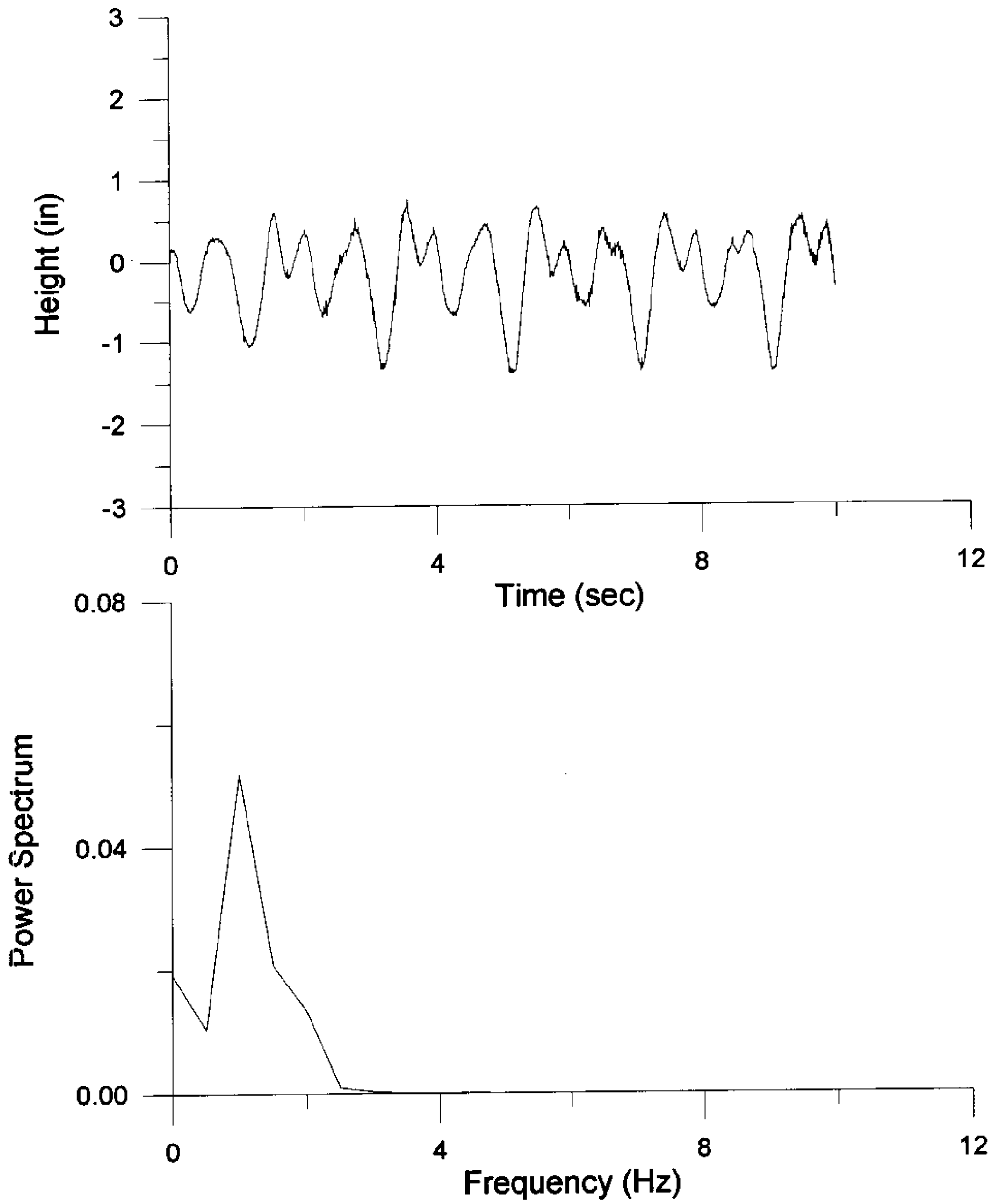


Figure F-13: Plots of wave profile and power spectrum. Radius = 9 inches; flume speed = 0.0 m/sec; wave flap frequency = 0.5 Hz.

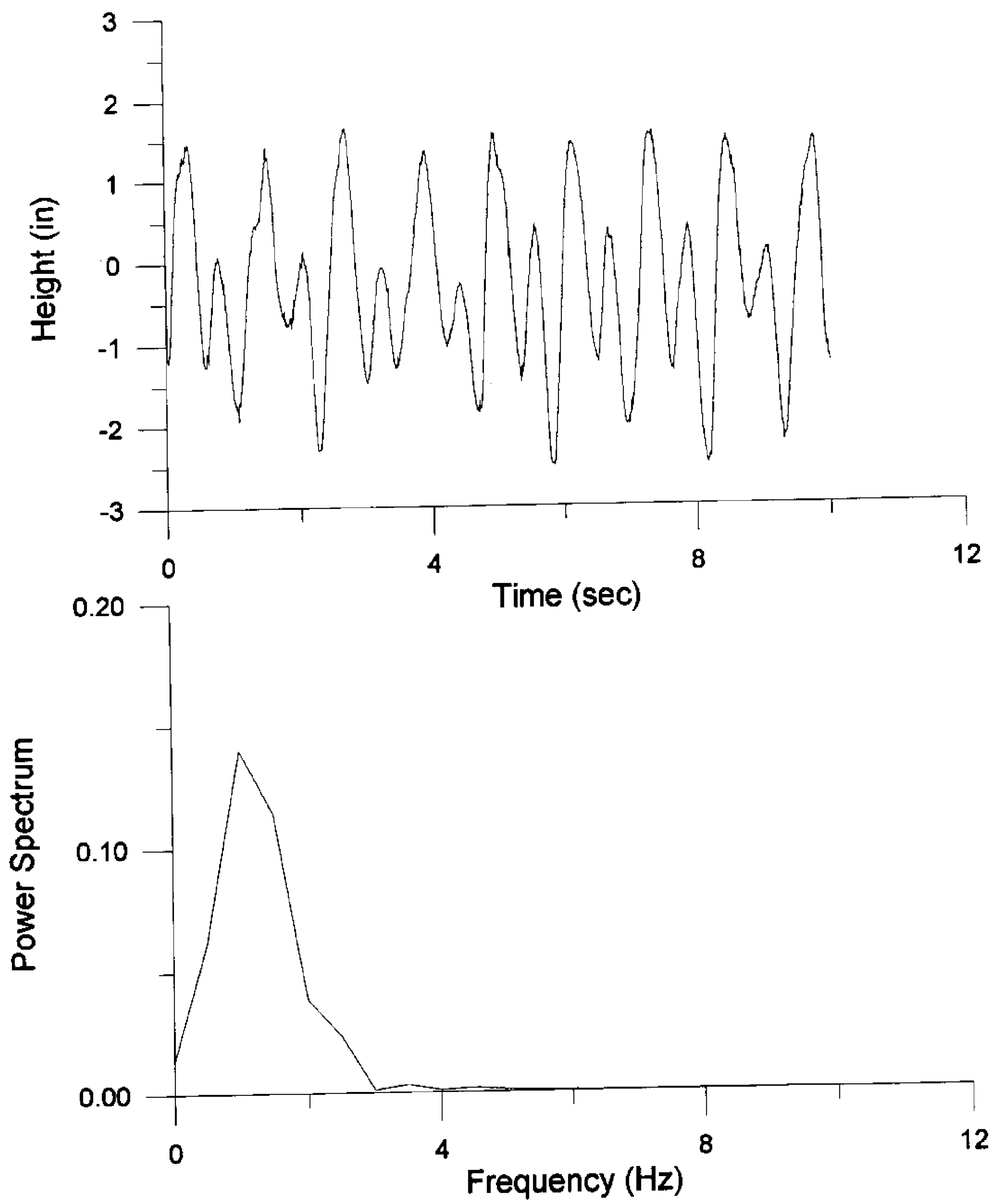
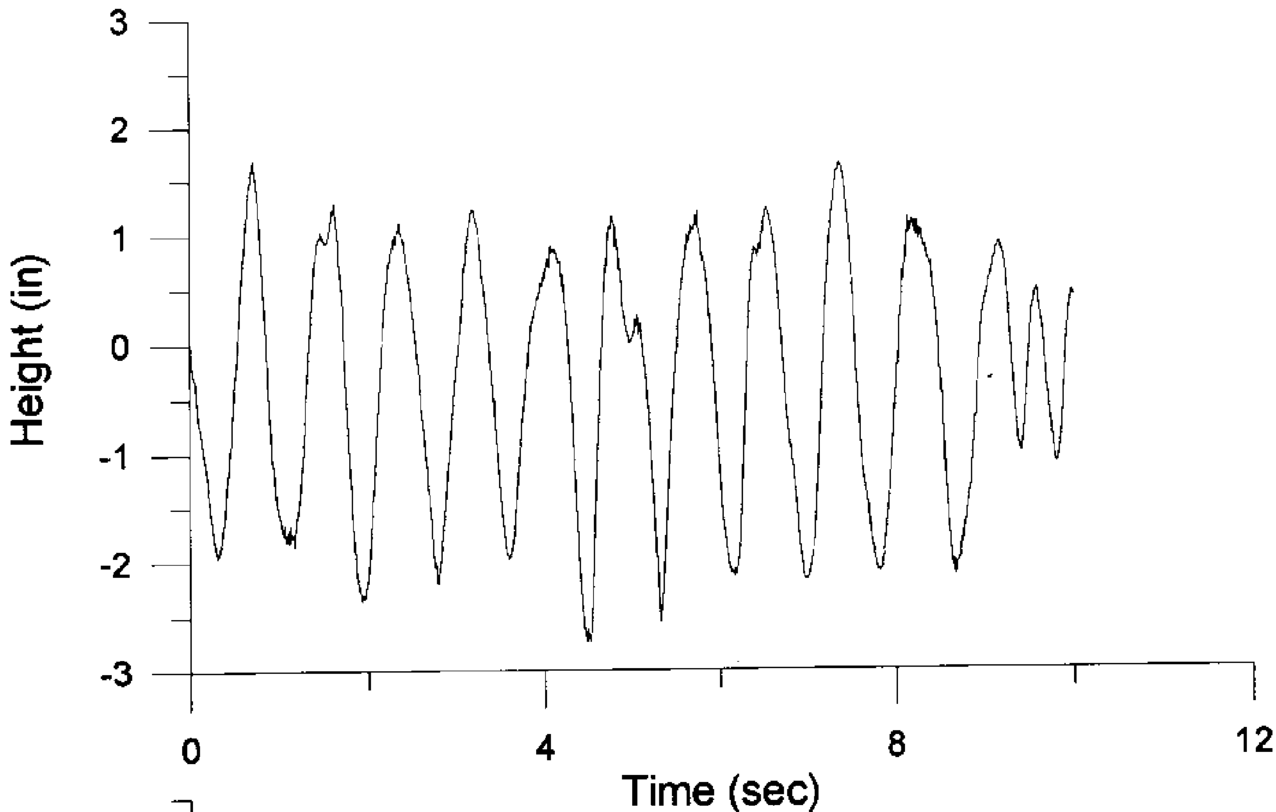


Figure F-14: Plots of wave profile and power spectrum. Radius = 9 inches; flume speed = 0.0 Hz; wave flap frequency = 0.833 Hz.



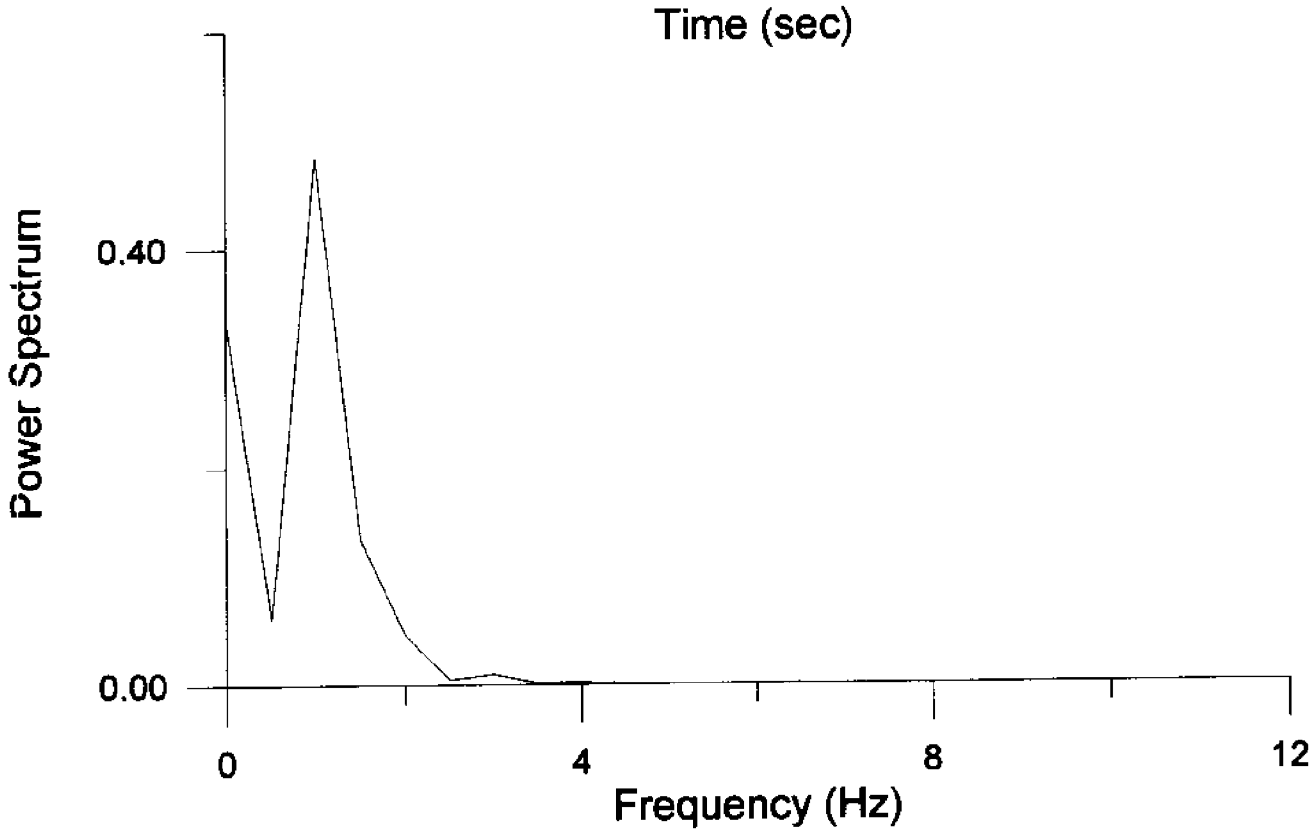


Figure F-15: Plots of wave profile and power spectrum. Radius = 9 inches; flume speed = 0.0 Hz; wave flap frequency = 1.167 Hz.

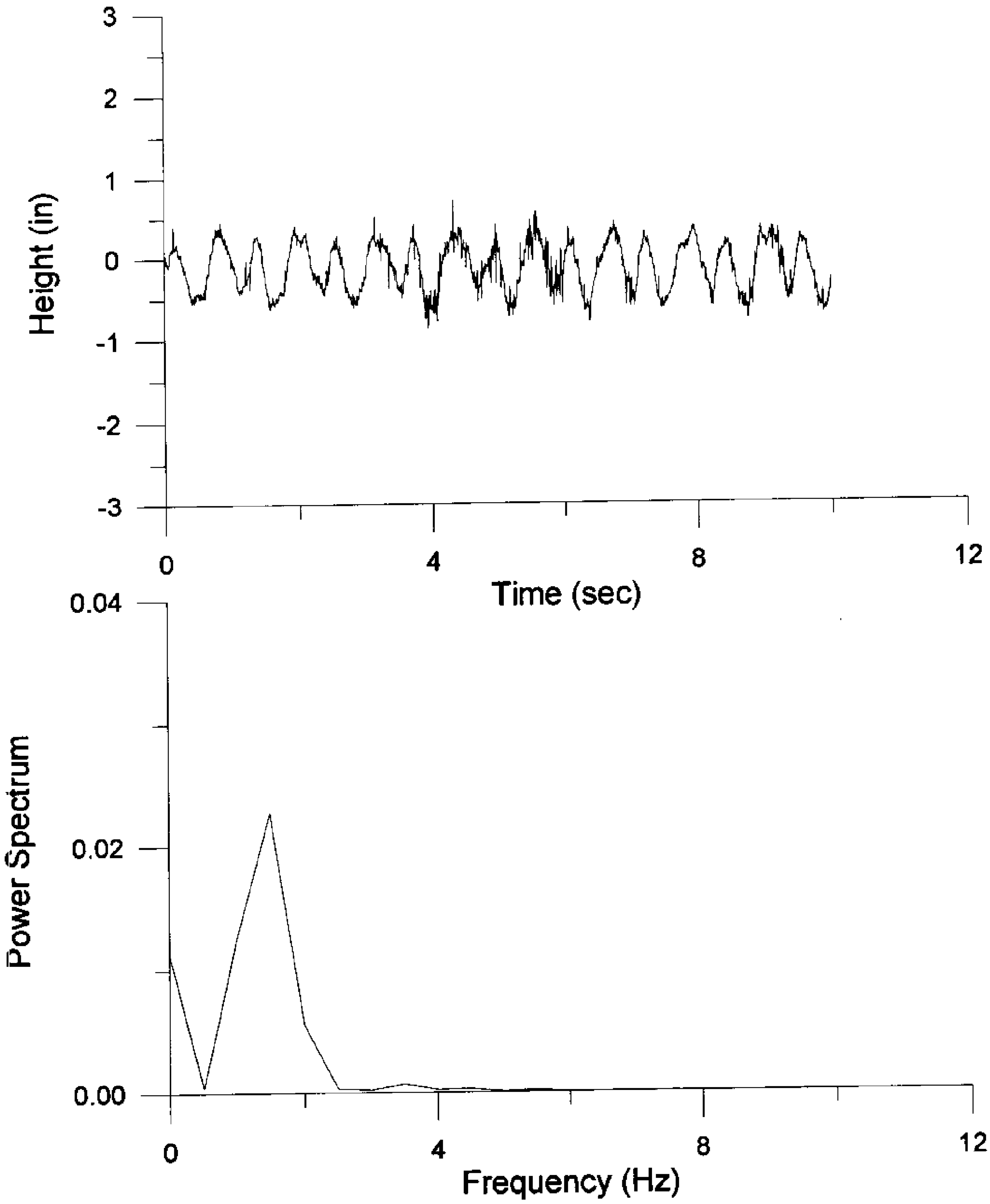


Figure F-16: Plots of wave profile and power spectrum. Radius = 5 inches; flume speed = 0.152 m/sec; wave flap frequency = 0.833 Hz.

