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Research on rapid measurement of medium short wave longitudinal road profiles

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***Abstract*—The longitudinal profile of a road causes vehicle vibration and thus an important parameter in research on the ride comfort and durability of vehicles. However, large-scale measured profiles of actual roads remain unavailable owing to technical measurement difficulties. We report a vehicle-mounted system for measuring short- to medium-wave road profiles in a broad frequency range. In this system, the longitudinal displacement of the vehicle is measured by incrementally revolving encoder, the vehicle attitude is measured by a gyroscope, and the vertical displacement is measured by laser displacement sensors in conjunction with dual accelerometers. An algorithm was designed to reconstruct road profiles on the basis of the double integral of acceleration with respect to time and vehicle attitude compensation, and used for the rapid measurement of short- to medium-wave longitudinal road profiles. The accuracy of the road profiles measured using this system were confirmed by comparison with results obtained using a precision level and a static laser scale. The proposed system can accurately and rapidly measure road profiles at a large-scale, and thus provide important information in vehicle-related research.**

Keywords- road profile, road spectrum, measurement vehilce, road load spectrum, road roughness

I. INTRODUCTION

The longitudinal profile of a road causes vehicle vibration and is a major factor in determining vehicle performances such as ride comfort and structural durability and fatigue. However, large-scale profiles of actual roads remain unavailable owing to technical measurement difficulties. Consequently, a large number of vehicle studies have been based on simulated road profiles.

Traditionally, road profiles were manually measured with instruments such as levels and 3 m rulers, and the road surface roughness, curves and power spectra were subsequently calculated. Although precise, the traditional method is inefficient and thus cannot be used to measure or survey road profiles on a large scale. In addition, and the method cannot be used to precisely measure centimeter-scale short-wavelength road profiles. Over the past three decades, instruments that are more efficient and automated have been developed for the measurement of road profiles. Examples are multi-wheel contact road profilometers such as the 8-wheel and 16-wheel profilometers. Although these new instruments increased measurement efficiency, the nature of their contact measurement limits the wavelength range in which they can be applied.

Laser sensor technology is developing rapidly and increasingly used in various areas of research. With the help of static laser scales and three-dimensional laser stereoscanners, road profiles can be precisely measured at centimeter and even millimeter levels. However, because these sensors are only suitable for static measurements, their efficiency is very low. Recently, vehicle-mounted rapid laser measurement systems have been developed [1,2]. However, because these systems were designed primarily to meet the needs of the road industry, the measured parameters mostly relate to the international roughness index,texture depth and surface texture, and usually the road profile is not output[3]. Additionally, the spatial frequency range of the road surface measured by these systems does not meet the requirements of the testing of vehicle performance.

This paper report a vehicle-mounted system developed for the large-scale measurement of longitudinal road profiles and for research relating to vehicle performances such as ride comfort, vehicle endurance and driving noise. In this system, the vertical displacement of a vehicle is measured in a broad vibration frequency range by dual accelerometers in conjunction with laser sensors, the longitudinal displacement is measured by incrementally revolving encoder, and the vehicle attitude is measured by a gyroscope to compensate the computation of the road profile. To meet the broad frequency range required in vehicle testing, the system was designed to efficiently measure medium- to short-wave longitudinal road profiles during high-speed movement.

II. DEVELOPMENT OF THE ROAD PROFILE MEASUREMENT SYSTEM

The major difference between road profile measurement systems designed for the road industry and those designed for the vehicle industry is the target spatial frequency range. Standards and research works have revealed that investigation of ride comfort, vehicle endurance, and road noise requires measurement of the spatial wavelength in the range from 0.01 to 100 m[4–6]. In this wavelength range, the long-wavelength (3–5 m or above) road profiles can be readily measured using a high-precision gyroscope or a differential global positioning system (D-GPS), whereas the accurate measurement of the short- to medium-wavelength (0.01m to several meters) profiles presents a major difficulty.

This system includes laser displacement sensors, accelerometers, and incrementally revolving encoder to measure the road profile. A gyro was used to measure the

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vehicle's attitude for compensation in the road profile computation. The system also includes a GPS measurement subsystem and a road-surface video capturing subsystem to collect supplementary information of the road surface. The laser sensors, accelerometer array, and gyroscope were placed in a laser bar installed in front of the vehicle, the GPS measurement system was placed on top of the vehicle, and the video cameras were installed in front of and behind the vehicle to capture video of the road surface in front of and behind the vehicle.

