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Technology for Measuring the Damping Force of Shock Absorbers and the Constant of Coil Springs Mounted on a Motorcycle by the Un-sprung Mass Vibration Method

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ABSTRACT

Technology for measuring and diagnosing the damping force of motorcycle shock absorbers and determining the constant of coil springs when mounted in-vehicle is difficult. Resultantly, it is clear that only the damping force can be detected by eliminating the spring force effect and the un-sprung mass, when the displacement of the wheel is zero.

INTRODUCTION

The performance of shock absorbers and springs is extremely important for motorcycle driving stability. As a result of deregulation in recent years, the shock absorber damping force and spring constant can now be changed to meet consumer preferences. Because no simple means to measure and diagnose shock absorber damping forces and spring constants were available in the market, it was impossible to (1) monitor shock absorber age deterioration and (2) achieve well balanced hard suspension tuning based on actual measurements. Therefore, an engineering technique was developed to measure and diagnose the damping force of shock absorbers and determining the constant of coil springs for motorcycles when mounted in-vehicle.

VEHICLE- MOUNTED DEVICE THAT ANALYZES SHOCK ABSORBER AND SPRING CONSTANT

MEASURING MECHANISM

(The author had presented about vehicle case's measuring mechanism in JSAE Review 1999)
Deviations in the phase of spring reaction forces and shock absorber reaction forces occur when the vehicle body moves vertically up-and-down. Consequently, as shown in Figure1, at the point where the body displacement of zero is crossed, the spring reaction is zero; thus, by measuring the tire's vertical load per road wheel (vertical reaction) at that point, It was obtained that the characteristic value of the shock absorber itself, excluding the effect of the spring. In short, the spring is proportional to the displacement, while the shock absorber is proportional to the velocity. Therefore, from the figure it is clear that the shock absorber's damping force can be extracted at the point where a displacement of zero is crossed. Also, if the speed of the body's vertical up-and-down motion is changed in stages, output data can be obtained at intervals of 0-0.3m/sec; thus, by drawing a linear approximation of a piecewise linear model, it was obtained through a general damping force characteristic diagram. Accordingly, since the shock absorber damping force can be found for a piston speed of 0.3m/s, the amount of deterioration can easily be evaluated by making a comparison with standard data found in a new vehicle manual or similar reference.

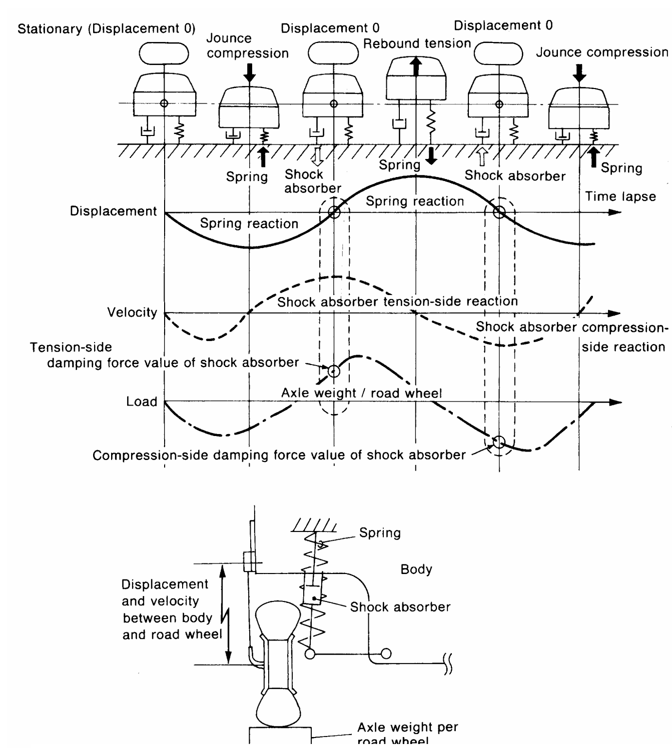

Figure 1 Measuring Mechanism

To eliminate the effect of the tire (tire deflection), the following must be detected:

・Displacement: relative displacement of the body and wheel

・Velocity: relative velocity of the body and wheel

The spring constant can be found from the relative displacement of the vehicle body, and can be found from the tire's vertical load.

