CREATION OF A VIRTUAL SIMULATION ENVIRONMENT FOR EXPERIMENTATION WITH THE KINEMATICS OF CRANE HOISTING OSCILLATORY MOTION

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ABSTRACT

Crane hoisting operations represent a significant portion of the work scope on construction sites, especially those that adopt a modularized approach to construction. Creating metrics that can be used in the automation of these processes can result in higher jobsite efficiencies from a safety and productivity perspective. This study seeks to create a virtual simulation environment that can be experimented with to generate the required metrics for crane hoisting automation. The equation of motion for this oscillatory motion will first be defined. Thereafter numeric solutions to this equation will be explored from a continuous simulation perspective using Simphony.NET. Work on this will commence by prototyping simple pendulum motion after which extensions will be made to mimic crane hoisting oscillatory motion.

1 INTRODUCTION

The Oscillation problem consists of dynamics that are composed of concepts from both the worlds of Physics and Mathematics. An example is the swing of a pendulum which involves both the Laws of Motion as described in Classical mechanics and vibration response analysis that allows for an efficient formulation of the equations of Motion using Differential calculus. Movement and Equations from the above scenarios can be modeled numerically using Simulation especially through Continuous Simulation.

Discrete Event Simulation (D.E.S) is concerned with mimicking a system as it changes with the progression of time. It does this by giving a representation of the real-life system at distinct points in time by showing its state at those instances of interest. Events are said to occur at those specific points and can be analyzed from then on.

D.E.S can be done by hand using calculations even though the amounts of data and processing involved are usually vast. This makes it more convenient to perform the same computations using digital Computing devices. Service facilities and queueing systems can be studied this way for example when determining the amount of time a customer spends in a banking hall before getting a chance to be served by a teller, for instance if they need to settle an electric utility bill. Another example would be when a refugee goes to a food distribution hall at specified times of a month to collect their in-kind food rations and leave the food corridors after undergoing biometrics checks to establish their identities.

Continuous Simulation (C.S) involves representing a system whose state variables keep constantly changing. On a normal basis, this entails formulating differential equations that give the rates at which state variables get modified with time. If they are simple enough, their solutions can be obtained analytically. If not, a numerical approach has to be taken towards solving the problem. Simphony as a software has the capability to carry out both types of simulations above.

2 PROBLEM STATEMENT

The construction industry carries out hosting of materials especially on residential, commercial and industrial projects. They all involve cranes which tend to be inefficient when a site is congested and heavy objects need to be lifted. The operations are all reliant on an operator's prior experience with the task. Studies in the past have shown that most crane accidents experienced are due to human errors made by the operator (Worker's Compensation Board of British Columbia1992).

Crane hoisting problems lend themselves easily to automation. Lifting operations can be encoded into Programmable Logic Controllers (PLCs) inside electronics that govern the movements of booms and jibs on a crane. Crane operators with less experience can also benefit from the above by getting guarantees of higher productivity and safety rates with minimal effort. As a starting operation, computer-based simulations can be applied in order to predict the motion of cranes abstracted as the swings of a simple pendulum.

2.1 Approach to problem solving

- *Step 1*: Develop **a proof of concept,** that is use a simple pendulum with a fixed support and length of string and excitations applied by displacing a mass,
- *Step 2*: Use **an actual system**, that is a complex pendulum with excitations applied at the support which will initially be moved to displace its mass / bob from the initial condition i.e. equilibrium position.

3 LITERATURE REVIEW

Cranes and derricks are types of mechanical devices that were primarily invented to assist in lifting and lowering loads. In the past, the techniques for designing Engineering equipment was limited by use of simplified methods that had to be carried out by hand using tables of data or rules of thumb. With the recent developments in the field of digital computing, there has been vast improvements in the ability to carry out more complex calculations. Together with advances in Materials Science, more sophisticated tooling is now available to carry out various tasks in Construction sites (Shapiro et al 1991).

One of the most important factors that affect the safety of a crane is its stability. This is a vital factor since they are most highly shared resource in a typical construction site. Accidents occur as a result of either the crane tipping or the load falling off the hook or slings (Al-Hussein et al 2009). Information regarding the lifting configuration, crane geometry and its component weight is hardly ever known beforehand. In addition, planning for mobile crane operations is normally based on the operator's experience and not an exact Scientific methodology such as results from experimental data collected.

