INTERNAL DAMPING RATES OF CONSTRUCTION CRANES

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Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

IN

CIVIL ENGINEERING

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May 1997

Blacksburg, Virginia

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(ABSTRACT)

The conveyance of payloads by construction cranes generates pendulations of the payload. This research provides a critical design parameter for the development of a device that aids in reduction of these pendulations. Previous research developed a tuned mass damping system, that effectively attenuated the energy of a pendulating payload. In order to be effective the internal damping rate of the tuned mass damper must be at least twice that of the system to be damped. Prototypes of a tuned mass damping system have achieved damping rates between 6 and 12 %, making cranes with damping rates below 3% attractive. This research indicates that the internal damping rate of construction cranes is on the order of one percent, suggesting that a tuned mass damping system could be retrofitted to today's construction cranes.

This thesis is an investigation of the internal damping rates of construction cranes. Three hydraulic and two lattice boom cranes were tested. The motion of pendulating payloads

was modeled after a simple pendulum. The internal damping rate was calculated using logarithmic decrement technique. Light to medium duty cranes were tested with loads similar to those used in duty cycle operations. Damping tests were performed both perpendicular and parallel to the mast of the crane. Values were calculated from data extracted from videos of a payload oscillating over a measurement scale.

A FMC Link Belt 25-ton hydraulic crane was tested at 6.4 % of capacity and displayed damping rates between 0.25 and 0.6 %. A 50-ton FMC Link Belt was tested at 10 % of capacity and had damping rates of 0.18 % for both tests. The third hydraulic crane was a 60-ton P&H T-600XL. The test parallel to the mast was performed at 6 % of capacity having a damping rate of 0.22 %. The test performed perpendicular to the mast was at 3.5 % of capacity with a damping rate of 0.65 %.

Two lattice boom cranes with capacities of 70 and 100 tons were tested. The 70-ton LIMA 778c's damping rates were 0.06 and 1.3 percent. This test was performed at 15 % of capacity. The 100-ton Link Belt LS318 was tested at 6.8 % of capacity and had damping rates between 0.07 and 0.08 percent.

ACKNOWLEGEMENTS

The author would like to thank his committee, family and friends. They have been supportive through out the research process.

Special thanks are extended to the companies who offered their time and construction cranes to this research. All of the companies are located in Roanoke, Virginia. They include IMF Crane & Rigging, Branch Highways Inc., and Branch and Associates.

The National Science Foundations provided the funding for this research.

TABLE OF CONTENTS

1. Introduction 1

1.1 Background 2

1.2 Scope Statement 4

1.3 Objective 5

1.4 Literature Review 6

1.5 Limitations 7

1.6 Methodology 7

1.7 Presentation Of Thesis 8

2. Pendulum Motion 11

2.1 Physics Of The Motion 11

2.2 Characteristics Of A Simple Pendulum 12

2.3 Method For Determining Divergence From Theory 17

2.4 Conclusion 19

3. Internal Damping Rates 20

3.1 Introduction 20

3.2 Types Of Damping 21

3.3 Mathematics That Describe The Damping 23

3.4 Conclusion 27

4. Experimental Design 28

4.1 Factors To Be Determined 28

4.2 Factors Affecting How The Data Is To Be Determined 32

4.3 Testing Methodology 37

4.4 Conclusion 39

5. Experimental Format 41

5.1 Test Number 41

6. Experimentation......52
6.1 Test 1......52
6.2 Test 2......61
6.3 Test 3......69
6.4 Test 4......78
6.5 Test 5......86
7. Summary and Conclusions......97
7.1 Summary......97
7.2 Recommended Uses And Significance......101
7.3 Future Extension......102
7.4 Conclusions......103
8. Bibliography......105
9. Vita......126

LIST OF FIGURES

Figure 1.1 Illustration Of A Tuned Mass Damping System ... 3
Figure 2.1 Model Of A Simple Pendulum ... 15
Figure 4.1 Illustration Of Distances To Be Determined ... 38
Figure 5.1 Illustration Of The Dimensions To Be Determine ... 43
Figure 5.2 Load Chart For A 50-Ton Hydraulic Crane ... 45
Figure 5.3 Example Of A Resonance Curve Generated From The Decay Of A Pendulating Payload ... 48
Figure 5.4 Graph Of Internal Damping Rate Vs. Number Oscillations ... 49
Figure 6.1 Dimensions Of Test 1 ... 54
Figure 6.2 Test 1, Perpendicular - Resonance Curve ... 56
Figure 6.3 Test 1, Perpendicular - Graph Of Internal Damping Rate ... 57
Figure 6.4 Test 1, Parallel - Resonance Curve ... 59
Figure 6.5 Test 1, Parallel - Graph Of Internal Damping Rate ... 60
Figure 6.6 Dimensions Of Test 2 ... 63
Figure 6.7 Test 2, Perpendicular - Resonance Curve ... 65
Figure 6.8 Test 2, Parallel - Graph Of Internal Damping Rate ... 66
Figure 6.9 Test 2, Parallel - Resonance Curve ... 67
Figure 6.10 Test 2, Perpendicular - Graph Of Internal Damping Rate ... 68
Figure 6.11 Test 3 - Dimension Of The Test ... 71
Figure 6.12 Test 3, Perpendicular - Resonance Curve ... 73
Figure 6.13 Test 3, Perpendicular - Graph Of Internal Damping Rate ... 74
Figure 6.14 Test 3, Parallel - Resonance Curve ... 76
Figure 6.15 Test 3, Parallel - Graph Of Internal Damping Rates ... 77
Figure 6.16 Dimensions Of Test 4 ... 80
Figure 6.17 Test 4, Perpendicular - Resonance Curve ... 82
Figure 6.18 Test 4, Perpendicular - Graph Of Internal Damping Rate ... 83

Figure 6.19 Test 4, Parallel - Resonance Curve 84
Figure 6.20 Test 4, Parallel - Graph Of Internal Damping Rate 85
Figure 6.21 Test 5, Perpendicular - Dimensions Of Test 89
Figure 6.22 Test 5, Perpendicular - Resonance Curve 90
Figure 6.23 Test 5, Perpendicular - Graph Of Internal Damping Rate 91
Figure 6.24 Test 5, Parallel - Dimensions Of Test 93
Figure 6.25 Test 5, Parallel - Resonance Curve 94
Figure 6.26 Test 5, Parallel - Graph Of Internal Damping Rate 95
Figure 7.1 Results Of Perpendicular Experiments 99
Figure 7.2 Results Of Parallel Experiments 100
Figure 7.3 Truth Plot 101

LIST OF TABLES

Table 6-1: Test Numbers With Type Of Crane And Percentage Of Capacity.................. 52
Table 6-2 Results Of Test 1 61
Table 6-3 Results Of Test 2 69
Table 6-4 Results Of Test 3 78
Table 6-5 Results Of Test 4 86
Table 6-6 Results Of Test 5 96

1. Introduction

Efficient material handling is a universal desire within the construction industry. The advent of the crane has dramatically increased our ability to handle materials. Technological breakthroughs have created a large variety of function-specific cranes, including the tower, mobile, container, and overhead. We can mine, refine, ship, manufacture, and construct more rapidly as a result of the crane.

Regardless of any crane's specific design, the physics of a load suspended from a cable introduces an inherent problem: payload pendulations. The movement of a construction crane or gust of wind, may excite a suspended payload into oscillations, called pendulations. These pendulations result in direct loss, the cost of which is realized by lost performance: delays to critically linked activities; damage to materials; and liability associated with accidents. A search for methods to combat this pendulation problem begins with a study of other industries.

The shipping and manufacturing industries perform many lifting cycles that require the accurate and efficient conveyance of numerous similar loads. Due to the massive quantities and similarity of the loads, productivity can be dramatically increased by minor improvements in each cycle. The relatively controlled environment and the similarity of the loads existent in these4 industries has allowed them to invest in damping technologies, such as computer optimization of crane control paths (Hubble, et al., 1992; Ridout, 1989; Virkkunen, et al., 1990). These types of technologies have ultimately increased both production and safety.

On construction sites, all types, sizes, and shapes of materials must be efficiently and accurately conveyed over a changing site to a variety of places. This conveyance occurs in varying environments. To apply the damping technology that other industries have employed, many conditions must be known. The dynamic nature of construction sites -- constantly changing loads and an unpredictable environment -- presents too many unknowns for the application of current damping methods. As a result the only methods currently being used to combat payload pendulation are operator control and the use of tag lines. The construction industry needs the benefits of damping technologies.

1.1 Background

Virginia Polytechnic Institute and State University initiated research to develop a method for controlling payload pendulations on construction sites. Previous work will be briefly discussed to develop a baseline of understanding. With this foundation, the rationale for the current research will be presented, and objectives stated.

1.1.1 Previous Research: A Dynamic Damping Device For Payload Pendulations Of Construction Cranes

This research began with a theoretical analysis of a construction crane's payload pendulation problem. Researchers then developed a strategy for attenuating the energy associated with the pendulations. The research culminated with physical experimentation, which proved that a tuned mass damper is capable of attenuating the energy of the pendulating payload (Figure 1.1).

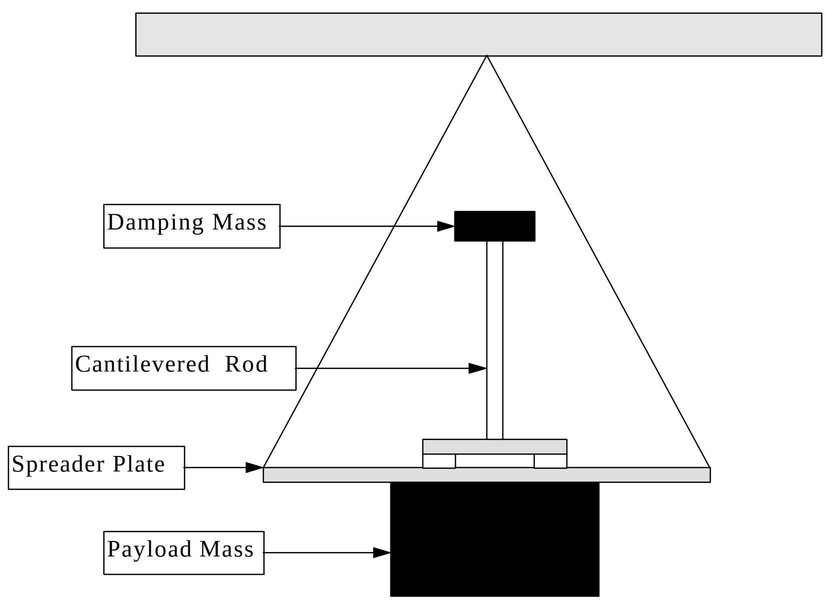

Figure 1.1 Illustration Of A Tuned Mass Damping System

The damping mass at the top of the cantilevered rod is positioned, or tuned, such that it has the same frequency as the oscillating payload. Any disturbances sufficient to initiate pendulation of the payload will also activate the tuned mass damper, which becomes directly out of phase with the payload and damps out the motion. This research proved that tuned mass damping is capable of significantly reducing pendulation of payloads.

There were many findings in route to achieving tuned mass damping. Most critical to the pursuit of developing a dynamic damping device was realizing the significance of internal damping rates. An internal damping rate is fundamentally defined as the rate at which the mechanical energy associated with a motion is lost. The faster the motion ceases, the greater the internal damping rate. In earlier experiments, tuned mass damping was not achieved because the internal damping rate of the scaled crane model was greater than that of the tuned mass damper. An increased knowledge base was gained from these experiments.

It was learned that the internal damping rate of a tuned mass damper must be at least twice that of the system that it is intended to damp. The relevance of this experiment to future research is great: if a tuned mass damping system is to be designed for a construction crane, then the internal damping rate of the construction crane must be determined. It is a critical design parameter.

1.2 Scope Statement

This thesis present an analysis of the pendulum motion of a payload suspended from a construction crane. The motion is classified, and a method for empirically determining the internal damping coefficient stated. A methodology is developed for the testing of the internal damping rates, and five construction cranes were tested. The results are analyzed, conclusions stated, and future extensions of the research offered.

1.3 Objective

It is the objective of this research to perform an investigation of the internal damping coefficients of construction cranes. This objective was achieved through a series of activities.

First, the theory required to design a test is developed. The internal damping rate of a system is dependent upon the type of motion and the type of damping. The motion has been quantified, and the physics that describe this motion identified. The assumptions necessary to model a pendulating payload are listed. Next, the types of damping offered by construction crane were identified, and a method for their quantification presented.

Experimental design is divided into two sections. The first section presents the information required to calculate the internal damping rate of construction cranes. This includes the types of cranes and payloads that should be tested, and the variables that must be experimentally determined. The succeeding section introduces the factors that impact how the data is to be captured. These issues include the accuracy that the research must return, time limitations imposed by the owner of the crane, and additional data that allows for experimental analysis and comparison. A method for experimentally capturing the data is offered.

The next phase of the research is the performance of the experiments. The results of each test conclusions are drawn, and recommendation for future work offered.

Ultimately, these results support research on low-frequency tuned mass dampers by providing a critical design parameter, the internal damping rate of construction cranes. The determination of the internal damping rate is a critical step toward realizing the safe and efficient material handling that tuned mass damping can provide to today's construction sites.

1.4 Literature Review

A literature review was performed and no information concerning the internal damping rate of construction cranes was discovered. This research is considered an initial investigation into the internal damping rate of construction cranes.

1.5 Limitations

This research has two portions, the development and the performance of a test to determine the internal damping rate of construction cranes. This research relies on many assumptions in modeling the motion of a pendulating payload. Issues such as secondary pendulations or rotation of the payload were not modeled. An experiment is developed based upon a list of assumptions to determine the internal damping rate under normal operating conditions.

Experiments were performed on five construction cranes to determine general information concerning damping coefficients. These five construction cranes do not represent all types of cranes. The cranes were not tested at near maximum capacities. This is consistent with the use of cranes on duty cycle work that is the intended area of maximum benefit expected by this research.

1.6 Methodology

A number of tasks were performed in the research process. These tasks are divided into a literature review, experimental design, physical experimentation, and performance evaluation. The results are incorporated into the thesis in a narrative format and are accompanied by relevant data and graphics to assist in visualization.

1. The research begins with a brief discussion of previous research. This discussion provides background and establishes the basis for the new research.
2. The motion of a pendulating payload is classified and described mathematically.
3. The types of damping present in a construction crane are investigated, and the mathematics that describes the damping stated.
4. The types of cranes and payloads to be tested are established and the parameters that must be experimentally determined are stated.
5. Factors affecting how to experimentally capture the data are presented. A testing methodology is developed.
6. Five construction cranes were tested.
7. The experimental data reduced and the internal damping rate calculated.
8. The results from all of the testing are compared and conclusions stated. Recommendations for future work are offered.

1.7 Presentation Of Thesis

This thesis presents the results of an investigation into the internal damping rates of construction cranes. Theory is incorporated into the creation of a test that determines the internal damping rate.

Chapter 2 - Pendulum motion

This chapter presents the motion of a pendulating payload and a simple pendulum. Assumptions that must be made to analyze a pendulation payload as a simple pendulum are stated. These assumptions act as the constraints of the experiments.

Chapter 3 -Internal Damping Rates

Internal damping rates are defined. The type of damping that a construction crane offers a pendulating payload are identified. The type of damping dictates the appropriate mathematics to calculate the internal damping rate of construction cranes.

Chapter 4 - Experimental Design

The types of cranes and payloads to be tested are established. Next, the variables that must be experimentally determined are stated. The following section of this chapter presents the issues that impact how to perform the experimentation. A testing methodology is developed, and the rational for its selection stated.

Chapter 5 - Experimental Format

This chapter introduces the format in which the experiments are presented. Each sub-section defines the issues that the section aims to communicate.

Chapter 6 - Tests

A narrative of the tests is given. Graphs and illustrations are given where relevant.

Chapter 7 - Summary and Conclusions

Thesis conclusions are presented and evaluated. A review of the research and its significance is provided.

2. Pendulum Motion

The method by which the internal damping rate of a system is determined is directly dependent upon the type of motion. The pendulum-like motion of an oscillating payload is analyzed as a simple pendulum. The characteristics of a simple pendulum are stated and compared to the actual motion of a pendulating payload. The assumptions required to model a pendulating payload as a simple pendulum are stated.

2.1 Physics Of The Motion

When an undisturbed payload is suspended from a crane, it resides at its stable equilibrium, vertically beneath the tip of the boom. A perturbation, such as movement of the crane or a gust of wind, provides a form of kinetic energy, which displaces the payload radially from its stable equilibrium. As the payload moves from its lowest position, it gains potential energy in the form of vertical displacement. This continues until all of the kinetic energy has been transformed into potential energy, and the payload achieves an oscillation peak.

Next, conservation of mechanical energy forces the displaced payload to reduce its potential energy by swinging to its lowest position. This motion provides the payload with momentum, which carries the payload to an oscillation peak on the opposite side of the stable equilibrium. The pendulum-like motion will continue as an oscillation or vibration, with a measurable frequency, f. Various damping forces acting on the system will gradually reduce the magnitude of the oscillation peaks, eventually stopping the motion.

2.2 Characteristics Of A Simple Pendulum

Many conditions are required to mathematically describe the motion of a simple pendulum. These conditions are listed and then contrasted with the actual conditions provided by construction cranes.

2.2.1 The Support Structure Of The Pendulum Is Static

In a mathematical analysis of a simple pendulum, it is assumed that the support structure of the pendulum does not move. The pendulum rotates about a static pivot point. Motion of the pivot point creates an effective pivot point, the location of which differs from the actual pivot point. This alters the effective length of the pendulum, and alters the frequency. Therefore, if there is motion of the pivot point, the mathematics that describe a simple pendulum will differ from the actual motion.

Construction cranes do not provide a perfectly static pivot point. All materials that bear the weight of the payload will deform under load. The ground beneath the crane will also deform when loaded. The cumulative effect of material deformation and play within load bearing joints is seen through movement of the pivot point, as this is where the forces are applied. Therefore, the support structure of a pendulating payload will not remain static.

The cable that attaches the payload to the pivot point is also a portion of the pendulums support system. The cable is assumed to be rigid and have no mass. For the case of a construction crane the woven steel wire that suspends the payload deforms and has mass. The deformations of the cable should be small for the test payloads. The mass of the cable should be negligible in comparison with the mass of the payload. Regardless, the actual conditions differ from theory.

2.2.2 The Pendulum Has A Stable Equilibrium

Stability is defined in terms of a body's relationship with an equilibrium position. There are three potential states of stability: neutral, stable, and unstable. The system is classified by its reaction to a displacement.

1. A neutral system will remain in its displaced state.
2. A stable equilibrium exists if the body returns to the original equilibrium position.
3. An unstable equilibrium exists if the body moves away from the equilibrium position.

