Measurement of vehicle-load using capacitance and acceleration transducers

Sanxu Yang¹, Wuqiang Yang²* and Yuanyuan Yang³

¹. Department of Physics, Shangqiu Normal College, 298 Wenhuazhong Road, Shangqiu, Henan 476000, China
². School of Electrical and Electronic Engineering, The University of Manchester, PO Box 88, Manchester M60 1QD, UK
³. College of Foreign Language, Henan Normal University, 46 Jianshedong Road, Xinxiang, Henan 453007, China

*E-mail:  w.yang@manchester.ac.uk

Abstract: Over-loading is a common problem in some developing countries. Currently, large and fixed measurement systems are used to measure the load of vehicles travelling on highways. This paper presents an on-vehicle measuring device, which is based on measurement of change in capacitance due to variation in distance between electrodes mounted on vehicles. The on-vehicle leaf springs are used as a key part of the weighing transducer. Acceleration transducers are used to measure the vehicle’s forward and the vertical accelerations. A feature of this on-vehicle measuring device is that it can provide both static and dynamic load measurements. The drivers can check the load in the cab, and the highway inspectors can check the load at any time and any place through radio communication, thus identifying over-loaded vehicles.

1. Introduction

In some developing countries, many vehicles are over-loaded. This causes many problems, e.g. dangerous and hence more accidents, and damaging road surface. Currently, two types of load measurement systems are commonly used on highway: (1) mechanical balance platforms and (2) axle-load detectors [1]. These two types of systems have the following problems: (1) they are fixed and hence can only measure vehicle-load at some location and at some time, (2) they are slow and hence cause long queue jam, (3) they are very large with complicated structure and are difficult to install, and (4) they are expensive to purchase and expensive to maintain.

The mechanical balance platforms can only provide static load measurement, while the axle-load detectors can only measure the load of vehicles at a speed lower than 5~10 km/h with a quite large error of ±5~30% [2]. If the driver of an over-loaded vehicle makes a trick by accelerating and then decelerating when he is passing an axle-load detector, the over-load cannot be found.

To solve the above problems, an on-vehicle measuring device based on capacitance measurement with acceleration compensation has been developed, which is described as follows.
2. Capacitance transducers

2.1 Mounting of capacitance transducers

The capacitance transducer designed for measuring vehicle-load consists of an upper unit and a lower unit (see Fig.1), each unit having a capacitance electrode and a shielding plate. The upper surface of the insulating layer of the lower unit is made into sphere shape for keeping the upper surface clean. A capacitance transducer is mounted upon each axle of a vehicle. The lower unit is mounted on the axle, and the upper unit under the vehicle frame.

When the load on the left side and the right side of the compartment is not balanced, the leaf springs on two ends of the axle are loaded differently, making the compartment slant (see Fig.2). To reduce the effect of slanting on measurement, the capacitance transducer is mounted right in the centre of the vehicle breadth, so that when the upper unit slants, the distance between the upper unit and the lower unit in the centre does not change.

![Figure 1. Structure and mounting of capacitance transducer (1– vehicle frame, 2– upper plate, 3– leaf spring, 4– lower plate, 5– axle)](image1)

![Figure 2. Non-parallel plate capacitor](image2)

Different vehicle-load causes different pressure on the leaf springs, different distance between the upper and lower units and hence different capacitance. The load of a vehicle, which either keeps still or is running at a constant velocity is

\[ m_i = \Sigma m_{L,i} \]  

(1)

where, \( i \) is the number of vehicle axles, and \( m_{L,i} \) is the load of each axle.

If the capacitance of all axles under different \( m_{L,i} \) is measured in advance, the corresponding \( m_{L,i} \) can be derived from the capacitance measured under different load, and then the vehicle-load can be calculated using equation (1).

2.2 Design of capacitance transducers

(a) Height of capacitance transducer. The distance between the inner surfaces of the upper and lower units is chosen to be 10~20 mm larger than the worst cast of distortion of the leaf springs, to make sure that the upper and lower units do not collide with each other.

(b) Area of capacitance electrodes. To achieve high sensitivity, the capacitance between the two units is chosen >0.5 pF when the distance between the upper and lower capacitance electrodes is at maximum. When the vehicle is moving, there is a little excursion of the axle relative to the vehicle frame. To reduce the effect of excursion on the measurement, the side length of the upper electrode is chosen longer than the lower electrode.

(c) Shape of capacitance electrodes. When the load in the left and right sides of the compartment...
is not balanced, the upper unit would slant (see Fig.2). The non-parallel-plate capacitance can be derived from the formula of parallel-plate capacitance as follows.

\[
C = \int_0^x \frac{\varepsilon b \, dx}{h + \frac{\varepsilon \, x}{c}} = \frac{\varepsilon \, cb}{e} \ln \left( 1 + \frac{e}{h} \right) \text{ (F)}
\]

where, \(\varepsilon\) is the dielectric constant of the medium between two plates, \(c\) is the length of the upper electrode in the horizontal plane along \(x\) axis (m), \(b\) is the breadth of the upper electrode (m), \(e\) is the height of right end of the upper electrode relative to the left end (m), and \(h\) is the height of the left end of the upper electrode.

