THE USE OF INERTIA SIMULATION IN BRAKE DYNAMOMETER TESTING

UTILISATION DE LA SIMULATION D'INERTIE DANS LES DYNAMOMÈTRES DE FREINS

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ABSTRACT

A thorough examination of the use of inertia simulation to provide dynamometers capable of accurately representing vehicle performance is presented. Using electrical simulation it is possible to replicate vehicle performance while compensating for non-vehicle losses in the dynamometer system. The limitations due to motor power and existing fixed inertia in the system are examined and data shown as to the useful range of different combinations of power and fixed inertia. Vehicle and dynamometer characteristics discussed include linear inertia, tire rolling resistance, bearing losses, windage, inclines, and motor field effects. Examples are provided to illustrate the capabilities in terms of inertia increments and dynamic changes to simulate on-road vehicle performance. Inertia simulation is shown to accurately model both steady state and transient vehicle performance.

Un examen approfondi de l'utilisation de la simulation d'inertie pour rendre les dynamomètres capables de simuler avec précision le véhicule est présenté. Avec la simulation électrique, il est possible de reproduire le comportement du véhicule en compensant les pertes non liées et provenant du système dynamométrique. Les limites en fonction de la puissance du moteur et de l'inertie fixe existante dans le système sont examinées et des données sont montrées quant à la gamme utile des différentes combinaisons de puissance et d'inertie fixe.. Les caractéristiques présentées du véhicule et du dynamomètre comprennent l'inertie linéaire, la résistance du pneu, les pertes de roulements, les effets du vent, l'inclinaison du véhicule et les effets de champ du moteur électrique d'entraînement. Des exemples sont fournis pour illustrer les capacités en termes d'incréments d'inertie et des changements dynamiques pour simuler le comportement du véhicule sur route. On montre que la simulation d'inertie amène une représentation précise, tant dans le domaine transitoire que le domaine stabilisé.

I. INTRODUCTION

Dynamometers are widely used to simulate vehicle braking system performance. An example of such a dynamometer is shown in Figure 1. There are many variations to this basic format, but the key elements remain the same. There is an electric motor inserting and absorbing power, an inertia section, and a test section where the brake is mounted. The disks of the inertia section are utilized to simulate the vehicle inertia. Each size of vehicle will require different amounts of inertia. Since these disks are in discrete steps, there is often a compromise among the number of disks, the smallest possible increment in inertia, and the maximum range of inertia that can be simulated. Many test procedures specify how much inertia should be used based on vehicle weight and wheel position.

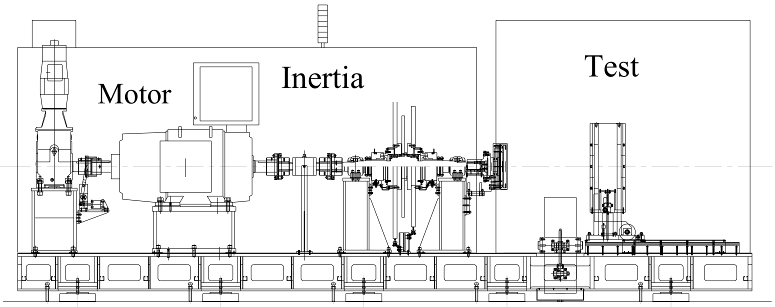

Figure 1: Typical Brake Dynamometer
Exemple de Dynamomètre pour Frein

The test procedures performed on brake dynamometers cover a wide range of operational conditions. They may simulate actual vehicle operations. For instance, in aircraft dynamometers it is typical to simulate actual operating conditions including taxing, take-offs, and landings. In passenger vehicle testing, standard procedures are often used which do not simulate typical vehicle operations, but instead, represent critical operational scenarios that test the limits of brake performance or elicit a specific type of performance characteristic. For instance, many noise test procedures incorporate brake drags with pressure variations that would not be seen in routine vehicle operation.