The mathematics that model pendulum motion assumes that the test system has a stable equilibrium. The stable equilibrium is the point vertically beneath the pivot of the pendulum. This is where the oscillations are centered, with oscillation peaks occurring on either side of the stable equilibrium. If a stable equilibrium does not exist, measurements of the magnitude of oscillation peaks will be erroneous.

Construction cranes are made from materials that deform when loaded. The forces of the pendulating payload are applied to the tip of the boom. Due to material deformations and play within the load bearing joints, the tip of the boom may move. If this occurs the location of the stable equilibrium will be altered.

2.2.3 The Angle Of Pendulation Does Not Exceed 15 Degrees

As the angle, ϕ (fig. 2.1), of displacement approaches, or exceeds 15 degrees, the motion becomes nonlinear, and the methods for mathematically modeling the situation become more difficult. Following is a diagram and the mathematics that describe the motion of a simple pendulum.

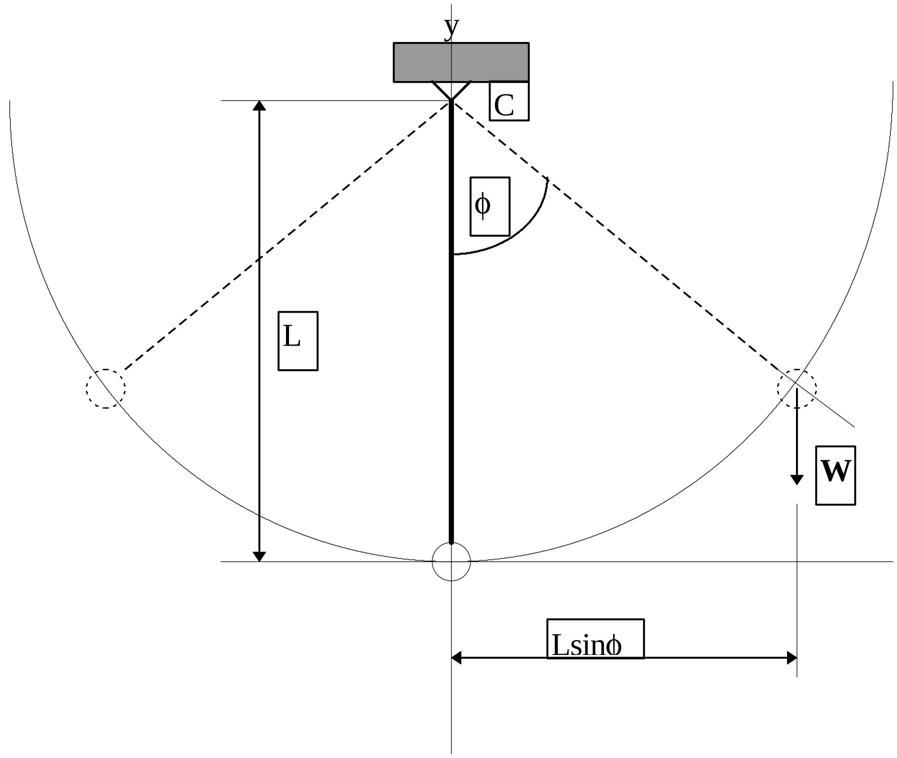

Figure 2.1 Model Of A Simple Pendulum

In Figure 2.1, L represents the length of the cable, W is the weight of the payload, C is the pivot point about which the pendulum oscillates, and ϕ represents the angle of displacement from vertical.

The motion of a simple pendulum is an example of geometric nonlinearity. In a position displaced by the angle ϕ from the vertical, the pendulum has a restoring moment about the pivot point C equal to $WL\sin\phi$. Thus, the equation for rotational motion about the pivot becomes

$$I\ddot{\phi} + WL\sin\phi = 0 \tag{2.1}$$

Substituting into this expression $I = WL^2/g$ for the mass moment of inertia, we have

$$\ddot{\phi} = -\frac{g}{L}\sin\phi = 0 \tag{2.2}$$

For small amplitudes, ϕ less than 15 degrees, $\sin\phi$ is approximately equal to the angle ϕ and can be considered as simple harmonic motion. If the amplitude is not small, the restoring moment is proportional to $\sin\phi$, which can be approximated by a power series. Substitution of the first two terms of the series into equation 2.2 gives

$$\ddot{\phi} + \frac{g}{L}\left(\phi - \frac{\phi^3}{6}\right) = 0 \tag{2.3}$$

In this case we see that the slope of the curve for restoring moment versus ϕ decreases as the rotation increases; so the frequency of oscillation decreases with amplitude. Therefore the system is nonlinear due to geometric consideration for large displacements (Timoshenko, 1974).

The angle of pendulation of payloads, on construction sites, should never approach 15 degrees. No pendulations were initiated during testing that exceeded 15 degrees.

2.2.4 There Is No Damping In The System

To achieve a pendulum system that behaves as the mathematics of a simple pendulum describes, there can be no damping. The static pivot point must provide frictionless rotation. The pendulum must also oscillate in a vacuum to prevent coupling with air. The rigid cable that attaches the load to the pivot point has no mass. If all of these assumptions are valid, the simple pendulum will continue to oscillate as mathematics describe.

Construction cranes provide damping to the motion of pendulating payloads. This research aims to quantify this damping. The different types of damping are presented in Chapter 3.

2.3 Method For Determining Divergence From Theory

Divergence from the first two conditions, static support structure and stable equilibrium, can be identified by examining the frequency of the pendulating payload. Divergence from these conditions will result in an actual frequency that differs from the frequency of a simple pendulum with the same cable length.

2.3.1 The Support Structure Of The Pendulum Is Static

A pendulating payload applies vertical and horizontal loads to the tip of the boom. These forces are opposed by equal and opposite forces provided by the ground and damping within the crane. Material deformation and play within load bearing joints results in movement of all load bearing materials and joints. The cumulative effect of these movements is seen through movement of the pivot point of the pendulum, as this is the location where the loads are applied. The result is an effective pivot point the location of which differs from the location the actual pivot point. This virtual pivot point produces an effective cable length that is different from the actual cable length.

The frequency of a simple pendulum, *f*, is dependent upon the length of cable (Lindeburg, 1992).

$$f = \frac{1}{2p}\sqrt{\frac{g}{L}} \tag{2.4}$$

where g is the acceleration due to gravity, and L is the length of the cable. If extensive deformation of the pendulums support structure occurs, the resulting effective cable length will differ from reality, yielding a frequency that differs from that of a simple pendulum. A comparison between the frequency of a pendulating payload and a simple pendulum indicates divergence from theory.

2.3.2 The Pendulum Has A Stable Equilibrium

An undisturbed payload resides vertically beneath the tip of the mast, defining the equilibrium position. If the tip of the mast moves as a result of the forces applied by the pendulating payload, then the equilibrium position is not stable. Comparing the actual frequency with the frequency of a simple pendulum indicates movement of the tip of the mast, which indicates an unstable equilibrium position. This comparison is made as part of the analysis.

2.4 Conclusion

The internal damping rate of a system is dependent upon both the type of motion and damping. This chapter determines that the motion of a pendulating payload can be analyzed as a simple pendulum if the following three assumption are made:

1. The support structure of the pendulum is static.
2. Construction cranes provide a stable equilibrium to the payload.
3. The angle of pendulation does not exceed 15 degrees.

These assumptions are viewed as constraints for experimentation. If they are violated, the theory that is employed to model a pendulation payload is not valid. The next chapter determines the type of damping that a crane offers a payload.

3. Internal Damping Rates

3.1 Introduction

Many complex systems exhibiting harmonic oscillations are the subjects of research; some of these systems include spacecraft, the Earth, suns, globular clusters, galaxies, quantal super strings, nuclei, molecules, buildings, bridges, and construction cranes. All of these complex structures have an equilibrium configuration. It is around this equilibrium configuration that "many-degree-of-freedom" motion occurs. When the payload and cable act as a pendulum, the "many-degree-of-freedom" motion is that of the payload pendulating in any direction with regard to the mast. The equilibrium configuration is the load hanging vertically beneath the tip of the mast.

These "many-degree-of-freedom" motions can often be resolved into many "one-degree-of-freedom" motions, all of which are simple harmonic oscillators, acting independently of their siblings. In the case of a pendulating payload, all potential pendulations can be resolved into motions either perpendicular or parallel to the mast of the crane. In theory, these simple harmonic oscillators can be combined to represent complex situations; however, when there is damping, these analyses tend to fail. It is the damping that often couples the simple harmonic oscillators, making their motions dependent upon one another. This dependency between the damped, simple harmonic oscillators prevents the accurate combining of these motions into a single complex motion. Regardless, the resolving of a complex system into a set of damped simple harmonic oscillators provides us with a vocabulary for describing the real motion.

A study of payloads pendulating parallel and perpendicular in relation to the mast of the crane should provide good simple harmonic oscillation. These motions are easy to initiate in a test situation, and allow for comparison with other cranes. Although all forms of motion may not be accurately resolved into perpendicular and parallel motion, a study of these motions yields a ‘window’ into the cranes’ damping characteristics.

Fundamentally, a motion is said to be damped when the mechanical energy associated with that motion is lost to it. The damping modulus is measured in terms of the rate of loss of this mechanical energy. The method by which the internal damping rate is determined is dependent upon the type of damping present.

3.2 Types Of Damping

The internal damping rate of a system is dependent upon the type of damping. Damping forces may arise from several different sources, such as friction between dry sliding surfaces, friction between lubricated surfaces, air or fluid resistance, electric damping, internal friction due to imperfect elasticity of materials, etc. (Timoshenko, 1974).

Following is a discussion of three different types of damping.

3.2.1 Viscous Damping

When mechanical systems vibrate in a fluid medium such as air, gas, water, or oil, the resistance offered by the fluid to the moving body causes energy to be dissipated. In viscous damping, the damping force is proportional to the velocity of the vibrating body. For the case of a pendulating payload, coupling with air offers viscous damping.

3.2.2 Coulomb or Dry Friction Damping

Here the damping force are constant in magnitude, but opposite in direction to that of the motion of the vibrating body. Dry friction damping is caused by friction between rubbing surfaces that are either dry or have insufficient lubrication. Cranes have many joints that bear the weight of the payload, each providing a source of Coulombic friction.

3.2.3 Material or Solid or Hysteretic Damping

When materials are deformed, energy is absorbed and dissipated by the material. This form of damping is due to friction between the internal planes, which slip or slide as the deformations take place. All materials on the crane bearing the mass of the payload will experience hysteretic damping (Rao, 1995).

The damping that a construction cranes provides to a pendulation payload is a combination of viscous, Coulombic, and hysteretic damping. It would be difficult to determine the proportion of damping that each form of damping contributes. Among all these sources of energy dissipation, the case where the damping force is proportional to velocity -- viscous damping -- is the simplest to deal with mathematically. For this reason, resisting forces of a complicated nature are very often replaced for purposes of analysis by equivalent viscous damping.

3.3 Mathematics That Describe The Damping

Damping due to internal friction can be replaced by an equivalent viscous damping force. This equivalent damping is determined in such a manner as to produce the same dissipation of energy per cycle as that produced by the actual resisting forces. (Timoshenko, 1974)

The direct method for determining the damping of a viscously damped system is with the logarithmic decrement equation. (Nashif, Jones, and Henderson, 1985).

$$\xi = \frac{\ln \frac{(x(t))}{(x(t+nt))}}{2\pi N} \qquad (3.1)$$

In the equation, x(t) represents the first oscillation peak over the defined number of peaks (N) in the sample. The value x(t + nt) corresponds to the oscillation peak at the N’th peak.

This logarithmic decrement equation has been in use since before the turn of the century and has been extensively verified. History has shown that the equation is subject to an error if there is an error in the "zero reference." For example, first suppose that the actual zero position is at "+0.00 inch" (i.e., there is no error larger than 0.00 inches in measuring the "zero position") and suppose your measurements are

x1 = +13.57

x2 = -12.28

x3 = +11.11

x4 = -10.05 etc.

where the values x1, x2, x3 and x4 represent the maximum displacement of an oscillation peak. The first oscillation peaked at 13.57 feet to the right of the equilibrium position, the second peak was at 12.28 feet to the left, etc.

Then the logarithmic decrement $d(x_1 x_2) = \ln \frac{x(t)}{x(t+nt)}$

d12 = ln (| +13.57 in / -12.28 in |) = 0.100

d23 = ln (| -12.28 in / +11.11 in |) = 0.100

d34 = ln (| +11.11 in / -10.05 in |) = 0.100 etc.

Now suppose that the actual zero position is at "+0.50 inch" (i.e., there is an error of 0.50 inches in the "zero reference"). In the case of a construction crane, imagine that the mast of the crane moves slightly and now the payload will come to rest 0.50 inches to the right of its original position.

Then the same positions would be recorded as

x1' = +14.07	(+13.57 + 0.5 = +14.07)
x2' = -11.78	(-12.28 + 0.5 = -11.78)
x3' = +11.61	(+11.11 + 0.5 = +11.61)
x4' = -9.56 etc.	(-10.05 + 0.5 = -9.56)

and this would introduce a serious irregularity into the computed values of the log-decs:

d12' = ln (| +14.07 in / -11.78 in |) = 0.178

d23' = ln (| -11.78 in / +11.61 in |) = 0.015

d34' = ln (| +11.61 in / -9.56 in |) = 0.194 etc.

Indeed, this zero-reference error would give ridiculous results as the amplitude approaches +/-1.0 inches.

For this reason, another equation is used, where the logarithmic decrement is

$$\Delta_{123} = \ln\left|\frac{x_1 - x_2}{x_2 - x_3}\right|$$

which eliminates a constant offset error:

$$\Delta_{123} = \ln\left|\frac{(+14.07) - (-11.78)}{(-11.78) - (+11.61)}\right| = 0.100$$

$$\Delta_{234} = \ln\left|\frac{(-11.78) - (+11.61)}{(+11.61) - (-9.56)}\right| = 0.100$$

Using this value for the logarithmic decrement, the internal damping rate can be calculated with the following equation (Liedecker, 1995):

$$\zeta = \frac{\ln\left|\frac{x_1 + x_2}{x_2 + x_3}\right|}{2\pi N} \qquad (3.2)$$

where ζ and N remain the same as in (1), x_1 and x_2 are the first and last oscillation peaks in the first N cycles, and x_2 and x_3 are the first and last oscillation peaks in the second N cycles. To utilize this equation the two intervals N must be equal.

Equation 3.2 will be used, as there will be some movement of the mast of the crane.

3.4 Conclusion

The internal damping rate of a construction crane can be calculated by using logarithmic decrement, provided that the motion is viscously damped, simple harmonic oscillations. The results of these tests are unique to the particular test configuration; however, they will provide a window into the damping characteristics of the test cranes.

This chapter provides an equation that can be used to quantify damping characteristics of a construction crane. Next, a methodology for collecting the data required to use the equation, is developed.

4. Experimental Design

The following chapter develops a methodology for calculating the internal damping rate of construction cranes from the theory presented in Chapters 2 & 3. The chapter is divided into three sections. The first presents all of the information that must be known in order to calculate the internal damping rate of construction cranes. The necessary information includes the types of cranes and payloads that should be tested and the quantities that must be experimentally determined.

The next section presents the factors that affect how the required data is captured. For example, the degree of accuracy that the experiment must return impacts how measurements must be made. Other factors include time limitations imposed by the owner of the crane and the measures used to indicate the validity of the results. The final section of the chapter states the selected method and provides the rationale for its selection.

4.1 Factors To Be Determined

The factors presented in this section are necessary for the calculation of the internal damping rate of construction cranes. The items included are the types of cranes and payloads that should be tested. The variables that must be experimentally determined in order to calculate the internal damping rate are stated.

4.1.1 Selection Of Cranes And Payloads

The first requirement is to determine what type of construction cranes to test. This is accomplished by determining the types of construction activities that will realize the greatest benefits from a tuned mass damping system. The types of cranes and payloads typical to these applications are the focus of the study.

4.1.1.1 Application Of Tuned Mass Damping System

The application of a tuned mass damping system will reduce payload pendulations, thereby placing the payload under greater control. Time usually spent controlling the payload can be productive instead. The risk associated with a payload injuring a worker or striking objects is minimized if the load does not pendulate.

Some construction activities, such as concrete placement or steel erection, require the completion of repetitive lifts. These types of high production activities are known as duty cycle operations. The repetitiveness of these activities leads to their being performed at greater speeds than other lifts. Greater speeds result in an increase of payload pendulations, which a tuned mass damping system could significantly reduce.

A tuned mass damping system must be tuned to the payload configuration. Duty cycle operations are characterized by the conveyance of similar loads. This offers an ideal forum for a tuned mass damping system, as production would not be diminished due to constantly tuning the system for a different load.

This thesis investigates light to medium duty hydraulic and lattice boom construction cranes. These cranes are commonly used for the performance of high production activities, such as the conveyance of concrete buckets.

4.1.1.2 Selection Of Payloads

Duty cycle operations are high-speed production operations. The high speed conveyance of payloads causes sideloading and swingout, which reduce the capacity of the cranes. Sideloading is the condition in which the payload swings to the side of the mast, and swingout is the condition in which the payload pendulates beyond the tip of the mast. In both cases the load radius increases. For this reason crane manufacturers offer separate load charts for duty cycle operations, or recommend reducing the values cited in standard load charts by 20% (Dickie, 1982).

Due to the extra stresses induced by high-speed production operations, cranes are selected so that the payload is light in comparison to the capacity of the crane. Therefore, test loads should be in the neighborhood of 10% of the maximum rated capacity of the crane, simulating typical duty cycle loads.

4.1.2 Data That Must Be Experimentally Determined

Chapter 2 determines that a construction crane can be analyzed as viscously damped, simple harmonic oscillator. The following equation can be used to empirically determine the internal damping rate of such a system.

$$z = \frac{\ln\left|\frac{x_1 + x_2}{x_2 + x_3}\right|}{2pN} \tag{3.2}$$

In this equation x_1, x_2 and x_3 represent the maximum distance from the stable equilibrium that the payload achieves on successive oscillation peaks. N is the number of complete oscillations between the interval x_1 and x_2, or between x_2 and x_3. Therefore, to determine the internal damping rate, the displacements, x_1, x_2 and x_3, and the relative number of each oscillation peak must be experimentally determined.

The method by which these variables: x_1, x_2, x_3, and N are determined is affected by many factors. Primarily, the accuracy that the experiment must return defines how accurately measurements must be taken. It is important to consider whose cranes are being tested; what additional measurements must be made to ensure reliable results; and measurements that allow for comparisons with other cranes.

4.2 Factors Affecting How The Data Is To Be Determined

Section 4.1 presents the factors that must be determined to calculate the internal damping rate of construction cranes. There are factors that affect how the data is to be collected, such as accuracy. These factors are presented, followed by the selected testing method.

4.2.1 Accuracy

The results of this research indicate the feasibility of future research. Previous research determined that the internal damping rate of a tuned mass damping system must be at least twice that of a construction crane. Before this research no published information on the internal damping rate of construction cranes exists. Therefore, in order to determine the required degree of accuracy that future research requires, damping experiments must be performed.

