Dynamometers Based on Acceleration Sensors -- Theory and Practice

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With the advances of microelectronics technology especially the MEMS (Micro Electronics Mechanical System) sensor technology, more and more dynamometers based on low cost 2/3 axis acceleration sensors are appearing in the market. But how well do they work? Some said that they are accurate while others said they are not very useful. If you search the Internet you will find that the experience of the users differs substantially. Few manufacturers reveal just exactly how those meters work and what the issues are. In this application note we are trying to explain the operating principle of those dynamometers and the accuracy they can achieve based on the operating principle.

The principle of accelerometer-based dynamometers is simple: when they are placed inside a vehicle the dynamometers measure its acceleration (the *rate* of speed increase/decrease) and compute the speed and distance based solely on acceleration. In theory, once you know the acceleration and the starting value of the speed and distance (both of them start from zero in practice), you can accurately compute the speed and distance at any point of time by integration (or by summation in discrete time). But in reality, what are the issues of doing this?

There are two main issues:

- The error of acceleration measurements, and
- The effect of acceleration measurement error to the speed and distance calculation.

Let's look at those two issues in detail.

The Error in Measurements of Acceleration

When a vehicle is in moving the vibration is large. This vibration can be caused by the road condition, the engine and any moving parts of the vehicle. For most cars the average G force is around 0.3-0.6 when it is in hard acceleration and 0.5-1.0 when it is in hard braking. However, the values registered in the sensor caused by vibration can exceed that by a large amount. It can be twice as big as the acceleration caused by the car's movement. The following diagram (Diagram 1) shows the acceleration/braking measurement of an average passenger car on a common city road. The red line is the raw measurement data and the green line is the estimates of the acceleration using advanced digital filter techniques. The vibration level may more or less depend on the type of vehicles, the road condition and the vehicle's speed, etc. But it is clear that the vibration level is large comparing to the actual acceleration we would like to measure. It is hard to know what the real acceleration value is so everything is just an estimate using various filter techniques. That is why if you use different brand of acceleration sensor based dynamometers to measure identical testing runs, the results are quite different. This is because different dynamometers use different filter techniques, thus generate quite different results.

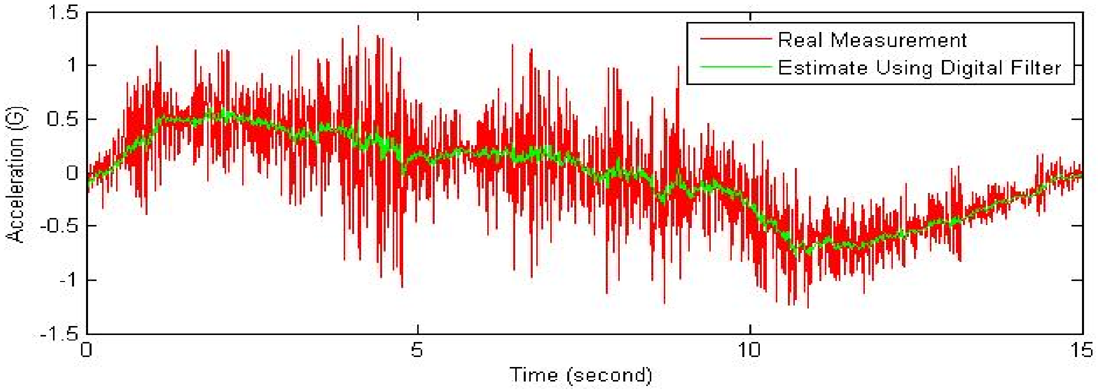

Diagram 1: Raw Measurement and Estimate for a Normal Acceleration/De-acceleration

Some people claimed that true acceleration values can be measured by using some different type of sensors, or by using a sensor which is “critically damped”. First, all MEMS acceleration sensors are critically damped, otherwise a sudden movement (a step function in math terms) would cause it to resonate and redeem it useless. Secondly, the vibration is real. It is not because of the sensor. The sensor itself has no way to distinguish between the acceleration caused by vibration or caused by the car’s movement. The only way to separate them is to use a filter, most likely a digital filter (instead of an analog filter) based on the fact that the acceleration caused by vehicle’s movement changes slower than that caused by vibration.

