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THEORETICAL AND EXPERIMENTAL ANALYSE ON STABILIZATION OF HUNTING MOTION BY UTILIZING THE RUNNING GEAR AS A GYROSCOPIC DAMPER

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Abstract. *A railway vehicle wheelset experiences the problem of hunting motion when the running speed becomes higher than a critical speed, which is known as a flutter-type self-excited oscillation owing to a nonconservative contact force acting between wheels and rails. Traditional methods preventing the hunting motion in the running on the straight rail are utilization of bolster, yaw-damper, or stiffer support. On the other hands, these methods make the running performance on the curved rail worse. In order to improve the running performance both on the straight rail and the curved rail, our research group has proposed the utilization of a gyroscopic damper. So far, the validity of the gyroscopic damper is theoretically and experimentally confirmed for the increase of the critical speed of the hunting motion. This control method does not need state feedback control, but it is not a passive control method because the gyroscope is rotated by an additional motor provided separately from the running gear. The weight increases due to the additional actuator has been a problem toward the practical use. In this paper, by utilizing the running gear as a passive gyroscopic damper, a new stabilization control mechanism is proposed so that the additional actuator rotating the gyroscope is not needed. Experiments were conducted using a simple apparatus with a roller rig and a gyroscopic damper which has the mechanism equivalent to the proposed one. The results show the validity of the passive gyroscopic damper in the proposed mechanism for the stabilization of hunting motion. Analytical model is a single railway vehicle wheelset and the scale is corresponding to the experimental equipment. From the eigenvalue analysis, it is found that the critical speed becomes higher with increase in the rotor revolution of the gyroscopic damper and the gyroscopic damper in the proposed mechanism is effective for the stabilization of hunting motion.*

1 INTRODUCTION

A railway vehicle wheelset experiences the problem of hunting motion when the running speed becomes higher than a critical speed, which is known as a flutter-type self-excited oscillation owing to a nonconservative contact force acting between wheels and rails [1-3]. Many interesting researches of hunting motion have been investigated using both theoretical and experimental approaches [4-7]. The effect of primary suspension on the hunting stability of a railway vehicle wheelset has been investigated in [8]. Traditional methods preventing the hunting motion in the running on the straight rail are utilization of bolster, yaw-damper, or stiffer support [9-11]. On the other hands, these methods make the running performance on the curved rail worse. In order to improve the running performance both on the straight rail and the curved rail, our research group has proposed the utilization of a gyroscopic damper [12]. So far, the validity of the gyroscopic damper is theoretically and experimentally confirmed for the increase of the critical speed of the hunting motion [13-15]. This control method does not need state feedback control, but it is not a passive control method because the gyroscope is rotated by an additional motor provided separately from the running gear. The weight increases due to the additional actuator has been a problem toward the practical use.

In this paper, by utilizing the running gear as a passive gyroscopic damper, a new stabilization control mechanism is proposed so that the additional actuator rotating the gyroscope is not needed. This mechanism can be realized by utilizing a ball-shaped gear which has arc-shaped tooth surface.

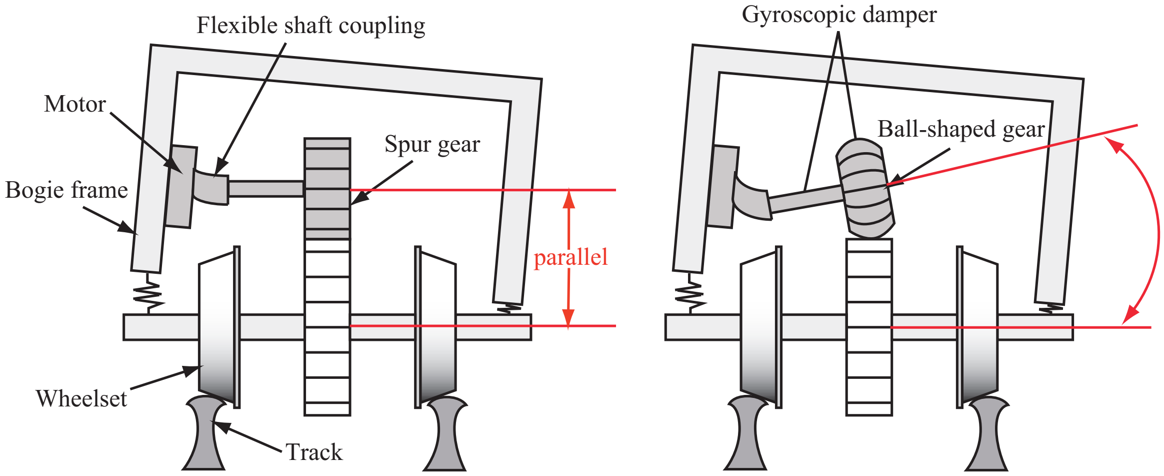
Experiments were conducted using a simple apparatus with a roller rig and a gyroscopic damper which has the mechanism equivalent to the proposed one. The results show the validity of the passive gyroscopic damper in the proposed mechanism for the stabilization of hunting motion.

