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Design and Implementation of an Experimental Test-rig for Tower Cranes

Mohamed H. Mabrouk
Head of Mechanical Equipment Department
M.T.C.
Cairo, Egypt

***Abstract*— Tower crane is considered as one of the most important materials handling equipment in modern construction field as it gives the best combination of height and lifting capacity that is essential for the construction of tall buildings as well as office and apartment blocks projects. This paper presents the design and implementation of a tower crane prototype that can be used as an experimental test-rig to execute indoor tests necessary for developing the tower crane theory of operation. The design procedures and part selection of the prototype structure, the structure stress analysis, the implementation of the prototype, and the installation of the control as well as measuring devices are discussed. Calibration of the measuring devices and the estimation of the prototype load chart assure the capability of using it as an experimental facility for tower cranes.**

Keywords*— materials handling equipment; mechanical systems; measuring instruments; scaled modeling

I. INTRODUCTION

Cranes are machines that are typically equipped with a hoisting system to move loads from one point to another in construction locations, factories and workshops in a way that becomes very crucial in our modern life. They exist in a wide variety of forms, each designed to suit a specific use, such as tower crane, overhead crane, boom crane, gantry crane and others. Tower crane is a modern form of balance crane that is usually fixed to the ground during operation. Different types of tower cranes include top-slewing, bottom-slewing, self-erecting, and special application. The most common type is the top-slewing tower crane which is considered in this paper.

The efficiency of tower cranes used in a project basically depends on their type, number and locations in the working site in a way that the appropriate consideration of these factors has a significant influence on the cost, time and safety of construction operations [1]. Due to this key role of tower cranes, many models have been created over the past thirty years for the development of tower cranes whether solving the problems raised during the cranes' operation or enhancing their performance. Some of the researchers address safety issues associated with tower cranes [2, 3], whereas others focus on improving the crane operation [4-8], or involve cost forecasting models [9].

Researchers have also developed mathematical models in an attempt to decrease total crane operational cost through developing genetic algorithms and an artificial neural network model (GA-ANN) for predicting tower crane operations and site layout [10]. Some other researchers modeled the tower crane to reach optimum use of the cranes within project site, in other words to provide each crane with collision-free path during operation, geographic information systems (GIS) based models [11] and building information modeling (BIM) models [12] give the answer to fulfill this need. Also the utilizing of visualization capabilities for GIS models developed a GIS based navigable 3D animation to review project schedules [13]. However, few attempts of the tower crane development research depend on measurements taken during experiments whether using a real tower crane or a tower crane scaled prototype. The advantages of using a scaled prototype for a tower crane can be summarized in assisting the researchers to build a mathematical model for the crane, enhancing the mathematical model through comparing its results to experimental results as well as increasing the integrity of the outputs.

This paper presents the design and implementation of a tower crane scaled prototype for a real conventional top-slewing tower crane, shown in Fig. 1, [14]. The prototype is intended to be used as an experimental test-rig to execute indoor tests to develop the tower crane theory of operation. In this paper, the prototype design procedures are explained in section II. Section III is devoted to discuss the computer model and design verification while section IV contains the implementation of the tower crane prototype. Calibration of the prototype measuring devices is presented in section V.

In standard top-slewing tower crane, crucial support for the crane is provided in the base that is usually bolted into a large ground concrete pad, Fig. 1, shows the main construction of the tower crane. This base is connected to a mast, which is typically a triangulated lattice structure that determines the tower crane height, and has a main job of stabilizing the crane. Attached to the very top of the mast is the slewing unit that gives the load the ability to rotate. The jib and counter jib are fixed linear steel structures that are mounted to the slewing unit which constitutes the slewing bearing and slewing machinery. The counter jib carries a counter weight, usually of concrete blocks, while the jib suspends the load from a trolley that is a wheeled carriage moved on rails suspended on the jib. The hoist motor and transmissions are located on the deck of the counter jib, while the trolley motor is located on the jib. The crane operator's cab is also located on top of the crane just below the horizontal jib The crane operator can control the crane either from the cabin at the top of the tower or remotely from the ground. The lifting hook is operated by using an electric motor to manipulate wire rope cables through a system of sheaves. The specifications of the real tower crane are; the maximum radius as 24.000 mm, the maximum hoisting capacity as 1500 kg and the hoisting distance as 65.000 mm. The tower crane components are made of St-37 [14].

