

# Monitoring Truck Cranes Operation with the Safety Management System on Construction Sites

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## Abstract

In the era of construction digitization, automating construction site management is becoming increasingly feasible by integrating site management systems with on-site facilities and equipment. For mobile cranes, including truck cranes operating at construction sites, safety is a critical concern alongside operational management and productivity. The high susceptibility of truck cranes to unsafe conditions, such as excessive vibrations during operation, underscores the importance of addressing these risks.

This article presents a research model focused on managing the vibration and tilt levels of truck cranes as part of the broader occupational safety challenges at construction sites. The study employs the finite element method to develop a structural model and applies analytical techniques to construct a continuous-discrete model of the crane, simulating unsafe conditions during operation.

The research further proposes a framework for monitoring crane operations with a safety focus, utilizing sensors and a safety controller device. These components communicate with the on-site safety management system to exchange real-time data, issue safety alerts, and generate warnings. Future studies aim to validate these findings by testing the crane element models and the proposed framework in practical, real-world scenarios.

## 1. Introduction

Cranes are industrial machines designed primarily for lifting and moving objects in various settings, such as manufacturing facilities, assembly lines, storage areas, power plants, and similar environments. They have capacity of lifting, loading, and unloading apparatus designed to raise loads of varying masses to different heights and radiuses [1]. The design elements of cranes differ significantly based on their primary operational parameters, which include the crane's position, geometric features, operating mechanisms, and environmental circumstances. Cranes can be considered as the most commonly used type of equipment in the construction industry in Vietnam, and in other countries [2]. Cranes can be categorized in different groups based on different criteria. The popular categories of cranes include overhead travelling cranes, gantry cranes, mobile cranes, telescopic cranes, tower cranes, crawler cranes, railroad cranes, floating cranes, aerial cranes and jib cranes. Another way to classify the cranes can lead to groups such as bulk handling cranes, loader cranes, stacker cranes, deck cranes, level luffing cranes, and hammer head cranes etc.. [3]. Among the groups, mobile cranes have great versatility, they can move freely around the construction site, also from job site to job site using the wheels or tracks that are part of the cranes. Superior mobility and rapid deployment are considered as the advantages of mobile cranes over other

types. Others can be limited spaces requirement, better adaptability to site conditions, especially in sites with unstable ground conditions.

Truck cranes belong to the group of mobile cranes, which differ from other subgroups in their better site accessibility. Because truck cranes are built with a truck chassis body, they provide greater site accessibility than other types of cranes. These cranes can reach the sites that other cranes might not be able to travel great distances on public roads and highways. Being considered as a dynamic object on construction site, a truck-crane can be less stable than a fixed crane since it can only lean on the wheels while moving around the site. Therefore, this type of crane has high potential for unsafety working on construction sites. When a truck crane is in operation, accidents can result in personal injury or property damage; accidents are a significant issue for the construction sector in terms of both direct and indirect expenses to the sector and humanitarian losses [4]. Therefore, to avoid the safety risk, the dynamics of the truck cranes working on sites must be paid significant attention to.

Recent evidence indicates substantial deficiencies in the safety management of truck cranes [5]. Statistical figures show that truck cranes are the least safe type of cranes; they involve in 73% of the accidents by all types of cranes [6]. Nearly 3% of such accidents lead to fatal cases and 8% of them result in permanent disability [7], which have brought significantly negative impact to the society. Therefore, it is very important to pay significant attention to ensuring safety for truck cranes working on sites. In the digitalization era, toward the automation of managing construction sites, crane operations need to be connected to the site management system, then unsafety issues can be discovered early and avoided. According to the literature, the excessive vibration and tilt of the truck cranes are the main cause for their accidents on construction sites [6]. Crane collapse is one of the main cause for cranes-related accidents [8]. Other causes include overloading, but it occurs less frequently due to the positive impact of safety education and management on sites. However, with the acceptable load, if the working model of the truck crane is abnormal, safety issues can occur.

The research questions raised include: 1. How to figure out the safety standards for operating truck cranes in various operational conditions? 2. How can the safety management system on construction sites monitor the vibration and tilt levels of a truck crane's key elements to avoid accidents in the digitalization era? Aiming to address the questions, this research study models the operation of the hydraulic telescopic truck crane KC-55713-1K with regard to vibration and the tilt levels as a case study using Modelling and Evaluation System (MES) approach then proposes a framework for using safety management system to monitor the truck crane operation safely.