Costs associated to cranes in a construction project are related to its size and how frequently or easy it is to relocate a unit. The larger the unit, the more time it takes on average to bring it apart into smaller and moveable pieces. It also requires a higher number of trucks to transport components to the destination which translates to more monetary expenses. The same applies during re-assembly. As a general rule, it is better to use larger difficult to move cranes on single sites where they are needed for longer durations of time. Smaller and more mobile units are preferable for shorter durations on sites.

The two major categories of cranes are Mobile cranes and Tower cranes (Puerifoy et al 2011). **Tower cranes** are of the type that are normally erected on site using component parts or is self-erecting. They are ideal for high-rise building projects. They are also used in circumstances where the movements of a mobile crane can be impeded or is not possible. The figure below shows components of a tower crane. It has the main parts that are common to most types of cranes for performing lifting of materials during a construction project, only that it is placed on top of a slab of concrete. An example is show in Figure 3.1.

Mobile Cranes are usually mounted on either a pair of continuous, parallel crawler tracks or a pair of wheels. Different types have the operator's cab inside a truck or placed on top of a turn-table. Mobile cranes are the most preferred method of lifting loads vertically in a construction site. The main reason is that they are quite flexible and can be made to change positions and move with a load depending on the ground conditions and space between structures present in a construction site. An example is in Figure 3.2

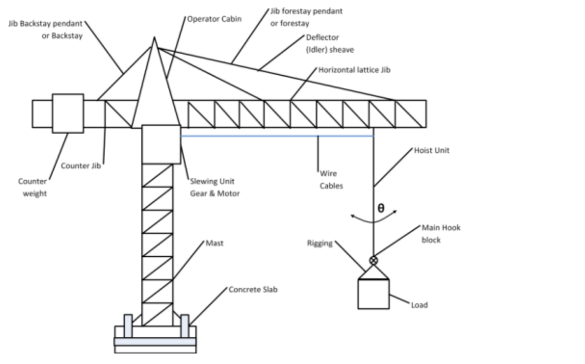


Fig. 3.1: Tower Crane

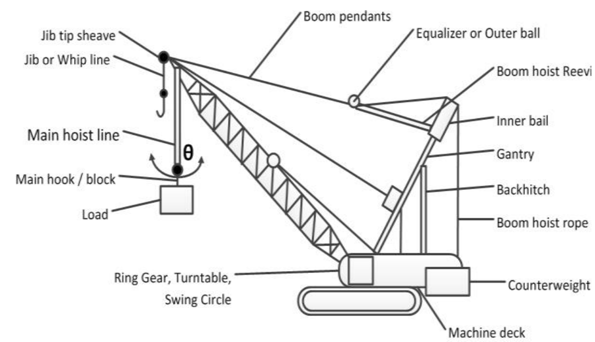


Fig. 3.2: Mobile Crane

There are three motions of interest for a crane during hoisting operations.
Hoisting Motion: Applied when lifting or lowering a load using a winch system,
Luffing Motion: Applied vertically in order to bring a load closer or further away from a crane's centre by moving the boom or jib,
Slewing Motion: Used by a crane to shift the load in a revolving manner from one position to the other.

3.1 Physics of the Problem

There are several types of pendulums with two being of more interest to the hoisting operation. It is important to note that a pendulum is being used to mimic the problem since it shows the same kind behavior as compared to a crane performing hoisting operations.

A simple pendulum is assumed to have its mass concentrated on a single point suspended from a fixed horizontal axis by a weightless cord. The mass moves about in the vertical plane due to the force of gravity it experiences. For that reason, Simple pendulums do not exist but can be modelled by a small but heavy bob hanging about a light, fine wire.
A complex pendulum is made up of a rigid body which is suspended from a fixed horizontal axis about which the body may swing in a vertical plane as a result of the push (not a pull) from Earth's gravitational forces.
A conical pendulum is similar to a simple pendulum with the variation that its suspended weight moves at a uniform speed around the circumference of a circle in a horizontal plane.

