

## **A PROTOTYPE FOR SIMULATING THE KINEMATICS OF CRANE RIGGING OSCILLATORY MOTION USING SIMPHONY.NET**

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### **ABSTRACT**

Crane hoisting operations represent a significant portion of the work scope on construction sites, especially those that have adopted 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 created a virtual simulation environment prototype that can be experimented with to generate the required metrics for crane hoisting automation. The equation of motion for this oscillatory motion was first defined. Thereafter numeric solutions to this equation were explored from a continuous simulation perspective using Symphony.NET. Then prototyping of simple pendulum motion was implemented using the continuous simulation services in Symphony.NET and verification done using Mathematica.

### **1 INTRODUCTION**

The construction industry's core business entails the production of infrastructure/facilities or components that are used in the erection of infrastructure/facilities. Just like any other production system, one of the major concerns of construction is the handling of various materials, most of which are bulky. Effective material handling requires logistics that facilitate their material manufacture, transportation/distribution, storage/warehousing, and disposal. Examples of such logistics include: manual, semi-automated, and automated equipment. There is a wide range of machines that fall in these categories, these include: conveyors, hoisting equipment, industrial robots, pallet jacks, lift trucks, etc.

There have been a number of trends in material handling that have been started with the sole purpose of improving the efficiency with which material handling is done. The first of these trends was started by Fredrick Taylor who is also regarded as the founding father of the industrial engineering domain (Robinson 2015). Taylor did most of his work in the area of improving manual loading processes and his work led to subsequent efforts that resulted in mechanization of the material handling process and later the automation of the machines used. The study presented in this paper seeks to follow this trend and further efforts that strive to achieve higher efficiencies in material handling. The focus is restricted to hoisting equipment, specifically cranes, because they are the most predominant type of equipment utilized in construction. For example, cranes are used for handling and lifting precast concrete sections, steel pieces, vessels, equipment, modules, etc., within construction sites. There are a number of issues that exist in rigging operations. The one being dealt with in this study is presented in the section that follows.

## **1.1 Rationale for the Study**

The rigging and hoisting sub-domains rely on the experience of equipment operators for the success of processes that involve these types of operations. A high reliance on human experts is not sustainable especially when there are not that many available in the industry. Also, human beings are prone to making errors in judgement that could result in undesirable outcomes. Consequently, there is a shift towards automating highly sensitive operations within the construction and other industries. Crane rigging is one of the areas that has been identified as having lots of potential to benefit from process automation. Currently, load cells are an integral part of some rigging equipment so that these halt rigging when load ratings are exceeded. The vision of the authors of this paper is that, similar smart devices could be made, which monitor the kinematics involved in rigging operations so that corrective actions are taken where necessary. However, for this to be possible, the necessary basic research work needs to be done, hence this paper.

The current state of practice is such that operators of cranes for rigging require experience to navigate large objects in highly congested construction sites. Often, safety issues arise from object collisions or there are productivity losses due to excessive oscillations of objects being hoisted. On some sites, strategies have been devised to minimize these issues by having a worker or workers tag the object as it is lifted to its final destination (See Figure 1).

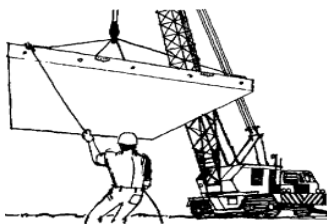


Figure 1: Tag lines to guide an object being rigged (Source: DOE, 2012).

Automating the monitoring and control of crane rigging kinematics minimizes the need for experienced operators and tagging crews hence resolving undesirable issues that could possibly arise from current practices and thus making construction more efficient. The research work presented in this paper is the first step towards achieving the envisaged automation. It involves formulating the crane rigging operation in such a way that a simulation-based prototype can be created. It is hoped that this prototype serves as a basis for developing a more extensive simulation model that can be experimented with prior to proceeding to robotic lab-based experiments and eventual field implementations.

## **2 THEORETICAL BACKGROUND**

This section of the paper is mainly concerned with providing background information that is a basis for developing the prototype for simulating crane rigging oscillatory motion. Useful basic information is presented on differential equations because they are an effective way of mathematically representing dynamic systems identical to those encountered in crane rigging oscillatory motion. Also, information is presented to facilitate an understanding of pendulums because they represent a precise abstraction of the crane rigging oscillations.

### **2.1 Cranes**

Cranes were invented and first used by the Ancient Greeks in the late 6th century BC (Coulton 1974). Although they were not so advanced at that time, they were used for the same purpose as today, i.e., to lift and move large and heavy objects. Cranes have different attributes; for example, they may be mobile or not. Also, they are of different sizes – these sizes are determined by the loads they are intended to lift.