The paper, presenting the research results, consists of 5 main sections: the introduction, the literature review, the research methodology, the research results and the conclusion. The research results section discusses a simplified model of the truck crane was used to simulate its operation in order to determine its oscillation-related safety standards, then a framework to monitor the safety of working truck cranes with the safety management system on the sites.

## 2. Literature Review

Many previous works have claimed that modelling the dynamics of a truck crane is a complicated problem [9, 10]. Some works emphasizes the influence of the ground characteristics on the stability of the truck crane [11, 12]. The earlier relevant works on finite element methods have discussed the identification of the finite elements and the dynamics of the crane chassis frames [13, 14]. Later research studies have examined the impact of the truck crane's remaining components, including the crane itself [15], or the telescopic extension arm in the lifting plane [16] on the vehicle's free oscillation.

Regarding the mechanism to connect the safety management system to working equipment in general and truck cranes in particular, the application of IoT is the significant solution. Saxena, et al. [17] proposed a monitoring solution of a multi-layered system architecture to monitor the real-time health of a sensor-integrated hand-tool. Fang, et al. [2] developed a framework for real-time pro-active safety assistance for mobile crane lifting operations which is developed under a prototype. Initially, crane poses are recreated in real-time based on the crucial movements of crane components recorded by a sensor system. Secondly, existing lift site conditions are automatically modeled and updated using point cloud data. Finally, the risk of the crane components and lifted load colliding with adjacent obstructions is proactively assessed, and alerts are communicated to the operator via a graphical user interface [2]. Hassan, et al. [18] have reviewed 114 previous publications and pointed out that different accelerometers and their technologies could be used to measure vibrations of heavy machinery, in which cranes belong to. That is the type of sensors and methods used for data collection deciding the prediction of machinery failures. Though focusing on gantry cranes, another type of cranes, the proposal of Hendrickson and Hinders [19] on using commodity IoT devices to monitor the cranes by collecting information on rolling standard deviation. This suggests that operational safety standards of cranes in different working status are not the same, so the standards should be simulated with a continuous model to reflect better the real-time behavior of the cranes.

All lessons learned from will be incorporated into this study's development of a comprehensive framework aimed at integrating real-time crane monitoring into the site's safety management system.

### 3. Research Methodology

This research study was conducted in two key stages. At the first stage, the research tries to model the operation of a truck crane, with the case study of the hydraulic telescopic truck crane KC-55713-1K. Two dynamic system modeling methods have been used, which are a discrete model developed using the finite element method and a discrete-continuous theoretical model.

The truck crane was simplified as a model consisting of interconnected components, such as:

- the chassis, the primary lifting base of the crane, supported by four elongated beams resting on the ground.
- the rotating section (body), which performs rotational motion along a vertical axis (movement within the rotational plane).
- the boom, attached via a pivot joint at the boom base, capable of movement along the vertical axis (in the lifting plane) and telescopic extension of the boom segments. The boom of the crane is assumed to be uniform along its entire length and perfectly rigid.

The vibration frequencies of the systems are tested in relation to the boom's elevation angle, the crane's length, the load mass, and the suspension length for both finite element models and discrete analytical models, using the MES approach. Additionally, the corresponding vibration modes are examined, focusing on the fundamental frequency of the crane's lateral vibrations within its lifting plane, as demonstrated in the finite element model. Calculations were conducted with the discrete-continuous model to identify the operating safety standards of the crane's key elements in different scenarios.

In the second stage, a framework was proposed to use the safety management system on sites to monitor the operations of the crane. The operating safety standards of the crane's key elements in different scenarios will be integrated into the safety management system. Sensors are attached to the crane to collect information on the vibration and the tilt levels of the crane elements, transmitting them to the central safety management system on sites, to trigger real-time warnings if the vibration and the tilt levels go beyond the standards. Then, informed decision can be made in real-time to avoid excessive vibration and tilt levels of the truck cranes to ensure the safety of people and property on construction sites.

