Stability and vibration analysis of a tractor-mounted Chinese cabbage collector

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Abstract. Korean farms for dryland crops are usually disordered and uneven. Thus, 43.4% of major farm machinery accidents occur due to instability and sharp turning conditions. Therefore, the objective of this study is to analyze the stability of a tractor-mounted Chinese cabbage collector using a simulation program and validate it via experiments. In the static condition, the ground slope angle was increased by 1° to obtain the overturning angle. In the dynamic condition, 10 cm high rigid obstacles were located to investigate the stability of the equipment with an approach angle of 135°. The simulation was conducted at four tractor forward speeds (0.15 m/s, 0.20 m/s, 0.25 m/s and 0.30 m/s). Additionally, the motion trajectory of the front wheel and rear axle were predicted for loaded and unloaded conditions. Furthermore, vibration sensors were placed at four locations to determine the vibration level of the Chinese cabbage collector, and the load condition and conveyor speed were considered the factors affecting the vibration level. The static overturning simulation suggested that the collector could reach critical angles of 45.6° and 33.2° and overturn at 52° and 36.1° on the right and left sides, respectively. In dynamic stability analysis, it was observed that the center of gravity could change and separate from the ground when the forward speed was more than 0.30 m/s. Apart from the first point, the maximum vibration level exceeded 1.15 m/s² at the remaining three points. Furthermore, the vibration level increased with an increase in the speed of the conveyor.

1. Introduction
Due to the development of tractors and agricultural machinery, accidental deaths are increasing, especially by accidents caused by the rollover of agricultural machinery, which accounts for 43.4% of total accidental deaths. Overturning during field operations is important in terms of work safety and the mechanized propulsion of sloping land. Although driving tests were required for dynamic stability analysis in various conditions, simulation analysis was used to avoid risks. A dynamic analysis program can interpret complex systems, predict results in advance, and reflect them in design changes by
simulating them in the pre-production phase. Furthermore, it is also used to interpret a prototype and use the results for performance improvement in future development stages. The result obtained from such simulations is often certified by comparing the results of experimental and theoretical analyses. In this study, the dynamic analysis program is used to evaluate the stability of the work machine through lateral overturning analysis of the tractor [1] and the obstacle passage and loading stability of the prototype small vehicle [2]. The stability of tractors and tractor-mounted implements are affected by vibration, which also affects the durability of the components [3, 4]. Vibration levels may vary depending on the speed, operating position, load condition, and environmental factors of the component [5, 6]. Nevertheless, it is very important to measure the vibration level to improve the overall working environment and stability of the vehicle in off-road conditions.

To summarize, the purpose of this study is to analyze the stability of the tractor-mounted Chinese cabbage collector while driving. This was achieved by providing inputs obtained by evaluating the stability of the prototype under various conditions via simulations and dynamic analysis programs and evaluating the vibration level of critical working parts.

2. Materials and Methods

2.1. Overview of the Chinese cabbage collector
A tractor-mounted Chinese cabbage collector was developed, which consisted of three major components, namely first conveyor (for collecting), second conveyor (for transferring), and a platform (for stacking the collected produce), as shown in Figure 1. Farmers need to collect the Chinese cabbages manually from the soil and put them on the first conveyor. Then, the inclined second conveyor carries the Chinese cabbages to the bag and packs them. The overall length, width, height, and weight of the collector were 7640, 1450, 1190 mm, and 670 kg, respectively.