Analytical model is a single railway vehicle wheelset and the scale is corresponding to the experimental equipment. From the eigenvalue analysis, it is found that the critical speed becomes higher with increase in the rotor revolution of the gyroscopic damper and the gyroscopic damper in the proposed mechanism is effective for the stabilization of hunting motion.

2 REALIZATION OF THE PASSIVE GYROSCOPIC DAMPER BY UTILIZING THE RUNNING GEAR

In the methods which we have been proposed so far, a mechanism that the relative angle between the axle and the gyroscope is not fixed and can be freely changed was necessary to get a gyro moment for the stabilization of the hunting motion. Additionally, the method is not a passive control method because the gyroscope is rotated by an additional motor provided separately from the wheel drive motor. In order to realize the passive control, keeping the configuration of the gyro relative the axle, we have to rotate the gyro without additional actuator. Unfortunately, it is impossible to use the running gear to rotate the gyro in the existing vehicle. The relative angle of the bogie flame and the motor axis is not fixed and can be freely changed by a flexible shaft coupling but the relative angle of the motor axis and the axle is fixed due to a spur gear shown as Figure 1(a).

To overcome such a difficulty, we propose a mechanism utilizing a ball-shaped gear instead of the spur gear shown in Figure 1(b). Ball-shaped gear enables the relative angle between the motor axis and the axle to freely change and can transmit the power between them because of arc-shaped tooth surface. Namely, it is possible to transmit the power between the motor and the axle continuously without changing the gear ratio even in the case the relative angle between



(a) Existing vehicle (b) Proposed mechanism

Figure 1: Vehicle model diagram representing the power transmission mechanism and the relationship between the axle and the rolling displacement of the bogie frame.

the axle and the gyroscope is changed by the ball-shaped gear. Consequently, by utilizing the ball-shaped-gear, the moment of the gyroscope occurs and hunting motion is stabilized.

For the reasons mentioned above, we think that stabilization of hunting motion by utilizing the running gear as the passive gyroscopic damper can be easily implemented to practical systems.

3 STABILIZATION OF HUNTING MOTION BY UTILIZING THE RUNNING GEAR AS A GYROSCOPIC DAMPER

3.1 Analytical model

Figure 2 shows the analytical model of a single railway vehicle wheelset with a gyroscopic damper [12]. The axle of the wheelset is suspended by springs to the bogie and moves forward at a constant speed V. The origin O of the moving coordinate system x-y-z is set at the center of the axle of the wheelset. The y-axis is set parallel to the axle of the wheelset in the static equilibrium state and the x-direction is set in the running direction of the wheelset. This coordinate system moves parallel to the x-direction at a constant speed. The wheelset has a fundamental two-degrees-of-freedom with respect to the lateral and yawing motions. On the other hand, an external gimbal is fixed to the bogie so that the vibration around yawing-axis of the axle affects the motion of the gyro. This structure results in the stability of the hunting motion, by the coupling of the yawing motion of the wheelset and the rolling motion of the gyroscope. The parameters of the wheelset model corresponding to the subsequent experiment are shown as follows:

M	mass of wheelset	17.00 kg
γ_e	wheel tread angle	0.0466
$2d_0$	distance between contact points of wheel and rail	0.0971 m
r_0	centered wheel rolling radius	0.0364 m
l	length of spring in the equilibrium state	0.0712 m