Both calculation using equation (2) and tests indicate that, with a rectangular flat electrode, if \(a > b\) in Fig.2, the relative error compared with parallel-plate capacitance is small. If \(a < b\), the relative error is large. Therefore, to reduce the error caused by the slant of electrodes, the long side is mounted along the vehicle width direction (see Fig.1), and the short side along the other direction.

### 2.3 Capacitance measuring circuit

The smallest capacitance value between the capacitance electrodes is designed to be 0.5 pF, while the stray capacitance is much larger than the capacitance being measured. Therefore, a stray-immune capacitance measuring circuit is needed. A four-phase charge transfer circuit [3] has been used in this system, with a resolution of 0.001 pF, and sensibility of >1 V/pF.

### 3. Operational principle of system

Let’s take a vehicle with two axles as an example. The overall vehicle-load measurement system is shown in Fig.3, which consists of two parts: an on-vehicle device and a handset.

Figure 3. Overall vehicle-load measurement system
Two on-vehicle capacitance transducers are mounted on the front and back axles, respectively. The capacitance measuring circuit converts the capacitance into a voltage. Two full-featured 2-axis acceleration transducers (ADXL202AE from ADI Co) are used, with the “Y” axis measuring the forward acceleration $a_H$, and the “X” axis measuring the vertical acceleration $a_V$. The capacitance and acceleration signals are sent to a micro-controller after A/D conversion. The micro-controller compensates non-linearity and integrates the signals from the transducers on two axles and gives the vehicle-load. The load value is amended according to the signals from the acceleration transducers and then sent to an on-vehicle digital displaying device. A radio communication set receives commands from the handset, sends the load value to the handset, and sends vehicle type, vehicle identification number to the handset, if demanded.

A 4-channel, 12-digit A/D converter (ADS7824) is used for data acquisition. A micro-controller (P89V51RD2) is used for data processing, which contains 64 kB Flash and 1024 bytes RAM. The program is written in assembly language.

As shown in Fig.4, after the system is switched on, the micro-controller and peripheral cells are initialised. The signal-acquisition and A/D conversion program is called to acquire the signals from the capacitance transducers and the acceleration transducers on both the front and back axles. The analogue signals are converted into a digital form by ADS7824. The micro-controller collects the digital signals via a parallel interface of ADS7824. In the data processing program, the front and back axle load data are obtained by a looking-up table.

The handset is held by a highway inspector. The radio communication set sends signals to the on-vehicle device to activate it, and receives data from it. The micro-controller system receives the data and sends them to the displaying device. It can also communicate with a PC.

4. Tests

4.1 Effect and compensation of hysteresis

The tests were carried out on a pick-up truck with a rated load of 500 kg. The truck has 2 axles, 4 wheels and leaf springs. During the static test, the truck was kept level, with two wheels of each axle on a platform scale vertically. The axle weight was read from the platform scale, and the output of the capacitance transducer was acquired via an USB interface to a Notebook [4]. From the recorded data, the static relationship between the back axle transducer output and the load is drawn, as shown in Fig.5. From Fig.5, it can be seen that if the load increases gradually from 0, the output of the capacitance transducer increases from the lowest point $A$ to the highest point $B$, along the Upward Curve. If the load decreases gradually, the output decreases from $B$ to $C$, along the Downward Curve. If the load increases again, the output increases from $C$ to $D$ and then to $E$, close or overlapping the Upward Curve. If the load decreases again, the output decreases from $E$ to $F$ and then to $C$, close or overlapping the Downward Curve.

The Upward Curve and the Downward Curve do not coincide with each other, indicating the hysteresis behaviour of the leaf springs, with the largest error of 14%. If the average curve is used as the static relationship between the transducer output and the load, the maximum error due to hysteresis can be reduced to 7%. Such a large error is still not acceptable and hence software compensation is

![Figure 4. Program flow chart](image-url)
needed. Separate looking-up tables are made for each of the axles based on the Upward Curve and Downward Curve. Before looking up the table, it is necessary to identify if the vehicle-load is increasing or decreasing.

The hysteresis problem is not a big issue with a moving vehicle because of vibration. If the vehicle is moving at a constant speed, the relationship between the transducer output and the load follows the Upward Curve in Fig. 5. From the output of the acceleration transducer in the vertical direction, it can be known whether the vehicle is moving or still. If the load is decreasing and the vehicle is still, the Downward Curve is used in the looking-up table. If the load is increasing or the vehicle is moving, the Upward Curve is used. The next is to add the front and back axle load values together.