VERIFICATION OF ASSUMPTION (CONFIRMATION BY MEAN OF TWO DEGREES –OF-FREEDOM EQUATION OF MOTION)

m_1 : mass of vehicle body (or motorcycle body) (sprung)

m_2 : mass of wheel and suspension (un-sprung)

x_1 : displacement of vehicle body (or motorcycle body) (sprung)

x_2 : displacement of wheel and suspension (un-sprung)

$\dot{x}_1$: velocity of vehicle body (or motorcycle body) (sprung)

$\dot{x}_2$: velocity of wheel and suspension (un-sprung)

$\ddot{x}_1$: acceleration of vehicle body (or motorcycle body) (sprung)

$\ddot{x}_2$: acceleration of wheel and suspension (un-sprung)

c : viscous damping coefficient

k_1 : spring constant

k_2 : tire's longitudinal spring constant

$P_0 \sin \omega t$: cyclic forced external force

To verify the aforementioned assumption, a theoretical check of its validity was conducted by using an equation of motion for a two degrees-of-freedom vehicle vibration model (which included the tires) as shown in Figure 2.

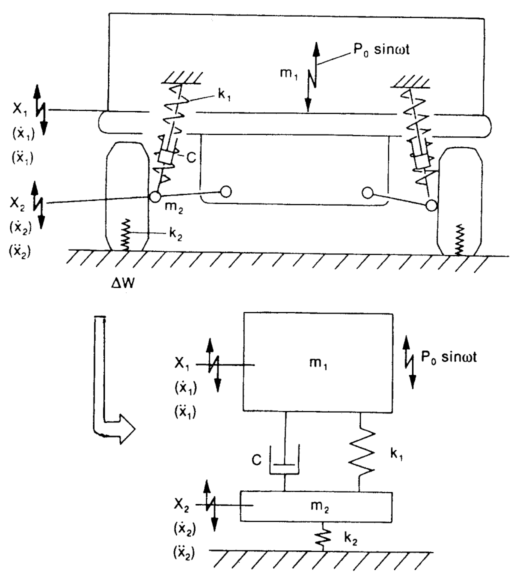

Figure 2 Vibration model of two degree-of-freedom systems on body and wheel

The equation of motion shown below applies when the vehicle body is moved cyclically up and down.

The equation of motion for sprung mass is as follows:

$$m_1\ddot{x}_1 + k_1(x_1 - x_2) + c(\dot{x}_1 - \dot{x}_2) = P_0 \sin \omega t \quad (1)$$

The equation of motion for un-sprung mass becomes:

$$m_2\ddot{x}_2 + k_2 x_2 - k_1(x_1 - x_2) - c(\dot{x}_1 - \dot{x}_2) = 0 \quad (2)$$

The fluctuation of the tire's vertical load/ fluctuating axle weight per wheel is expressed as

$$\Delta W = k_2 x_2 \quad (3)$$

Substituting equation(3) into equation(2)(the equation of motion for un-sprung mass), I obtain

$$m_2\ddot{x}_2 + \Delta W - k_1(x_1 - x_2) - c(\dot{x}_1 - \dot{x}_2) = 0$$

Transforming this equation, I obtain

$$m_2\ddot{x}_2 + \Delta W = k_1(x_1 - x_2) + c(\dot{x}_1 - \dot{x}_2) \quad (4)$$

Next, the natural frequency for un-sprung mass f_2, which is expressed as $\sqrt{k_2/m_2}/2\pi$, greatly differs from the natural frequency for sprung mass f_1, which is expressed as $\sqrt{k_1/m_1}/2\pi$, because $m_2 > m_1$ and $k_2 > k_1$. In fact, $f_2 > f_1$(in general, f_1 is 1-2 Hz, and f_2 is 12-17 Hz)

In short, the un-sprung inertia term $m_2\ddot{x}_2$ in equation(4) can be disregarded in relatively low-frequency excitation states such as when the vehicle body is subjected to up-and–down motion by hand. Specifically, the vibration width of the wheel is about 5mm. The inertia under the spring is about 10N, considerably smaller than the attenuation value. equation(4) thus becomes:

$$\Delta W = k_1(x_1 - x_2) + c(\dot{x}_1 - \dot{x}_2) \quad (5)$$

However, if an external force is applied cyclically and artificially, equation(5) becomes the following at the point where the relative displacement $(x_1 - x_2)$ between sprung mass m_1 and un-sprung mass m_2 become 0:

$$\Delta W = c(\dot{x}_1 - \dot{x}_2) \quad (6)$$

In other words, the shock absorber's damping force $c(\dot{x}_1 - \dot{x}_2)$ can be determined by measuring the vertical load fluctuation ΔW at the point where the relative displacement between the vehicle body and wheel crosses zero when the body is subjected to an artificial external force or a similar low frequency mechanical external force. The tension side damping force is determined as the body moves upward from the downward side and crosses a relative displacement of zero. Conversely, the compression side damping force is determined as the body moves downward from the upward side and crosses a relative displacement of zero. The shock absorber's damping force $c(\dot{x}_1 - \dot{x}_2)$, on the other hand, varies nonlinearly in relation to the relative velocity $(\dot{x}_1 - \dot{x}_2)$ of the vehicle body and wheel; thus, the shock absorber's damping force at different piston speeds can be determined by making slight changes in the vibration amplitude and frequency.