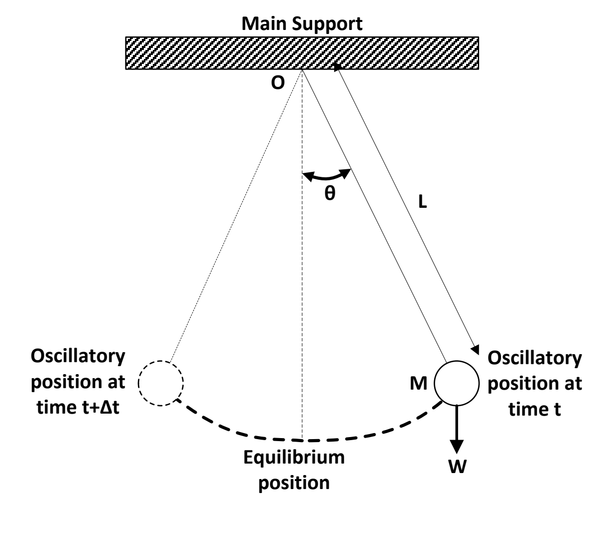


Fig. 3.3: Simple pendulum

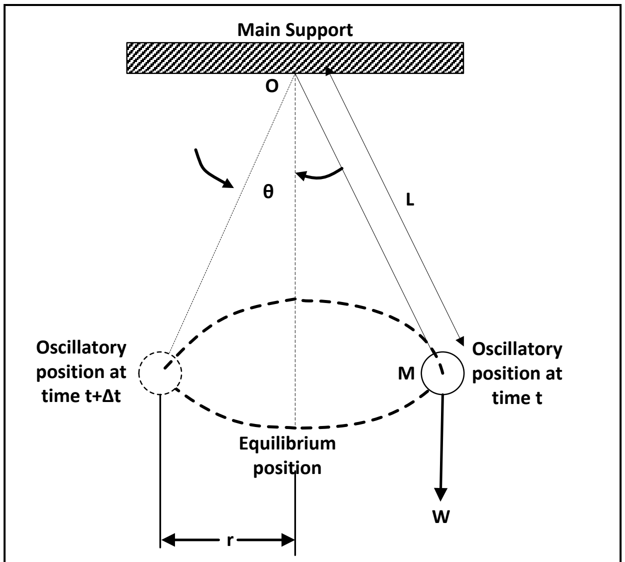


Fig. 3.4: Conical pendulum

Ordinarily, differential equations from Newtonian Mechanics are used are used to calculate equations of motion (Apostol, 1966). These determine instantaneous rates of change for different quantities such as the exact speed of a car in acceleration or the rates of fluid flow inside pipes. The most common differential equation is Newton's Second law of Motion:

$$F = m * a$$

Boundary value problems refers to a differential equation together with a set of initial conditions. **Initial boundary conditions** consists of an ordinary differential equation together with a specified value or a set of values that will allow us to determine which solution we would like to have at particular points. For a pendulum, the initial condition(s) appears below:

$$\theta''(0) = \theta_0$$
$$\theta_0 = 0$$

3.2.1 Equation of motion

These are equations that describe the behavior of physical systems in terms of its motion as a function of time **t**. For the pendulum motion, we are going to use its coordinates in space (***x, y pair*** to describe its position) together with its angular velocity $\boldsymbol{\omega}$ and its angle of swing $\boldsymbol{\theta}$

$$\theta'' + \frac{g}{l}\theta = 0$$

The equation above is the specific equation of motion for a body. Its general solution is as follows:

$$\theta(t) = e^{\frac{-at}{2}}(A \cos \boldsymbol{\omega}\, t + B \sin \boldsymbol{\omega}\, t)\ \textbf{(*)}$$

In order to arrive at the specific solution, the following steps have to be performed:

Compare the General Equation of Motion (Differential Equation – DE) to the Specific Equation:

$$y = 0$$
$$a = 0 \textbf{ (1)}$$
$$b = \frac{g}{l} \textbf{ (2)}$$
$$\boldsymbol{\omega} = \sqrt{b - 0.25^2} \textbf{ (3)}$$