The application of this research is to provide a critical design parameter for further research on low-frequency tuned mass damping systems. Once knowledge of the internal damping rate of construction cranes exists, then the feasibility of a tuned mass damping system can be considered and subsequently developed. Some fundamental statistics provide insight as to the accuracy that an experiment of this nature requires.

Most phenomena in real life are nondeterministic. For example, the tensile strength of a steel cable or the dimension of a machined part is nondeterministic. If many experiments were performed, the results would fluctuate about a mean value. The internal damping rate of construction cranes is a nondeterministic quantity, referred to as a random variable or probabilistic quantity. If experiments are conducted to determine a random variable, each experiment will return a sample point, the value of which is not a function of any parameter. Many experiments must be performed to establish the sample space of the random variable (Rao, Singiresu, 1995). Generally, the greater the complexity of the random variable, the larger the distribution of the sample space.

Construction cranes are numerous and complex, indicating that the distribution of the internal damping rates will be large. Since the value of a nondeterministic variable is not a function of any parameter, many sample points must be determined to establish the sample space. The priority of this research is to investigate the feasibility of applying a tuned mass damping system to construction cranes. Many different types and sizes of cranes were tested. This precludes a statistical analysis, but it provides insight as to the types of cranes that are suitable for the application of tuned mass damping.

4.2.2 Availability Of Cranes

Test cranes were obtained from local construction sites and crane distributors. The time required to test the crane affects the potential of being granted permission to do so. For example, a construction manager would be more likely to allow a test requiring fifteen minutes than one requiring two hours. For the purpose of an initial investigation into the damping characteristics of construction cranes, the number of cranes tested is critical to establishing the sample space. Therefore, an experiment that can be executed quickly enhanced the chances of gaining permission to test a crane.

4.2.3 Experimental Analysis

As part of the experimental design process, a method for evaluating the performance of the test was built into the test. To allow for this analysis, some additional measurements were taken during the experiment. The values returned from the testing are dependent upon the validity of the assumptions needed to mathematically model a pendulating payload. These assumptions are summarized, and a method for analyzing their validity presented.

4.2.3.1 The Cranes Support System Is Static

In order to model a pendulating payload as a simple pendulum, it is assumed that the pivot point of the pendulum does not move. The pivot point of the pendulum is the sheave wheel at the tip of the crane's mast. Movement of the pivot point of the pendulum will alter the effective length of the cable, affecting the frequency of the pendulating payload. If the pivot point of the pendulum moves, the frequency will differ from that of a simple pendulum with similar cable lengths.

4.2.3.2 Construction Cranes Provide A Stable Equilibrium To The Payload

This assumption means that the payload will return to the exact location that it occupied prior to the initiation of the pendulation. If the mast of the crane moves as a result of the forces applied by the pendulating payload, then the equilibrium position will also move. The mathematics that describe the motion assume that the equilibrium position does not move.

4.2.3.3 The Angle Of Pendulations Does Not Exceed 15 Degrees.

No pendulations exceeding 15 degrees were initiated during a test.

4.2.4 Frequency Comparisons

The validity of the assumption necessary to model a pendulating payload as a simple pendulum must be investigated. The frequency of the oscillating payload will be the same as that of a simple pendulum if the assumptions are valid. If the assumptions are violated, the frequency exhibited during the experiment will differ from that of a simple pendulum. Measurements will be taken to allow for this comparison.

The natural frequency, f, of a simple pendulum is

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{L}} \tag{2.4}$$

where g is the acceleration due to gravity, and L is the length of the cable. The frequency of a pendulum is dependent upon the length of the cable, which was experimentally determined.

As a part of the experiment, the period of the oscillating payload was recorded. The period can be used to calculate the frequency of the oscillating payload. To determine the natural frequency of a simple pendulum the length of the cable was determined. The frequency of a simple pendulum was calculated and compared to that of the pendulating payload. If the frequencies are equal, then the pendulating payload is acting as a simple pendulum.

4.2.5 Method For Comparison With Other Cranes

Measurements were taken to allow for comparison with other cranes. The comparison includes the type of crane, its internal damping rate, and the percentage of capacity at which the experiment was performed. For example, a 50-ton FMC hydraulic crane has an internal damping rate of 1 percent when tested at 10 percent of capacity.

To determine the capacity of the crane at the test location, the location of the test was determined and used in conjunction with a load chart. Payloads with known masses were selected.

4.3 Testing Methodology

This section develops a method for determining the variables needed to calculate the internal damping rate of construction cranes.

4.3.1 Method For Determining Oscillation Information

To allow for the rapid testing of cranes, tests were videotaped. This allowed for a detailed analysis to be performed without seriously impacting site operations. A measurement scale was placed beneath a pendulating payload, and oscillation peaks were extracted using freeze-frame viewing. The time between successive oscillations was calculated by calibrating the counter on the VCR. The remaining data was collected prior to initiating pendulations.

4.3.2 Variables to be collected

In addition to the oscillation peak information, other variables were collected to allow for comparisons with other cranes and to provide accuracy indicators. The following variables were experimentally determined: the distance of the load from the pivot point on the mast of the crane, D; the length of the boom, B; and the mass of the payload, M.

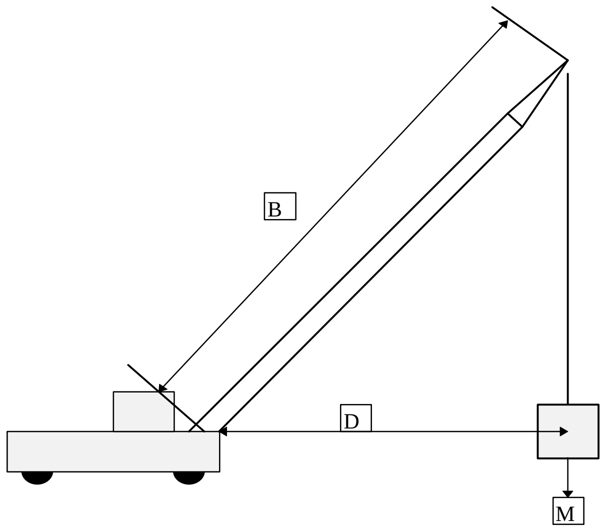

Figure 4.1 Illustration Of Distances To Be Determined

4.3.2.1 Distance Of The Load From The Pivot Point On The Mast Of The Crane, D

The distance of the load from the pivot point of the mast of the crane has two purposes. It is used to determine the capacity of the crane at the test locations. This is needed to allow for comparisons with other cranes. Second, the measurement is used in the calculation of the length of cable, to allow the determination of the frequency of a simple pendulum. This distance was determined with a tape measure.

4.3.2.2 Length Of The Boom, B

The length of the boom is used along with the distance of the load measurement previously mentioned to calculate the length of the cable. The length of the boom is determined from the crane's specifications, as with the case of a lattice boom crane, and by observing the length marking on the side of a variable length boom crane.

4.3.2.3 Mass Of The Load, M

The mass of the payload is used to determine the percentage of capacity of the test configuration. There are a few factors that contributed to selection of a load:

- availability: what was around the site of a known mass?
- mass: what percentage of capacity was desired for the test?
- shape: how does the shape of the object lend itself to data extraction?

4.4 Conclusion

Light to medium, duty hydraulic and lattice boom construction cranes were tested to determine their internal damping rates. The test loads were between 3.5 and 10 percent of the maximum rated capacity of the construction crane, simulating duty cycle conditions.

The following data was collected by physical measurements and by extracting values from video of the experiment:

1. The maximum displacement associated with each oscillation peak;
2. The sequential number and time of each oscillation peak;
3. The length of the mast of the crane;
4. The distance of the payload from the crane; and
5. The mass of the payload.

The first two values (1 & 2) were extracted from video of the experiment, and the third and fourth values (3 & 4) were measured. A payload of a known mass was selected.

This chapter developed a method for capturing the data necessary to calculate the internal damping rate of construction cranes. Additional measurements were made to validate the results and to allow for comparison with other tests.

The following chapter illustrates the format of the presentation of the experiments.

5. Experimental Format

The experiments were performed as described at the end of Chapter 4. This chapter serves to illustrate the format of the presentation of the experiments. The contents of each section describe what that section aims to communicate and why. The actual experiments follow in Chapter 6 in the format presented here.

5.1 Test Number

This heading is used to show the reader the test number. For example, the third experiment will be included as section 6.3 Test 3. The contents of each experiment include a general description of the experiment and the results of the tests performed perpendicular and parallel to the mast of the crane.

5.1.1 Similar Test Parameters

Experiments were performed with oscillations initiated both perpendicular and parallel to the mast of the crane. There are parameters, such as the site description, that are similar to both the tests, so they are presented first.

5.1.1.1 Site, Crane And Payload Description

The presentation of each experiment begins by describing the site where the experiment was performed. The pertinent information concerning the testing situation is included as narrative to preface each experiment. The following items are included in this discussion.

Type Of Crane: This research tested two types of construction cranes; lattice boom and hydraulic. Lattice boom cranes have a mast constructed of a steel lattice. The booms are a fixed length. Hydraulic cranes have a mast constructed out of telescoping tubular steel beams, which provide an adjustable mast length. Both are commonly used on construction sites.

Type Of Payload: The ideal payload was selected to enhance data extraction. To determine an oscillation peak, a video of the experiment was reviewed, frame by frame. When the payload achieved a peak, the video was stopped, and a reference made to the measurement scale below. The center of gravity of the payload was used as the reference point from which to take measurements. Provided that the payload is symmetric, the position of the center of gravity is not be impacted by rotation. Therefore, symmetrical payloads were desired.

Other factors controlling the selection of payloads were their availability and knowledge of their mass. These factors are presented in the description of the experiment.

Number Of Cables Suspending The Payload: The number of cables that are used to suspend the payload is cited. Cranes often use multiple cables to suspend the payload. A four-part line suspends the payload from four steel cables. Conversation with crane operators reveals that payloads tend to pendulate more with a single-part line; single-part lines line offer less damping, allowing the payload to oscillate more than it would with a four-part line. It is logical that the number of cables affects the internal damping rate, hence it is stated.

5.1.1.2 Dimensions Of Test

A diagram similar to the one below is given with each experiment; it illustrates the length of the mast, distance of the payload from the crane, and the mass of the payload.

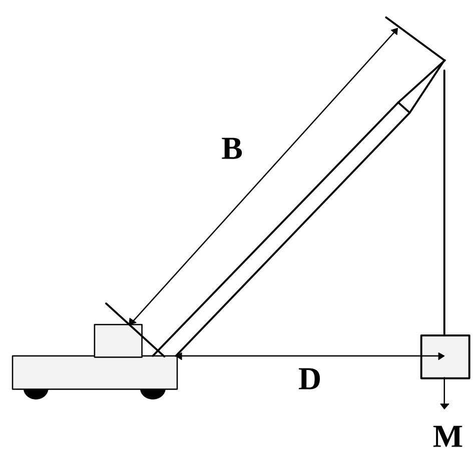

Figure 5.1 Illustration Of The Dimensions To Be Determine

In the illustration, **B** represents the length of the boom, **D** is the distance from the payload to the crane, and **M** is the mass of the payload. In the case of a lattice boom crane, the length of the boom was determined from the crane's specifications; in the case of hydraulic cranes this was done by observing the markings on the telescoping boom. The distance from the payload to the crane was measured. Payloads with a known mass were selected.

5.1.1.3 Percentage Of Capacity

The percentage of capacity of a test was determined to allow for comparisons with other cranes. It is suspected that the internal damping rate increases with the percentage of capacity.

The percentage of capacity of a test is dependent upon the mass of the payload and its position relative to the crane. The mass of the payload and its position were determined prior to performing the test. Given this information, the crane’s load chart was consulted to determine the lifting capacity at a given distance from the crane. The percentage of capacity is determined by dividing the mass of the payload by the lifting capacity of the crane at the test location.

A crane's load chart states the lifting capacity of the crane for every permissible lifting configuration. Below is an example of a load chart for a 50-ton hydraulic crane. Note that different boom lengths are given to accommodate for the variable-length mast of a hydraulic crane. As the distance of the load from the crane increases, the lifting capacity of the crane decreases.

Load Radius (feet)	Boom Length			
	40'	48'	56'	62'
	Lifting Capacity (lbs.)			
10	72,100	70,800	68,100	
12	72,100	70,800	68,100	64,500
15	68,700	66,400	64,200	56,300
20	50,000	50,000	50,000	46,200
25	40,000	40,000	40,000	38,000
30	31,200	31,200	31,200	31,200
35		24,000	24,000	24,000
40		18,900	18,700	18,900
45			14,500	15,400
50			11,400	12,600
55				10,500

Figure 5.2 Load Chart For A 50-Ton Hydraulic Crane

All cranes have a permanent load chart affixed to the inside the cab of the crane. This load chart was consulted to determine the percentage of capacity for the tests. When a test location fell between cited values in the load chart, linear interpolation was used to determine the percentage of capacity. The entire load chart is not be given for each test.

The lifting capacity of the crane is established prior to the presentation of either the perpendicular or parallel tests. If the percentage of capacity changed between tests, the new percentage of capacity is cited where appropriate.

5.1.1.4 Picture Of The Experiment

A picture of each experiment is given to aid in visualization of the experiment.

5.1.2 Perpendicular Test

The following section presents tests performed perpendicular to the mast of the crane. The section includes a resonance curve generated by the decay of the payload, a graph of the internal damping rate versus oscillations, a comparison between the actual and theoretical frequency, and the results of the experiment.

5.1.2.1 Resonance Curve

The resonance curve is generated by plotting the distance of the load from the equilibrium position versus time. The curve takes the form of a sine curve and aids in visualizing the decay of the payload. The peaks of the curve represent the maximum displacement from the stable equilibrium, and are known as oscillation peaks. Note that the maximum displacements decay over time. The rate of this decay is related to the rate of internal damping. The greater the damping rates, the faster the maximum displacements approach the axis, or stable equilibrium. Following each resonance curve, there is a short discussion summarizing significant features of the curve.

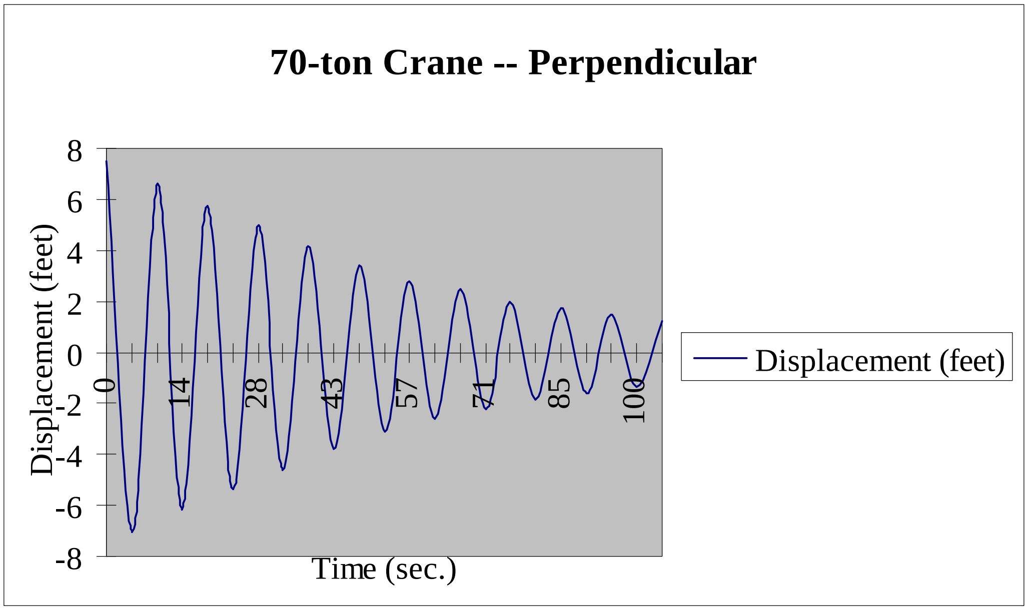

Figure 5.3 Example Of A Resonance Curve Generated From The Decay Of A Pendulating Payload

This graph is the curve created by the decay of a payload suspended form a 70-ton construction crane. The oscillations were initiated perpendicular to the mast. The first measured oscillation peak was approximately 7 feet from the stable equilibrium. Over the course of 12 oscillations or 100 seconds, the oscillation peaks decreased to 2 feet.

5.1.2.2 Graph of Internal Damping Rate vs. Oscillation number

A graph of the internal damping rate versus oscillation number is given for each experiment. An example follows.

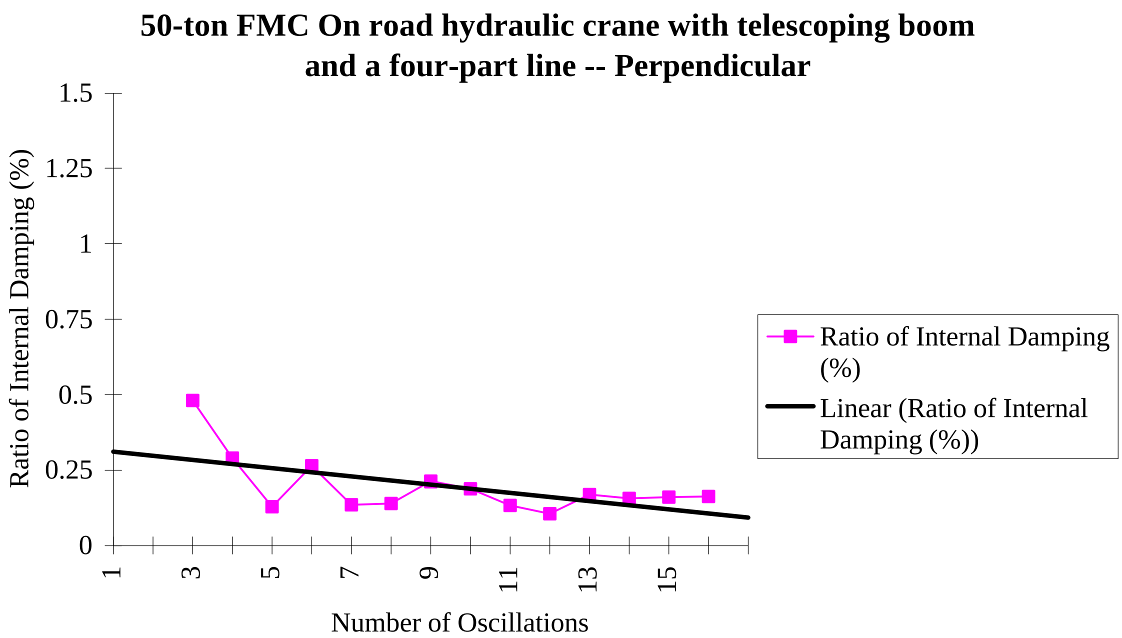

Figure 5.4 Graph Of Internal Damping Rate Vs. Number Oscillations

Discussion follows each graph and focuses on significant features of the test. In this example the value of the internal damping rate decreased across the sample.