![Figure 1. 3-D model of the Chinese cabbage collector showing major components: 1st conveyor, 2nd conveyor, and platform.](image)

2.2. Simulation of the static overturning angle
The 3D model of the tractor-mounted Chinese cabbage collector was prepared using SolidWorks and then imported to RecurDyn to analyze the driving stability by subjecting it to lateral overturning and driving over obstacles. RecurDyn is a dynamic simulation software suitable for dynamic analysis between soil and vehicles [7]. The center of gravity of the tractor-mounted Chinese cabbage collector was calculated using the specifications of the tractor (Kukje Machinery, LUXEN 74, Okcheon, Chungcheongbuk-do, Republic of Korea). The simulation condition for the static stability of the Chinese cabbage collector is shown in Figure 2. For analyzing lateral overturning based on the folding angle of the conveyor, the simulation was replicated three times for the folding angles of 0°, 45°, and 90°. Because the length of the conveyor in the collection area was 4720 mm, there was a high risk of driving
if the angle was 90°. In the boundary condition, the test jig was modeled and the revolute joint was applied to the lower right front. The contact and test jig were set to touch the ground surface and body while overturning.

![Simulation images](image)

**Figure 2.** Simulation of static stability of the tractor-mounted Chinese cabbage collector: right side overturning (a, b, and c), and left side overturning (d, e, and f).

### 2.3. Simulation of the dynamic overturning angles

In field farming, the ground is uneven and the working environment is diverse and difficult. Thus, for stability analysis while driving, a driving simulation was performed to analyze the stability of the Chinese cabbage collector when it passes over an obstacle. The barrier was modeled in the form of rhombic steel with a height of 10 cm and an approach angle of 135°. The simulation was performed for multiple driving speeds of 0.10 m/s, 0.20 m/s, and 0.30 m/s. When the Chinese cabbage collector passed over the obstacle, the predicted kinetic trajectory of the front wheel and rear axle confirmed the separation from the ground by analyzing the change in the center of gravity position.

![Overturning test images](image)

**Figure 3.** Overturning test: right side overturning (a, b, and c), and left side overturning (d, e, and f).

### 2.4. Validation of static overturning angles

The overturning test of the Chinese cabbage collector was performed at the Foundation of Agricultural Technology Commercialization and Transfer (Iksan, Jeollabuk-do). Motors and hydraulic actuators were used to generate artificial inclinations on the ground to overturn the tractor. The inclination angle with respect to the ground was displayed digitally in the situation room, where it measured and recorded the necessary data when the overturning occurred. The experiment was performed for three folding angles of the conveyor, i.e., 0°, 45°, and 90°, as shown in Figure 3 and repeated five times for both sides.
2.5. Vibration measurement test
To measure vibration, field tests were performed on farms affiliated with Chungnam National University Yuseong-gu, Daejeon. The vibration sensors were attached to a data acquisition device (NI USB 6234, National Instrument, Texas, USA) and LabVIEW was used to conduct the test after programming. NI USB 6234 was attached for emergency use and the vibration data were measured from the collector using a sampling frequency of 1000 Hz. In total, four vibration sensors were attached to the starting point of the conveyor at the collection part, first folding joint, second folding joint, and transport endpoint of the collector. During operation, the vibration level was measured for unloaded and loaded conditions at various conveyor speeds of 0.10 m/s, 0.20 m/s, and 0.60 m/s as shown in Figure 4.

![Figure 4. Vibration test under different conditions using the Chinese cabbage collector.](image)

3. Results and Discussion

3.1. Simulation of the static and dynamic overturning condition
From the lateral overturning simulation under static conditions, the lateral overturning angles were 53.49°, 53.32°, and 52.59° when the Chinese cabbage collector was tilted toward the right side. Similarly, the lateral overturning angles were 12.28°, 32.49°, and 40.45° for the left side. When the Chinese cabbage collector was tilted toward the left side, the length of the collector conveyor was long. Therefore, when the transverse overturning angle began to tilt above 12°, it was faced with ground. Figure 5 shows the change in the center of gravity position of the front wheel(a) and rear axle (b) when the Chinese cabbage collector passes over an obstacle while being driven at different speeds. The center of gravity position of the front wheels was predicted to rise above the ground by approximately 2 cm at a driving speed of 0.30 m/s, and the change in the center of gravity position of the rear axle was predicted to be stable even over obstacles. Furthermore, it was considered safe to drive at 30–40% deceleration in the area of obstacle passage.