Substitute (1) and (2) into (3)

$$\boldsymbol{\omega} = \sqrt{\frac{g}{l} - 0.25^2 * 0} = \frac{g}{l}$$

Substitute (1) and (4) into (*)

$$\theta(t) = e^{\frac{-0*t}{2}}(A * \cos\sqrt{\frac{g}{l}} * t + B * \sin\sqrt{\frac{g}{l}} * t)$$

$$\theta(t) = A\cos\sqrt{\frac{g}{l}} * t + B\sin\sqrt{\frac{g}{l}}\, t \textbf{ (*)(*)}$$

Apply the boundary conditions

$$\theta_0 = \theta_0 \textbf{ (5)}$$
$$\theta_0 = 0 \textbf{ (6)}$$

To find A and B we apply these boundary conditions

$$\theta''(t) = -A * \sqrt{\frac{g}{l}}\, \cos\sqrt{\frac{g}{l}} * t + B * \sqrt{\frac{g}{l}}\, \sin\sqrt{\frac{g}{l}} * t \textbf{ (*) (*) (*)}$$

Substitute (5) into (*) (*)

$$\theta_0 = A\cos(0) + B\sin(0)$$
$$\theta_0 = (A * 1) + (B * 0)$$
$$A = \theta_0$$
$$\theta(t) = \theta_0\cos\sqrt{\frac{g}{l}} * t + B\sin\sqrt{\frac{g}{l}}\, t \textbf{ (*)(*)(*)(*)}$$

Substitute (6) into **(*) (*) (*)**

$$\theta = -A\sqrt{\frac{g}{l}} * \mathbf{0} + B\sqrt{\frac{g}{l}} * 1$$

$$\theta = B * \sqrt{\frac{g}{l}}$$

Finally, when B = 0

$$\theta(t) = \theta * \cos\sqrt{\frac{g}{l}} * t$$

4 DATA COLLECTION / INPUT MODELLING / ASSUMPTIONS

The following assumptions have been made in order to model the crane hoisting problem as a pendulum in order to reduce the problem's complexity,

1. Motion is from a fixed (main) support,
2. Motion is observed in two dimensional space (as a simple pendulum) and not three (conical pendulum),
3. Damping forces have completely been ignored,
4. Rigging may be too complicated, so it has been reduced to a single sling,
5. The sling is weightless as compared to the pendulum's bob,
6. There is no secondary motion on the sling i.e. the sling experiences no wobbling.

Also, it is important to take note that most simulation problem, such as the analysis of Construction operations will typically have a data input component. This part was missing, so instead Math and Physics formulations were utilized to sample input data and experimented with.

5 MODEL LAYOUT AND DESCRIPTION

5.1 Global attribute designations

The model has four scenarios. Each is a essentially a duplicate of the other except that either the length of sling for the pendulum varies (5 m or 2.5m) or the initial displacement from the equilibrium position is different (20 or 15 degrees). The global variables that are therefore common to them are:

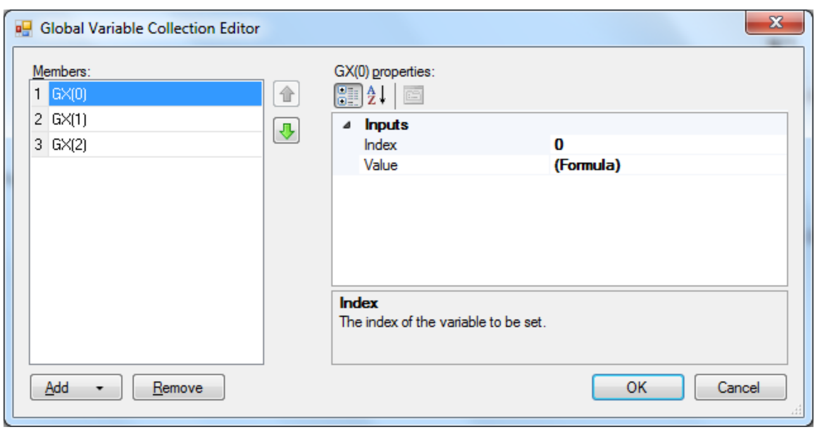


Fig. 5.1: Global variable designation

Variable	Description	Initial Value
GX[0]	Gravitational constant, which accounts for the pendulum's acceleration due to the force of gravity	9.8 m /s^2
GX[1]	Holds the length of the pendulum in metres for each scenario	5m or 2.5m
GX[2]	Has the initial value of the angle of displacement of the pendulum's bob from the equilibrium positon	20 or 15 degrees