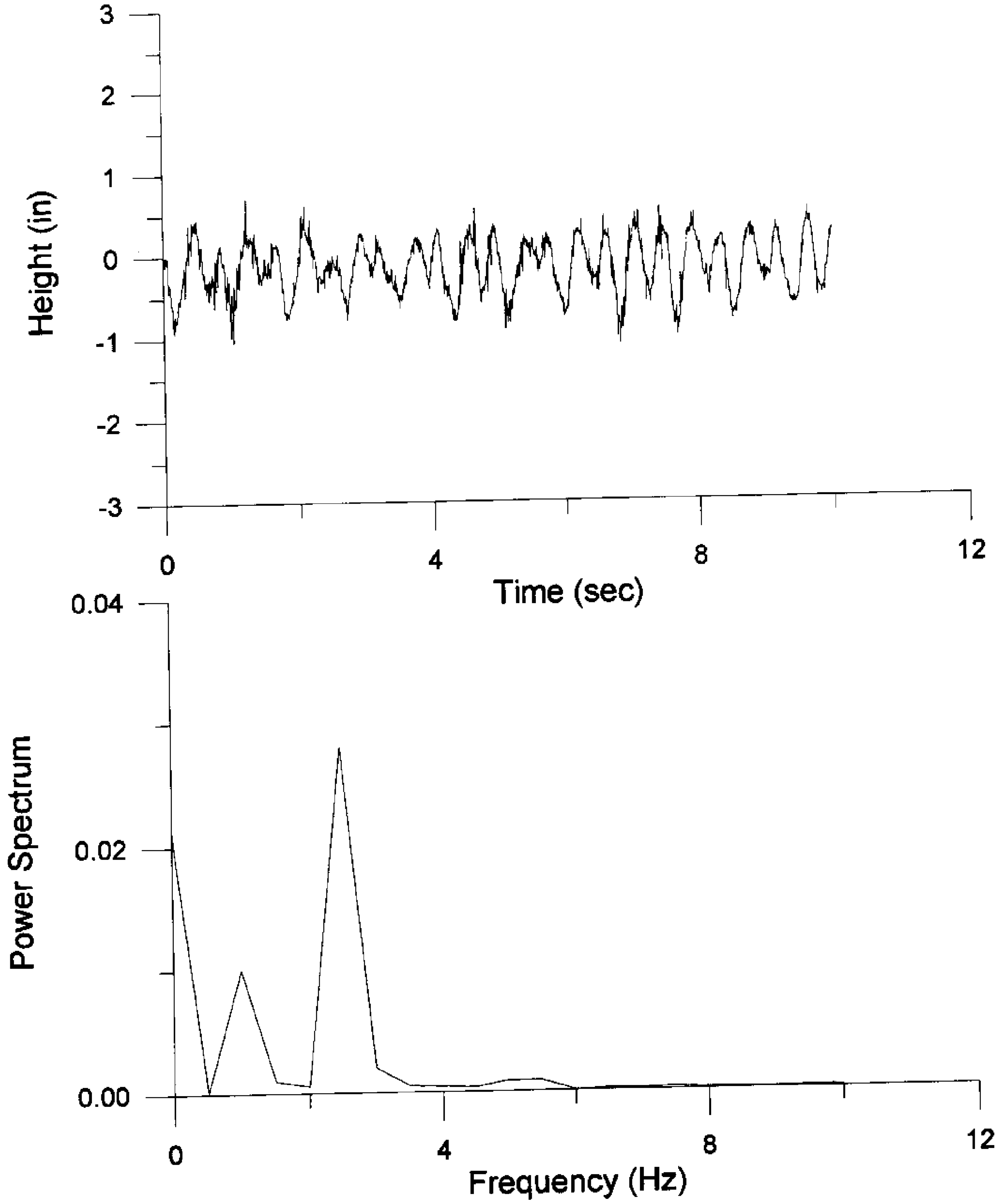


Figure F-17: Plots of wave profile and power spectrum. Radius = 5 inches; flume speed = 0.152 m/sec; wave flap frequency = 1.167 Hz.

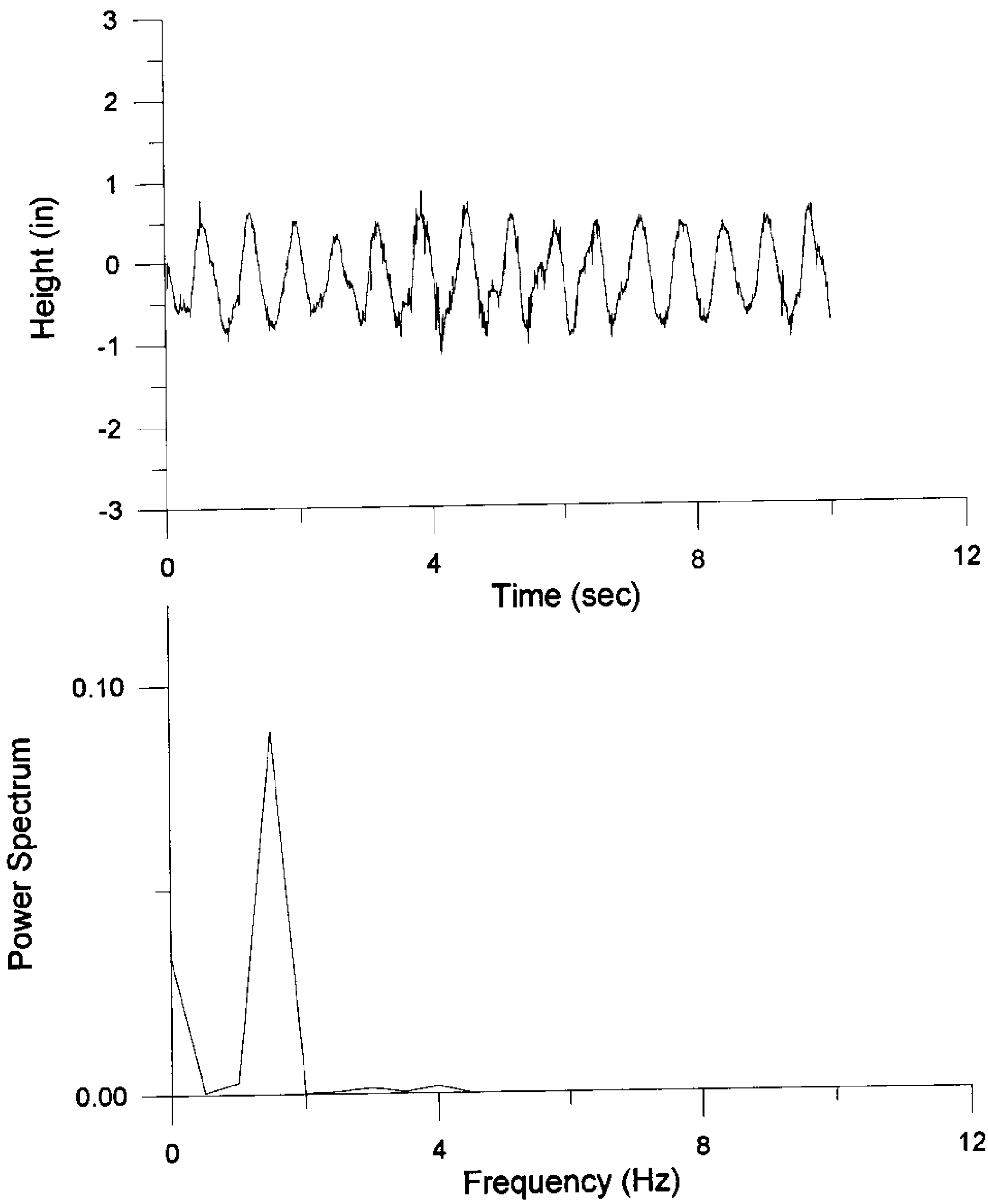


Figure F-18: Plots of wave profile and power spectrum. Radius = 5 inches; flume speed = 0.152 m/sec; wave flap frequency = 1.5 Hz.

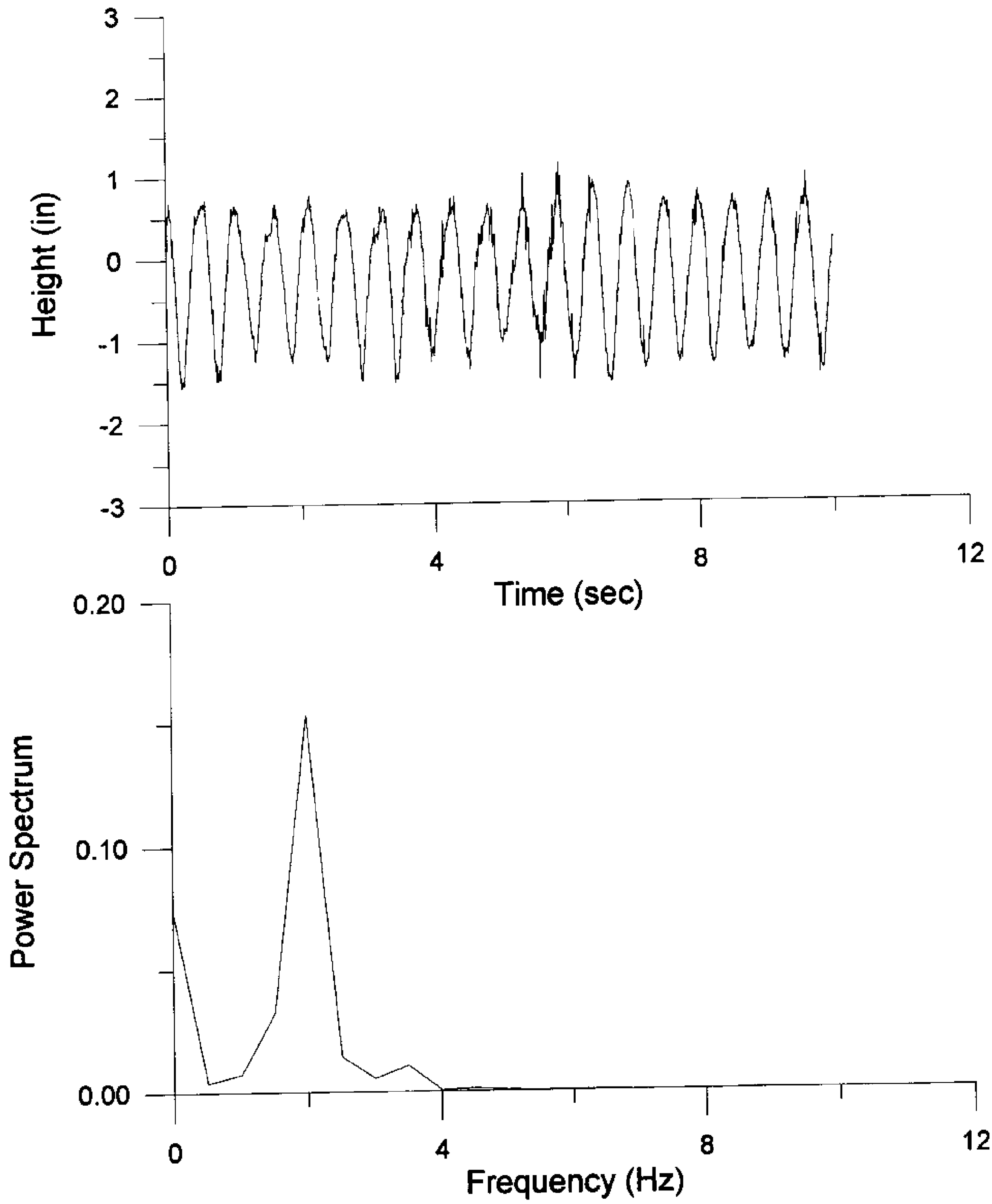


Figure F-19: Plots of wave profile and power spectrum. Radius = 5 inches; flume speed = 0.152 m/sec; wave flap frequency = 1.833 Hz.

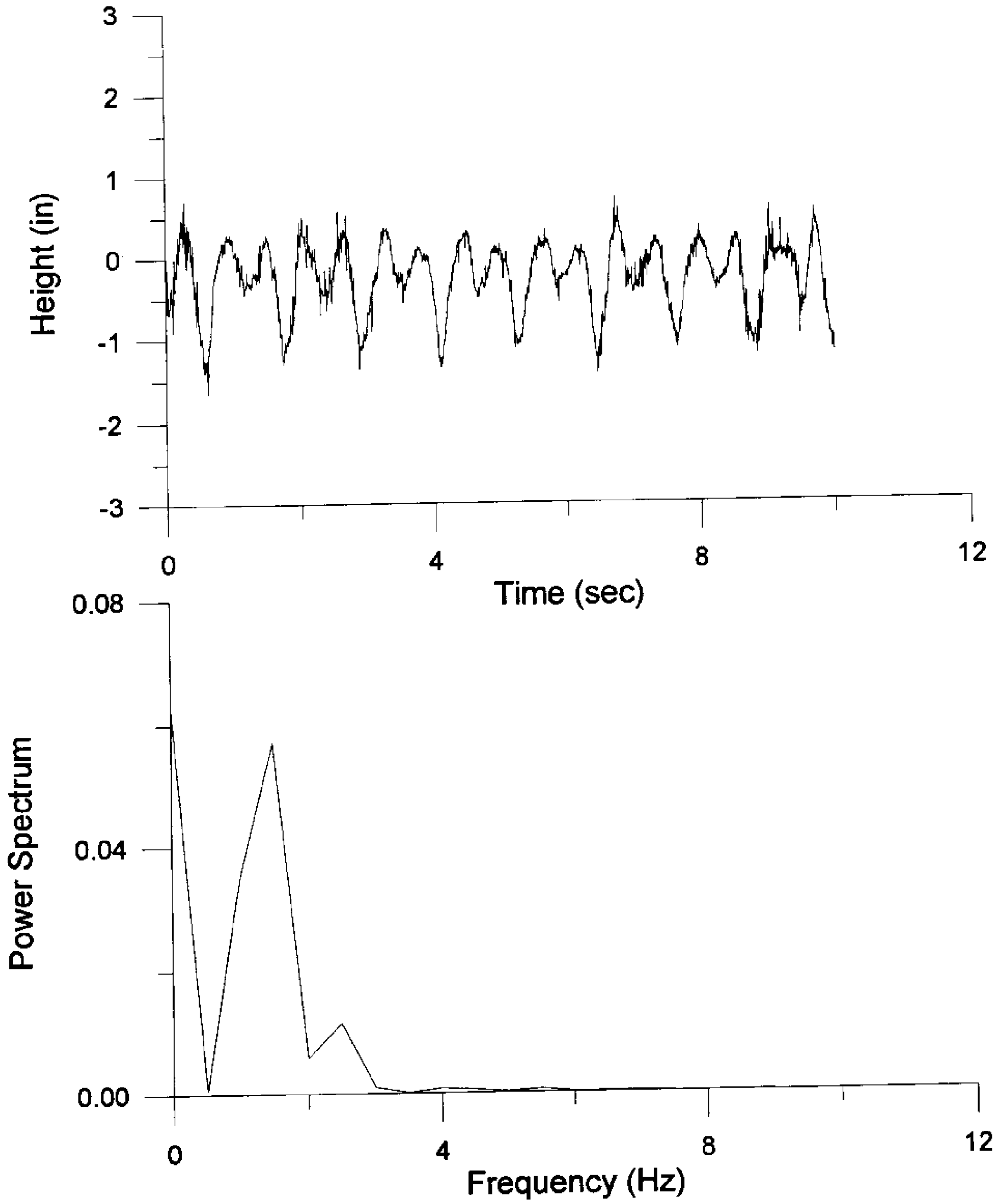


Figure F-20: Plots of wave profile and power spectrum. Radius = 6 inches; flume speed = 0.152 m/sec; wave flap frequency = 0.833 Hz.

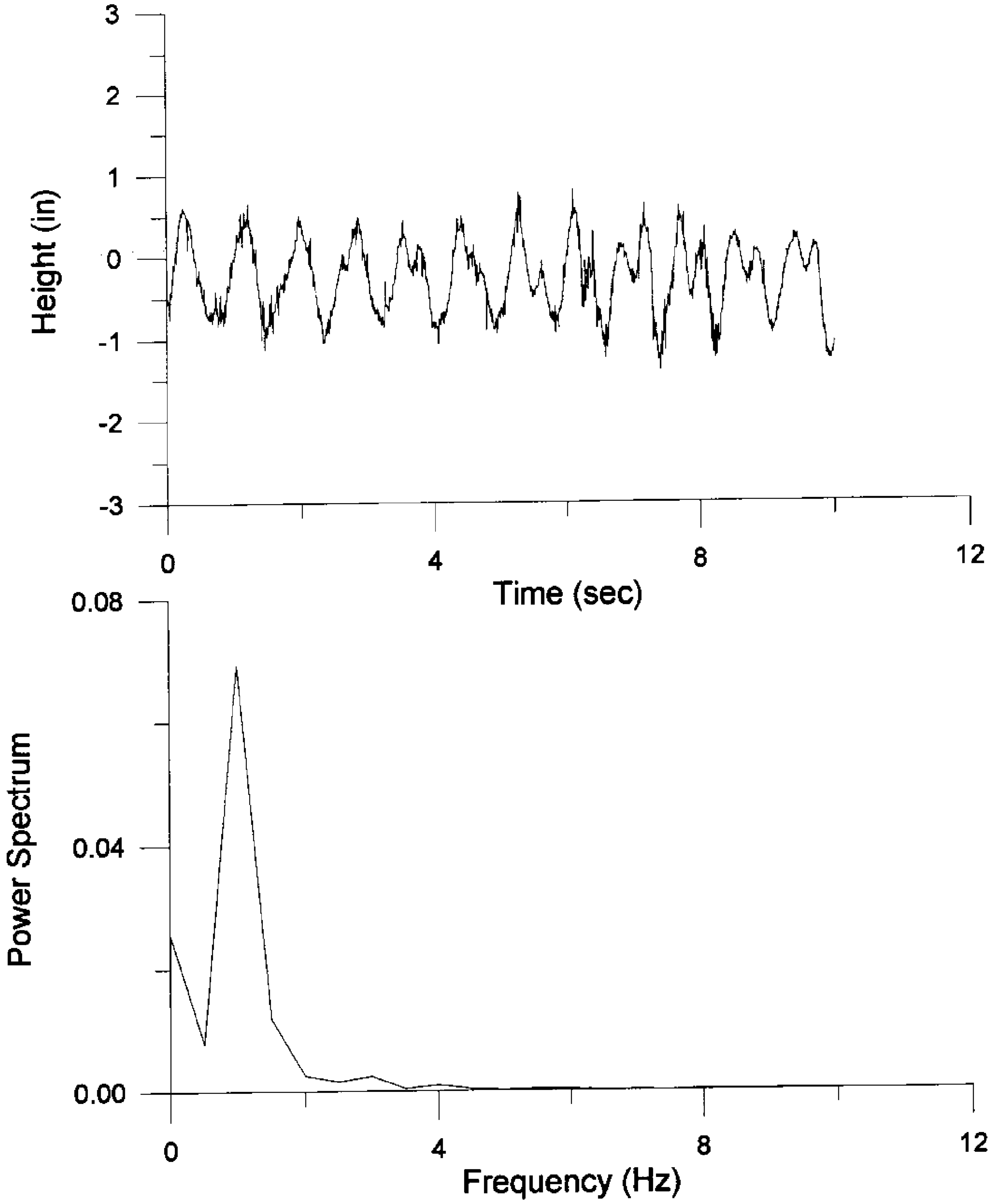


Figure F-21: Plots of wave profile and power spectrum. Radius = 6 inches; flume speed = 0.152 m/sec; wave flap frequency = 1.167 Hz.