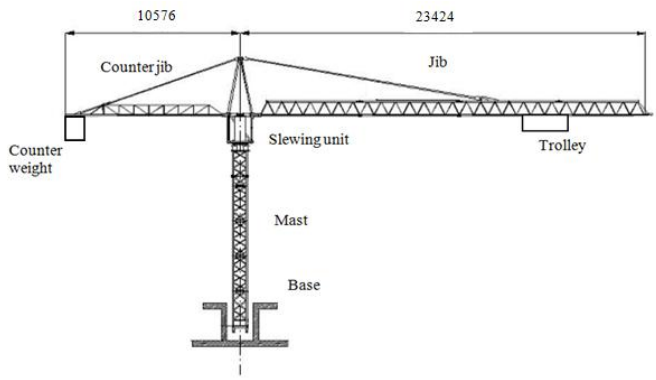

Fig. 1. Tower crane main parts [14]

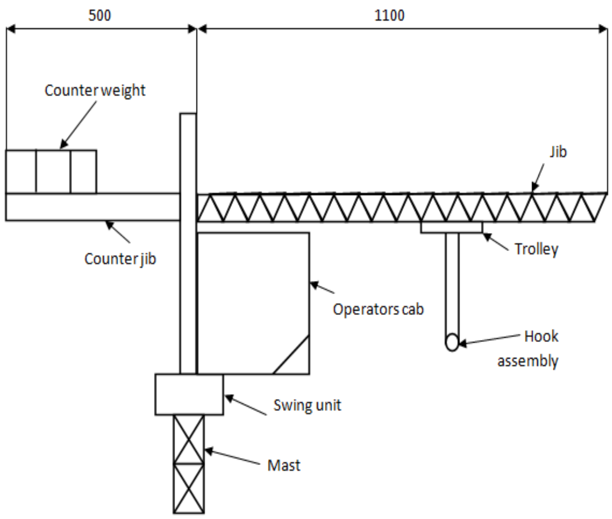

Fig. 2. Prototype main parts

II. PROTOTYPE DESIGN PROCEDURES

A. *Preliminary design of structure*

For the design of the tower crane prototype, some factors should be taken into consideration. It is important to note that the moment is generally several times greater at the base than at the top of the crane. Therefore, good fixation at the base is necessary to keep the system in balance. On the other hand, it is intended to have the center of gravity of the system located at the base, and so the center of mass obligates the system to remain in balance, regardless of the magnitude of the load, which is much less than the total mass of the crane. Also, another limitation related to the balance generated by the counter weight and load is the principle of operation that limits the load which can be lifted by making it dependent on the distance to move on the jib compared to the counter weight and its position on the counter jib.

Other factors to be considered during the design of a real crane can be summarized in the resistance due to nominal slewing, the influence of the wind, and the acceleration of the linear moving and rotating masses. However, these factors are ignored during the design of the prototype considering high rigidity of the chassis structure due to relatively lower dimensions, lack of wind effect, and choosing low speeds for load hoisting and movement. Another important factor is to ensure the operating safety as a simple mistake can lead to tragic accidents most of which are caused by unsecured load and load capacity exceeded [15].

Calculating for the preliminary design for the chassis and the counter weight, empirical formulae from [14] are considered. General information about the prototype are that the crane is to carry maximum load of 8 kg net weight, hoisting speed is limited to 0.05 m/s, and the speed gear reduction transmission ratios range from 3 to 5. The main construction of the prototype are the support frame (chassis) that consists of base, mast, jib, counter jib, slewing unit, counter weight, and load hoisting assembly that consists of the trolley mechanism and the load raising and lowering mechanism. The main parts of the prototype, shown in Fig. 2, are as follows:

1) Prototype chassis: The chassis that consists of the base (footing area), mast, jib, counter jib are standard steel parts that are connected using welding and bolted joints to form the final prototype structure. All structure parts, welding and bolted joints are checked for shear stress and bending moments stresses using the recommended factors of safety [14].

2) Slewing unit: Slewing unit is attached to the boom through a cylinder to give space for the controls devices and the wiring system which should be located in operator's cab. The slewing unit consists of reduction gear train, slewing bearing, and a driving electric motor.