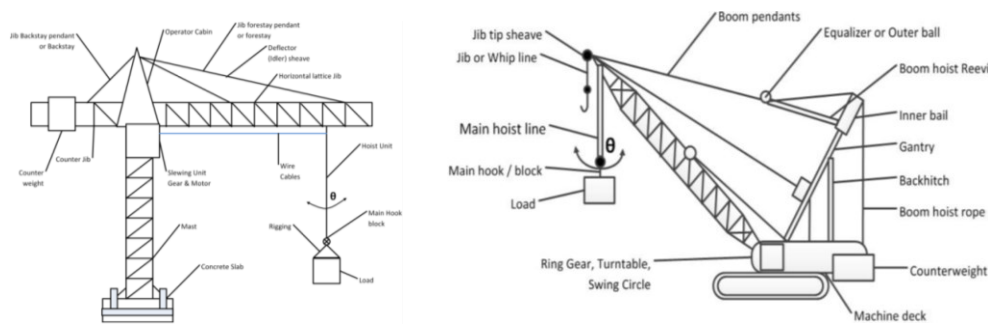


Figure 2 : Sketches of a tower crane (left) and a mobile crane (right).

There should be serious design considerations undertaken to guarantee efficient and safe use of cranes. These typically relate to crane capacity, i.e., from the mechanical advantage of the lever arm and the pulley system, stability, i.e., supporting surface should be firm enough to avoid toppling, and integrity of the crane's body i.e., to avoid rapture. There are different types of cranes that are in existence today. Those commonly used within the construction domain include the mobile crane (see Figure 2), tower crane (see Figure 2), overhead, jib crane, etc. Rigging is a big part of operating cranes. As such, brief background information on this is presented for the benefit of the reader.

## 2.2 Rigging

In construction, there are a lot of objects that need to be moved around and they vary significantly in shape, size and weight. It is permissible for some of these objects to be moved manually by the construction workers while there are others, especially those that are large or heavy, which can only be moved using specialized lifting equipment such as cranes, hoists, etc. (Fedock and Wilcox 1999). In order to ensure the safety of those involved in a lift and those in the vicinity of a lift, there are specific guidelines and rules that bind the fashion in which objects are lifted. These guidelines also aim at avoiding incidents that could result in the damage of objects being lifted and those that may be involved in the incident. The term "rigging" is often used when discussing the subject of lifting objects and material handling, especially in construction and could be used as a noun or a verb. When the term "rigging" is used as a noun, it refers to the equipment used to secure objects that are to be moved or lifted (Vincoli 2000). Examples of these will be discussed in the following section. When used as a verb, the term "rigging" refers to the process of setting up or preparing the equipment required to secure an object that needs to be moved or lifted (Vincoli 2000; UL Workplace Health & Safety 2012).

### 2.2.1 Rigging Equipment

This section presents an overview of the equipment made use of during rigging but excludes the actual equipment that performs the lift operation. Examples of such equipment are: hooks, shackles, spreader bars, and slings. A sling is the link between the hook and the load (object being lifted). A shackle is an accessory that secures the hook-sling interaction. Sometimes, a sling can be directly attached to a hook without the need of a shackle. However, if two or more slings are to be attached to a hook, a shackle should be used. Spreader bars facilitate the creation of a stable rigging configuration. Some spreader bars are adjustable (to facilitate the assembly and take down) while others are not. There are different types of slings that can be used and these include: a wire rope, chain sling, synthetic web, etc. See Figure 3 for their visual appearance.



Figure 3: Rigging equipment - wire rope, chain sling, and synthetic web sling (Source: DOE, 2012).

### 2.2.2 Rigging Configurations

The process of securing an object for lifting often results in a specific setup for the rigging equipment. This setup is frequently referred to as a rigging configuration. Rigging configurations are dictated by the type of equipment available for rigging and the size, shape and weight of the object that is to be lifted or moved. The objective is to always adapt a configuration that is safe and efficient i.e. takes the least amount of time and effort to setup and take down.

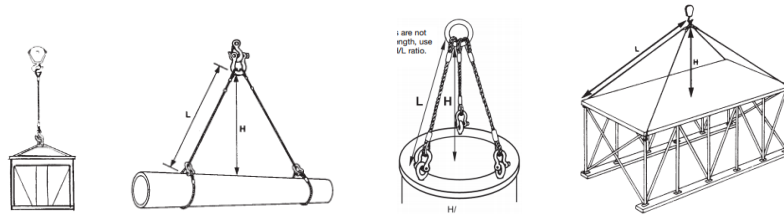


Figure 4: Sample crane rigging configurations (Source: DOE, 2012).

It is not uncommon for the term “rigging configurations” to be referred to as “rigging trees”. Examples of simple rigging trees are shown in Figure 4, however, there are other more complex tree configurations in use in practice.