Modern computer controls have permitted the use of electrical simulation of inertia to overcome some of the limitations of discrete inertia disks. In electrical simulation the electric motor is used to add or absorb power to represent inertia effects. For instance, when greater inertia is required to simulate a specific vehicle, the motor is used to add power to the system. Since these inertial effects are speed dependent, careful control of the motor is required to obtain an accurate simulation.

This paper will describe the computation and control of electrically simulated inertia and present examples of its use. In addition, the use of electrical inertia simulation to compensate for bearing drag, windage, and other dynamometer effects will be discussed. It will be shown that the use of electrical simulation can be highly effective in representing inertia.

II. Implementation of Inertia Simulation

The most apparent way to simulate inertia is to match the torque that should be present in a given braking situation and use torque feedback to the motor controller to maintain the proper amount of torque. This type of control requires a torque cell to provide feedback to the controller on the shaft torque. There are limitations to this approach.

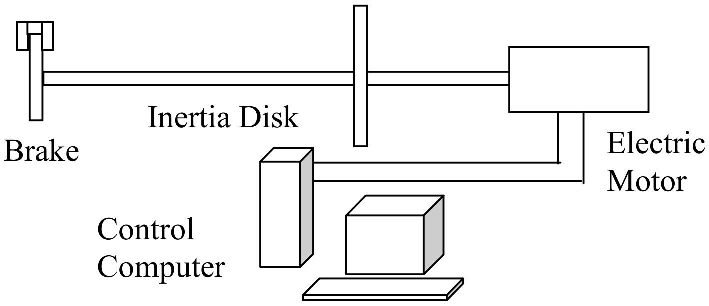

Figure 2: Inertia Simulation Through Motor Current Control
Simulation d'Inertie par Contrôle du Courant Moteur

The alternative approach is speed control, which is used in the ProLink control and data acquisition software package to accomplish inertia simulation. Such a system is shown in Figure 2. Knowing the measurement time interval (10 milliseconds), the measured brake torque with filtering during the time interval, the desired inertia, and the current speed set point; the new speed set point can be reduced by a computed required deceleration rate. Drive speed loops are typically too sluggish to control speed accurately using this scheme. The ProLink control software switches the drive into current control when the brake is applied, and a fast reacting custom speed loop is used to calculate the required armature current 100 times per second. The loop consists of a PID control loop (using speed feedback and the computed speed set point) with a fast feed-forward. Using feed-forward after the PID loop makes the current set point to the drive respond instantly to changes in brake torque. The above motor torque equation is computed and the resultant torque is converted to a best guess current required using motor rated power, base speed and current speed. This guess is immediately sent to the drive and the PID control loop removes any error from the feed-forward guess. The ordinary speed PID control loop in the drive creates excessive lag because speed error must exist prior to a change in motor current command.

This method has some major advantages over the first method. If anything changes in terms of losses, the only effect will be a slightly incorrect first guess on the feed forward, for which the PID loop will compensate. This speed loop is also used during drag type stops to virtually eliminate the speed sag that would otherwise occur at the start of the brake application. The sources of error in this method are listed below.

a. If speed or brake torque feedback is not properly calibrated, the system has no way to detect the resulting error. Inertia, speed, and torque values will appear correct, but the brake will have actually experienced a different amount of energy absorption than intended. It is possible to diagnose this lack of calibration by comparing pad and rotor temperatures with previous tests run under the same conditions, but this will likely find only large errors.

b. The speed of the machine must match the computed set point. Failure of the drive to quickly attain speed set point will show up in the data as a computed inertia error. If the drive spins at the requested speed at all times and the torque and speed are calibrated exactly, the inertia simulation will be absolutely perfect. At extremely high and low deceleration rates, the error is at its maximum, usually no more than 1% of the machine's full-scale inertia capability. In the midrange decelerations, from 0.15 G to 0.8 G, the inertia simulation error is typically below 0.35% full scale. These examples assume a standard automotive shaft type inertia dynamometer.

