Research Report

Detection of Tire Lateral Force Based on a Resolver Mechanism

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レゾルバを用いたタイヤ横力検知

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Abstract

To observe the frictional state of a tire and improve the active safety control system of a vehicle, it is necessary to sense the tire-generated forces.

This paper presents a technique for detecting a lateral tire-force. This is based on the resolver mechanism that is used as a rotational speed sensor for a wheel. It is realized simply by replacing a conventional wheel speed sensor, and can detect tire lateral force by magnetically sensing the positional offset of the rotating shaft that occurs due to the stiffness of the shaft and axle hub bearing. Therefore, there is no need for complex machining and the system can accommodate variations in the tire characteristics caused by changes in temperature, inner pressure, aspect ratio, and so on. The principle of the technique has been confirmed by experiments on a tire test machine and on a test vehicle.

Keywords Resolver, Lateral force, Differential phase shift, Stiffness, Moment

要　旨

タイヤの摩擦状態の観測や車両制御の性能向上のためには，タイヤの摩擦力を検知することが望まれる。本稿では，レゾルバという回転角センサを用いたタイヤ横力検知について述べる。この方法は，従来の車輪センサの置き換えだけで実現され，車軸や軸受けの剛性に依存して発生する軸変位を磁気的原理に基づいて検知することにより，タイヤ横力を検出するものである。したがって，煩雑な加工は必要なく，また，温度や空気圧，偏平率等の変化によるタイヤ特性の変動に対してもロバストな性能を有する。本手法の原理を，タイヤ試験機および実車による走行試験を通じて確認した。

キーワード　レゾルバ，横力，差動位相シフト，剛性，モーメント

1. Introduction

To observe the frictional state of a tire and improve the active safety control system[1] of a vehicle, it is a necessary to sense tire-generated forces such as the longitudinal force, self-aligning torque, and lateral force. Of these force components, the longitudinal force and self-aligning torque can be sensed by vehicle control equipment, such as the ABS hydraulic pressure sensor and the EPS torque sensor. The tire lateral force, however, has always been assumed to be difficult to detect using conventional sensors.

Many methods of detecting tire-generated forces have been proposed. One typical method involves detecting the tire-generated forces by embedding a strain gauge in a suspension knuckle,[2] while another method uses a magnetic marker on the surface of the tire to detect tire deformation.[3] Unfortunately, both of these methods require complex machining of the knuckle or tire, and lack wide applicability. Also, the detection accuracy is poor and they cannot be regarded as being reliable.

This paper presents a tire lateral force detection technique that is based on the resolver mechanism that is used as a rotational speed sensor for a wheel. It can be realized simply by replacing a conventional wheel speed sensor, and detects tire lateral forces by magnetically sensing the positional offset of the rotating shaft that occurs due to the stiffness of the shaft and axle hub bearing. Therefore, it needs no complex machining and can accommodate variations in the tire characteristics resulting from changes in temperature, inner pressure, aspect ratio, and so on. The validity of this method has been confirmed by experiments on a tire test machine and on a test vehicle.

2. Detection mechanism

2. 1 Principle of the resolver

Figure 1 shows the configuration of a rotary transformer resolver. It features a rotary transformer on the rotor and multiple coils on the stator that are laid out such that the phase difference in the output signals is $\pi/2$. When a high frequency AC voltage $E \sin \omega t$ is applied to the rotary transformer, voltages expressed by the following equations are induced in the stator coils by electromagnetic induction.

$$\left.\begin{aligned} Ec &= KE \cos\theta \sin\omega t \\ Es &= KE \sin\theta \sin\omega t \end{aligned}\right\} \cdots\cdots (1)$$

where, K is a coupling coefficient. The magnitudes of the induced voltages vary in accordance with the rotational angle θ of the rotor.

The R/D converter shown in **Fig. 2** determines and then outputs the angular position of the rotor from Es and Ec. It has two multipliers and a subtracter that generate a signal, as follows:

$$KE \sin\omega t \sin(\theta - \phi). \cdots\cdots (2)$$

Then, the synchronous commutator removes the $\sin\omega t$ from the above signal. The voltage control oscillator (VCO) outputs counter up-down pulses corresponding to the magnitude of the voltage $KE \sin(\theta - \phi)$, and adjusts the value of ϕ such that it coincides with the rotational angle θ, namely, $\theta = \phi$. As a result, digital output angle ϕ becomes equal to the actual angle position θ of the rotor.

