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Short Communication

Static Stability Analysis on Mini Excavator Chassis with Articulated Boom for Oil Palm Harvesting

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Abstract: Harvesting machine is a promising technology for palms above 5 m in height. The stability of oil palm harvesting machines equipped with articulated booms is crucial for ensuring safety, operational efficiency, and reduced mechanical wear during harvesting activities. A machine with a 2.5-t mini excavator chassis and a 300 kg lightweight articulated boom with 3-degrees-of-freedom scissor-type cutter has been developed to evaluate its performance. The machine could reach up to 12 m in height. This study investigated the static stability of such machines under varying operational conditions, particularly in response to terrain slope changes. The influence on the machine's centre of gravity (CoG) and tipping moment was evaluated, along with moment distribution and tipping-over stability. Results showed that extending the load weight significantly shifted the CoG, reducing the stability factor (SF). Machine stability factors were calculated at boom angles of 30° (SF = 2.68), 45° (SF = 1.90), and 60° (SF = 1.54), all of which exceeded the critical value of 1, confirming the system's stability under these conditions. The combined system's CoG was determined as CGx = 1.52 m and CGy = 1.12 m, incorporating the base and boom contributions at a static condition. The critical tipping angle of the machine was 35.7°, or approximately a 60% slope grade. These findings confirmed that the modified chassis of existing work machinery can be utilised as a safe machine, reducing development time and allowing for quick deployment in oil palm harvesting.

Keywords: Articulated Boom; Harvesting Machine; Oil Palm Fresh Fruit Bunch

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1. Introduction

In the past, oil palm fronds (OPFs) and fresh fruit bunches (FFBs) were harvested manually using basic tools such as sickles or chisels. This method was labour-intensive, timeconsuming, and physically demanding, requiring significant human effort. Additionally, the reliance on foreign workers to perform these tasks highlighted the challenges of labour availability and cost (Parveez *et al.*, 2023). Manual harvesting posed safety risks to workers and limited the efficiency and scalability of oil palm harvesting. To address the inefficiencies of manual harvesting, the Malaysian Palm Oil Board (MPOB) has developed motorised tools such as CANTAS and CKAT (Jelani *et al.*, 2008). These innovations significantly improved harvesting efficiency by reducing the time and energy needed to perform the task. However, CANTAS and CKAT had limitations, such as adjustability issues and limited reach. Furthermore, despite being motorised, these tools still relied on humans' strength to manoeuvre the tools, which restricted their effectiveness for taller trees (Azwan *et al.*, 2016).

Mechanised oil palm harvesting machines equipped with adjustable booms were developed to overcome the shortcomings of the CANTAS and CKAT. These machines utilise articulated booms (flexible, jointed arms) or telescopic booms (extendable arms) to reach oil palm trees with varying heights. The adjustable booms eliminated the need for manual pole adjustments, significantly reducing the time required to harvest OPF and FFB. It also reduced labour's dependency, and the machines can be adapted to different tree heights and terrains.

Harvesting machines could potentially overcome issues and challenges in the oil palm industry. However, their operations at different lifted boom angles posed significant challenges, including instability, tipping risks, and reduced operational efficiency. These issues affected productivity and raised concerns about operators' safety (Váliková, 2013). In addition, advancements in agricultural machinery have shown that smaller and more compact machines are often more convenient for field operations, as they offer better manoeuvrability and accessibility, especially in dense plantations (Ramdhan Khalid & Rahim Shuib, 2014). Although reducing the size of machinery improved access, it can compromise stability, particularly on slopes and uneven terrain. The trade-off between size and stability highlights the need for comprehensive studies on the static and kinematic stability of harvester cranes under real-world operating conditions (Wu *et al.*, 2014). This gap in research limited the development of safer and more efficient designs, which are essential for the sustainable growth of the oil palm industry.

This study analysed the static stability of harvester cranes operating at different lifted boom angles and on slopes and uneven terrain. The scope of the study included moment and static stability calculations, as well as tipping angle analysis for stability evaluation. It also investigated the effects of uneven ground and slope angles on machine performance and examined the impact of tipping moment on operational safety. This study also considered the broader context of the oil palm industry, including the need for efficient and safe machinery to support sustainable harvesting practices.