III. An Example of Inertia Simulation

Despite the descriptions above, it is clearly important to show that inertia simulation can give accurate results and be used in real world dynamometer test sequences. To demonstrate this capability, a series of tests were conducted comparing the performance of a state-of-the-art dynamometer with and without inertia simulation. In this particular case, the dynamometer employed a 185 kW motor and had mechanical inertia ranging from 0.69 kg-m-s^2 to 12.44 kg-m-s^2. For the results shown in Figure 3, the required inertia was 4.43 kg-m-s^2. This inertia value was chosen because the machine had a 4.43 kg-m-s^2 minimum mechanical inertia increment capability. Three cases are shown in this graph. In one case the exact required inertia is mounted on the dynamometer and no simulation is required. In the other two cases plotted the mechanical inertia is either lower or higher than the required inertia and simulation is employed to compensate. The largest differences in the actual inertia compared to the nominal value of 4.43 kg-m-s^2 are for the case of purely mechanical inertia. This is because windage, bearing drag, and other losses are not considered in setting the mechanical inertia and thus the actual inertia is significantly higher than the mechanical inertia applied. As Figure 3 shows, there is clearly a bias to higher than required inertia values for this case. Both of the simulation cases show closer correlation to the nominal value of inertia. The use of inertia simulation with its ability to compensate for system losses results in lower inertia than that obtained with purely mechanical inertia applied unless system losses are taken into account in setting the mechanical inertia.

Tables 1-3 provide statistical analysis of the results of these three tests. Clearly the simulated cases provide as great or greater accuracy in representing the nominal inertia as evidenced by the Full Scale Inertia Errors ranging from only 0.16-0.21% for the three cases.

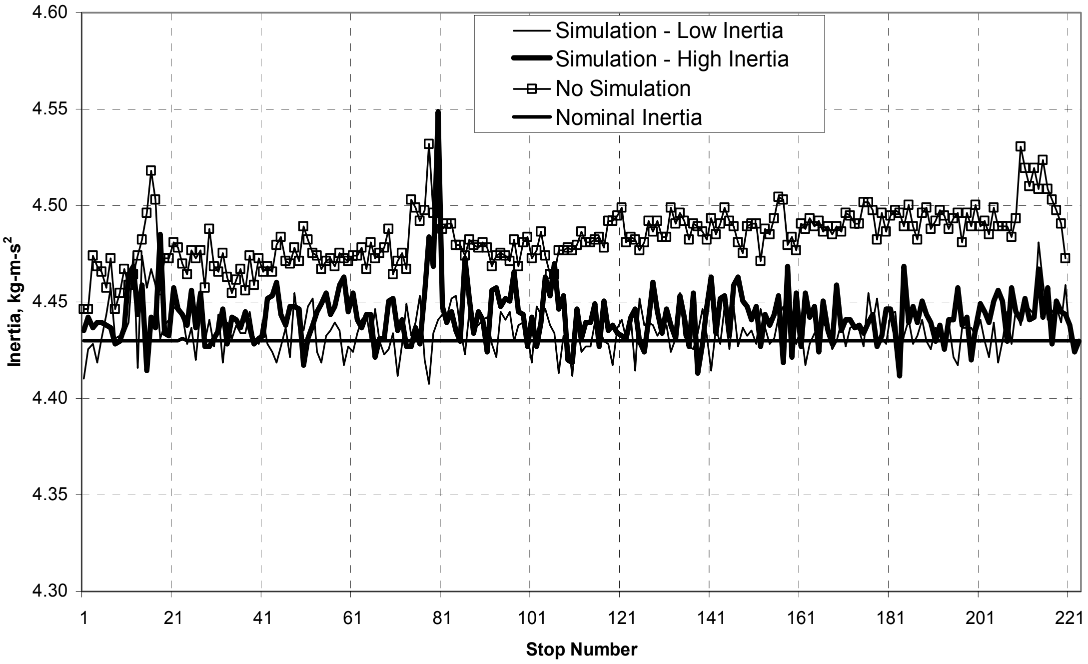

Figure 3: Example of Inertia Simulation Results
Exemple de Résultats de Simulation d'inertie

Table 1: Summary of Results from Simulation for Low Inertia
Résultats résumés de Simulation pour une Inertie Inférieure