3) Load hoisting assembly: Load hoisting assembly consists of the trolley mechanism and the load raising and lowering mechanism. Trolley mechanism consists of a sprocket-idler arrangment that is driven by a reduced electric motor, the sprocket drives a chain that is attached to the four wheeled carriage which moves on the rails fixed on the jib deck. The load raising and lowering mechanism consists of drum and system of pulleys, speed gear reduction, and an electric motor. It also includes the hook and steel wire ropes. All parts and systems are chosen according to the load using empirical formulae from [14].

4) Counter weight: The counter weight consists of various reinforced concrete blocks that are fixed on counter jib. The calculations of the net counter weight are governed by the balance equation whose parameters are the lengths of both the jib and the counter jib and the estimated net load capacity of the crane that include the load, the jib weight, and the trolley assembly weight.

B. *Motor selection*

According to power calculations, a 20 watt reduced electric motor is used to drive the load raise and lower mechanism with speed equals 0.05 m/s, while a reduced (SG-7755125000-510) electric motor is used to drive the carriage in the trolley assembly with speed equals 0.03 m/s. For the slewing mechanism, a reduced electric motor with speed equals 2 rpm is used.

III. COMPUTER MODELING AND DESIGN VERIFICATION

To make sure that the prototype structure design is appropriate, one step that cannot be ignored is to create a computer model of the prototype. A computer model of the prototype structure has been created with all forces, moments and constraints assigned to it. Von mises stresses, first principal stresses and third principal stresses have been calculated. The results show acceptable safety factors, first principal strains, third principal strains and equivalent strains as shown in Fig. 3 to Fig. 11.