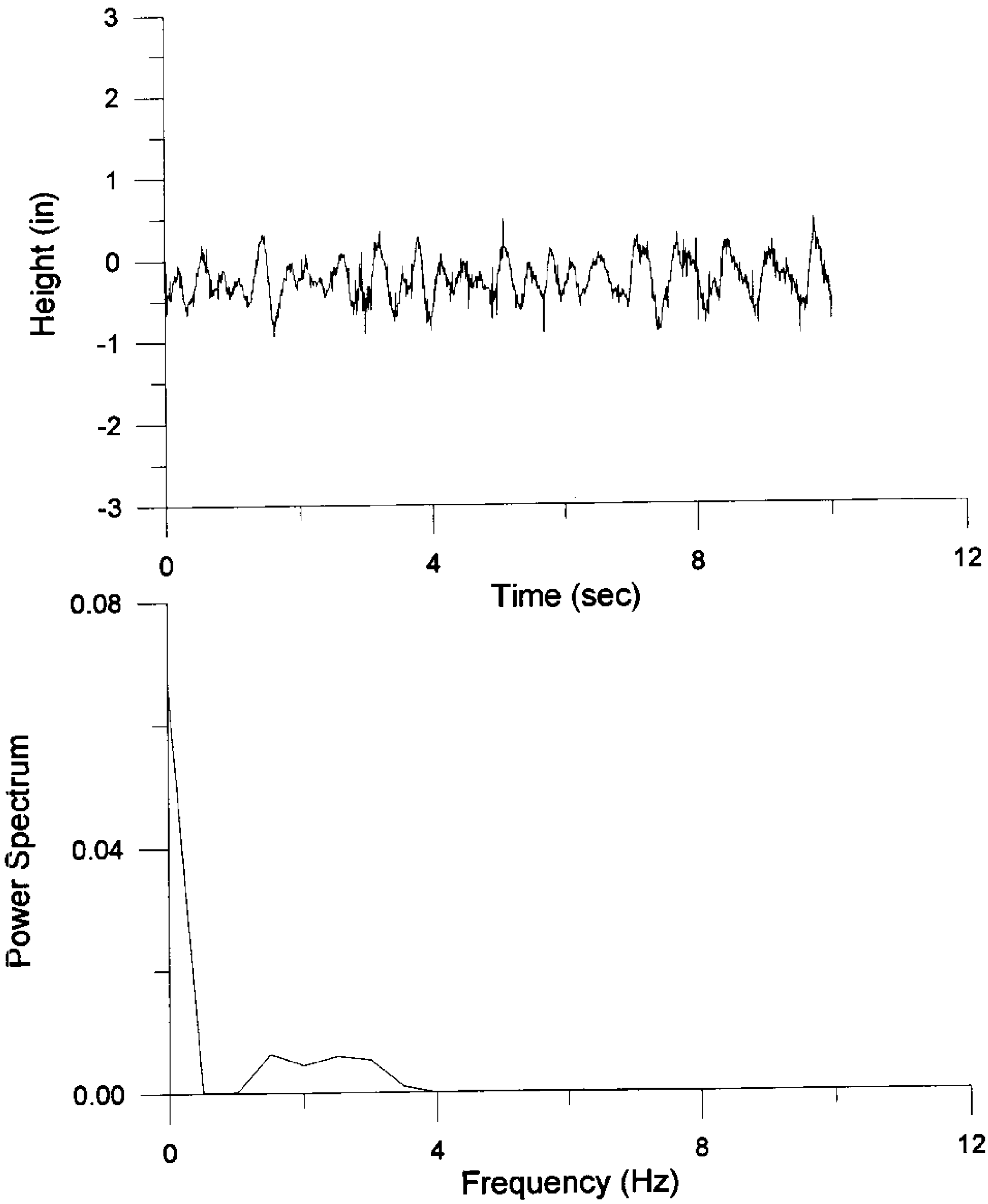


Figure F-22: Plots of wave profile and power spectrum. Radius = 6 inches; flume speed = 0.152 m/sec; wave flap frequency = 1.5 Hz.

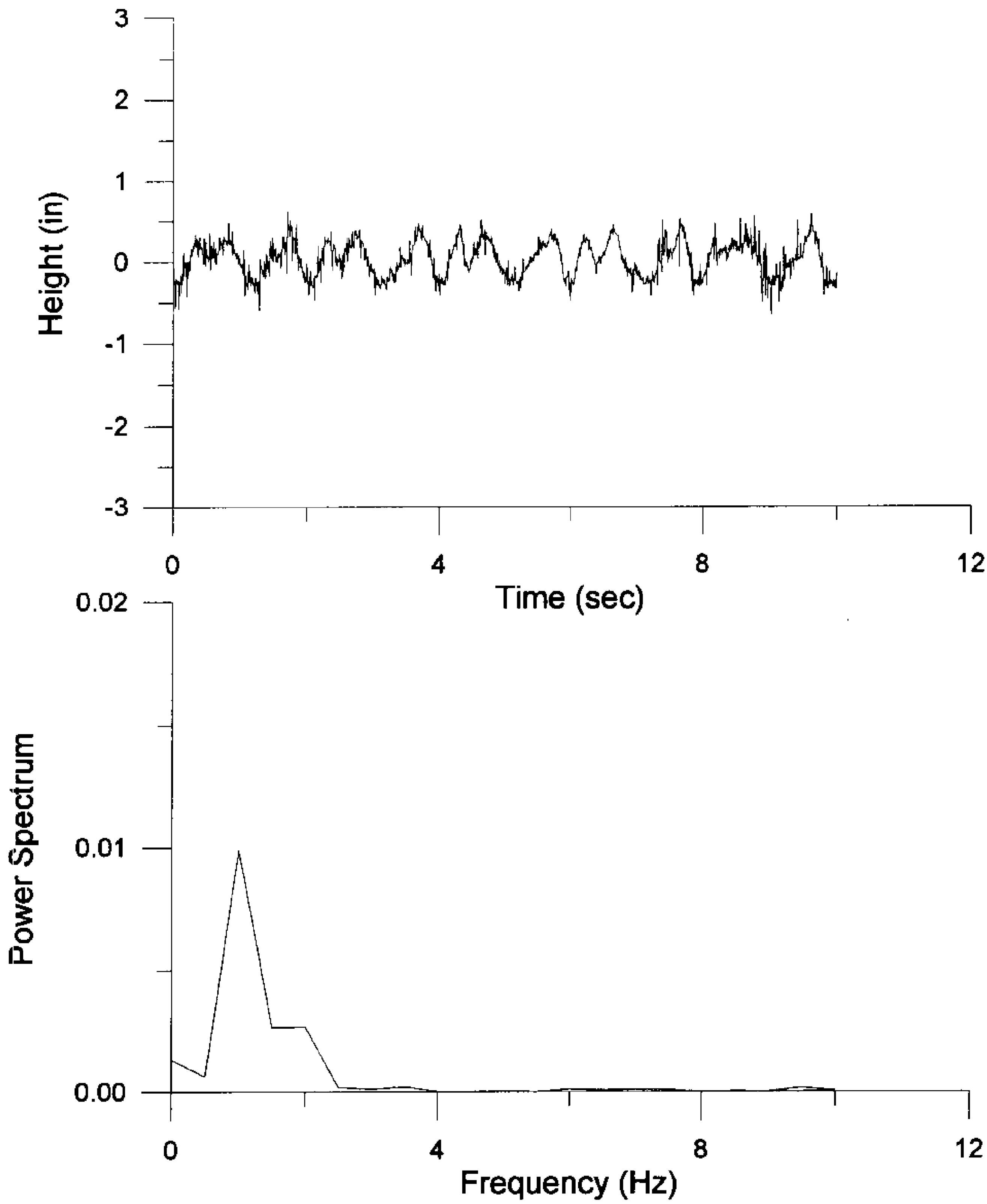


Figure F-23: Plots of wave profile and power spectrum. Radius = 7 inches; flume speed = 0.152 m/sec; wave flap frequency = 0.5 Hz.

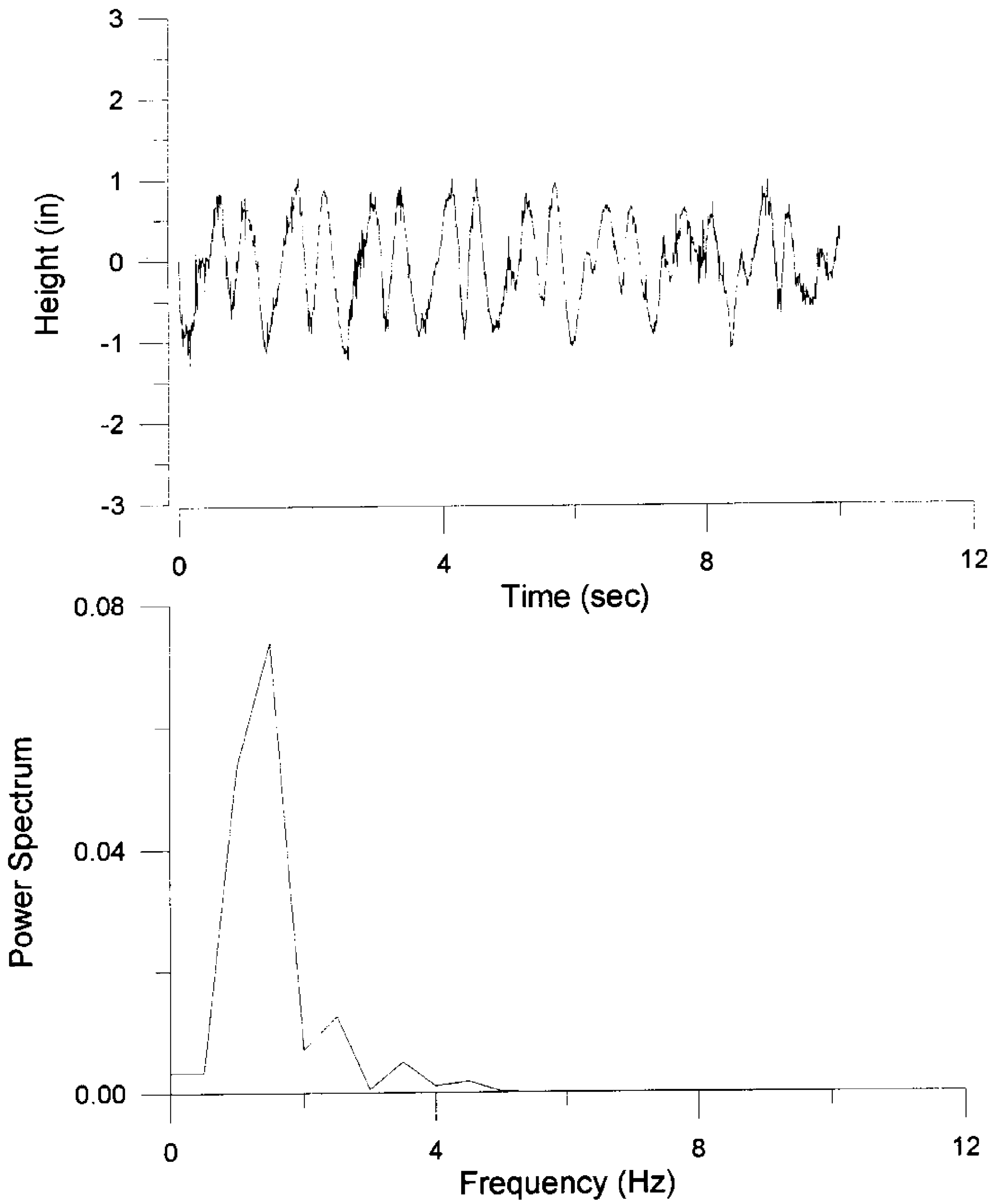


Figure F-24: Plots of wave profile and power spectrum
Radius = 7 inches; flume speed = 0.152 m/sec wave flap frequency = 0.833 Hz

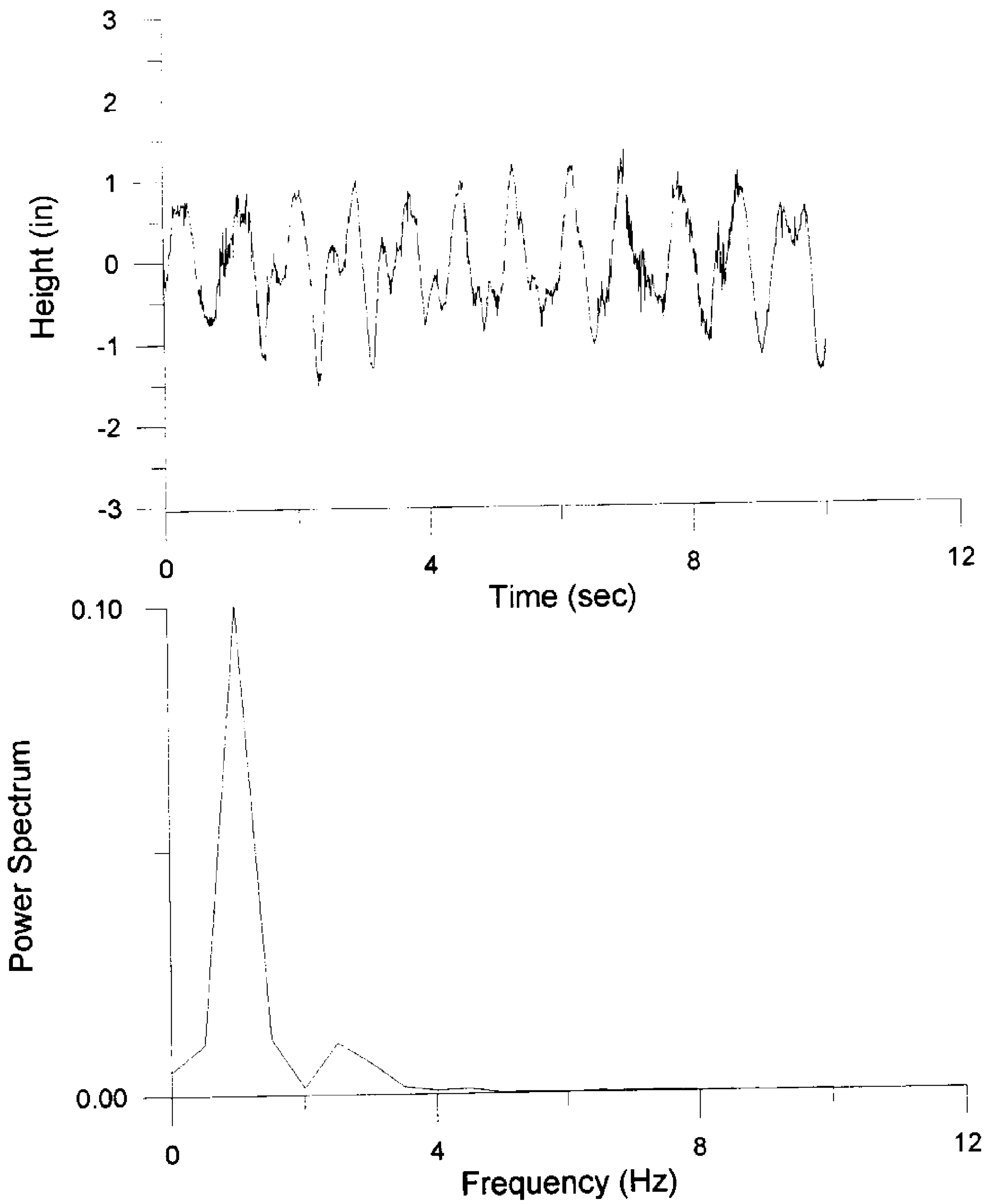


Figure F-25: Plots of wave profile and power spectrum
Radius = 7 inches; flume speed = 0.152 m/sec wave flap frequency = 1.167 Hz

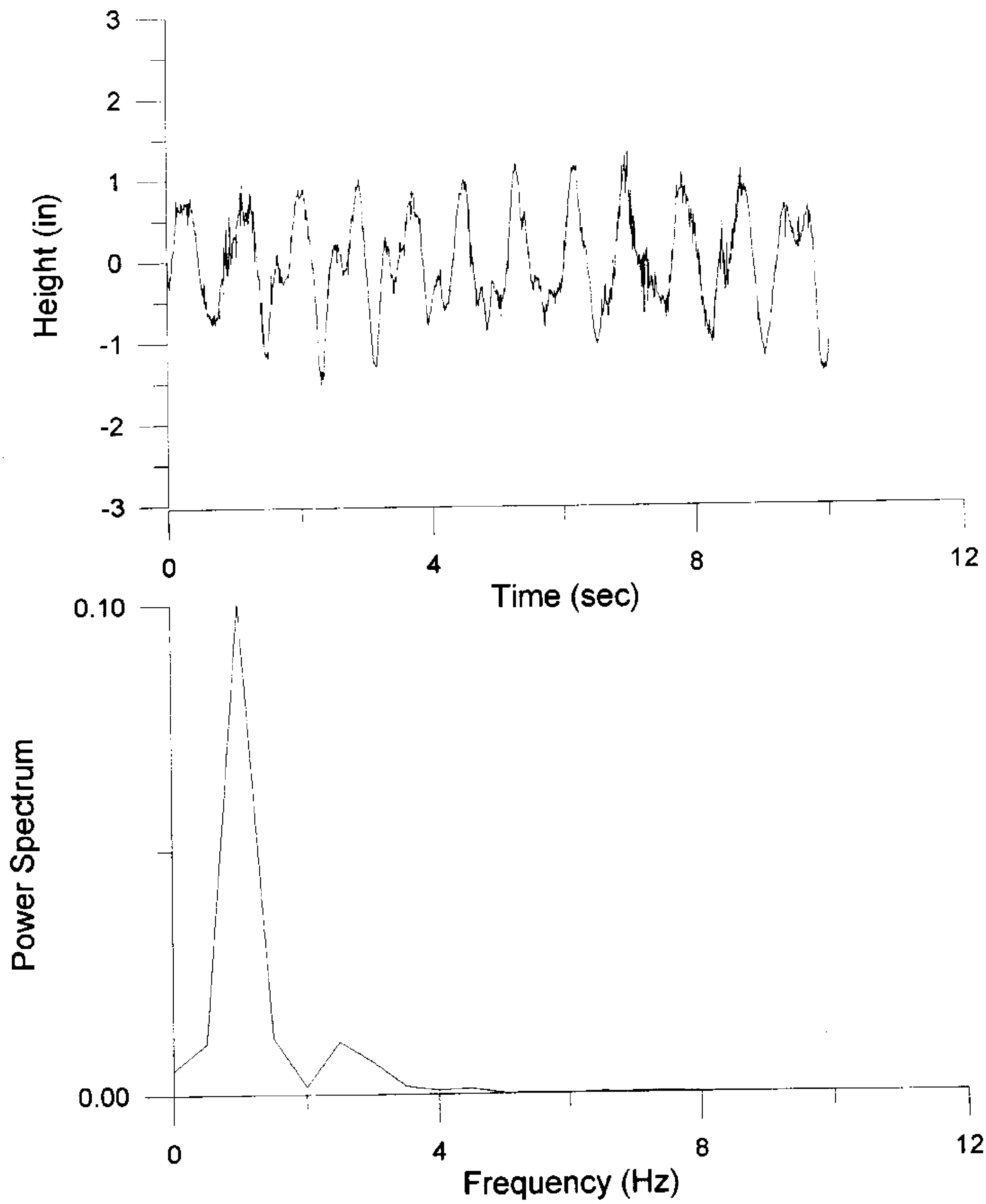


Figure F-26: Plots of wave profile and power spectrum
Radius = 7 inches; flume speed = 0.152 m/sec wave flap frequency = 1.167 Hz

