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RESEARCH & KNOWLEDGE

Research Article

Predictive suspension control system by inclinometer and accelerometer

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Abstract - This paper presents a conceptual idea of a predictive suspension control system using two simple sensors, which are a bi-axial inclinometer and a bi-axial accelerometer, for measuring four input signals. The inclinometer is for measuring road parameters that consist of a slope angle and an incline angle, while the accelerometer is for measuring dynamic parameters that consist of an accelerating G-force and a turning G-force. A suspension control unit (SCU) is for calculating the four output signals using the concept of vehicle weight distribution. The percentage of the vehicle weight distributed to each wheel are the output signals for controlling the adjustable suspension parts, such as spring and shock absorber on each wheel independently. This article relates to the first phase of developing a conceptual idea. However, the prototyping and experimental phases will be conducted in the next phase.

Keywords: Predictive suspension control, inclinometer, accelerometer

1. Introduction

The vehicle weight distributed to each wheel is influenced by two factors: a static factor and a dynamic factor. In the static mode, the vehicle weight distribution depends on the vehicle parameters and the road parameters. The vehicle parameters consist of the vehicle dimensions and the position of the center of gravity (CG); while, the road parameters consists of the slope angle and the incline angle (Gillespie, 2014; Janzar, 2009; Popp *et al*., 2010; Rajamani, 2005). The position of the CG is identified by three components in the x-, y-, and z-axis. In a dynamic mode, the vehicle weight distribution is affected by dynamic effects consisting of the acceleration effect and the turning effect. The vehicle suspension is designed for support under all conditions (static and dynamic modes); however, standard suspension parts cannot be adjusted. Recently, there have been many studies that have developed the adjustability of suspension parts, including patents (Fukumura *et al*., 1990; Naganathan and Thirupathi, 1995; Henry *et al*., 1995; Armstrong, 2010) and research (Gonzalez Rodriguez *et al*., 2011; Lee *et al*., 2012; Milecki and Hauke, 2012; Donoso *et al*., 2013). Not only the suspension parts, but the control systems have been continuously developed (Poussot-Vassal *et al*., 2008; Dugard *et al*., 2012; Poussot-Vassal *et al*., 2012; Koch *et al*., 2010). Traditionally, a feedback signal has been used as an input signal for the control unit to control the adjustable suspension. The feedback signal is normally measured by force sensors (load cell) or defection sensors installed at the suspension parts on each wheel. The problems are that these sensors are expensive and their installation is difficult. They have to be installed on moving parts, such as a shock absorber (Koch *et al*., 2010), a spring, or an un-sprung part (Poussot-Vassal *et al*., 2012). The sequence of the feedback control system is shown in Table 1. The vehicle weight distributed to each wheel (front/rear and right/left) is influenced by the static and dynamic effects. On each wheel, the sensors are installed to measure the force or the defection independently, and their signals are used as four input signals. The control unit uses these input signals for the calculation, and then sends the feedback signals to control the adjustable suspension parts on each wheel separately.

This article aims to develop a new conceptual idea to pre-control an adjustable suspension using a predictive signal instead of a feedback signal. As shown in Table 1, a bi-axial inclinometer and a bi-axial accelerometer were used for detecting the static and the dynamic conditions, respectively. An inclinometer is for measuring the slope and the incline angle, while an accelerometer is for measuring the accelerating and the turning g-force. These sensors can be included in a suspension control unit (SCU). The signals from both sensors are used as the input signals for the SCU for the calculation. The predictive signals from the control unit are sent to each wheel to pre-control the adjustable suspension parts. The advantages of this system are the cost of these sensors, the convenience of their installation, and the possibility to combine these sensors in the SCU to avoid an installation problem.

This article is divided into five sections. The concept of the vehicle weight distribution is overviewed in the next section, and the vehicle parameter identifications are presented in the third section. A case study is provided in the fourth section, and then the article is concluded in the last section. Moreover, the source code for the analysis is also provided in an appendix.

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Table 1. Feedback control and predictive control.

