ジャイロスコープダンパーの使用による独立回転輪を有する鉄道車両の走行性能向上

○ロナク・プラティク[東京大学大学院]，林 世彬, 王 宇，霜野 慧亮, 須田 義大 [東京大学　生産技術研究所]，道辻　洋平 [茨城大学]

Running performance improvement of a railway vehicle with Independently rotating wheels by using Gyroscopic dampers

○Ronak Prateek (Graduate School, The University of Tokyo), Shih-Pin Lin, Yu Wang，Keisuke Shimono, Yoshihiro Suda　(Institute of Industrial Sciences, The University of Tokyo), Yohei Michitsuji (Ibraki University)

Independently Rotating Wheels (IRW), due to the lack of a rigid rotational speed coupling between its wheels, have theoretically no hunting oscillation and thus no resulting “critical speed” or negative impact on ride comfort on a straight track. However, the self-centering and self-steering moments resulting from the longitudinal creep forces are small in conventional IRW and also it is statically unstable due to negative restoring moment generated by the gravitational-restoring forces of the tread conicity. Therefore, by changing the direction of the gravitational-restoring forces by changing the tread shape of the wheel, a Self-steering wheel structure namely independently rotating wheels using negative tread conicity (NTCIRW) was proposed by the author of this paper. Since the proposal of this structure, several semi-active and active steering concepts have been considered. However, further improvement is required in the bogie running performance to get compatibility between tight-curving ability and high-speed stability of NTCIRW. In this study, the theoretical investigation and numerical simulations with a full-scale LRT vehicle model and NTCIRW is done which shows the effectiveness of the proposed gyroscopic damper.

キーワード：独立回転車輪 (IRW)，逆踏面勾配独立回転車輪 (NTCIRW), ジャイロスコープダンパー，走行安定性，曲線操舵性能

Key Words : Independently Rotating Wheels (IRW), Negative Tread Conicity Independently Rotating Wheels (NTCIRW), Gyroscopic Damper, Running Stability, Curving Performance

１. Introduction

Light rail transit (LRT) system is now-a-days considered as the urban transportation system for next generation mobility in the urban areas of Japan and Europe. The ability to perform well in tight curves is crucial in LRT because of the existence of inevitably many tightly curved tracks. This limitation of the curve-passing ability in the conventional rigid-wheelset method is obvious due to the fundamental design conflict between running stability and curve negotiation [1].

Therefore, to meet the specific low-floor requirement of LRT, the axle of a conventional IRW can be made into a cranked axle, thus lowering the floor height of the vehicle. However, bogie with IRW has no self-steering ability due to the loss of longitudinal creep force [2]. On the straight track, the IRW usually drift to one side of the track and can’t return to the center of the track, and on the curved track, the IRW have larger attack angle, which usually causes the flange-rail contact that not only creates serious wheel-rail wear but also increases the risk of derailment.

Then in order to obtain self-steering ability with IRW, the Einel-rad-Einelfahrwerk or EEF bogie which makes use of gravity stiffness to generate restoring motion was proposed [3], but it has a complex structure with many linkage mechanisms in the bogie. In order to improve curve passing ability of railway vehicle with independently rotating wheels, a special self-steering wheel structure namely independently rotating wheels using negative tread conicity (NTCIRW) was also proposed [4]. By applying active steering control on railway vehicle with NTCIRW, the curve passing performance was further improved [5]. While the Steering control method is essentially based on state feedback and well-designed control strategy, in the present study a simpler stabilization control method without state feedback control using a gyroscopic damper is proposed to further improve the bogie running performance to get compatibility between tight-curving ability and high-speed stability of NTCIRW.

To this end, a few researches involving the utilization of a gyroscopic damper in conventional railway vehicles with solid axle wheelsets to improve its performance has been done [6-8].

Therefore, this research involves the utilization of passive stabilization control of a gyroscopic damper in LRT vehicle with NTCIRW to improve its performance, i.e. Running stability and curve negotiation behavior from theoretical view-point and numerical simulations. Initially, the stability analysis is carried out for a simplified linear wheel-pair model of NTCIRW which is then followed by the precise numerical analysis of the full-scale LRT vehicle model in general purpose multibody dynamics analysis software of SIMPACK.

