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Transducers for measuring dynamic axle load of farm tractor

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Summary

The functional principle of instrumented strain-gage based transducers for the farm tractor rear axle as well as the particularities of constructive design and the calibration technique was explained. The capable of measuring dynamic axle load of the transducers was verified using the results of ride performance tests. The experimental data indicated that the proposed method of dynamic axle load measurement is capable of monitoring the real-time vertical wheel load of a moving vehicle and provides a tool for further studies on vehicle dynamics and dynamic wheel-soil interaction. The time histories and frequency compositions of the experimental data showed that the dynamic axle load was strongly excited by tire non-uniformity, tire lugs. When tractor moved on asphalt road and sandy loam field, the tire non-uniformity dominated the excitation of tires with low inflation, while the tire lugs dominated the excitation of tires with high inflation pressure.

Key words: Dynamic axle load, Strain-gage-based transducer, Farm tractor

I. Introduction

The analysis of the wheel load of a moving vehicle is of great importance for the basic investigation of wheel-soil interaction, tire characteristics as well as for the input and validation of vehicle dynamic simulations. Although the effects of dynamic wheel load on wheel-soil interactions and tractive performance have been considered in many investigations (Wiermann, 1999; Botta, 2002; Jun, 20005), the dynamic wheel loads in these studies were kept at constant levels during a given test run. The lack of accurate data for transient wheel load in studying the dynamic performance of vehicle promotes further investigations.

In order to evaluate accurately the effect of change in dynamic wheel load on the overall performance of an off-road vehicle, it is necessary to measure the soil reaction directly on the drive axle for analyzing the correlations between the dynamic wheel load and the wheel-soil contact forces as well as the wheel slip. Gobbi (2005) developed an instrumented hub for measuring all the three forces and three moments acting on a wheel in order to characterize front and rear tractor tires both on road and off road. Furthermore, some commercial transducers are available for measuring forces and moments applied to wheel hub of both on road and off-road vehicles (Rupp, 1997; Spath, 2001; Decker, 2002), but they require complex hardware and materials, and are very expensive. It should be noted that the use of instrumented hub for measuring wheel forces might essentially change the characteristics of wheel-tire assembly such as stiffness and weight. Therefore, it may be difficult to evaluate the real characteristics of the system. Accordingly, a new method which not only requires simple materials and design but also can adapt for different applications is necessary for measurement of the forces acting on wheels.

The objective of this research is to develop an easily implemented method based on the dynamic response of a moving 2WD tractor instrumented with strain gage-based transducers so as to obtain accurate measurements of transient wheel load. The proposed method for evaluation of real-time vertical axle load was based on the measurements of torque and moments applied to a drive axle due to wheel-soil interactions. This method does not modify any parameter of wheel-tire assembly and requires only conventional strain gages, so that it can be widely applied to research and development activities of performance of full-scale vehicles. The measurement of dynamic axle load makes it possible both to carry out and to verify vehicle dynamic simulation, finite element analysis and experimental evaluation of dynamic wheel-soil interactions. It is also useful for strength and fatigue evaluation of chassis components as vehicles move through obstacles or when sudden bake is applied.

II. Materials and Methods

1. Method of dynamic axle load measurement

Assume that a farm tractor is in straight-line steady-state motion, a free-body diagram of a rear tire and wheel assembly would be shown approximately like in Fig. 1. Assume that the moment arms r_H and r_R about wheel center of wheel thrust H and rolling resistance R, respectively are equal to dynamic tire rolling radius r_L, and the eccentricity e between action line of dynamic wheel load W_d and wheel center is approximately zero, equation (1) can be obtained based on the equilibrium of the system:

$$W_d = \sqrt{\left(\frac{M}{L}\right)^2 - \left(\frac{T}{r_L}\right)^2} = \sqrt{\left(\frac{M_X + M_Z}{L}\right)^2 - \left(\frac{T}{r_L}\right)^2} \qquad (1)$$

where T is drive axle torque (kNm); M is total moment applying to the cross-section 2-2 (kNm); M_X and M_Z are component moment of M on X and Z axis, respectively (kNm).

If the tractor is in stationary state, then:

$$W_d = \frac{M}{L} \qquad (2)$$

In order to evaluate the soil vertical reaction experimentally, it is necessary to measure moment M, axle torque T, and dynamic rolling radius r_L. While T and r_L can be determined easily, it is difficult to measure the component moment of M, *i.e.*, M_X and M_Z about X and Z axis in stationary coordinates XZ because the axle rotates (Fig. 1). With respect to a reference coordinates xz which rotates together with drive axle, total moment M can be calculated by Eq. (3). By measuring the component moments M_x and M_z about x and z axis, respectively, we can calculate moment M at arbitrary rotation angle θ of the rear axle.