The vibration error is just one factor contributing to the measurement errors. There are other factors such as the errors in the sensor itself, the pitch and roll factor, the uneven of the road and so on. For instance, many commercially available MEMS acceleration sensors have relatively large error margins such as temperature coefficient, zero error and zero drift error, non-linear error, and so on. Some of the errors, such as the sensitivity variation of the sensor, can more or less be corrected by calibration. Some are hard to correct such as temperature coefficient and non-linearity of the sensitivity of the sensor. Some are correctable only if you know their true value such as the pitch and roll factors of the vehicle but in reality you don't know the true value of those factors unless you have other sophisticated instrument to measure them.

The Integration Effect

Once we have the acceleration measurements (strictly speaking, those are only the estimates of the acceleration), speed can be obtained by integrating the acceleration, and distance can be obtained by integrating speed (i.e., second degree integration of acceleration). However, integration has one very important effect: any error in the acceleration measurement will last forever in the speed and distance calculation. It is like integration "remembers" everything happened in the past. The following three diagrams illustrate this effect. Those diagrams are generated by computer simulation to illustrate the point.

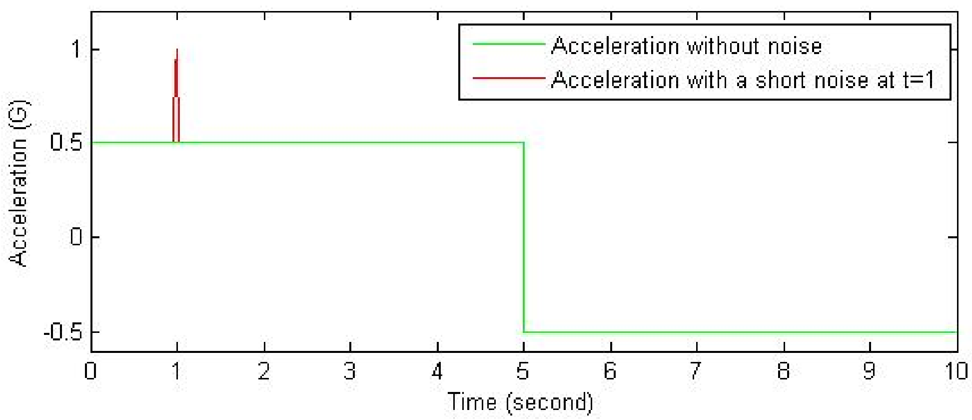

Diagram 2: Acceleration vs. Time

Diagram 2 above shows the acceleration. The red curve and the green curve are two simulated measurements. Those two curves are identical most of the time (so only the green curve is shown most of the time because the red line is underneath it). The only exception is around time=1 where the red curve has a small jump representing some measurement errors, resulting from vibration or other factors.

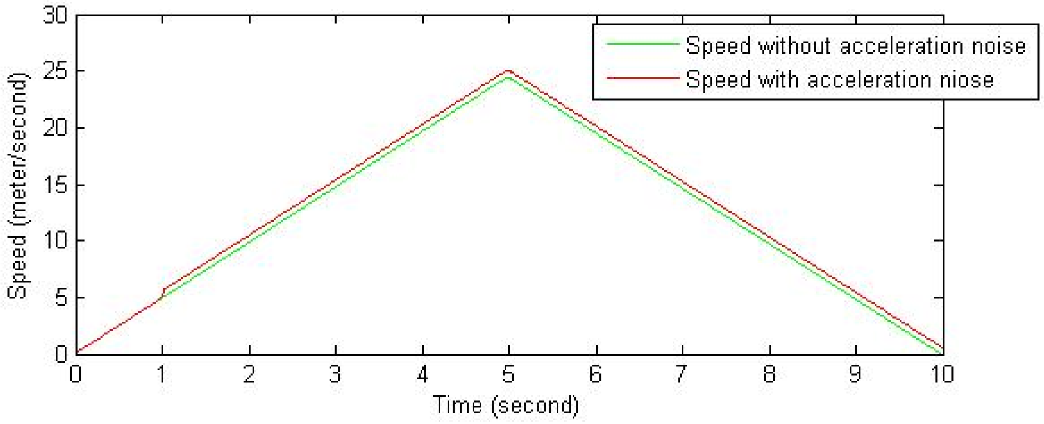

Diagram 3: Speed vs. Time

Diagram 3 shows the speed which is the integration of the acceleration. One can see after the measurement error at t=1, the two speed curves differ from that point on, even if there is no error in acceleration measurement after that. This is because the integration has the property of "remembering" all events in the past including the occurrence of the error.