2. 2 Differential phase shift (DPS)

To detect the lateral force of a tire, the rotary transformer is mounted on a drive shaft and the stator coils are fixed to the knuckle. When the lateral force Fy occurs as shown in **Fig. 3**, a moment Mx, which is a product of Fy and the tire radius R, is

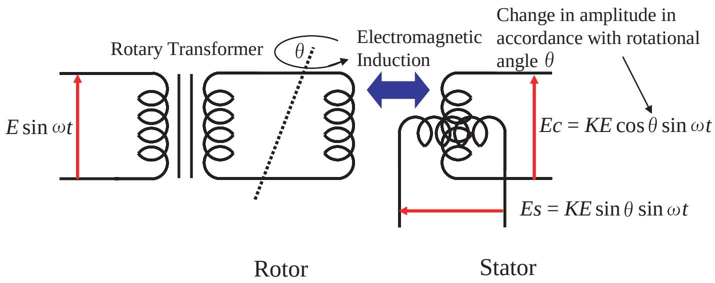


Fig. 1 Configuration of resolver.

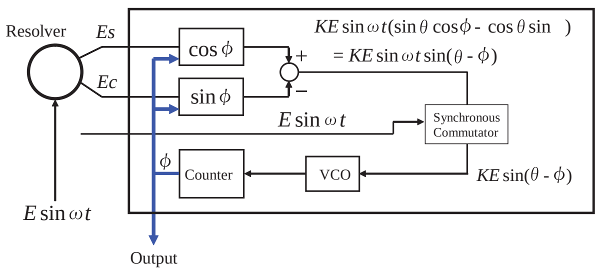


Fig. 2 R/D Converter.

applied to the rotating shaft and bearing. Then, the position of the shaft is offset by γ due to the stiffness of the shaft and bearing.

In this case, the voltages induced in the resolver, *Ec* and *Es*, are as follows:

$$Ec = KE \cos(\theta + \delta_c) \sin \omega t$$
$$Es = KE \sin(\theta + \delta_s) \sin \omega t \quad \cdots\cdots (3)$$

Then, VCO and the counter of the R/D converter determine the digital output angle ϕ, such that

$$\sin(\theta - \delta_s)\cos\phi - \cos(\theta + \delta_c)\sin\phi \to 0 \quad \cdots\cdots (4)$$

Equation (4) derives

$$\sin\left\{\phi - \tan^{-1}\left(\frac{\sin(\theta - \delta_s)}{\cos(\theta + \delta_c)}\right)\right\} = 0 \text{ ,}$$

which can be approximated to

$$\phi = \theta + \frac{1}{2}\{(\delta_c - \delta_s) - (\delta_c + \delta_s)\cos 2\theta\} \quad \cdots\cdots (5)$$

by assuming that δ_c, δ_s<<1.

Here, the speed change rate is obtained by differentiating Eq. (5), as follows:

$$\frac{\hat{v} - v}{v} = (\delta_c + \delta_s)\sin 2\theta \text{ ,} \quad \cdots\cdots (6)$$

where $\hat{v}$ is the detected speed and v is the true speed. Since v cannot be measured, the average speed during one rotation is used instead of v. This equation indicates that if a lateral force is generated, the rate of change of the speed fluctuates periodically in the magnitude of (δ_c + δ_s) and at a frequency equal to twice the rotational speed of the wheel.

Generally, given that the number of magnetic poles is P, the period of the speed change rate is P times the number of rotations of the wheel:

$$\frac{\hat{v} - v}{v} = (\delta_c + \delta_s)\sin P\theta \quad \cdots\cdots (7)$$

Since (δ_c + δ_s) indicates the difference between the phase shift in the voltage induced in the two coils, it is defined as the "Difference Phase Shift (DPS)" in this paper.

The lateral force can be detected from Eq. (7), provided the characteristic relationship between DPS and the lateral force, namely the stiffness of the shaft and bearing, has been determined in advance.

3. Experiment using a tire test machine

To confirm the lateral force detection principle, we performed an experiment using a tire test machine.

3. 1 Experimental system

A general view of the tire test machine and the resolver installed on the axle hub is shown in **Fig. 4**. To sense the actual forces, we used a six-axis force sensor. The resolver used in this experiment has eight poles and is of the variable reluctance type. This has the same characteristics to the rotary transformer type shown in Fig. 1.