$$M = \sqrt{M_x^2 + M_z^2} \qquad (3)$$

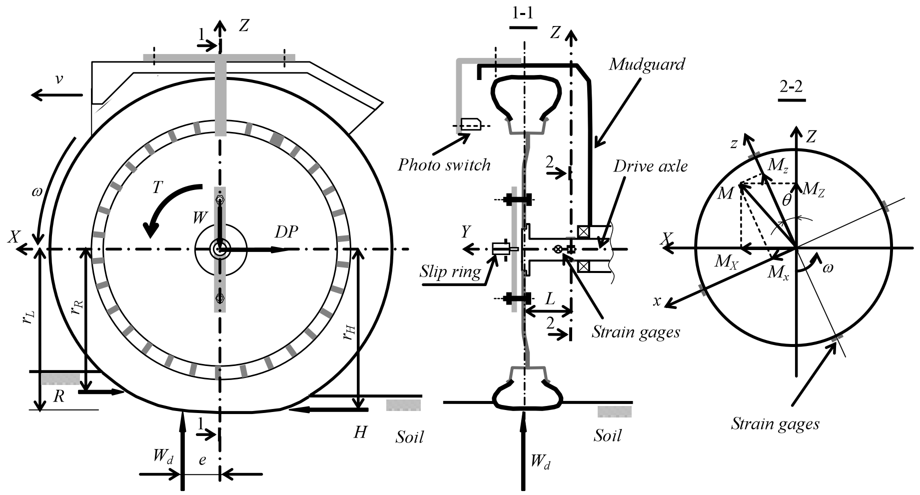


Fig. 1. Forces and torque acting on rear tire, and instrumentation of tire-wheel assembly

where M_x and M_z are component moment of M about x and z axis, respectively (kNm).

The relationship between axle strain at the cross-section 2-2 and vertical reaction at any angle θ can be expressed by Eq. (4):

$$W_d(\theta) = \frac{\pi d^3 E}{32} \times 10^{-6} \times \sqrt{\frac{\varepsilon_x^2(\theta) + \varepsilon_z^2(\theta)}{L^2} + \left[\frac{2\varepsilon_s}{(1+\nu) r_L}\right]^2} \tag{4}$$

where d is drive axle diameter in m; E in kN/m^2 and ν are Young's modulus and Poisson's ratio of axle material, respectively; ε_x and ε_z in $\mu\varepsilon$ are axle bending strain in xY and zY plane (Fig. 1), respectively; ε_s is shearing strain of any axle cross-section in $\mu\varepsilon$.

2. Design of strain-gage-based transducers

The torque and moments acting on the left rear axle were measured arbitrarily at any rotation angle of the left rear wheel by three strain gage-based transducers mounted between the axle flange and axle case. The arrangement of strain gages is shown in Figs. 2 and 3. The strain gage applications were conducted in a number of consecutive steps in accordance with the manufacturers' guidelines.

The bending moment M_x and M_z were measured by two transducers, which were mounted around a cross-section of rear axle at a distance L = 100 mm from the left rear wheel center. In order to provide high sensitivity and temperature compensation, the transducers were designed based on two full bridge circuits (Wheatstone bridge) formed by eight strain gages (KFG-5-120-C1-11, Kyowa). Each pair of two strain gages was bonded on either side of a line parallel to the axle axis at interval of 90 ° around axle surface. Each two pairs of strain gages at opposite sides were connected to form a 4-active-gage system. Two transducers monitored bending strains that are proportional to both vertical and horizontal wheel forces at the tire-ground contact surface and converted into corresponding electrical signals.

The torque T of the left drive axle was measured by a transducer made of two sets of 90 ° rosette strain gages (KGF-3-120-D16-11, Kyowa) bonding at 45 ° shear planes on opposite sides of the axle. The mounted strain gages were connected in a full bridge circuit for measuring the shear

