Development and Numerical Analysis of a Differential Gear for the Mechanical Encoder of a Single-Failure-Proof Polar Crane for Nuclear Power Plant

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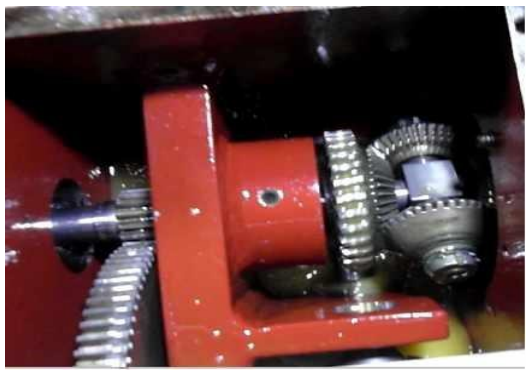
1. Introduction

In 1979, EDERER developed the X-SAM (eXtra Safety And Monitoring) system and released a technical report to enhance the safety and reliability of nuclear crane systems [1]. In 2008, Baek et al. studied the implementation of single-failure-proof technology for gantry cranes in compact dry storage facilities under NUREG-0554 [2] and ASME NOG-1 [3] standards, though their work focused primarily on the rated capacities of the wire rope reeving and braking systems. More recently, in 2025, Jang et al. suggested equations of motion based on multibody dynamics to control three-dimensional overhead cranes [4]. Despite these advancements, limited research has evaluated the EDERER X-SAM system currently operating in nuclear power plants. Accordingly, this study performs a numerical analysis for the development of a differential gear used in the mechanical encoder, which is a vital element of the single-failure-proof mechanism.

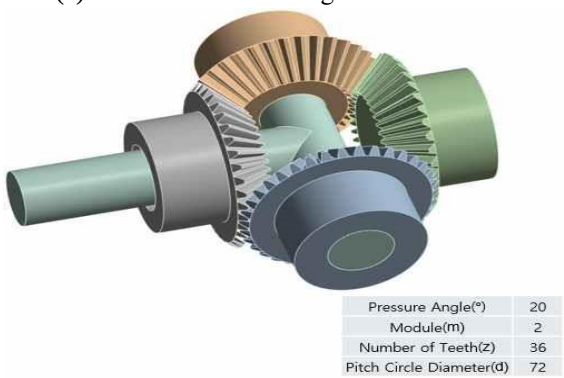
2. Methods and Results

2.1 Analysis Methods

In this study, Ansys Motion & Mechanical 2025R2 was employed to evaluate the structural safety and operational kinematics of the designed system. The mechanical encoder operates through a complex assembly of multiple interconnected gears, among which the differential gear serves as the most critical internal component. As shown in Fig. 1, the numerical model of the differential gear was constructed via reverse engineering of the actual X-SAM system utilized in nuclear power plants. As illustrated in Fig. 1(b), the gear is designed with a pressure angle of 20°, a module of 2, 36 teeth, and a pitch circle diameter of 72 mm. Furthermore, rotational speed (RPM) analyseswere conducted to evaluate both threvolution and rotation behaviors of the differential gear.



(a) X-SAM differential gear



(b) simulation model for differential gear

Fig. 1. Model of differential gear: (a) X-SAM differential gear, (b) Simulation model for differential gear.

2.2 Analysis Boundary Conditions

For the differential gear analysis, a frictionless contact condition was assigned to the gear meshing interfaces to ensure smooth rotational transmission without frictional losses. Additionally, revolute joints were applied to both the drum and motor sides to allow rotational degrees of freedom. Based on the operational rotational speeds measured during the hoisting operation in actual nuclear power plants, specific rotational speeds were applied to the drum shaft and motor bevel gear (8 RPM for the drum

shaft and 14 RPM for the motor bevel gear under normal hoisting). Furthermore, the rotational speed differential between the drum shaft and motor bevel gear was evaluated to determine the rotational direction of the trigger bevel gear under emergency conditions.

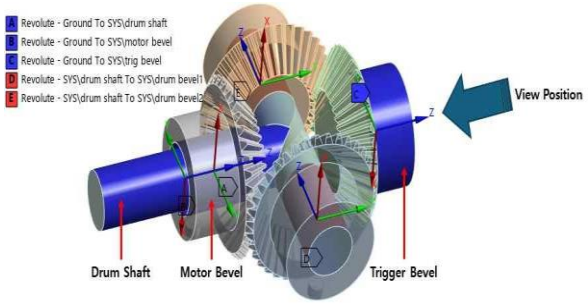


Fig. 2. Boundary conditions for simulation of the differential gear.

The rotational speed conditions applied in this numerical analysis are summarized in Table I, comprising the hoisting (up) and lowering (down) operations of the crane. Under the normal hoisting condition, the drum shaft and motor bevel gear rotate at 8 RPM and 14 RPM, respectively. During the hoisting operation, the two-block condition simulates an event where the drum shaft is immobilized due to structural jamming or mechanical interference. The shaft broken condition during hoisting accounts for a scenario in which a shaft failure (such as in the reducer connected to the drum) causes an instantaneous free fall of the crane hook due to the suspended load. Similarly, under the lowering operation, the shaft broken condition considers the instantaneous free fall induced by the suspended load resulting from a shaft fracture in the drive train/reducer connected to the drum.

