Reduction of Maximum Torque of Driving Shafts Concurrently Driven by Rubber V-belt for Monorail Traveling on Worn Rack Rail for Construction Uses

Kohei Nagao, Kazuya Okubo, Toru Fujii, and Shoji Uchida

***Abstract*—The purpose of this study is to propose a technique to reduce the torque applied onto driven shafts of monorail for urban constructions and forest industries. To reduce the maximum torque contribution ratios of driven shafts, a modified transmitting system for the monorail was proposed. The system is concurrently driven by two v-belts in which the phase difference of rotational angle was allowed. To evaluate the difference of torques produced on the shaft, two types of gearboxes of the vehicle were prepared to experimentally drive on the rack rail with short range (250mm) in test field. Two rack rails in which observed wear depth of the rack tooth was *w*=0 and 3mm were prepared. The variations of torques of driven shafts were measured with respect to the rotational angle of the shaft when the driven pinion gears were engaged with original and worn rack rail in which the wear depth of tooth was *w*=3mm, respectively. The torque contribution ratio of rear driven shaft was reduced down to about 63% by applying modified power train, while that was highly 89% through the conventional power train, even when the test systems were driven on worn rack rail. The increase of the torque contribution ratio of driven shafts was prevented in comparison with those by applying the conventional power train. This study found that the modified power train where two pinion gears were concurrently driven by two v-belts should be applied to reduce the maximum torque contribution ratio of driven shafts.**

***Index Terms*—Monorail, driven shaft, torque contribution ratio, V-belt.**

I. Introduction

The monorail for urban constructions and forest industries is utilized widely as a transport machine which can transport a large number of workers and heavy equipment in the steep slope and the non- levelling of ground [1]. By utilizing the monorail for urban constructions and forest industries, the traveling time to the work site is shortened and to the work efficiency is improved dramatically [2]. Although the monorail has many advantages, there have been fatal accidents, caused by the failure of the driven shaft of the power unit due to over loading beyond carrying capacity on the bogie. Previous studies showed that the failure of shafts was initiated due to application under the severe conditions [3]-[6]. It has been also known that uneven deviation of torques on two driven shafts also initiates the failure of shaft, when the monorail is driven on worn rack rail [7], [8] at urban construction and forest industrial site. However, the torque contribution ratios of driven shafts was not stabilized due to complicated mechanism in which the phase difference of rotational angle was not allowed by transmitting the driven torque through a normal gear to front and rear driven gears when the conventional power train were engaged with worn rack rail. This study discussed on the differences of torque contribution ratios of driven shafts due to application of the modified transmitting system for the monorail concurrently driven by two v-belts in which the phase difference of rotational angle was allowed. Due to relative sliding between the belt and the pulleys, a difference could be arisen between the speeds of the driver and driven pulleys [9]-[11]. To evaluate the difference of torques produced on the shaft, two gearboxes of driven vehicle were prepared on the rack rail with short range (250mm) to drive experimentally in test field. The two rack rails in which the observed wear depth of the rack tooth was *w*=0 and 3mm were prepared to experimentally investigate the behavior of monorail passing on worn rack rail, respectively. The variations of torques of driven shafts were measured with respect to the rotational angle of shaft when the driven pinion gears were engaged experimentally with original and worn rack rail in which the wear depth of tooth was *w*=3mm, respectively.

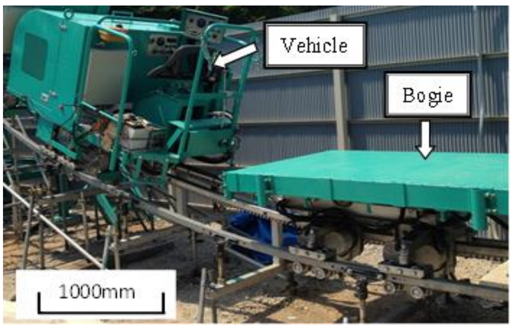

Fig. 1. Appearance of commercial monorail.

II. Procedure for Paper Submission

A. Basic System of Monorail for Urban Construction and Forest Industry

Fig. 1 shows the appearance of commercial monorail (DH-4000, UCHIDA INDUSTRY Co., LTD., Japan) investigated in this study. The monorail used in this study is conventional type for urban constructions in which the

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maximum transportable weight is 4000kg. The monorail has characteristic functions in which traction force is produced on the driving vehicle to lead the bogie cars at climbing uphill, while breaking force is also supported by the driving vehicle at going downhill on the single track rack rail, respectively.