It is assumed that the errors associated with each data point are normally distributed about a central mean. Each sample point is independent of its siblings. Therefore, the overall mean damping rate for the entire test should be reflective of the true mean.

Linear regression using the least squares method is fitted to each graph. This line should approximate the true mean across the entire sample interval.

5.1.2.3 Frequency Comparison

For the results of this research to hold merit, it is necessary to verify the assumptions needed to model a pendulating payload as a simple pendulum. This is done by comparing the frequency exhibited during an experiment with the frequency of a simple pendulum with a similar cable length. The discrepancy between these quantities indicates the validity of the assumptions. If a large discrepancy exists, the motion of the pendulating payload is not that of a simple pendulum.

This section of the report makes the comparison between the observed and the theoretical frequencies. If a discrepancy exists, a theory is developed as to its cause.

5.1.3 Parallel Test

The presentation of the test performed parallel to the mast of the crane follows the same format as the perpendicular test.

6.#.3.1 Resonance Curve

6.#.3.2 Graph of Internal damping rate

6.#.3.3 Frequency Comparison

6.#.3.4 Results of parallel test

For example, the Graph of Internal Damping rate for the fourth experiment is in section 6.4.3.2.

5.1.4 Discussion Of Tests

This section summarizes the results of both tests. A table that summarizes all of the information is given.

This chapter presents the format in which the experiments are presented. The following chapter presents the experiments in the format presented here.

6. Experimentation

The following chapter presents the experiments that this research performed. The data is included in Appendix A. The methods used to capture and reduce the data are also included as appendices. Appendix B lists the procedure used in performing the experiments. The methods used to reduce the data from video footage are included in Appendix C. The experiments follow in the order they were conducted.

Table 6-1: Test Numbers With Type Of Crane And Percentage Of Capacity

Type of Crane	Capacity (Tons)	Percentage of Capacity	Test Number
LS318 Link Belt - Lattice Boom	100	6.8%	Test 1
FMC Link Belt - Hydraulic	50	10.0%	Test 2
778c LIMA - Lattice Boom	70	15.0%	Test 3
FMC Link Belt - Hydraulic	25	6.4%	Test 4
T-600XL P&H - Hydraulic	60	6.0%	Test 5

6.1 Test 1

The actual test data is included in Appendix A**.**

6.1.1 Similar Test Parameters

This section describes all of the parameters that are the same for both tests performed perpendicular and parallel to the mast of the crane.

6.1.1.1 Site, Crane, And Payload Description

The first test was conducted on the Virginia Tech campus at the construction site of the new mechanical engineering building. The sub-contractor drilling the caissons had a 100-ton Link Belt LS 318 crawler crane on site. This crane has a 120-foot lattice boom, and suspends its payload from a single woven steel cable.

The test load was a 42” caisson auger weighing approximately 2200 pounds. This cylindrical steel auger makes an ideal test payload due to its symmetry. The center of gravity can be identified from any direction, improving data extraction.

6.1.1.2 Dimensions Of Test

The location of the test relative to the crane, the length of the crane's mast, and the mass of the payload are given by the following illustration. The distances are in feet and the weight is in pounds.

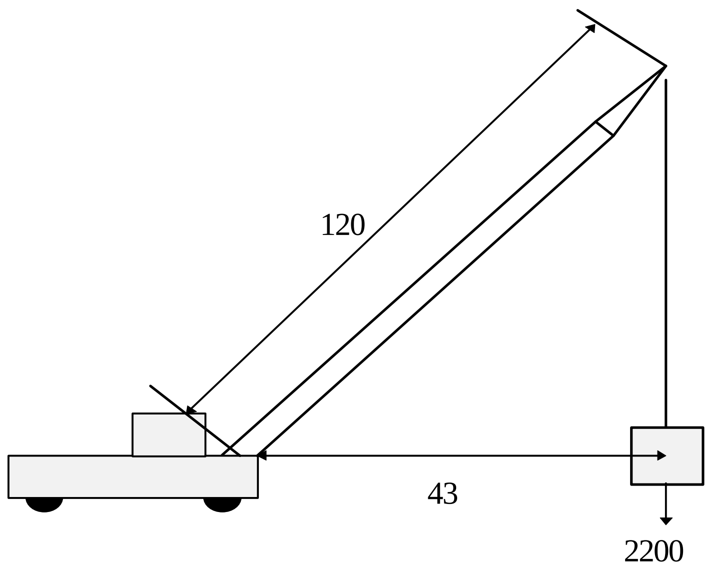

Figure 6.1 Dimensions Of Test 1

6.1.1.3 Percentage Of Capacity

The lifting capacity of the LS318 at 43 feet is 32,195 lbs. With a payload of 2200 pounds, the percentage of capacity is 6.8%.

6.1.1.4 Picture Of The Experiment

6.1.2 Perpendicular To The Mast

This experiment begun with oscillations initiated perpendicular to the mast of the crane.

6.1.2.1 Resonance Curve

The oscillation peaks produced by the decay of the payload decrease slowly over time.

This indicates a low rate of internal damping.

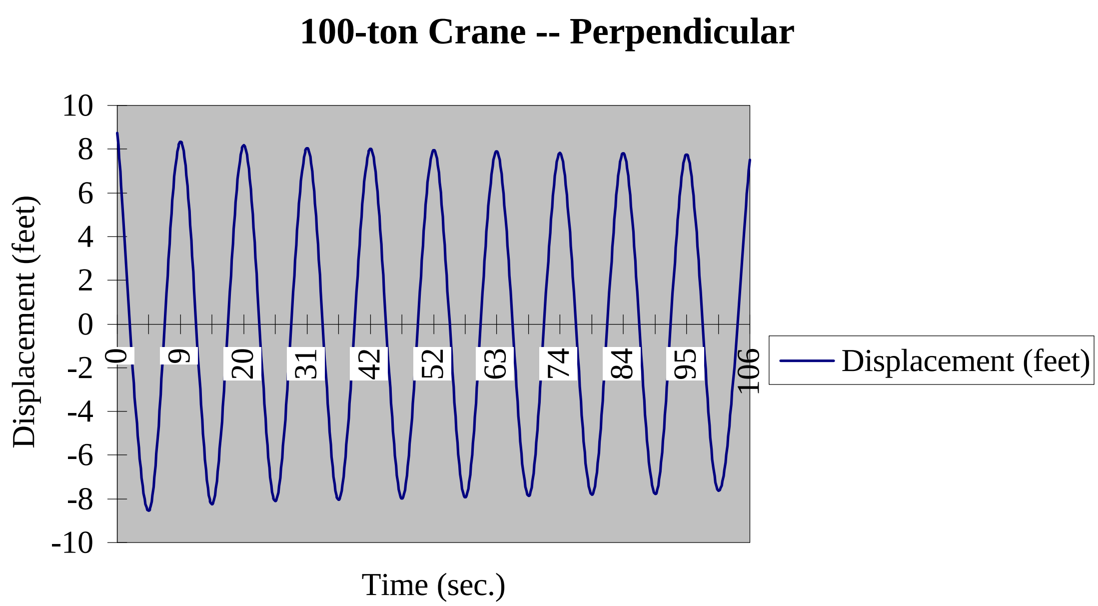

Figure 6.2 Test 1, Perpendicular - Resonance Curve

This experiment begun with a group of four students initiating oscillations of the payload perpendicular to the mast of the crane. The first oscillation peak approached 9 feet. This decayed to 7.5 feet over 106 seconds, or 9 complete oscillations.

6.1.2.2 Graph of Internal Damping Rate vs. Oscillation number

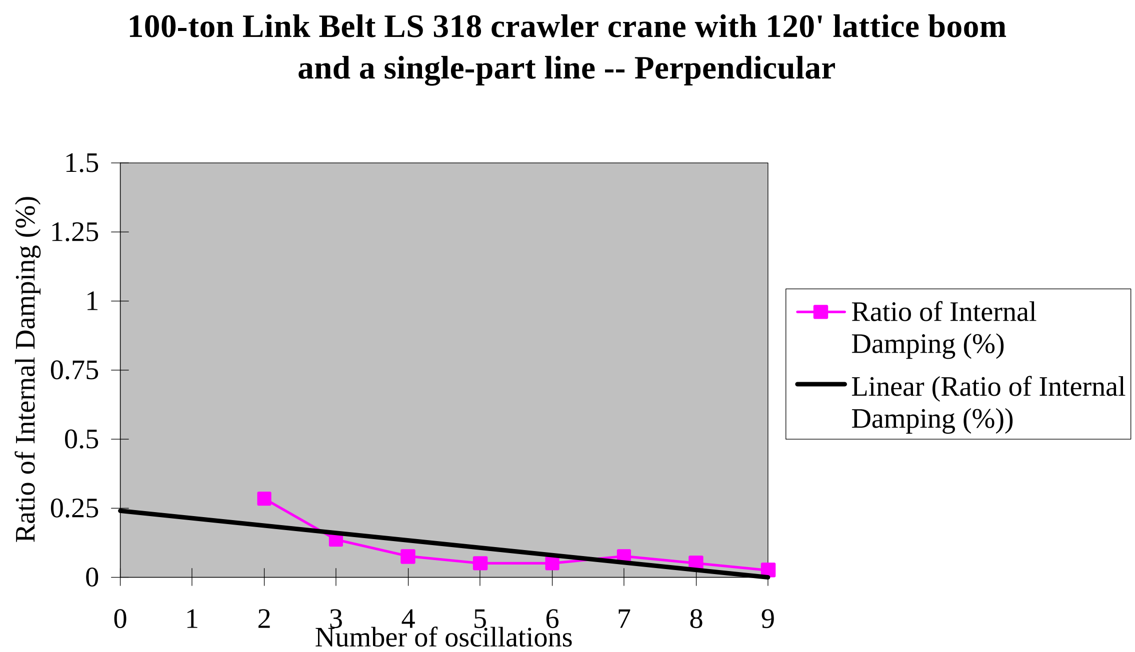

Figure 6.3 Test 1, Perpendicular - Graph Of Internal Damping Rate

The internal damping rate decreased with the oscillation peaks. The values achieved were averaged across the interval, discarding the first data point, and the resulting internal damping rate was 0.08%.

6.1.2.3 Frequency Comparison

The frequency exhibited during the experiment is compared with that of a simple pendulum with similar cable lengths. A frequency that differs from that of a simple pendulum indicates that the actual conditions were not ideal. A number of factors can cause the frequencies to differ.

The cable length for this experiment was 112 feet, producing a natural frequency of 0.085. This frequency has a period of 11.7 seconds. The period exhibited by the payload was 10.6 seconds. The shorter period has a shorter effective cable length. Possible causes include; movement of the pivot point, an unstable equilibrium, and the existence of damping forces.

6.1.3 Parallel To The Mast

The second part of the first experiment was to initiate oscillation parallel to the mast of the crane.

6.1.3.1 Resonance Curve

The oscillation peaks decrease slowly over the courses of the sample, indicating a low internal damping rate.

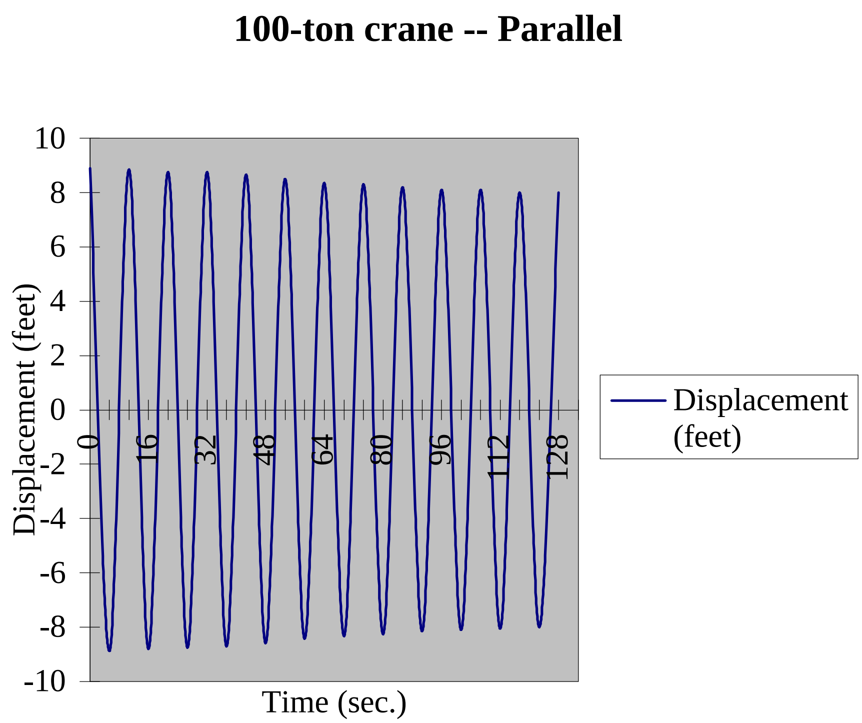

Figure 6.4 Test 1, Parallel - Resonance Curve

Oscillations were initiated parallel to the mast of the crane. The first recorded peak was almost 9 feet from the equilibrium position. Over the course of 11 oscillations, taking 128 seconds, the oscillation peaks decreased to 8 feet.

6.1.3.2 Graph of Internal Damping Rate vs. Oscillation Number

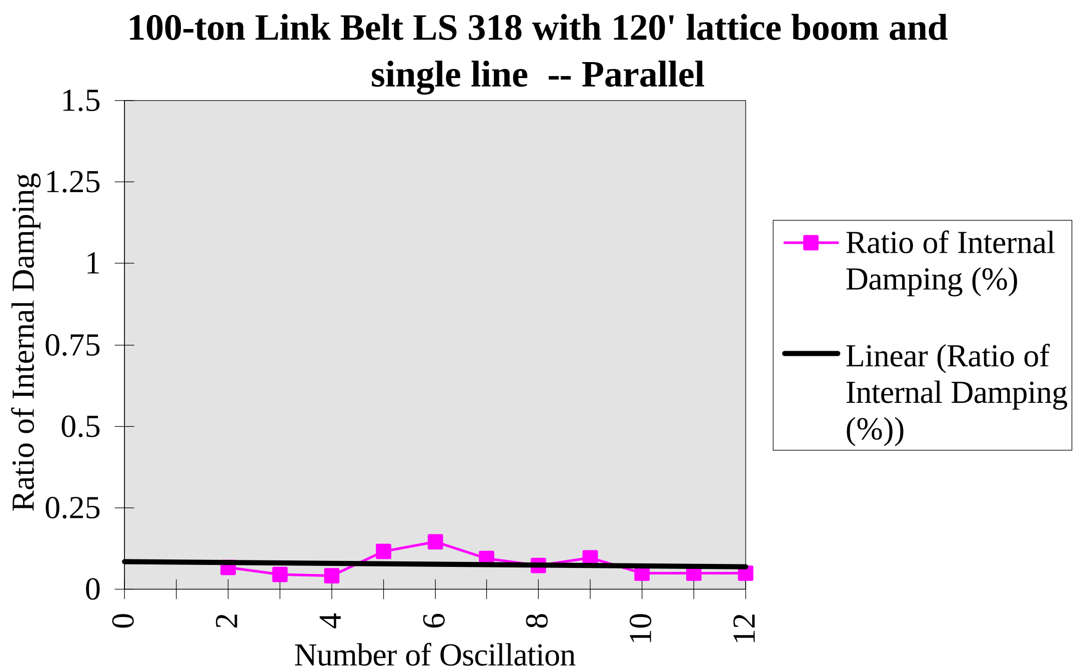

Figure 6.5 Test 1, Parallel - Graph Of Internal Damping Rate

The internal damping rate remained relatively constant across the test interval. The average is 0.07 %.

6.1.3.3 Frequency Comparison

The cable length for this experiment was 112 feet, producing a natural frequency of 0.085. This frequency has a period of 11.7 seconds.

The period exhibited by the payload was 10.7 seconds. This discrepancy indicates a divergence from the conditions required for simple pendulum motion.

6.1.4 Results

The internal damping rates achieved by this experiment are low. The discrepancy in the periods indicates that pendulating payloads do not behave exactly as a simple pendulum would. Despite the discrepancy in the periods, the experiment has provided insight towards this cranes damping characteristics.

Table 6-2 Results Of Test 1

Test Direction	Internal Damping Rate (%)	Percentage of Capacity	Theoretical Period	Observed Period
Perpendicular	0.08	6.8	11.6	10.6
Parallel	0.07	6.8	11.6	10.7

6.2 Test 2

The actual test data is included in Appendix A**.**

6.2.1 Similar Test Parameters

This section describes all of the parameters that are similar to both tests performed perpendicular and parallel to the mast of the crane.

6.2.1.1 Site, Crane, And Payload Description

The second test was conducted at IMF Crane and Rigging's crane yard. The test crane was a 50-ton FMC Link Belt on-road rubber tire hydraulic crane.

The test payload was a 1500-pound clamshell bucket. This payload is symmetrical about the axis created by the lifting cable. A four-part line suspended the payload.

6.2.1.2 Dimensions Of Test 2

The location of the test relative to the crane, the length of the crane's mast, and the mass of the payload are given in the illustration that follows.

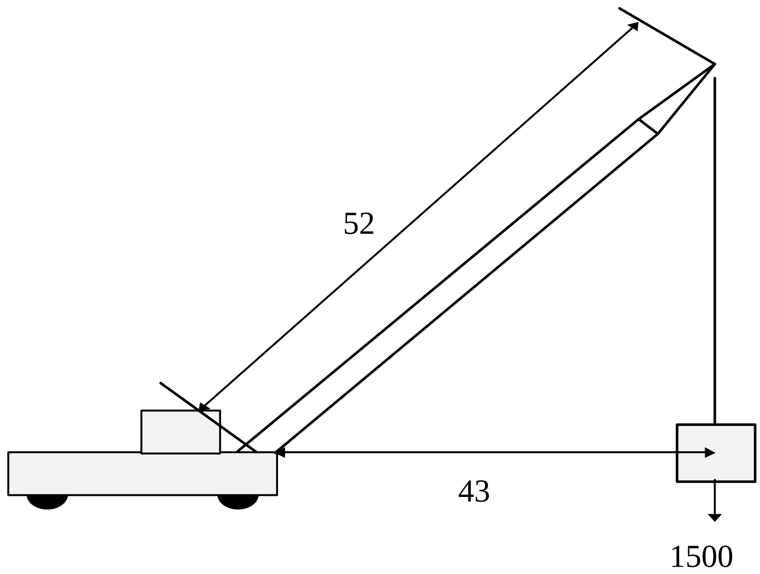

Figure 6.6 Dimensions Of Test 2

6.2.1.3 Percentage Of Capacity

The lifting capacity of the FMC Link Belt crane at 43, with a 52-foot mast, is 15,000 lbs.