3.2. Validation of the static overturning condition
The overturning test of the Chinese cabbage collector was performed at the Foundation of Agriculture Technology Commercialization and Transfer (Iksan, Jeollabuk-do). Motors and hydraulic actuator were used to generate artificial inclinations on the ground until the tractor overturned. The inclination angles were measured and recorded when the tractor overturned. The overturning of the tractor was tested for three angles of 0°, 45°, and 90°, and the overturning test was performed five times each for either side. The lateral overturning angles of the tractor when it was tilted toward the right side were 31.20°, 22.40°, and 31.15° for 0°, 45°, and 90°, respectively. Similarly, the lateral overturning angles for the left side were 15.11°, 20.60°, and 30.92° for 0°, 45°, and 90°, respectively. As observed in the simulation results, while tilting toward the left side, it was assumed that there was a high risk of colliding with the ground when the conveyor touched the floor. Furthermore, the conveyor was fully extended when tilting from the working condition. Table 1 compares the simulation result with the lateral overturning test result.
performed in the laboratory. According to ISO 16251-2, the stability angles for agricultural machinery in off-road situations vary from 15° to 45° [8]. In this study, the overturning angles for both sides were within the range 15.11° to 31.20° for various conveyor angles of the Chinese cabbage collector. Thus, it meets the ISO criteria.

![Figure 5](image-url)\textbf{Figure 5.} Variation of center of gravity position of the front wheel (a), and rear axle (b) when passing over an obstacle.

| Folding condition of conveyor | Simulation | Validation |
|------------------------------|------------|------------|
|                              | Right overturning angle (°) | Left overturning angle (°) | Right overturning angle (°) | Left overturning angle (°) |
| Horizontal (0°)              | 53.49 ± 0.21 | 12.28 ± 0.75 | 31.20 ± 0.24 | 15.11 ± 0.18 |
| Inclined (45°)               | 53.32 ± 0.18 | 32.49 ± 0.68 | 22.40 ± 0.38 | 20.60 ± 0.22 |
| Vertical (90°)               | 52.59 ± 0.42 | 40.35 ± 0.39 | 31.15 ± 0.52 | 30.92 ± 0.19 |

3.3. \textit{Vibration measurement test}
In this study, four vibration sensors were placed at four locations to determine the vibration level of the collector. Furthermore, load conditions (unloaded or loaded) and conveyor speeds were considered the factors affecting the vibration level of the Chinese cabbage collector. According to the Korea Occupational Safety and Health Agency (KOSHA) safety technical guidelines on reducing the risk of full-body vibration while using agricultural machinery, the exposure action value is 0.5 m/s² when exposed daily to full-body vibration and should not exceed the exposure limit of 1.15 m/s² [9]. Apart from the first point, the maximum vibration level at the remaining three points on the Chinese cabbage collector exceeded 1.15 m/s². Moreover, the vibration level increased with the speed of the conveyor, as shown in Figure 6. Therefore, the Chinese cabbage collector not only damages the components of the collector but also creates an unpleasant working environment. Thus, the efficiency of the Chinese cabbage collection work, damage strength of the work machine, and working environment should be optimized.
4. Conclusions
This study was conducted to analyze the lateral and dynamic overturning risk of a tractor-mounted Chinese cabbage collector in a working environment. The vibration levels of the major components of the Chinese cabbage collector were also measured to optimize the damage strength and maintain a standard working environment. The overturning angles in the static and dynamic conditions were determined through simulations and validated through tests. The determined lateral overturning angles conform to the ISO standards, as they were in the range 15.11° to 31.20° when the conveyor was folded at 0°, 45°, and 90°. During the dynamic stability test, the change in the center of gravity position of the front wheel was predicted to rise above the ground by approximately 2 cm at a speed of 0.30 m/s, whereas that at the rear axle was adequately stable. However, the vibration levels exceeded the ELV of 1.15 m/s². Hence, further research is needed for optimizing the design of the machine to reduce the vibration level.

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