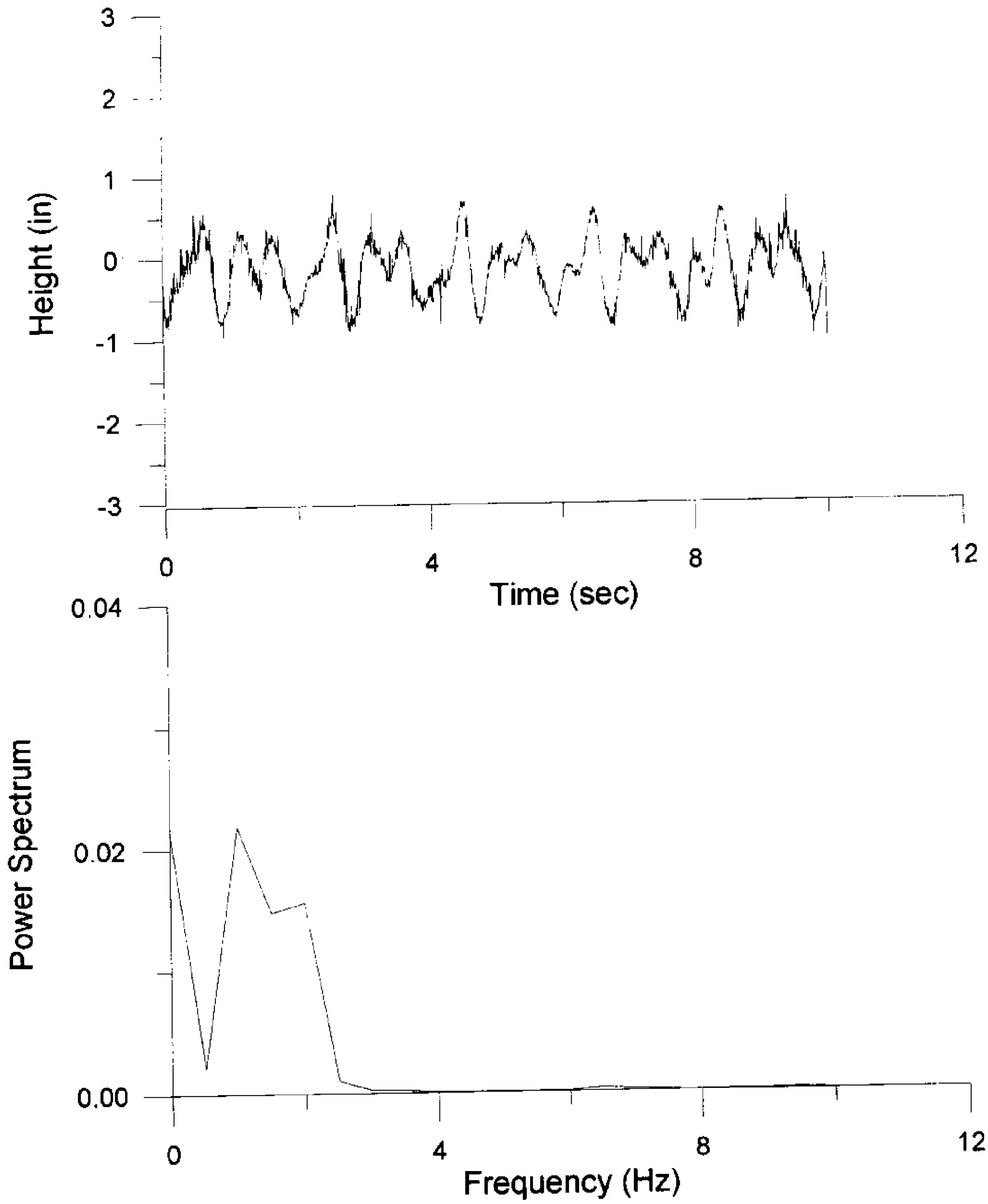
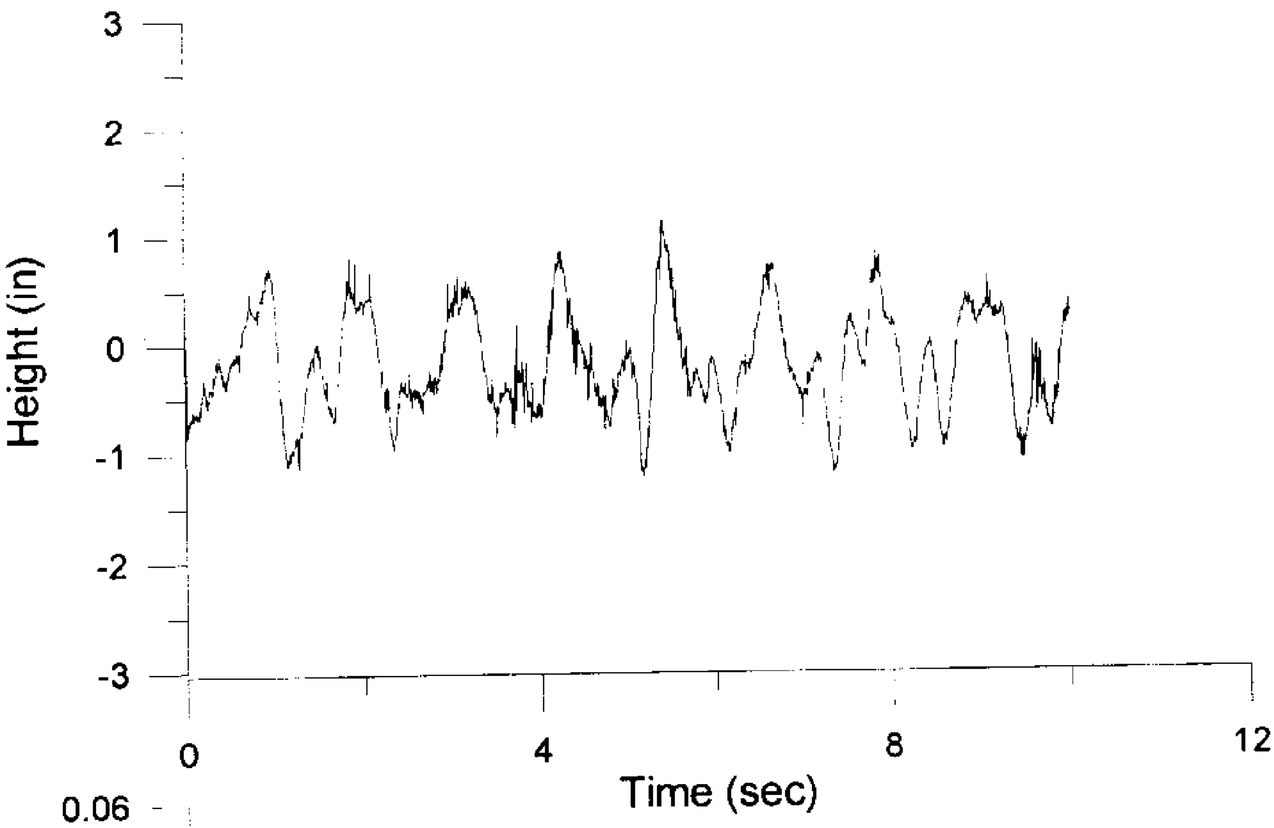


Figure F-27: Plots of wave profile and power spectrum
Radius = 8 inches; flume speed = 0.152 m/sec wave flap frequency = 0.5 Hz



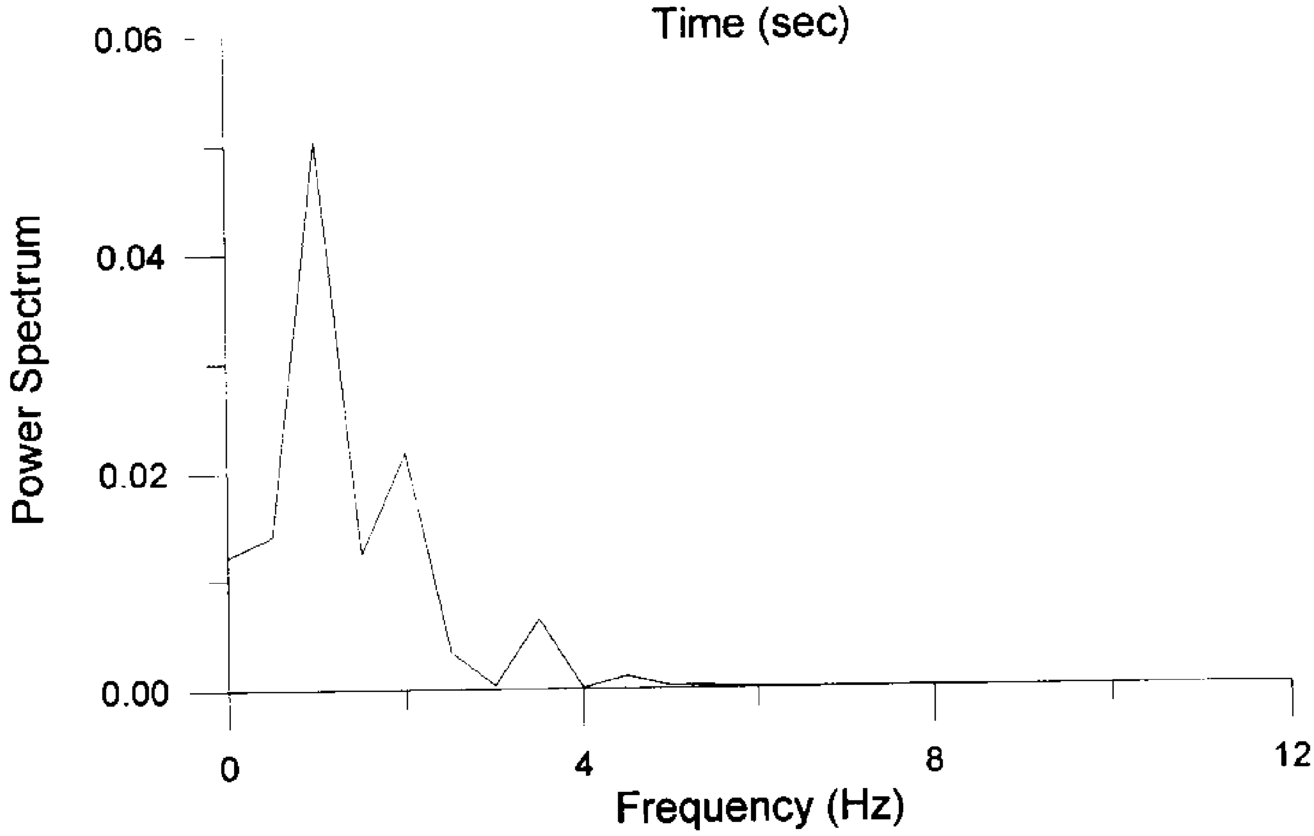


Figure F-28: Plots of wave profile and power spectrum
Radius = 8 inches; flume speed = 0.152 m/sec wave flap frequency = 0.883 Hz

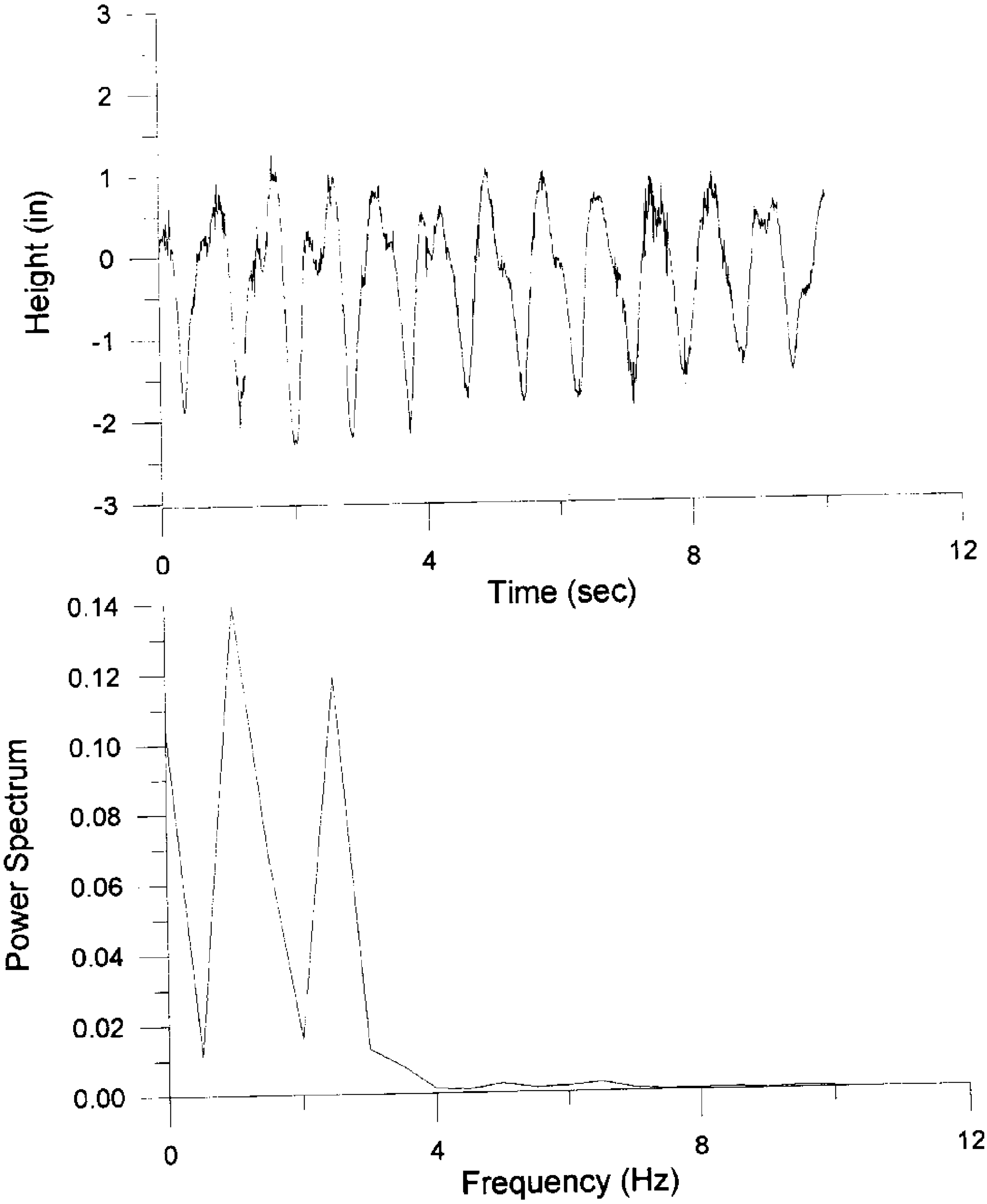


Figure F-29: Plots of wave profile and power spectrum
Radius = 8 inches; flume speed = 0.152 m/sec wave flap
frequency = 1.167 Hz

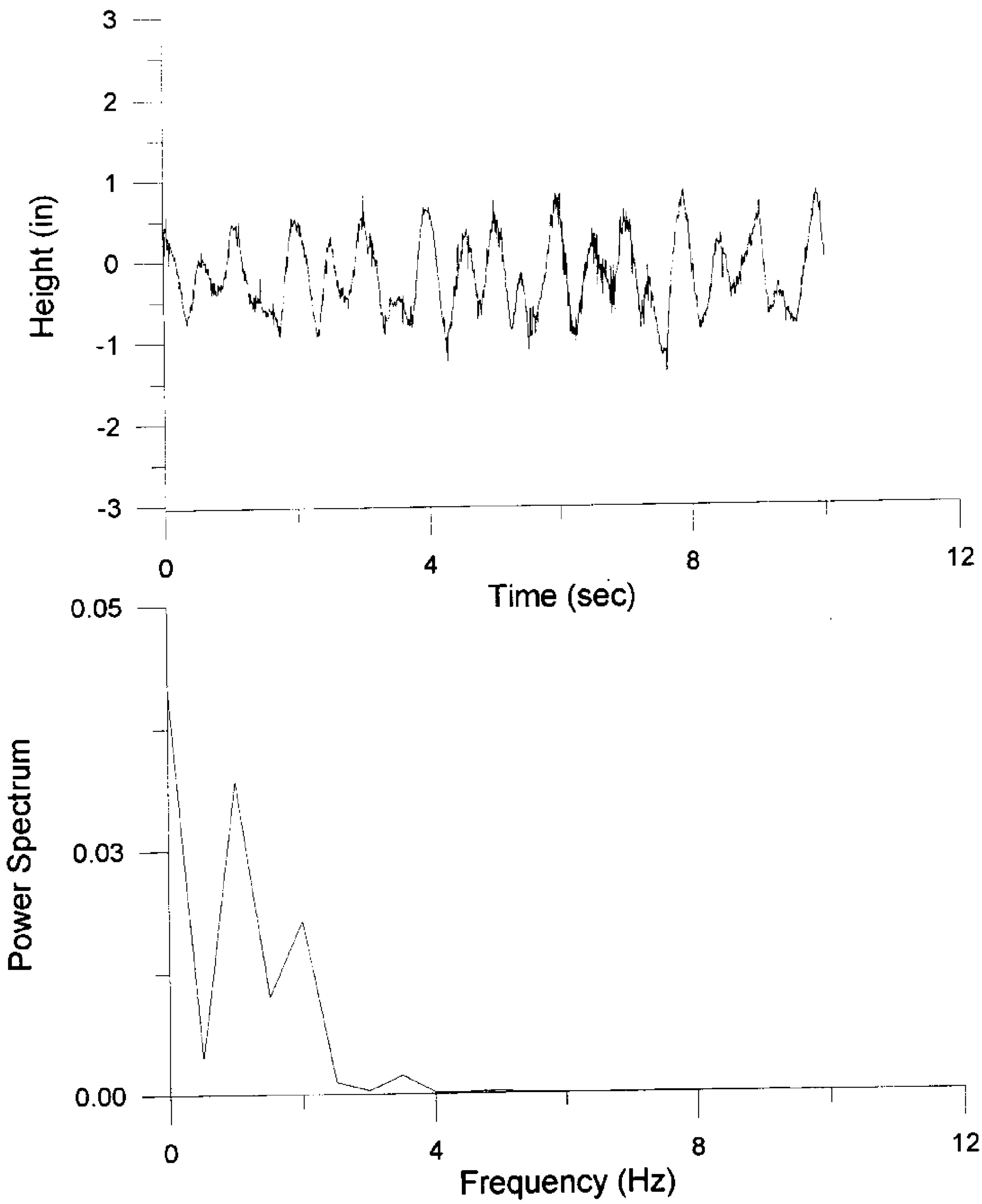


Figure F-30: Plots of wave profile and power spectrum
Radius = 9 inches; flume speed = 0.152 m/sec wave flap frequency = 0.5 Hz