This value was obtained by linear interpolation between values cited in the load chart.

With a payload of 1500 pounds, the percentage of capacity is 10 percent

6.2.1.4 Picture Of The Experiment

6.2.2 Perpendicular To Mast

This experiment begun with oscillations initiated perpendicular to the mast of the crane.

6.2.2.1 Resonance Curve

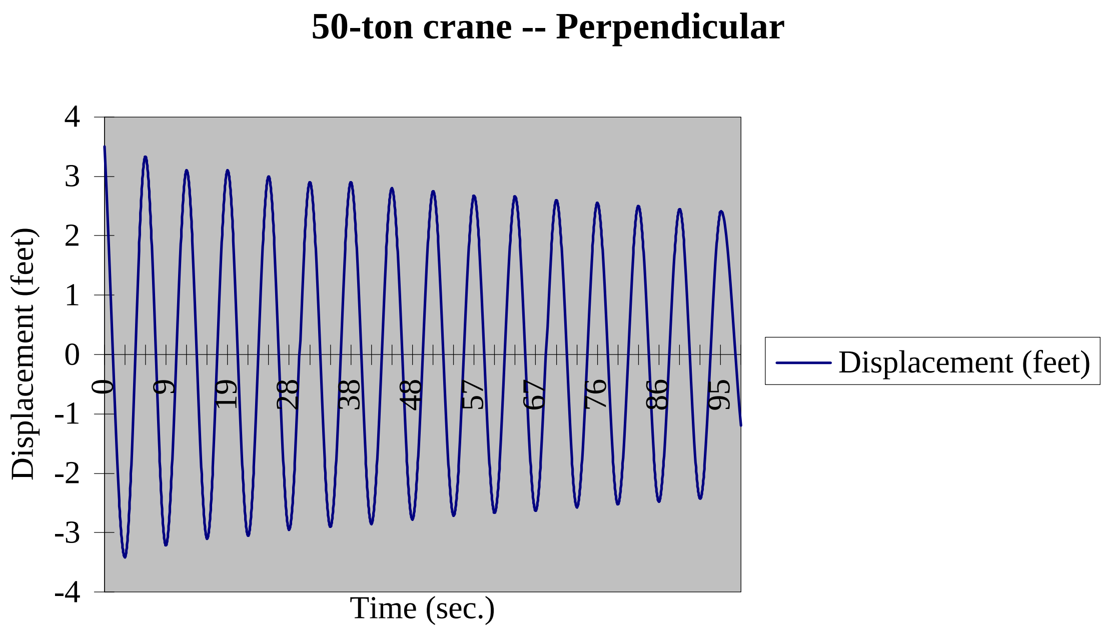

Figure 6.7 Test 2, Perpendicular - Resonance Curve

This experiment began with two students initiating a 3.5-foot oscillation. Over 95 seconds, or 15 complete oscillations, the oscillation peak decreased to 2.4 feet. This is a slow rate of decay, indicating a low internal damping rate.

6.2.2.2 Graph of Internal Damping Rate vs. Oscillation Number

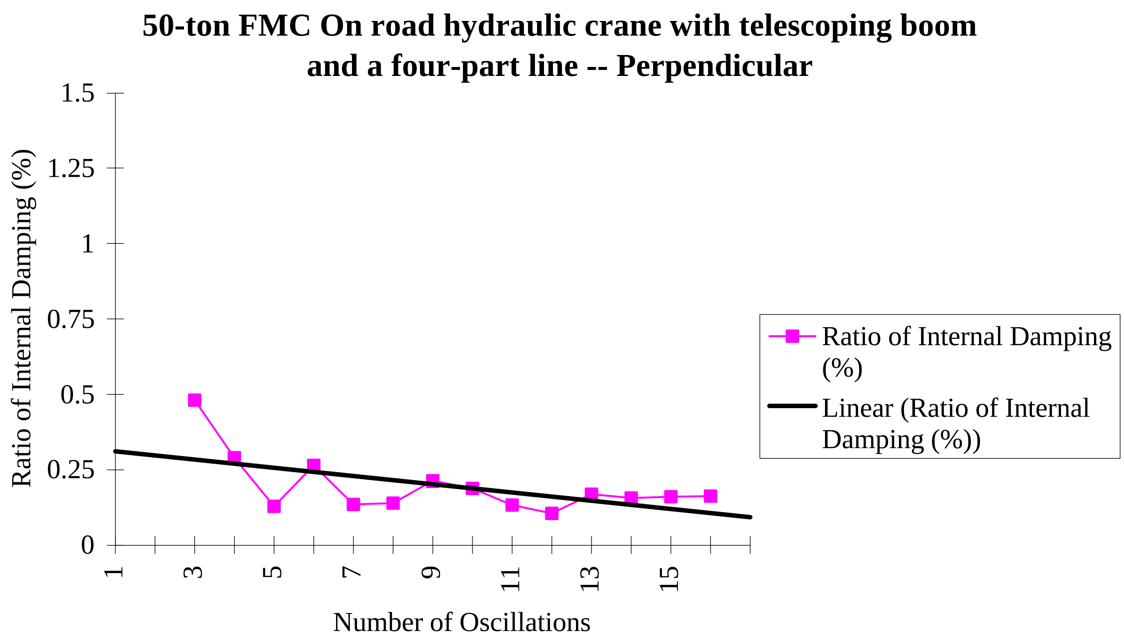

Figure 6.8 Test 2, Parallel - Graph Of Internal Damping Rate

The internal damping rate decreases across the test interval. The values were averaged, producing an average internal damping rate of 0.18 percent.

6.2.2.3 Frequency Comparison

The cable length used during this experiment was 29 feet, yielding a theoretical frequency of 0.17. The period of this frequency is 6 seconds.

The period of the actual test was 6.3 seconds. The longer period indicates an effective cable length that is longer than the actual cable length. The extendible mast may have allowed movement of the pivot point, which would contribute to the differing periods.

6.2.3 Parallel To The Mast

For the second part of this test, oscillations were initiated parallel to the mast of the crane.

6.2.3.1 Resonance Curve

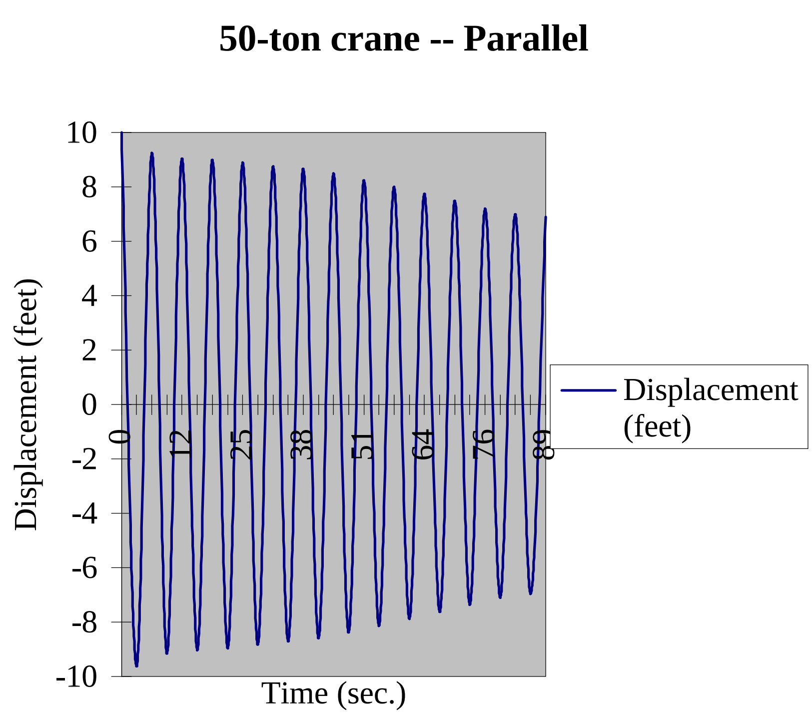

Figure 6.9 Test 2, Parallel - Resonance Curve

The parallel test began with two students initiating an oscillation of 10 feet. The oscillation peaks decrease slowly across the test interval, with the final peak of 6.9 feet. The test was conducted over 89 seconds, or 14 complete oscillations.

6.2.3.2 Graph of Internal Damping Rate vs. Oscillation Number

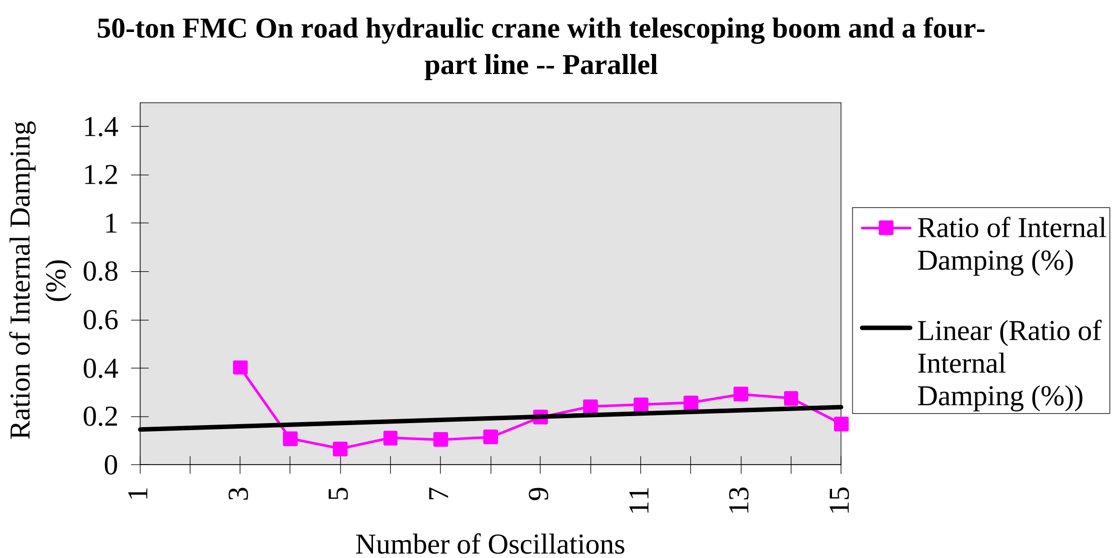

Figure 6.10 Test 2, Perpendicular - Graph Of Internal Damping Rate

The internal damping rate was determined to be 0.18. The first data point was discarded. The internal damping rate increases slightly across the interval.

6.2.3.3 Frequency Comparison

The cable length used during this experiment was 29 feet, yielding a theoretical frequency of 0.17. The period of this frequency is 6 seconds.

The period of the actual test was 6.35 seconds. This small discrepancy indicates a slight discrepancy form theory.

6.2.4 Results

The internal damping rates produced by this experiment are relatively low. The discrepancy in the periods was mainly attributed to movement of the mast of the crane. The joints that allow the mast to extend and the turntable to rotate, exhibit play under cyclic loading.

Table 6-3 Results Of Test 2

Test Direction	Internal Damping Rate (%)	Percentage of Capacity	Theoretical Period	Observed Period
Perpendicular	0.08	10	11.6	10.6
Parallel	0.07	10	11.6	10.7

6.3 Test 3

The actual test data is included in Appendix A.

6.3.1 Similar Test Parameters

This section describes all of the parameters that are the same for both tests performed perpendicular and parallel to the mast of the crane.

6.3.1.1 Site, Crane, and Payload Description

The third experiment was performed at the site of a bridge being constructed on I-81 in Salem, VA. The contractor performing operations had a 70-ton rubber tire LIMA 778C crane on site. This crane has a 100-foot lattice boom and suspends its payload with a single-part line.

The test load was a 2.4-ton cylindrical concrete counter weight. This was an ideal test load, due to its symmetry and mass.

6.3.1.2 Dimensions of Test

The location of the test relative to the crane, the length of the crane's mast, and the mass of the payload are given in the illustration that follows.

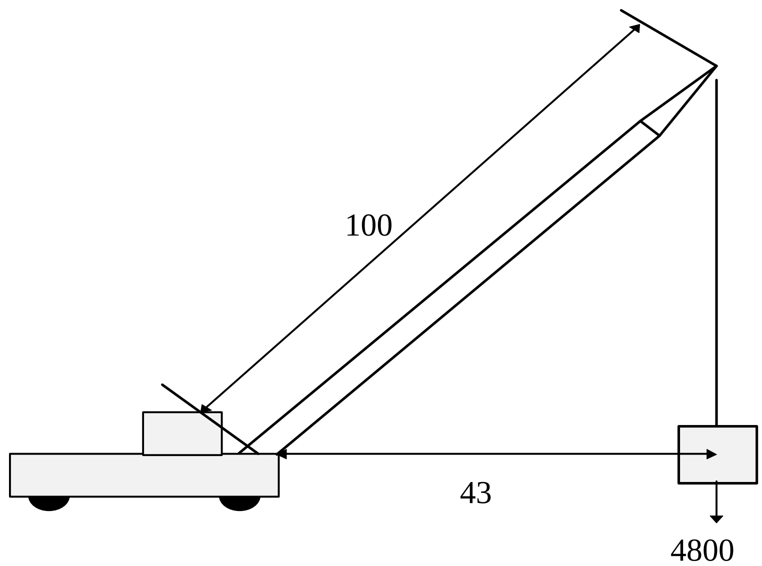

Figure 6.11 Test 3 - Dimension Of The Test

6.3.1.3 Percentage Of Capacity

The lifting capacity of the LIMA 778C at 43 feet is 31,900 pounds. With a payload of 4800 pounds, the percentage of capacity is 15 percent.

6.3.1.4 Picture Of The Experiment

6.3.2 Perpendicular To The Mast

This experiment begun with oscillations initiated perpendicular to the mast of the crane.

6.3.2.1 Resonance Curve

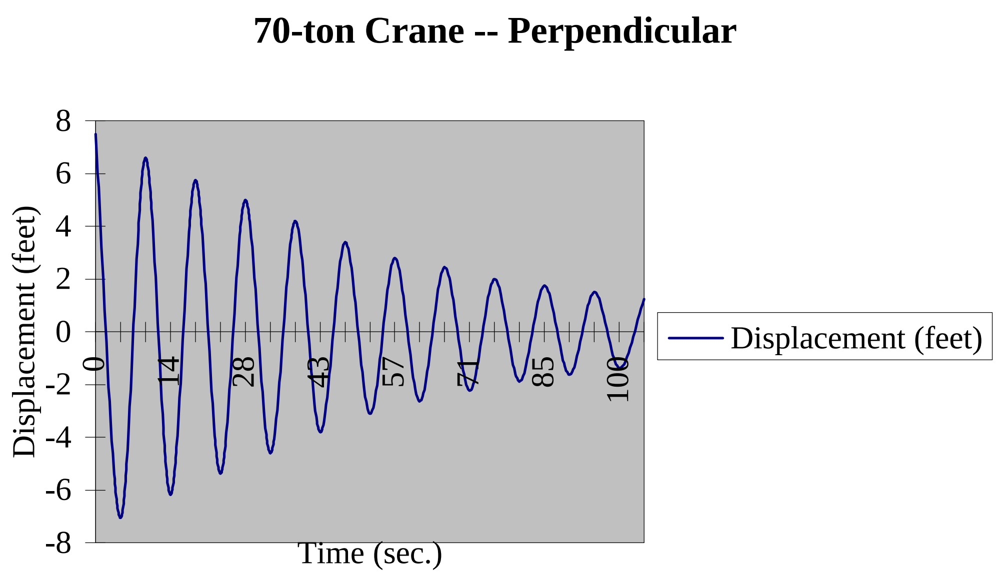

Figure 6.12 Test 3, Perpendicular - Resonance Curve

The first recorded oscillation peak was 7.5 feet. The payload was allowed to oscillate for 105 seconds, or 11 complete periods. The final peak was 1.25 feet from the equilibrium position. The oscillation peaks approach the axis more rapidly than they did during other tests. This indicates that the internal damping rate is larger than in previous experiments.

6.3.2.2 Graph Of Internal Damping Rate Vs. Oscillation Number

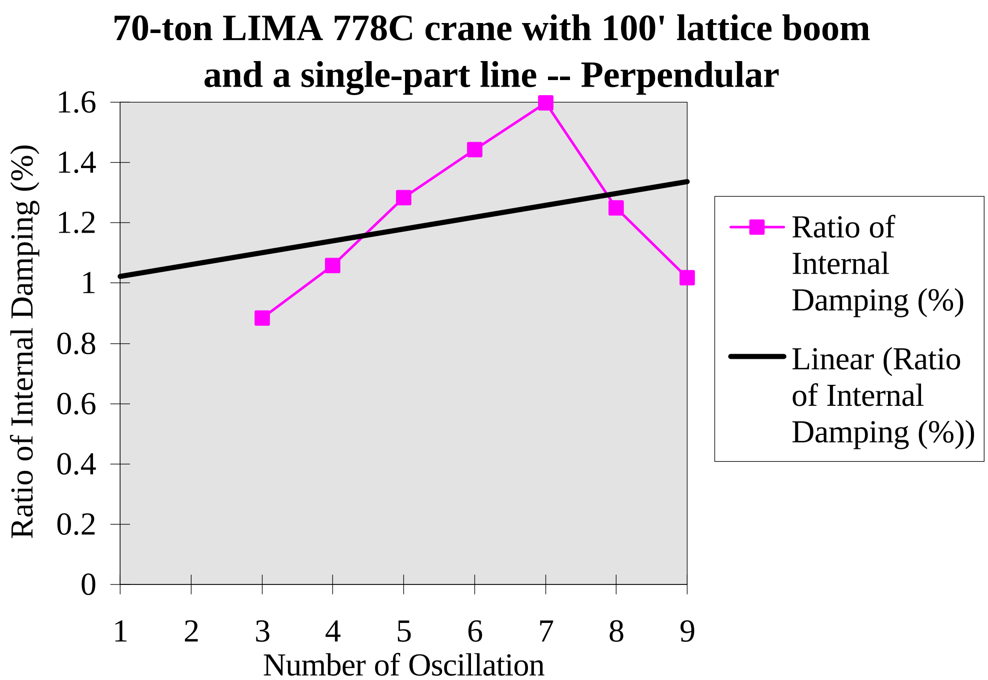

Figure 6.13 Test 3, Perpendicular - Graph Of Internal Damping Rate

The internal damping rate was averaged across the interval. The result is an average internal damping rate of 1.3 percent. The internal damping rate increased slightly across the interval.

6.3.2.3 Frequency Comparison

The cable length for this experiment was 90 feet, yielding a theoretical frequency of 0.095. This frequency has an oscillation period of 10.5 seconds.

The period produced by the pendulating payload was 9.5 seconds. Slight movement of the mast was observed during the test. Additionally, an unstable equilibrium and damping forces combined to produce a shorter period than theory predicts.

6.3.3 Parallel To The Mast

Pendulations were initiated parallel to the mast of the crane for the second portion of the experiment.