### 3 PENDULUM SYSTEMS

Physical systems that have an object suspended from a pivot about which they swing freely are referred to as pendulums. Oscillation in pendulum systems is activated by the displacement of the suspended object from its equilibrium position. The motion takes place because the object experiences a gravitational force that strives to restore it in its equilibrium position. If the system experiences frictional forces, it oscillates until it comes to rest. If there is no friction (assumed), the object would continue oscillating and keep going. There are various types of pendulum systems in existence. Figure 5 shows a simple and a conical pendulum. The simple pendulum is the type used in this study.

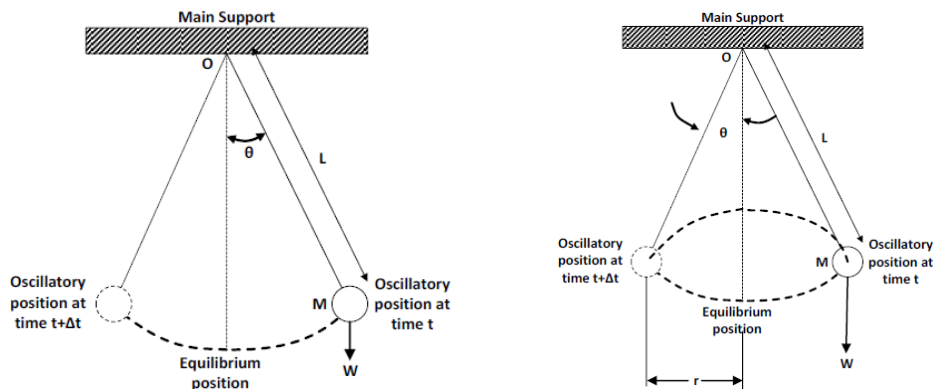


Figure 5: A Schematic diagram of a simple pendulum (left) and a conical pendulum (right).

Pendulum systems are comprised of a number of different parts which will be referred to in the discussions that follow. It is therefore important that we define what those are before using them. The parts include:

- i. *Object/mass support*: In a pendulum system, objects are suspended at the end of a rod or a sling. The vertical rod or sling serves as a support of sorts for the object and is referred to in here as a mass/object support.
- ii. *Main support*: This refers to the part of the pendulum system that supports the entire structure. It is the point to which the string or sling is attached.

Pendulums belong to a family of dynamic systems. This dynamic behavior can be tracked using appropriately selected state variables for the system. In the case of the pendulum, the following state variables could be tracked as time varies: the angle of swing ( $\theta$ ), the position of the suspended object ( $x$ ,  $y$ ), and the length of the rod or sling ( $l$ ). The type of pendulum that is of interest in this research work is a simple pendulum that oscillates only in the  $x$ - $y$  plane. A number of assumptions were made to facilitate the process of formulating the crane rigging/hoisting problem into a pendulum system and subsequently into a simulation model that mimics the oscillatory motion of the system. They include:

- i. *Inextensible sling*: Slings often used for hoisting objects using cranes may be made of material that is elastic in nature. Subjecting such a sling to an object that is of significant weight results in the sling straining. As the object is subjected to oscillatory motion, the vertical component of its weight keeps changing resulting in varying strains in the sling. This results in secondary dynamic effects. This behavior will be ignored to simplify the analysis.
- ii. *Limited sling deformation*: Most slings used in rigging and hoisting operations are flexible in nature and could deform along their length during the oscillatory motion of the suspended object. However, in order to simplify the analysis, it was assumed that such deformation does not exist. Therefore, the sling was assumed to be straight at all times.
- iii. *Oscillation of the mass*: When the suspended mass is in equilibrium, it rests in the vertical position. After it has been displaced, it oscillates. Although there can be multiple degrees of freedom that this object could oscillate in, the analysis was restricted to only two degrees of freedom, i.e., the horizontal ( $x$ ) and vertical ( $y$ ) directions.
- iv. *Initial conditions*: The support onto which the sling is attached is assumed to be fixed at all times during the oscillatory motion of the suspended object. This implies that the only initial conditions that the pendulum system is subjected to is the initial displacement of the object from the equilibrium position. Letting the sling support move would introduce additional initial conditions or extra excitation.
- v. *Damping effects*: Oscillatory motion of a suspended mass is typically subjected to a number of resisting forces that dampen its motion as time passes. Examples of these include: air resistance, internal friction in the sling that suspends the object, etc. These were ignored in the simulation work done in this paper. Consequently, the oscillation was expected to go forever, as is expected as a response in undamped dynamic systems.
- vi. *External exciting forces*: As an object oscillates that is suspended freely, it could be subjected to currents of wind that could cause additional excitation to the system. These types of excitation were ignored. Excitation from the initial displacements imposed on the object were the only ones considered.