## 4. Research results

### 4.1 Modelling the Oscillation of the Truck Crane on Construction Site

#### 4.1.1 Crane's MES Model

The research study was conducted with the case of a hydraulic telescopic truck crane KC-55713-1K (Figure 1). The model was developed using the finite element method, and to simplify the modeling process, certain details—such as mounting holes, equipment brackets, small bending radii, and plates—were omitted. In the modeling process, the following fundamental structural elements were applied for linear analysis:

- Shell: Thin-walled elements with isotropic properties, meshed as triangular shapes, used to model the primary structural plates of the frame and boom.
- Solid: Three-dimensional elements with isotropic properties, used to model structural components such as struts, the frame, and the boom.
- Spring: Elastic elements used to model the elasticity of the supporting legs.
- Rbar: Rigid bar elements with two nodes, used to model connecting components between the chassis and the rotating frame (turntable) or the boom.
- Mass: Mass elements used to model selected concentrated masses of crane components (e.g., counterweights, motors) and the load.



This modeling approach eliminates the need for the computational systems typically required for building finite element models, making it simpler to implement modifications and adapt to systems with similar structures. The discrete-continuous crane model, depicted in Figure 2, closely mirrors the real system by incorporating key elements such as the suspended load's mass on the cable, the actual system geometry, and equivalent masses representing the boom segments, hoisting winch, and counterweights.

The model reduces the mass at the boom tip and the equivalent mass of the entire crane to the rotational axis, ensuring accuracy in representation. It also accounts for the crane's equivalent stiffness, considering isolated boom elements that influence the beam's stiffness within the modeled system. Furthermore, the elasticity of the servo motor used to adjust the crane's outreach is included, enhancing the model's alignment with real-world dynamics.

During the model development process, several simplifications were made through the following assumptions:

- The system's beams are considered as Bernoulli-Euler beams.
- The crane's chassis is assumed to be non-deformable.
- A spring model is applied to simulate the elasticity of the support legs at the fixed points where the boom connects to the rotating frame.
- The mass of the crane chassis and the rotating frame are only replaced along the vertical direction within the lifting plane of the boom.

The vibrations of the system are modelled using Hamilton's principle:

$$\delta \int_{t_1}^{t_2} (T - V) dt = 0 \quad (1)$$

Where:

T: The system's kinetic energy.

V: The system's potential energy.

W: Work completed by external forces.

This principle provides a foundation for deriving the equations of motion, ensuring the system's dynamics are accurately captured based on energy interactions.

The kinetic energy  $T$  is calculated as the sum of the kinetic energies of the crane elements, which are modeled as beams and concentrated masses within the system:

$$T = \sum_{i=1}^3 \frac{1}{2} \int_0^{l_i} \rho_i A_i \left[ \frac{\partial W_i(x_i, t)}{\partial t} \right]^2 dx_i + \frac{1}{2} M_{hw} \left[ \frac{\partial W_1(0, t)}{\partial t} \right]^2 + \frac{1}{2} M_b \left[ \frac{\partial W_2(0, t)}{\partial t} \right]^2 + \frac{1}{2} M_f \left[ \frac{dX_5(t)}{dt} \right]^2 + \frac{1}{2} M_h \left[ \frac{\partial W_2(l_2, t)}{\partial t} \right]^2 + \frac{1}{2} m \left[ \frac{dX_6(t)}{dt} \right]^2 \quad (2)$$

where:  $\rho_i$  - density of beam material.

$A_i$  - the cross-sectional area of a beam,  $i = 1, 2, 3$ .

$M_{hw}$  - the equivalent mass modelling masses of hoisting winch and counterweight.

$M_b$  - the equivalent mass modelling mass of piston rod of servomotor of change in crane radius.

$M_f$  - the equivalent mass modelling mass of crane chassis.

$M_h$  - the mass of roller slope.

$m$  - the mass of the load.

$t$  - time.

The total potential energy  $V$  of the system is the sum of the potential energies due to internal forces (such as elastic deformation) and the work done by external forces (such as gravity and external loads). It can be expressed as:

$$V = \sum_{i=1}^3 \frac{1}{2} \int_0^{l_i} E_i J_i \left[ \frac{\partial^2 W_i(x_i, t)}{\partial x_i^2} \right]^2 dx_i - \sum_{i=1}^3 \frac{1}{2} \int_0^{l_i} P_i \left[ \frac{\partial W_i(x_i, t)}{\partial x_i} \right]^2 dx_i + \frac{1}{2} \left[ (k_f + k_s) (X_5(t) \cos \beta)^2 - 2k_s X_4(t) X_5(t) \cos \beta + k_f X_4(t)^2 + k_l (X_6(t) - W_2(l_2, 0) \cos \alpha)^2 \right] \quad (3)$$

where:  $P_2 = mg \sin \alpha, P_1 = mg \sin \alpha - P_3 \cos \delta, P_3 = k_f x_4, \beta = 90^\circ - (\alpha + \delta)$

$E_i$  - Young's modulus of beam material.