6.3.3.1 Resonance Curve

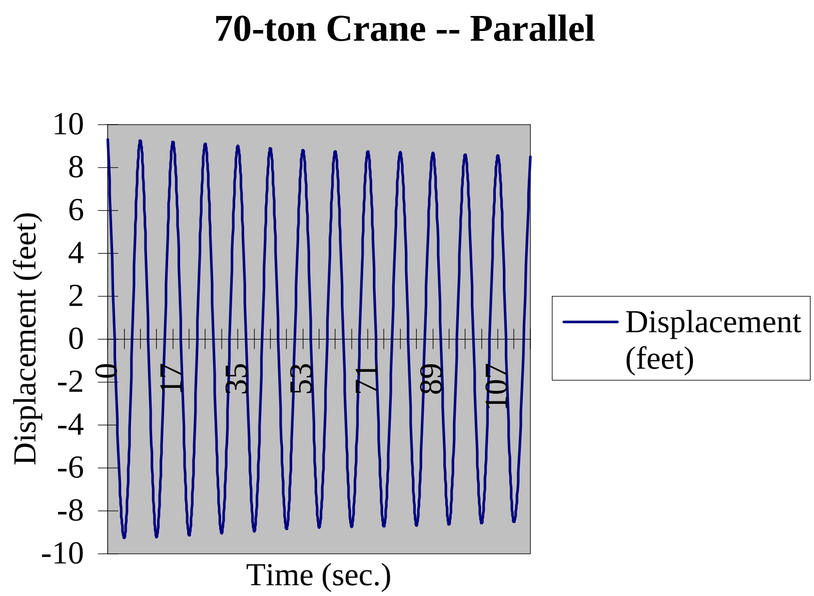

Figure 6.14 Test 3, Parallel - Resonance Curve

In the test performed parallel to the mast of the crane, the first recorded oscillation peak was 9.3 feet. The oscillation peaks do not decrease as rapidly, over 13 oscillations, as they did in the test performed perpendicular to the mast of the crane. The test was terminated after 116 seconds, with a final oscillation peak of 8.5 feet. This indicates a smaller internal damping rate than the test perpendicular to the mast of the crane.

6.3.3.2 Graph Of Internal Damping Rate Vs. Oscillation Number

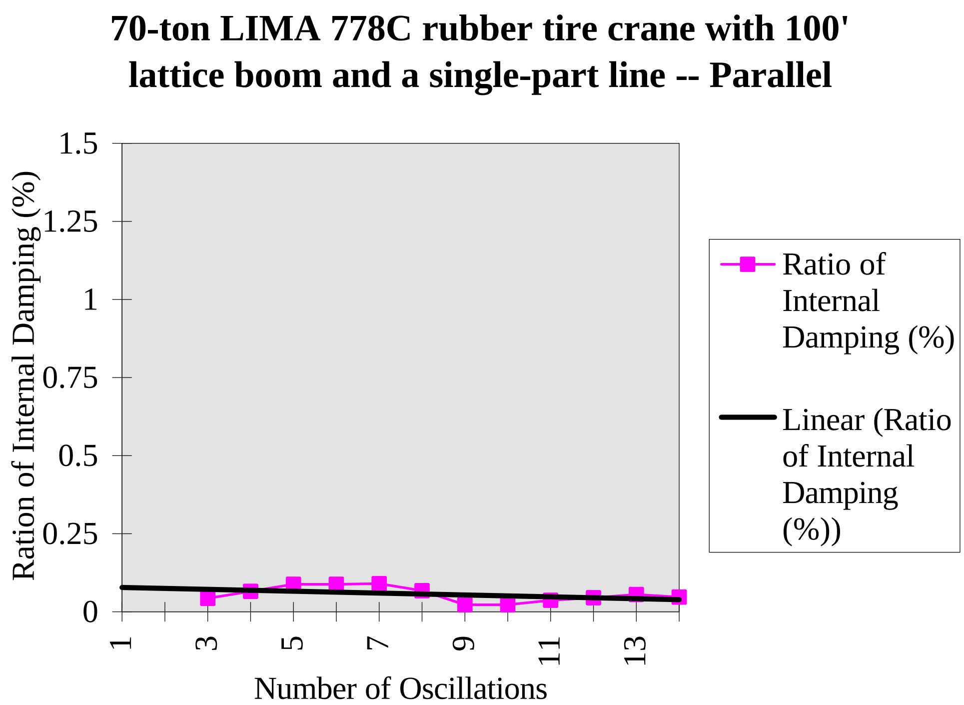

Figure 6.15 Test 3, Parallel - Graph Of Internal Damping Rates

The internal damping rate remained relatively constant over the interval. The average internal damping rate is 0.06 percent.

6.3.3.3 Frequency Comparison

The cable length for this experiment was 90 feet, yielding a theoretical frequency of 0.095. This frequency has an oscillation period of 10.5 seconds. The period produced by the pendulating payload was 8.3 seconds.

6.3.4 Results

The internal damping rates differed greatly between the test-performed perpendicular and parallel to the mast. The values of the test-performed perpendicular were considerably larger than that of the parallel test.

The frequency comparison indicated that the test-performed perpendicular to the mast was closer to that of a simple pendulum.

Table 6-4 Results Of Test 3

Test Direction	Internal Damping Rate (%)	Percentage of Capacity	Theoretical Period	Observed Period
Perpendicular	1.3	15	10.5	9.5
Parallel	0.06	15	10.5	8.3

6.4 Test 4

The actual test data is included in Appendix A.

6.4.1 Similar Test Parameters

This section describes all of the parameters that are the same for both tests performed perpendicular and parallel to the mast of the crane.

6.4.1.1 Site, Crane, And Payload Description

The fourth experiment was performed at the IMF Crane and Rigging's crane yard. A 25-ton on-road FMC Link Belt rubber tire hydraulic crane was tested. The crane has a variable length mast and suspends its payload from a single-part line.

The test load was a 2 cubic yard concrete bucket weighing approximately 800 pounds. This payload is symmetrical.

6.4.1.2 Dimensions Of Test 4

The location of the test relative to the crane, the length of the crane's mast, and the mass of the payload are given in the illustration that follows.

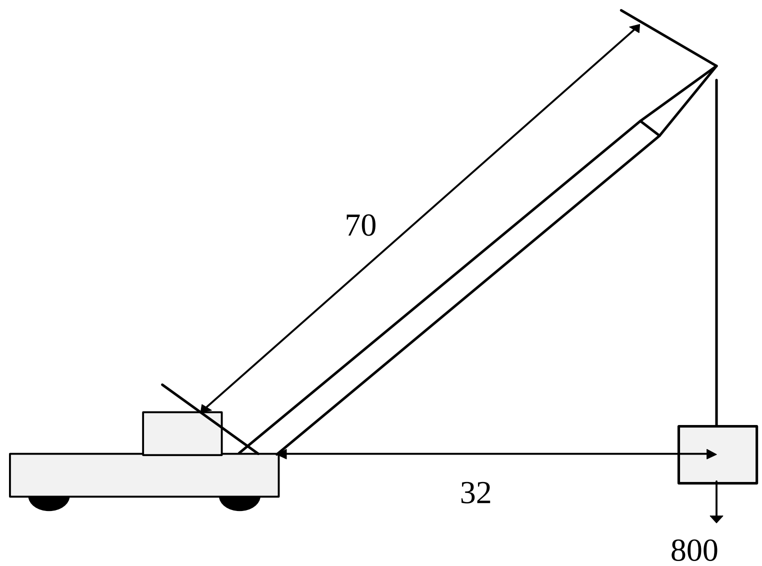

Figure 6.16 Dimensions Of Test 4

6.4.1.3 Percentage of Capacity

The lifting capacity of the 25-ton FMC Link Belt crane at 32 feet is 12,580 pounds. With a 800 pound load, the percentage of capacity is 6.4 percent.

6.4.1.4 Picture Of The Experiment

6.4.2 Perpendicular To The Mast

This experiment begun with oscillations initiated perpendicular to the mast of the crane.

6.4.2.1 Resonance Curve

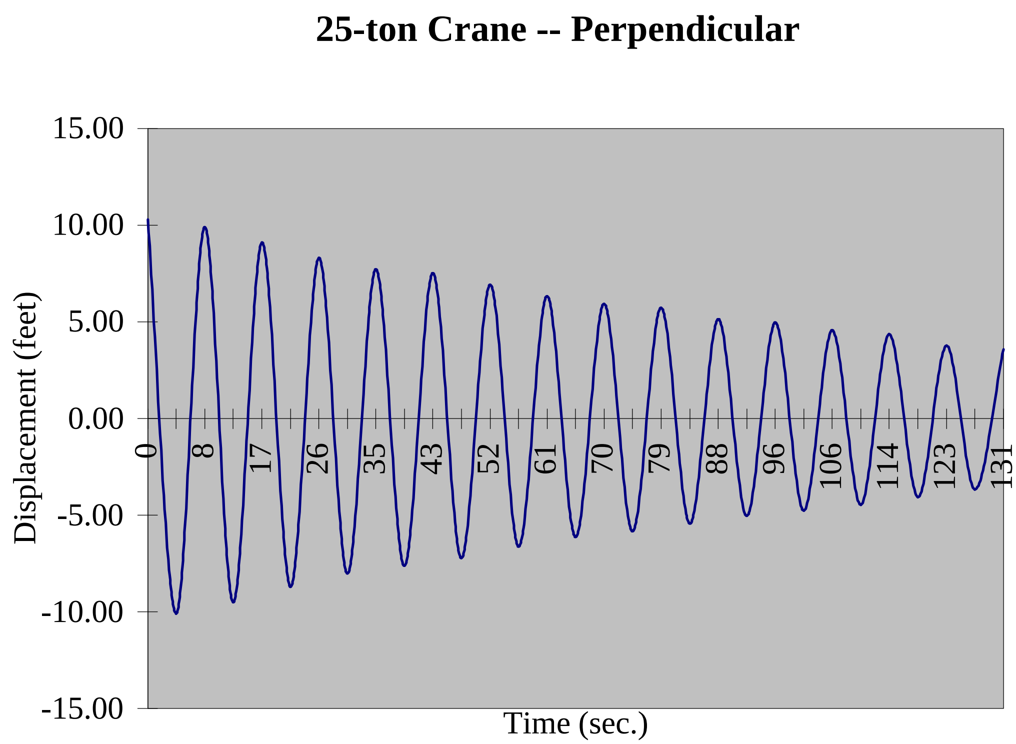

Figure 6.17 Test 4, Perpendicular - Resonance Curve

The first recorded oscillation peak was 10.3 feet from the equilibrium position. The peaks decayed to 3.6 feet over 15 complete oscillations, requiring 131 seconds. The oscillation peaks decay across the test interval.

6.4.2.2 Graph Of Internal Damping Rate Vs. Oscillation Number

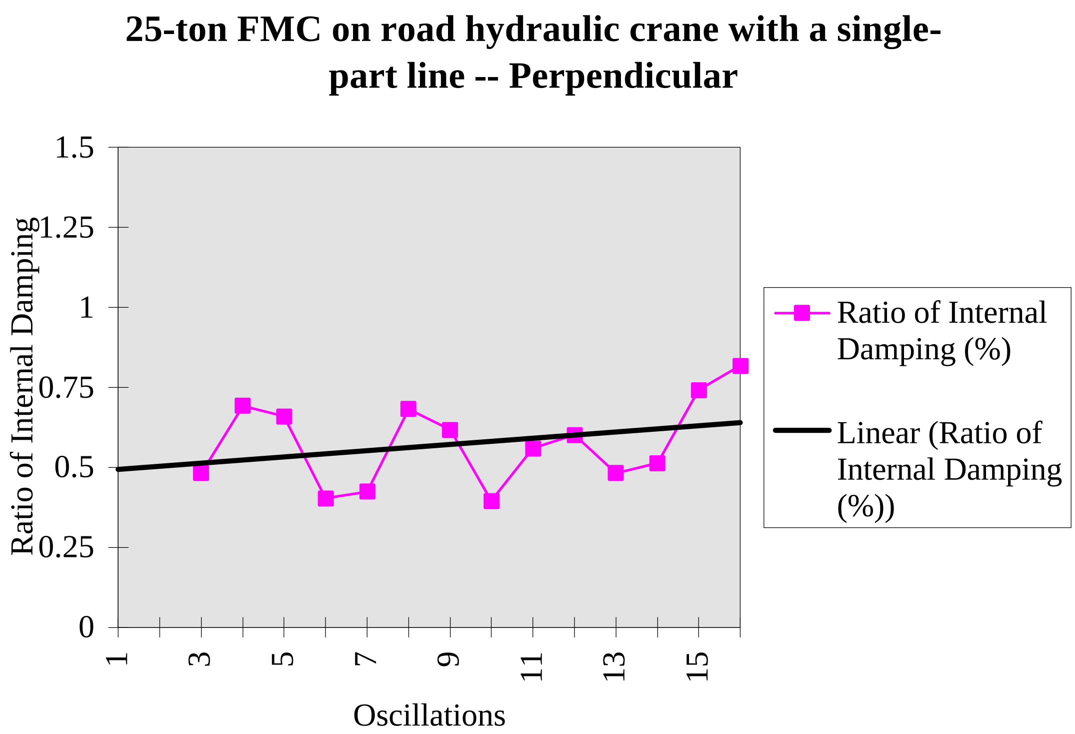

Figure 6.18 Test 4, Perpendicular - Graph Of Internal Damping Rate

The internal damping rate increased across the interval. The average is 0.58 percent.

6.4.2.3 Frequency Comparison

The cable length for this experiment was 62 feet, producing a theoretical frequency of 0.115. This frequency has a period of 8.7 seconds. The period exhibited during the experiment was 8.7 seconds.

6.4.3 Parallel To Mast

The second portion of this experiment was to initiate pendulations parallel to the mast of the crane.

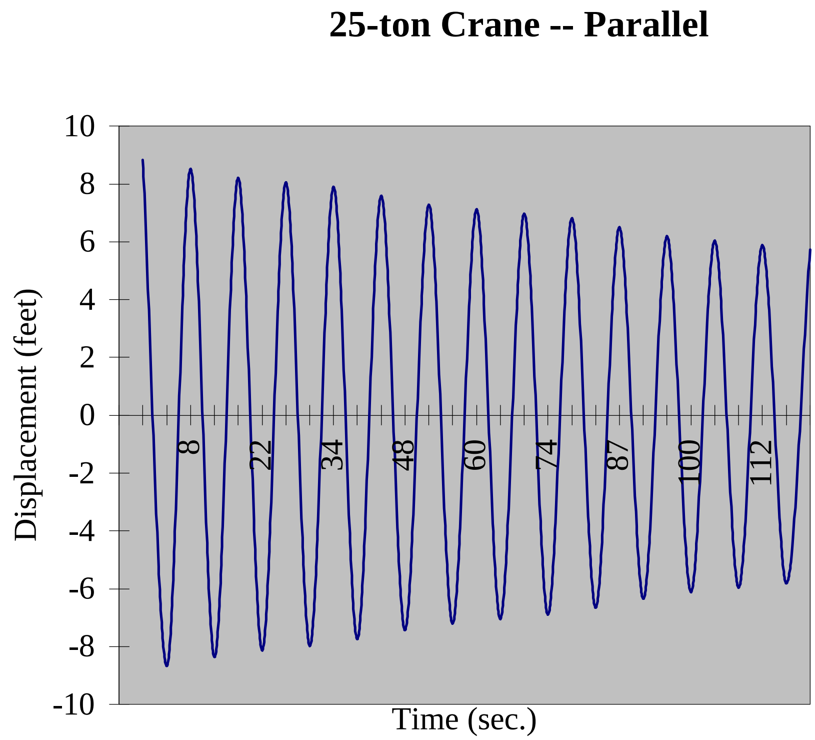

Figure 6.19 Test 4, Parallel - Resonance Curve

The oscillations initiated parallel to the mast of the 25-ton crane decrease slowly across the interval. The first peak was almost 9 feet from the equilibrium, while the last peak was less than 6 feet from the equilibrium. The payload was allowed to oscillate for 121 seconds, or 14 oscillations.

6.4.3.1 Graph Of Internal Damping Rate Vs. Oscillation Number

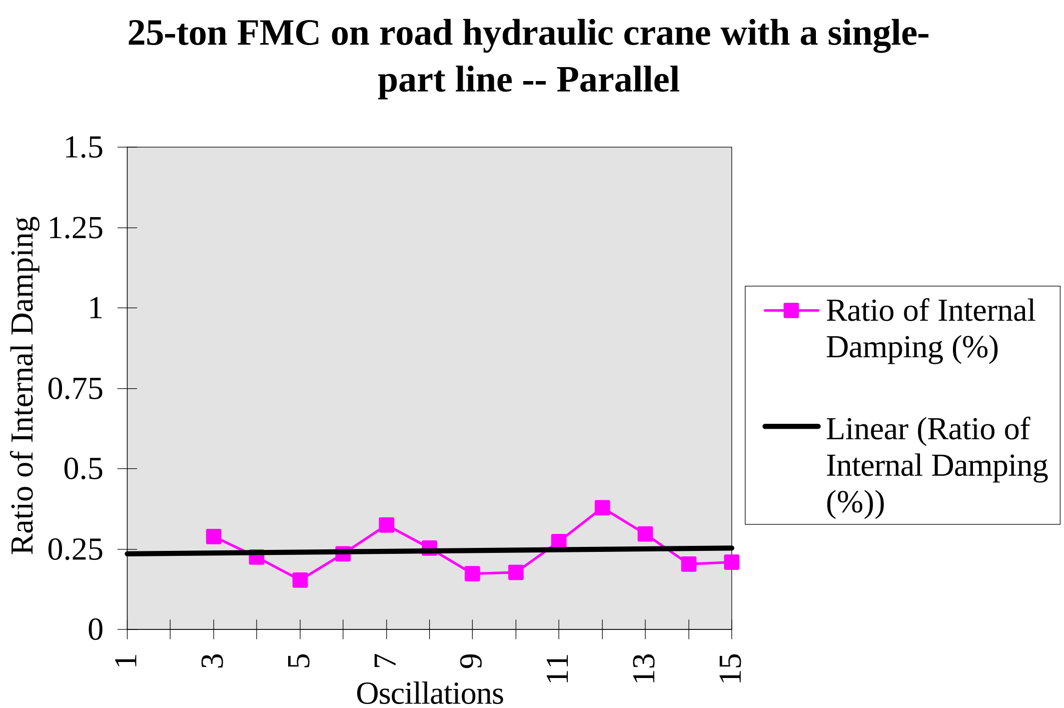

Figure 6.20 Test 4, Parallel - Graph Of Internal Damping Rate

The internal damping rates remained relatively constant over the interval. The average internal damping rate is 0.25 percent.

6.4.3.2 Frequency Comparison

The cable length for this experiment was 62 feet, producing a theoretical frequency of

0.115. This frequency has a period of 8.7 seconds.

The period exhibited during the experiment was 8.6 seconds.

