
WHEEL FORCE TRANSDUCER “RIPPLE”

Introduction

Certain types of on-road and in-lab testing of wheeled vehicles requires transducers that can sense tri-axial forces (fore/aft, vertical, lateral) and moments (torque, camber, and steer) introduced into the spindle of a vehicle’s suspension. Common transducer designs for this purpose incorporate load sensing elements within a wheel – or more specifically, in the space between the tire and the wheel hub. This type of six-channel multi-axial transducer is commonly referred to as a *Wheel Force Transducer* (WFT).

An advantage of a WFT is the relative ease of interchangeability among a vehicle’s spindles as well as between spindles of different vehicles – not unlike a standard production wheel. The consequence of incorporating sensing elements within the wheel however is that the transducer coordinate system (a.k.a. *wheel coordinates*) rotates with respect to the spindle. In some applications, e.g. wheel testing, this is not a problem. However, for many other types of applications, e.g. suspension, brake, and ride/handling type testing, having the force and moment data with respect to rotating *wheel coordinates* is not convenient, rather, it is preferred to have wheel load data in *spindle* coordinates*.

To transform wheel coordinate data into spindle coordinate data, angular position of the wheel with respect to the spindle must be known. This is usually obtained from a resolver or encoder built into the WFT system. Coordinate transformation is then performed using some relatively simple mathematics.

The coordinate transformation process may introduce an error commonly referred to as “ripple”. A properly designed, built, and set-up WFT measurement system can minimize ripple to an acceptable level. This technical note discusses the various causes and manifestations of ripple.

*Also sometimes referred to as “vehicle” coordinates, however “spindle” coordinates is a more accurate term because the spindle can move relative to the vehicle chassis e.g. during steering.

WFT Ripple

WFT ripple is defined here to be the **erroneous** sinusoidal content of coordinate-transformed WFT raw data. Ripple (when it occurs) is a consequence of the mathematics involved in the transformation of rotating wheel coordinate data to non-rotating spindle coordinate data.

The mathematics utilized in the coordinate transformation involves summation and multiplication operations of four sinusoidal parameters.

For example: $F_{zv} = (F_{xw} * \sin) + (F_{zw} * \cos)$

Where:

F_{zv} = vertical force in spindle coordinates

And the four sinusoidal parameters (WFT "raw" data) in this case are:

\sin = sine of angular position of wheel with respect to spindle

\cos = cosine of angular position of wheel with respect to spindle

F_{xw} = *rotating* WFT x-axis force output

F_{zw} = *rotating* WFT z-axis force output

With regard to the mathematics of the transformation equation: the multiplication of sinusoids with each other will create sum and difference frequencies and the subsequent summation operation will combine these frequencies.

In the example presented above the transformation equation to calculate spindle vertical force F_{zv} was used. The transformation equations to calculate fore/aft spindle force, and the steer & camber spindle moments are similar and are subject to the same sort of ripple errors. It should be apparent to the reader that no coordinate transformation is necessary to obtain lateral spindle force and torque moment.

Coordinate Transformed Data without Ripple

Let us evaluate transforming rotating wheel transducer forces F_{xw} and F_{zw} into spindle vertical force F_{zv} with regards to ripple. We select spindle vertical force F_{zv} as an example because the coordinate transformation to get F_{zv} is intuitive and easy to physically check by performing a “roll test” i.e. moving a vehicle at constant speed in a straight line on a smooth level surface. Ideal WFT performance during this “roll test” will produce a coordinate-transformed result for F_{zv} that is of constant magnitude (ripple-free) and equal to the portion of total vehicle static weight supported by the spindle. To obtain a ripple-free result, the frequencies of all four raw sinusoidal signals need to be: 1) purely first order (i.e. one-cycle per wheel revolution), 2) properly phased, and 3) of proper amplitude and offset. In the ideal case, the “sum-frequencies” created by the multiplication operation are second order components and these second order components exactly cancel in the summation operation. As for the “difference-frequencies” created by the multiplication operation, these ideally manifest as constant magnitude (i.e. zero order) “DC shifts”. The net result of the summation operation will produce a ripple-free (flat-line) output that represents the portion of static vehicle weight supported by the spindle, F_{zv} .

Coordinate Transformed Data with Ripple

Now consider the case of a transformation result that contains ripple. This will occur when non-ideal WFT raw sinusoidal signals exist. Specifically:

1)FIRST ORDER RIPPLE (one cycle of erroneous content per wheel rev):

Caused by a DC offset error in one or more of the four raw one-cycle/rev signals.