$J_i$  - moment of inertia of beam intersection,  $i = 1, 2, 3$ .

$k_s$  - replacing coefficient of elasticity modelling elasticity of stays.

$k_f$  - coefficient of elasticity modelling elasticity of liquid in servomotor of change in outreach.

Substituting equations (2) and (3) into equation (1) and performing the necessary transformations, we obtain the equation of motion. The geometric boundary conditions, when incorporated into equation (1) along with the considerations from equations (2) and (3), provide additional natural boundary conditions. By separating the variables into the equations of motion and boundary conditions, the system can be expressed by substituting:

$$W_i(x_i, t) = w_i(x_i) \cos(\omega t), (i = 1, 2, 3) \tag{4}$$

and

$$X_i(t) = x_i \cos(\omega t), (i = 4, 5, 6) \tag{5}$$

The resulting equations of motion are obtained as follows:

$$E_i J_i w_i^{IV}(x_i) + P_i w_i''(x_i) - \rho_i A_i \omega^2 w_i(x_i) = 0, (i = 1, 2, 3) \tag{6}$$

The geometrical boundary conditions and continuity conditions define the constraints and relationships within the crane system to ensure an accurate representation of its behavior. These conditions can be described as follows:

$$\begin{aligned} w_1(0) \cos \alpha &= x_5 \\ w_1(l_1) &= w_2(0) \\ w_1(0) \cos \alpha &= x_5 + x_4 \cos \alpha \sin \delta \\ w_2(l_2) &= w_2(0) \frac{l_t}{l_1} \\ w_3(0) &= w_2(0) \cos \delta \\ w_3(l_3) \cos \alpha &= x_5 \cos \delta \\ w_1'(l_1) &= w_2'(0) \end{aligned} \tag{7}$$

The natural boundary conditions derived from the formulation are expressed as follows:

$$\begin{aligned} w_1''(0) = 0, w_2''(l_2) = 0, w_3''(0) = 0, w_3''(l_3) = 0, E_1 J_1 w_1''(l_1) = E_2 J_2 w_2''(0) \\ [E_1 J_1 w_1'''(0) + P_1 w_1'(0) + \omega^2 M_{hw} w_1(0)] \cos \alpha + M_f \omega^2 x_5 - k_s x_5 = 0 \\ E_1 J_1 w_1'''(l_1) + P_1 w_1'(l_1) - E_2 J_2 w_2'''(0) - P_2 w_2'(0) + M_b \omega^2 w_2(0) - k_f x_4 \sin \delta = 0 \\ E_2 J_2 w_2'''(l_2) + P_2 w_2'(l_2) + M_h \omega^2 w_2(l_2) - m_f \omega^2 x_6 \cos \delta = 0 \\ M_f \omega^2 x_5 - x_5 (k_f \cos \beta + k_s) - 2k_f x_5 \cos \beta = 0 \\ m \omega^2 x_6 - k_l [2w_2(l_2) \cos \alpha - x_6] = 0 \end{aligned} \tag{8}$$

The solution to equation (6) is the function:

$$w_i(x_i) = C_{i1} ch \frac{\lambda_i}{l_i} x_i + C_{i2} sh \frac{\lambda_i}{l_i} x_i + C_{i3} \cos \frac{\bar{\lambda}_i}{l_i} x_i + C_{i4} \sin \frac{\bar{\lambda}_i}{l_i} x_i, \tag{9}$$

where:  $C_{i1} \div C_{i4}$  - constants.

$$\frac{\lambda_i}{l_i} = \sqrt{-\frac{\beta_i^2}{2} + \sqrt{\frac{\beta_i^4}{4} + \gamma_i}}, \frac{\bar{\lambda}_i}{l_i} = \sqrt{\frac{\beta_i^2}{2} + \sqrt{\frac{\beta_i^4}{4} + \gamma_i}},$$

where:  $\gamma_i = \omega^2 \frac{\rho_i A_i}{E_i J_i}, \beta_i^2 = \frac{P_i}{E_i J_i}, l_i$  - the length of the  $i$ -th beam,  $i = 1, 2, 3$ .