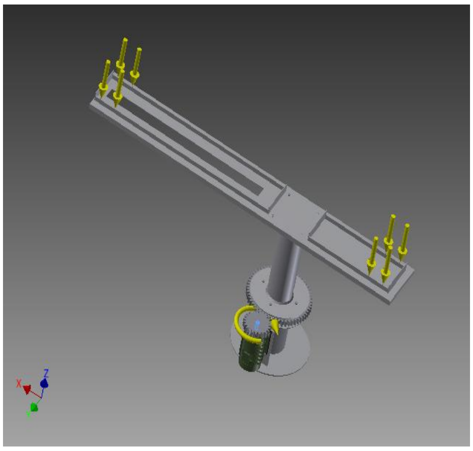

Fig. 3. Model for the chassis with forces and moments distribution

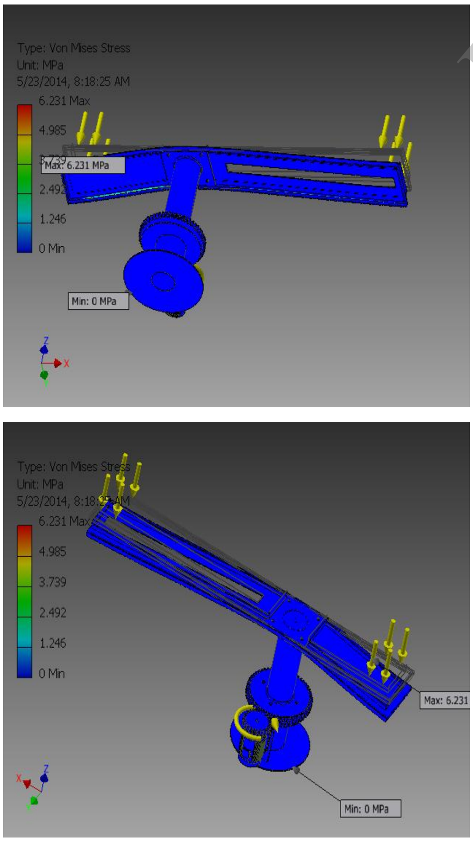

Fig. 4. Von Mises stress

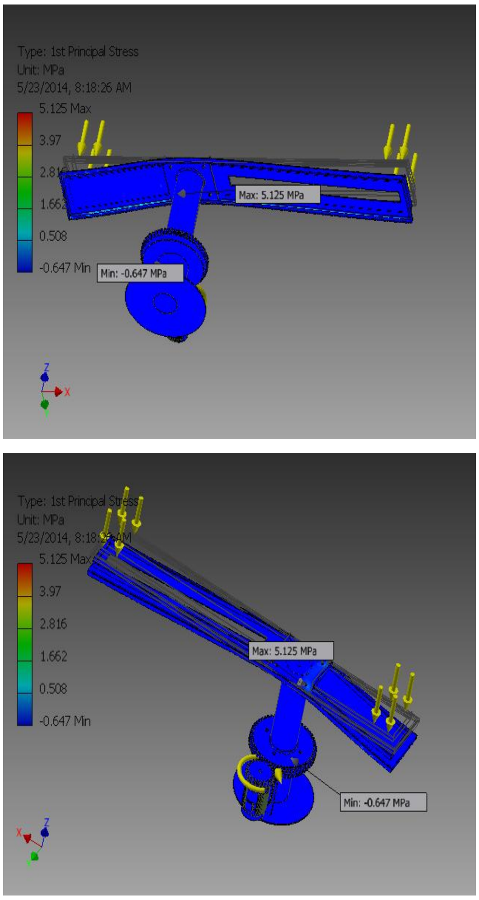

Fig. 5. First principal stress

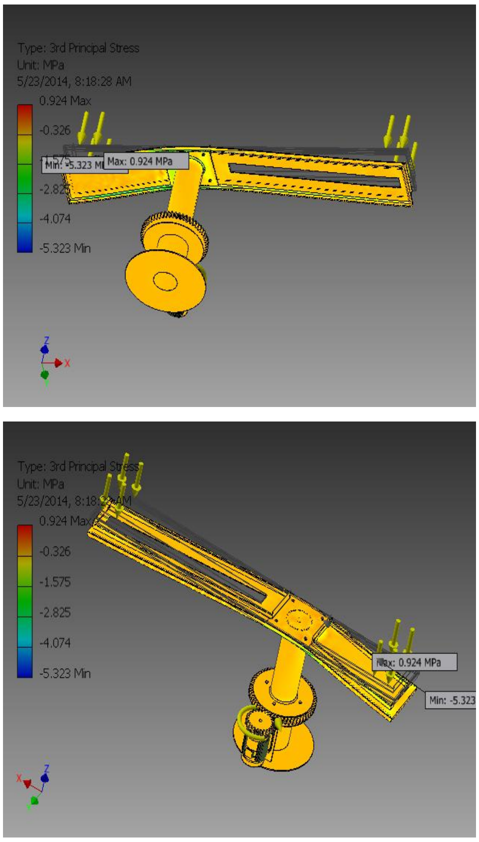

Fig. 6. Third principal stress

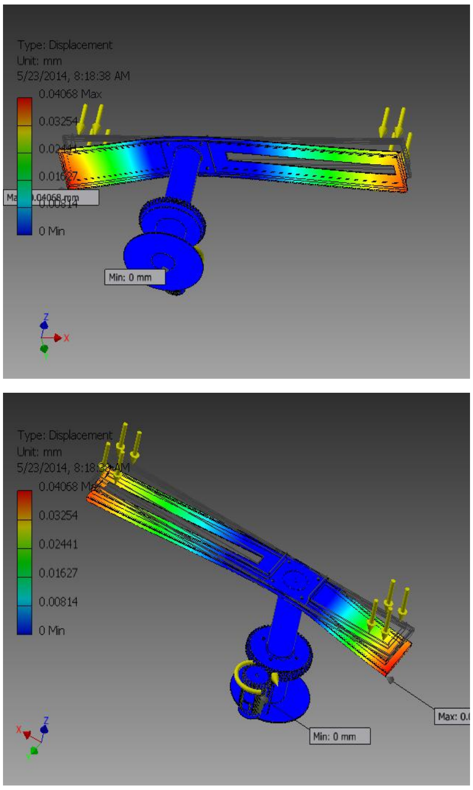

Fig. 7. Displacement

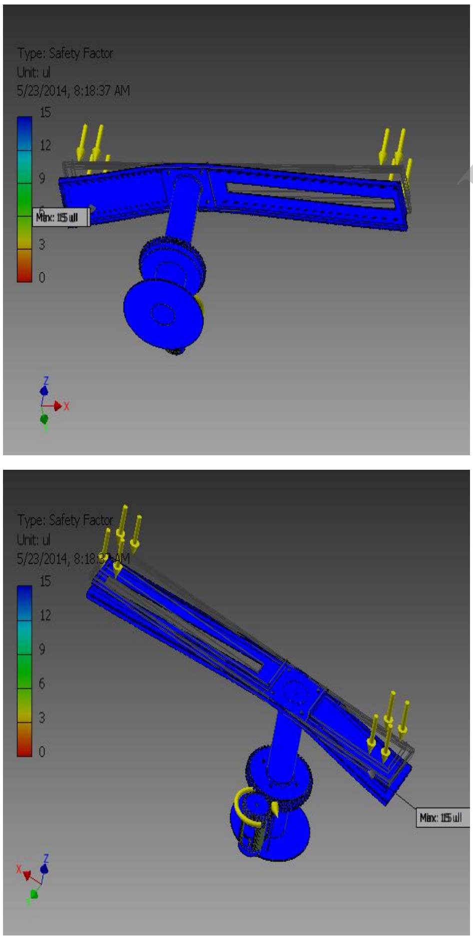

Fig. 8. Safety factor

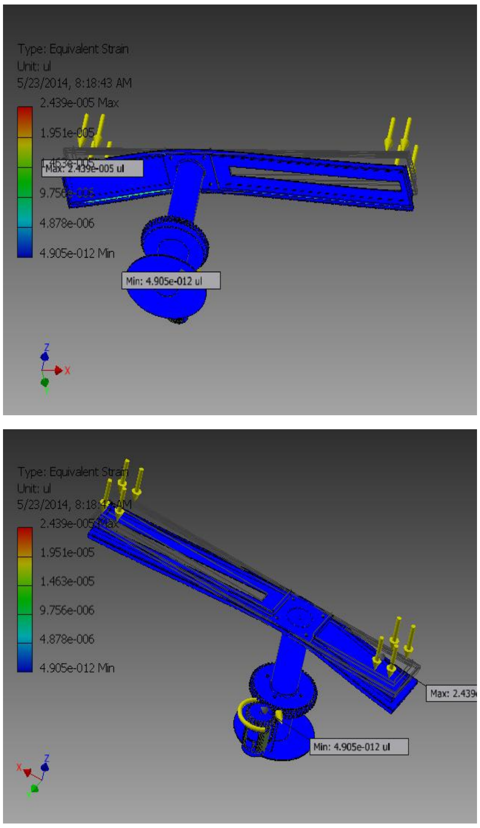

Fig. 9. Equivalent strain

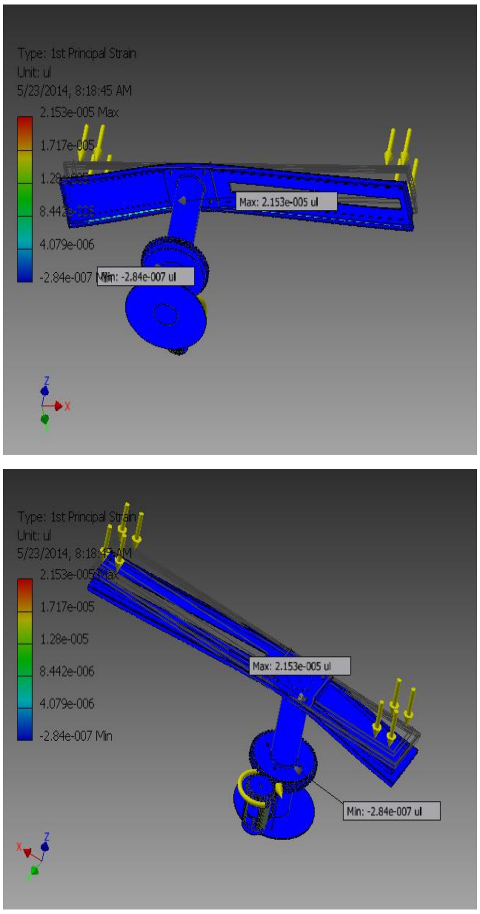

Fig. 10. First principal strain

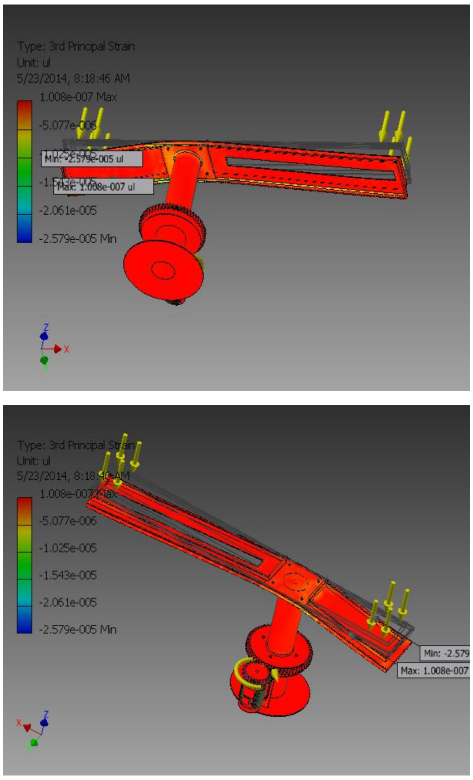

Fig. 11. Third principal strain

IV. IMPLEMENTATION OF TOWER CRANE PROTOTYPE

The design of the tower crane prototype discussed in previous sections gives the detailed dimensions that have been used to implement the prototype structure in the department of mechanical equipment, MTC, as shown in Fig. 12. The main technical specifications of the prototype can be summarized as the tower initial height is 45 cm that can be extended up to 100 cm using steel structure mast units so that the prototype reaches the scaled height of the crane under test. The jib length is 110 cm while the counter jib is 50 cm.