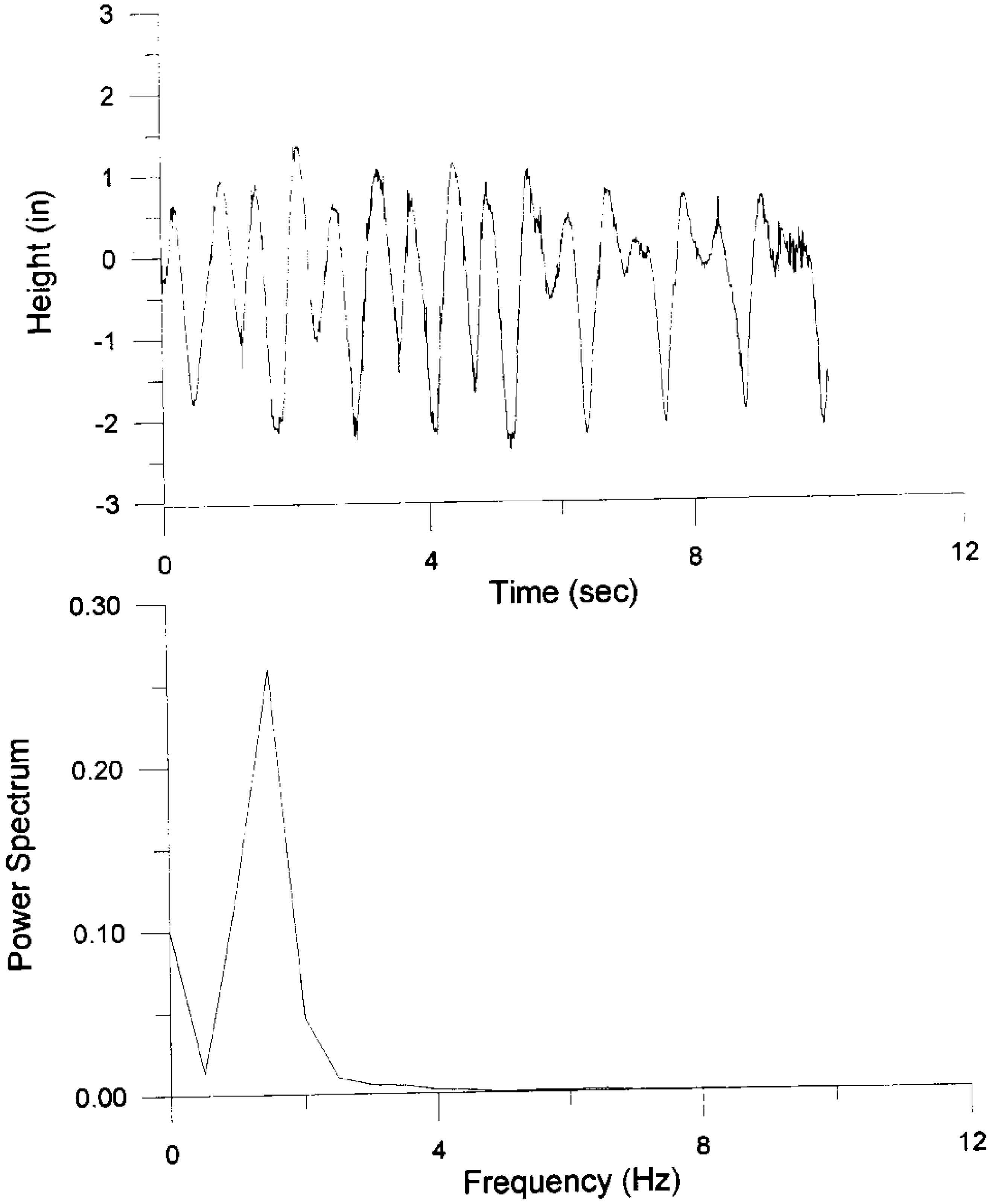


Figure F-31: Plots of wave profile and power spectrum
Radius = 9 inches; flume speed = 0.152 m/sec wave flap frequency = 0.833 Hz

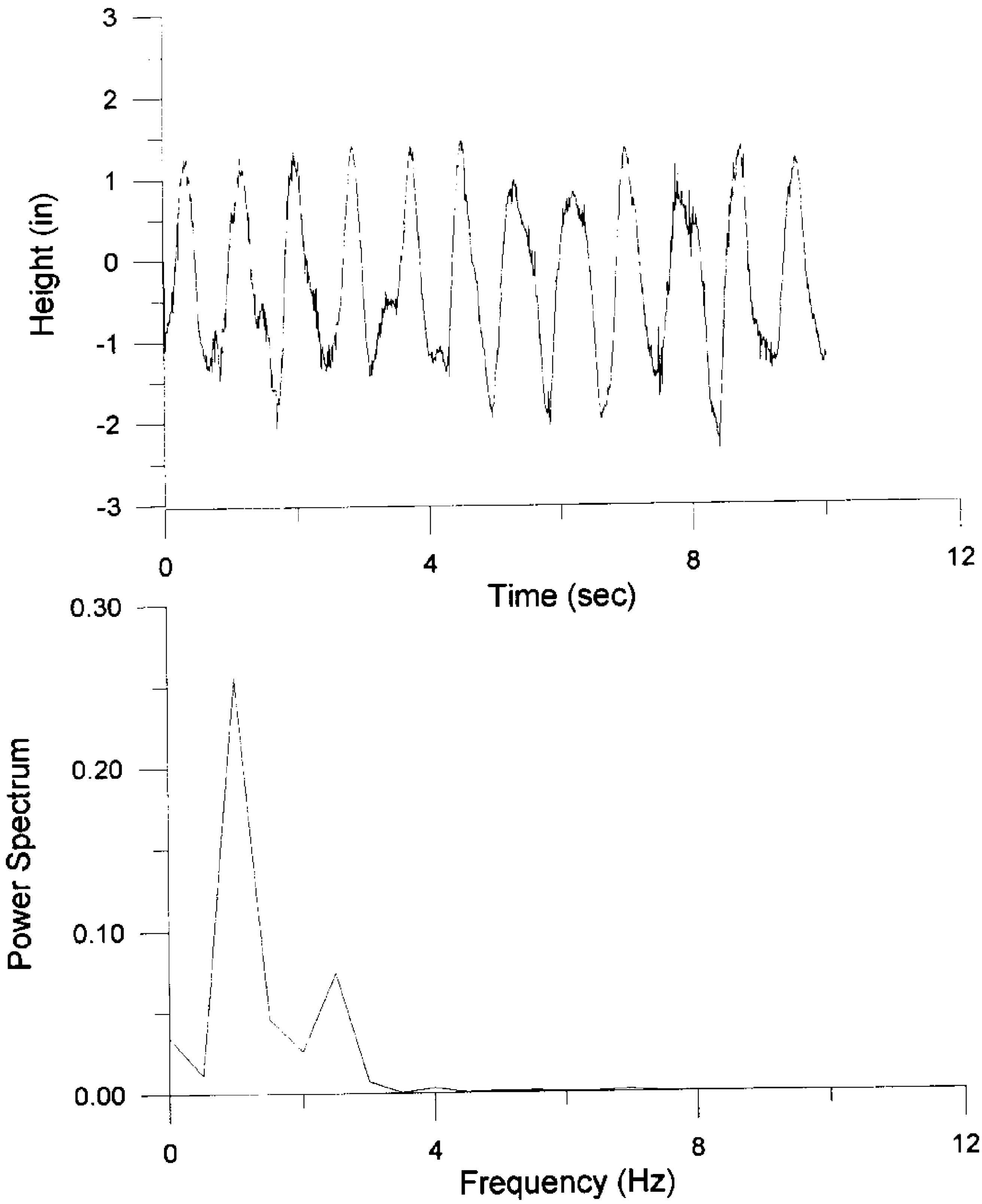
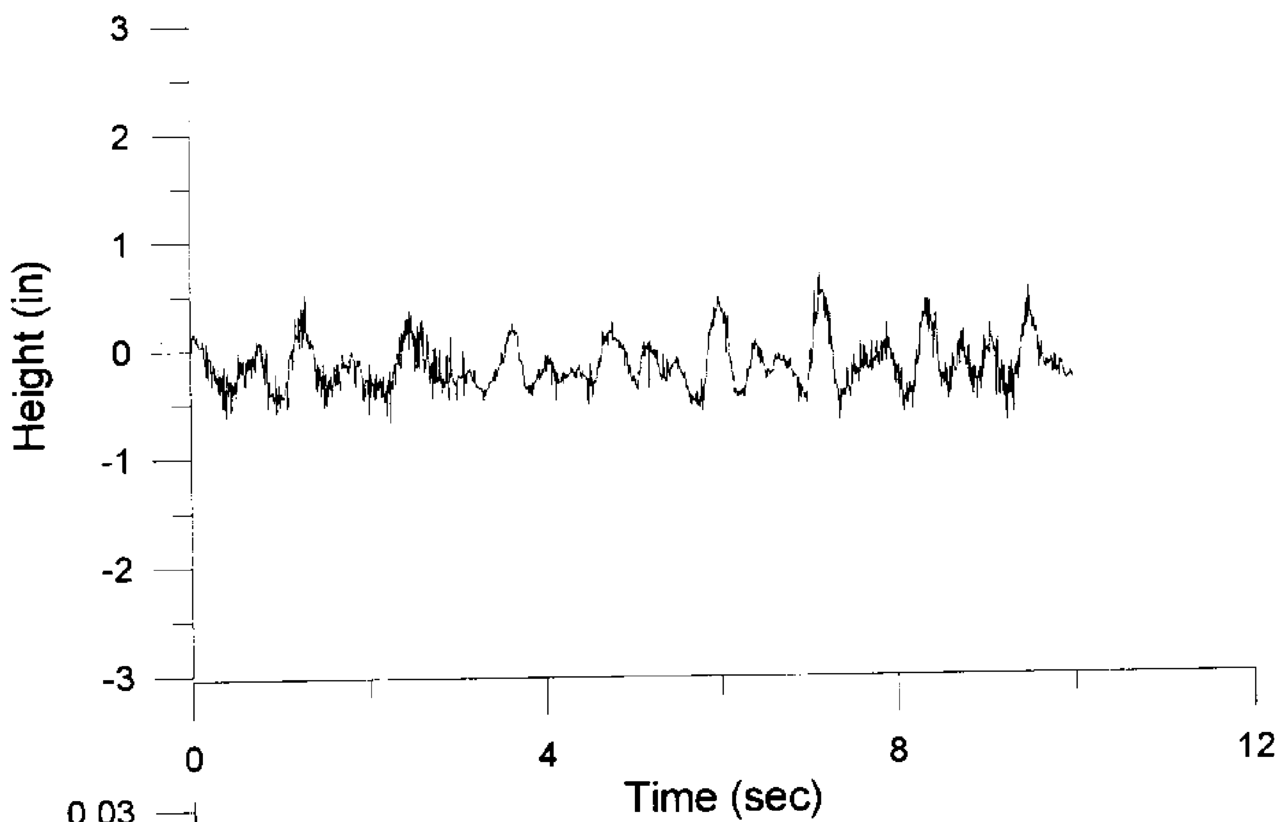


Figure F-32: Plots of wave profile and power spectrum
Radius = 9 inches; flume speed = 0.152 m/sec wave flap
frequency = 1.167 Hz



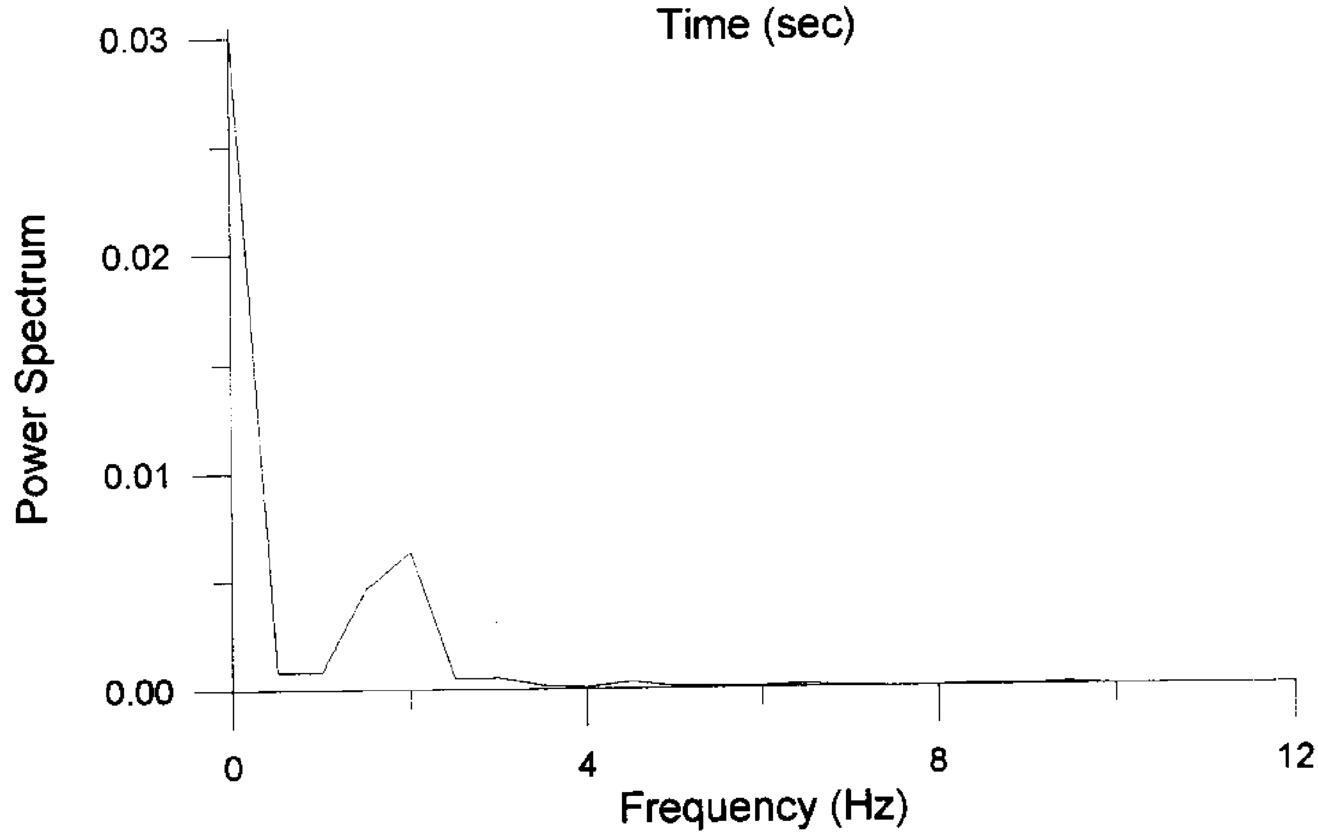


Figure F-33: Plots of wave profile and power spectrum
Radius = 5 inches; flume speed = 0.304 m/sec wave flap frequency = 0.833 Hz

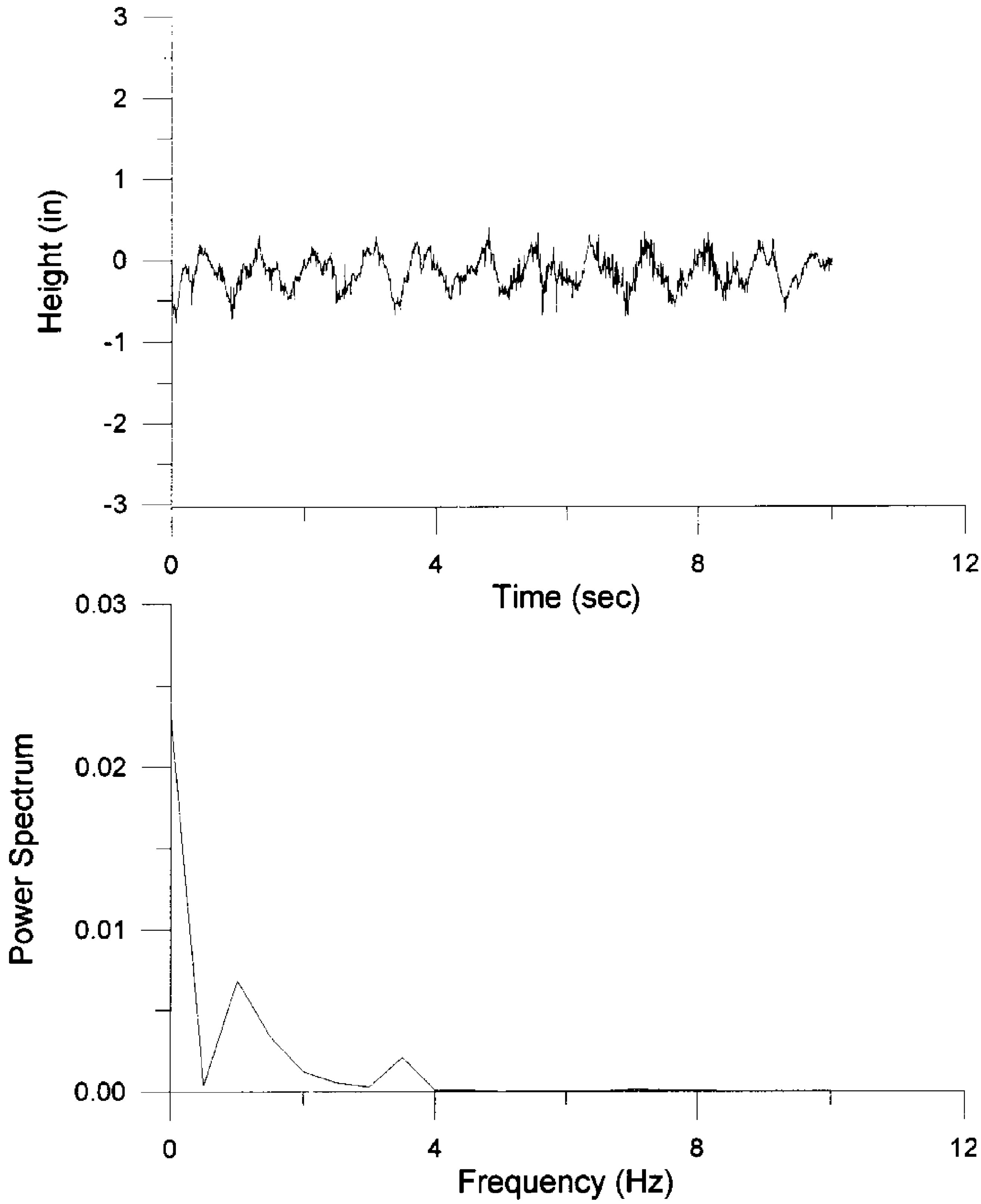


Figure F-34: Plots of wave profile and power spectrum
Radius = 5 inches; flume speed = 0.304 m/sec wave flap
frequency = 1.167 Hz