5.2 Model layout and description

A continuous model has been used to generate the value of time variable. The model's layout is shown below in Figure 5.2:

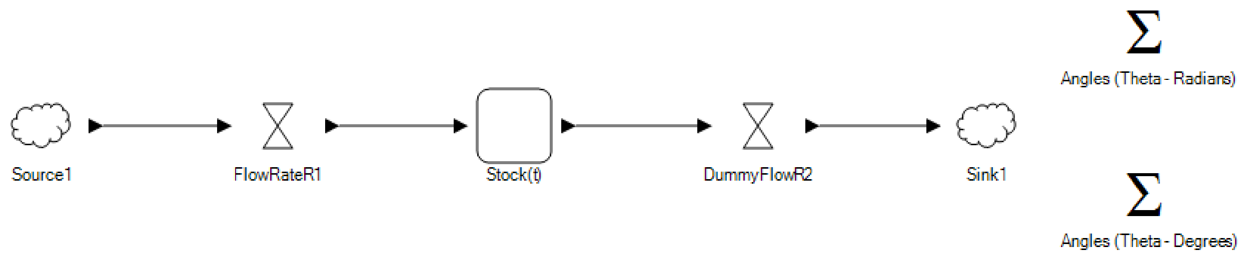


Fig. 5.2: Pendulum swing simulation model layout

Source element (Source1) represents the initial position of the pendulum's bob before it is subjected to an excitation. The stock element (Stock(t)) keeps track of the passage of time in seconds, incrementing in steps of 1 second each time there is a change. In between the source and stock, there is a Flow element (FlowRateR1). It determines the angular velocity of the bob at a particular point in time after it starts to swing, gets the current time during the simulation and uses both of these values to calculate the angle of displacement of the sling from the equilibrium position. This is finally stored in the Statistic element Angles (Theta) which are in both in radians and degrees. The simulation time is being modeled so as to keep track of the swinging of the pendulum.

The two elements that follow the stock element, DummyFlowR2 and Sink1 have been added for completeness. They make the whole model appear balanced. They serve no actual purpose besides that.

5.3 Model setup

The model was configured in the following ways:

- It is meant to run for 60 seconds which emulates the swing of a pendulum for a minute,
- The run count for each scenario is 1 since the problem is quite deterministic once the length of the sling and the initial angle of displacement from the equilibrium position has been established,
- The step size for each simulation has been set to 0.05 of the units in use which are seconds. The main reason is to allow the simulation to generate more observations in smaller unit intervals in order to have a smoother curve for the sine wave generated using plotted values of angle theta from swings,
- Finally the flow returns a value of 1.0 in order to allow the simulation to keep track of time that has elapsed during the simulation.

5.4 Formula for Angular Velocity

The angular velocity is computed from first finding the square root of the quotient of the Gravitational constant (G) and the length of the pendulum's sling (l)

$$\omega = \sqrt{\frac{g}{l}}$$

```
/* Calculate the angular velocity of the swinging pendulum based on the
length and gravitational constant G */
angularVelocity = System.Math.Sqrt(GX[0] / GX[1]);
```

After that, the sling's angle of swing is obtained from a cosine of the product of angular velocity calculated above and the time an observation is taken during the simulation.

$$\theta'' = \theta * \cos\left(\sqrt{\frac{g}{l}} * \mathrm{t}\right)$$

```
/* Determine the angle of swing in Radians */
swingAngleRadians = GX[2] * System.Math.Cos(angularVelocity * currentTime);
```

This is in radians at first since those are the values the .NET framework's Math libraries for calculating trigonometric sine and cosine functions are designed to return. Conversion can be done from radians to degrees as shown below:

```
// Determine the angle of Swings in both degrees and Radians
const double PI_RADIANS = 180.00;

swingAngleDegrees = (swingAngleRadians * PI_RADIANS ) / System.Math.PI;
```