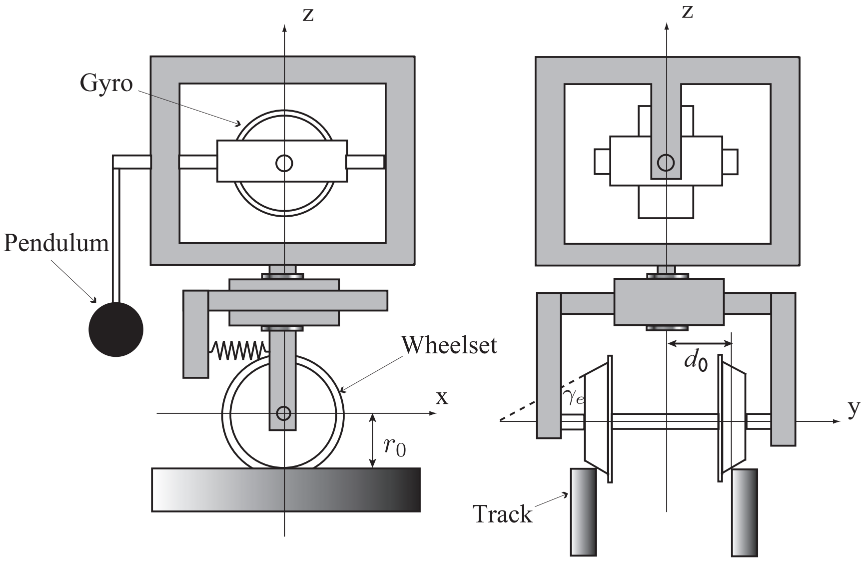


Figure 2: Analytical model of a single railway vehicle wheelset that has a fundamental two-degrees-of-freedom model with respect to the lateral and yawing motions of the wheelset.

l_0	natural length of spring	0.0700 m
x	running direction	
y	lateral motion	
ψ	yawing motion	
ξ	angular displacement of internal gimbal	
k_x	suspension elastic stiffness coefficient	1390 N/m
κ_x	creep coefficient in x direction	5322 N
κ_y	creep coefficient in y direction	4257 N
ω_y	natural frequency in lateral direction	7.8540 rad/s
ω_ψ	natural frequency in yawing direction	18.850 rad/s
ω_ξ	natural frequency in rolling direction	6.2832 rad/s
J''_x	moment of inertia of gyroscope around x''-axis	$0.00003\ \mathrm{kgm^2}$
J''_y	moment of inertia of gyroscope around y''-axis	$0.00006\ \mathrm{kgm^2}$
J''_{xig}	moment of inertia of internal gimbal with gyroscope around x''-axis	$0.00018\ \mathrm{kgm^2}$
J_0	moment of inertia of wheelset with gyroscope around z''-axis	$0.06187\ \mathrm{kgm^2}$
v	running speed	m/s
v_c	running speed causing hunting motion	m/s
Ω	angular velocity of gyroscope	$\mathrm{rad/s}$
Θ	rotational revolution of gyroscope ($= \Omega \times 60/2\pi$)	rpm

3.2 Equation of motion

The linearized equations governing the lateral and yawing motions of the wheelset and the rolling motion of the gyroscope, y, ψ and ξ, are expressed as follows:
Lateral motion of wheelset

$$M\frac{d^2y}{dt^2} + \frac{2\kappa_y}{v}\frac{dy}{dt} + k_x\left(1 - \frac{l_0}{l}\right)y - 2\kappa_y\psi = 0 \tag{1}$$

Yawing motion of wheelset

$$J_0\frac{d^2\psi}{dt^2}+\frac{2d_0^2\kappa_x}{v}\frac{d\psi}{dt}+\frac{2d_0\kappa_x\gamma_e}{r_0}y+k_xd_1^2\psi+J_y''\Omega\frac{d\xi}{dt}=0 \tag{2}$$

Rolling motion of gyroscope

$$(J_x''+J_{xig}'')\frac{d^2\xi}{dt^2}+J_y''\Omega\frac{d\psi}{dt}+d_j\frac{d\xi}{dt}+m_pgl_p=0. \tag{3}$$

Equations (2) and (3) show that the angular displacement of the rolling motion of the gyroscopic damper ξ is coupled the angular displacement of the yawing motion of the wheelset ψ. Namely, the yawing motion is directly coupled to the motion of the gyroscopic damper. This interaction stabilizes of the hunting motion.