MOTORCYCLE MOUNTED DEVICE THAT ANALYZES SHOCK ABSORBER AND SPRING CONSTANT

An engineering technique was developed to measure and diagnose the damping force of shock absorbers and the constant of coil springs for motorcycles, when the shock absorbers and coil springs are mounted on a motorcycle. As motorcycle is hard to vibrate sprung mass because motorcycle body will be fallen easily, it is found that effects of the un-sprung mass's inertia can be eliminated by the un-sprung mass vibration methods. And the study is clarified about separated measuring of damping force by which parameter measuring.

CONFIRMATION BY MEAN OF TWO DEGREE-OF-FREEDOM EQUATION OF MOTION AT FREED SPRUNG MASS

Initially, simulation calculation with two degree-of-freedom equation at freed sprung mass has been tried. (Figure 3)

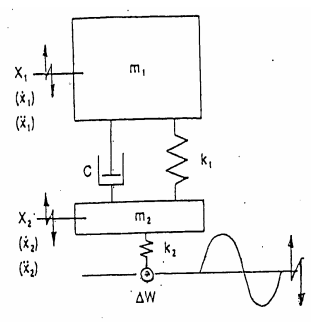

Figure 3 Vibration model of two degree-of-freedom system on body and wheel

When same vibration stroke $(\pm a)$ applied from initial situation to floor point up-and-down direction, the equation of motion is as follows. The equation of motion for sprung mass is as follows:

$$m_1\ddot{x}_1 + k_1(x_1 - x_2) + c(\dot{x}_1 - \dot{x}_2) = 0 \qquad (7)$$

The equation of motion for un-sprung mass becomes:

$$m_2\ddot{x}_2 + k_2 x_2 - k_1(x_1 - x_2) - c(\dot{x}_1 - \dot{x}_2) = k_2 a \cdot \sin\omega t \qquad (8)$$

Equation(8) becomes the following.

$$m_2\ddot{x}_2 + k_2(x_2 - a\cdot\sin\omega t) - k_1(x_1 - x_2) - c(\dot{x}_1 - \dot{x}_2) = 0 \qquad (9)$$

The fluctuation of the tire's vertical load/ fluctuating axle weight per wheel is expressed as

$$\Delta W = k_2(x_2 - a\cdot\sin\omega t) \qquad (10)$$

Substituting equation(10) into equation(9)(the equation of motion for un-sprung mass), I obtain

$$\Delta W = k_1(x_1 - x_2) + c(\dot{x}_1 - \dot{x}_2) - m_2\ddot{x}_2 \qquad (11)$$

Equation (11) becomes the following at the point where the relative displacement $(x_1 - x_2)$ between sprung mass m_1 and un-sprung mass m_2 becomes 0.

$$\Delta W = c(\dot{x}_1 - \dot{x}_2) - m_2\ddot{x}_2 \qquad (12)$$

The shock absorber's damping force $c(\dot{x}_1 - \dot{x}_2)$ becomes the following at the point where the relative displacement $(x_1 - x_2)$ between sprung mass m_1 and un-sprung mass m_2 becomes 0.

$$c(\dot{x}_1 - \dot{x}_2) = \underbrace{\Delta W}_{①} + \underbrace{m_2\ddot{x}_2}_{②} \qquad (13)$$

Accordingly, it's represent that the shock absorber's damping force becomes total value of

① .the tire's vertical load/fluctuating axle weight per wheel, and

②.applied force of un-sprung mass's inertia.

at the point relative displacement zero between body and wheels.

Accordingly, it's found that the shock absorber's damping force can't measure by un-sprung mass's vibration at freed sprung mass, if both ①item and ②item aren't measured. At the next, simulation of two degree-of- freedom model has been performed, and the effect of un-sprung mass's inertia has been clarified. The equation of motion solves by the method of Runge-Kutta-Gill. The value of the parameter applied following;

The frequency of vibration; 2Hz

The stroke of vibration; ±25mm

(These values simulated at the case of the actual device.)

m_1 =(the tire's vertical load/fluctuating axle weight per wheel;400N)/(acceleration of gravitation; 9.8m/sec^2) =408kg

m_2 =(un-sprung mass's weight per wheel; 200N) /(acceleration of gravitation; 9.8 m/sec^2) =20.4kg

k_1 =20kN/mm

k_2 =200kN/mm

c =(Tension side damping force; 0.5kN+Compression side damping force; 0.5kN)/(0.3m/s) =3.33kN·s/m

This result becomes Figure 4 and Figure 5.