Some of the assumptions (e.g., i) stated are inherited from the derivations of the physics equations of motion. In order to make use of the equations, there was a need to restate and adhere to them. Other assumptions were made to simplify the simulation modelling for this prototyping phase. Issues such as damping effects, secondary motion of the string, e.t.c., will be accounted for explicitly in the next phase.

### 3.1 Differential Equations

Differential equations are an effective way of representing the variation of state variables of dynamic systems. There are different families of differential equations such as first order differential equations, second order differential equations, ordinary differential equations, partial differential equations etc. In this paper, the focus is second order ordinary differential equations because they describe pendulum oscillatory motion appropriately. The general form for this type of equation is shown next (Kreyszig 1999).

$$y'' + ay' + by = 0$$

The analytical solution of this type of equation first requires expression in the form shown below, i.e., as a characteristic equation. Solving this equation either results in distinct real roots, double real roots, or complex conjugate roots. This then leads to a general solution to which boundary conditions are applied and a particular solution obtained.

$$\lambda^2 + a\lambda + b = 0$$

Differential equations can be solved either analytically (explained above) or numerically. Finite difference methods and finite element analysis are numeric techniques that could also be used for solving these types of equations. Both approaches lend themselves to computer simulation but in different ways (See Figure 6).

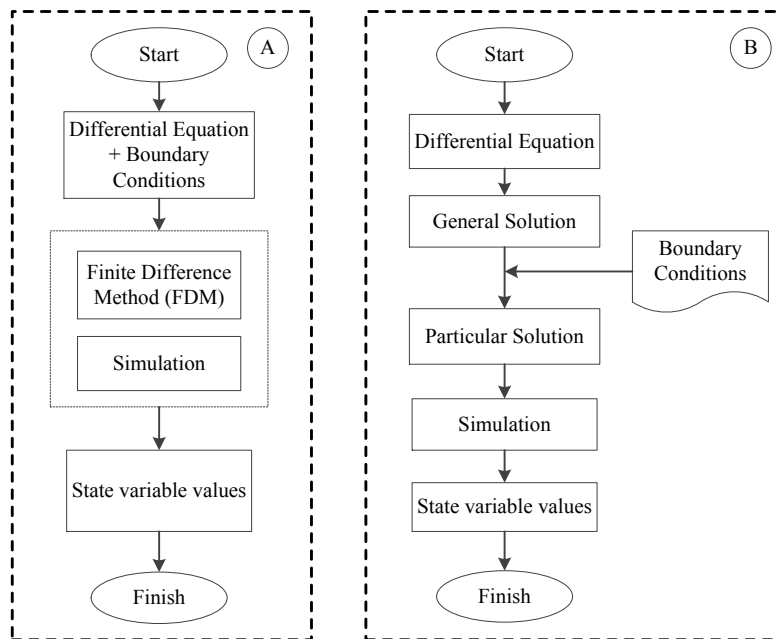


Figure 6: Strategies for simulating state variables that have definitive differential equations.

### 3.2 Formulations for Simulating a Simple Pendulum

The formulations used in this paper for the abstraction and simulation of crane rigging operations (i.e., as a simple pendulum), were based on the texts by Chopra (2012) and Kreyszig (1999).

Figure 7 (right) shows the forces that act on the pendulum system to maintain dynamic equilibrium. Statics and dynamics (i.e., Newton’s law of motion) are used together with this schematic, to obtain the Equation Of Motion (EOM), below.

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

This was solved together with boundary conditions using the approach described in Section 3.1. The expression given below is obtained.

$$\left. \begin{aligned} \theta(t) &= A \cos \sqrt{\frac{g}{l}} t + B \sin \sqrt{\frac{g}{l}} t \\ \theta(0) &= \theta_0 \\ \dot{\theta}(0) &= 0 \end{aligned} \right\} \Rightarrow \theta(t) = \theta_0 \cos \sqrt{\frac{g}{l}} t$$

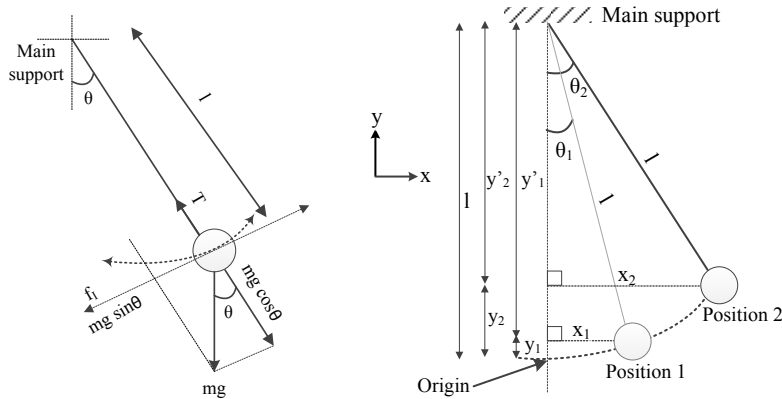


Figure 7: Kinematic parameters for a simple pendulum system.