Describing the construction of prototype, we begin with the base that can be bolted to a ground concrete pad or a table equipped with a fixture to support the prototype. The base is then connected to the mast, which can be elongated to give the prototype the scaled height of the tower crane under study.

Attached to the top of the mast is the slewing unit that allows the jib to rotate. The slewing unit, shown in Fig. 13, consists of a steel frame that is rotated via gear train whose pinion is powered by an electric motor that is fixed on a stand below the unit’s large rotational gear. Attached to the slewing unit is the jib through a steel cylinder where the operator's cab is supposed to be located. The trolley runs on rails that are fixed on the jib deck to move the load.

The trolley consists of a metal carriage that has four wheels that help the trolley to move on rails fixed along the jib through sprocket and chain arrangement that is powered by an electric reduced motor fixed on the counter jib, as shown in Fig. 14. The sprocket and chain arrangement has the advantages of preventing sliding and skidding of trolley as well as facilitating position control. The trolley hosts the winch geared electric motor that lifts the load through a system of pulleys. The counter jib with the counter weights and prototype control electronics fixed on it extends in horizontal alignment to the jib.

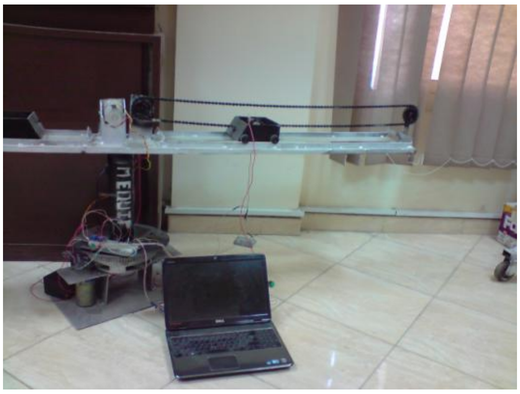

Fig. 12. Tower crane prototype

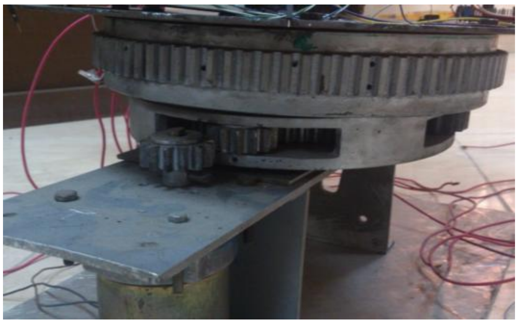

Fig. 13. Slewing unit

Fig. 14. Trolley assembly

An Adriano Uno is used as a microcontroller board to control the electric motors. The motor drivers can be controlled by simply applying a (0 or 1) logic to the direction pin for that motor and a pulse width modulation (PWM) signal to the speed pin. In this way, the speed and direction of three separate motors can be controlled independently from only 6 GPIO pins. Twelve step rotary encoders are used for controlling the motors' position. Installing the encoder inputs on the driver board, each pair of encoder inputs is mixed using an XOR gate to make it possible to read both inputs from using only one interrupt pin. Reading the current sensor output is easy, each current sensor pin will output about 1V for each Amp of current drawn by the associated motor up to 5V. By connecting the current sensor pin to the analog input of the controller, the stalls and other motor problems can be detected. There are two power connectors on board, one is for 5V logic and the other is for the motor supply. The board is rated for a maximum motor supply voltage of 12V.