Figure 4 is represented that trajectory of on acceleration of un-sprung mass $(\ddot{x}_2)$ ~ relative displacement $(x_1 - x_2)$ plane.

Figure 5 is represented that the result of calculation by time lapse. Accordingly, as the up-and-down acceleration of un-sprung mass is passed at the point A or the point B that is across at the point relative displacement zero between body and wheels, it will be recognized that the un-sprung mass's inertia can not ignore. Consequently, at zero body and wheel displacement, it will be recognized the un-sprung mass's inertia approximately ±41N will be added to the tire's vertical load per road wheel (Figure 4,Figure 5).

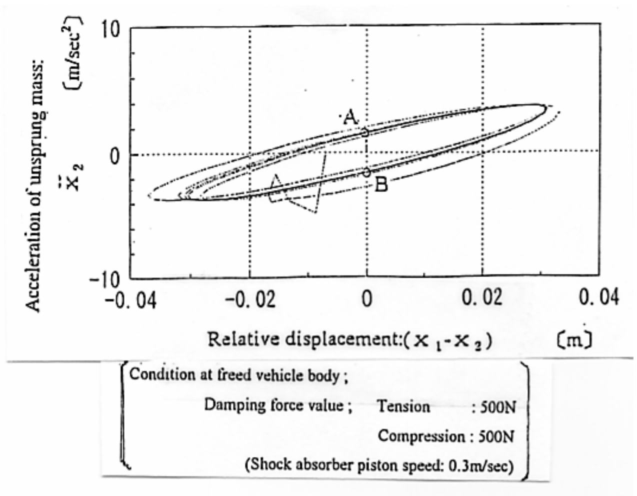

Figure 4 Trajectory on acceleration of un-sprung mass: $\ddot{x}_2$ - relative displacement: $(x_1 - x_2)$ plane

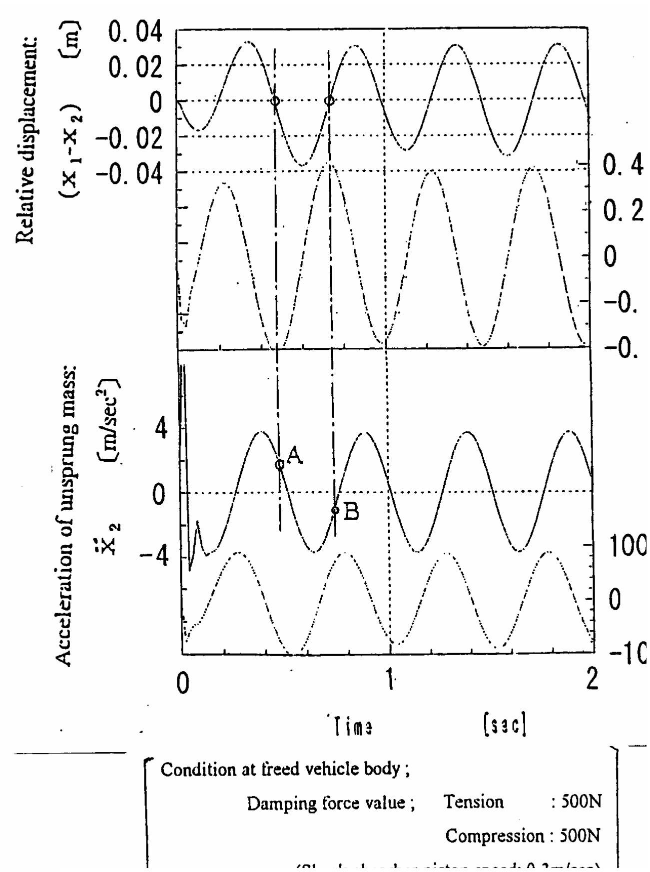

Figure 5 Result of calculation (Time lapse)

CONFIRMATION BY MEAN OF ONE DEGREE-OF-FREEDOM EQUATION OF MOTION AT FIXED SPRUNG MASS

At the next step, simulation of calculation at fixed sprung mass has been tried. (Figure 6)

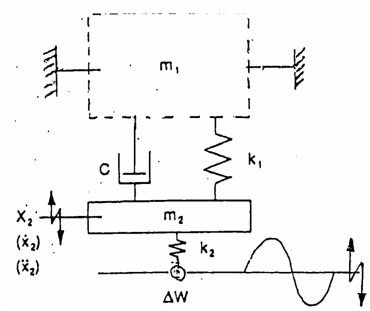

Figure 6 Vibration model of two degree-of-freedom systems

Though it's represent that freed sprung mass's vibration case have to measure not only ①(load transfer value of wheel's fluctuation) but also ②(force of un-sprung mass). The equation of motion at fixed un-sprung mass is able to pick up by replace $x_1 = 0_1$, $\dot{x}_1 = 0_1$, $\ddot{x}_1 = 0_1$ at equation(8) of motion for un-sprung mass at before item. The equation of motion for un-sprung mass becomes:

$$m_2\ddot{x}_2 + k_2 x_2 - k_1(-x_2) - c(-\dot{x}_2) = k_2 a \cdot \sin \omega t \tag{14}$$