3. 2 Detection of DPS

The algorithm used to detect the lateral force using DPS is shown in **Fig. 5**. According to Eq. (7), DPS can be detected as the magnitude of the speed

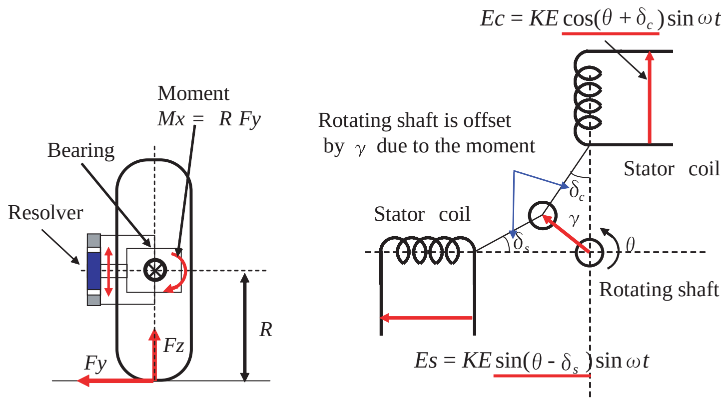


Fig. 3 Moment and phase shift of resolver.

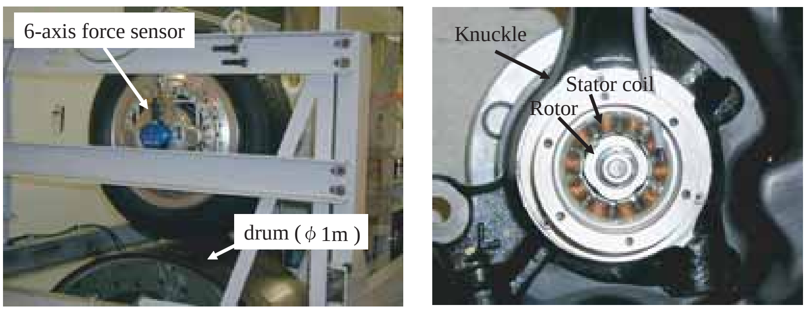


Fig. 4 Tire test machine and resolver.

change rate. The rotational speed is obtained as follows:

Normally, the R/D converter is designed so as to have an angular resolution of 16 bits per rotation by using a 16-bit register in the counter. If we look at the time series signal of each bit of the register, we see that a signal of one pulse rises at MSB within a single rotation, and that 2^{15} pulses rise at LSB. In this experiment, the bit position to be measured is selected so that 256 pulses rise in one rotation. By measuring the interval between the rising or falling edges (the period of the pulse), the rotational speed $\hat{v}$ in Eq. (7) can be obtained.

Figure 6 shows the results of measuring the wheel speed for a case in which the lateral force is almost zero (slip angle 0 deg) and a case in which a lateral force is generated (slip angle 4 deg). We can show that the fluctuation of the wheel speed clearly appears to have eight periods in one rotation when a lateral force is generated.

DPS $\delta(N)$, which is the value at the Nth pulse in one rotation, is calculated by using the following equations:

$$R_e(N)=\frac{1}{128}\sum_{i=N-255}^{N}\alpha(i)\sin(2\pi Pi/256)$$
$$I_m(N)=\frac{1}{128}\sum_{i=N-255}^{N}\alpha(i)\cos(2\pi Pi/256) \qquad \cdots(8)$$
$$\delta(N)=\delta_c(N)+\delta_s(N)=\sqrt{R_e^{\,2}(N)+I_m^{\,2}(N)}$$
$$\delta_f(N)=K_f\delta_f(N-1)+(1-K_f)\delta(N),\ 0<K_f<1$$

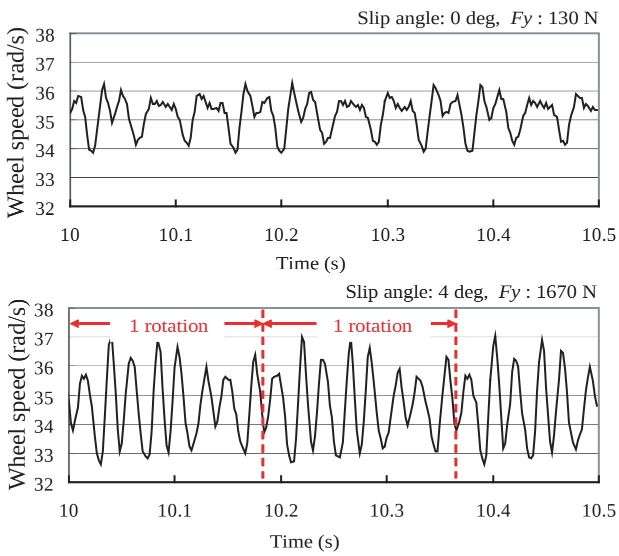
where,
$$v(N)=\frac{1}{256}\sum_{i=N-255}^{N}\hat{v}(i),\ \ \alpha(N)=\frac{\hat{v}(N)-v(N)}{v(N)}$$

and $\delta_f(N)$ is the output from the lowpass filter. The lowpass filter suppresses noise from the load surface.