The rates change of mass' Angular velocity are obtained from a stock value since it is easier to accumulate them into the element and later dump them in a file together with their observation times using Simphony for further analysis of the data obtained.

```
/* Gather value of the angle of swing on the statistics element throughout
the run. This is in Radians and Degrees */
CollectStatistic("Angles (Theta - Radians)", swingAngleRadians);
CollectStatistic("Angles (Theta - Degrees)", swingAngleDegrees);
```

6 RESULTS AND DISCUSSION

6.1 Results

These are tabulated in an Excel worksheet extracted from a run of the simulation in 60 seconds as shown in Figure 6.1.

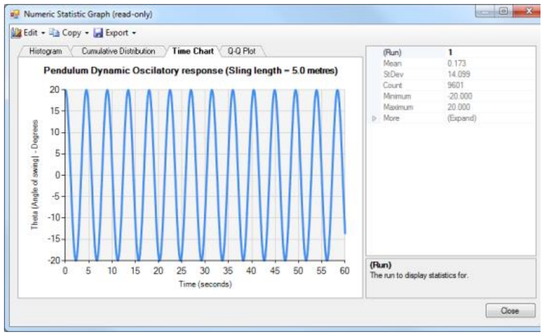
A	B	C	D	E	F	G	H	I
Time	Theta - radians (5	Theta - degrees (	Theta - radiar	Theta - degrees	Theta - radians (	Theta - degree	Theta - radians	Theta - degrees
0	0.34906585	20	0.261799388	15	0.34906585	20	0.261799388	15
0	0.34906585	20	0.261799388	15	0.34906585	20	0.261799388	15
0.0125	0.349012401	19.99693758	0.261759301	14.99770318	0.348958954	19.99387531	0.261719216	14.99540648
0.01875	0.348945593	19.99310977	0.261709195	14.99483233	0.34882535	19.98622033	0.261619012	14.98966525
0.046153846	0.348337403	19.95826305	0.261253052	14.96869728	0.347609463	19.91655513	0.260707097	14.93741635
0.05	0.348210988	19.95102001	0.261158241	14.963265	0.347356824	19.90208001	0.260517618	14.92656001
0.025	0.348852069	19.98775125	0.261639052	14.99081344	0.348638332	19.975505	0.261478749	14.98162875

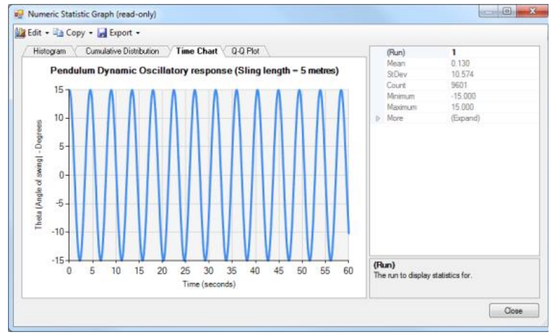
Fig. 6.1: Output data from a simulation run in Simphony

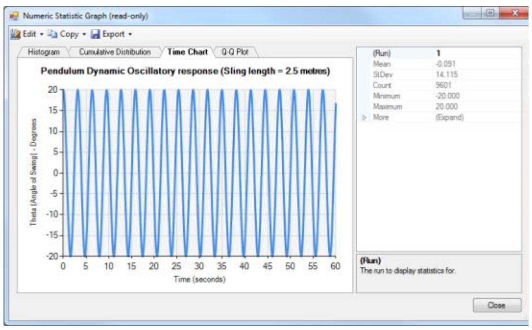
6.2 Time chart

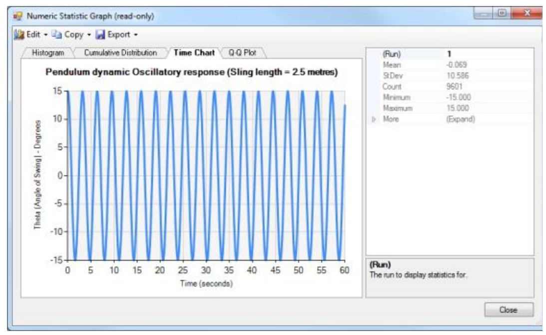
This outputs the sine wave form that should be displayed when the angular velocity of the wave is plotted against the passage of time. It is important to note that since there are no damping forces taken into account that,

- The extreme values of 20 and 15 degrees are observed in the outputs as they are the original angles of displacement of the bob from the pendulum's equilibrium position,
- Shorter sling lengths result in higher frequency graphs.



