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DYNAMIC AXIS SCALE WITH HIGH ACCURACY FOR HIGH SPEED MEASUREMENT OF VEHICLE MASS

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Abstract – As the demand for measuring objects in motion is increasing the need for a system to measure vehicles has been developed to measure mass of vehicle in dynamic motion. Using the concept of measuring the inertial mass of a moving vehicle instead of gravitational mass has proven successful for a purely dynamic problem.

Since the measurement of a dynamic motion requires high speed sampling a scanning speed of the signal information is set at 1μs/sample. This is to ensure the movement of the structure is captured to full extent.

Using dynamics, the inertial mass correlation between the Dynamic Axis Scale and the vehicle can be calculated from the dynamic state of the vehicle in motion. The achieved result is instantaneous and currently reliable from 0 km/h up to 80 km/h with an high accuracy with ± 5% of error tolerance of the measured mass provided the vehicle mass is restricted to EU regulation for public roads of 20 ton. Measuring the momentum of the vehicle and calculating the speed to the relation of mass, it can verify the dynamic calculation and thus confirm the inertial mass of the vehicle.

Keywords: dynamic mass, momentum, vehicle mass measuring

1. INTRODUCTION

Measuring the mass or weight of a moving vehicle on public roads faces many problems. When the velocity increases the disturbing forces acting upon the object and measuring device becomes so great that using load cells or piezoelectric transducers as force actuators limits high accuracy of the results. This can be seen in current weigh-in-motion, because the sum of forces applied on the measuring device consists of more than only the force of the vehicle itself. These additional forces are vibrational forces and impulses; therefor it is difficult to determine the force contributed by the vehicle alone. This is the case when the measuring device is based solely on force sensing.

Conventional weigh sensing is based on gravitational mass. Gravitational mass is the subject of empirical studies over several thousands of years and is derived from gravitational force which varies at different locations around the Earth. To be able to measure the static gravitational force it is necessary to have perfectly still condition. The Earth crust has an Eigen frequency of 1/54 Hz which makes it impossible to have a perfect static condition on Earth. When using the gravitational mass as subject for dynamic weighing, the fundamental concept of measuring a static force during dynamic states becomes unclear. Therefor the authors have taken the concept of mass according to Jim Hammer [1] to full extent. Dynamic weighing should measure the mass which is based on dynamic theory of mass from Newtonian mass, the inertial mass.

2. CURRENT TECHNOLOGY

The Dynamic Axis Scale (DAS) is a new applicable measurement system based on multiple photo detectors and optical units in a mechanical structure, with response time of less than 1μs, to measure the instantaneous vertical force and instantaneous vertical acceleration of the running vehicle and in addition the vertical movement of the combined system of the DAS and the running vehicle to eliminate external forces. The analysing system samples the acquired signal at a rate of 1μs/sample, assuring the mechanical structure motion to be captured.

2.1. Dynamic Axis Scale Mechanical Structure

The DAS structure is based on four Dynamic Load Sensors [2] (DLS), where two DLS are linked together by a frame and a top plate to form one side of the DAS. Each of the top plates is designed to receive the dynamic force of one tire of each axis from a vehicle. Each side of the DAS is attached to a base plate that makes the sensor system sturdier, which is shown in Fig. 1.

The construction of DAS was designed to measure a vehicle target mass of maximum 20 ton. This makes each DLS constructed with a target mass of 5 ton. The measuring system is constructed to withstand an overload of the target mass by a factor of two.

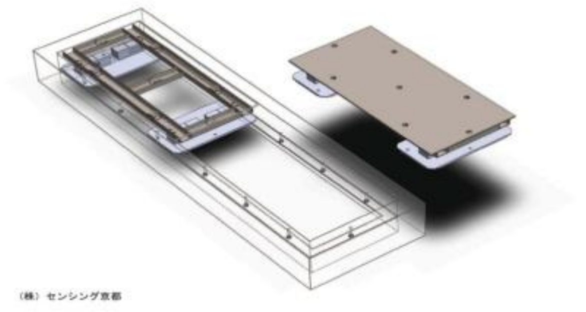

Fig. 1. Dynamic Axis Scale structural design model (3200 x 500 x 90 mm).

