Electrical Wind Tunnel External Balance System

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Abstract

Aerodynamics force measurement for testing vehicles in wind tunnels is measured by a six component force balance system embedded in the turntable (wind tunnel external balance). At modern wind tunnel facility for vehicle testing, one challenge is to cope with heavy tare weight created by equipment such as the moving belt system and weight of vehicles. To cope with this issue, conventional external balance systems use a mechanical balance system in order to cancel the tare weight. The new here introduced balance system uses electronics technology to eliminate the need for a mechanical system and measures six component force directly at the sensor.

1 Introduction

Due to the steady raising requirements on fuel economy or CO2 reduction, vehicle aerodynamics are becoming more and more important for the all over vehicle efficiency. Accurate and repeatable measurement of the aerodynamic forces during the vehicle development process is one of the key development issues for achieving fuel economy improvement. More and more technologies for measuring vehicle aerodynamics under realistic conditions are applied to wind tunnel facilities. One example is to install a steel belt system on the floor level in order to improve the aerodynamics boundary layer especially under vehicle flow condition. This technology was first introduced to model scale wind tunnel systems with a large single belt system which covers the total vehicle footprint area. This has the advantage of creating realistic boundary conditions. However, with this kind of system, the force measurement sensor has to be installed inside the model vehicle. These systems are called internal balances. An additional strut which is connected to the model vehicle from above fixing the model vehicle inside the wind tunnel and connects to the internal balance had to be applied. The strut is carefully designed to have minimum aerodynamic influence; however it is still a disturbance obstacle for aerodynamics and therefore will have a influence on the aerodynamic force. For passenger car aerodynamics measurement, 5 belt systems are widely used. These systems have the advantage that the vehicle fixing can be done by relatively small Rocker panel fixing system, which have relatively small influence on the aerodynamics of the vehicle. 5 belt system have a large centre belt which goes under the centre position of the model vehicle and 4 small belt systems which each support a wheel of the vehicle. These small belt systems are called wheel drive unit (WDU) and allow to measure aerodynamic force with spinning wheels. The centre belt guarantees good vehicle under floor flow conditions. At the same time, these designs allows to use a large balance system which is integrated into the turntable so called external balance. Task of the external balance is to measure aerodynamics forces introduced to the vehicle with very high resolution. The challenges with this external balance system are;

1. The balance has to measure aerodynamic lift force (Fz) with high resolution in a heavy tare weight(which is coming from the vehicle itself and all structure needed to lead the force to the balance including the WDU, Rocker arm system). Classically, some mechanical system are used to cancel out tare weight and measure only the aerodynamic force using load cell sensor.
2. Using one axis load cells to measure each component force separately makes the external balance system very complex.
3. Due to these mechanical nature of the system, the eigen-frequency of the balance system is typically less than the 10Hz and the total system itself vibrates at during wind load conditions.
4. The size of the balance becomes large and unwieldy. Maintenance of the balance consumes time.
5. In order to eliminate force fluctuation occurring due to vibration, a long integral time filter had to be applied to the measurement.
6. Low eigen-frequency with long integral time filter was not suitable for dynamic aerodynamics measurement.

2 Introducing an electrical balance system to wind tunnels

The main idea for an improved external balance system is to integrate the measurement of all components in one six component sensor which offers high range ability at lift force without using a complex mechanical system for tare compensation. This solution is achieved with an electrical balance system which is shown in figure 1.

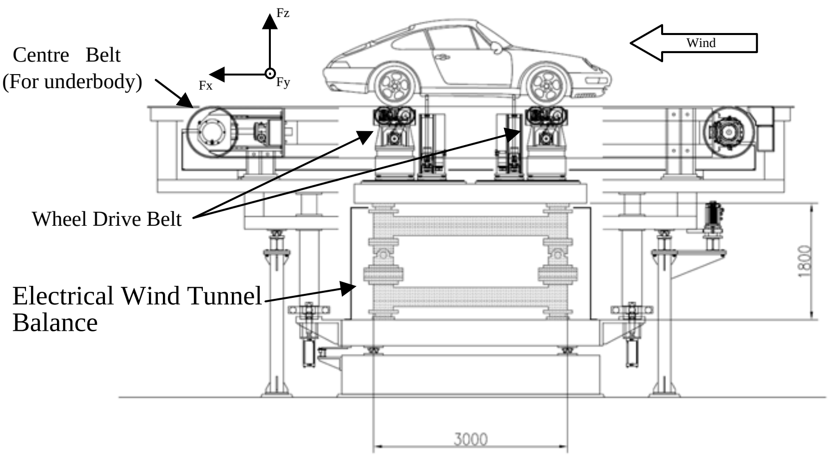

Figure 1

Figure 2 shows an external balance for wind tunnel applications. Four sensor cells (6 component force sensor) are integrated to one sensor plate frame to create one large six component force sensor.