The geometric relations between the kinematic parameters of a simple pendulum, also shown in Figure 7, are summarized in the following two equations. These are specifically used to depict the position of a suspended object at any point in time.

$$\begin{aligned} x_i &= l \sin \theta_i \\ y_i &= l(1 - \cos \theta_i) \end{aligned}$$

Mathematical formulations that represent the dynamic behavior of a simple pendulum can then be simulated from this point on. The formulation and simulation process are summarized in the conceptual diagram shown in Figure 8.

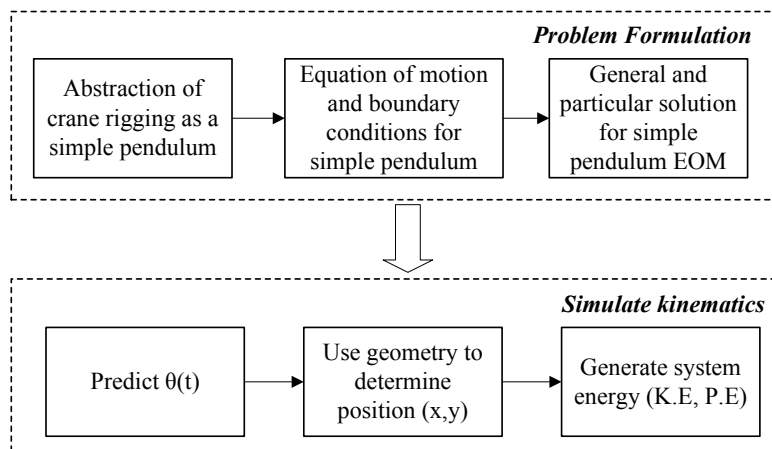


Figure 8: Problem formulation and simulation.

## 4 CONTINUOUS SIMULATION MODEL

In order to simulate the particular solution for the simple pendulum oscillatory motion, there is a need to provide values for the initial displacement angle ( $\theta_0$ ) and cumulative values of time ( $t$ ). The initial displacement angle,  $\theta_0$ , is known for a given experiment given that it represents the excitation the suspended object is subjected to. This was stored within a global attribute in the Symphony.NET simulation system. Values for time,  $t$ , were obtained from the simulation. There was a need to have a model that keeps autonomously progressing in time without explicit simulation events being scheduled. It is for this reason that a continuous simulation paradigm was used. A Stock element was used to represent the cumulative value for time as the simulation progresses. The continuous simulation model layout shown in Figure 9 was created within Symphony.NET to simulate the particular solution for the oscillatory motion of a simple pendulum.

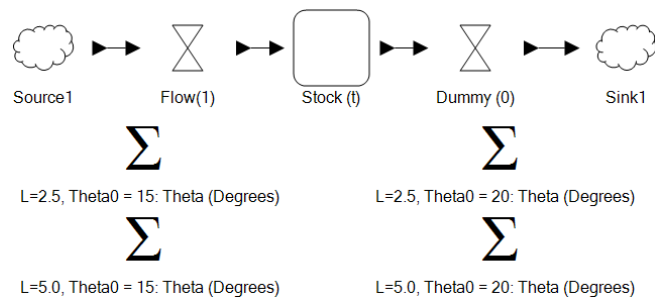


Figure 9: Continuous simulation model layout for pendulum oscillation in Symphony.NET.

### 4.1 Stock Values

One Stock modelling element was used to represent the simulation engine time. This could also have been obtained directly from the simulation engine. The same model layout would still have to be maintained even if the simulation time was obtained from the engine. The stock was set to an initial value of zero. In order to obtain the current simulation times within the Stock, a value of 1.0 had to be returned by the flow rate feeding into this stock. At the same time, no flow out of the Stock element would be permitted so that the time step value was returned every time numeric integration was performed.