2. Materials and Methods

A static stability analysis was conducted to evaluate the tip-over stability of the harvesting machine with an articulated boom while it is at rest, focusing on its ability to maintain balance under various load conditions and boom angles (Fujioka *et al.*, 2009). The harvesting machine used in this study was a track-type mini excavator chassis equipped with a lightweight articulated boom lift (Figure 1). The articulating boom enabled flexible movement in various directions, making it easier to reach and cut oil palm fruits. Specifications and measurements of the harvesting machine are listed in Table 1.

Figure 1. Prototype of the harvesting machine with an articulated boom developed by MPOB.

Table 1. Specifications of the experimental harvesting machine.

Total mass of machine, kg	3266.01
Mass of prime mover, kg	3000.00
Mass of individual boom section, kg	78.67
Mass of cutter, kg	30.00
Boom length, m	3.50
Wheel spacing, m	1.14
Centre of Gravity (CoG) from surface, m	1.11

Experiments were conducted with the boom of the harvester machine extended at various angles, specifically at rest, 30°, 45°, and 60°. Additionally, tipping analysis was conducted to determine the critical slope angle at which the machine becomes unstable and tipping is likely to occur. These varying angles allowed for a comprehensive assessment of the machine's stability across various potential working environments. Several calculation methods were employed in stability analysis, each targeting a different aspect of the machine's performance. Equation 1 was employed for moment analysis, which determined the forces acting on the machine and assessed its balance (Wu *et al.*, 2014).

$$\mathrm{M} = \mathrm{F} \times \mathrm{d} \times \sin\theta \tag{1}$$

Where F is the force acting on the material, d is the distance or length of the material, and $\boldsymbol{\theta}$ is the lifted angle. Equation 2 was used to calculate the stability factor, which helped evaluate whether the machine remained stable or was at risk of losing stability based on the estimated parameters (Váliková *et al.*, 2013).

$$\mathrm{SF} = \frac{\text{Restoring Moment}}{\text{Overturning Moment}} > 1\ ;\ \text{stable} \tag{2}$$

The restoring moment is the weight of the machine acting through the base width, and the overturning moment is the force acting through the centre of gravity (CoG). Finally, Equation 3 was applied for tipping analysis, identifying the critical angles at which the machine could tip over (Fujioka *et al.*, 2009).

$$\theta_T = 90° - \tan^{-1}\left(\frac{\mathrm{h}}{\mathrm{x}}\right) \tag{3}$$

Where θ_T is the tipping angle of the harvester crane, α is the angle from the pivot to the CoG, h is the height of the harvester crane, and x is the base width. These methods provided a detailed understanding of the machine's stability under various operating conditions, laying the groundwork for further analysis and design improvements. The schematic diagram of the harvesting machine on uneven terrain or a slope is shown in Figure 2.

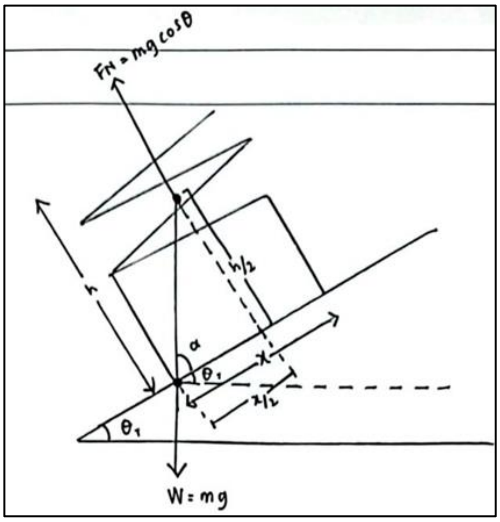

Figure 2. Schematic diagram of the harvesting machine tilted on the slope until it reaches its tipping point.

3. Results and Discussions

Results showed that the stability of the harvesting machine depended mainly on the relationship between the moment generated by the prime mover and the moment produced by the articulated boom. Specifically, the machine remained stable when the moment of the prime mover was greater than the moment of the articulated boom, ensuring balance during operation. This finding was crucial for the safe operation of the machine, particularly under varying load conditions and terrain. When the moment of the prime mover exceeded the moment of the articulated boom, the machine was in a stable operational state, reducing the risk of tipping or overturning (Table 2).