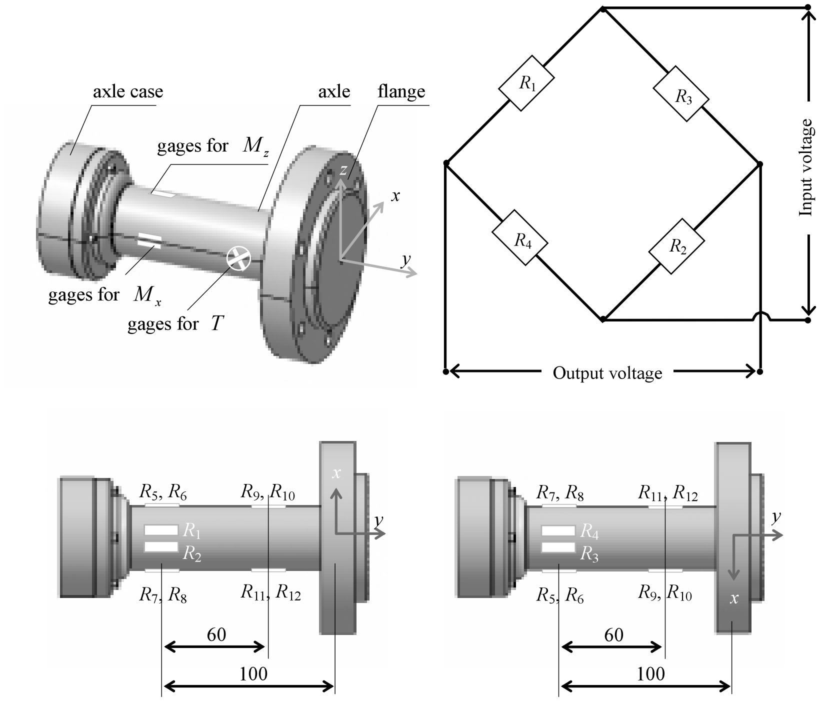


Fig 2. Strain gage arrangement and Wheatstone bridge for measuring M_x

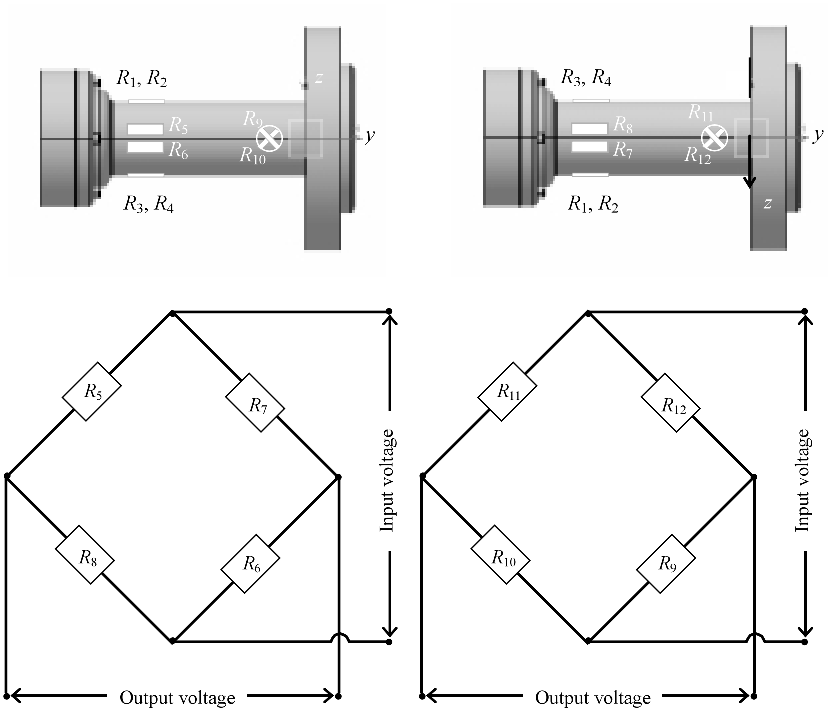


Fig 3. Strain gage arrangement and Wheatstone bridges for measuring M_z and T

strain, which was proportional to torque input. The shear strain was converted into electrical signal.

3. Tractor instrumentation

A 2WD tractor (Kubota L200) with 15kW engine power was instrumented with strain gage-based transducers, spot pressure sensors, photo switches, and load cell for measuring torque and bending moments applied to driving axle, wheel angular velocity, and tractor drawbar pull (Fig. 4).

Fig. 4. Tractor instrumentation: a) strain-gage based transducers; b, c) reflective tapes; d, e) photo switches; f; data acquisition system; g) slip ring

Six strain-gage-based transducers were mounted between the axle flanges and the axle cases of both the left and the rear axles (Fig. 4a) in order to measure the dynamic axle loads of the left and the right rear wheels. In order to measure the dynamic axle load accurately, static calibrations of three transducers were conducted to eliminate the defects due to the transducers construction such as strain-gage positioning error, axle tolerance, etc. Bending strain transducers were calibrated at four axle positions corresponding to $\theta = 0$, $\theta = 90^\circ$, $\theta = 180^\circ$, and $\theta = 270^\circ$, so that one transducer provided the maximum output, while the other produced zero output at each position of calibration. Five combinations of known loads were applied to the wheel by axle weight and added weights for each calibration, and the signals from the transducers were acquired. The calibration data indicated that the output signals of two transducers at the same calibration position and load are almost the same, and the output signals of torque transducer were approximately equal to zero (Fig. 5).

To calibrate the torque transducer, a horizontal rigid beam was fixed to axle flange through the wheel center at one end, and five combinations of known point load were applied to the other end (Fig. 6). All static calibrations showed excellent linearity of the measurements with correlation coefficients approximate to one. A calibration equation for two moment transducers and one for torque transducer were obtained by least squares method from the measured calibration data. Static demonstration tests were conducted at four axle positions corresponding to $\theta = 45^\circ$, $\theta =$