### 4.2 Flow Rates

Two Flow modelling elements were used within the model layout. The Flow to the right of the Stock element was used for aesthetic purposes and was therefore assigned a value of zero so that it does not participate in the simulation process. The Flow element to the left of the Stock was put to serve three purposes. First, it was meant to return a value of 1.0 whenever numeric integration was performed so that the step size was generated as an integrand and used to update the Stock element's value to the current simulation time. This Flow element was also used to compute the state variable for the angle of swing of the suspended object,  $\theta(t)$ , at every integration point. These values were collected into a Statistic modelling element. Finally, the position of the suspended object was derived from its angle of swing and collected into statistics nodes. The C# code snippet written within the Formula editor for this Flow element is shown next.

```
//Computing the stiffness of the system for the scenarios
double glRatio_2Point5Meters = System.Math.Sqrt(GX[4]/GX[0]);
double glRatio_5Meters = System.Math.Sqrt(GX[4]/GX[1]);
//Computing the initial angular displacement in radians
double Radians_15Degrees = GX[2]*System.Math.PI/180.0;
```



```
double Radians_20Degrees = GX[3]*System.Math.PI/180.0;
//Retrieving simulation time from the Stock
double time = GetStockValue("Stock (t)");
//Calculating and current angle of swing in Degrees
CollectStatistic("L=2.5, Theta0 = 15: Theta
(Degrees)", (180.0/System.Math.PI)*Radians_15Degrees*System.Math.Cos (glRatio_2
Point5Meters*time));
CollectStatistic("L=2.5, Theta0 = 20: Theta
(Degrees)", (180.0/System.Math.PI)*Radians_20Degrees*System.Math.Cos (glRatio_2
Point5Meters*time));
CollectStatistic("L=5.0, Theta0 = 15: Theta
(Degrees)", (180.0/System.Math.PI)*Radians_15Degrees*System.Math.Cos (glRatio_5
Meters*time));
CollectStatistic("L=5.0, Theta0 = 20: Theta
(Degrees)", (180.0/System.Math.PI)*Radians_20Degrees*System.Math.Cos (glRatio_5
Meters*time));
//Return the flow rate
return 1.0;
```

### 4.3 Simulation Model Configuration

Pure continuous simulation models in Symphony.NET don't require to be seeded or setup for a Monte Carlo type simulation. Consequently, the default seed was used. However, there were other aspects that needed to be customized and these included:

- *The units of measure:* ISO units of measure were assumed in the model development, i.e., meters for length and seconds for time. Consistency was maintained in the use of the different units of measure when modeling this problem so that precise results were obtained.
- *Simulation termination:* The termination time at the scenario was used to end the simulation. Simulation experiments were executed for 60 seconds.
- *Step Size:* Set sizes typically vary depending on the type of problem being analyzed and the precision that is desired. Step sizes of 0.05 seconds were found to generate desirable results for this simulation model.
- *Initial Conditions:* Parameters for the pendulum system, such as, sling length, angular displacement of suspended object from the equilibrium position, etc., had to be initialized at the start of the simulation. Values experimented with are presented.

The parameters of the physical system that were modelled, were represented using global attributes in the Symphony.NET simulation system. Table 1 summarizes details of these attributes.

Table 1: Global attribute designations and initializations for the simulation model.

Attribute	Designation	Initial Value
GX[0]	Length of the sling (scenario 1)	2.5 m
GX[1]	Length of the sling (scenario 2)	5.0 m
GX[2]	Displacement angle from equilibrium position (scenario 1)	15°
GX[3]	Displacement angle from equilibrium position (scenario 2)	20°
GX[4]	Acceleration due to gravity	9.81 m/s <sup>2</sup>

The initial values were set using the collection editor for the Initialize property of the Scenario in Symphony.NET (See Figure 10).

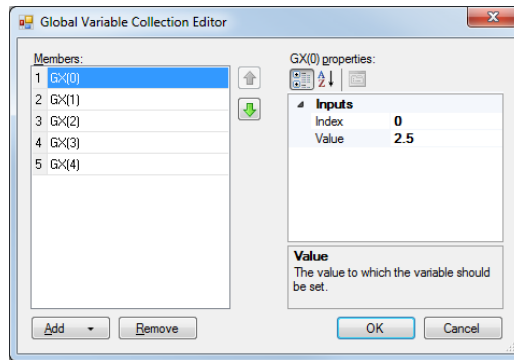


Figure 10: Collection editor for initializing pendulum parameters in Symphony.NET.

## 5 SIMULATION RESULTS AND DISCUSSION

Four scenarios were created using a stiff ( $l=2.5$  m) and less stiff ( $l=5.0$  m) pendulum setup, and initial angle of swing of  $15^\circ$  and  $20^\circ$ . Observations collected in the Statistics elements within the Symphony model, were exported to Mathematica and superimposed charts generated (Figure 11).