The DLS is constructed with two force sensors and one kinematics sensor. Correlation between the three sensors gives the possibility to measure dynamic states of a moving object.

2.2. Signal Processing

The sensors of DLS type are used for collecting the movement of the application specific structure. These signals from four DLS systems/one DAS system are amplified as analogue signals and then digitalized to be filtered by the FILTER stage. The signal package is then going through signal processing stages including un-modelled theory, and momentum based theory, which is shown in Fig. 2.

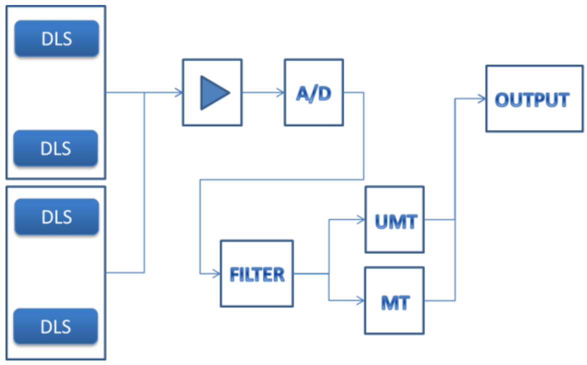

Fig. 2. Structural movement of the four DLS in the DAS system is amplified, digitalized, filtered and signal processed through un-modelled (UMT) theory and momentum theory algorithms.

The A/D converter is sampling at the speed of 1µs/sample from each sensor, this is to ensure that as much of the phenomena is measured from the structure of DAS. High speed measurement gives a high accuracy of determine the speed and direction of the vehicles tires, based on the orientation and position of the DLS.

2.3. Un-modelled Theory

Information collected from the sensors and digitalized through the process of A/D converting leads to the calculation and estimation of the mass of the object in question. E. Tada with the base of inertial dynamic theory formed the un-modelled theory and created a program that can use signals from any type of sensor and then apply the algorithm and receive a result with high accuracy. This algorithm is based on the energy equilibrium that Lagrange formulated in (1).

$$\frac{d}{dx}\left(\frac{\partial T}{\partial \dot{z}}\right) - \frac{\partial T}{\partial z} + \frac{\partial U}{\partial x} - \frac{\partial W_d}{\partial z} = \frac{\partial W_{ex}}{\partial z} \qquad (1)$$

Where T is the kinematic energy, U the potential energy, W_d is the viscous damping work and W_d is the work of external forces [3] [4] [5] [6].

2.4. Momentum Based Theory

The vertical force applied on the DAS by a horizontally moving vehicle is measured by high speed sampling of the sensors. The time it takes for a vehicle to arrive to the settling level of the system with a high damped system depends on speed. If the speed is increased twofold the settling time is then half of before. The new gradient coincides with the gradient of the case of a vehicle with the slower speed and a twofold mass, as shown in Fig. 3.

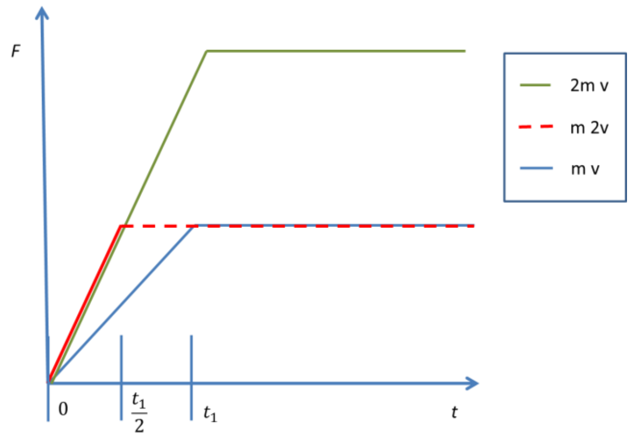

Fig. 3. Momentum lines from the relation $p = mv$. From measuring the speed and then integrating the impulse force the mass can be acquired.

This relation is directly correlated to (2)

$$p = mv \qquad (2)$$

With the assumption that the mechanical structure used for the specific application is designed for a specific area off mass.

2.5. Characteristics of the System

DAS compared to conventional dynamic weighing systems such as WIM and piezoelectric measurement system is shown in Table 1. It is then clarified that not only the systems are based on different technology, but also on different scientific theory and approach.

