Measurement and Frequency Analysis of Dynamic Vertical Wheel Load of Farm Tractor

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Abstract

Field experiments investigated the vertical wheel-load variations of the left rear wheel of a tractor driven at different combinations of static loads and tire pressures. The dynamic wheel load was measured on rigid and deformable grounds using strain-gage-based transducers. Frequency analysis presented a combination of the effects of the ground profile and tire characteristics on wheel-load variations. On an asphalt road, both the nonuniformity of the wheel-tire assembly and tire lugs excited the wheel-load variations at their first- and second-order frequencies, while these self-excitations had less effect as the ground deformability increased during the tests on sandy loam and clay soils. However, the nonuniformity of a low-pressure tire moving on extremely deformable clayey field critically affected the wheel-load fluctuations.

[Keywords] dynamic wheel load, strain-gage-based transducer, ground profile, tire characteristics, frequency analysis

I Introduction

The analysis of tire loading under operational driving conditions has been found to be important for the studies of vehicle mobility as well as for the input and validation of computer simulations of tire characteristics. In practical off-road operations, the wheel loads significantly vary in its intensity and frequency due to the scattered soil properties, ground surface roughness, and dynamic interactions between the tire and the terrain. The complex behavior of the dynamic multiaxial loads and subsequent deformations of the ground and tires result in the variation of vehicle performance. In terms of the traction mechanics of off-road vehicles, the dynamic vertical wheel load that is correlated with the slip, inflation pressure, tractor speed, and ground profile has been recognized as an important variable. Although the effects of wheel load on wheel-soil interactions and tractive performance of off-road vehicles have been studied in many previous works, the dynamic wheel load has been considered to be constant during a given test run. Detailed investigations are required to obtain accurate data on a transient wheel load to study the dynamic performance of the vehicle.

The measurement of the dynamic loads of the farm tractor tires is very hard to achieve even on a ground with a good profile. Test rigs or prototype vehicles have been utilized to measure forces and moments generated between the wheel and the ground in the steady state or in a slow-speed motion (Itoh, 1995; Shmulevich, 1996; Raeman, 2003). A few applications, which are referred to as wheel hubs, also exist to measure the steady-state or slowly varying forces and moments generated between the ground and tires for deriving both the on-road and off-road tire characteristics (Rupp, 1997; Späth, 2001; Brinkmann, 2001; Decker, 2002; Gobbi, 2005). However, such measuring devices have complicated structures and require complex materials; hence, their applications are limited to research and development activities. The use of instrumented hubs for measuring wheel forces might essentially change the characteristics of the wheel-tire assembly, such as stiffness and mass. Therefore, it may be difficult to evaluate the real characteristics of the system. In particular, the measured data in these studies have not been analyzed in the frequency domain for the detailed investigation of the effects of the ground profile and tire characteristics on the variations in the dynamic wheel load.

In this study, the dynamic vertical load of a driven wheel was measured by using strain-gage-based transducers mounted on the left rear axle of a 2WD farm tractor. A number of experiments were conducted on...
an asphalt road and agricultural fields for deriving the dynamic wheel load of the wheel. The tractor was self-propelled under a steady-state condition at different combinations of static wheel load, tire inflation pressure, and tractor speed. The measured data were analyzed in both the time and frequency domains to investigate the effects of ground deformability, surface roughness, and tire characteristics such as tire nonuniformity and tire lugs on the variation of the dynamic wheel load. In addition, the multiresolution analysis of signals measured during the tests on rigid surface were conducted by the wavelet coefficient selection method for providing an intuitive vision of the wheel load fluctuation in time domain due to tire nonuniformity or tire lugs alone.

II Materials and methods

1. Tractor instrumentation

A 2WD farm tractor (Fig. 1a) with 15kW engine power was equipped with strain-gage-based transducers and photo switches for measuring the dynamic wheel load of the left rear tire and angular velocities of the front and rear tires.

(a) Measurement of the dynamic wheel load

The principle for the measurement of the dynamic wheel load is based on the dynamic response of a rear tire moving in a straight line in a steady-state condition. A free-body diagram of a driven tire and wheel assembly would be shown approximately like in Fig. 1b. Assume that the moment arms rH and rR about wheel center of wheel thrust H and rolling resistance R, respectively are equal to dynamic tire rolling radius rL, and the eccentricity e between action line of dynamic wheel load Wd and wheel center is approximately zero, equation (1) can be obtained based on the equilibrium of the system:

\[ W_d = \sqrt{\left(\frac{M_x + M_z}{L}\right)^2 - \left(\frac{T}{r_L}\right)^2} \]  

where T is drive axle torque (kNm); Mx and Mz are moments applying to cross-section 2-2 about X and Z axis, respectively (kNm); L is the distance from the intersection of the centerline of drive axle and the action line of dynamic wheel load (m).