Target Inertia / Consigne Inertie	4,43	(kg m s2)
Mechanical Inertia Mounted / Inertie Mécanique en Place	3.30	(kg m s2)
Inertia Amount Simulated / Part d'Inertie Simulée	1.11	(kg m s2)
99,9% confidence (4 sigma) / intervalle de confiance de 99,9 % (4 sigma)	0.33	(kg m s2)
Full Scale Inertia Error / Erreur d'Inertie Ramenée à la Pleine Echelle	0,16	(%)
Average Inertia Differnece / Différence d'Inertie Moyenne	0,002	(kg m s2)
Sigma (Standard Deviation of Inertia Difference) / Ecart Type de la Différence d'Inertie	0,082	(kg m s2)

Table 2: Summary of Results from Simulation for High Inertial
Résultats résumés de Simulation pour une Inertie Supérieure

Target Inertia / Consigne Inertie	4,43	(kg m s^2)
Mechanical Inertia Mounted / Inertie Mécanique en Place	5,42	(kg m s^2)
Inertia Amount Simulated / Part d'Inertie Simulée	-0,97	(kg m s^2)
99,9% confidence (4 sigma) / intervalle de confiance de 99,9 % (4 sigma)	0,41	(kg m s^2)
Full Scale Inertia Error / Erreur d'Inertie Ramenée à la Pleine Echelle	0,21	(%)
Average Inertia Differnece / Différence d'Inertie Moyenne	0,009	(kg m s^2)
Sigma (Standard Deviation of Inertia Difference) / Ecart Type de la Différence d'Inertie	0,103	(kg m s^2)

Table 3: Summary of Results for Only Mechanical Inertia, No Simulation
Résultats résumés pour une Inertie Mécanique seule, sans simulation

Target Inertia / Consigne Inertie	4,43	(kg m s2)
Mechanical Inertia Mounted / Inertie Mécanique en Place	4.43	(kg m s2)
Inertia Amount Simulated / Part d'Inertie Simulée	0.00	(kg m s2)
99,9% confidence (4 sigma) / intervalle de confiance de 99,9 % (4 sigma)	0.41	(kg m s2)
Full Scale Inertia Error / Erreur d'Inertie Ramenée à la Pleine Echelle	0,20	(%)
Average Inertia Differnece / Différence d'Inertie Moyenne	0,049	(kg m s2)
Sigma (Standard Deviation of Inertia Difference) / Ecart Type de la Différence d'Inertie	0,102	(kg m s2)

IV. Limitations of Inertia Simulation

There is a fundamental limitation for any application of electrical inertia simulation. This is the available power from the electric motor. One cannot simulate inertia amounts that require more power than is available from the motor.

Equation 1 below describes the calculation of the available inertia from simulation for a given size motor. This expression is correct for all ranges of the motor operation.

At or below the base speed of the motor, the maximum torque is constant. Therefore, the only variables become RR and a.

$$I_a = \frac{P_m * RR * 9549.3}{RPM * a * g} \tag{1}$$

where:

I_a = Available inertia, kg-m-s^2
P_m = Maximum motor power, typically 150% of rated power, kW
RPM = Rotational speed of interest, rev/m
g = Acceleration of gravity, 9.81 m/s^2
a = Vehicle acceleration, m/s^2

To better illustrate the limitations of inertia simulation, a calculation was done for a 200 kW motor on a dynamometer. The results of this calculation are shown in Figure 4. From this figure, it is clear that above the motor base speed there is a clear limitation to the amount of inertia that can be simulated.