Table 1. Dynamic Weighing Systems

	DAS	WIM	Piezoelectric measurement system
Type of Mass	Inertial Mass	Gravitational Mass	Gravitational Mass
Principle of measuring	Newton's Law of Motion	Empirical Laws	Empirical Laws
Physical Property	Absolute	Relative	Relative
Measured Object Condition	Moving, high speed and at rest	Moving and at rest	Moving
Measuring conditions	No vibrations to high vibrations	No vibrations to Low vibrations	No vibrations to high vibrations
Additional Information (1 Sensor)	Speed Momentum relation	-	-

This concludes the broadness of the DAS to be able to cover the application areas of current measuring systems on the market today in one single package.

3. APPLICATION AND FIELD TESTING

Fall 2009 the authors had the opportunity to use a large outdoor test facility to perform extensive running tests of the DAS system with vehicles spanning from 2 tons to 22 tons. The test vehicles could by precise manoeuvring achieve a constant speed of 60 to 80 km/h depending on the mass of the vehicle, as shown in Fig. 4.

Fig. 4. Field testing with the DAS system. Truck with 16 ton mass used for running test up to 70 km/h.

3.1. Dynamic Mass Calculation

Correlating the force sensor signals with the kinematics sensor signal and applying numerous complex algorithms the estimation of a vehicle mass can be presented at a high accuracy with relative error of ± 5%.

The force sensors monitor the movement of the contact point between the vehicle and the measuring system. The kinematics sensor monitors the vibrational movement of the combined system and detects the external forces applied on the total system. Thus by correlation calculation, the inertial movement applied from the vehicles inertial mass can be extracted from the signals, shown in Fig. 5.

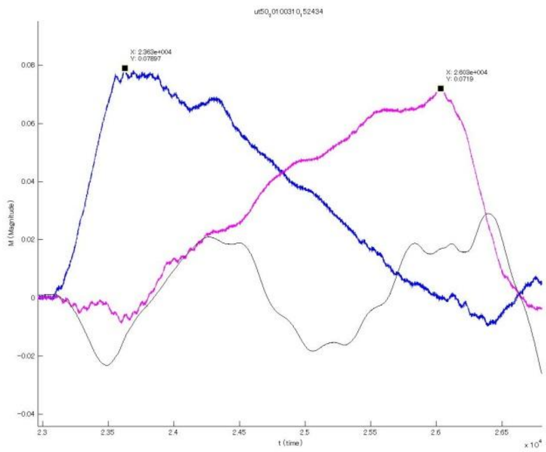

Fig. 5. Force sensor signals, blue and pink, and kinematics sensor signal, black, from a 4 ton truck running at 50km/h.

3.2. Momentum Based Mass Calculation

Applying the momentum theory on the signals acquired from the DAS system including the specific structure of the system itself the mass of a vehicle can be measured before it has left the measurement system.

The time period of the external force acting upon the system is measured from the kinematics sensors vertical movement during the applied force change. Force applied from a vehicle is measured from the slope of the force sensor signal during the time period, shown in Fig. 6.

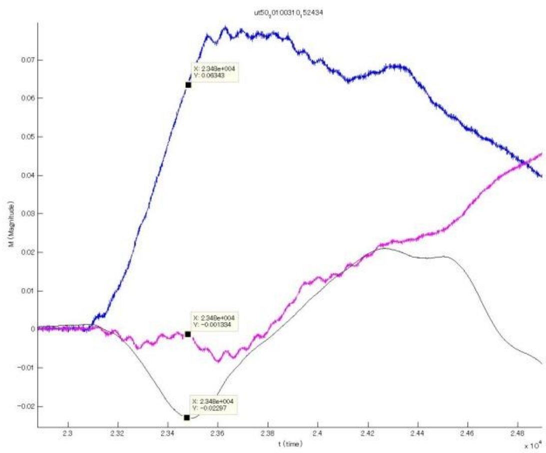

Fig. 6. Changing force from a vehicle is measured from the slope of the force sensor signal, blue and pink. The time period of the force building up is extracted from the kinematics sensor signal, black.