2)SECOND ORDER RIPPLE (two cycles of erroneous content per wheel rev):

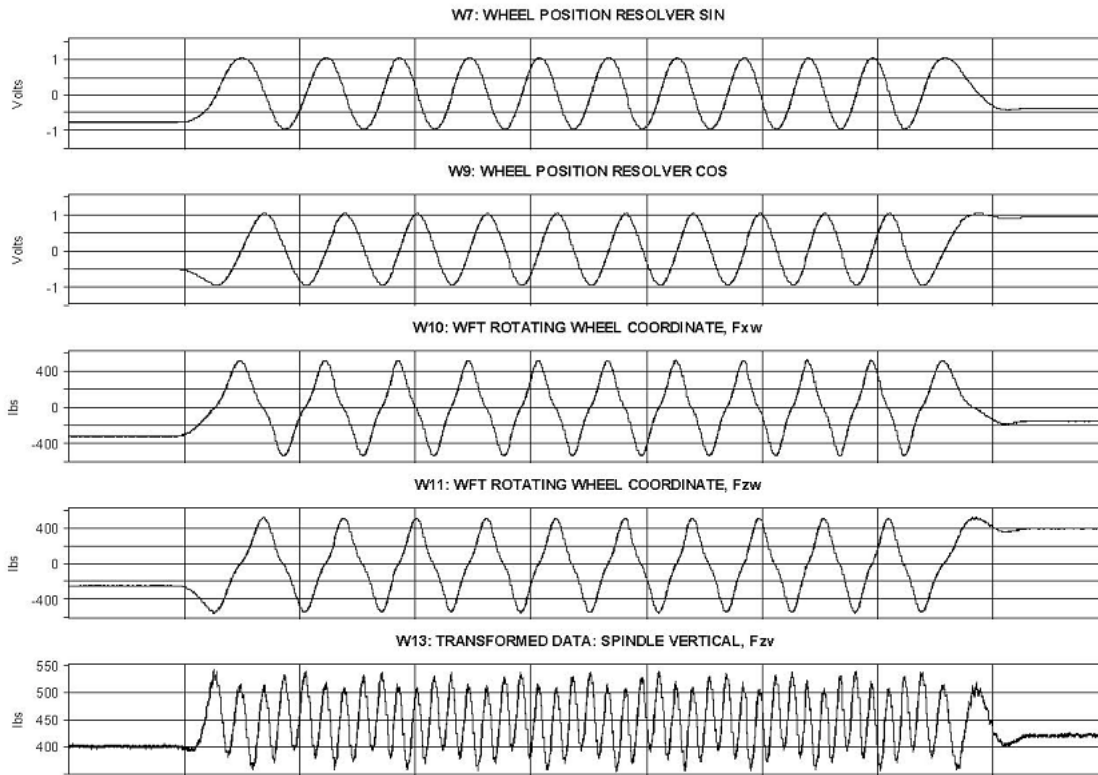
Caused by amplitude error in one or more of the four raw one-cycle/rev signals or by improper phasing between the four raw one-cycle/rev signals.

3)OTHER ORDERS OF RIPPLE (other orders of erroneous content)

Caused by one or more of the four raw signals containing frequencies other than purely one-cycle/rev. A prime source of non-one-cycle/rev content is multi-axial transducer vector-summing error. In the particular case of calculating F_{zv} , it is due to “non-uniform radial sensitivity” of the transducer. More about this next.

Case Study of Ripple Due to Non-Uniform Radial WFT Sensitivity

The time history data shown below is an example of “roll test” data from an actual WFT (NOT a Michigan Scientific Corp. WFT). This data shows the effects that non-uniform radial sensitivity can have on producing significant ripple error.



Lab test data from slow, smooth, level rolling of an installed WFT to evaluate ripple (NOT a Michigan Scientific Corp. WFT)

Ideally these should be true sine-wave-shaped. Deviation from sine wave shape is an indication of non-uniform sensitivity to radial force. For example, a force applied midway between transducer axes “x” and “z” does not produce transducer channel F_{xw} and F_{zw} output data that vectorially sum to equal the applied force. For this particular transducer, the waveshape indicates that the “x” and “z” channels are more sensitive to force applied near their on-axis direction than they are to a force applied near their off-axis direction.

An FFT spectrum analysis of the triangular shaped WFT data shows, as expected, that the predominant frequency content of the signal is first order. The other main frequency component (albeit of lesser amplitude) is third order. It is this third order content that when multiplied with the first order wheel position data creates a sum-frequency of fourth order content that ultimately appears as severe ripple in the coordinate-transformed data. This is shown in the plot of F_{zv} above.