6.4.4 Results

The internal damping rate was greater for the test performed perpendicular to the mast of the crane. In both cases the internal damping rate increased slightly across the test interval.

In both cases the frequency was very close to that of a simple pendulum.

Table 6-5 Results Of Test 4

Test Direction	Internal Damping Rate (%)	Percentage of Capacity	Theoretical Period	Observed Period
Perpendicular	0.58	6.4	8.7	8.7
Parallel	0.25	6.4	8.7	8.6

6.5 Test 5

The actual test data is included in Appendix A.

6.5.1 Similar Test Parameters

This section describes all of the parameters that are the same for both tests performed perpendicular and parallel to the mast of the crane.

6.5.1.1 Site, Crane, And Payload Description

The last experiment was performed at the IMF Crane and Rigging's crane yard. A 60-ton on-road P & H T-600 XL rubber-tire hydraulic crane was tested. This crane has a variable length mast and suspends its payload from a four-part line.

The test load was a 2 cubic yard concrete bucket, weighing approximately 800 pounds. This payload is symmetrical.

6.5.1.2 Picture Of The Experiment

6.5.2 Perpendicular To Mast

The first portion of the test initiated pendulations perpendicular to the mast of the crane.

6.5.2.1 Dimensions of the test

The location of the payload with respect to the crane, the length of the mast, and the mass of the payload are depicted in the illustration that follows.

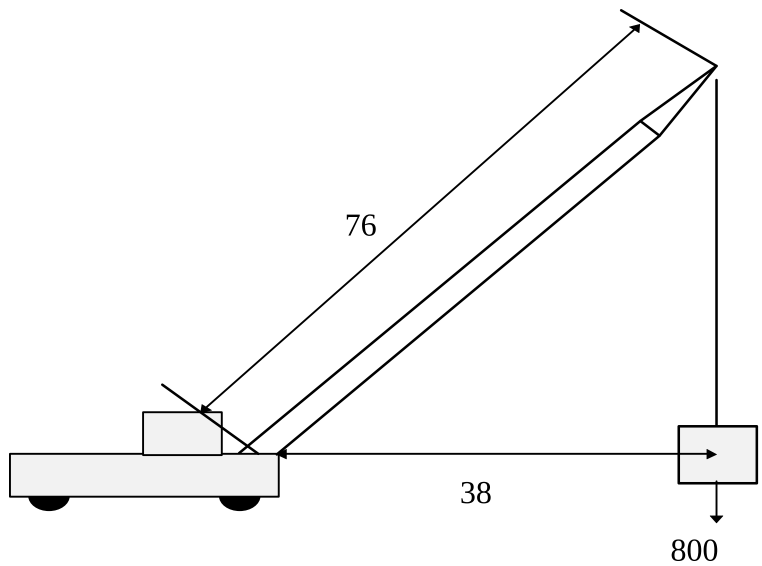

Figure 6.21 Test 5, Perpendicular - Dimensions Of Test

6.5.2.2 Percentage Of Capacity

The lifting capacity of the P & H crane at 38 feet, with a 76-foot mast, is 22,980 pounds. With a payload of 800 pounds, the percentage of capacity is 3.5 percent.

6.5.2.3 Resonance Curve

The oscillation peaks decrease slowly across the test interval, indicating a low internal damping rate.

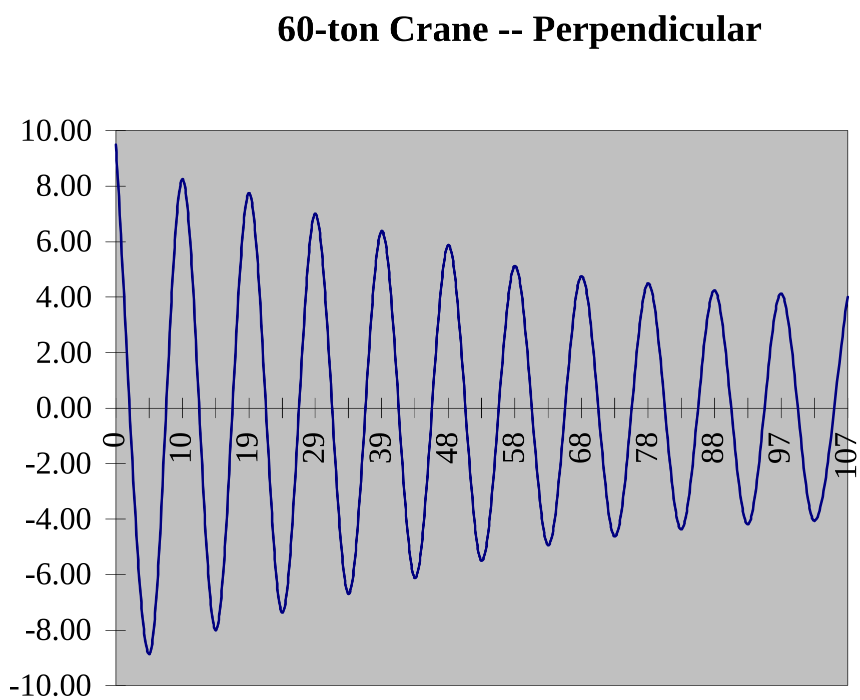

Figure 6.22 Test 5, Perpendicular - Resonance Curve

The oscillation peaks decreased from 9.5 feet to 4 feet in 107 seconds. The payload was allowed to pendulate thorough 11 complete oscillations.

6.5.2.4 Graph Of Internal Damping Rate Vs. Oscillation Number

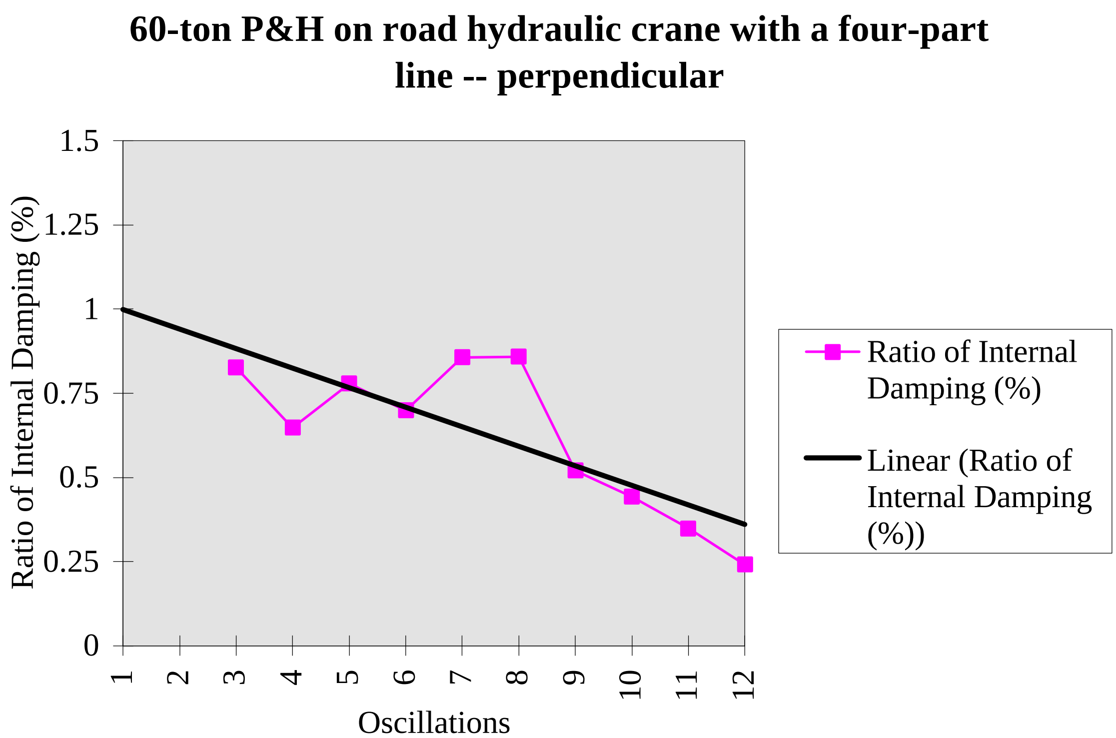

Figure 6.23 Test 5, Perpendicular - Graph Of Internal Damping Rate

The average internal damping rate was calculated to be 0.65 percent. The internal damping rate decreases across the test interval.

6.5.2.5 Frequency Comparison

The natural frequency of a simple pendulum with a 66-foot cable is 0.11. The period of which is 9 seconds.

The frequency of the oscillating payload was 9.7 seconds. The longer period is attributed to divergence from the conditions of simple pendulum motion. No single cause was observed during the experiment.

6.5.3 Parallel To The Mast

The second portion of the experiment pendulations were initiated parallel to the mast of the crane.

6.5.3.1 Dimension Of The Test

Due to overhead power lines the payload had to be moved, to allow for pendulations parallel to the mast. The new parameters are illustrated below.

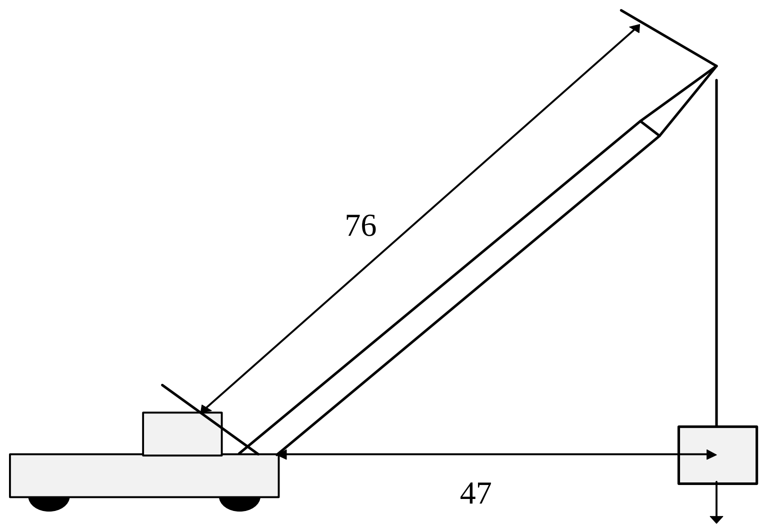

Figure 6.24 Test 5, Parallel - Dimensions Of Test

6.5.3.2 Percentage Of Capacity

The lifting capacity of the P & H at 47 feet from the crane is 13,240 pounds. With a 800 pound payload, the percentage of capacity is 6.0 percent.

6.5.3.3 Resonance Curve

The oscillation peaks slowly approach the axis, indicating a low internal damping rate.

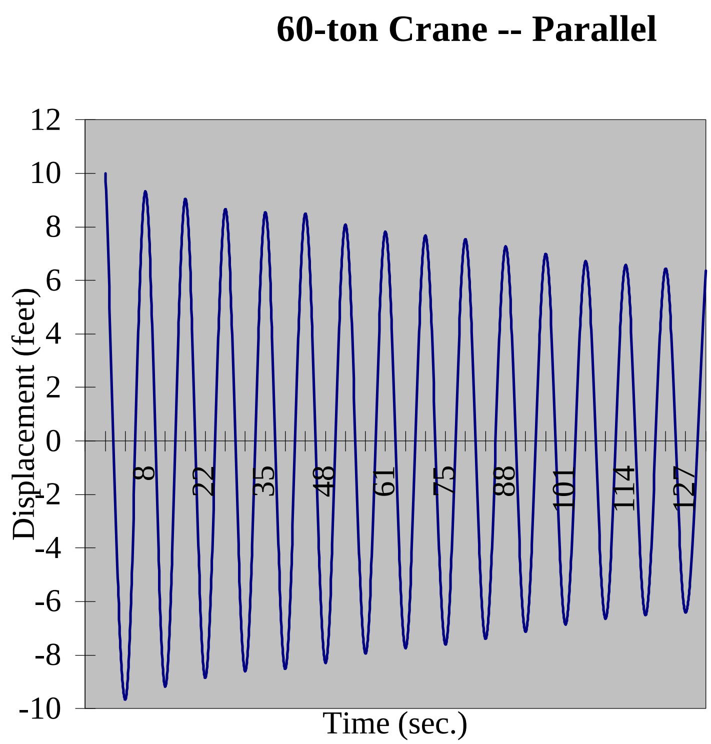

Figure 6.25 Test 5, Parallel - Resonance Curve

The test performed parallel to the mast was allowed to oscillate through 15 periods, requiring 131 seconds. The oscillation peaks decreased from 10 feet to 6.4 throughout the course of the test.

6.5.3.4 Graph Of The Internal Damping Rate Vs. Oscillation Peaks

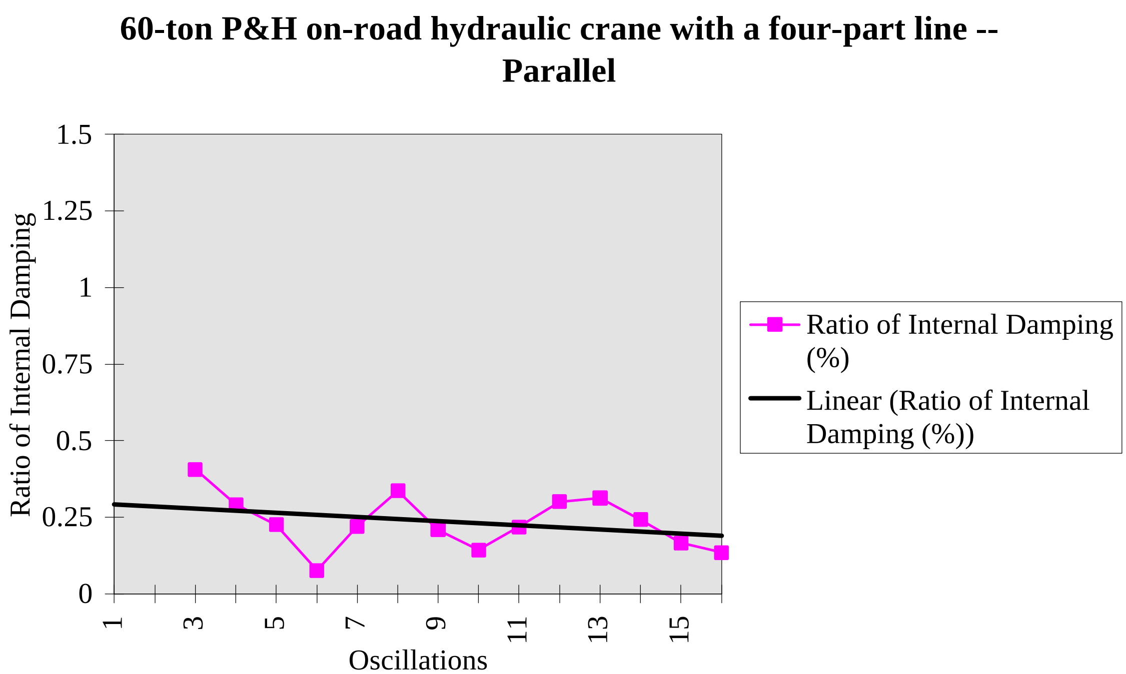

Figure 6.26 Test 5, Parallel - Graph Of Internal Damping Rate

The average internal damping rate was calculated to be 0.22 percent. The value of the internal damping rates decreased slowly across the interval.

6.5.3.5 Frequency Comparison

The natural frequency of a simple pendulum with a 60-foot cable is 0.12, having a period of 8.6 seconds.

The frequency observed during the experiment was 8.7 seconds.

6.5.4 Results

The test-performed perpendicular to the mast returned a greater internal damping rate than that of the test performed parallel to the mast. The value of the internal damping rate decreased across both of the test intervals.

Table 6-6 Results Of Test 5

Test Direction	Internal Damping Rate (%)	Percentage of Capacity	Theoretical Period	Observed Period
Perpendicular	0.65	3.5	9	9.7
Parallel	0.22	6	8.6	8.7

7. Summary and Conclusions

7.1 Summary

The objective of this research is to determine if the internal damping rate of construction cranes is sufficiently low to allow a tuned mass damping system to operate. Recall that the allowable internal damping rate for a crane is determined by the internal damping rate of the tuned mass damping system. As long as the tuned mass damping system has an internal damping rate at least twice that of the construction crane, then tuned mass damping is feasible.

In determining the internal damping rate of construction cranes, the motion of a pendulating payload was modeled as a simple pendulum. The internal damping rate of simple harmonic motion can be determined using the logarithmic decrement equation. Experiments were performed with a payload oscillating over a measurement scale. Data was extract from video to the experiments.

To make statistically accurate predictions about a particular construction crane's internal damping rate would require a large data base of similar construction cranes tested under similar conditions. The objective of this research is to broaden the base of knowledge about the internal damping rate of construction cranes. This knowledge provides insight towards the types of construction cranes that are most suitable for the application of a tuned mass damping system.   To obtain this objective many different types and sizes of cranes were tested.

Two lattice boom and three hydraulic cranes were tested. Their capacities ranged from 25 to 100 tons. These cranes represent a spectrum of cranes that are often used on construction sites. The experiments were designed to simulate duty cycle operations, the most probable application of a tuned mass damping system. This research suggests that, under duty cycle conditions, the damping rate appears to be on the order of 1 percent.

A FMC Link Belt 25-ton hydraulic crane was tested at 6.4 % of capacity. It's internal damping rates ranged between 0.25 and 0.6 percent. The lower value represents the test performed parallel to the mast of the crane, and the upper value is reflective of test performed perpendicular to the boom. A 50-ton FMC Link Belt was tested at 10.0 % of capacity and had a damping rate of 0.18 percent for both tests. The third hydraulic crane was a 60-ton P&H T-600XL. It was tested at 6.0 % parallel and 3.5% perpendicular to the mast. It exhibited damping rates between 0.22 and 0.65 percent, respectively.

Two lattice boom cranes with capacities of 70 and 100 tons were tested. The 70-ton

LIMA 778c's damping rates were between 0.06 and 1.3 percent. This test was performed at 15% of capacity. A 100-ton Link Belt LS318 was tested at 6.8% of capacity and had damping rates between 0.07 and 0.08 percent.