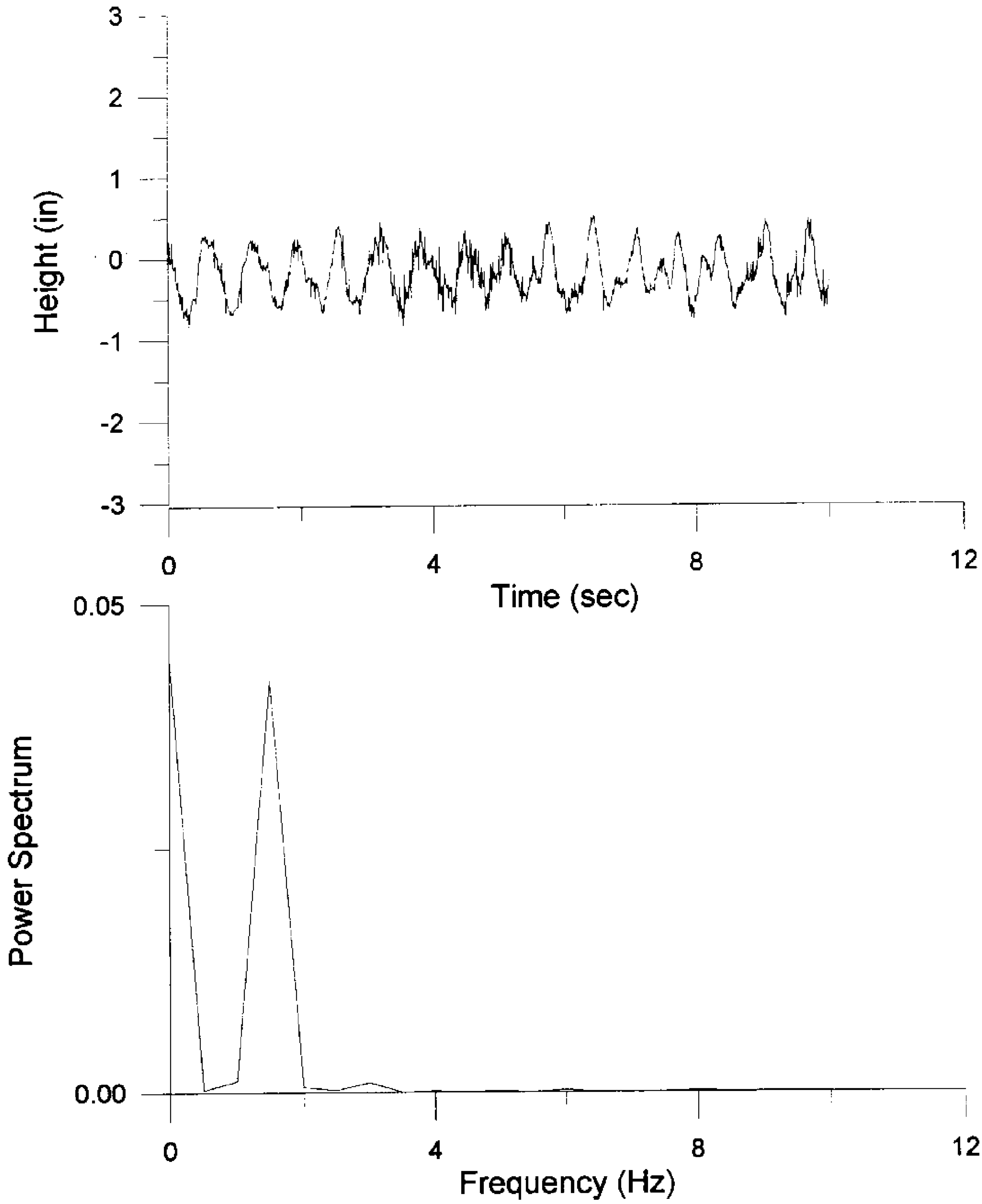
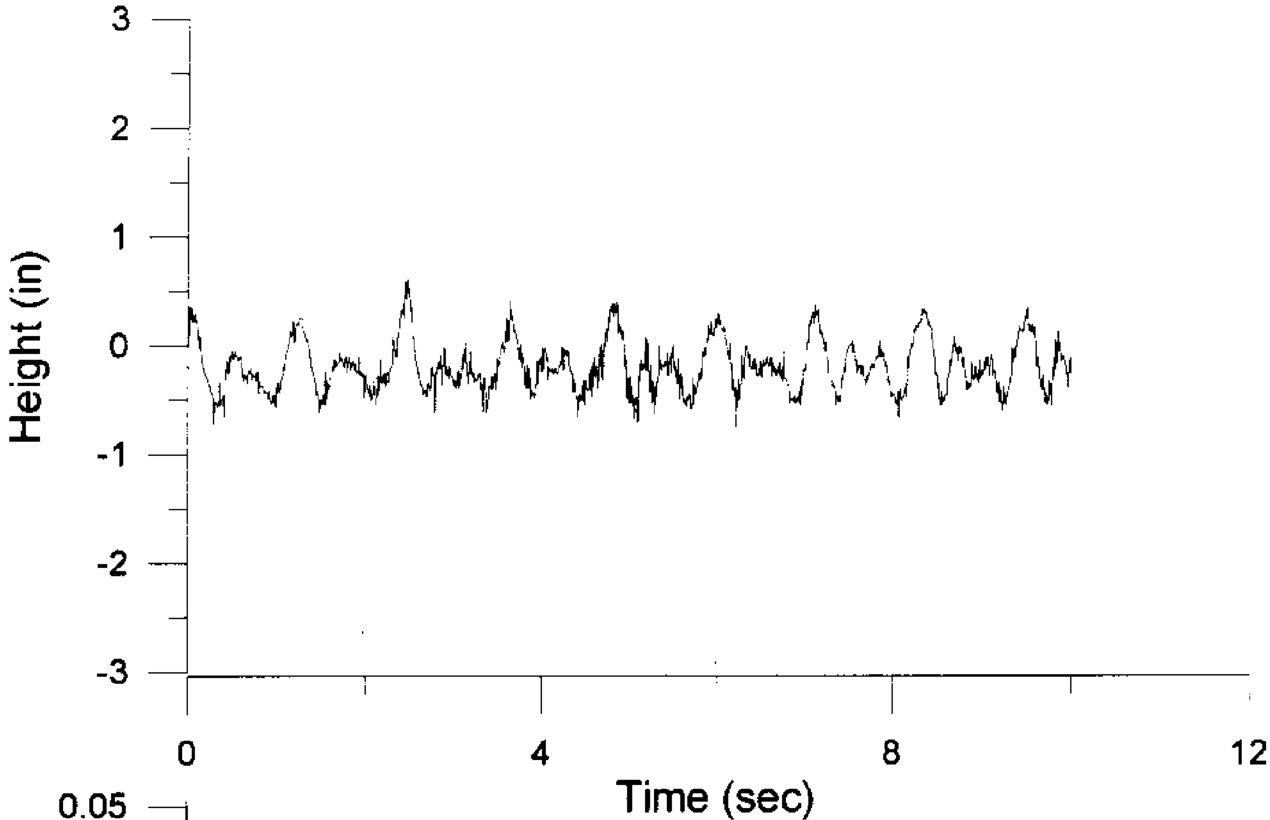


Figure F-35: Plots of wave profile and power spectrum
Radius = 5 inches; flume speed = 0.304 m/sec wave flap
frequency = 1.5 Hz



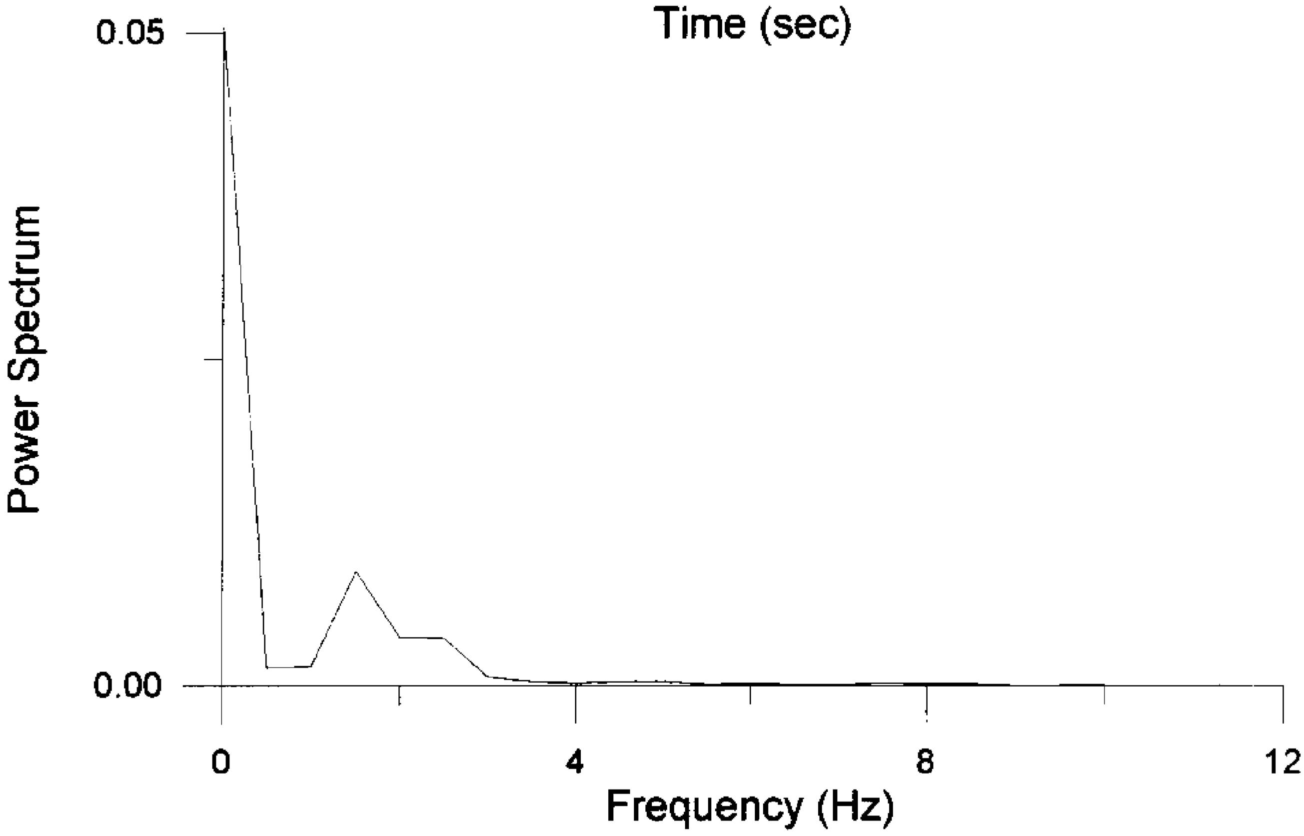
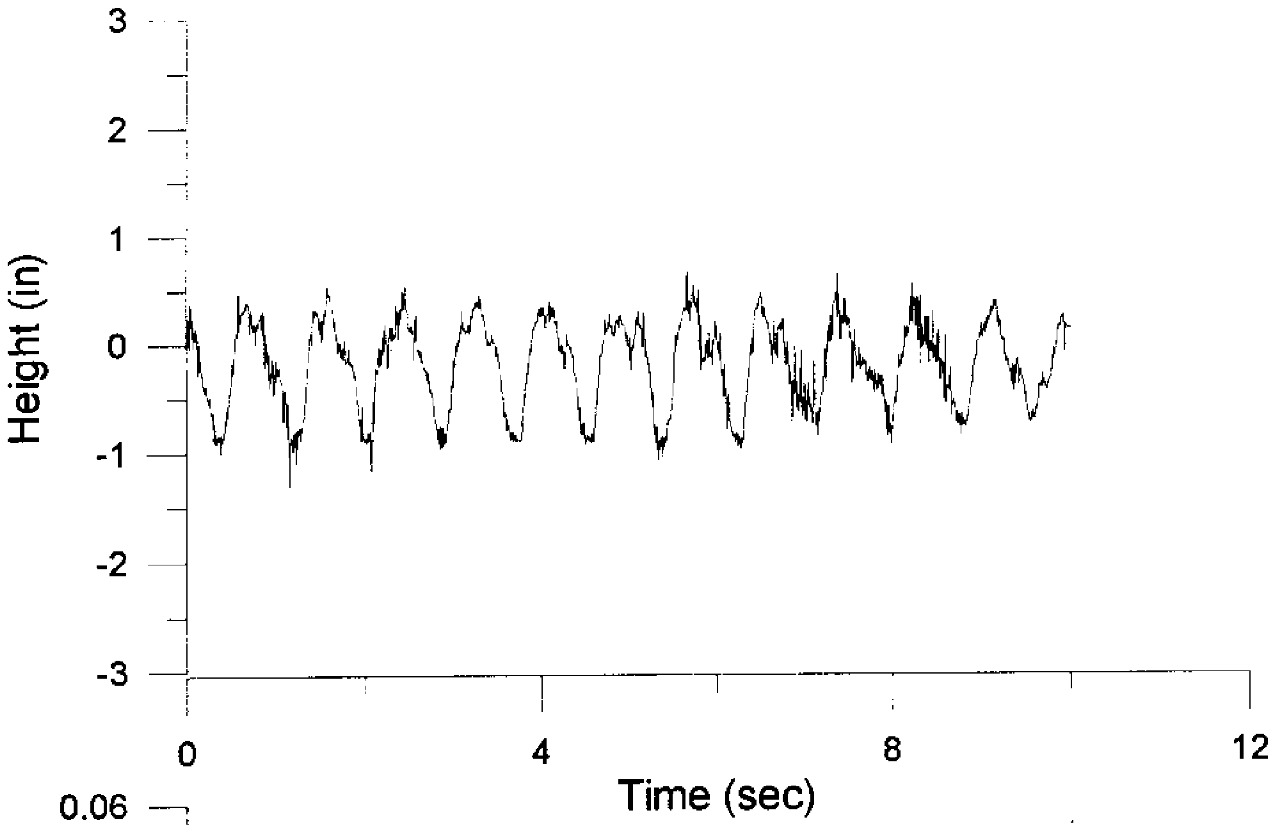


Figure F-36: Plots of wave profile and power spectrum
Radius = 6 inches; flume speed = 0.304 m/sec wave flap frequency = 0.833 Hz



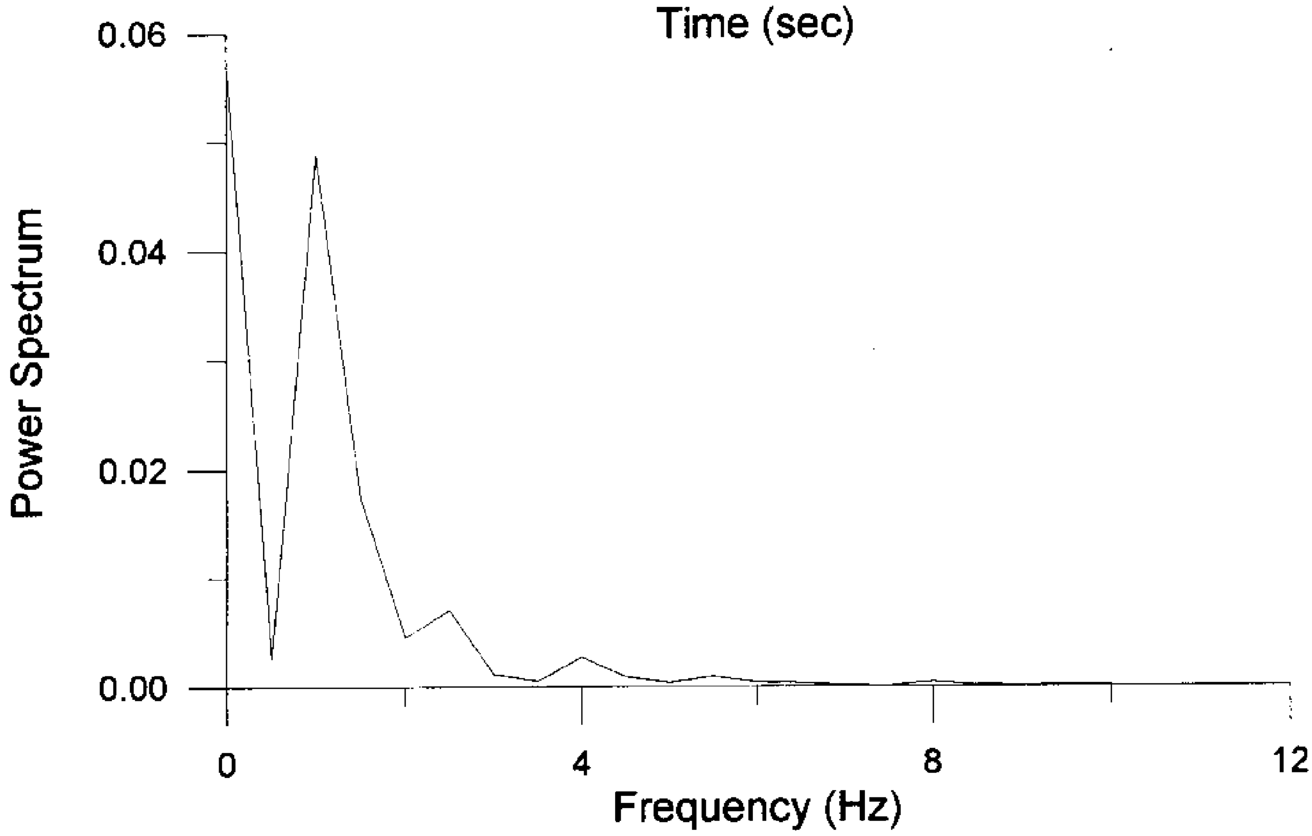


Figure F-37: Plots of wave profile and power spectrum
Radius = 6 inches; flume speed = 0.304 m/sec wave flap
frequency = 1.167 Hz