2. NTCIRW: Single unit small-scale Model

In this section, the equations of motion of a simplified wheel pair of NTCIRW with gyroscopic damper has been derived and analyzed for Running stability obtained by linear eigenvalue analysis.

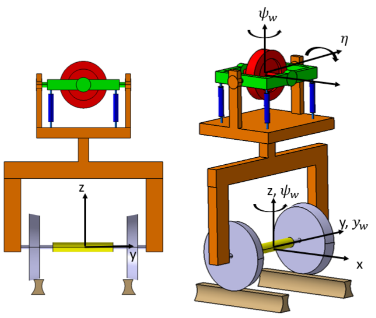

Figure 1: Analytical model of NTCIRW with gyroscopic damper

2.1 Analytical Model of Gyroscope

In Figure 1, the analytical model of a gyroscopic damper is shown. The gyroscopic damper consists of an internal gimbal supporting a rotating gyroscope and an external gimbal supporting the internal gimbal through springs and dampers as shown in Figure 1. The dimensions of the gyroscopic damper are given in Table 1 [6].

2.2 Straight Track Dynamics: Equations of motion

A mathematical model of a single railway vehicle wheelset that has two degrees of freedom: lateral motion y_w and yawing motion ψ_w has been shown in Figure 1. The wheel-pair unit having negative nonlinear tread profile is moved forward at a constant speed, v on a straight track to investigate running stability. The two wheels mounted on the same axle are able to rotate independently with respect to each other. The Gyroscopic damper is connected to the wheel-pair unit in such a way that the yawing motion of the wheel-pair is directly coupled to the yawing motion or the precession of the gyroscopic damper. The parameters of the one-tenth scale of NTCIRW model are shown in Table 1 [6].

Table 1: NTCIRW and Gyroscopic Damper Parameters [6]

m_g	Mass of gyroscopic damper (0.41 kg)
I_{xg}	Moment of inertia of gyroscope around x-axis (0.00037 kgm^2)
I_{yg}	Moment of inertia of internal gimbal with gyroscope around y -axis (0.00013 kgm^2)
I_{zg}	Moment of inertia of internal gimbal with gyroscope around z-axis (0.00013 kgm^2)
I_{zw}	Moment of inertia of wheelset around *z*-axis
k_g	Spring constant around y-axis (0.0045 Nm)
c_g	Damping coefficient around y-axis (0.00063 Nms)
Ω	Angular velocity of gyroscope (rad/s)
η	Angle of internal gimbal
ζ	Angle of external gimbal = ψ_w
d_g	Distance between the supporting point of the internal gimbal and the supporting point of the spring
m_w	Mass of wheelset (2.53 kg)
m_t	Total mass of wheelset (2.53+0.41) kg
$2b$	Track gauge (0.098 m)
r_0	Centered wheel rolling radius (0.036 m)
I_{zw}	Moment of inertia of wheelset around z-axis
v	Forward speed of wheelset
x	Running direction
y_w	Lateral motion
ψ_w	Yawing motion
k_{22}	Creep coefficient in y direction (171 N).
P	Vertical Load acting on the wheelset
$\gamma_1 =$ 0.8, γ_0 =0.025	Wheel tread conicity, $\gamma = \gamma_0 + y\,\gamma_1$

Lateral dynamics

$$m_t\ddot{y}_w + \frac{2k_{22}}{v}\dot{y}_w - 2k_{22}\psi_w + 2P\gamma_1 y_w = 0 \qquad (1)$$

Yaw dynamics

$$(I_{zw} + I_{yg})\ddot{\psi}_w + 2P\gamma_0 b\psi_w - I_{xg}\Omega\dot{\eta} = 0 \qquad (2)$$

Gyroscope Pitching or Nutation

$$I_{yg}\ddot{\eta} + I_{xg}\Omega\dot{\psi}_w + k_g d_g^2\eta + c_g d_g^2\dot{\eta} = 0 \qquad (3)$$

2.3 Eigenvalue Analysis

The characteristic equation of the system, i.e. equations (1), (2) and (3) have six characteristic roots or eigenvalues for which the root locus plots are obtained in MATLAB as shown in figure 2.