Feedback control system	Predictive control system
1. Static effect (slope angle and incline angle) and dynamic effects (accelerating effect and turning effect). 2. Vehicle weight distributed to suspension part on each wheel (front/rear, right/left). 3. Force or defection sensor installed at suspension part for measuring the input signals. 4. SCU installed in cabin area for calculation. 5. Feedback signals for post-control of the adjustable suspension part.	1. Inclinometer and accelerometer installed in cabin area for measuring the input signals. 2. SCU installed in cabin area for calculation. 3. Predictive signals for pre-control of the adjustable suspension system.

2. Vehicle weight distribution

The vehicle weight distribution on each of the four wheels (front/rear and right/left) is influenced by four factors, which are a front wheel factor, a right wheel factor, an accelerating factor, and a turning factor (see Table 2.). The weight distributed to each of the four wheels is considered in terms of a weight fraction or a percentage of the total weight (the value in the curly brackets '{}'). A critical point happens when the weight fraction of one wheel (or more) becomes zero. It means that the wheel does not touch the road surface. Moreover, the weight fraction can be negative. The meaning is that there is an external force acting upward at that wheel to turn over the vehicle. The weight distributed to the wheel also affects a friction force based on the friction coefficient between the tire and the road. This friction force influences the accelerating ability, the braking ability, and the turning ability.

Table 2. Vehicle weight distribution on each wheel.

	Left wheel	Right wheel
Front wheel	$W\{(f_f - f_a)(1 - f_r - f_t)\}$	$W\{(f_f - f_a)(f_r + f_t)\}$
Rear wheel	$W\{(1 - f_f + f_a)(1 - f_r - f_t)\}$	$W\{(1 - f_f + f_a)(f_r + f_t)\}$

2.1 Front wheel factor

The front wheel factor (f_f) is the fraction of the vehicle weight distributed to both front wheels (right and left) depending on the position of the vehicle's center of gravity (CG) in the x- and y-axis and the slope angle (θ_s) , as shown in Equation 1. The position of the CG along the length of the vehicle is defined in the CGx fraction (x_{CGx}), which is the ratio of the horizontal distance between the CG from the rear axis and the wheelbase (see Fig.1.).The position of the CG along the height of the vehicle is defined in the CGy fraction (x_{CGy}) , which is the ratio of the vertical distance of the CG from the road and the wheelbase. The slope angle is specified as positive for an upward slope, while it is specified as negative for a downward slope. It is measured by an inclinometer.

$$f_f = x_{CGx} \cos\theta_s - x_{CGy} \sin\theta_s \quad (1)$$

2.2 Right wheel factor

The right wheel factor (f_r) is the fraction of the vehicle weight distributed to both right wheels (front and rear) depending on the position of the CG, the wheel track fraction (x_T), and the incline angle (θ_I) , as shown in Equation 2. The position of the CG along the width of the vehicle is defined in the CGz fraction (x_{CGz}), which is the ratio of the horizontal distance from a middle line to the CG and the wheelbase. It is positive if the CG is on the right side of the vehicle (driver side for Thailand). The wheel track fraction is the ratio of the distance between the centerline of the right to the left wheels and the wheelbase. If there is a different between the front track and the rear track, an average value is typically used. The incline angle is positive in a case where the incline is upward from the right wheel to the left wheel. It can be measured by an inclinometer.

$$f_r = \left(\frac{1}{2} + \frac{x_{CGz}}{x_T}\right) \cos\theta_I + \left(\frac{x_{CGy}}{x_T}\right) \sin\theta_I \quad (2)$$

2.3 Accelerating factor

The acceleration factor (f_a) is the effect of the accelerating G-force (G_a) on the front wheels and the rear wheels, as shown in Equation 3. The G-force is measured and compared to the acceleration of gravity. The accelerating G-force is positive for an acceleration (increasing the speed), while it is negative for a deceleration (decreasing the speed). It can be measured by an accelerometer. Theoretically, the effect of the accelerating G-force is to increase the weight distributed at the rear wheels, while it decreases the weight distributed at the front wheels (Gillespie, 2014; Popp *et al*., 2010; Garrett *et al*., 2001).