The solution to the boundary problem leads to a system of homogeneous equations involving the unknown constants  $C_{ik} (i = 1, 2, 3, k = 1, 2, \dots, 4)$  and  $x_n (n = 4, 5, 6)$ . This system can be expressed in matrix form as follows:

$$[a_{pq}] \text{col}\{C_{ik}, x_n\} = 0 \quad (10)$$

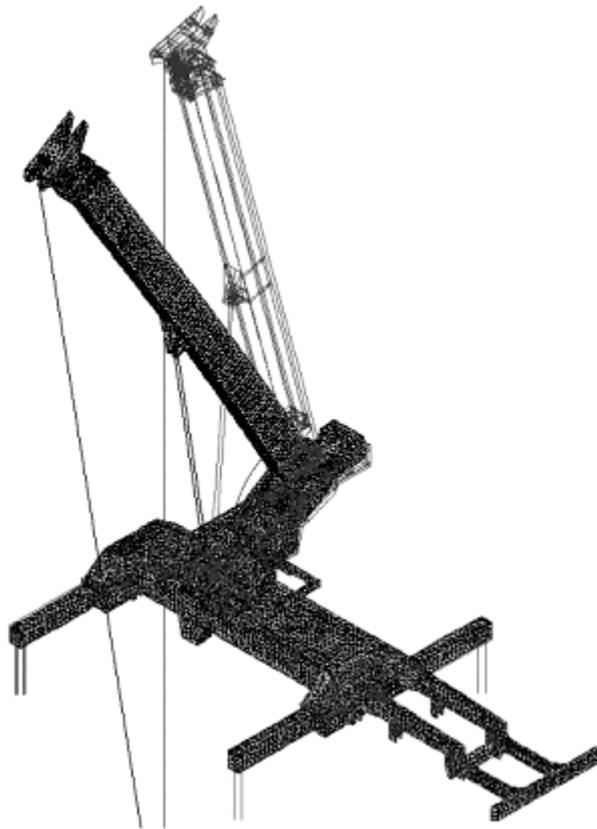
If the eigenvalues of matrix  $[a_{pq}]$  are found, it is high time to determine the frequency of vibrations of the considered system.

#### 4.1.3 Calculations Results

The variation in vibration frequencies corresponding to selected values of geometric parameters and load conditions is presented as the result of solving the vibration problem for the analyzed system. The study focuses on the variation in vibration frequencies of the first bending mode of the crane boom in the lifting plane (Figure 3). The results are presented in the form of graphs depicting how the vibration frequency values change in relation to selected parameters. Time-based plots, combining the selected parameters while keeping one of them constant, were generated. For the calculations, the chosen position of the crane assumed the boom to be perpendicular to the chassis relative to the rotating frame.

The parameters defining the boom's position in space and its dimensions were varied within a specified range. These parameters include:

- Boom elevation angle,
- Total boom length,
- Load weight, and
- Length of the suspended load.



**Fig. 3** The finite element model of the crane boom being bent in the lifting plane, MES method

The study was conducted using the following parameters:

- Boom Elevation Angle:  $\alpha = 0 \div 75^\circ$ , boom angle sensor, displayed on the screen the current position of the boom.
- Boom Length:  $l_t = 10 \div 24$  m, including the extension of internal boom segments.
- Load Values:  $m = 0 \div 30.000$  kg

Figures 4 and 5 illustrate the results of the research on the vibrational frequencies of the system as the boom length varies ( $l_t = 10 \div 24$  m), and changeable load of the crane ( $m = 5000 \div 30000$  kg) are shown. The lifting angle of the boom,  $\alpha$ , was equal to  $75^\circ$ .

The variation in the selected parameters,  $l_t$  (boom length) and  $m$  (load mass), places some of the results within the range where the loads exceed the crane's hoisting capacity limits for the specified boom length. To illustrate this, Figures 4 and 5 include a plotted curve that separates the safe load region (above the curve) from the overloaded region (below the curve). This visualization effectively highlights the operational boundaries, providing a clear distinction between safe and unsafe conditions, thus supporting the evaluation and management of crane performance under different loading scenarios.