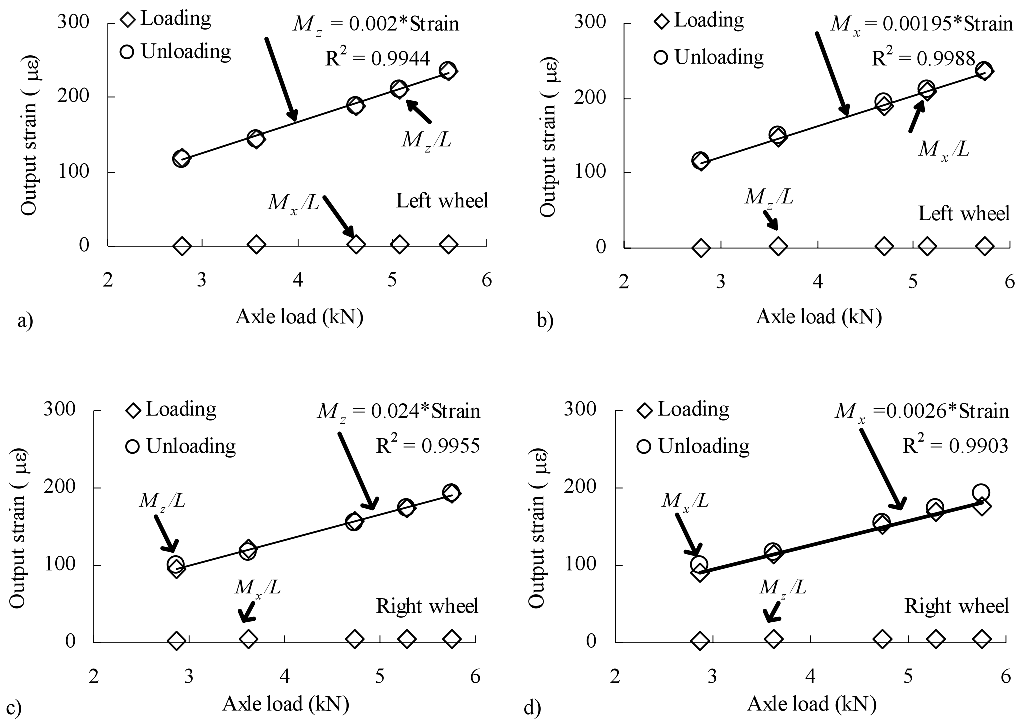


Fig. 5. Calibration data for: a, b) left wheel axle; b) right wheel axle

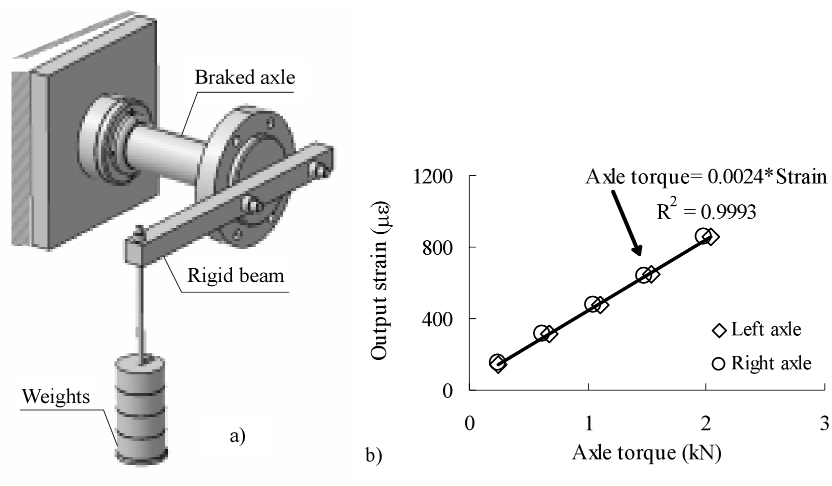


Fig. 6. Torque transducer calibration: a) calibration method; b) calibration data

135 °, θ= 225 °, and θ= 315 ° to measure static axle load. The results showed excellent measurements with maximum deviation of 1.2% between measured load and rated load.

The angular velocity of the front and rear tire were measured by three photo switches (PW-41J, Keyence) and reflective tapes, and the rear tire's slip was calculated from these angular velocities (Fig. 4).

4. Data acquisition

A DC 2V excitation voltage for transducers was supplied by an acquisition system (NR-500, Keyence) (Fig. 4f). The tractor battery provided DC 12V excitation voltage for 3 photo switches. Ten strain and voltage signals were transmitted from the axle, load cell, and photo switches to acquisition system using two slip rings (SR-12, Michigan) mounted on center part of rear wheels (Fig. 4g). The signals were sampled at a rate of 500Hz, and were recorded on a portable computer. All devices for data acquisition were fixed on tractor.

5. Experimental conditions

A demonstration test for the transducers was conducted on concrete surface by driving the tractor over an obstacle with height of 0.0025 m and length of 0.1 m at an approximate ground speed of 0.75 m/s. The inflation pressure (P_i) was 200 kPa for front tire and 160 kPa for rear tire. Both the rear wheels passed the obstacle simultaneously.

The experiments were conducted on a dry smooth asphalt road of 50 m length and on a plane sandy loam field of 40 m length at different combinations of tire inflation pressure and tractor velocity. The field allowed carrying out tests on different test tracks with a relatively similar soil condition. Each field test was conducted on a separate track with topsoil of 15 cm depth, 21 % water content and 1.23 g/cm^3 bulk density. The dynamic wheel loads were measured during self-propels of the tractor in a total of four treatments (Table 1) at three constant forward speeds of approximately 2.6 m/s for tests on asphalt road and at a constant forward speed of approximately 0.6 m/s for tests on sandy loam soil. Tire inflation pressure was 330 kPa for all the tires, and 200 kPa for the front tires and 80 kPa for the rear tire during the tests.