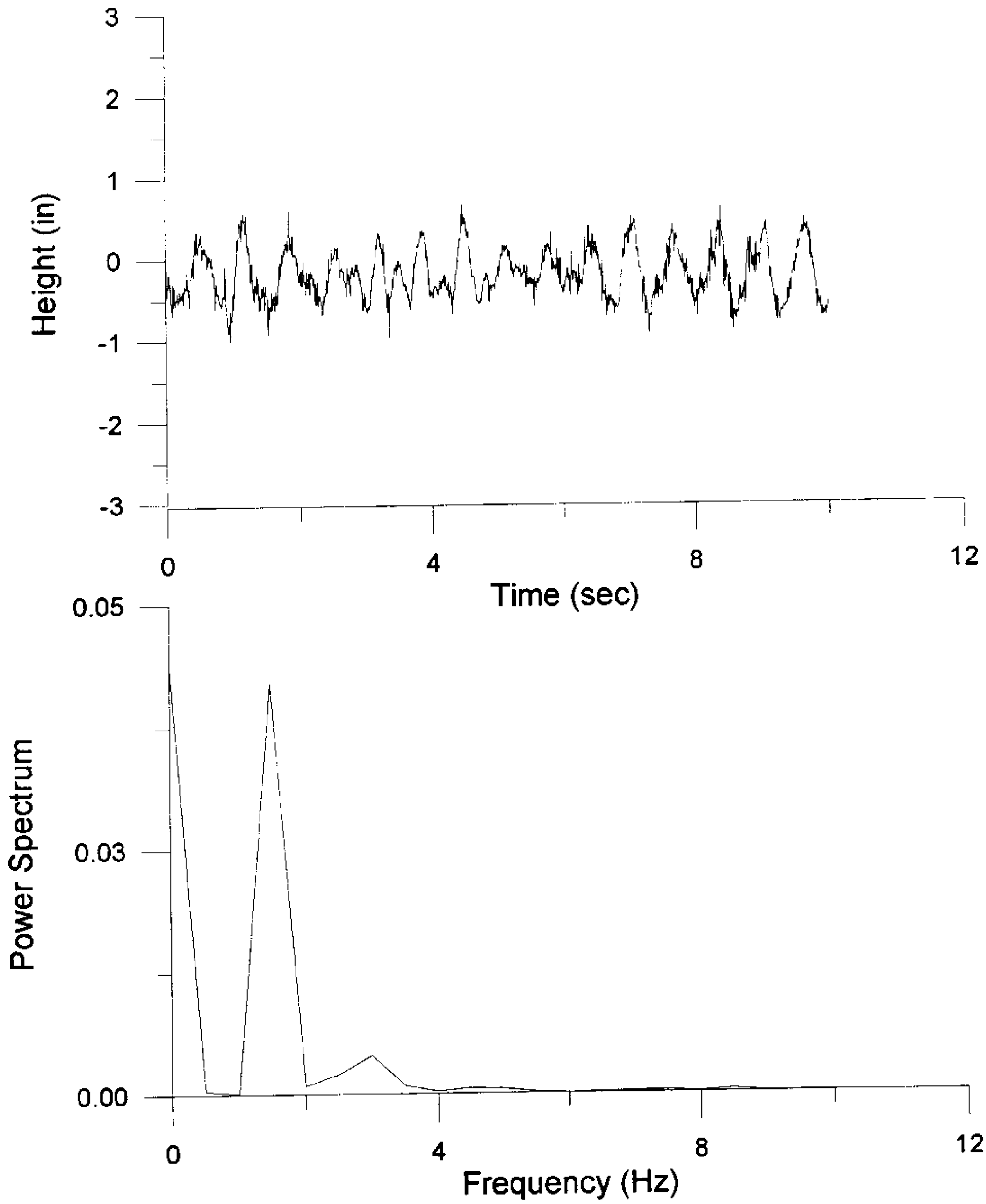


Figure F-38: Plots of wave profile and power spectrum
Radius = 6 inches; flume speed = 0.304 m/sec wave flap
frequency = 1.5 Hz

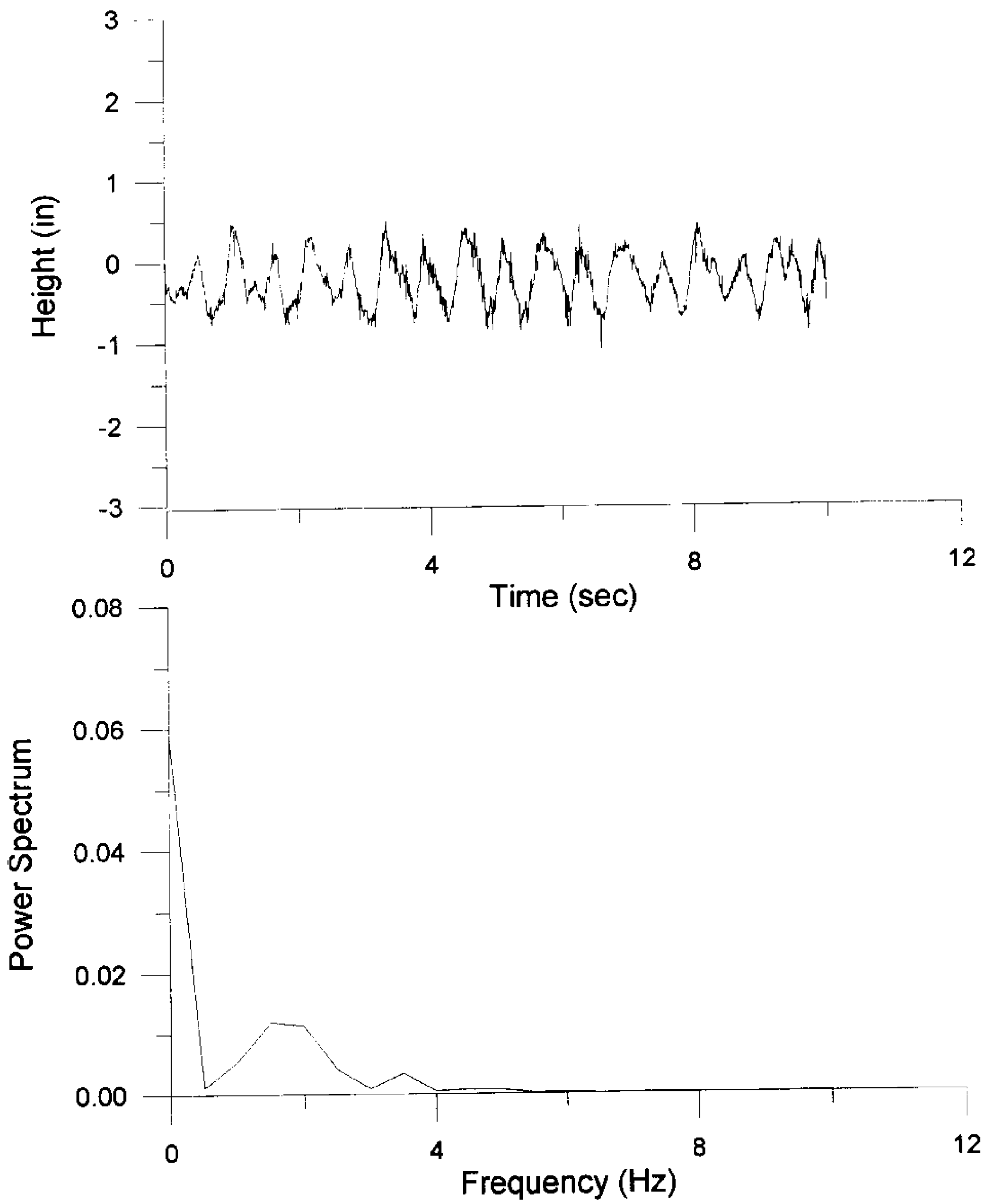


Figure F-39: Plots of wave profile and power spectrum
Radius = 7 inches; flume speed = 0.304 m/sec wave flap frequency = 0.833 Hz

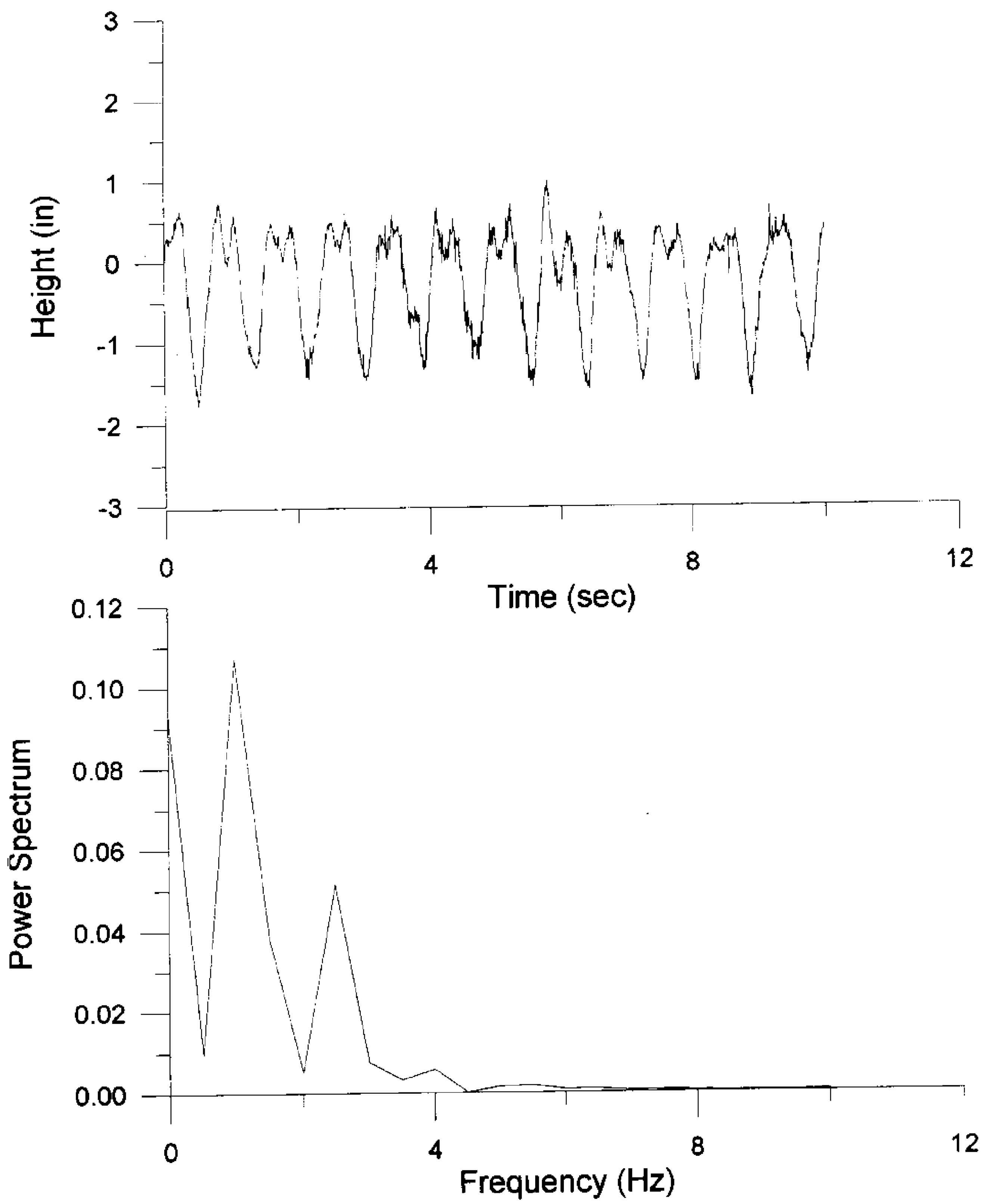


Figure F-40: Plots of wave profile and power spectrum
Radius = 7 inches; flume speed = 0.304 m/sec wave flap
frequency = 1.167 Hz

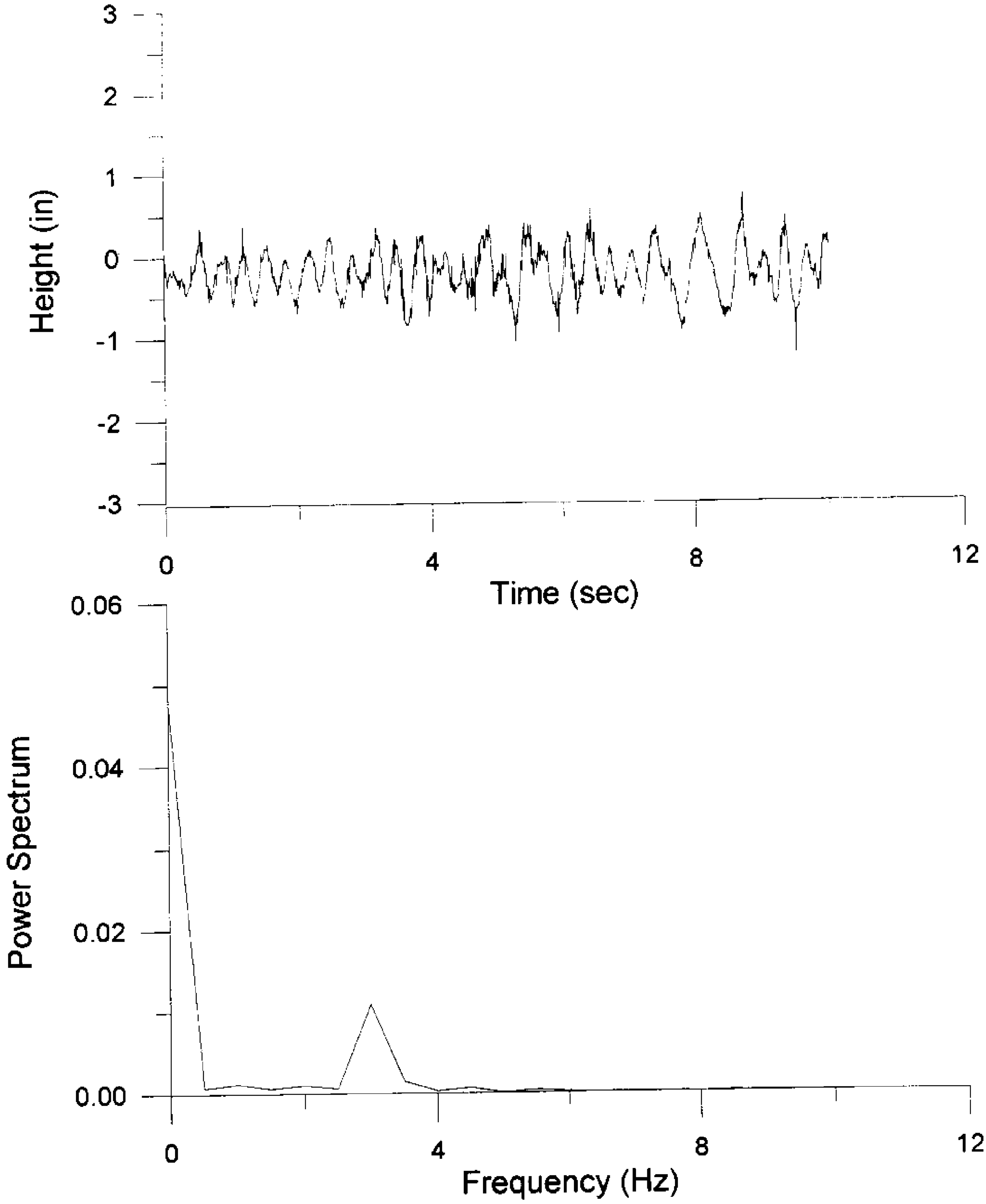


Figure F-41: Plots of wave profile and power spectrum
Radius = 7 inches; flume speed = 0.304 m/sec wave flap
frequency = 1.5 Hz

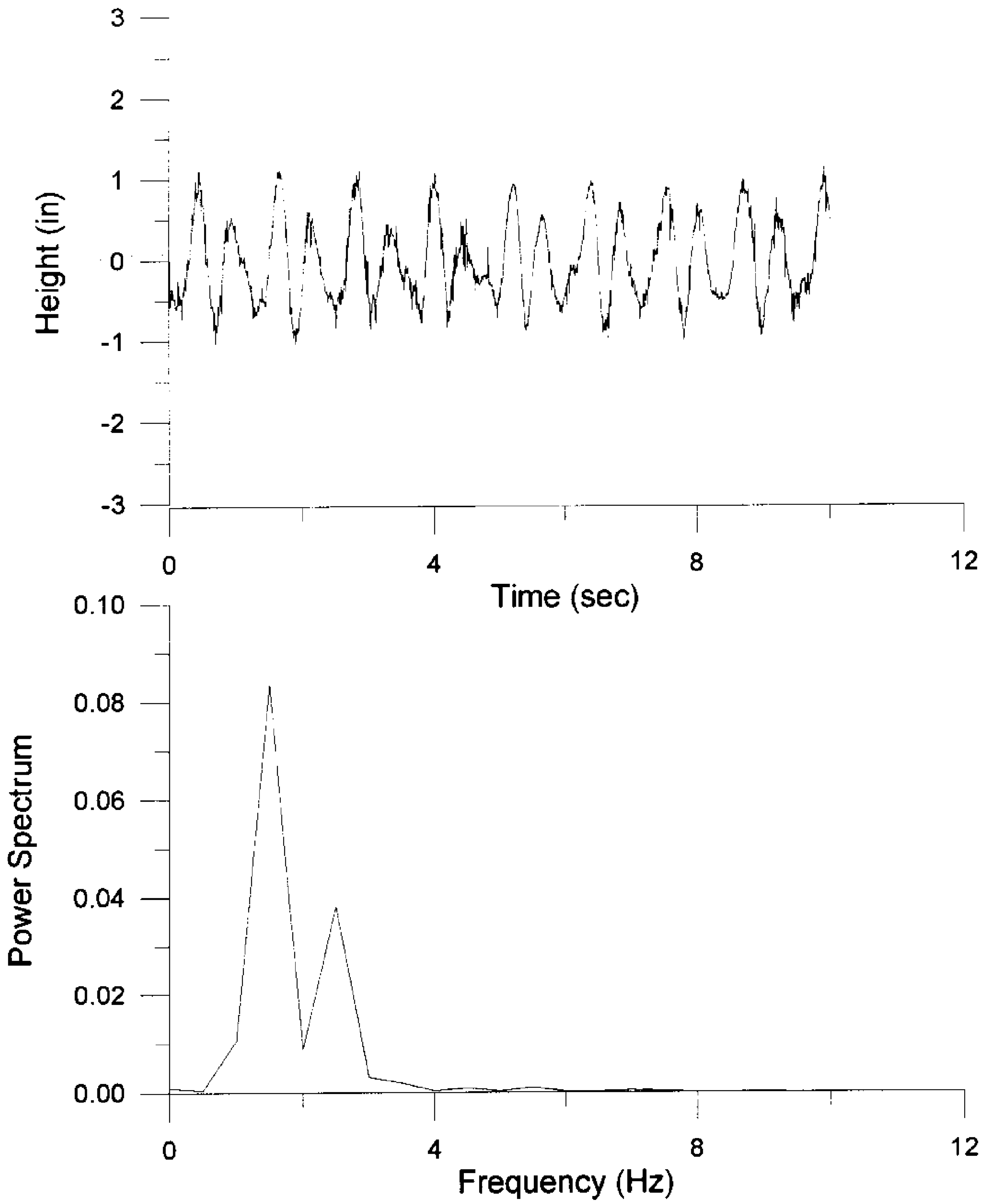
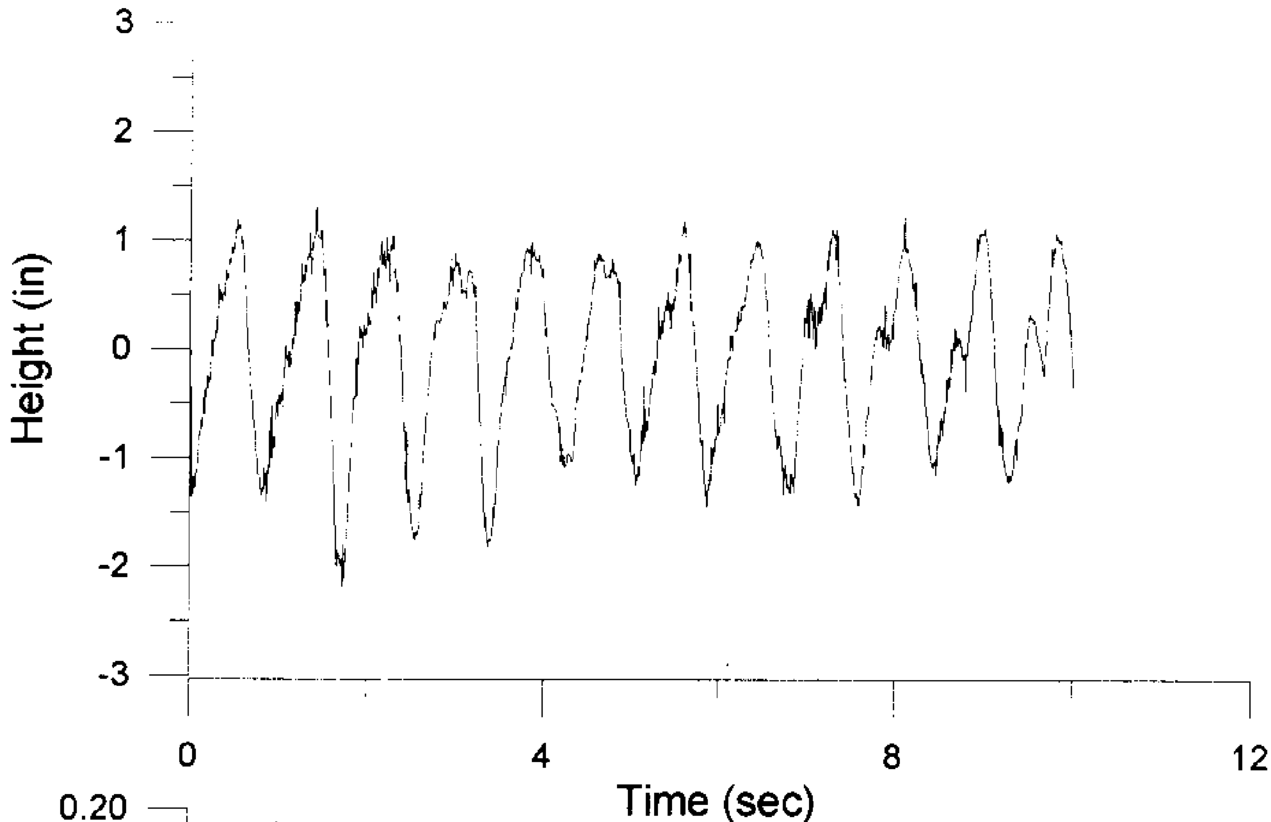