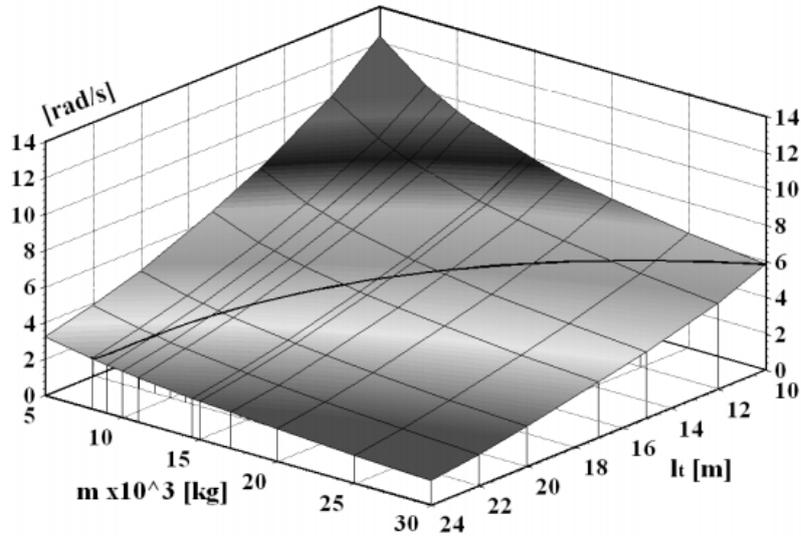


Fig. 4 Diagram of vibrational frequency's changes with various values of load, analytical method

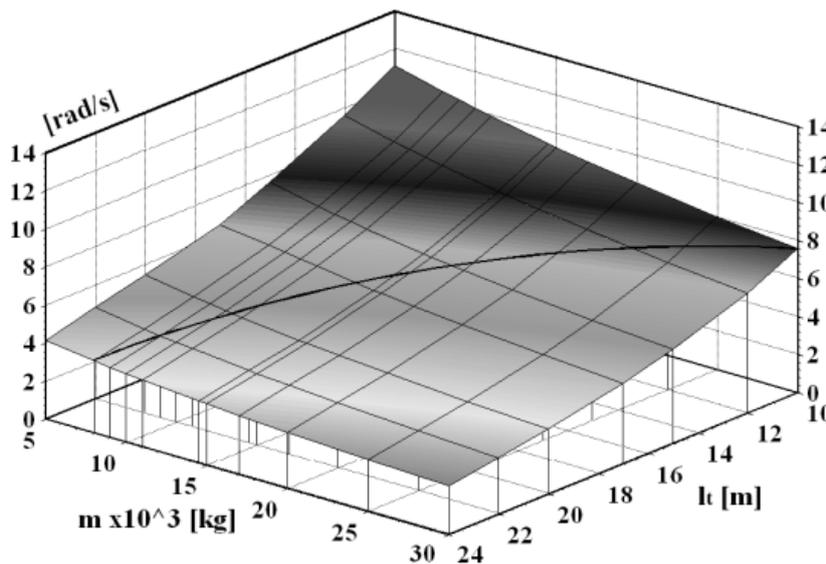
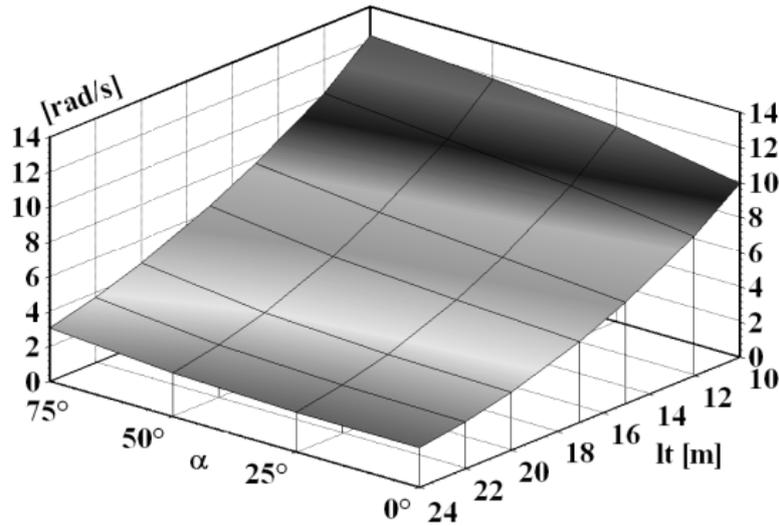
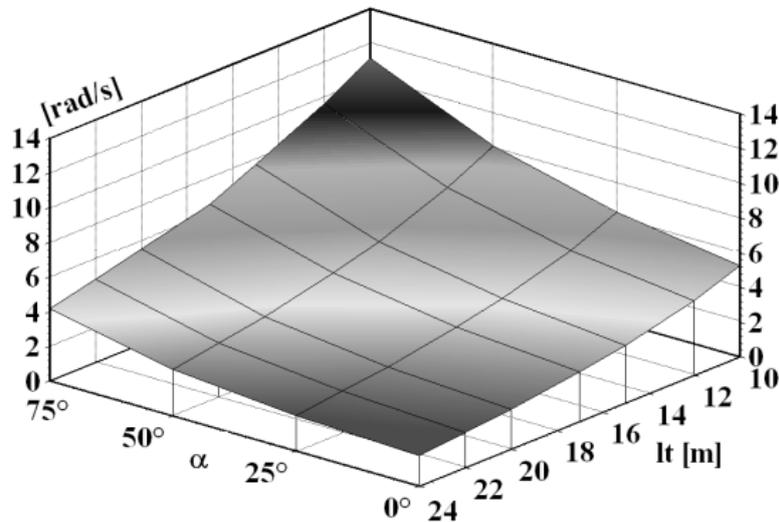