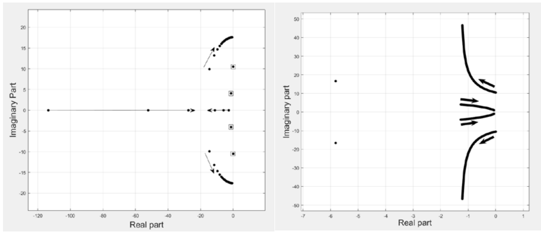

Figure 2: Root locus of eigenvalues as a function of velocity of bogie (left) and RPM of gyro (right)

In figure 2, when the velocity of bogie i.e. v was increased from 1 to 100 m/s with RPM of gyro fixed at 10, then out of 6, 4 eigenvalues (shown in box) are fixed while the other 2 eigenvalues move along the arrows from left-right to top-bottom but never cross the y-axis. This implies that the system is Stable for the given range of v. Also, when the RPM of gyro unit was increased from 0 to 1000 rpm with speed of bogie fixed at 10 m/s, then out of 6, 2 Eigenvalues (towards left) are fixed and the other 4 eigenvalues move along the arrows as shown in Figure 2. However, they never reach origin or cross y axis making the system stable for the given range of RPM.

2.4 Time response of the system

The equations of motion derived (1), (2) and (3) is then integrated and solved numerically in MATLAB-SIMULINK software assuming the initial conditions at t = 0; as $y_w = 0.001$m, $\dot{y}_w =$ 0 m/s, $\psi_w = 0.314$ radians, $\dot{\psi}_w = 0$ radians/s, $\eta = 0$ radians and $\dot{\eta} = 0$ radians/s. Numerically obtained time histories for some conditions of running speed ($v = 10$ m/s) and rotational speeds of the gyroscope (RPM = 0, 100, 200 rpm) are shown in Fig 3 & 4. In the state where the gyroscope is not rotated, motions in lateral and yawing directions are only critically stable. But once the gyro is switched ON and the RPM is increased first to 100 and then to 200, the lateral and yaw motions are stabilized and when that is achieved the oscillation of inner gimbal carrying gyroscope also goes to rest position and the running stability is achieved as in figure 4.

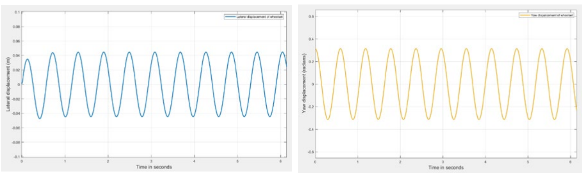

Figure 3: Time history of y_w & ψ_w when Gyro is OFF

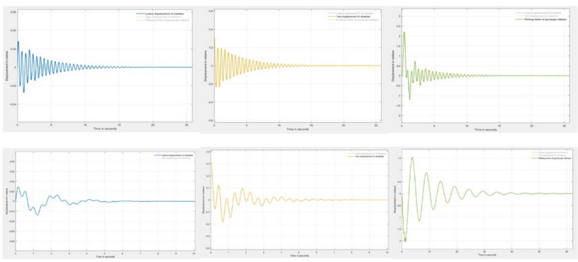

Figure 4: Time history of y_w, ψ_w & η when Gyro is ON, (Top: 100 RPM) & (Bottom: 200 RPM) $v = 10$ m/s

3. NTCIRW: Full-scale LRT Vehicle model

3.1 3D Modelling and Parameterization

Full-scale LRT vehicle consisting of 2 bogies (single wheel-pair each) with NTCIRW and Gyroscopic damper is modelled with 28 degrees of freedom in general purpose multibody dynamics analysis software of SIMPACK as shown in Fig 5 and parameters in Table 2.