4 THEORETICAL ANALYSIS

The governing equations of the wheelset with a gyroscopic damper are equations (1-3). We nondimensionalize these equations using the representative length quantities: the representative length is d_0 and the representative time is $1/\omega_\psi$. Introducing dimensionless displacement, time and dimensionless parameters as follows:

$$y^*=\frac{1}{d_0}y,\quad t^*=\omega_\psi t(\omega_\psi=\frac{k_xd_1^2}{J_0}),\quad v^*=\frac{v}{d_0\omega_\psi},\quad \Omega^*=\frac{1}{\omega_\psi}\Omega,$$

the governing equations are transformed into dimensionless form as

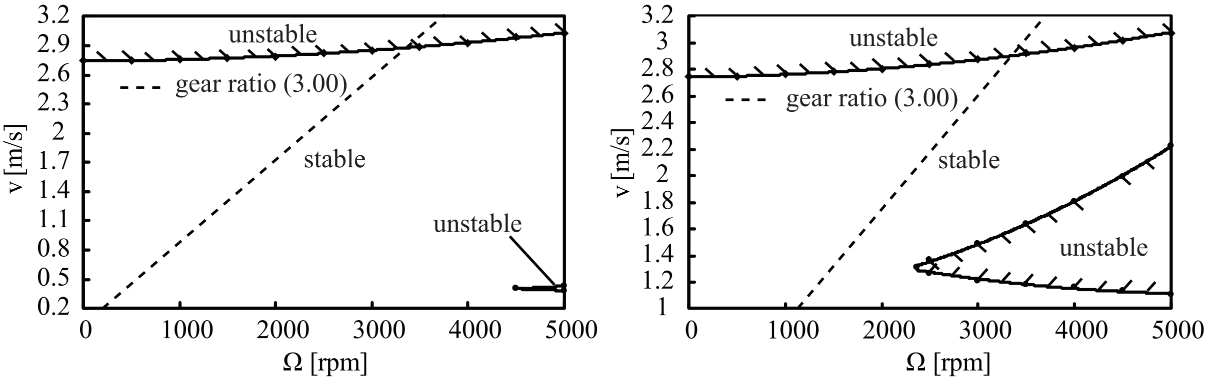
$$\ddot{y}^*+\frac{d_{c11}}{v^*}\dot{y}^*+k_{c11}y^*-k_{c12}\psi^*=0 \tag{4}$$

$$\ddot{\psi}^*+k_{c21}y^*+\frac{d_{c22}}{v^*}\dot{\psi}^*+\psi^*+d_{c23}\Omega^*\dot{\xi}^*=0 \tag{5}$$

$$\ddot{\xi}^*-d_{c32}\Omega^*\dot{\psi}^*+d_{c33}\dot{\xi}^*+k_{c33}\xi^*=0, \tag{6}$$

where the dot denotes the derivative with respect to the dimensionless time t^* and the dimensionless coefficients are

$$\begin{aligned}
d_{c11} &= \frac{2\kappa_y}{Md_0\omega_\psi^2}=29.034\\
k_{c11} &= \frac{(l-l_0)\omega_y^2}{l\omega_\psi^2}=0.00292\\
k_{c12} &= \frac{2\kappa_y}{Md_0\omega_\psi^2}=29.034\\
k_{c21} &= \frac{2\kappa_xd_0^2\gamma_e}{r_0\omega_\psi^2J_0}=1.4094\\
d_{c22} &= \frac{2\kappa_xd_0}{\omega_\psi^2J_0}=23.505\\
d_{c23} &= \frac{J_y''}{J_0}=0.00056
\end{aligned}$$



(a) kc33 = 0.01111

(b) kc33 = 0.11111

Figure 3: Relationship between the angular velocity Ω and the critical speed v_c.

$$
\begin{aligned}
d_{c32} &= \frac{J''_y}{J''_x + J''_{xig}} = 0.00032 \\
d_{c33} &= \frac{1}{\pi}\frac{\omega_\xi}{\omega_\psi} \ln \frac{\xi(t_n)}{\xi(t_{n+1})} = 0.00813 \\
k_{c33} &= \frac{\omega_\xi^2}{\omega_\psi^2} = 0.11111.
\end{aligned}
\tag{7}
$$

The values correspond to those of the subsequent experimental apparatus. Figure 3(a) and (b) shows the relationship between the angular velocity Ω and the running speed v from eigenvalue analysis of the three dimensionless equations (4-6). The system is unstable in the case when the combination of the running speed v and the rotational speed Ω is located in the hatched region. A dotted line is a gear ratio between the axle and the gyroscope. The critical speed becomes higher than the running speed calculated by the gear ratio while stabilization effect is obtained by the rotation of the gyro. Therefore, the system is stable until the dotted line crosses the unstable region. In the case when k_{c33} is lower than the value of the experimental apparatus shown as (a), the critical speed becomes higher with increase in the angular velocity of the gyroscopic damper. Additionally, there is a small unstable region where the running speed is low. On the other hand, in the case when k_{c33} corresponds to the value of the experimental apparatus shown as (b), the critical speed becomes higher with increase in the angular velocity of the gyroscopic damper but there is a large unstable region where the running speed is law. However, in the experimental setup described later, this region was not observed and a theoretical investigation of its appearance will be a future research topic. However, even if there is the unstable region in the low running speed, the effect of the gyroscopic damper can be realized by increasing the running speed so as to avoid the unstable area.