The method for evaluation of real-time wheel load was derived by the measurements of torque and moments applied to a drive axle due to the interactions between the tire and the ground. Consequently, the dynamic vertical wheel load of the left rear drive wheel was calculated by equation (1). The torque and moments acting on the left rear axle were measured at the arbitrary rotation angle of the wheel by three strain-gage-based transducers mounted between the axle flange and the axle case. The instrumentation and calibration of each transducer were described in detail in a previous study (Nang et al., 2007).

(b) Velocity measurements

In order to measure the velocity of the tractor (hereafter named v), two photo switches (PW-41J, Keyence) and reflective tapes were used to measure the angular velocity of the front and rear tires. Eighteen reflective tapes were attached to the inner side of the front wheel rim at an angular interval of 20°. The same arrangement was used for the rear wheel with 30 reflective tapes attached to the outer side of the rear wheel rim at angular intervals of 12° (Fig. 1b). Two photo switches were mounted on the rigid beams connected to the front axle and tractor mudguard. They detected the reflected signals and generated electrical pulses at distance of 0.15m. Furthermore, the rolling radii of the tires (rL) at different wheel loads and inflation pressures were measured for calculating the tractor velocity. The measurement results are presented in Table 1.

2. Data acquisition

In this study, three strain-gage-based transducers were used to measure the torque and moments exerted on the drive axle due to tire-ground interactions,
and two photo switches were used to measure the angular velocities of the tires. A DC excitation voltage of 2 V was supplied to the transducers by an acquisition system (NR-500, Keyence). The tractor battery provided a DC excitation voltage of 12 V to two photo switches. Five strain and voltage signals were transmitted from the axle and photo switches to the acquisition system using a slip ring (SR-12, Michigan) mounted on the central part of the left rear wheel. The signals were sampled at a rate of 100 Hz and recorded on a portable computer. All devices for data acquisition were fixed on the tractor. Most of the off-road vehicles encounter frequencies between 0.1 and 20 Hz (Young, 1990), while typical natural frequencies of the forces acting on the wheel range from approximately 1 to 4 Hz (Gobbi, 2005). Therefore, the measured signals from the transducers were filtered with a 30 Hz low-pass filter to eliminate the effects of higher frequency vibrations due to the unbalanced rotation of engine parts and transmission system.

3. Test sites
Experiments were conducted on six types of grounds including the dry asphalt road, pre-prepared sandy loam field, tilled sandy loam field, and heavy clay fields, which consisted of a pre-prepared cracked clay field, dry and wet rice fields after harvest. Each field had approximately 20-m length and allowed of conducting each experiment on separate test track. The soil profiles are shown in Table 2. For pre-prepared test sites, the fields were thoroughly tilled and leveled to constant depth of 150 mm, and left for naturally consolidating in one month. A relatively uniform soil and medium profile were obtained for a sandy loam field, while random cracks with shallow depths were observed for a heavy clay field, resulting in a non-homogeneous soil and medium profile. After the experiments on the firm sandy loam soil were completed, the field were tilled and leveled again to the same depth before carrying out the experiments. Furthermore, a poor profile with stubble was observed for both dry and wet rice fields after harvesting.

4. Experimental procedure
The 2 WD tractor was driven in a straight path with four different combinations of static wheel loads and tire inflation pressures (here after named p1) as shown in Table 1. The static loads of the front and rear wheels depended on the position of an attached rotary tiller, i.e., trailing or mounting. Each test was conducted one time under a steady-state condition at constant forward velocities in an approximate range of v=0.2–0.6 m/s with all the tires inflated to pressures of p1=100 kPa and 330 kPa.