Table 1 Experimental treatments

Test site	Treatment	v (m/s)	p_i (kPa)		r_L (mm)		f_w (Hz)		f_L (Hz)	
			Front tire	Rear tire	Front tire	Rear tire	Front tire	Rear tire	f_{L1}	f_{L2}
Asphalt road	1	2.6	330	330	292	492	1.43	0.85	15.28	30.56
	2	2.4	200	80	289	473	1.34	0.82	14.78	29.56
Sandy loam	3	0.63	330	330	292	492	0.28^+	0.21	3.70	7.39
	4	0.6	200	80	289	473	0.28^+	0.21	3.76	7.52

$^+$20 % slip of rear tire occurred

6. Data processing

Since the data were recorded at arbitrary position of transducers as the drive axle was loaded, so the trend of the data for bending strain was parallel but not coincident with the abscissa as shown in Fig. 7, and required a special treatment for further calculation. In order to obtain the fluctuation of measured bending strain about the abscissa, the MATLAB function “detrend” was used to remove the trend from the data. This technique also removes the linear trend caused by the drift of transducers and sensors. Fig. 7 also shows samples of strain output from transducers and load cell.

Time domain analysis was used to investigate the variations of the axle loads, while frequency domain analysis was used to investigate the effect of the self-excitations such as tire nonuniformity and tire lugs as well as the soil deformation on the variations. Since the axle load may be strongly excited at firing frequency of the engine, the excitation, which is caused by the firing orders of the engine, needed to be removed from the original signals. Therefore, the wavelet coefficient selection method was applied to the measured data by decomposing the original signals

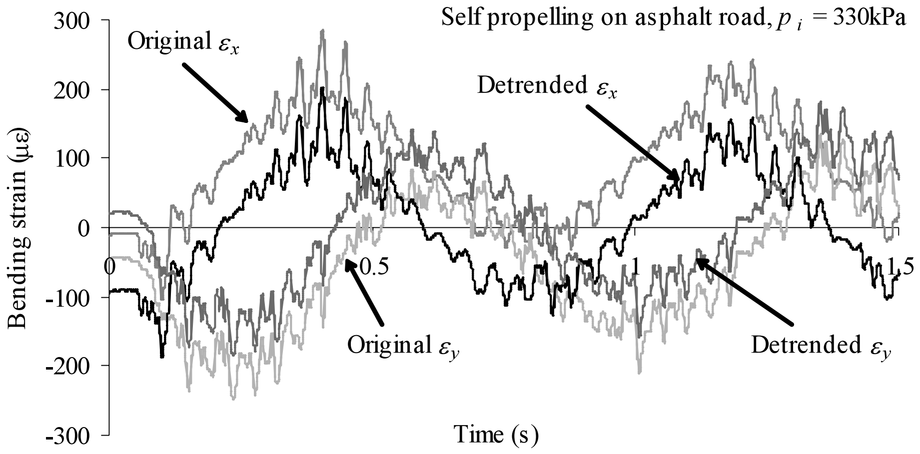
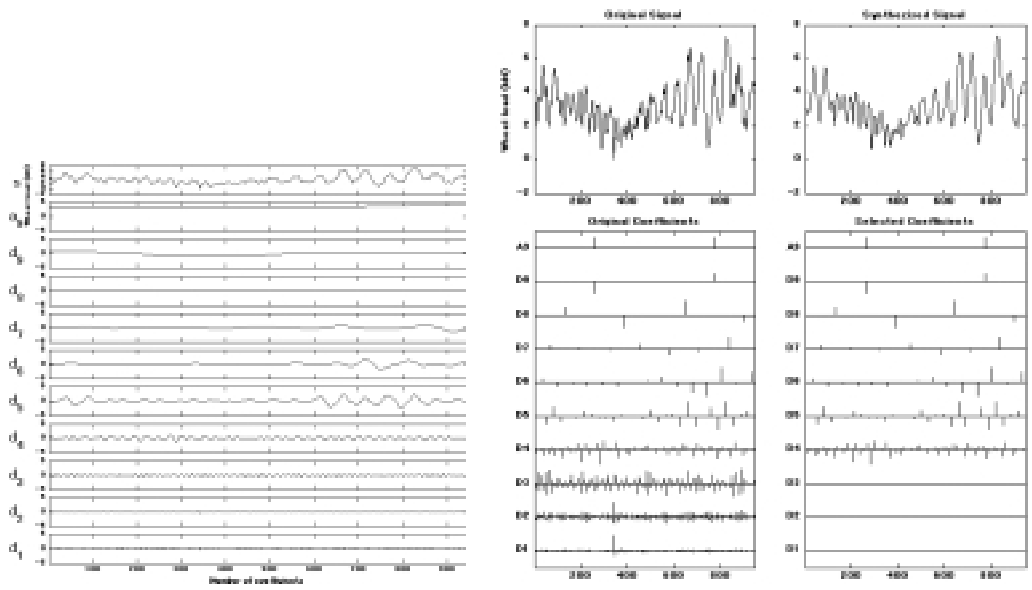


