

Technical Note No. 106

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. For wheel engineers interested in wheel loads per se this is not a problem. However for suspension, body, and ride/handling engineers, having the force and moment data with respect to rotating *wheel coordinates* is not convenient – 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. 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 moves relative to the vehicle e.g. during steering.

WFT Ripple

WFT ripple is defined here to be the erroneous sinusoidal content of coordinate-transformed WFT “raw” data. Ripple 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 the summing of the products of sinusoids.

For example:

$$F_{zv} = F_{xw} \sin + F_{zw} \cos$$

Where:

F_{zv} = vertical force in spindle coordinates

And the “raw” sinusoidal signals are:

\sin = resolver or encoder derived wheel angular position

\cos = resolver or encoder derived wheel angular position

F_{xw} = rotating wheel coordinate transducer x-axis output

F_{zw} = rotating wheel coordinate transducer z-axis output

Let us now evaluate the potential for ripple due to the transformation of rotating wheel forces F_{xw} and F_{zw} into spindle vertical force F_{zv} . We chose F_{zv} because the coordinate transformation to get vertical spindle force while moving a vehicle in a straight line on a smooth level surface is physically intuitive and easy to check. 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 weight supported by the spindle. To obtain this ripple-free result, the frequency of all four “raw” sinusoidal signals need to be purely 1st order (i.e. one cycle per wheel revolution), properly phased, and of proper amplitude and offset.

With regard to the transformation equation mathematics: the multiplication of sinusoids with each other will create sum and difference frequencies and the subsequent summation operation will combine these frequencies either constructively or destructively. In the case of the ripple-free “roll test” example, the “sum-frequency” created by the multiplication operation will create 2nd order components that exactly cancel in the summation operation. The “difference-frequency” created by the multiplication operation will manifest as a DC shift of constant magnitude and thus produce the desired ripple-free signal.

Now consider the case of non-ideal coordinate transformation of vertical spindle force during a “roll test”. Listed below are the various sources of ripple due to specific non-ideal “raw” data.

1) FIRST ORDER RIPPLE:

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

2) SECOND ORDER RIPPLE:

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

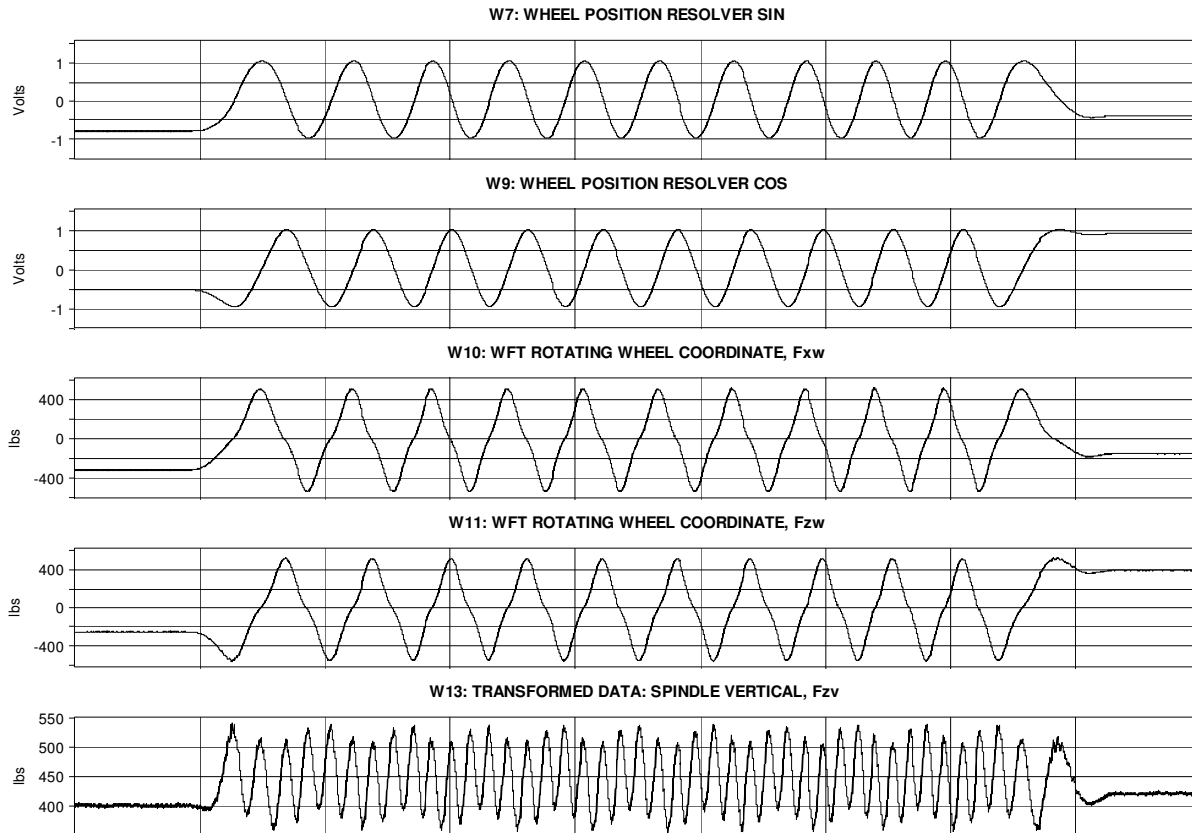
3) OTHER ORDERS OF RIPPLE:

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 case of calculating Fzv in particular, it is due to “non-uniform radial sensitivity” of the transducer. More about this in the next section.

In the example presented above the transformation equation to calculate vertical spindle force 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.

Case Study of Ripple Due to Non-Uniform Radial 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)

Note the triangularly shaped WFT rotating coordinate transducer signals Fxw and Fzw. 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 Fxw and Fzw 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 triangularly shaped WFT data shows that, as expected, the predominant frequency content of the signal is 1st order. The other main frequency component (albeit of lesser amplitude) is 3rd order. It is this 3rd order content that when multiplied with the 1st order wheel position data creates a sum-frequency of 4th order content that ultimately appears as severe ripple in the coordinate-transformed data.