The distributed force measurement method is introduced with each sensor cell.

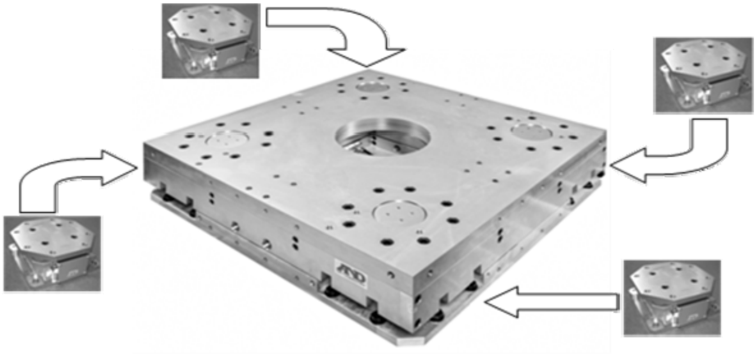

Figure 2

Advantages for wind tunnel applications:

1. Very stiff sensor → High eigen-frequency and durability
2. Simple design → Requires less maintenance
3. Compact size → Easy to install in a wind tunnel facility

3 Elemental technologies for electrical wind tunnel external balance systems

3.1 Distributed force detection sensor

Conventional six component force sensors are designed to detect six component forces independently. Therefore the sensor is designed to eliminate other component forces as much as possible and detect only the target component force. (e.g. By strain gauge or load cell) However, this method has the disadvantage of cross talk errors and electrical noise issues. Therefore, high measurement range ability is difficult to achieve. Therefore conventional method is not suitable to overcome the above mentioned challenges for wind tunnel external balance application.

The objective of the distributed force detection method is to detect force as vector. Eight strain gauge bridges are applied to a spring element. The spring element of the sensor cell is designed to detect the distributed force of applied external forces. Therefore each of the strain gauge bridges has sensitivity to any external force. Using this approach, one single strain gauge bridge information does not express useful physical data, but combining all bridge signals allows re-composing the distributed forces will provide the force information as a vector. This means the eight strain gauge bridge signals provide each component force information. In another words, eight pieces of force information are used to compose one component of the external force.

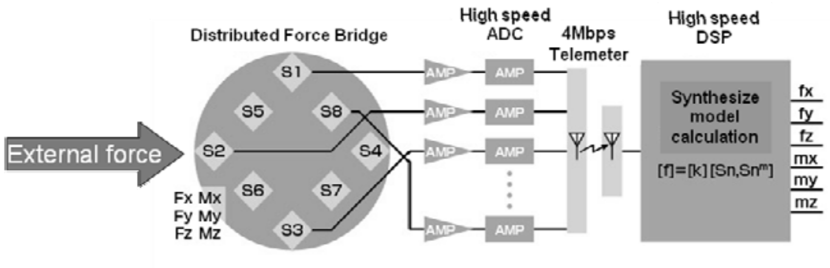

Figure 3

Therefore, each component force contains eight times more information than using conventional method. In order to systematically process the measurement system, electronic data processing technology is essential.

As shown in Figure 3, each strain gauge signal is individually converted into a digital signal using high speed A/D converters. The digital data is transferred to a digital signal processing (DSP) unit. Data transfer via a telemetry close to the sensor guarantees galvanic isolation of the sensor unit. Digitalized sensor signals are re-composed as a force signal using a force re-composition calculation matrix which is processed by a high-speed digital signal processing unit. Also, a high-speed telemetry data transfer unit and high-speed digital signal processing unit enable the system to extract six component force data with a 1 kHz sampling rate which is suitable for a wind tunnel external balance system.

3.1.1 Small angle variance of force vector measurement with component force measurement.

With the distributed force measurement method, the electrical wind tunnel external balance system is capable of detecting a force vector angle with a high degree of precision.