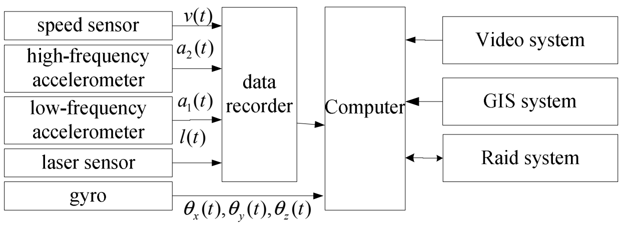

Figure 1 Schematic diagram of the measurement system

The structure of the signal collection system is shown in Fig. 1. According to the required spatial wavelength range, SLS 5000 laser sensors were selected for the measurement of displacement. The sensors had a sampling rate of 16 kHz, a measurement range of 20–40 cm, and a sampling interval of less than 3 mm at a vehicle speed of 30 m/s. The accelerometer array consisted of a low-frequency accelerometer A1 (0–150 Hz, SRJ-1) and a high-frequency accelerometer A2 (1 Hz–10 kHz, PCB 352C33), this combination extended the measurement range to 0–10 kHz. The vehicle attitude was measured by an attitude and heading reference system three-axis gyroscope, which provided (root mean square) precision of 0.4 degrees to the dynamic measurement of the vehicle pitch angle and roll angle. The vehicle speed pulses were recorded by an Omron photoelectric encoder (2048 pulses per cycle). The measurement vehicle is shown in Fig. 2.

Figure 2 The measurement vehicle

III. RECONSTRUCTION OF THE SHORT- TO MEDIUM-WAVE ROAD PROFILE BY INTEGRATION AND VEHICLE ATTITUDE COMPENSATION

The medium- to short-wavelength road profiles were reconstructed by integration using data from the laser displacement sensors and the dual accelerometers, and with compensation for the vehicle attitude (Fig. 3). The target road profile is expressed by the vertical distance between each point on the road surface and an imaginary longitudinal baseline. This vertical distance, h(t), can be calculated from the vertical vibrational displacement, d(t), and the distance measured by the laser displacement sensors, l(t). Additionally, because the data measured with this vehicle-mounted system were affected by the vehicle attitude (pitch and roll), the pitch angle and θx(t) and roll angle θy(t) were measured by the gyroscope and used to compensate the determination of the vertical distance.

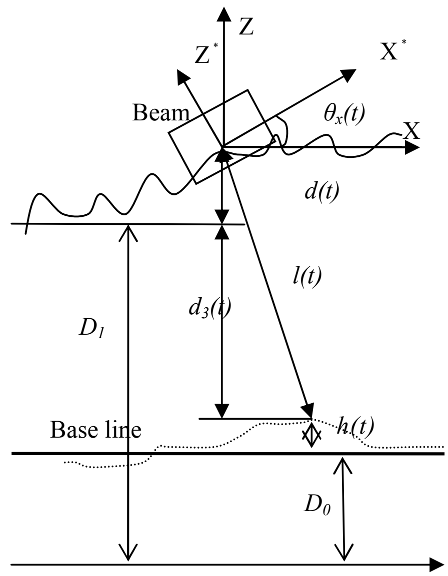

Figure 3 Principle of the measurement of the road profile

From Fig. 3, it is clear that

$$h(t) = D_1 - D_0 - d_3(t) \tag{1}$$

where D_1 is the initial height of the accelerometer sensor and D_0 is the height of the baseline. These values are both constants and thus do not affect the spectral analysis of the road profile. $d_3(t)$ is the vertical distance between the starting height of the laser bar and the road surface at time t and can be calculated using

$$d_3(t) = l'(t) - d(t) \tag{2}$$

where $l'(t)$ is the vertical projection of the distance measured by the laser displacement sensor, $l(t)$, and $d(t)$ is the vertical displacement measured by the accelerometer during the vehicle motion. Furthermore, for a given vehicle attitude,

$$l'(t) = l(t)\cos\theta_x(t)\cos\theta_y(t) \tag{3}$$

where $\theta_x(t)$ is the pitch angle and $\theta_y(t)$ is the roll angle.

$$d(t) = \int_0^t \int_0^t a(\tau)\, d\tau d\tau \tag{4}$$

The acceleration is detected by a low-frequency accelerometer A1 in conjunction with a high-frequency accelerometer A2. The signal from A1 is band-pass filtered between f_0 and f_1 to give $a_1(t)$; similarly, the signal from A2 is band-pass filtered between f_1 and f_2 to give $a_2(t)$:

$$\begin{aligned} a_1(t) &= a(t),[f_0, f_1] \\ a_2(t) &= a(t),[f_1, f_2] \end{aligned} \tag{5}$$

Integrating $a_1(t)$ and $a_2(t)$ gives

$$d_1(t) = \int_0^t \int_0^t a_1(\tau)\, d\tau d\tau$$
$$d_2(t) = \int_0^t \int_0^t a_2(\tau)\, d\tau d\tau \qquad \textbf{(6)}$$

Define $l_1^{'}(t)$ as the laser signal band-pass filtered between f_0 and f_1, and $l_2^{'}(t)$ as the laser signal filtered between f_1 and f_2:

$$l_1'(t) = l(t)\cos\theta_x(t)\cos\theta_y(t), [f_0, f_1]$$
$$l_2'(t) = l(t)\cos\theta_x(t)\cos\theta_y(t), [f_1, f_2] \qquad (7)$$

According to the requirement of the road profile spectrum, f_0 is set at 0.1 Hz, f_1 at 3 Hz, and f_2 at 3 kHz.

$$d_3(t) = [l_1'(t) - \int_0^t \int_0^t a_1(\tau)\, d\tau d\tau] + [l_2'(t) - \int_0^t \int_0^t a_2(\tau)\, d\tau d\tau] \qquad (8)$$

The road profile can then be reconstructed by combining eqs. (1) and (8):

$$h(t) = D_1 - D_0 - l_1'(t) + \int_0^t \int_0^t a_1(\tau)\, d\tau d\tau] - l_2'(t) + \int_0^t \int_0^t a_2(\tau)\, d\tau d\tau \qquad (9)$$

Equation (9) shows that the road profile can be determined from the distance signal from the laser sensor, the acceleration signal from the accelerometer, and the attitude signal from the gyroscope. Thus, the short- to medium-wavelength road profiles can be measured.