Figure F-42: Plots of wave profile and power spectrum
Radius = 8 inches; flume speed = 0.304 m/sec wave flap
frequency = 0.883 Hz



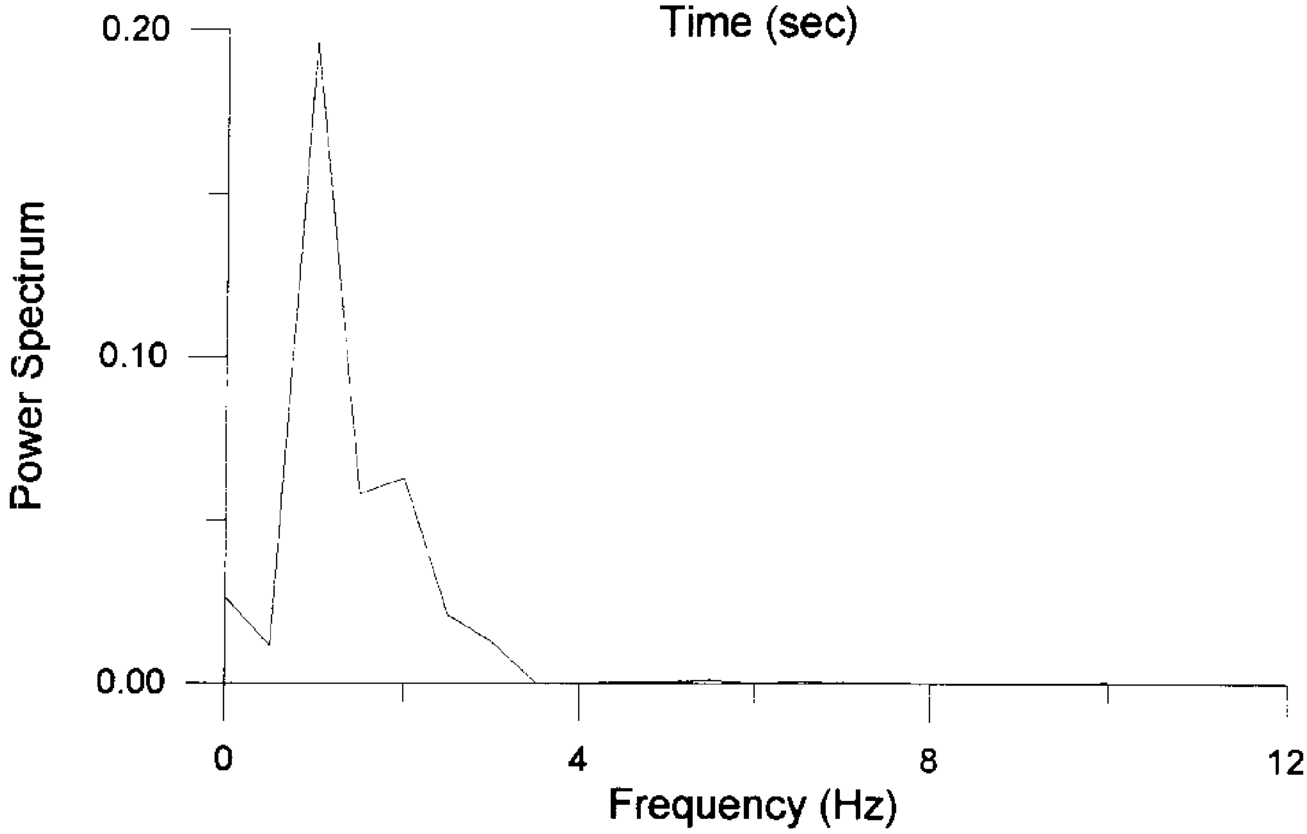


Figure F-43: Plots of wave profile and power spectrum
Radius = 8 inches; flume speed = 0.304 m/sec wave flap frequency = 1.167 Hz

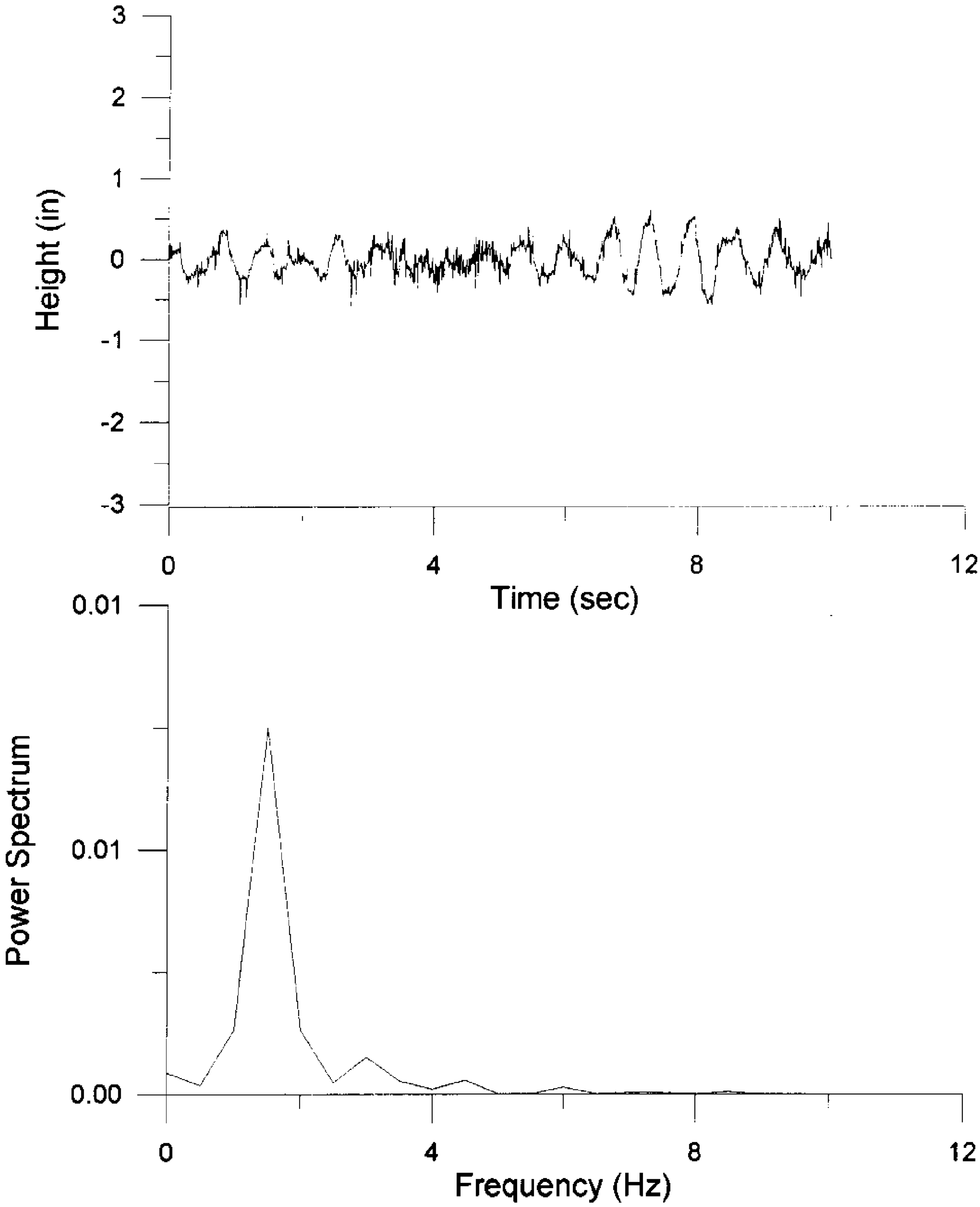


Figure F-44: Plots of wave profile and power spectrum
Radius = 9 inches; flume speed = 0.304 m/sec wave flap frequency = 0.5 Hz

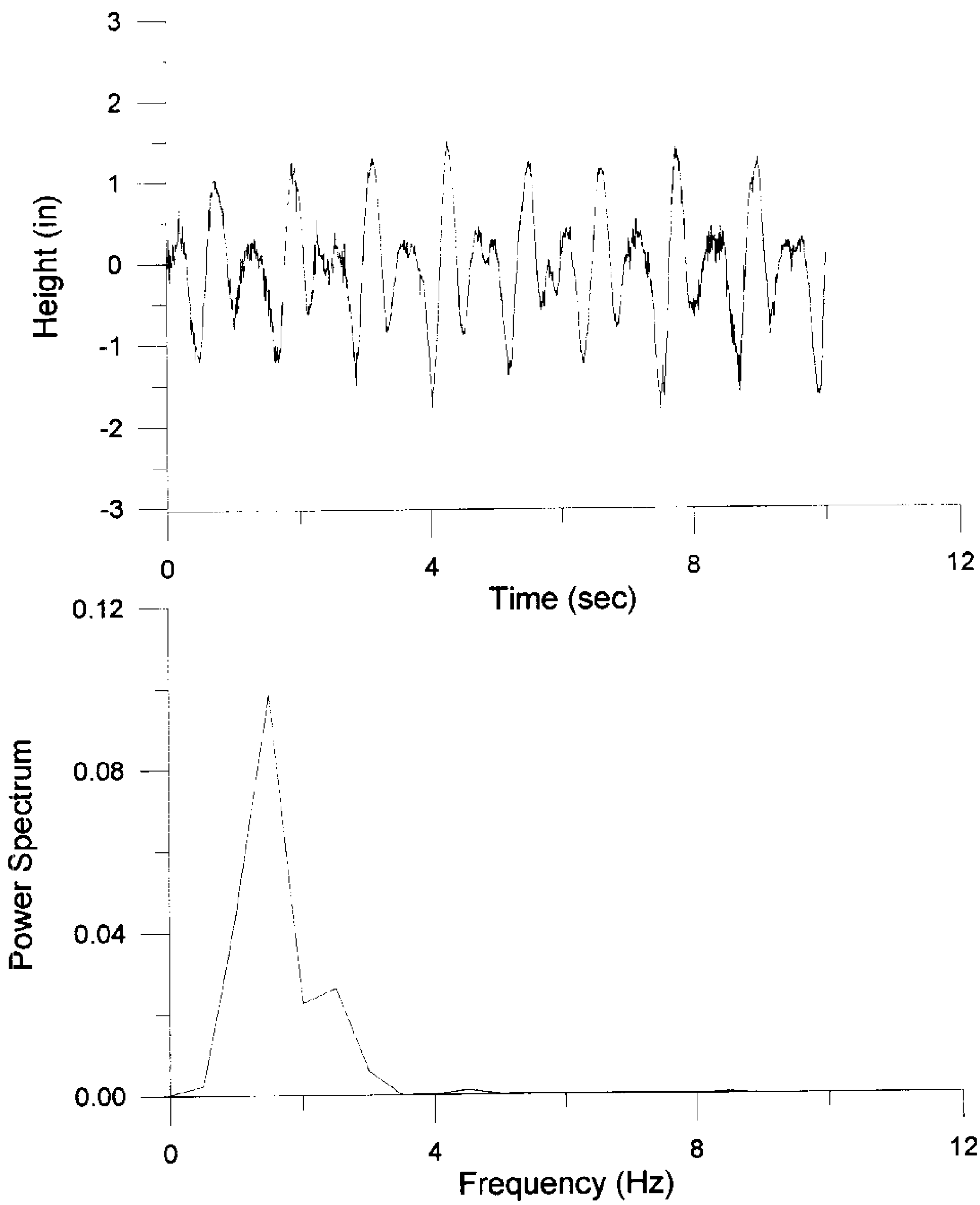


Figure F-45: Plots of wave profile and power spectrum
Radius = 9 inches; flume speed = 0.304 m/sec wave flap frequency = 0.833 Hz

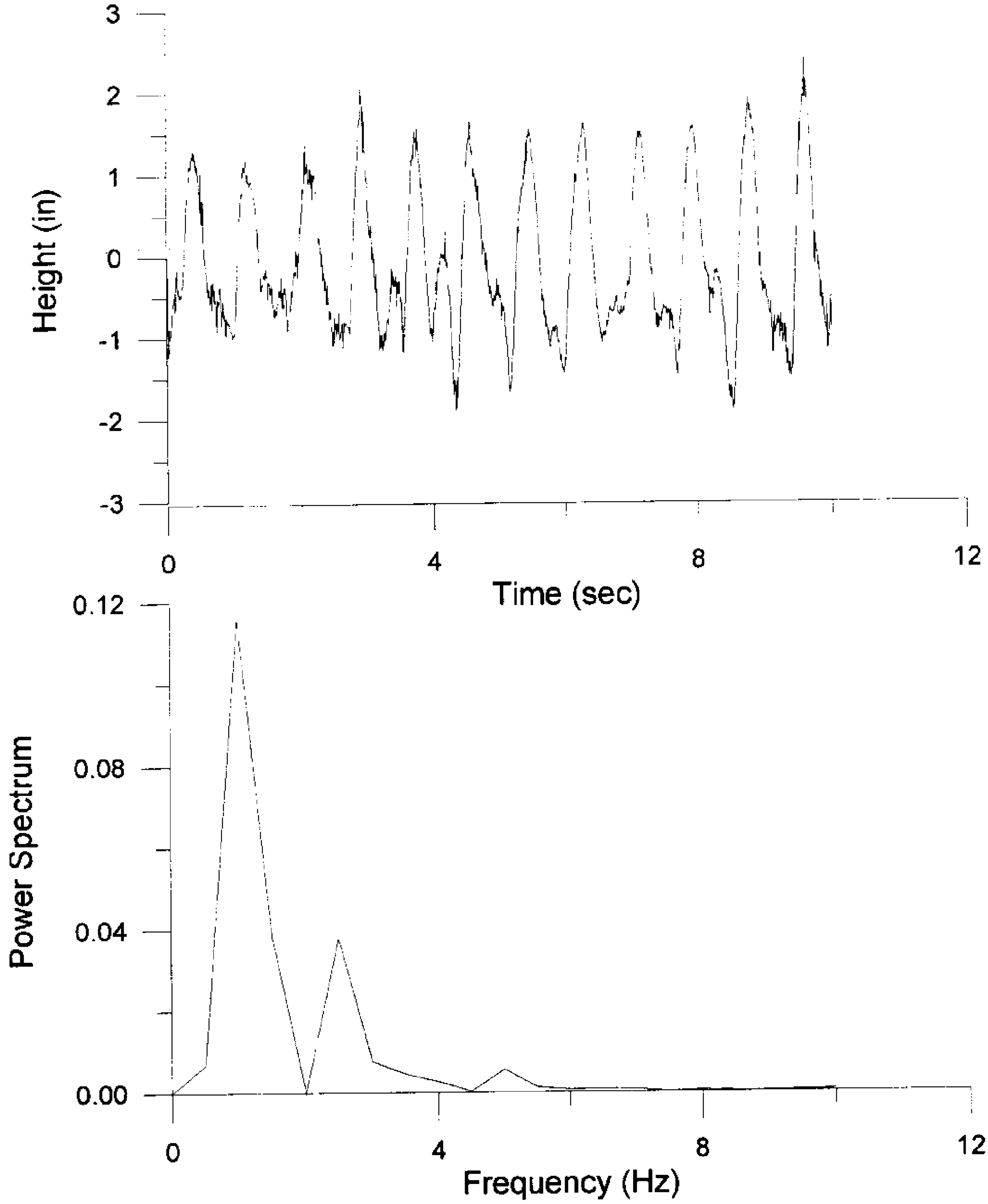


Figure F-46: Plots of wave profile and power spectrum
Radius = 9 inches; flume speed = 0.304 m/sec wave flap
frequency = 1.167 Hz