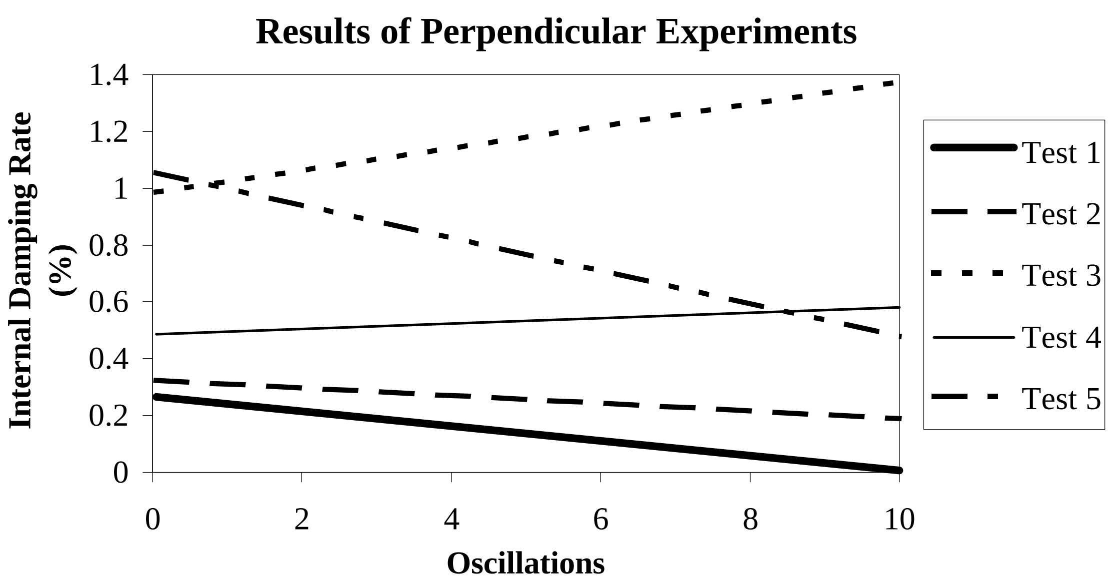

Figure 7.1 Results Of Perpendicular Experiments

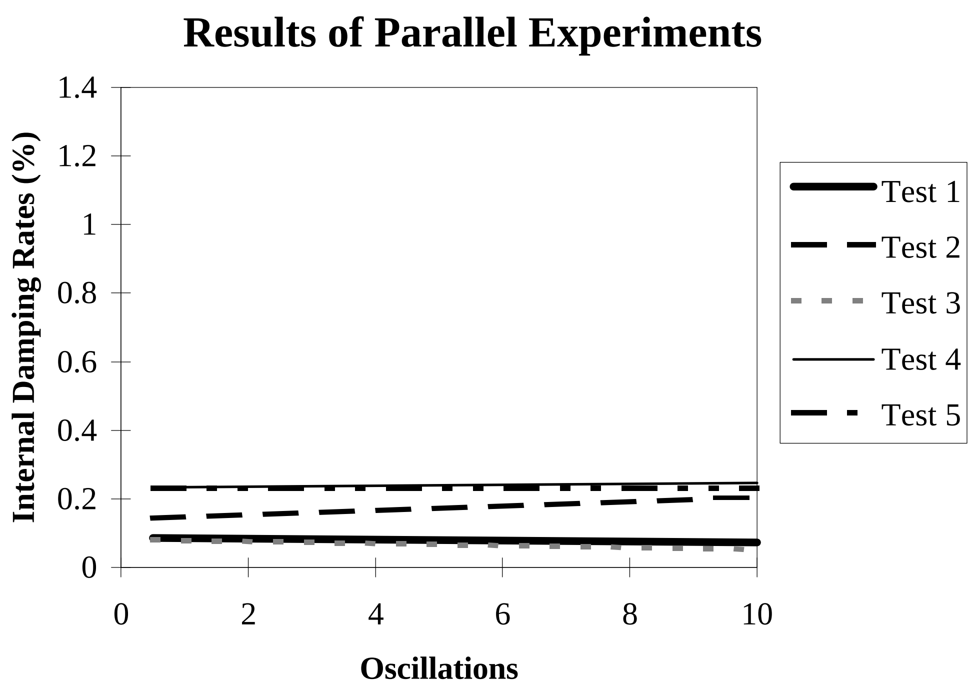

Figure 7.2 Results Of Parallel Experiments

For every crane the experiment performed perpendicular to the mast of the crane returned a larger damping rate than the test performed parallel to the mast of the crane. The graph shows that the internal damping rates are on the order of one percent. A truth plot is used to examine the validity of the results.

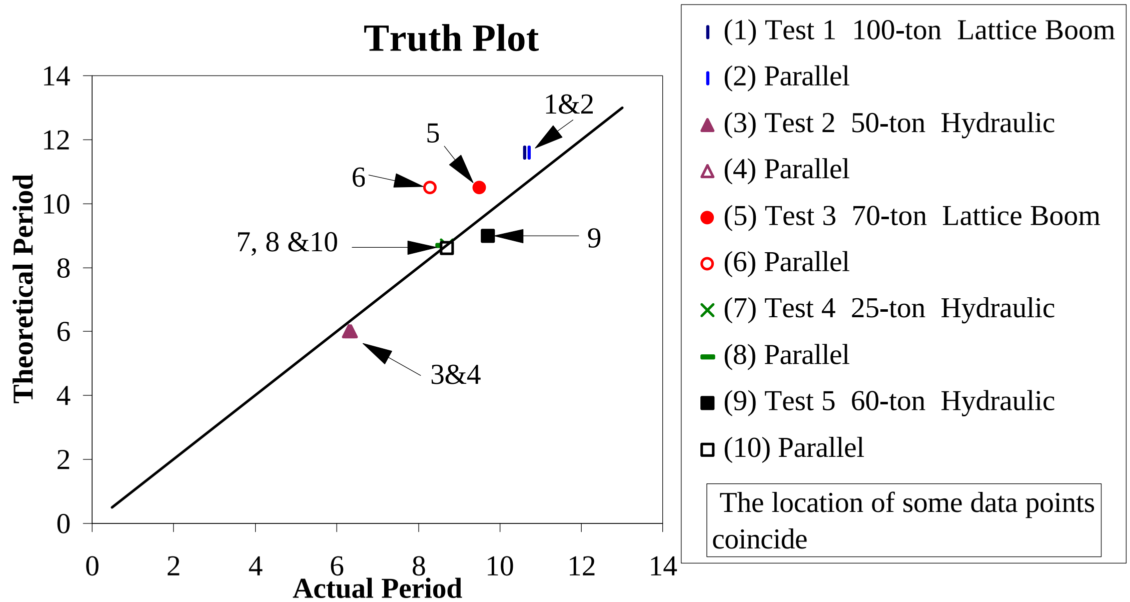

Figure 7.3 Truth Plot

In the graph, the actual values for the period of oscillation are plotted against the period of a simple pendulum. If the value of the actual results coincide with theory, then the points will lie on the x = y line. If the test diverged from the theory, then the point will lie to either side of the truth line. The graph shows that the results are reflective of theory.

7.2 Recommended Uses And Significance

This research was initiated to determine the feasibility of applying a tuned mass damping system to the problem of payload pendulations. Previous research concluded that tuned mass damping is a potential means of attenuating the energy of a pendulating payload.

However, in order to be effective the internal damping rate of the tuned mass damping system must be at least twice that of the construction crane. To design an effective tuned mass damping system for application to construction cranes, the internal damping rate of the construction crane must be quantified. Ultimately, this research aids in the designing of a tuned mass damping system, to combat payload pendulations.

Prototypes of tuned mass damping systems have been developed with damping rates as high as 12%. This research determined that the internal damping rate of the construction cranes tested is on the order of 1 percent. This is sufficiently low to indicate that a tuned mass damping system could be applied to construction cranes.

7.3 Future Extension

The research presented here is considered an initial investigation of the internal damping rate of construction cranes. Future research extensions include a detailed analysis of the motion of a pendulating payload and the performance of more damping tests.

Through out the performance of this research, the motion of the pendulating payload was often not that of a simple pendulum. Secondary pendulations often arose about the turnbuckle located above the hook. The payload would often leave planer motion and begin to scribe ellipses. The mast of the crane moved when large loads were applied.

These motions are not the motion of a simple pendulum, and were noted during the performance of the damping tests. In order to accurately determine the internal damping rate of construction cranes, the motion of a pendulating payload could be more accurately modeled.

This research was limited to testing five construction cranes. A much larger statistical base is needed to make confident predictions about the internal damping rate of all construction cranes. Additional experiments should include a detailed analysis of cranes under many load configurations, including tests at greater percentages of capacity. The greatest internal damping rate achieved by this research was at the greatest percentage of capacity.

7.4 Conclusions

The tests performed by this research indicate that the internal damping rate of construction cranes is sufficiently low for the application of a tuned mass damping system. The internal damping rate of construction cranes, performing duty cycle operations, is on the order of one percent.

The forces applied to the crane by the pendulating payload appear to have the greatest impact upon the internal damping rate. Large loads or oscillation peaks increase the forces applied to the mast of the crane. The damping rate increases as the magnitude of the loads increases. This theory is substantiated by a number of factors.

- Test 3 was performed at the greatest percentage of capacity. It displayed the greatest internal damping rate and divergence form theory.
- The internal damping rate for the majority of the tests decrease as the oscillation peaks decrease.
- The internal damping rate is greater when the load pendulates perpendicular to the mast of the crane.

This research determined that the internal damping rate is on the order of one percent for construction cranes operating under duty cycle conditions. This suggests that a tuned mass damping system could be applied to payload pendulation problems. If the internal damping rate increases with a particular configuration, the increased damping rate will naturally decrease the magnitude of the pendulations.

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Appendix A

Experimental Data

The following appendix presents the data from which the results were calculated.

Test 1

Site Location: Virginia Tech campus, Site of the new mechanical engineering building

Host: Branch and Associates, Inc.

Type of crane: 100-ton crawler crane

Manufacture: Link Belt LS 318

Boom type and length: 120-foot lattice-boom crane

Type of line: Single-part line

Load information: 2200 lb. 42” caisson auger

Perpendicular to mast

Table A-1: 100-ton Link Belt - Perpendicular

Number of oscillations	Displacement (feet)	Time (sec.)	Ratio of Internal Damping (%)
0	8.75	0	
1	8.33	9	
2	8.15	20	0.28
3	8.05	31	0.14
4	8	42	0.07
5	7.95	52	0.05
6	7.9	63	0.05
7	7.8	74	0.08
8	7.8	84	0.05
9	7.75	95	0.03
10	7.5	106	0.16

Parallel to mast

Table A-2: 100-ton Link Belt - Parallel

Number of oscillations	Displacement (feet)	Time (sec.)	Ratio of Internal Damping (%)
0	8.9	0	
1	8.85	10	
2	8.75	21	0.07
3	8.75	32	0.05
4	8.66	42	0.04
5	8.5	53	0.12
6	8.35	64	0.15
7	8.3	74	0.10
8	8.2	85	0.07
9	8.1	96	0.10
10	8.1	106	0.05
11	8	117	0.05
12	8	128	0.05

Test 2

Site Location: IMF crane yard

Host: IMF Crane & Rigging, Inc.

Type of crane: 50-ton rubber tire hydraulic crane (on-road)

Manufacture: FMC Link Belt

Boom type and length: Variable boom length (telescoping steel box beams)

Type of line: Four-part line

Load information: ~1500 lbs. clamshell bucket

Perpendicular to mast

Table A-3: 50-ton Link Belt - Perpendicular

Number of oscillations	Displacement (feet)	Time (sec.)	Ratio of Internal Damping (%)
1	3.5	0	
2	3.33	6	
3	3.1	12	0.48
4	3.1	19	0.29
5	3	25	0.13
6	2.9	31	0.27
7	2.9	38	0.14
8	2.8	44	0.14
9	2.75	51	0.21
10	2.67	57	0.19
11	2.66	63	0.13
12	2.6	70	0.11
13	2.55	76	0.17
14	2.5	83	0.16
15	2.45	89	0.16
16	2.4	95	0.16

Parallel To The Mast

Table A-4: 50-ton Link Belt - Parallel

Number of oscillations	Displacement (feet)	Time (sec.)	Ratio of Internal Damping (%)
1	10	0	
2	9.25	6	
3	9.05	12	0.40
4	9	19	0.11
5	8.9	25	0.07
6	8.75	31	0.11
7	8.67	38	0.10
8	8.5	44	0.12
9	8.25	51	0.20
10	8	57	0.24
11	7.75	64	0.25
12	7.5	70	0.26
13	7.2	76	0.29
14	7	83	0.28
15	6.9	89	0.17

Test 3

Site Location: Bridge being constructed in Salem, on I-81.

Host: Branch Highways, Inc.

Type of crane: 70-ton rubber tire crane

> **Manufacture:** LIMA 778C
>
> **Boom type and length:** 100’ lattice boom
>
> **Type of line:** Single-part line

Load information: 2.4 ton cylindrical concrete counter weight

Perpendicular To The Mast

Table A-5: 70-ton LIMA - Perpendicular

Number of oscillations	Displacement (feet)	Time (sec.)	Ratio of Internal Damping (%)
1	7.5	0	
2	6.6	9	
3	5.75	18	1.06
4	5	28	1.10
5	4.2	38	1.24
6	3.4	47	1.52
7	2.8	57	1.62
8	2.45	66	1.32
9	2	76	1.32
10	1.75	85	1.36
11	1.5	94	1.14
12	1.25	105	1.33

Parallel To Mast

Table A-6: 70-ton LIMA - Parallel

Number of oscillations	Displacement (feet)	Time (sec.)	Ratio of Internal Damping (%)
1	9.3	0	
2	9.25	9	
3	9.2	17	0.04
4	9.1	26	0.06
5	9	35	0.09
6	8.9	44	0.09
7	8.8	53	0.09
8	8.75	62	0.07
9	8.75	71	0.02
10	8.7	80	0.02
11	8.67	89	0.04
12	8.6	98	0.05
13	8.55	107	0.06
14	8.5	116	0.05

Test 4

Site Location: IMF crane yard

Host: IMF Crane & Rigging, Inc.

Type of crane: 25-ton rubber tire hydraulic crane (on-road)

Manufacture: FMC Link Belt

Boom type and length: Variable boom length (telescoping steel box beams)

Type of line: Single-part line

Load information: 2 CY concrete bucket weigh approximately 800 pounds.

Perpendicular To Mast

Table A-7: 25-ton Link Belt - Perpendicular

Number of oscillations	Displacement (feet)	Time (sec.)	Ratio of Internal Damping (%)
1	10.3	0	
2	9.9	8	
3	9.1	17	0.48
4	8.3	26	0.69
5	7.7	35	0.66
6	7.5	43	0.40
7	6.9	52	0.42
8	6.3	61	0.68
9	5.9	70	0.62
10	5.7	79	0.39
11	5.1	88	0.56
12	4.9	96	0.60
13	4.6	106	0.48
14	4.4	114	0.51
15	3.8	123	0.74
16	3.6	131	0.82

Parallel To Mast

Table A-8: 25-ton Link Belt - Parallel

Number of oscillations	Displacement (feet)	Time (sec.)	Ratio of Internal Damping (%)
1	8.8	0	
2	8.5	8	
3	8.2	17	0.29
4	8.1	26	0.22
5	7.9	34	0.15
6	7.6	43	0.24
7	7.3	52	0.33
8	7.1	60	0.25
9	7.0	69	0.17
10	6.8	78	0.18
11	6.5	87	0.27
12	6.2	95	0.38
13	6.0	104	0.30
14	5.9	112	0.20
15	5.7	121	0.21

Test 5

Site Location: IMF crane yard

Host: IMF Crane & Rigging, Inc.

Type of crane: 60-ton rubber tire hydraulic crane (on-road)

Manufacture: P & H T-600 XL

Boom type and length: Variable boom length (telescoping steel box beams)

Type of line: four-part line

Load information: 2 CY concrete bucket weigh approximately 800 pounds.

Perpendicular To Mast

Table A-9: 60-ton P&H - Perpendicular

Number of oscillations	Displacement (feet)	Time (sec.)	Ratio of Internal Damping (%)
1	9.5	0	
2	8.3	10	
3	7.8	19	0.83
4	7.0	29	0.65
5	6.4	39	0.78
6	5.9	48	0.70
7	5.1	58	0.86
8	4.8	68	0.86
9	4.5	78	0.52
10	4.3	88	0.44
11	4.1	97	0.35
12	4.0	107	0.24

Parallel To Mast

Table A-10: 60-ton P&H - Parallel

Number of oscillations	Displacement (feet)	Time (sec.)	Ratio of Internal Damping (%)
1	10.0	0	
2	9.3	8	
3	9.0	17	0.41
4	8.7	26	0.29
5	8.6	35	0.22
6	8.5	43	0.08
7	8.1	52	0.22
8	7.8	61	0.34
9	7.7	70	0.21
10	7.5	79	0.14
11	7.3	88	0.22
12	7.0	96	0.30
13	6.7	106	0.31
14	6.6	114	0.24
15	6.4	123	0.17
16	6.4	131	0.14

Appendix B

Testing procedure

Following is a list of the procedures that were used in the testing of cranes.

1. Locate a suitable crane, and gain permission to perform a test.
2. Collect required materials for testing
    - tape measure
    - video camera
    - tripod
    - scale, (2) 8’ boards with 1/4’ increments
    - note pad
3. Select a suitable load and determine the mass
4. Have operator rig load.
5. Determine the distance of the payload from the crane to provide the desired lifting capacity.
6. Suspend the load at the desired location and confirm the distance form the load to the pivot point of the mast.
7. Determine the length of the mast
8. Place the scale beneath the load, perpendicular the direction of the test

9. Position the video recorder and begin filming

10. Initial pendulation

11. Film the decay

12. Reposition the camera and scale for the succeeding tests, and repeat.

Appendix C

Data Reduction

The end product from the experimentation is data. This data must be converted from its raw form into usable information. Following an experiment the video footage containing the oscillation peaks must be reduced into a data table. The purpose of this appendix is to describe the methods used to ensure an accurate reduction of the data.

To calculating the internal damping rate, the relative number of the oscillation peak and it's maximum displacement, must be determined. The proceedings were video taped, so as to minimize the interference to site operations. To determine the maximum displacement of an oscillation peak a scale was position beneath the payload. When replaying the footage of the experimentation, if the tape is advanced frame by frame, then an oscillation peak can be identified and quantified.

At the first oscillation peak, of the sample interval, the counter is reset to zero. This represents the first oscillation peak at time 0.

In determining the maximum displacements measurements must be made form the center of gravity of the payload. Therefore, at the conclusion of the experiments the load was rotated while pendulating. Objects rotate about their center of gravity. From this simple procedure, the center of gravity of the payload could be visually identified.

When an oscillation peak has been identified, by advancing and reversing the frames of the video, the center of gravity of the payload located. The maximum displacement is determined by extending a vertical line from the center of gravity of the payload to the scale on the ground below. The intersection of this vertical line with the center of gravity of the payload at its maximum displacement is called an oscillation peak.

Once identified the number of the oscillation, displacement, and time are recorded. This procedure is performed over the desired interval.

Vita

The author, Paul Ely, was born on 31 July 1969 in Washington, DC. He was raised in Charlottesville, VA and graduated from Charlottesville High School in 1987. In December of 1991, he earned a Bachelor of Science degree form Virginia Polytechnic Institute and State University in Civil Engineering. Upon graduation, he began work for a soil and environmental consultant. Following two years of work, he returned to Virginia Polytechnic Institute and State University to pursue a Master of Science degree in Civil Engineering. Upon receiving his Master of Science, the author hopes to begin work within the industry.