Equation(14) becomes the following.

$$m_2\ddot{x}_2 + k_2(x_2 - a \cdot \sin \omega t) - k_1(-x_2) - c(-\dot{x}_2) = 0 \tag{15}$$

The fluctuation of the tire's vertical load/ fluctuating axle weight per wheel is expressed as

$$\Delta W = k_2(x_2 - a \cdot \sin \omega t) \tag{16}$$

Substituting equation(16) into equation(15)(the equation of motion for un-sprung mass), I obtain

$$\Delta W = k_1(-x_2) + c(-\dot{x}_2) - m_2\ddot{x}_2 \tag{17}$$

It is recognized that x_2 and $\ddot{x}_2$ become 0 at the point where the un-sprung mass's displacement (x_2) across 0 (initial situation), when external vibration at the $\pm a$ amplitude apply at the tire contact point.

$$\Delta W = c(-\dot{x}_2) \tag{18}$$

Therefore,

It is recognized that simulation of one degree-of freedom has been tried. Simulation of one degree-of freedom model (Figure 6) is performed, above assumption was clarified. The value of parameter is equal to before item's case. (The stroke of vibration is ±30mm at this case.) The results of simulation become to Figure 7 and Figure 8. As un-sprung mass's displacement (x_2) is linear, it is recognized that x_2 and $\ddot{x}_2$ become 0 at the point where the un-sprung mass's displacement (x_2) across middle point of vibration stroke (initial situation). It cleared that measuring method can be obtained without the effect of un-sprung mass's inertia, because un-sprung mass's inertia will be obtained using one degree-of-freedom vibration, at the body is fixed, and because up-and-down acceleration of wheels approach to zero, when same vibration stroke applied from initial situation to floor point up-and-down direction. Consequently, at the point relative displacement zero between body and wheels, damping force will be obtained by eliminating the effect of spring reaction and un-sprung inertia (Figure 7, Figure 8). This result is equal to the case of applying the non-linear shock absorber damping force (ex; tension side is not equal to compression side. Figure 9, Figure 10)

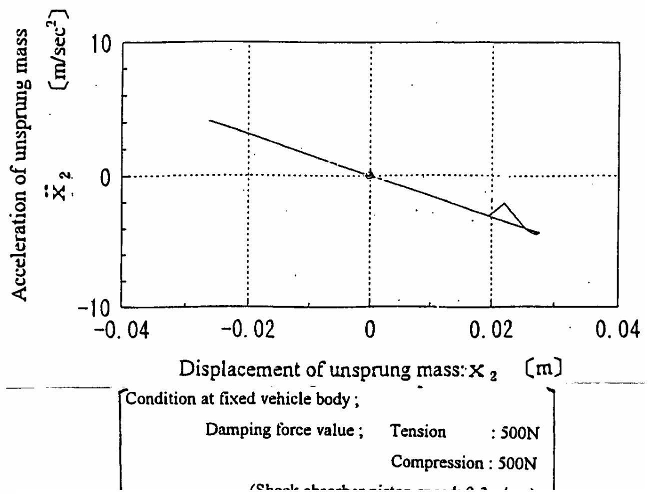

Figure 7 Trajectory on acceleration of un-sprung mass: $\ddot{x}_2$ - displacement of un-sprung mass: x_2 plane