A simple Fourier transform is applied in the above steps to extract the periodic component from the speed change rate $\alpha(N)$.

3. 3 Results

Figure 7 shows the results of an experiment in which the vehicle weight *Fz* and the wheel speed were varied and the lateral force was set to zero. In this figure, we can see that DPS has a certain offset



(Wheel load: 2000 N, Speed: 40 km/h)

Fig. 6 Wheel speed signal from resolver.

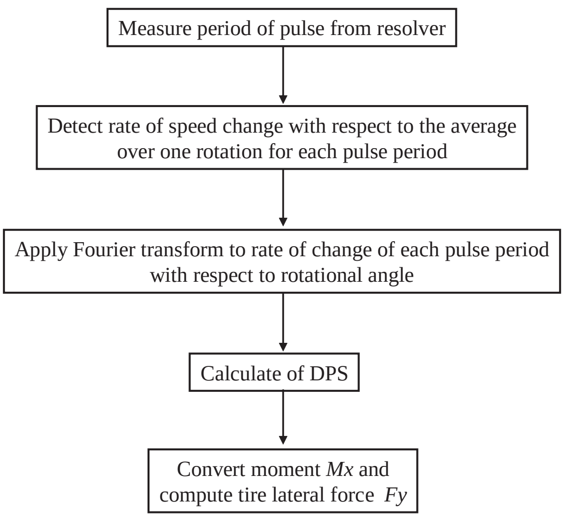


Fig. 5 Lateral force detection algorithm.

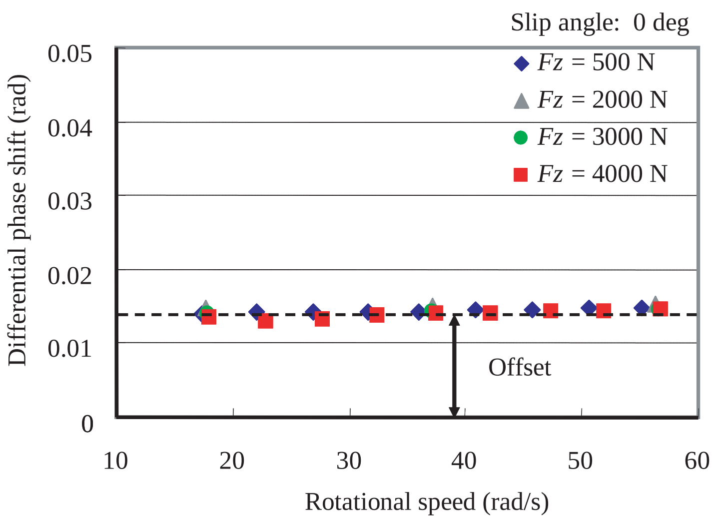


Fig. 7 Offset of resolver.

value, but it is not affected by either *Fz* or the wheel speed. It is believed that this offset is derived from the alignment accuracy and electrical imbalance between the two coils in the stator.

Since this offset is fixed regardless of the change in *Fz* and the wheel speed, a corrected DPS can be obtained by subtracting the offset from the actual DPS. **Figure 8** shows the results obtained from an experiment that uses the corrected DPS with respect to the moment *Mx*(=*FyR*) which is applied to the bearing center. In this case, the vehicle weights *Fz* are 2000N and 3000N, and each wheel speed is set to 20, 40, and 60 km/h. This figure indicates that the corrected DPS depends on *Mx* or *Fy* and is not affected by any other parameters.

Therefore, if the relationship between *Mx*(or *Fy*) and the corrected DPS are known in advance, the lateral force can be detected from DPS.

4. Experiment using a test vehicle

The test vehicle was a rear-drive car with the resolver installed on the axle hub of the right-front wheel. For this experiment, we used a rotary transformer resolver.

Figure 9 shows the wheel speed detected by the resolver when the test vehicle was run through a slalom. We can see that the fluctuation in the detected speed increased as the lateral acceleration increased. This fluctuation appears to be caused by the previously mentioned differential phase shift.