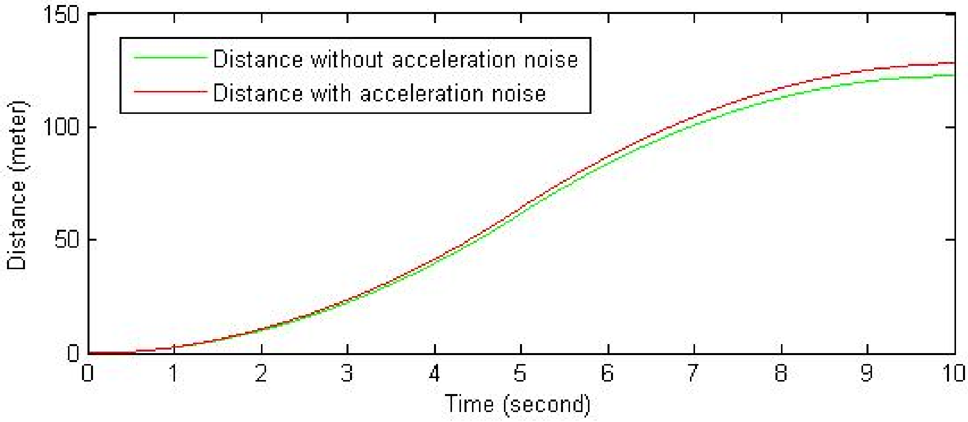

Diagram 4: Distance vs. Time

Diagram 4 shows the distance which is the integration of the speed (or the second degree integration of acceleration). The situation is even worse. Now the difference not only exists permanently but it also increases over time! This is because the error in speed is "adding up" in distance!

From those 3 diagrams you can see even an isolated, short-lived error in the acceleration measurement can cause permanent error in speed and distance, and the error increases over time in the later case. This is the inherent property of integration.

Now let’s get back to the real world of using acceleration to measure speed and distance. Because of vibration and other factors, the acceleration measurements are not very accurate. Because of the integration effect, the speed and distance results can be even worse. Therefore those dynamometers based solely on acceleration sensors are hard to get accurate results, especially over relative longer time period (greater than a few seconds). The shorter the time interval, the more accurate they can be.

It is worth pointing out that the integration effect is not always bad. For instance, if the vibration is perfectly symmetric (it goes up and down by exactly the same amount around the true value) then the integration effect can actually alleviate the error by canceling out the deviations. Of course in reality vibration especially that caused by road conditions is not symmetric. Moreover, errors caused by things like the sensitivity variance or pitch/roll factors are certainly not symmetric. They will cause the accumulation of speed and distance errors very quickly in a short time.

There are various claims about the accuracy of acceleration sensor based dynamometers, supported by test results. However, those tests were probably done in a very controlled environment such as using some certain types of vehicles in near perfect road condition. In reality, those tests are hard to duplicated, especially in cases where you don't have the freedom to select your own vehicle and road condition.

The Solution: Combination of GPS and Acceleration Sensors

GPS (Global Positioning System) receivers can accurately measure both speed and distance. Those receivers typically calculate speed by measuring the frequency shift (Doppler shift) of the GPS D-band carrier(s). Therefore, the measurement is very accurate. For speed, they can achieve 0.1 meters/s (0.22 miles/hour) accuracy. If you travel along a straight line, distance measurement is also very accurate, usually within 3-5 meters. Unlike the integration method, the accuracy of measurements using GPS does not change over time.

However, there is one issue to use GPS to measure vehicle performance: most generally available GPS receivers in the market only update the data once every second. This is in large part due to the intense computation required to generate one speed and position output. In vehicle acceleration/braking tests where speed changes rapidly, it usually requires 100 samples per second to record all the dynamics. So the 1Hz sampling rate of most GPS receivers falls short of that.

The HD3800 Vehicle Performance Test System from Handheld Design, Inc. combines the accelerometer and GPS technologies with a handheld computer. It is the most advanced and accurate system in the industry. The acceleration of a vehicle is sampled at a rate of 100 times per second, and the GPS is sampled every second for speed and location data. The measurements from GPS are then used as references to correct the results calculated from the acceleration measurement. In this way the HD3800 can meet the requirements of rapid dynamic changes, and also has the accuracy of GPS technology. The system can be used not only in applications traditionally served by dynamometers but also in applications where dynamometers are not well suited such as calibrating speedometer or accurately measuring distance between two locations.

If you have any questions or comments on this application note, please send them to support@handhelddesign.com. We love to hear from you.