Fig. 7. Samples of strain output measured by transducers

Table 2 Resolution levels and correspondent bandwidths

Level	Bandwidth (Hz)	Level	Bandwidth (Hz)	Level	Bandwidth (Hz)
1	125－250	4	15.63－31.25	7	1.95－3.9
2	62.5－125	5	7.81－15.63	8	0.98－1.95
3	31.25－62.5	6	3.91－7.81	9	0.49－0.98



a) b)

Fig. 8. A sample of a) data decomposition; b) reconstruction within one wheel rotation on asphalt road

into nine levels using the db4 wavelet (Daubechies wavelet), as shown in Fig. 8. The bandwidth of measured data at every resolution level is shown in Table 2. The time histories of measured data were reconstructed from the wavelet coefficients of resolution levels, which had bandwidths spanning the excitation frequencies of the wheel-tire assembly (f_w), and the first- and second-order excitation frequencies of tire lugs (f_{L1}, f_{L2}) as shown in Table 2. The f_{L1} and f_{L2} are produced by successive lugs and mutual lugs respectively. The synthesized data for the tests at the tractor speed of approximately 0.6 m/s were calculated from the approximate coefficients of resolution level 9 (a9) and the detail coefficients of resolution levels 6 － 9 (d6 - d9), while the approximate coefficients of resolution level 9 and the detail coefficients of resolution levels 4 － 9 (d4～d9) were used to reconstruct the data for the tests at tractor speed of 2.6 m/s. A sample of data decomposition and reconstruction is shown in Fig. 8.

III. Results and Discussion

As a sample of data analysis using wavelet transform, the time histories of axle load within three rotations of the rear wheel as tractor moved on concrete surface, asphalt road and sandy loam are depicted in Figs. 9. Before the obstacle was driven over, axle load variations resulted from the pitching and rolling of the tractor and from lug excitation (Fig. 9a). The passing of ob-

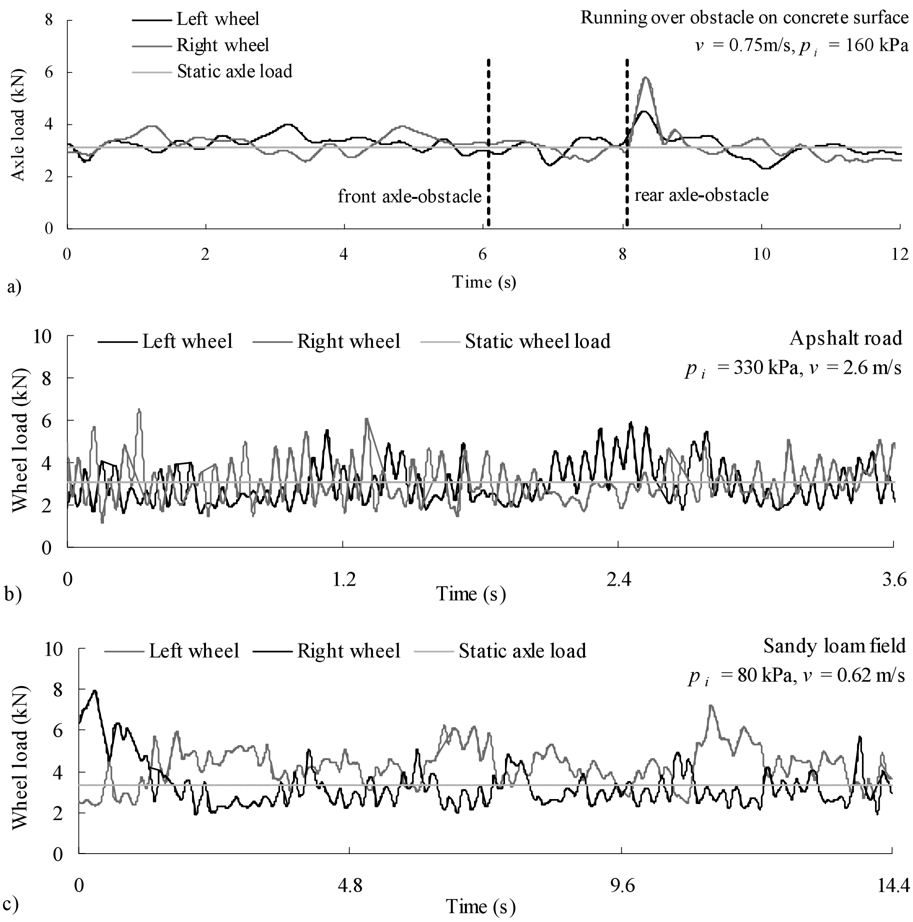


Fig. 9. Time histories and frequency composition of dynamic axle loads within three wheel rotations on: a) running over obstacle; a) asphalt road; c) sandy loam field

stacle by front axle did not exert any significant influence on the load at the rear axle. When the rear axle passed the obstacle, considerable peak axle loads occurred. This indicated that the instrumented strain-gage based transducers allowed the effect of running over obstacle on dynamic axle load to be monitored in real time. The time histories of data measured on asphalt road show a relatively similar trend of axle load for every wheel rotation (Figs. 9b), while this could not be observed clearly for data measured on sandy loam field due to soil non-homogeneity (Fig. 9c).