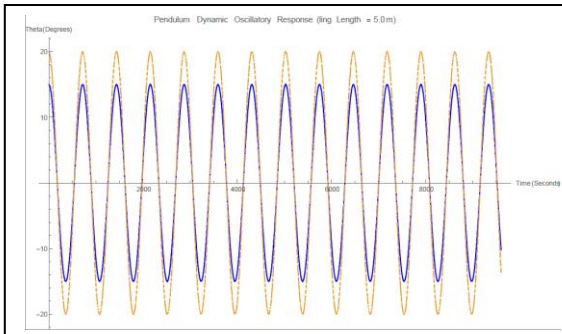




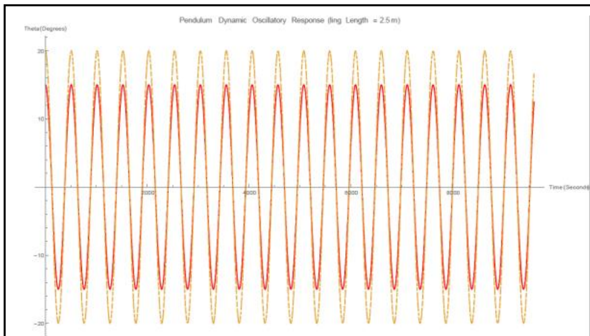


Data from Simphony was extracted in .csv format from a run of the simulation model and plotted using Mathmematica for comparison. Line graphs for both pendulums with slings of 5 metres and 2.5 metres plotted produced curves that are consistent with those from Simphony.

The expected outcome is that you get higher frequency waves with shorter sling lengths. The wavelengths remain the same however for the same for the same sling lengths regardless of the initial angle of displacement from equilibrium. This was observed in the time chart from Simphony.



5 metre sling pendulum



2.5 metre sling pendulum

7 VALIDATION / VERIFICATION

Verification was done with the output data from the simulation captured in an Excel worksheet and formatted as input to the Software Mathematica for further analysis. Figure 7.1 below has more information