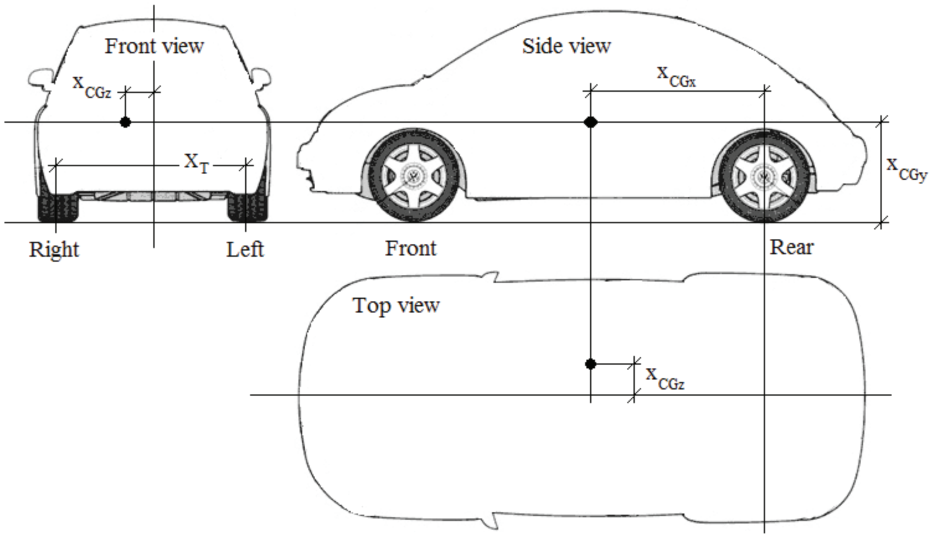

Figure 1. Vehicle distance fraction.

$$f_a = G_a x_{CGy} \tag{3}$$

2.4 Turning factor

The turning factor (f_t) is the effect of the turning G-force (G_t) on the right wheels and the left wheels, as shown in Equation 4. For this paper, the turning G-force is defined as being positive for left-turning, while it is defined as being negative for right-turning. Theoretically, when turning left, the effect of the turning G-force increases the weight distributed to the right wheels, while it decreases the weight distributed to the left wheels.

$$f_t = G_t \left(\frac{x_{CGy}}{x_T}\right) \tag{4}$$

3. Vehicle parameter identification

The application of this concept must be initiated by identifying the vehicle parameters that are all the CG fractions in x-, y-, and z-axis and the wheel track fraction. There are two steps to determine the CG fractions that must be done in a laboratory or a workshop. Firstly, the vehicle weight at each wheel is measured on flat ground. The CGx fraction (x_{CGx}) is calculated from the weight distributed to the front wheels (right and left) (R_F) and the total weight (the summary of four wheels) (W), as shown in Equation 5. The CGz fraction (x_{CGz}) is calculated from the weight distributed to the right wheels (front and rear) (R_R), the total weight (W), and the wheel track fraction (ratio of the wheel track and the wheelbase) (x_T), as shown in Equation 6.

$$x_{CGx} = \frac{R_F}{W} \tag{5}$$

$$x_{CGz} = x_T \left(\frac{R_R}{W} - \frac{1}{2}\right) \tag{6}$$

Secondly, the scales for measuring the weight at the rear wheels (right and left) are lifted up equally, and then the weight distributed to the front wheels is re-measured (R_F^*). The CGy fraction (x_{CGy}) can be determined from the wheel radius (r_w), the wheelbase (wb), and the lift (h), as shown in Equations 7 and 8.

$$x_{CGy} = \left(\frac{r_w}{wb}\right) + \left(\frac{R_F^*}{W} - x_{CGx}\right) \cot\beta \tag{7}$$

$$\beta = \operatorname{asin}\left(\frac{h}{wb}\right) \tag{8}$$

These are the processes to identifying all GC position fractions. The only parameter that affects the CG position is the wheel radius. In the case that the wheels are changed (tire, rim, or both), the measurement must be redone. Another vehicle parameter needed for the analysis is the wheel track fraction, which can be simply calculated from the wheel track and the wheelbase. These values can be from the vehicle specification or measurement.