Table I: Rotational speed conditions for differential gear simulation.

Crane Condition	Drum Shaft (RPM)	Motor Bevel (RPM)	State
Hoisting	8	14	Normal
	0	14	Two-Block
	-8	14	Shaft Broken
Lowering	-8	-18	Normal
	-10	-18	Shaft Broken

2.3 Analysis Results

In the normal hoisting state, applying 8 RPM to the drum shaft and 14 RPM to the motor bevel gear resulted in a counterclockwise (CCW) rotation of approximately 2 RPM (+RPM) from the reference view position; consequently, the single-failure-proof system remains inactive, as shown in Fig. 3.

Under the two-block hoisting state, applying 0 RPM to the drum shaft and 14 RPM to the motor bevel gear caused a clockwise (CW) rotation of approximately -14 RPM (-RPM) from the view position, which triggers the single-failure-proof system to arrest the drum, as illustrated in Fig. 4.

Under the shaft broken hoisting state, applying -8 RPM to the drum shaft and 14 RPM to the motor bevel gear led to a clockwise rotation of approximately -30 RPM (-RPM), successfully actuating the single-failureproof system to stop the drum, as depicted in Fig. 5.

In the normal lowering state, applying -8 RPM to the drum shaft and -18 RPM to the motor bevel gear resulted in a counterclockwise rotation of approximately 2 RPM (+RPM) from the view position, keeping the single-failure-proof system inactive, as shown in Fig. 6.

Conversely, under the shaft broken lowering state, applying -10 RPM to the drum shaft and -18 RPM to the motor bevel gear yielded a clockwise rotation of approximately -2 RPM (-RPM) from the view position, thereby activating the single-failure-proof system to bring the drum to a stop, as shown in Fig. 7.

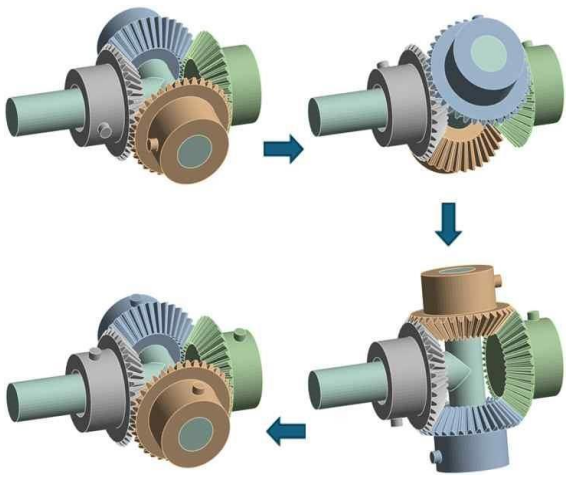


Fig. 3. Result for hoisting condition in normal state.

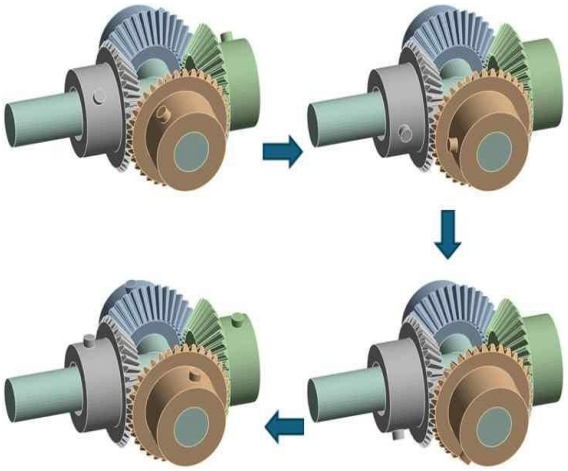


Fig. 4. Result for hoisting condition in two-block state.

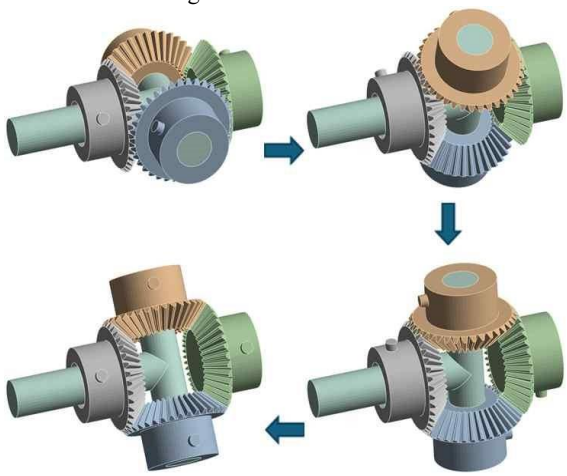


Fig. 5. Result for hoisting condition in shaft broken state.