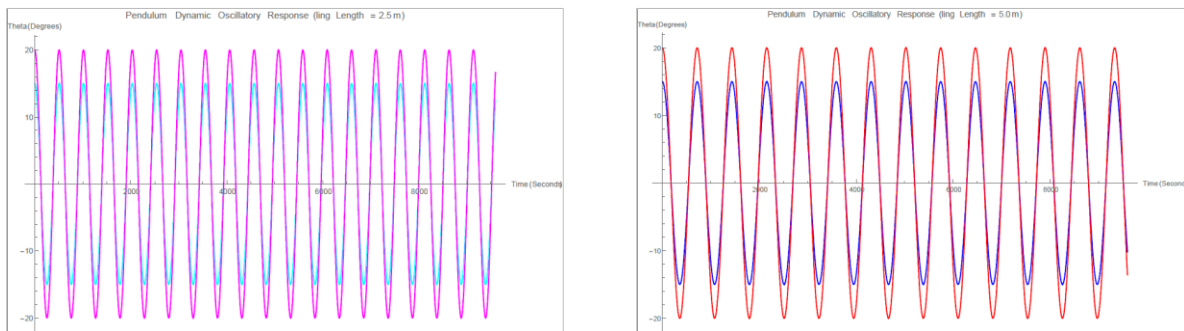


Figure 11: Angle swing of a suspended object in a stiff (left) and less stiff (right) pendulum.

The results on the angle of swing match expectations. First, the amplitude remains the same as the initial angle of displacement – this is because no damping was considered in the simulation. The scenarios were purposely setup to demonstrate the fact that a shorter sling (i.e.,  $l = 2.5$  m) would result in a stiffer pendulum system that oscillates with a higher frequency compared to a pendulum with a longer sling. This demonstrates one of the effects of changing rigging equipment and configuration. Besides a change in the effective length of a pendulum sling system, varying the rigging equipment and configuration results in a change in effective mass. However, derivations of the equation of motion revealed that mass does not influence the oscillatory motion. Although, additional data was generated such as the position of the suspended object, and the energy of the system, these were not reported on because of space constrains in the paper.

## 6 SIMULATION MODEL VERIFICATION AND VALIDATION

Not every simulation model that is developed, run and that generates a result, is valid. The most challenging type of simulation models to verify and validate are those that contain continuous simulation components. The difficulty arises from the fact that continuous simulation is not performed using flowing entities but rather involves numeric integration that takes place behind the scenes, i.e., within the simulation engine. There are two main problems that are often encountered when building and executing continuous or combined simulation models within the Symphony.NET simulation system. These include:

1) failure to initialize attributes (especially global attributes), and 2) failure to explicitly halt the simulation. The first problem that relates to attribute initializations is often encountered in combined discrete event-continuous models. This is because global attributes are used to facilitate the communication that takes place between the discrete event and continuous portions of the model. The second problem on the other hand is often encountered in both pure continuous and combined discrete event – continuous simulation models. The simulation in these types of models has to be explicitly halted otherwise the continuous elements will continue performing numeric integrations using the predefined time steps and stand the risk of going forever until the simulation application crashes.

As a first step in the verification process, due diligence was done to ensure that these problems don't exist within the continuous simulation model developed for the problem presented in this paper. Another effective strategy for verifying continuous simulation models that was applied in this piece of research work, involves tracing values of state variables at different points in time. The last verification strategy that was applied involved using Mathematica to simulate the same simple pendulum oscillatory problem. The results obtained from Mathematica were exactly the same as those obtained from Symphony.NET. This confirms the reliability and stability of the numerical integration algorithm that Symphony.NET's simulation engine is utilizing. The code snippet written within Mathematica is shown in Figure 12.