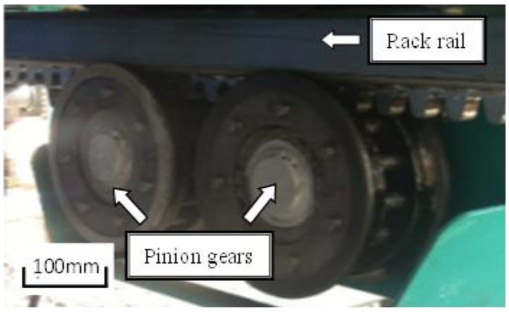
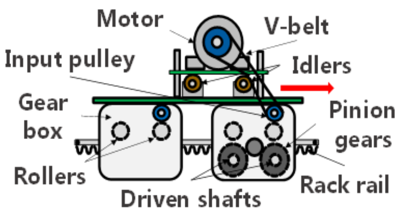
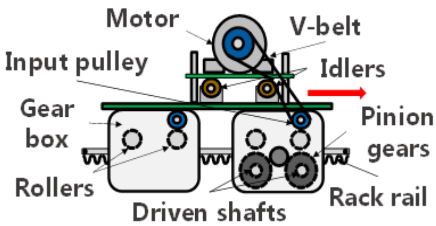


Fig. 2. Magnified picture of rack rail and driving unit with pinion gears.

To drive the monorail, two pinion gears are engaged with rack rail while serious rolling motion was prevented by two supporting rails as shown in Fig. 2.



(a) Conventional power train



(b) Modified power train

Fig. 3. Schematic view of test system.

B. *Test System*

Fig. 3 (a), Fig. 3(b) shows the schematic views of test systems used in this study. To evaluate the torque produced on the shaft, two gearboxes of driven vehicle were prepared on the rack rail with short range (250mm) to drive experimentally in test field.

To investigate the behavior of conventional monorail, original test system was prepared in which driving torque was transmitted through a normal gear to two pinion gears in gearbox as shown in Fig. 3(a). Modified transmitting system for monorail was also proposed where two pinion gears were concurrently driven by two v-belts as shown in Fig. 3(b). The driven torque was tentatively applied to the front and rear pinion gears through the gearbox of the monorail by AC motor in this study. The reaction force was applied by the conventional electromagnetic break to the pull rod dragged by the driving vehicle to be in equilibrium to the traction force (resultantly applied by the driving torque), as shown in Fig. 4.

The similar tests were implemented in past studies [1], [2], [7]. The condition of traction force was changed to 0, 9, 18kN by changing the number of applying electromagnetic breaks. In this test applied traction force was monitored by a load cell inserted between the parts of pull rod. Strain gages were attached on the surfaces located 70mm far from the tip of rear and front driven shafts, respectively. Torsional moments (torque) applied onto the rear and front driven shafts were continuously measured by the strain gages. Torsional moments (torque) applied onto the rear and front driven shafts were continuously measured by the strain gages under the condition of 2.0m/min of the velocity of vehicle.

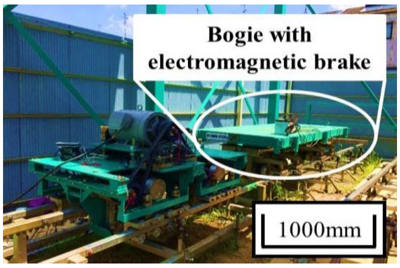
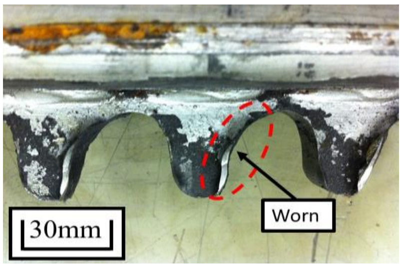


Fig. 4. Appearance of bogie with electromagnetic brake.



(a) Commercially worn rack rail

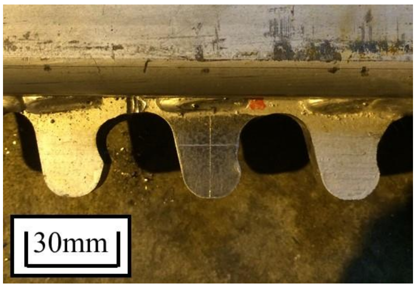
(b) Original rack rail

Fig. 5. Appearance of rack rails.