IV. EXPERIMENTAL VALIDATION OF MEASURED ROAD PROFILES

It is difficult to directly validate short-wave road profiles measured by the measurement vehicle for technical reasons. Although the road profile can be accurately determined using instruments such as static laser scales, under our experimental conditions, it is impractical to control the driving path of the measurement vehicle so that it is identical to the path scanned by the laser scale. Therefore, the road profile can't be validated by direct shape comparisons. However, because profiles measured using the two techniques are both spatially closed random curves, their statistical and spectral characteristics can be compared.

In the spectral comparison of such random signals, the random error associated with the spectral estimation of a single sample was as high as 100%. Therefore, the smoothed periodogram method was used to reduce the random error in the estimation. In this method, L subsamples of identical length $h(t)$ were selected and windowed, the amplitude spectrum of each segment was calculated, and then all segments were averaged. The process can be expressed as

$$H(f) = \int_0^T h(t) e^{-j2\pi ft} dt \qquad (10)$$

Hanning windows with window lengths of 9 were used:

$$w(k) = 0.5 - 0.5 * \cos(2\pi k / 10) \qquad k = 1...9 \qquad (11)$$

Each segment was windowed:

$$\bar{H}(K) = H(K) * W(K) \qquad (12)$$

Segments were averaged:

$$\hat{\bar{H}}(K) = \frac{1}{L} \bar{H}(K) \qquad (13)$$

The spectrum of the profile measured by the measurement vehicle was analyzed and compared with the spectrum of the more accurate road profile measured using the static laser scale.

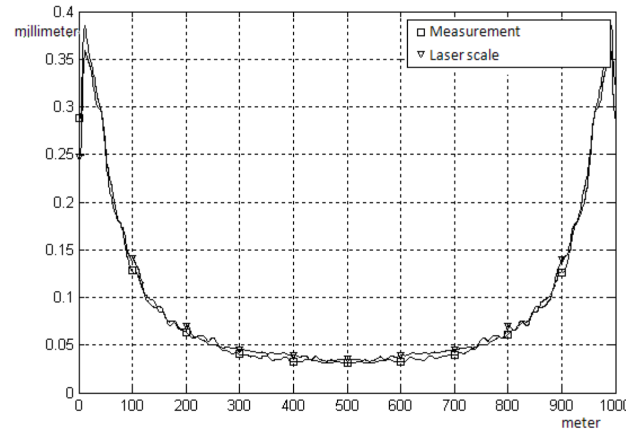

Figure 4 Comparison of road profile spectra measured by the measurement vehicle and static laser scale.

The road spectra measured using the two techniques were similar (Fig. 4). The two spectra had consistent trends and high correlation in the short- to medium-wave range (correlation coefficient of 99.69%, relative error of approximately 4%).

To further validate the road profile measurement in the medium-wave range, an experimental road with a standard waveform profile was measured by the measurement vehicle and the measured profiles were compared with profiles measured using a precision level. The road profiles measured by the two techniques had high correlation (coefficient of correlation of 98.4%). In addition, the mean measurement error for the measurement vehicle was calculated to be 3.06 mm; this level of precision satisfy the requirements of measurement of road profiles.

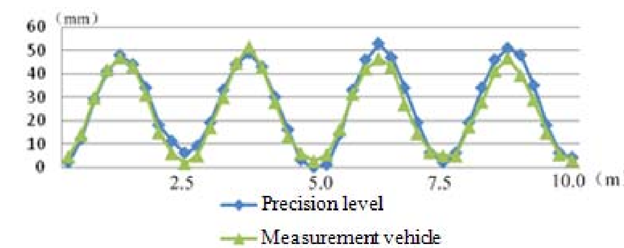

Figure 5 Comparison of road profiles measured by the measurement vehicle and a precision level.

V. CONCLUSION

The in-vehicle rapid road profile measurement system was developed by combining laser displacement sensors, accelerometers, and a gyroscope. An algorithm based on the double integral of acceleration with respect to time and vehicle attitude compensation was designed to reconstruct road profiles for the rapid measurement of short- to medium-wave longitudinal road profiles. The accuracy of the road profiles measured using this system was confirmed by comparison with the results of static measurement. The proposed system can measure road profiles in a wide frequency range and satisfies the requirements of vehicle performance tests. This efficient measurement system is suitable for large-scale road measurement and surveys.

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