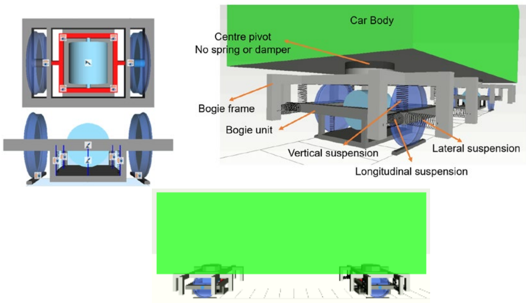

Figure 5: NTCIRW Bogie unit and Full-scale LRT Model

Table 2: Parameters of LRT Vehicle with NTCIRW

Inertia Properties of LRT Vehicle				
Body	Mass [kg]	Moment of Inertia [kgm^2]		
		I_{XX}	I_{YY}	I_{ZZ}
Wheel frame	200	78.07	52.23	115.54
Wheel	600	25.13	21.25	25.13
Bogie frame	500	276.3	163.14	404.7
Body	2000	3000	18166.7	18166.7
Outer gimbal	100	12.78	11.32	24.03
Inner gimbal	500	22.04	26.45	26.45
Parameters of Primary Suspension				
NTCIRW	z	y	x	Body-bogie
Spring N/m	86700	86700	86700	0
Damper Ns/m	21000	0	21000	0
Gyroscope	k_z = 86700 N/m, c_z = 21000 Ns/m			

3.2 Running Stability

In Figure 6, the Running stability of the full-scale LRT running at 50 m/s is analyzed when a sinusoidal track excitation of wavelength 50 m and amplitude 10 mm is given as input on a straight track and the simulation is done for two cases, 1st when Gyro damper is OFF, or its RPM is 0 and 2nd when it is switched ON at 2000 RPM.

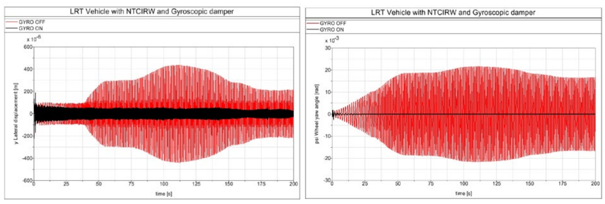

Figure 6: Lateral displacement (Top) and yaw angle (Bottom) of LRT bogie unit with Gyroscopic damper in OFF & ON states

It is evident from the figure 6 that when the gyroscopic damper is switched ON, the lateral displacement becomes smaller to the orders of 10^{-6} m and yaw angle becomes 0 in steady state outperforming the critically stable first case where gyroscopic damper was OFF, and hence achieving Running Stability on a straight track.

3.3 Sharp Curve Passing Performance

In this section, the sharp curving performance is assessed from the perspective of LRT that it encounters while negotiating tight curves. The track used in this numerical simulation has five segments, that are straight line, entry transition curve, steady curve with radius of 50 m, exit transition curve and ending straight line, in sequence. Initially, the speed of the vehicle is set to 5 m/s for a sharp curve of 50 m radius and the results are compared for two cases, 1st when Gyro damper is OFF, or its RPM is 0 and 2nd when it is switched ON at 2000 RPM. LRT vehicle, when the gyroscopic damper is switched ON at 2000 RPM, is able to negotiate the curve of 50 m radius with improved transients and steady state responses of lateral and yaw dynamics realizing ideal steering on curving than the case when the Gyroscopic damper is OFF as shown in Figure 7. To analyze the wheel/flange-rail contacts and the subsequent risk of wheel derailment, the Lateral Rail Contact Force and the Derailment coefficient at the innermost wheel (since negative wheel tread profile) comparison for both the cases are obtained in figure 8. It shows that the gyroscopic damper helps in reducing the lateral rail forces during curving and also the value of derailment coefficient to prevent the risk of wheel climb.

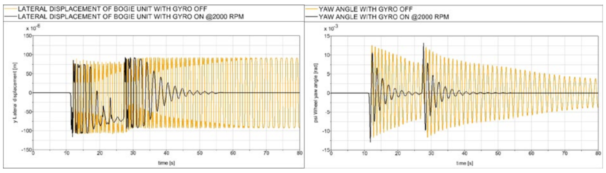

Figure 7: Lateral (Left) and yaw angle (Right) of bogie when the Gyro is OFF and ON @ 2000 RPM & vehicle velocity as 5 m/s

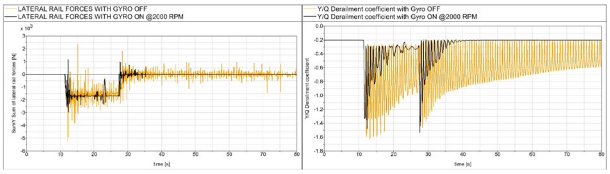

Figure 8: Lateral Rail Contact Force (L) and Derailment coefficient (R) comparison when Gyro is OFF and ON @ 2000 RPM

In order to closely monitor the effect of gyroscopic damper in improving the speed potential for curving, the speed of the LRT vehicle is then increased to 8 m/s. Initially, the LRT vehicle at 8 m/s with NTCIRW and Gyroscopic damper in switched OFF state is tested. But it is observed that the bogie gets derailed and cannot negotiate the tight curve as shown in Figure 9.