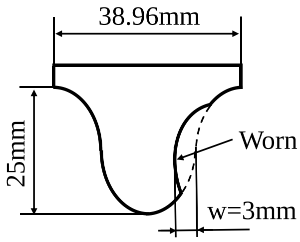
C. *Types of Rack Rails*

Fig. 5 (a), Fig. 5(b) shows the appearances of original and worn tooth of rack rail employed after about 200 hours at civil engineering construction site, respectively. Geometrical change of the tooth was remarkably observed due to wear after the monorail was repeatedly passed on the rack rail. Geometrical change of the tooth which was about 3 mm in maximum was remarkably observed due to the wear after the monorail was repeatedly passed on the rack rail. Fig. 6 shows appearances and the geometries of original and necked rack rail tooth used in this study, respectively, where the tooth near the surface was partly removed by a mill machine to experimentally investigate the behavior of monorail passing on worn rack rail. Table I shows specifications of rack rail. The observed wear depth of the rack rail was *w*=3mm, as shown by the solid line in Fig. 6(a), Fig. 6(b).

To compare the test results, original rack rail having un-worn shape as shown by the dashed line in Fig. 6 was also used.



(a) Experimentally worn rack rail



(b) Geometry of experimentally worn rack rail tooth

Fig. 6. Appearance of experimentally worn rack rail.

TABLE I: SPECIFICATION OF RACK RAIL

Height	h[mm]	25
Width	w[mm]	12
Pitch	Ip[mm]	38.96
Material		Steel (WEL-TEN590RE)

D. Pinion Gear

Fig. 7 and Table II show the layout and specification of the pinion gears used in this study, respectively. The module, number of pins, pitch circle diameter of pin, external diameter of pin of pinion gear and length were 12.408mm, 14, 175.085mm, 16mm and 77mm respectively.

TABLE II: SPECIFICATION OF PINION GEAR

		Pinion gear
Module	m[mm]	12.408
Number of pins	N_p	14
Pin pitch	I_p[mm]	38.96
Pitch circle diameter	d_0[mm]	175.085
External diameter of pin	d_p[mm]	16
Length	L[mm]	77

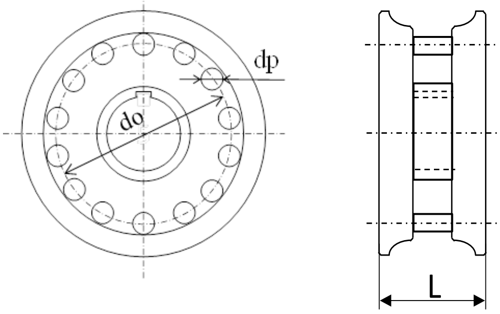
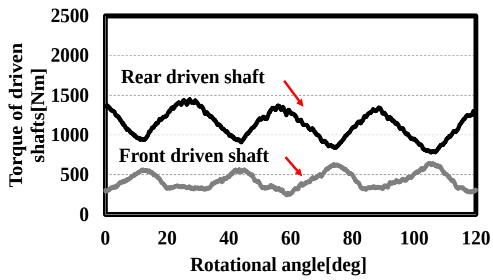


Fig. 7. Structure of pinion gear.

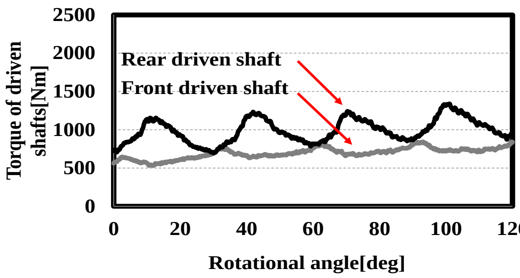
III. RESULTS AND DISCUSSION

A. Variations of Torsional Moments (Torques) of Driven Shafts

Fig. 8 (a), Fig. 8(b) shows the variations of torsional moments (torques) of driven shafts with respect to the rotational angle of shaft under the condition of 18kN of traction force when the driven pinion gears of conventional power train and modified power train were engaged with original rack rail, respectively. Fig. 9(a), Fig. 8(b) also shows the variations of torsional moments (torques) of driven shafts with respect to the rotational angle of shaft under the condition of 18kN of traction force when the driven pinion gears were engaged with worn rack rail in which the wear depth of tooth was *w*=3mm, respectively. The maximum torque of rear driven shaft was about 1340Nm by applying modified power train, while that was 1450Nm through the conventional power train when the pinion gears were engaged with original rack rail. On the other hand, when the pinion gears were engaged with worn rack rail in which the wear depth of tooth was *w*=3mm, the maximum torque of rear driven shaft was about 1610Nm by applying modified power train, while that was 1120Nm through the conventional power train. When the modified power train was driven on original rack rail, the reduction ratio of the maximum torque of rear driven shaft was obtained about 8%. And the reduction ratio of the maximum torque of rear driven shaft was about 30% by applying modified power train when the pinion gears were engaged with worn rack rail in comparison with those by applying the conventional power train.