3.3. Endurance Test

Performing an endurance test of the DLS with full load at 10 million times proves that the structure has a high reliability. Displacement of the sensor is calculated to be 0.1 mm after the full 10 million times as shown in Fig. 7.

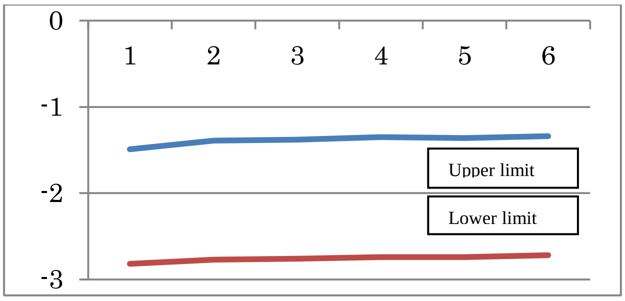

Fig. 7. 20 Hz, 6 days of endurance test with full load, 10 million times and the result of deformation less than 0.1mm.

4. CONCLUSIONS

Creating a dynamic measurement system on the principles of Newtonian dynamics gave the result with an advantage to modern dynamic weighing systems.

From the extensive field testing resulted in the verification of the un-modelled theory to be suitable for this application with unnoticeable changes up to the speed of 80 km/h. At higher speed the new application specific algorithm using momentum proved to be sufficient for the speeds up to 80 km/h, both algorithms with an accuracy of ±5% error tolerance.

5. EFFECTS OF THE SYSTEMS

The first intended area of application for the DAS was the instantaneous calculation of running vehicles mass. The application changed naturally to what the name now implies to measure the amount of axes that crosses one DAS system. Additional information extracted from the system made it possible to acquire the velocity of a vehicle, and then derive that to speed. These three important information points gives rise to the basic information required for a Dynamic Traffic Management (DTM) system. This can be applied on city level, country level or pan-continental level. Useful for redirecting heavy transports away from damaged road or even give heavier transports a higher toll fee. Detecting vehicles with a speed higher than regulations to fine them accordingly is a welcome effect.

Evolving the basic information used for DTM systems to include Dynamic Traffic Flow based on the efficiency the vehicles travel in relative to the planned flow of the traffic.

6. FUTURE WORKS

In order to make it possible to construct a measurement system that can measure the mass of vehicles at speed up to 150 km/h and increase the accuracy to ± 1% error tolerance, it is required to make a stronger structure, and make it smaller to maintain the cost of the system. Production of a thin type DAS (DAS TT), shown in Fig. 8. and Fig. 9. The new hardware is planned for endurance field testing summer of 2010.

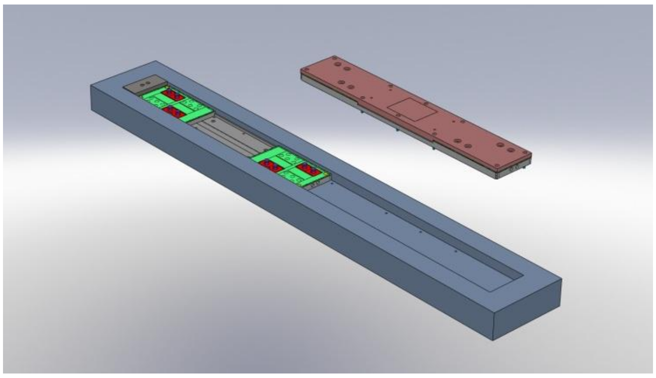

Fig. 8. Dynamic Axis Scale Thin Type structural design model (3200 x 300 x 75 mm).

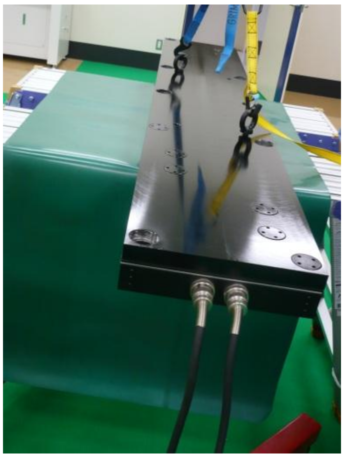

Fig. 9. Dynamic Axis Scale Thin Type before endurance field test.

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