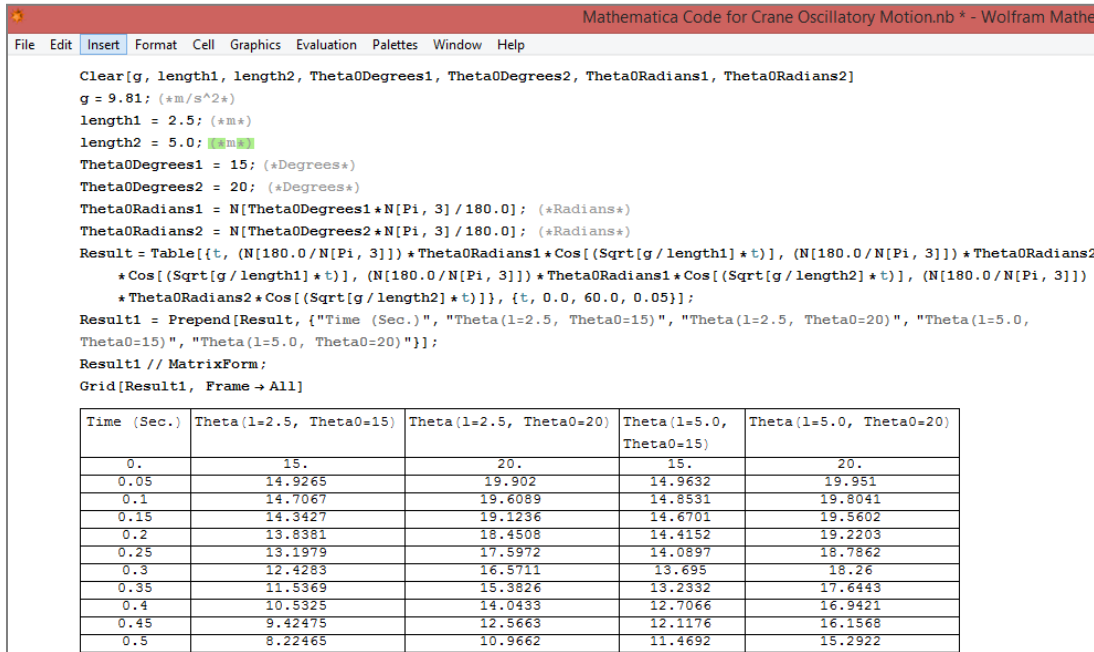


Figure 12: Pendulum oscillatory motion verification in mathematica.

A comparison with data sets of the real system or operation that is being analyzed is the most effective way of validating a simulation model and the results that it generates. However, in construction and other domains that predominantly conduct basic research similar to this one, it may not always be possible to access quality data in reasonable amounts for validation. Consequently, other strategies were used for validating the model and its results. An intuitive assessment was made of the results to determine their face validity. For example, it was expected that the amplitude of the oscillating object would remain constant as time progresses given that the system was undamped. This was the case in the results generated and charts plotted (see Figure 11). Also, when the length of the sling was reduced, i.e., the stiffness of the system increased, the frequency increased as expected (i.e., a higher number of cycles per period - see Figure 11). These assessments confirm that the formulations used, the assumptions made, the simulation model developed, and the results generated are all valid.

## 7 CONCLUSIONS AND RECOMMENDATIONS

Background information has been presented on crane rigging operations along with the issues that face them. This research work was done as a starting point for addressing issues that arise from excessive oscillation of suspended objects. Crane rigging was abstracted as a simple pendulum. A number of simplifying assumptions were made and a prototype (i.e., no damping and a stationary fixed support) formulation and continuous simulation model completed to demonstrate the feasibility of adapting a simulation-based approach to addressing the issues. The formulations, model, and the results generated are precise.

Developed prototypes can be used as a basis for creating enhanced formulations and simulation models that mimic the actual crane rigging operations more precisely. For example, excitation to the suspended object can be introduced by the initial motion of the main support – as is the case in actual rigging operations. Also, damping effects can be explicitly accounted for so that the time that it takes for excited suspended objects to come to rest in different conditions can be investigated. It was also assumed that the sling attached to the object does not deform during the oscillatory motion. Numeric methods will be used to model the deformation of this sling as the oscillatory motion progresses. Once this phase has been completed successfully, robotic prototypes can be experimented with in a lab prior to deployment on cranes and other rigging equipment within the field. Robotic lab experiments can be done in parallel with simulated animations and visualization of the kinematics of rigging operations. This is one of the main reasons that simulation was explored as a way of abstracting this physical oscillatory motion.

## REFERENCES

- Chopra, A. K. 2012. *Dynamics of Structures: Theory and Applications To Earthquake Engineering*. 4<sup>th</sup> ed. Upper Saddle River, New Jersey, Pearson Education, Inc., publishing as Prentice Hall.
- Coulton, J. J. 1974. "Lifting in Early Greek Architecture." *The Journal of Hellenic Studies* 94: 1–19, doi:10.2307/630416.
- Department of Energy (DOE). 2002. *Hoisting and Rigging Fundamentals for Riggers and Operators*. Report Number: TR244C, Rev. 5
- Fedock, S. Dennis, and The Babcock and Wilcox Company. 1999. "Construction Loads Produced During Heavy Lifting, Rigging and Handling Operations." American Society of Civil Engineers, 1999 Structures Congress.
- Kreyszig, E. 1999. *Advanced Engineering Mathematics*. 8<sup>th</sup> ed. 605 Third Avenue, New York: John Wiley & Sons.
- Infrastructure Health & Safety Association. 2012. *Hoisting and Rigging Safety Manual*.
- Robinson, A. 2015. The Evolution and History of Supply Chain Management. Accessed April 9, 2016. <http://cerasis.com/2015/01/23/history-of-supply-chain-management/>.
- UL Workplace Health & Safety. 2012. "Basic Rigging for Construction." Accessed April 23, 2016. <http://ondemand.puresafety.com/course-library/basic-rigging-construction>.
- Vincoli. 2000. "Rigging." *Jeffrey W. Lewis' dictionary of occupational and environmental safety and health*. Boca Raton: Lewis Publishers.

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