One example of this is detection of the force vector angle from Fx and Fy. First, a force should be loaded to an external balance with a Fx calibration device, with the turntable then turned slightly to a small degree. From the Fx and Fy values, the applied force vector angle can be calculated.

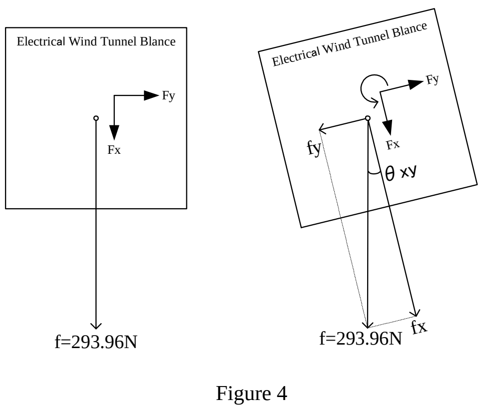

Figure 4

$$\theta_{xy} = \tan^{-1}\left(\frac{fy}{fx}\right) \quad (1)$$

Below is the data from applying a constant force and turning the turntable to a small degree:

Turntable: 0°

	fx[N]	fy[N]	fz[N]	θ xy[deg]
1	293.95	0.03	0.18	0.006
2	293.93	0.03	0.02	0.006
3	293.94	0.02	0.04	0.004

Turntable: -0.1°

	fx[N]	fy[N]	fz[N]	θ xy[deg]
1	293.97	-0.52	0.07	-0.101
2	293.95	-0.52	0.13	-0.101
3	293.97	-0.50	0.18	-0.097

Turntable: -0.4°

	fx[N]	fy[N]	fz[N]	θ xy[deg]
1	293.95	-2.05	0.10	-0.400
2	293.95	-2.07	0.00	-0.403
3	293.95	-2.07	0.06	-0.403

From the measured force data, the force vector angle shows the same angle as from the turntable.

A conventional load cell external balance detects each component force directly. This means a single load cell is optimized to detect a single component force such as Fx, Fy and Fz, and does not detect force as a vector. For such a balance, the mechanical design of the external balance is optimized to eliminate cross talk. Therefore, small angle detection is not possible as it is dismissed as cross talk. With the distributed force detection method, force is detected as vector and therefore has the advantage of detecting not only the component force, but also small angle changes in the force measurement.

3.2 Mechanical sensitivity and electrical sensitivity

Wind tunnel external balance applications require wide range ability for lift force measurement. The expected tare in a model wind tunnel with a moving belt system is around 2,500N, required measurement range for the lift force is 2,500N and required measurement resolution is 0.5N. This means the total sensor range for lift force direction is over 8,000N, including the overload safety margin, and the sensor needs to detect at least 0.25N, which requires 1/32,000 resolution. For this range ability of a sensor, signal noise reduction is one of the essential items.

Basically, sensor sensitivity is proportional to Mechanical sensitivity times Electrical sensitivity. In order to have high eigen-frequency for dynamic measurements, the mechanical design of the spring element needs to be very stiff. This results in a reduction of the mechanical sensitivity. In order to achieve above mentioned high resolution, increasing electrical sensitivity is necessary. However, this requires very low noise measurement signal, advanced temperature compensation technology and high resolution A/D conversion technology.

3.2.1 Eigen-frequency

Measured Eigen-frequency of balance with hammering test

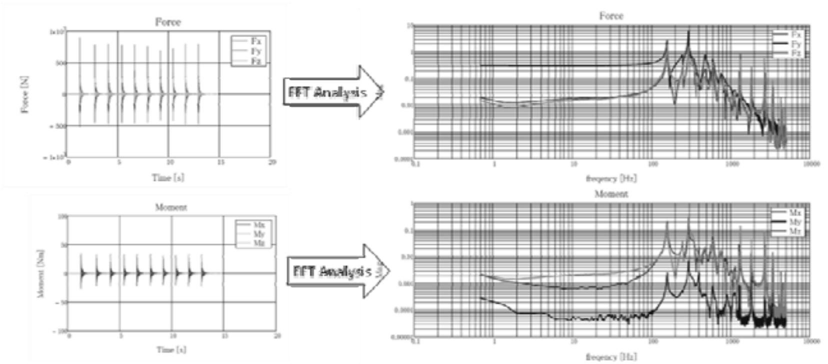

Figure 5

The lowest peak was around 150 Hz. However, for wind tunnel applications, tare has to be considered. Therefore, the same test has been conducted with 2.5kN tare. Figure 6 shows the frequency characteristics.