Fig. 5 Diagram of vibrational frequency's changes with various values of load, MES method

The subsequent graphs (Figures 6 and 7) pertain to alterations in the vibrational frequency of the boom crane in relation to its adjustable length ( $l_t = 10 \div 24$  m) and changeable angle of its inclination ( $\alpha = 0 \div 75^\circ$ ) with a constant load value equaling  $m = 5000$  kg. In all tested cases, the length of the line was equal to  $l_l = 5$  m.



**Fig. 6** Diagram of vibrational frequency's changes with various angle of boom lifting, analytical method



**Fig. 7** Diagram of vibrational frequency's changes with various angle of boom lifting, MES method

The above graphs are used to simulate the operation of the crane when integrated into the site management system through sensors to aid the automation of the crane control process. This ensures the crane's safety during operation as the boom length or angle changes, indicated by vibration frequencies exceeding standard conditions.

#### 4.2 A Framework to Monitor the Truck Crane Operation with On Site Safety Management System

The proposed framework is illustrated in Figure 8. The framework consists of:

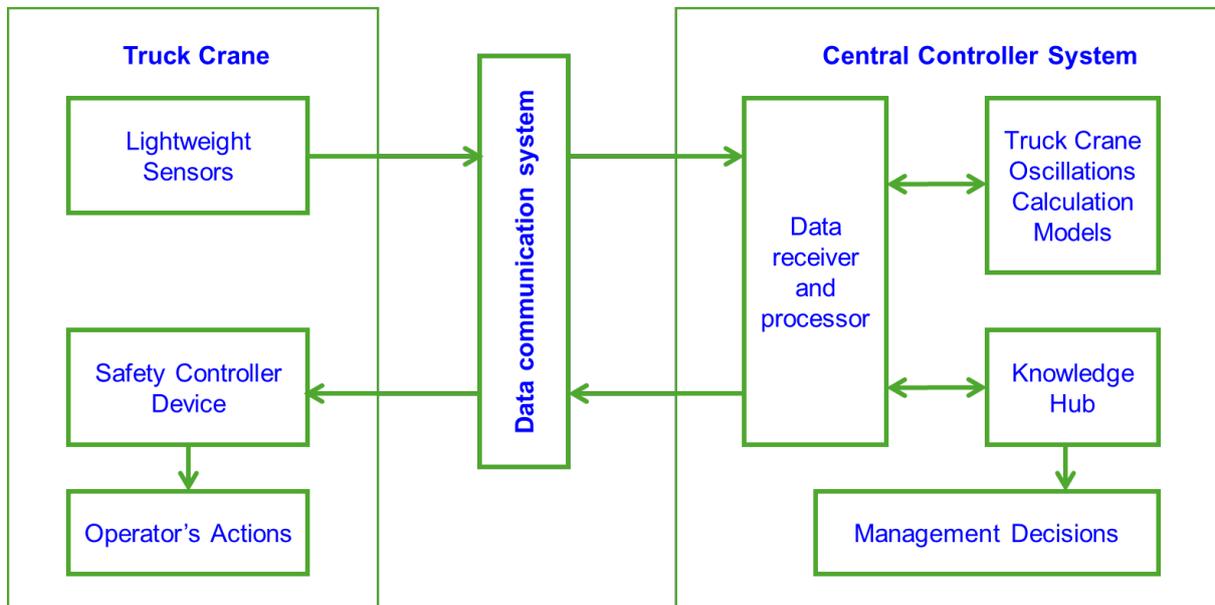
- The placement of lightweight sensors at strategic points in the crane to measure the vibration and tilt levels of the crane's elements: chassis, rotating section and the boom. Data collected will be sent through a data communication system to the central control system. Lightweight sensors are recommended due to their advantages of achieving high sensitivity and functionality without the bulk, making them ideal for applications in various fields.
- Data communication system: to send the data to be monitored, which includes real-time vibration and tilt levels of the crane while working, via internet, to the central control system, to be stored in a database for future reference. Alerts and warnings generated from the central control system can be sent back to the safety controller devices attached to the crane.