According to Fig. 5, during vehicle-loading, when the Upward Curve reaches point E, which is lower than the highest point B, and the unloading starts, the unloading transition curve, EF, appears, which is close to and then overlaps the Downward Curve. During unloading, if the vehicle is loaded again, a loading transition curve appears, which is close to and then overlaps the Upward Curve (e.g. GH). To save the storage space in the EMS memory by reducing the number of look-up tables for the transition curves, adjacent transition curves, which are similar in shape, are saved as one looking-up table.

When vehicle-load is increasing, the load value obtained after each data processing procedure is stored in an EMS memory. If load decreases from point E (see Fig. 6), the corresponding look-up table for the unloading transition curve is first checked according to the decrement in the transducer output voltage, $\Delta U_1$, to acquire the decrement of load $\Delta m_1$. Making use of $m_E$, which was stored in the EMS memory beforehand, $(m_E - \Delta m_1)$ is compared with $m_J$, which was obtained by checking the Downward Curve look-up table. If $m_E - \Delta m_1 > m_J$, $(m_E - \Delta m_1)$ is chosen to be the actual load. If $m_E - \Delta m_1 = m_J$, the Downward Curve look-up table is checked.

When vehicle-load is decreasing, the load value obtained after each data processing procedure is also stored in the EMS memory. If load increases from the point G, the corresponding look-up table for the loading transition curve is first checked according to the augment in the transducer output voltage, $\Delta U_2$, to acquire the augment of load $\Delta m_2$. Making use of $m_G$, which was stored in the EMS memory beforehand, $(m_G + \Delta m_2)$ is compared with $m_K$, which was obtained by checking the Upward Curve look-up table. If $m_G + \Delta m_2 < m_K$, $(m_G + \Delta m_2)$ is chosen to be the actual load. If $m_G + \Delta m_2 = m_K$, the Upward Curve look-up table is checked.

![Figure 5. Static relationship between back axle transducer output and load](image)

![Figure 6. Hysteresis compensation](image)
4.2 Effect and compensation of acceleration

In the tests, 300 kg load was placed evenly in the front and middle parts of the compartment. During the accelerating and braking processes, data are collected and processed. The relationship between the load and acceleration is shown in Fig.7. When the vehicle was braking, the load on the front axle increased and the load on the back axle decreased, and the whole vehicle load increased. When it was accelerating, the load on the front axle decreased and the load on the back axle increased, and the whole vehicle load decreased. Comparing \( a_H = 0 \) with \( a_H = -4 \text{ m/s}^2 \), the load on the front axle, which was measured by the capacitance transducer, increased 122.5\%, the load on the back axle decreased 60.7\% and the whole vehicle load increased 14.9\%. When \( a_H = 1.8 \text{ m/s}^2 \), the load on the front axle decreased 55.7\%, the load on the back axle increased 14.6\% and the whole vehicle load decreased 14.4\%. It is concluded that acceleration has a big effect on the vehicle-load measurement and software compensation is needed.

The acceleration value \( a_V \) was nearly 0 when the vehicle was still. When the vehicle was moving, \( a_V \) varied dramatically, but its average value was still nearly 0. Therefore, vertical acceleration has little effect on the vehicle-load measurement. Whether a vehicle is still or moving can be judged by \( a_V \).

The output of the acceleration transducer in the forward direction of the moving vehicle is first converted into a digital form. Based on this digital value, it is necessary to check the relative error of load weight. Then the load of the whole vehicle is amended. The vehicle-load is displayed by a 4-digit, 7-segment LED.

5. Conclusion

A vehicle-load measurement system described in this paper can be used for both static and dynamic load measurement, while most of the current measuring instruments cannot do so. It can measure the load of a fast-moving vehicle. With a rather large change in acceleration, 2\% accuracy can be achieved, which is well below the required ±6% [2]. Because the system can perform dynamic measurement, vehicle-load can be measured without stopping, thus the vehicle-passing rate can be improved and the over-loaded vehicles can be monitored effectively.

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References

[1] G Y Duan, X X Xie, X R Zhang, Research of the test for highway dynamic weighing system, Measurement Technique, 4, 2006, pp 9-12
[2] S X He, The history, current condition and prospect of the vehicles dynamic weighing technique, Journal of China & Foreign Highway, 24 (6), 2004, pp 104-108
[3] S X Yang and W Q Yang, A portable stray-immune capacitance meter, Review of Scientific Instruments, 73 (4), 2002, pp 1958-1961
[4] Y Xie, S S Xu and S X Yang, Development of the system for measuring capacitance weighing transducer’s static characteristics, Electrical Measurement & Instrumentation, 43 (9), 2006, pp 21-24