(a) Conventional power train on original rack rail



(b) Modified power train on original rack rail

Fig. 8. Variation of torque of driven shafts with respect to rotational angle.

B. Variations of Torque Contribution Ratios of Driven Shafts

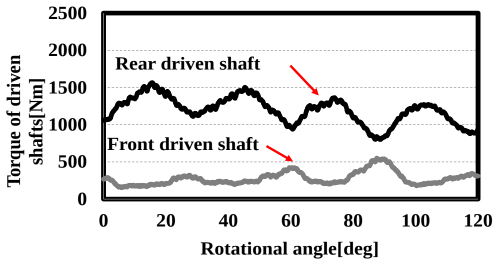
Fig. 10 shows the changes of torque contribution ratio of rear driven shaft when the driven pinion gears of conventional power train and modified power train were engaged with original and worn rack rail in which the wear depth of tooth was w=3mm, respectively. Here, torque contribution ratio was defined with torsional moments as equation bellow Equation (1).

$$\alpha = \frac{T_{rear}}{T_{front} + T_{rear}} = \frac{T_{rear}}{T_{total}} \times 100 \qquad (1)$$

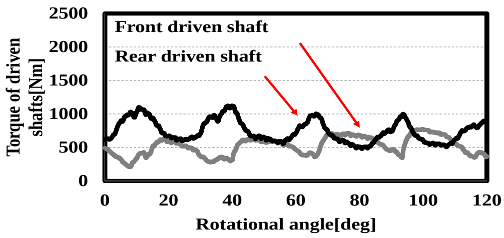
T_{front}: Torsional moment of front shaft

T_{rear}: Torsional moment of rear shaft

The torque contribution ratio of rear driven shaft was reduced down to about 64% by applying modified power train, while that was 82% through the conventional power train, when the test systems were driven on original rack rail. Even if the test system was driven on worn rack rail, the torque contribution ratio of rear shaft was reduced down to about 63% from 89% of the ratio of which the conventional one was applied when modified power train was applied. The increase of the torque contribution ratio of driven shafts was prevented in comparison with those by applying the conventional power train. About 0.1% of advance of rotational angle of front pulley was observed in comparison with those by applying the conventional power train when the modified power train concurrently driven by v-belt was applied. The result suggested that the peak torque of driven shafts was reduced due to the mild slip between v-belt and rear input pulley. This study found that the modified power train where two pinion gears were concurrently driven by two v-belts should be applied to reduce the maximum torque contribution ratio of driven shafts.



(a) Conventional power train on worn rack rail



(b) Modified power train on worn rack rail

Fig. 9. Variation of torque of driven shafts with respect to rotational angle.

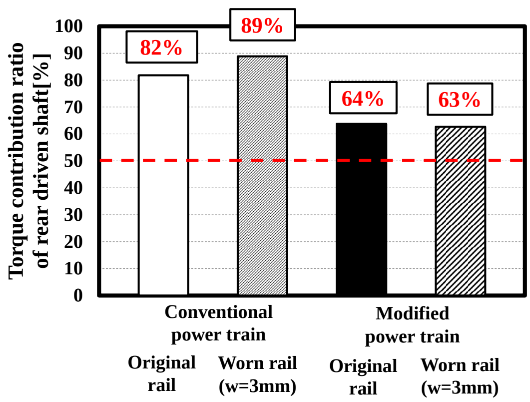


Fig. 10. Torque contribution ratios of rear driven shaft.

IV. Conclusion

1) When the modified power train was driven on original rack rail, the reduction ratio of the maximum torque of rear driven shaft was obtained about 8%.

2) The reduction ratio of the maximum torque of rear driven shaft was about 30% by applying modified power train when the pinion gears were engaged with worn rack rail in comparison with those by applying the conventional power train.

3) The torque contribution ratio of rear driven shaft was reduced down to about 63% by applying modified power train, while that was highly 89% through the conventional power train, even when the test systems were driven on worn rack rail.

4) The modified power train where two pinion gears were concurrently driven by two v-belts should be applied to reduce the maximum torque contribution ratio of driven shafts.

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