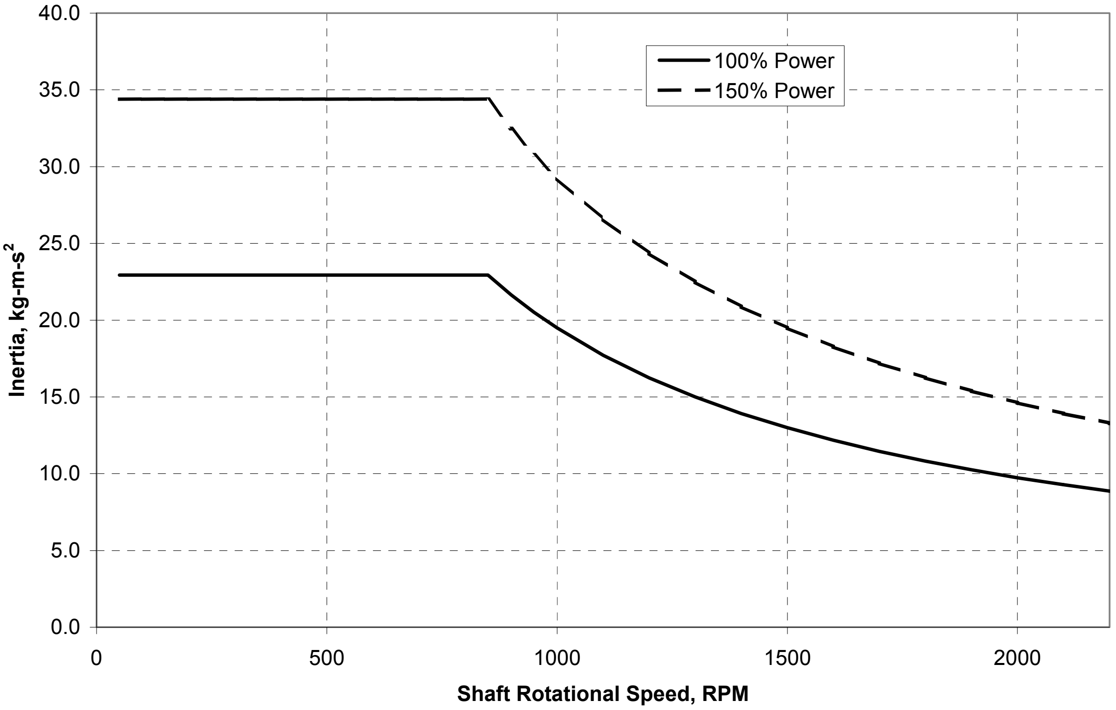

Figure 4: Example of Inertia Simulation Limitations for 200 kW Motor
Example de Simulation d'Inertie avec un moteur de 200 kW

V. Compensating for Non-Vehicle Losses

There are many potential losses in the dynamometer that are not representative of a vehicle. The arrangement and type of bearings in the dynamometer have little correlation with those in the driveline of the vehicle. These usually display a linearly increasing loss with increasing speed. This loss will also change with temperature as lubricants change viscosity and bearing preload changes due to heating.

Perhaps a more apparent example is the windage losses seen by the inertia discs. These losses can be substantial. The more disk faces exposed to free air, the more windage losses will be experienced. These losses increase geometrically with speed.

Another difference from actual vehicle operation is that DC motors have a different coast torque when the field is energized than when the field is turned off. This small torque difference may be noticeable when running with a very light inertia.

With proper calibration and baseline studies these effects can be corrected using inertia simulation as described above. The ProLink system offers the ability to use calculated values as control variables to insure that accurate corrections are made.

VI. Simulation of Vehicle Losses

Another option in using inertia simulation is to incorporate simulation of the losses seen in an actual vehicle. One example is the rolling resistance losses seen in tires. This loss increases with increasing deceleration rates. Other losses in the vehicle include aerodynamic drag, bearing losses, and power train parasitic losses. Such losses can be simulated if there is sufficient information available or if the vehicle manufacturer makes available models of these losses for the particular vehicle.

VII. Conclusions

It has been shown that inertia simulation can be useful in augmenting mechanical inertia in brake dynamometers. The limitations of simulation have been described and a formula provided to predict the capability to simulate inertia on a particular system. It has been shown that the potential exists to more accurately represent actual vehicle operation using inertia simulation.

The methodology used in the ProLink software package has been described and the accuracy of inertia simulation clearly illustrated with actual examples from dynamometer testing.