The results of wavelet and Fourier analyses for the measured data within one rotation of the rear wheels at different combinations of forward velocity and tire inflation pressure as the tractor moved on asphalt road and sandy loam field are shown in Figs. 10 ― 11. Figures 10a and b shows the time histories and frequency compositions of synthesized axle load during the tractor self-propelling on asphalt road at a forward speed of 2.6 m/s and tire pressure of 330 kPa in treatment 1. In the time analysis, the dynamic axle load varied with high amplitude about a static value, and there was a phase difference of the variation between the left and the right axle loads (Fig. 10a). These behaviors were also observed in analyses of the other treatments. The frequency analysis of axle load (Fig. 10b) indicated that the variation was strongly excited at the first-order excitation frequeny of tire lug (f_{L1} = 15.25 Hz), while tire non-uniformity was slightly excited the axle load at the wheel frequency and its harmonics (f_w = 0.85Hz and 3.39Hz). As the tire pressure was reduced to 80 kPa at a forward speed of 2.4 m/s in treatment 2 (Fig. 10c), the axle-load variation was reduced because the effect of tire lug excitation was insignificant and the axle load was predominantly excited at f_w = 0.82 Hz (Figs. 10d).

When the tractor moved on a sandy loam field with high deformability at a forward speed of

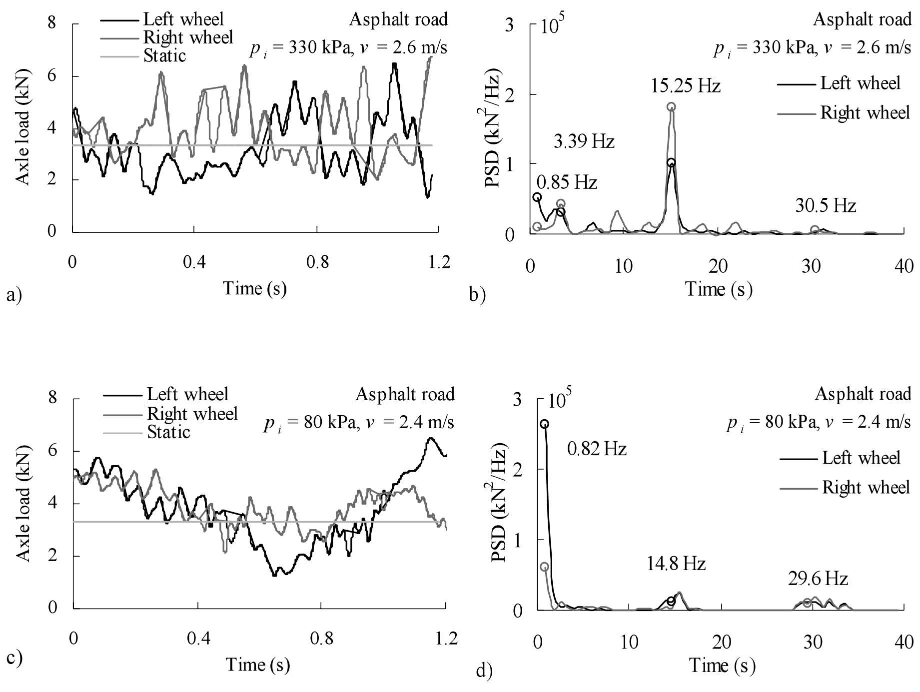


Fig. 10. Time histories and frequency composition of axle loads within one wheel rotation on asphalt road

approximately 0.6m/s resulting in deep wheel sinkage and tire slip, the behaviors of dynamic axle load showed a different trend. Comparing the form and amplitude of axle load it appears that the axle-load variation, indicated on hard ground (Figs. 10a, c), increased and decreased rapidly with high amplitude, this on soft ground (Figs.11a, c) fluctuated slowly with smaller amplitude. This implies that the vertical damping behavior of the soft soil reduced the effect of self-excitations due to tire lug and tire non-uniformity on the axle-load variation. The frequency compositions of dynamic axle load indicated that, for tire with high inflation pressure the tire lug strongly excited the axle-load variation at both the first -order frequency and a harmonics (f_{L1} = 3.7 Hz and 13 Hz), while the tire non-uniformity dominated the excitation at wheel frequency and its harmonics (f_w = 0.21Hz, 0.42 Hz and 0.83 Hz).

It should be noted that, deep wheel sinkage and tire slip would increase the eccentricity of the vertical soil reaction resulting in a considerable error for the measurement of dynamic vertical wheel load by the proposed method. An improvement of the measurement method has been made by utilizing rosette analysis to obtain the magnitude and direction of principle strain of a rear axle. Consequently, the magnitude and direction of resultant force applying to rear axle will be determined. The result will be presented in a further paper.