- The central control system which can generate safety standards based on the real-time behavior of the crane, integrated with the oscillations calculation models of the truck crane as proposed in this research study. A knowledge hub and a decision-making supporter are also key elements of the central control system. The knowledge hub collects lessons learned and operational documentation of the truck cranes, which can be used for making management decisions, such as providing additional training to crane operators who often make mistakes putting the crane in dangerous situations.
- The safety controller device, which must be fitted to truck cranes as required by the design.

The safety controller device has several functions:

- Motion limiting function to stop a specific crane motion before the crane moves out of its limits into an unsafe situation. Motion limiting devices are employed to avert physical damage to the crane or its components by restricting movement beyond the designated range of motion.
- Indicating function to visually or audibly warn the crane operator that the crane may be approaching its set limits or an unsafe situation.
- As a rated capacity limiter, it halts all pertinent crane operations upon detecting an overload to avert crane overloading.

Rated capacity means the maximum load that may be attached and handled by the crane and may not include the weight of the hook block, falls of rope, slings and rigging hardware. The load to be raised must include the weight of all lifting appliances that are not permanently attached to the crane. The crane's load chart will provide guidance on any deductions that may need to be made.



**Fig. 8** The proposed framework to monitor the truck crane operation with on site safety management system

## 5. Conclusion

This paper presents an approach to integrate truck crane oscillations calculation models into the safety management system on construction sites to prevent safety hazards in connection with crane operation. Using the two calculation models: finite element model and discrete-continuous model, to simulate the operation of the crane elements, taking an example of a hydraulic telescopic truck crane KC-55713-1K, the research study has successfully modelled the operation of the crane and its key elements, resulting in the methods and formulas to figure out the safety standards in connection with the vibration and tilt levels of the elements while in operation.

The paper presents a proposed framework to monitor the truck crane operation with on site safety management system, which consists of four key components. The sensors and the safety controller devices attached to the truck crane will assist with collecting real-time operation data and facilitating the decisive controlling of the operator. The central controlling system will process data collected and send out alerts, warnings and support management decisions. The data communication system facilitates the information exchange between the crane and the central controlling system.

This research study has several limitations. Firstly, it needs experimenting with the models used for simulating the crane operations with a real case study on site to validate what has been found. Secondly, the proposed framework needs further study to test the type of sensors, safety controller devices and the

communication system, especially with large sites. However, it plays as the first steppingstone to the automated controlling of equipment on sites, of which there is a gap in developing countries, including Vietnam.

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## Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

## Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Duc Hieu Tran, Sy Nam Nguyen; **data collection:** Duc Hieu Tran; **analysis and interpretation of results:** Duc Hieu Tran, Sy Nam Nguyen; **draft manuscript preparation:** Duc Hieu Tran, Sy Nam Nguyen. All authors reviewed the results and approved the final version of the manuscript.

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