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Driving force distribution based on tyre energy for independent wheel-drive vehicle on rough ground

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Abstract

The driving force of a wheel is an important factor to determine the travelling performance of vehicles on rough grounds. An excessive driving force induces a large slip, whereas insufficient driving force prevents vehicles from overcoming obstacles. Hence, an optimum driving force distribution is necessary to improve the travelling performance of off-road vehicles on rough grounds. In this study, the driving force distribution method of four independent wheel-drive vehicles based on the energy-loss ratios of the wheels is proposed. The squared sum of the energy-loss ratios is minimized in the proposed method. To validate the proposed method, travelling tests were conducted using a model vehicle on a rough and rigid ground and a soft ground. Moreover, simulation tests were performed on a rough and rigid ground. The results obtained using the proposed method were compared with those of the distributions based on the tyre work-load, even force, and wheel-velocity control. The experimental and simulation results confirm that the proposed method is the most efficient for vehicles moving on a rigid ground. The movement of the vehicle on the soft ground was the most stable when the proposed method was employed.

Keywords: Off-road vehicle; Driving force distribution; Slip; Rough ground; Driving efficiency

1. Introduction

The travelling performance of off-road vehicles, such as sports utility vehicles, agricultural machines, and construction machines, on soft and rough grounds should be high. However, the travelling performance and driving efficiency decrease on such grounds when a wheel slips because of excessive torque or stops at an obstacle because of insufficient torque. Hence, a traction control system (TCS) has been developed (Inoue and Ishida, 2008) to prevent the wheel from slipping and an anti-lock braking system has been developed for a braking performance on rough terrain (Ivanov et al., 2015; Penny and Els, 2016). The TCS generates a braking torque on the slipping wheel and improve the wheel performance. However, the TCS needs more driving energy because of braking. Hence, a driving force distribution is capable of preventing the wheel slip without braking energy is required to improve the travelling performance and driving efficiency. Distribution methods have been developed for rear wheel-drive vehicles (Ando and Fujimoto, 2010) and independent wheel-drive vehicles (Margolis and Cleveland, 1988; Motoyama et al., 1993). The distribution method based on tyre work loads (Mokhiamar and Abe, 2004; Ono et al., 2006), energy losses due to tyre slippage (Suzuki et al., 2014), and power losses of drivetrains (Dizqah et al., 2016) have been proposed for independent wheel-drive vehicles. Moreover, a distribution method which minimizes the energy losses due to tyre slippage for multi-axles vehicle with independent wheel-drive has been developed (Yamakawa and Watanabe, 2006). The independent wheel-drive is imple-

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mented in the in-wheel motors (Hori et al., 1998) or magnetorheological-fluid viscous couplings (Nagaya et al., 2007). However, these studies were conducted considering the vehicle motion on a flat and rigid ground. The study on distribution method for vehicle movement on rough ground was conducted (Yamakawa et al., 2007). However, this method considered the distribution of only front and rear tyres. The distribution methods for four wheel-drive remain unexplored.

In this study, a driving force distribution method is proposed for four independent wheel-drive vehicles based on the energy-loss ratios of the wheels. The simulation and model tests were conducted to evaluate the effectiveness of the proposed method. The test results obtained using the proposed method were compared with those using distribution methods based on tyre workload, even distribution; which is a vehicle model with a centre differential; and even velocity control; which is a vehicle model with locking differentials.

2. Driving force distribution method

A driving force distribution method is proposed to improve the travelling performance of off-road vehicles. The squared sum of the energy-loss ratios of the wheels undergoing slippage is minimized in the proposed method.