4. Case study

This article provides a case study that illustrates the application of the concept. The information of the case is shown in Table 3. In this case, the slope angle and the incline angle were specified as zero (non-slope and non-incline); however, in real-time use, they are measured by a bi-axial inclinometer (one axial for the slope angle and another axial for the incline angle).

Table 3. Case study.

Vehicle parameters			
CG_x fraction	0.40	CG_z fraction	0.05
CG_y fraction	0.20	Wheel track fraction	0.60
Road parameter			
Slope angle	0 degree	Incline angle	0 degree

The calculation processes can be simply done via spreadsheet software, such as Microsoft Excel, for one-position analysis, as shown in Figure 2. For multiple-position analysis to cover a range of accelerating G-forces and turning G-forces, it is more appropriate to calculate via mathematical software, such as SCILAB. The results are shown in Figure 3. The source code for SCILAB is also provided in the appendix.

Based on the vehicle parameters and the road parameters in Table 3, for the case where the accelerating G-force is 0.20 and the turning G-force is 0.20, the weight distributed to each wheel can be determined. There would be 12.60% and 23.40% of the vehicle weight distributed to the front-left wheel and the front-right wheel, respectively. The summary of the weight distributed to the front wheels is found to be 36.00% of the total weight. There would be 22.40% and 41.60% of the vehicle weight distributed to the rear-left wheel and the rear-right wheel, respectively. The summary of the weight distributed to the rear wheels is found to be 64.00%. The summary of the weight distributed to the left wheels and the right wheels would be 35.00% and 65.00%, respectively. The vehicle weight distribution for other values of the accelerating G-force and the turning G-force can be determine from the graph in Figure 3. In real-time use, these G-forces are measured by a bi-axial accelerometer (one axial for the accelerating G-force and another axial for the turning G-force).

Vehicle parameters	
CGx fraction	0.40
Cgy fraction	0.20
CGz fraction	0.05
Track fraction	0.60

Road parameters	
Slope angle (degree)	0.00
Incline angle (degree)	0.00

Dynamic parameters	
Accelerating G-force	0.20
Turning G-force	0.20

Calculation	
Front wheel factor	0.40
Right wheel factor	0.58
Accelerating factor	0.04
Turning factor	0.07

	Left	Right	Total
Front	12.60%	23.40%	36.00%
Rear	22.40%	41.60%	64.00%
Total	35.00%	65.00%	100.00%

Figure 2. Analysis via Microsoft Excel.