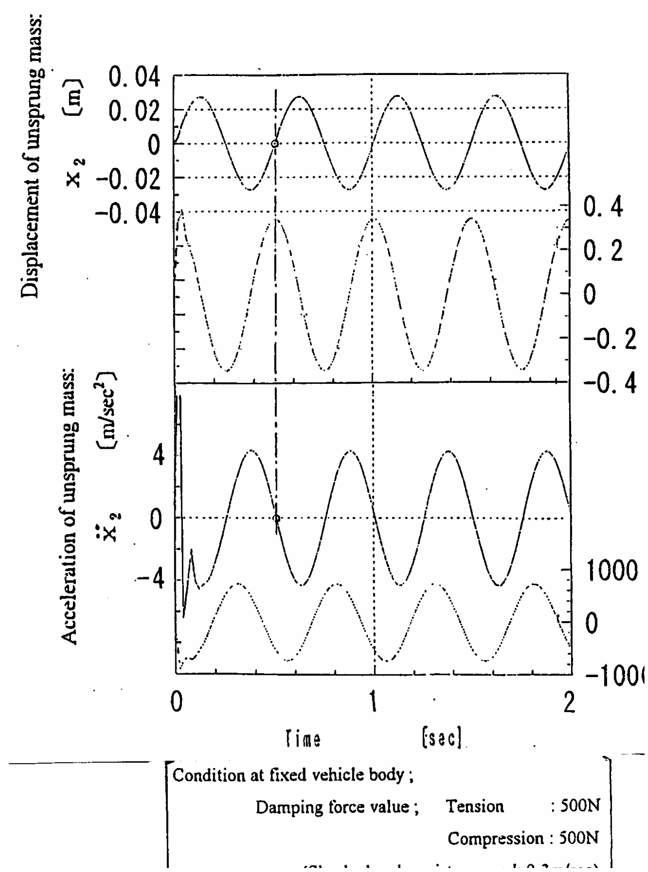

Figure 8 Result of calculation (Time lapse)

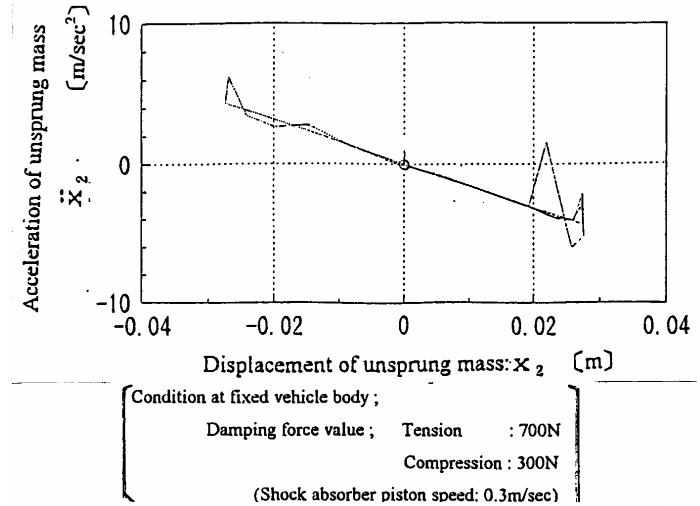

Figure 9 Trajectory on acceleration of un-sprung mass: $\ddot{x}_2$ - displacement of un-sprung mass: x_2 plane

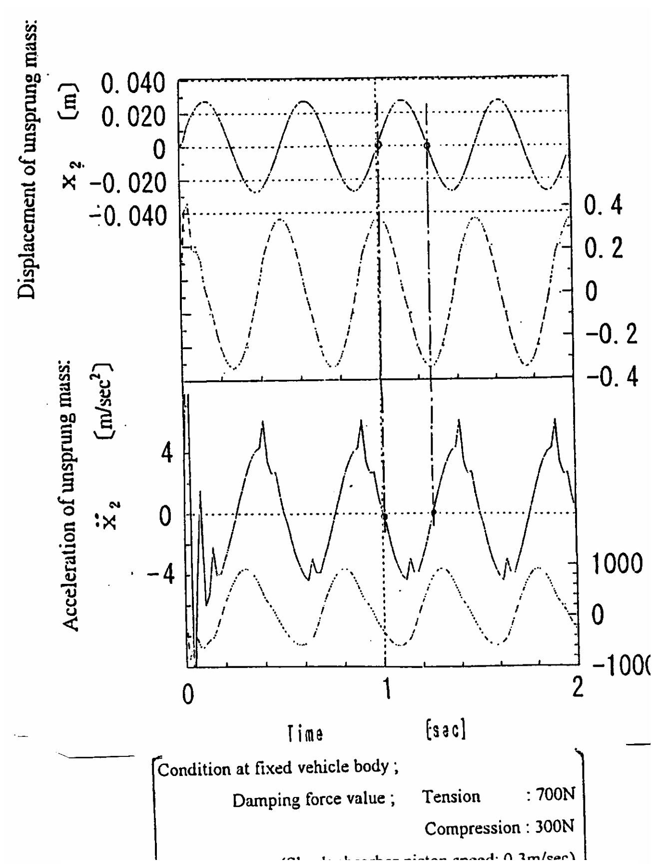

Figure 10 Result of calculation (Time lapse)

VERIFYING WITH A TESTER

Based on the aforementioned assumptions, these simulation results, motorcycle's testing device was built to verify by un-sprung mass vibration's method (Figure 11,Figure 12).