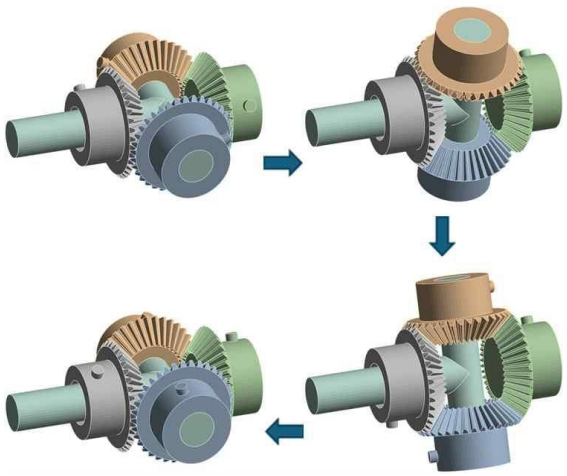


Fig. 6. Result for lowering condition in normal state.

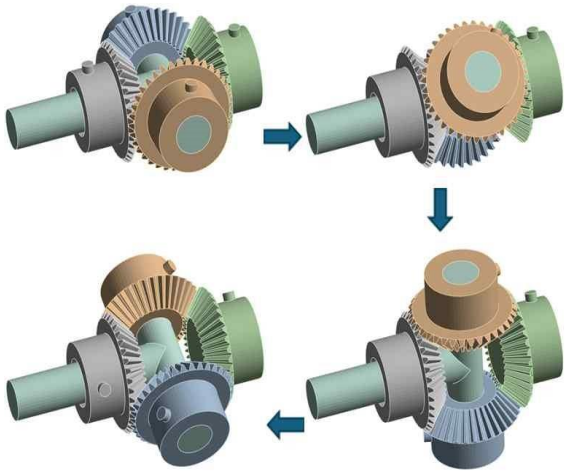


Fig. 7. Result for lowering condition in shaft broken state.

The graph in Fig. 8 illustrates the time-dependent rotational speed (RPM) of the trigger bevel gear corresponding to each operational state. The results demonstrate that positive RPM values (+RPM) correspond to the inactive state of the single-failureproof system, whereas negative RPM values (-RPM) actuate the system to engage the safety mechanism and arrest the drum.

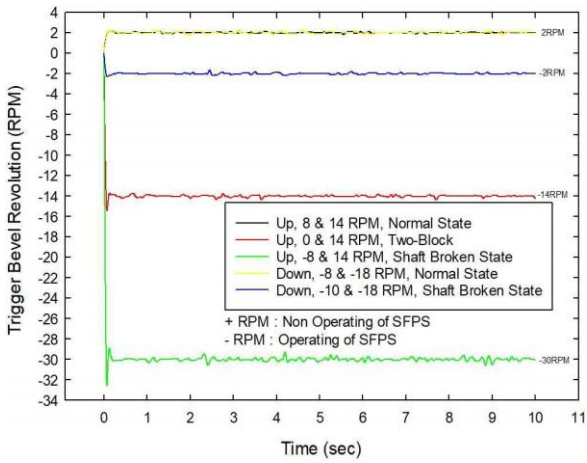


Fig. 8. Rotational speed of the trigger bevel gear for each operational state.

3. Conclusions

In this study, a numerical analysis was conducted using Ansys Motion & Mechanical 2025R2 to evaluate the operational kinematics and functional reliability of the mechanical encoder differential gear applied to the XSAM single-failure-proof polar crane in nuclear power plants. The primary findings are summarized as follows:

1. Kinematic Modeling via Reverse Engineering: A detailed multi-body dynamic simulation model of the differential gear (pressure angle of 20°, module of 2, 36 teeth, pitch diameter of 72 mm) was established based on reverse engineering of the operational X-SAM system.

2. Normal Operating Behaviors: Under normal hoisting (drum shaft: 8 RPM, motor bevel: 14 RPM) and lowering (drum shaft: -8 RPM, motor bevel: -18 RPM) conditions, the trigger bevel gear maintained a counterclockwise rotation at approximately +2 RPM (+RPM), ensuring that the single-failure-proof safety mechanism correctly remains inactive.

3. Emergency Actuation Characteristics: Under emergency scenarios—such as two-block (drum shaft: 0 RPM, motor bevel: 14 RPM), shaft breakage during hoisting (drum shaft: -8 RPM, motor bevel: 14 RPM) and lowering (drum shaft: -10 RPM, motor bevel: -18 RPM)—the trigger bevel gear transitioned to clockwise rotation (-14 RPM, -30 RPM, and -2 RPM, respectively). The negative rotational speed (-RPM) reliably triggered the safety system to arrest the crane drum.

In conclusion, the numerical results verified the differential speed mechanism and operational criteria of the mechanical encoder according to operational states. The established numerical model is expected to serve as fundamental design data for the localization and structural integrity assessment of single-failure-proof crane components in nuclear facilities.

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※ **Acknowledgment**
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