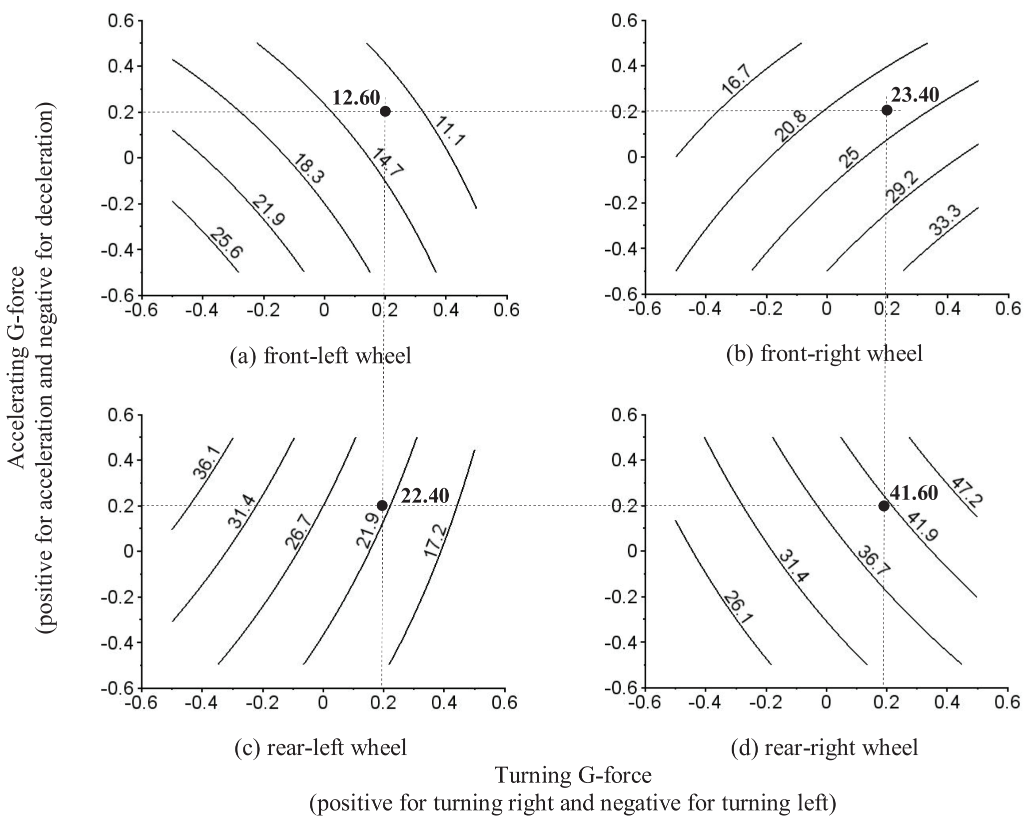

Figure 3: Vehicle weight distribution (via SCILAB)

The vehicle weight distributed to each wheel can be used as the input signals to the SCU for the calculation, then the SCU will send the predictive signal to control the adjustable suspension part. Figure 4 presents a diagram of the predictive control system. The bi-axial inclinometer is for measuring the slope and the incline angles, and the bi-axial accelerometer is for measuring the accelerating and a turning G-force. Both sensors can be installed separately or included with the SCU. Four input signal are sent to the SCU for the calculation, then the four output signals are used to control the adjustable suspension parts at each wheel. The advantages of this system are using a predictive signal to pre-adjust the suspension, using simple and inexpensive sensors, and easy installation.

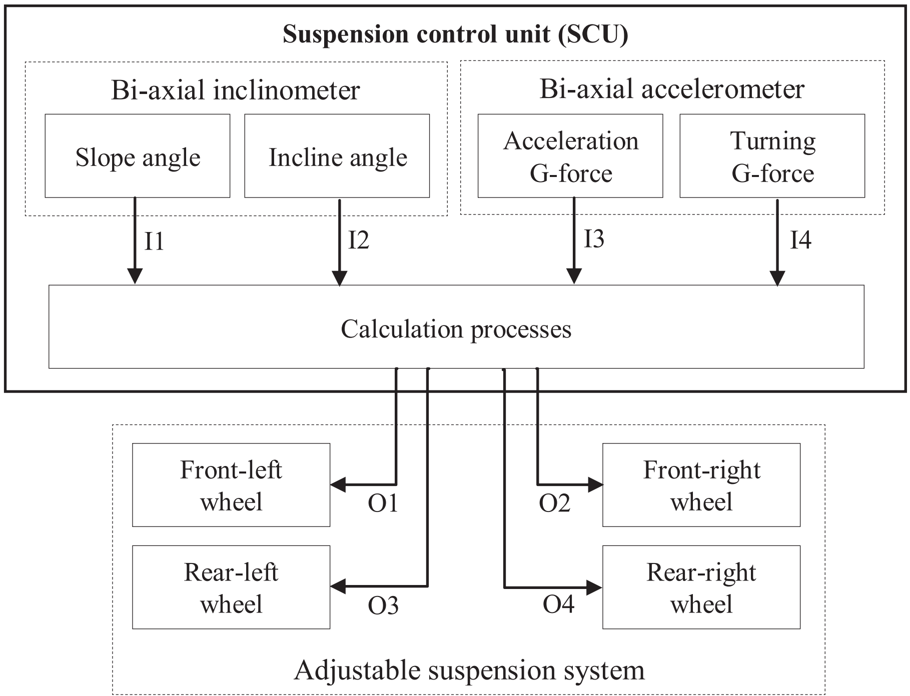

Figure 4. Predictive suspension control diagram.