Root-mean-square (RMS) of axle loads within one rotation of the rear wheels of each treatment were calculated and are reported in Table 3. The RMS of axle loads of both the left and the right wheel was always higher than static axle load. No significant differences for the left wheel were found. Moreover, the RMS of axle load almost always increases as the tire pressure decreases for the all tests. This indicates that low-pressure tires may have more excitations on the

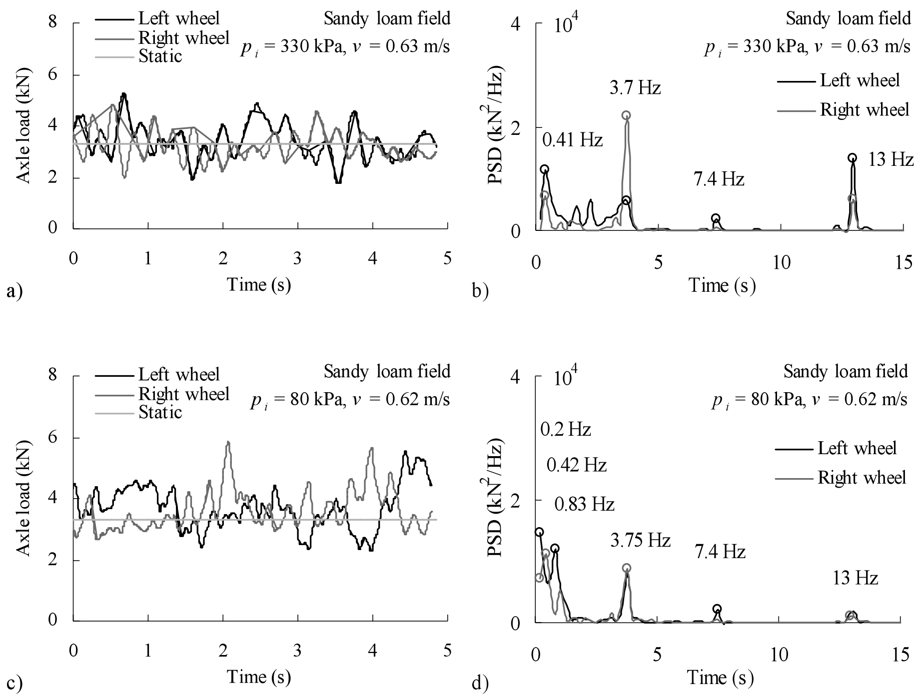


Fig. 11. Time histories and frequency composition of axle loads within one wheel rotation on sandy loam soil

Table 3 Values for the root-mean-square axle loads

		Asphalt road $\nu \approx 2.6$ m/s	Sandy loam $\nu \approx 0.6$ m/s
p_i = 330 kPa	Left wheel	3.56 kN	3.51 kN
	Right wheel	3.62 kN	3.31 kN
p_i = 80 kPa	Left wheel	4.08 kN	3.76 kN
	Right wheel	4.07 kN	3.66 kN

wheel-load variations. As inflation pressure of rear tire moving on asphalt road decreased from 330 kPa to 80 kPa, the RMS increased from 3.56 to 4.08 kN and 3.62 to 4.07 kN for the left and right wheels, respectively. When the tractor moved on sandy loam field, the RMS of axle load also increased from 3.51 to 3.76kN for the left wheel and from 3.31 to 3.66 kN for the right wheel as tire inflation pressure decreases due to a less soil surface smoothing effect of the tire with low inflation pressure.

IV. Conclusions

This paper introduced a simple method for monitoring transient axle load of a moving farm tractor and analyzed the influences of tire configuration and ground profile on axle-load variations. The tests were conducted on asphalt road and sandy loam field using a 2WD farm tractor at different tire inflation pressures. During the tests, the dynamic vertical load of the left and the rear wheels were measured by the proposed method and evaluated by wavelet and Fourier analyses. The main conclusions are as follows:

1. The proposed method for measuring the vertical soil reaction is comparatively simple and capable of monitoring the dynamic axle load as vehicle moves on different ground profiles.
2. The non-uniformity of driven tire strongly affects the axle-load variations at the first-order frequency and harmonics. This effect increases as the tire inflation pressure decreases.
3. The axle-load variation is excited exactly at or near to the first- and the second-order frequencies of tire lugs. During tests on the asphalt road, tire lugs predominately excite the axle-load fluctuation at high tire inflation pressure. Tire lugs have a small effect as the tractor moves on soft soil.

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農業トラクタの車輪動荷重の測定トランスデューサー に関する開発研究

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要　　旨

本研究では農業トラクタの区動後輪の動荷重を測定するひずみゲージに基づくトランスデューサーの機能原則・構造デザイン・カリブレーションを解明した．トランスデューサーの測定能力を検証するために，異なるタイヤ空気圧や地番の組み合わせで試乗実験を行った．実験結果より，走行時の車輪動荷重をリアルタイムで計測することが可能であり，車両の動特性や土壌と車輪の相互作用についても有益な資料を提供することができる．実験データの時間及び周波数領域から，車輪特性（空気圧，不均一性，ラグ数など）は車輪に作用する動荷重に大きな影響していることが分かった．アスファルトと土壌の上で走行時にタイヤの不均一性は空気圧が低いタイヤの動荷重を支配的に加振したが，ラグ数は空気圧が高いタイヤの動荷重を支配的に加振した．

［キーワード］車輪動荷重，ひずみゲージに基づくトランスデューサー，農業トラクタ