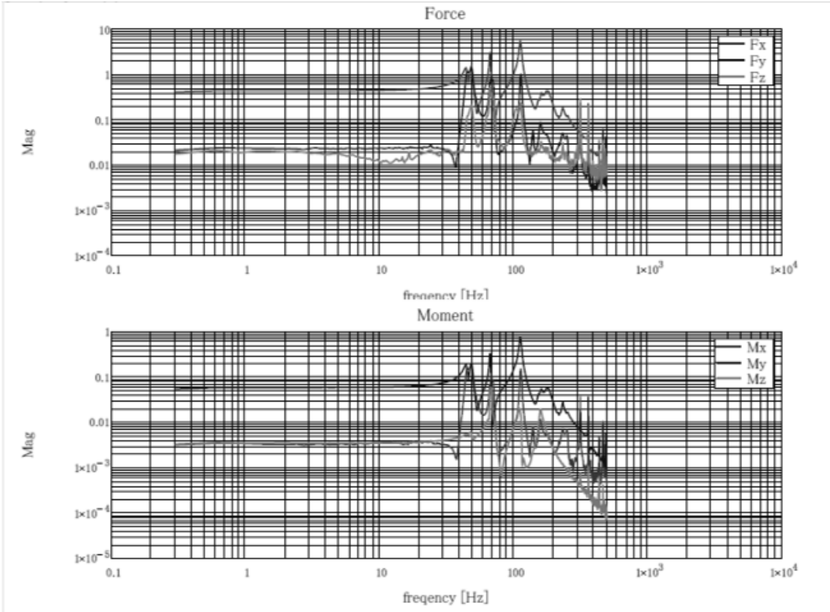

Figure 6

With 2.5kN tare, the eigen-frequency of the total balance system is around 42Hz.

Resonance frequency of a 1/3 model vehicle is under 20Hz. Therefore, eigen-frequency of 42Hz for a balance system is sufficient for measuring the dynamic effect of aerodynamics.

3.2.2 Lift force static measurement

The most critical measurement in a wind tunnel application is lift force (Fz) measurement, since heavy tare is applied to the measurement. Tare weight is 2,500N.

Figure 7 shows linearity performance under full range conditions (0 to -2,500N)

Figure 8 shows linearity performance under small range conditions (0 to – 100N)

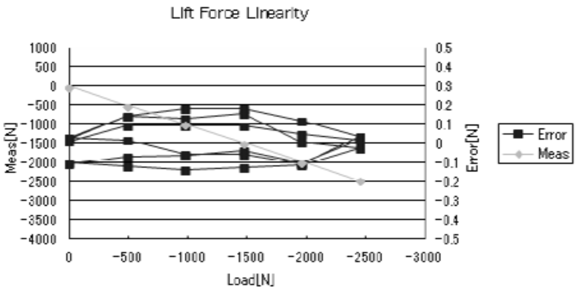

Figure 7

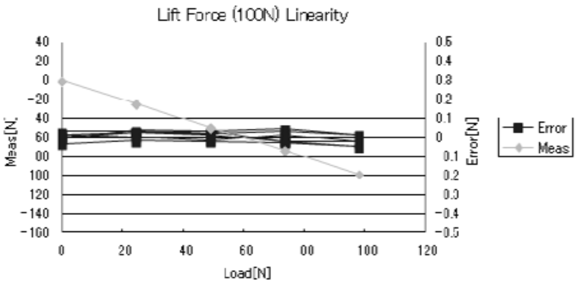

Figure 8

At full span (0 to -2,500N), linearity is in the range of ±0.3N. For small span (0 to -100N), linearity is in the range of ±0.1N.

3.3 Noise reduction

3.3.1 Four elements strain gauge and temperature distribution

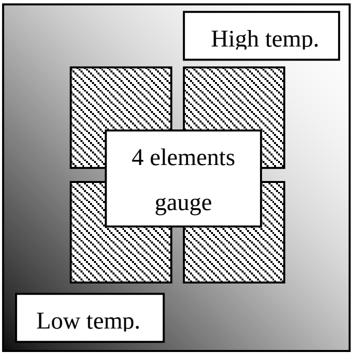

Figure 9

The distributed force measurement method allows force measurement with just a small area of spring element. This makes it possible to construct a strain gauge bridge over a small area. Therefore, a four element strain gauge can be manufactured from the same gauge material, which makes the bridge robust against temperature effects. (Gauge materials have the same relative temperature coefficient.) Also, since the gauge layout is within just a few millimetres in width, temperature variance across the four strain gauges is quite small. Therefore the sensor itself is intrinsically robust against temperature effect. Due to this this layout characteristic the sensor is robust against even dynamic temperature change.