V. CALIBRATION OF TEST-RIG MEASUREMNET DEVICES

Accuracy is, of course, the most important factor regarding measurements. Therefore it is crucial to ensure proper installation and then calibration of the devices in the crane prototype. A load cell is used here to measure force which results from the load weight. A load chart, shown in Fig. 15, has then been estimated for the crane prototype using the readings of the load cell for several load weights and distances along the jib. This process has the benefits of ensuring correct measurements as well as using the load chart as a guide to plan tests later on during the use of the prototype as a part of crane's performance enhancing. The comparison between the load chart of the scaled prototype and that of the real tower crane shown in Fig. 16, assure the capability of using the prototype as an experimental facility for conventional top-slewing tower cranes.

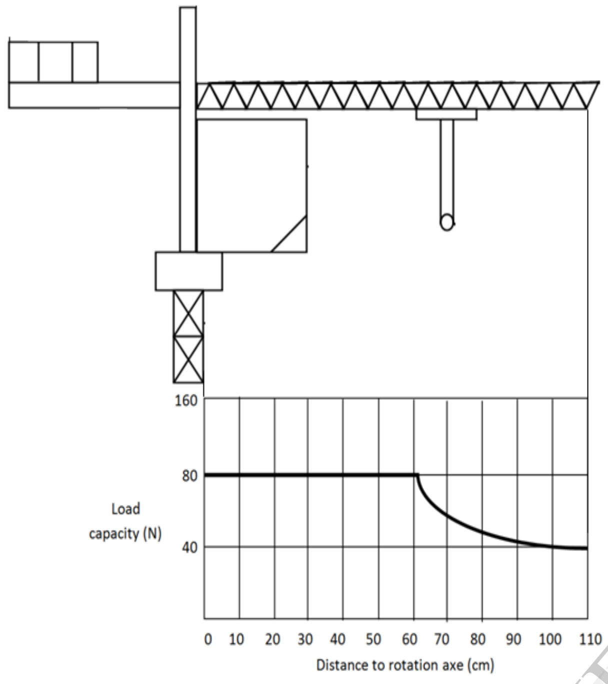

Fig. 15. Tower crane prototype load chart

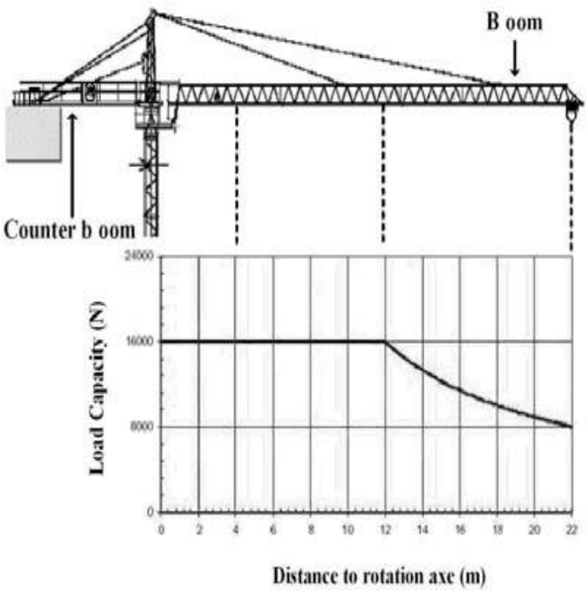

Fig. 16. Real crane load chart

CONCLUSIONS

In modern construction projects, tower cranes play a key role in transporting heavy loads vertically and horizontally within their comparatively large working zone. Tower cranes can be simply described as a central shaft with a long boom and counter weights used to balance the crane's load. This paper presents the design and implementation of an experimental test-rig to execute indoor tests to develop the tower crane theory of operation. The prototype structure preliminary design procedures, the structure stress analysis, the implementation of the prototype, and the calibration of the measuring devices are discussed. Comparing the estimated prototype load chart to the real tower crane load chart assure the capability of using it as an experimental test-rig for conventional top-slewing tower cranes.

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