5 EXPERIMENT

5.1 Experimental setup

5.1.1 Experimental equipment

The experiment was conducted to investigate the effect of the gyroscopic damper, which has the mechanism equivalent to the proposed one, on the critical speed for the hunting motion. The

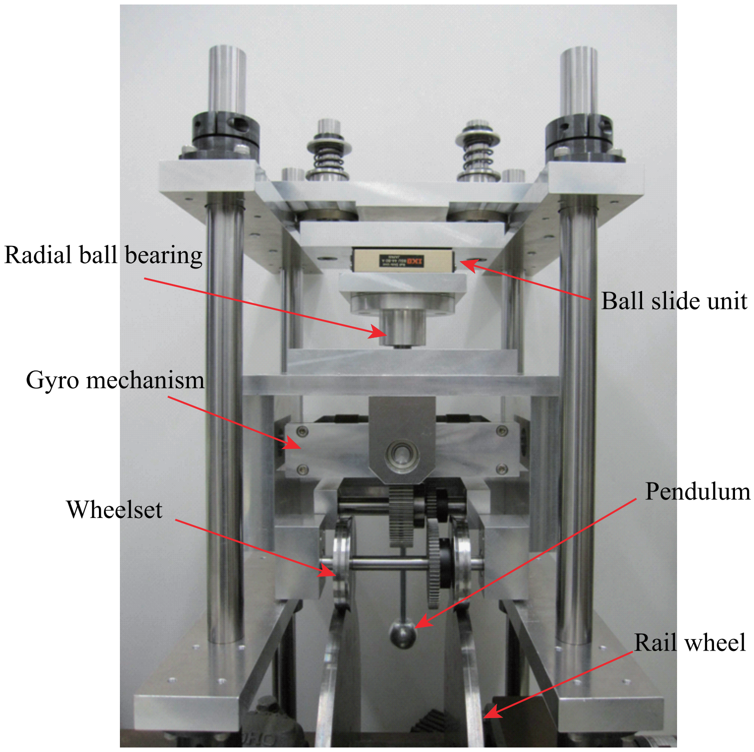
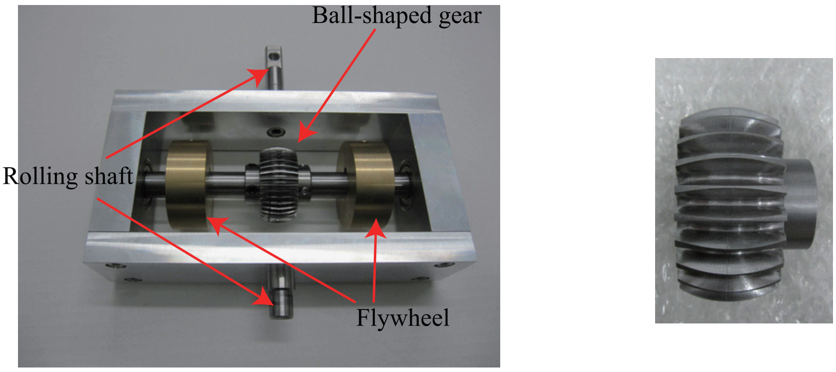


Figure 4: Experimenntal equipment designed to observe the stabilization of hunting motion by utilizing the running gear as a gyroscopic damper.



(a) Internal gimbal

(b) Ball-shaped gear

Figure 5: Internal gimbal and ball-shaped gear

experimental setup is shown in Figure 4. The radius of the roller rig rotated using a motor (Miki Pulley Corp. SEM-400B). The rotational speed is measured using an encoder (Fuji-Keisoku Corp., PG-10800, Resolution: 10800 P/R) and the pulse data is transformed into the velocity of the peripheral speed of the roller rig v.

The experimental equipment has fundamental two-degrees-of-freedom respect to the lateral and yawing, y and ψ, motions by using ball slide unit (Nippon Thompson Corp. BSU44-80A) and radial ball bearing (NSK Ltd. 6003ZZ), respectively. Furthermore, tension springs provide a restoring force against lateral and yawing motions.