Table 2. Moment analysis of the harvesting crane with an articulated boom.

	Distance (m)	Mass (kg)	Force (N)	Moment boom (Nm)		
				30	45	60
Cutter	1.00	30.00	300.00		300.00	
Boom 1	3.50	78.67	1071.75	1875.57	2652.45	3248.58
Boom 2	3.50	78.67	1843.51	3226.13	4562.44	5587.83
Boom 3	3.50	78.67	2615.26	4576.70	6472.43	7927.08
Base	3.00	3000.00	29430.00		44145.00	

The stability factor is a key indicator in determining the overall safety and operational stability of the machine. Table 3 provides further insights into the stability factor of the lifted boom at different angles (30°, 45°, and 60°). Results indicated that at these angles, the harvesting machine remained stable since the stability factor remained above one. This confirmed that even as the boom was lifted to different heights, the machine could maintain its balance, which is essential for safe operation in the field.

Table 3. Stability factor at different lifted boom angles.

Boom angle (°)	Base width (m)	CoG (m)	Stability factor
30			2.70
45	3	1.11	1.91
60			1.56

Tipping analysis was conducted by calculating the tipping angle, which indicates the critical slope angle at which the harvesting machine is likely to tip over in uneven terrain. This is a crucial parameter, as it determines the machine’s ability to operate safely on inclined surfaces. If the tipping angle is exceeded, the machine may lose balance and overturn, posing significant safety risks. The results highlighted the importance of understanding the tipping angle to prevent accidents and improve operational safety (Table 4).

Table 4. The tipping angle of the harvesting machine at the terrain slope.

Wheel spacing, l (m)	Wheel width, a (m)	Height CG, h (m)	Tipping angle, α (°)
1.14	0.48	1.11	43.4

The combined evaluation of moment analysis, stability factor, and tipping angle was crucial in determining the overall stability of the harvesting machine. The moment analysis ensured that forces acting on the machine remained balanced, preventing excessive tilting. The stability factor calculated whether the machine is within a safe operating range, while the tipping angle identified the maximum allowable slope for safe operation. By integrating these three parameters, a comprehensive assessment of the machine’s stability can be achieved, which helps in design optimisations and operational guidelines to enhance safety and efficiency.

Figure 3 shows the lifted articulated boom of the harvester crane at different angles, representing the boom in its resting position, at 50% lift, and at 100% lift. These different stages are essential for understanding the crane's stability. The articulated boom can reach a maximum height of 12 m in static position at 100% lift, representing the crane’s highest lifting capability without dynamic movement.

(**a**) (**b**) (**c**)

Figure 3. Harvester crane when boom (a) at rest, (b) 50% lift, and (c) 100% lift

4. Conclusions

This study has successfully addressed the primary objectives concerning the static stability of the harvesting machine by evaluating the moment equilibrium between the prime mover and the articulated boom, the stability factor at various boom angles, and the tipping angle on inclined terrain. Results confirmed that the machine remained stable when the moment of the prime mover exceeded that of the articulated boom, ensuring safe operation under various load conditions. Results from stability factor analysis further validated these findings, with values remaining above one across boom angles of 30°, 45°, and 60°, indicating consistent balance during lifting operations. Results from the tipping angle calculation showed a critical slope threshold of 43.4°, beyond which the risk of overturning increased significantly. Understanding this limit is essential for safe field operation, especially on uneven terrain. These findings contributed to a comprehensive understanding of the harvesting machine's static stability, forming a solid foundation for further investigation.

5. Recommendations for future work

To expand on current findings, it is recommended that future work focus on a comprehensive kinematic stability analysis. This next phase is crucial to understanding the dynamic behaviour of the harvesting machine under varying operational conditions, such as different speeds, loads, and terrain conditions. The analysis will employ vector loop equations and MATLAB simulations to evaluate the system's performance in motion. Insights gained from this dynamic evaluation will support design refinements, enhance operational safety, and ensure optimal functionality in real-world agricultural environments.

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