5. Data processing
Each test resulted in six rotations of rear wheel and only data of two rotations were used for analysis. Since the time domain analyses can be used to investigate only the variation of the wheel load, they do not substantially explain the effects of the ground profile and tire characteristics on the variation. Therefore, power spectral density (PSD) analyses in the frequency domain are necessary. The discrete Fourier analysis was utilized to investigate the effect of ground deformability, surface roughness, tire nonuniformity and tire lugs on the variation of the dynamic wheel load. In addition, the wavelet coefficient selection method was applied to the results of the tests performed on the asphalt road by decomposing the original signals into nine levels using the db4 wavelet. The time histories of measured data were reconstructed from the wavelet coefficient levels, which are related to the excitation frequencies of the wheel-tire assembly, in order to investigate the effects of the tire nonuniformity and tire lugs on wheel-load variation. The excitation frequencies of the wheel and tire lugs were calculated from the angular velocity of the wheel and number of tire lugs. Moreover, the electrical pulses generated per second by the two photo switches were used to determine the angular velocity of the front and rear tires and the ground speed of 2
Fig. 2  Time histories and frequency compositions of wheel load in two rotations during tests on asphalt road

WD tractor.

III  Results and discussion

The time histories and frequency compositions of the dynamic vertical load of the left rear wheel are presented in Figs. 2–7. In all the tests, the wheel load varied with different magnitudes depending on tire parameters and ground profiles. The variations about the 4.6 kN static load of the wheel load (W) measured on the asphalt road within two revolutions of the left rear wheel take the form shown in Fig. 2. Since the roughness and deformability of the ground were negligible, the fluctuation of the vertical wheel load around the static wheel load was caused by self-excitations due to the nonuniformity of the wheel-tire assembly, such as mass imbalance, dimensional variations, stiffness variations, and tire lugs. For the tests performed at a tractor speed of 0.2 m/s, the frequency composition of the wheel load showed that the load fluctuation is caused by the first- and second-order frequencies of the wheel (0.065 Hz and 0.13 Hz), which were produced by the nonuniformity of the wheel-tire assembly, and by the first- and second-order frequencies of tie lug (1.2 Hz and 2.4 Hz), which were produced by mutually adjoining lugs and successively arriving lugs (Fig. 2e). The composite load variation of the left wheel takes different forms for high- and low-pressure tires (Fig. 2a, b). The variation in the wheel load of a tire at a pressure of 330 kPa about the static load occurs in a higher magnification than that for a tire at pressure of 100 kPa. This is because low inflation pressure results in a more damped system and more tie lugs in contact with the ground; therefore only the second-order frequency of the left wheel excited the wheel load fluctuation of the tire at a pressure of 100 kPa; whereas, for the tire at a pressure of 330 kPa, the high spectral amplitudes occurred at both the first- and second-order frequencies of the wheel. Both the first- and second-order frequencies of tire lugs excited the wheel-load variation, and this had a greater effect...
in the case of the high-pressure tire. The first-order excitation frequency of tire lugs was predominant in the case of the tire at a pressure of 330 kPa, while the second one occurred at the highest amplitude of PSD. When the tractor speed was increased to approximately 0.6 m/s (Fig. 2c, d and f), the effects of tire nonuniformity and lugs were reduced since the high amplitudes of the PSD considerably decreased in comparison to the tests at 0.2 m/s tractor speed. The wavelet-synthesized data are presented in Fig. 2a-d showing the variation of the wheel load due to tire lugs (W’') or tire nonuniformity (W’) alone. This indicates that the tire lugs strongly excited a variation in the tractor wheel load, even on hard surfaces with good profiles. At a higher tractor speed, the tire nonuniformity of a low-pressure tire had a small effect, while the tire-lug excitation had a greater effect on the wheel-load fluctuation in comparison to that of the high-pressure tire, as shown in Fig. 2f. It should be mentioned that the tire nonuniformity and tire lugs also excited the wheel-load variations in the right drive tire. Consequently, the phase difference between the lugs of left and right tires caused the load transfer in the lateral direction. This effect will be considered in the next study.

When the tractor moved on deformable grounds, the variation in the dynamic vertical wheel load was found to be large due to soil deformation and surface roughness. Figure 3 shows the time histories and frequency compositions of the wheel load measured during tests at a tractor speed of 0.2 m/s on the dry rice field after harvest with low deformability and a poor profile. The variations of wheel load occurred randomly and mainly depended on the surface roughness and the non-uniformity of the tire, as shown in the frequency composition of the wheel load (Fig. 3c). Only the second-order frequency of wheel (0.13 Hz) dominated the wheel load excitation, while the excitation frequencies of tire lugs (1.2 Hz/2.4 Hz) had almost no effect. Moreover, the load variations showed similar trend and amplitude for tires with low and high inflation pressure. This implies that the tire inflation pressure had a little effect on the variation in the vertical wheel load of tires on hard soil with a rough surface. When the tractor speed was increased to 0.4 m/s during the test with a tire at a pressure of 330 kPa, the effect of soil roughness and tire nonuniformity on wheel-load variation decreased, while that of the tire lugs remained unchanged, as shown in the frequency composition of the wheel load (Fig. 3c). By comparing the amplitudes of wheel-load variations, it can be observed that as tractor moved on soft ground, the variations were significantly different from those on hard surface. While the wheel load fluctuated rapidly during the tests on the asphalt road, it took a long time to decrease after being excited by the field-surface irregularities and tire characteristics during the tests on deformable grounds. This is because of the higher damping of clayey soil. Since the dynamic wheel load was excited by the soil surface roughness as well as soil deformability, the rear wheel-load variation obviously interfered with the variation in the front wheel load and vice versa. In combination with the pitching of the tractor, this effect may result in
critical load transfer between the front and rear axles. This effect requires further investigation.