2.1. Vehicle model

Fig. 1 shows the model of the independent wheel-drive vehicle. Assuming that the front-left and right steering angles of the wheels are negligible, the equations for the forces and yaw moment can be expressed as follows:

$$\begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ -\frac{b_F}{2} & l_F & \frac{b_F}{2} & l_F & -\frac{b_R}{2} & -l_R & \frac{b_R}{2} & -l_R \end{bmatrix} \mathbf{x} = \begin{bmatrix} F_0 \\ M \end{bmatrix} \quad (1)$$

$$\mathbf{x} = [F_{xFL} \ F_{yFL} \ F_{xFR} \ F_{yFR} \ F_{xRL} \ F_{yRL} \ F_{xRR} \ F_{yRR}]^T, \quad (2)$$

where F_0 is the driving force of the vehicle, F_{xFL}, F_{xFR}, F_{xRL}, and F_{xRR} are the longitudinal forces of each wheel,F_{yFL}, F_{yFR}, F_{yRL}, and F_{yRR} are the lateral forces of each wheel,

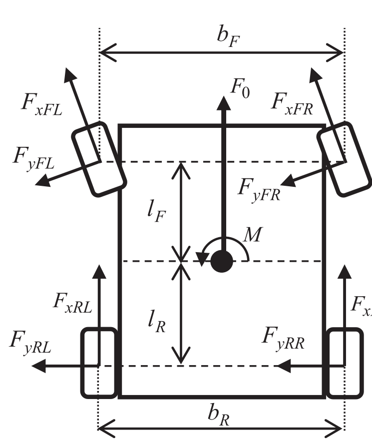

Fig. 1. Vehicle model.

M is the yaw moment of the vehicle, b_F and b_R are the tread widths of the front and rear axles, and l_F l_R are the distances from the centre of mass to the front and rear axles, respectively. The coefficient matrix on the left-hand side is defined as $\mathbf{A}$. The matrix for the driving force and yaw moment of the vehicle is defined as $\mathbf{f}$. Thus, Eq. (1) can be written as $\mathbf{Ax} = \mathbf{f}$.

2.2. Distribution method based on tyre workload

The longitudinal force F_{xi} and lateral force F_{yi} of a wheel i with vertical load F_{zi}, moving on a road with friction coefficient μ_i are limited as follows.

$$\mu_i F_{zi} \geqslant \sqrt{F_{xi}^2 + F_{yi}^2}, \quad (3)$$

where i can take values of the front-left (FL), front-right (FR), rear-left (RL), and rear-right (RR) wheels. The tyre force generated from the interaction between the tyre and road does not exceed the friction between the tyre and road. If the tyre force is saturated, tyre slippage is induced. The tyre workload η_i is defined as follows:

$$\eta_i = \frac{\sqrt{F_{xi}^2 + F_{yi}^2}}{\mu_i F_{zi}} \quad (4)$$

When the tyre workload η_i is above one, the tyre slips, thereby reducing the travelling performance of the vehicle. Hence, the workload needs to be sufficiently small to prevent the driving force from saturating. An evaluation function is defined as the squared sum of the tyre workloads and is expressed as follows.

$$J_1 = \sum_i \eta_i^2 = \sum_i \frac{F_{xi}^2 + F_{yi}^2}{(\mu_i F_{zi})^2} = \mathbf{x}^T \mathbf{W}_1^{-1} \mathbf{x}, \quad (5)$$

where weighting matrix $\mathbf{W}_1$ is defined as follows.

$$\mathbf{W}_1 = \mathrm{diag}\left[\frac{1}{(\mu_{FL} F_{zFL})^2} \quad \frac{1}{(\mu_{FL} F_{zFL})^2} \quad \frac{1}{(\mu_{FR} F_{zFR})^2} \right. \times \frac{1}{(\mu_{FR} F_{zFR})^2} \quad \frac{1}{(\mu_{RL} F_{zRL})^2} \quad \frac{1}{(\mu_{RL} F_{zRL})^2} \left. \times \frac{1}{(\mu_{RR} F_{zRR})^2} \quad \frac{1}{(\mu_{RR} F_{zRR})^2} \right] \quad (6)$$

The solution to Eq. (5), which helps minimize the evaluation function $J_{1,}$ is obtained using the following equation.

$$\mathbf{x} = \mathbf{W}_1^{-1} \mathbf{A}^T (\mathbf{A} \mathbf{W}_1^{-1} \mathbf{A}^T)^{-1} \mathbf{f} \quad (7)$$

2.3. Distribution method based on energy loss due to slippage

When a tyre i is driven, the absolute travel velocity V_i of the tyre is different from the circumferential velocity $r\omega_i$ because the tyre undergoes elastic deformation and slip-