3.3.2 Parallel sensing and over sampling effect

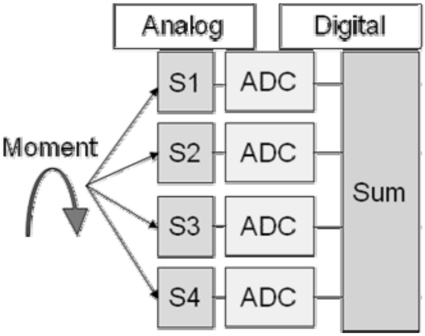

Figure 10

Noise from the strain gauge bridge circuit and A/D converter becomes random white noise from temperature noise when eliminating noise from the power source and clock noise. Random white noise has a $1/\sqrt{N}$ effect by the averaging and superposition method. The distributed force measurement method will measure a single component moment with four strain gauge bridge circuits (parallel sensing). The bridge signal is directly converted to a digital signal and summarized and averaged digitally by the DSP unit. As a consequence, random white noise is halved ($1/\sqrt{4}$) and the moment signal noise ratio (S/N) is doubled. The internal sampling rate is oversampled eight times over the maximum sampling rate of the balance system. From this oversampling effect, noise reduction is a function of $1/\sqrt{\ }$ of the oversampling ratio (internal sampling/output sampling). Therefore, from an eight times oversampling effect, white noise is reduced to almost 1/3 ($1/\sqrt{8}$). Also, as a wind tunnel external balance consists of four sensor cells to measure one total set of six component force, this has a parallel sensing effect as well, as the white noise will be reduced by half ($1/\sqrt{4}$). Total noise reduction from parallel sensing and the oversampling effect is $1/\sqrt{4}$ (strain gauge brides) $\times$ $1/\sqrt{8}$ (over sampling ratio) $\times$ $1/\sqrt{4}$ (sensor cells) = 1/11.3. Therefore, when applying a higher sampling speed to the measurement system, greater noise reduction can be expected.

3.3.3 High speed telemetry technology

The distributed force measurement method requires significant data transfer ability in order to recompose force with a high sampling rate.

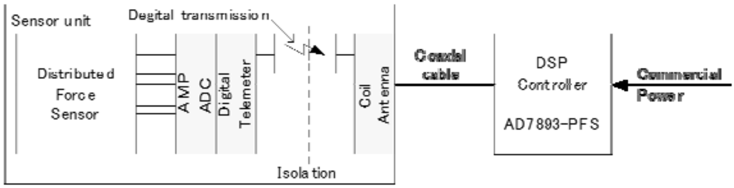

Figure 11

It is difficult to reduce noise from the power source sufficiently with just filters and grounding. Therefore, noise isolation is one of the most effective approaches for reducing power source noise that telemetry technology introduces to the balance system.

3.4 Digital signal processing technology

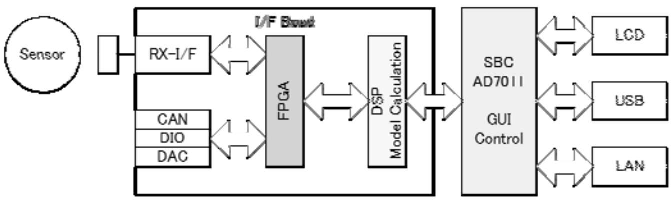

Figure 12

Distributed force measurement needs to calculate and convert vector force into six component force. This calculation cannot be achieved with analogue circuits that have to be processed digitally.

In order to achieve a high-speed sampling rate, FPGA technology and real-time data processing technology is introduced with the DSP unit. The distributed force measurement method is realized with this hardware performance.

4 Conclusion

Introducing the distributed force measurement method to the wind tunnel external balance system has many advantages compared to conventional load cell balance systems.

The most significant advantages are:

1. It offers high eigen-frequency to the system which allows it to measure the aerodynamics effect in dynamic conditions.
2. Simple design with low maintenance requirements allows optimized operation of expensive wind tunnel facilities.