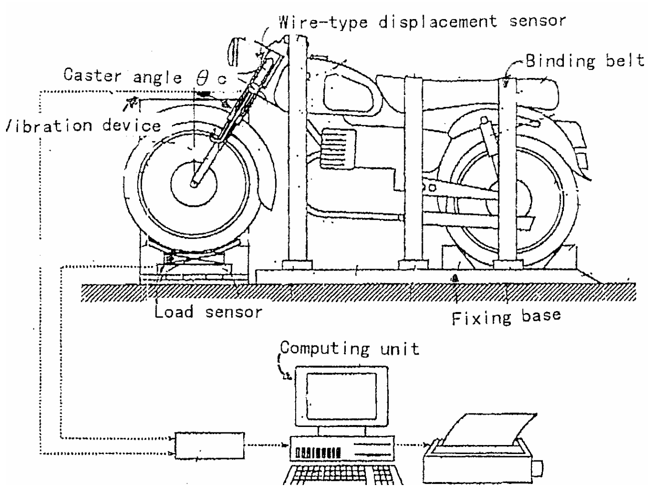

Figure 11 Test equipment

As caster angle of motorcycle is large, it is transferred that tire's vertical load per road wheel to weight transfer of caster angle's direction.

Weight transfer of caster angle's direction

$$(\Delta W_{CAS}) = \Delta W / \cos\theta_c \qquad (12)$$

As caster angle is large, road wheel is slide tendency back and forth, this system equipped slide mechanism at load sensor (Figure 13). Road wheel is vibrated by air vibration device (Figure 14).