5. Conclusion

The conceptual idea of a predictive suspension control system was developed for controlling adjustable suspension parts. This system uses two simple sensors, which are a bi-axial inclinometer and a bi-axial accelerometer, for measuring the road parameters and the dynamic parameters, respectively. The road parameter consists of the slop angle and the incline angle, while the dynamic parameters consist of the accelerating G-force and the turning G-force. These sensors can be included with the SCU to avoid the installation problem, installed separately in the cabin area, or by using a sensor in a mobile phone. By using the vehicle weight distribution concept, the weight distributed to each wheel can be determined and used as the output signals for pre-controlling the adjustable suspension parts, such as spring and shock absorber.

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Appendix: SCILAB source code

```
clc; clear
// vehicle weight distribution project by JK
//vehicle parameters
xcgx=0.40//cgx fraction
xcgy=0.20//cgy fraction
xcgz=0.05//cgz fraction
xt=0.60//wheel track fration
//road parameters
slope=0//slope angle(degree)
incline=0//incline angle(degree)
//calculation
gmin=0//minimum g-force(g)
gmax=0.5//maximum g-force(g)
interval=0.1//calculating interval(g)
msize=(gmax-gmin)/interval*2+1//matrix size
frontright=zeros(msize,msize)//front-right wheel matrix
frontleft=zeros(msize,msize)//front-left wheelmmatrix
rearright=zeros(msize,msize)//rear-right wheel matrix
rearleft=zeros(msize,msize)//rear-left wheel matrix
gacc=zeros(msize)
gturn=zeros(msize)
for i=1:msize
gacc(i)=-gmax+(i-1)*interval//accelerating g-force
for j=1:msize
gturn(j)=-gmax+(j-1)*interval//turning g-force
frontfactor=xcgx*cos(slope*%pi/180)-xcgy*sin(slope*%
    pi/180)//front wheel factor   rightfactor=(1/2+xcgz/
    xt)*cos(incline*%pi/180)+xcgyxt*sin(incline*%
    pi/180)//right wheel factor
accfactor=gacc(i)*xcgy//accelerating factor
turnfactor=gturn(j)*xcgy/xt//turning factor
frontleft(j,i)=(frontfactor-accfactor)*(1-rightfactor-turnfac-
    tor)*100//front-left wheel(percentage)
frontright(j,i)=(frontfactor-accfactor)*(rightfactor+turnfa
    ctor)*100//front-right wheel(percentage)
rearleft(j,i)=(1-frontfactor+accfactor)*(1-rightfactor-turn-
    factor)*100//rear-left wheel(percentage)
rearright(j,i)=(1-frontfactor+accfactor)*(rightfactor+turnf
    actor)*100//rear-right wheel(percentage)
end
end
//Ploting the results
scf(0)
subplot(221)//front-left wheel
contour(gturn,gacc,frontleft,5)
xtitle('front-left wheel',' ','accelerating g-force')
subplot(222)//front-right wheel
contour(gturn,gacc,frontright,5)
xtitle('front-right wheel',' ',' ')
subplot(223)//rear-left wheel
contour(gturn,gacc,rearleft,5)
xtitle('rear-left wheel','turning g-force','accelerating g-
force')
subplot(224)//rear-right wheel
contour(gturn,gacc,rearright,5)
xtitle('rear-right wheel','turning g-force',' ')
scf(1)//front-left wheel
contour(gturn,gacc,frontleft,5)
scf(2)//front-right wheel
contour(gturn,gacc,frontright,5)
scf(3)//rear-left wheel
contour(gturn,gacc,rearleft,5)
scf(4)//rear-right wheel
contour(gturn,gacc,rearright,5)
```