Figure 4 shows the time histories and frequency compositions of the dynamic vertical load of the left rear wheel moving on the firm sandy loam field with a medium profile and deformability. It can be observed that the wheel load still varies significantly, even when the tire inflation pressure was reduced and the soil surface became smoother (Fig. 4a). While the reduced inflation pressure decreased the effect of soil surface roughness, it increased the effect of self-excitation in both the wheel and tire lugs. The wheel load of the low-pressure tire was found to be critically excited at the second-order frequency of the wheel (0.13 Hz) and the first-order frequency of tire lugs (1.2 Hz), as observed in Fig. 4b. For a high-pressure tire, the wheel load was mainly excited by the field roughness, and this influence increased with the increase in tractor speed from 0.2 to 0.46 m/s. The first-order frequency of the wheel (0.14 Hz) dominated the wheel-load excitation as the tractor speed increased up to 0.42 m/s. When the static load of the low-pressure tire was increased up to 4.6 kN, the surface-smoothing effect also occurred because the tire stiffness was higher than the soil stiffness (Fig. 5b). These imply that the effect of tire stiffness becomes more significant with the increase in ground deformability.

Figure 6 shows the time histories and frequency compositions of the dynamic wheel load of the left rear wheel moving on the soft clay field with a medium profile and excessive nonhomogeneity of the soil at a tractor speed of 0.2 m/s. In all the tests with different combinations of static wheel loads and tire inflation pressures, the variations in the dynamic wheel load were magnified by the increasing deformation and nonhomogeneity of the clay soil (Fig. 6a, c). It was found that after the wheel load reached the peak, the loading or unloading of the wheel on soft soil occurred more slowly in comparison to the tests on sandy loam field, particularly for tires with low inflation pressure,
showing that the tire-soil interaction has a stronger effect on soil response with an increase in the deformability of the ground. It appeared that the high deformability of clay soil increased the effect of tire nonuniformity on wheel-load variations since both first- and second-order frequencies of wheel (0.06 Hz/0.12 Hz) were at the predominant excitation frequency (Fig. 6b, d). This was observed again when the tractor moved on the wet rice field with extremely soft and poor ground profile (Fig. 7). For a tire with 100 kPa pressure, the excitation of tire nonuniformity on the dynamic wheel load at the second-order frequency
(0.13 Hz) at which a very high amplitude of PSD occurred became very critical (Fig. 7b). This indicated that the interactions between the tire with a low inflation pressure and the soft clay soil with large irregularity is very complex and requires further study.

IV Conclusion

The main conclusions of this study are as follows:

1) The nonuniformity of the wheel-tire assembly significantly excites variations in the wheel load at the first- and second-order frequencies. This effect reduces as the tire inflation pressure decreases or the tractor speed increases during the tests on rigid surface; however, this effect becomes critical as the low-pressure tire moves on grounds with high deformability during the tests on agricultural fields.

2) The tire lug causes the excitation of wheel-load variation at the first-order frequency produced by successive lugs and at the second-order frequency produced by the mutual lugs. On the hard surface, these frequencies dominate the wheel-load fluctuation, while they have a small effect as the soil stiffness decreases.

3) The soil-tire interaction along with the ground profile and tire characteristics has significant effects on the variation of the dynamic wheel load. When the ground stiffness is lower than the tire stiffness, tires with a high load filter the ground surface irregularity resulting in a small variation in the dynamic wheel load. Furthermore, clayey soil with extremely high deformability makes the nonuniformity of the low-pressure tire to critically excite the wheel-load variation.

References


(Received : 13. August. 2007 • Question time limit : 30. September, 2008)