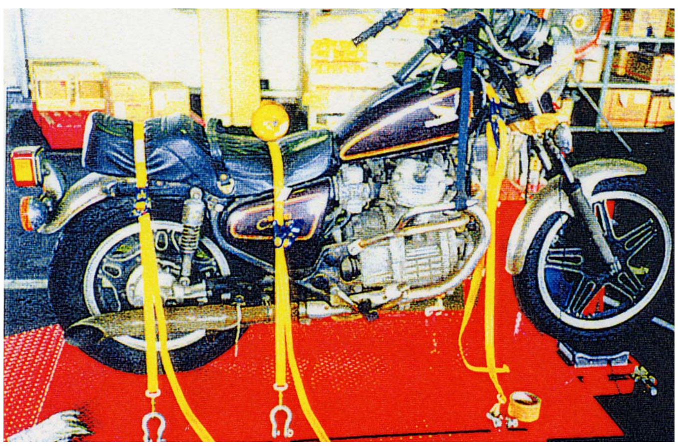
Figure 12 Placement our test equipment

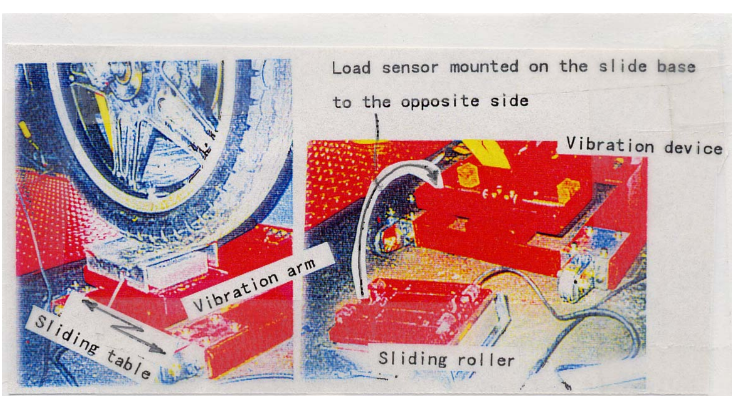

Figure 13 Sliding mechanism of before and after

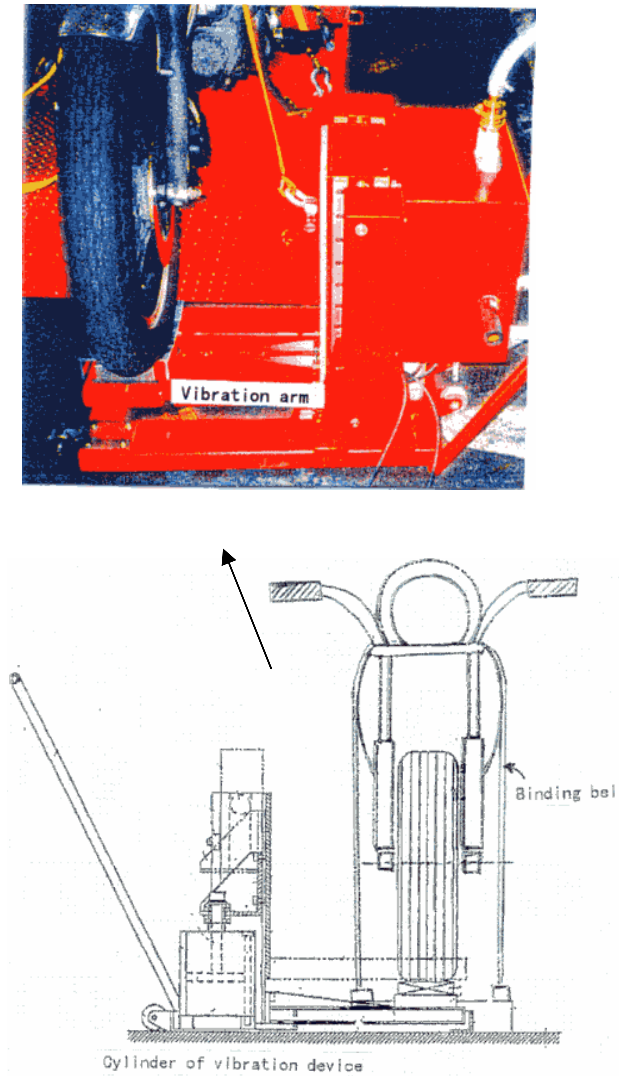

Figure 14 Set situation of vibration device

At the test device, motorcycle is fixed at fixing base by binding belt (Figure 12). And the initial situation is little raising tire contact point. At this point, it is applied same vibration stroke applied from initial situation to floor point up-and-down direction. And the wheel's displacement has been measured by the relative displacement between body and wheels, because of decrease the very small vehicle effect of body's up and down negligible stroke. The spring constant can be found from the relative displacement of the vehicle body, and can be found from the tire's vertical load. A motorcycle was mounted onto the load detector, and about 10 up-and-down motions were applied to the body, gradually increasing in severity from gentle rocking to strong rocking. During this time, the computing unit executed the aforementioned arithmetic processing, and the result of the computation was printed out (Figure 15, Table1). A device has been developed that can separate and measure individual characteristics while attached to the motorcycle body.

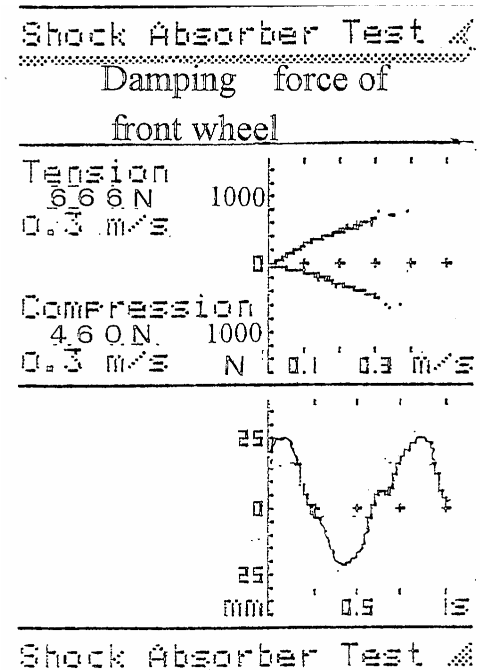

Figure 15 Example of print out

Table 1 Comparison between specific data and measuring value

	Damping force value (N)		Spring constant (N/mm)
	Tension	Compre-ssion	
Spec. data	647	451	15
Measuring value by our test equip-ment	666	460	14

(Shock absorber piston speed:0.3m/sec)

(Total value of right and left shock absorber and spring)

(Example of front wheel)

CONCLUSION

An engineering technique was developed to measure and diagnose the damping force of shock absorbers and the constant of coil springs for motorcycle when mounted on a motorcycle. As a result, the following conclusions were reached.

(1) It was determined that the measuring method can be obtained without the effect of un-sprung mass's inertia, because un-sprung mass's inertia will be obtained using one degree-of-freedom vibration, as the body is fixed, and because the up-and-down acceleration of wheels approach zero, when the same vibration stroke applied from initial situation to floor point up-and-down direction. Consequently, at the point relative displacement is zero between the body and wheels, damping force will be obtained by eliminating the effect of the spring reaction and un-sprung inertia.

(2) As caster angle of motorcycle is large, it is transferred to the tire's vertical load per road wheel to weight transfer of caster angle's direction. As caster angle is large, road wheel is slide tendency back and forth, this system equipped slide mechanism at load sensor. Consequently, it was determined that the measuring method can be obtained without the effect of caster angle.

ACKNOWLEDGMENTS

It was studied that technology for measuring and diagnosing the damping force of shock absorbers and the constant of coil springs independently without removing them from the motorcycle. In closing, it was expressed sincere appreciation to the people at Nissan Altia co.,ltd who cooperated during research.

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