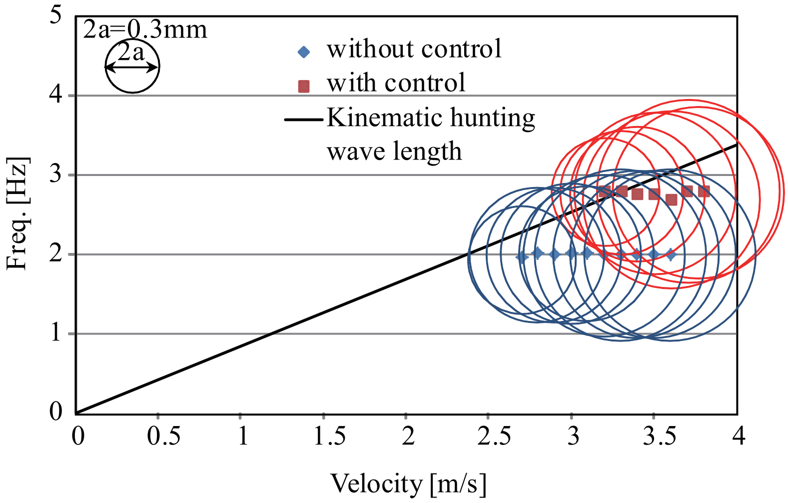


Figure 6: Campbell diagram for relationship between velocity and frequency when the hunting motion occurs. The size of the circle is proportional to the magnitude of the amplitude.

5.1.2 The structure of internal gimbal and the mechanism of transmission of rotation of gyro

In the gyroscopic damper (internal gimbal), ball-shaped gear and two flywheels are built to the rotational axis of gyroscope shown as Figure 5(a). The ball-shaped gear transmits the rotation of the axle to the gyroscope and flywheels have the moment of inertia which is necessary to generate the moment of the gyroscope. The internal gimbal is supported to a bogie by two radial ball bearings (NSK Ltd. 6001ZZ) and can move in the rolling direction. Furthermore, a pendulum which is connected to the rotational axis of the internal gimbal gives the restoring force to the internal gimbal in the equilibrium state. To generate the moment of gyroscope, the mechanism that enables the rotational axis of gyroscope to move freely in the rolling displacement against the axle is necessary. To realize such mechanism, we adopt a ball-shaped gear (Nagaoka Gear Works Corp.,) shown as Figure 5(b).

Ball-shaped gear enables the relative angle between the motor axis and the axle to freely change and can transmit the power between them because of arc-shaped tooth surface. Namely, it is possible to transmit the power between the motor and the axle continuously without changing the gear ratio even in the case the relative angle between the axle and the gyroscope is changed by the ball-shaped gear. In addition, the rotational speed of the gyroscope is determined by a gear ratio between the axle and the axis of the gyroscope because the gyroscope is connected directly to the axle.

5.2 Experimental results

To verify the effect of the gyroscopic damper for the stabilization of hunting motion, experiment is conducted in the cases of fixing the internal gimbal not to move in the rolling direction (the moment of gyroscope does not occur; without control) and of not fixing the internal gimbal freely to move in the rolling direction (the moment of gyroscope occurs; with control). The lateral motion of the wheelset is measured by the laser displacement sensor (KEYENCE Corp. LB-01). Figure 6 shows a campbell diagram for relationship between velocity and frequency when the hunting motion occurs. The size of the circle is proportional to the magnitude of the amplitude of hunting motion. The theoretical value of frequency of the hunting motion is obtained by the kinematic hunting wave length S_1 expressed as follows [16]:

$$S_1 = 2\pi\sqrt{\frac{d_0 r_0}{\gamma_e}}. \tag{8}$$

In the case which the internal gimbal is fixed (the moment of gyroscope does not occur; without control), the critical speed v_c is 2.70m/s. And in the case which the internal gimbal is not fixed (the moment of gyroscope occurs; with control), the critical speed v_c is 3.20m/s. Therefore, it is obvious that the critical speed becomes higher 18.5$\%$ by utilizing the running gear as the passive gyroscopic damper.

6 CONCLUSIONS

In this paper, we have proposed a passive stabilization control method of the hunting motion in a railway vehicle wheelset by a new mechanism utilizing a running gear as a gyroscopic damper. It is the advantage of this method not to need the additional actuator to rotate the gyroscope. Additionally, this method can be easily implemented to practical systems by utilizing the ball-shaped gear. It is theoretically verified by analyzing the equation of motion of the three-degrees-of-freedom vehicle model that the proposed gyroscopic damper increases the critical speed for hunting motion. Also the validity is experimentally confirmed by equipment with the mechanism equivalent to the proposed one.

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