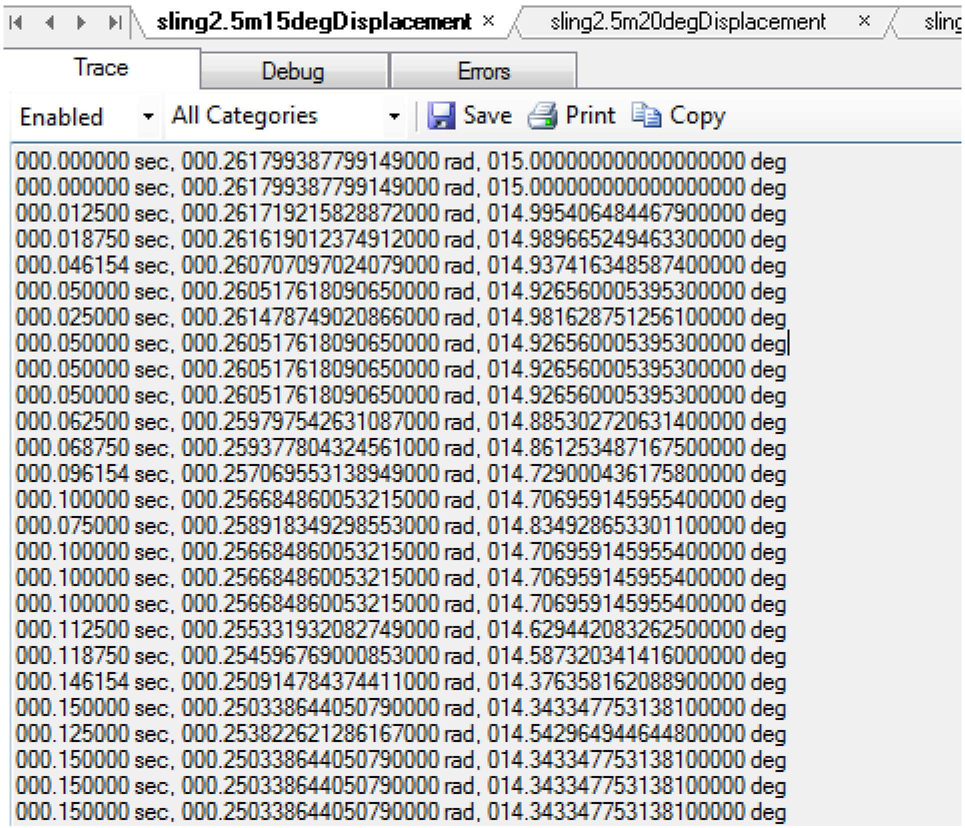


Fig. 7.1: Traces of output from a Simulation run in Simphony for the model

The above figure shows a sample of the trace window with the same data collected from a sample run of the simulation in Simphony. It is valid since it contains the correct values that should be observed if the correct Math and Physics equations were used to produce the same data using hand calculations. If no damping forces are taken into account, oscillations of the pendulum should continue uninterrupted.

8 CONCLUSION / RECOMMENDATIONS

A better understanding of the pendulum swing problem and the possibility of using Simphony to model it has been demonstrated. The next step to take would be to do away with the simplifying assumptions for example damping of the motion. Also the main support will be taken to be in motion initially with it coming to a stop eventually, a process which should trigger the oscillation of the pendulum's bob. Once that is well formulated and simulated, work can proceed on robotic experimentation and finally be implemented in the field.

ACKNOWLEDGMENTS

The invaluable guidance of Dr. Ekyalimpa, Ronald is heavily acknowledged. Ronald offered very helpful advice throughout each stage in this project, right from inception up until its conclusion.

A APPENDICES

Sample Python code used to extract angle values for verification on Mathematica :

```
import csv

with open('Pendulum simulation - Results.csv') as csvfile:
    reader = csv.DictReader(csvfile)
    result = []
    for row in reader:
        # result.append(float(row['Theta - radians (5 m, 20 degrees)']))
        # result.append(float(row['Theta - degrees (5 m, 20 degrees)']))
        # result.append(float(row['Theta - radians (5 m, 15 degrees)']))
        # result.append(float(row['Theta - degrees (5 m, 15 degrees)']))
        # result.append(float(row['Theta - radians (2.5 m, 20 degrees)']))
        # result.append(float(row['Theta - degrees (2.5 m, 20 degrees)']))
        # result.append(float(row['Theta - radians (2.5 m, 15 degrees)']))
        result.append(float(row['Theta - degrees (2.5 m, 15 degrees)']))

    print (result)
```

REFERENCES

Apostol, T. M. 1967. *Calculus, One Variable Calculus with an Introduction to Linear Algebra.* Volume I. John Wiley & Sons.

Apostol, T. M . 1969. *Calculus, Multi Variable Calculus and Linear Algebra, with Applicationsto Differential Equations and Probability*. Volume II. Xerox College Publishing.

Hasan, S., Al-Hussein M., Hermann, U. H., Safouhi, H. 2009. *Integrated Module for Mobile Crane Dynamic Instability Analysis and Supporting System Design*. American Society of Cicil Engineers.

Hardison, T. B. 1979, *Introduction to Kinematics*, Resting Publishing Company, Inc.

Peurifoy, R. L., Schexnayder, C. J., Shapira, A. and Scmitt, R.L. 2011. *Construction Planning, Equipment and Methods. 8th* ed. New York: McGraw-Hill, Inc.

Shapiro, H. I., Shapiro, J. P, Shapiro, L. K. 1991. *Cranes and Derricks*, 2nd ed. New York: McGraw-Hill, Inc.

Worker's Compensation Board of British Columbia. 1992. *Mobile Cranes, A Manual of Standard Practices*.