Figure 10 shows the relationship, experimentally determined in advance, between the DPS and moment *Mx* applied to the bearing center of the axle hub. The estimated values of *Mx* and *Fy* obtained from filtered DPS δ_f by using the characteristic shown in Fig. 10 are depicted in **Fig. 11**. In this figure, *Fy* is computed by simply dividing the estimated moment *Mx* by the tire radius *R*. To

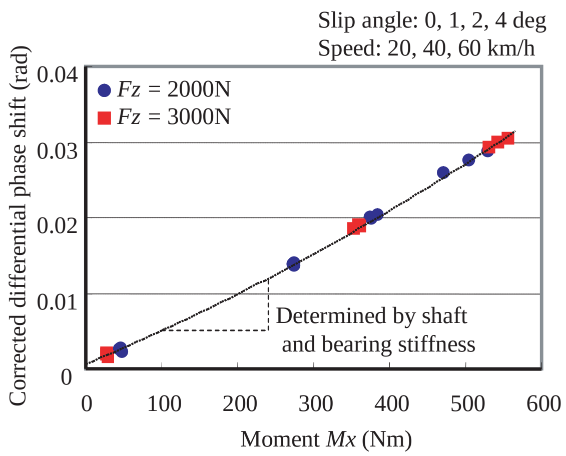


Fig. 8 Moment vs. corrected DPS.

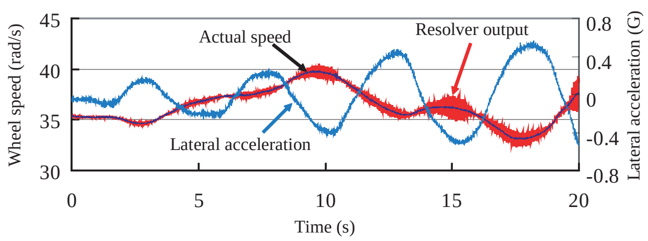


Fig. 9 Resolver output during slaloming.

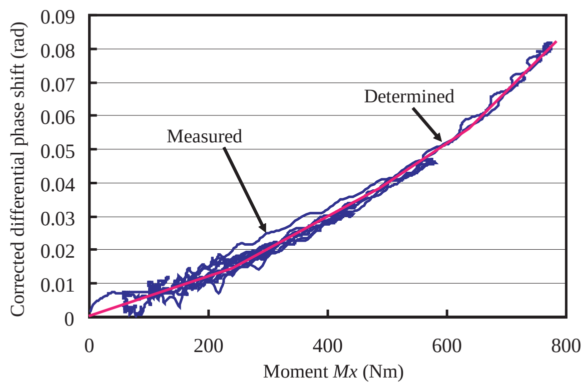


Fig. 10 Relationship between *Mx* and DPS of test vehicle.

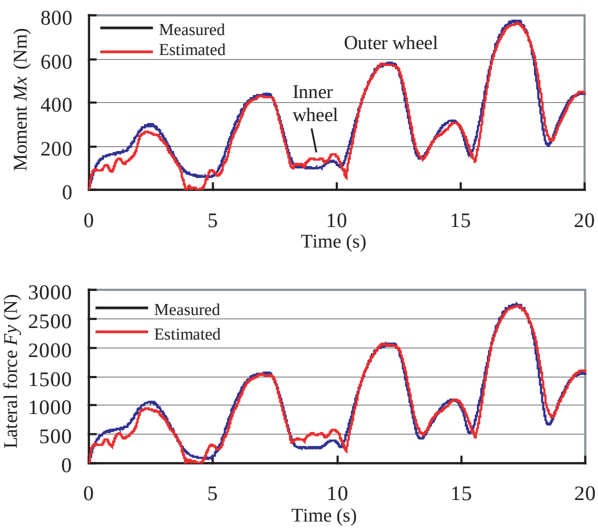


Fig. 11 Results of estimation.

compare this with the measured value, the filtered absolute values of *Mx* and *Fy* as sensed by the 6-axis force sensor are shown in this figure. The highly accurate detection can clearly be seen, especially in that area when the right-front wheel is the outer wheel in a turn.

5. Conclusion

This paper has presented a tire lateral force detection technique that is based on a resolver mechanism. It can be realized simply by replacing a conventional wheel speed sensor, and detects the tire lateral force by magnetically sensing the positional offset of the rotating shaft that occurs as a result of the stiffness of the shaft and the axle hub bearing. Therefore, it needs no complex machining and can accommodate variations in the tire characteristics due to the change in the temperature, inner pressure, aspect ratio, and so on. The method has been confirmed by experiments in a tire test machine and on a test vehicle.

Currently, this method is software-based and can only detect the absolute value of the lateral force. In the future, we aim to develop a hardware-based method that can directly detect signed forces.

References

1) Hattori, Y., et al. : "Force and Moment Control with Nonlinear Optimum Distribution for Vehicle Dynamics", Proc. AVEC'02, (2002), 595, JSAE

2) Miyazaki, N. : Examined Patent Pub. H04-331336 (in Japanese)

3) Giustino, J. : US Patent No. US 6550320 B1

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