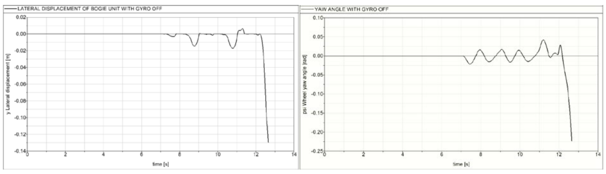

Figure 9: Lateral displacement (L) and yaw angle (R) of LRT bogie when the Gyro is switched OFF and velocity of vehicle is 8 m/s

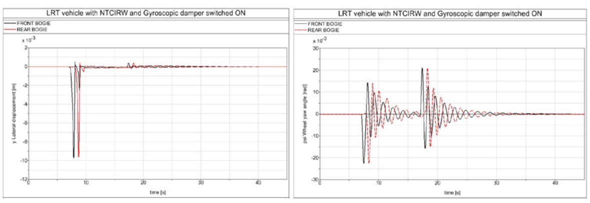

Figure 10: Lateral (Left) and yaw angle (Right) of bogie when the Gyro is switched ON @ 2000 RPM & vehicle velocity is 8 m/s.

Then, the same vehicle is tested with Gyroscopic damper in switched ON state at 2000 RPM. The vehicle is then able to negotiate the sharp curve easily as shown in Figure 10. This means that the speed potential of the vehicle for sharper curve negotiation also increases due to the stabilizing effect of Gyroscopic damper. It can be seen from figure 10 that during curving the yaw angle reduces to 0.001 rad due to the stabilizing effect of the gyroscopic damper during the steady curve which is expected from the perspective of reducing wheel wear. It can also be noticed from Fig. 10 that, the lateral displacement of LRT bogie unit regardless of being large at the curve entry due to flange contact, reduces to zero after the curve section because of the stabilizing effect of gyroscopic damper.

4. Conclusion

A gyroscopic damper is shown to enhance the running performance when considering the simplified model of an IRW wheelset initially. Thereafter, the running stability and the sharp curve passing performance of LRT vehicle using IRW with negative tread conicity and gyroscopic damper is assessed from multibody dynamics analysis from which the effectiveness of proposed gyroscopic damper in increasing the curving speed potential can also be confirmed. Thus, a Gyroscopic damper can effectively improve the running performance of an LRT vehicle using NTCIRW

References

1) Brickle B.V., Railway Vehicle Dynamics, Physics in Technology 17, 181–186, 1986.
2) Dukkipati R.V., S.N. Swamy, M. Osman: Independently Rotating Wheel Systems for Railway Vehicles, Vehicle System Dynamics, 21(1), 297–330, 1992.
3) Frederich F., Dynamics of a bogie with independent wheels, Vehicle System Dynamics, 19, 217–232, 1989.
4) Suda Y., The Possibility of a New Concept of Self-steering Truck with Independently Rotating Wheels. J-Rail. 473–476, 2008.
5) Wang Y., Lin S., Tajima H., & Suda Y., Assessment of Curve Passing Performance and Active Steering Control of Railway Vehicle with Independently Rotating Wheels Using Negative Tread Conicity, Proceedings of the 26th Symposium of the IAVSD, 785–792, 2019.
6) Yabuno H., Takano H., & Okamoto H., Stabilization control of hunting motion of railway vehicle wheelset using gyroscopic damper, JVC/Journal of Vibration and Control, 209–230, 2008.
7) Lin S., Nishimura K., Okamoto H., Yabuno H., & Suda Y., Stabilization of hunting motion by gyroscopic damper, The Proceedings of the Symposium on the Motion and Vibration Control, Session ID 1C26, 1–10, 2010.
8) Yoshino H., Hosoya T., Yabuno H., Lin S., & Suda Y., Theoretical and experimental analysis on stabilization of hunting motion by utilizing traction motor as passive gyroscopic damper, 9–12, 2013.