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THE VEHICLE INERTIA PARAMETER EVALUATION RIG II, A DEVICE FOR MEASURING INERTIA PARAMETERS OF ALL SIZES OF MILITARY VEHICLES

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ABSTRACT

This paper describes the VIPER II, the Vehicle Inertia Parameter Evaluation Rig, developed by SEA, Ltd at the request of the US Army's Tank Automotive Research, Development and Engineering Center (TARDEC). The previous machine was the VIPER I, built in 2000. The new machine is built to measure vehicle center-of-gravity height, the pitch, roll, and yaw moments of inertia, and the roll/yaw cross product of inertia. It is made to test nearly all of the Army's wheeled vehicles, covering a range of weights from 3000 to 100,000 lbs, up to 150 inches in width and up to 600 inches in length. Commercial vehicles could also be tested. The machine was installed in March, 2014 in the TARDEC facility in Warren, MI. The paper describes the need for such measurements, the basic features of the machine, the test procedure, and the results of early testing. The design specification for accuracy was 3% for all measurements, but the actual VIPER II accuracy is usually better than 1%.

BACKGROUND

For a vehicle the inertia and suspension properties are the keys to prediction of the handling properties. Military vehicles are often subject to conditions far beyond those of ordinary road vehicles, including the need to drive up, down, and across hills; over various large bumps and combinations of bumps; and under a variety of loading, armor, and armament configurations. One can predict the handling while the vehicle is in the design stage, but it is also important to measure and understand the handling after a vehicle is built. Inertia properties can be estimated, but it is preferable to directly measure them. Since the middle of the recent Iraq and Afghanistan wars, Mine Resistant Ambush Protected (MRAP) vehicles have become common, and these vehicles typically feature very heavy armor, which affects the inertia and handling of the vehicle considerably. Thus, the US Army has a particular need to measure the inertia properties of vehicles, especially large and heavy vehicles.

The authors of this paper have developed a machine to measure the inertia characteristics of a wide range of military vehicles. The machine is called the VIPER II, Vehicle Inertia Parameter Evaluation Rig, and replaces the previous VIPER I which was installed in 2000. The VIPER II has increased capacity, much better accuracy, and is easier to use than the VIPER I. The authors also have considerable experience with inertia measurement of commercial vehicles up to 10,000 lbs with their Vehicle Inertia Measurement Facility (VIMF) which was developed in the 1990's and is the subject of a number of papers (References 1-3).

OVERALL DESCRIPTION

The inertia properties typically measured are the center of gravity (CG) location in three dimensions; the roll, pitch, and yaw moments of inertia; and the roll-yaw cross product of inertia. This last item can be significant when there is a lot of weight high in the rear of the vehicle and the engine low in the front, or some similar condition. (The other two cross products, roll-pitch, and yaw-pitch, are typically near zero since vehicles are generally nearly symmetric left-right.)

The measurement of the inertia properties of military vehicles is identical in principle to the measurement of commercial vehicles, but military vehicles have some unique requirements due to their size. Military vehicle can be very heavy, very high, and very wide, especially with the MRAP armor packages. Military vehicles sometimes have boom or crane appendages that give them very large roll-yaw cross products.

The specifications for this machine were that it should be able to measure vehicles up to 600 inches long, from 3,000 to 100,000 lbs total weight, from 55 to 110 inches in track width, up to 150 inches overall width, and up to 5 axles. The accuracy was to be 3% for all measurements, except the cross product which was to be 3% of the smallest moment of inertia (since the cross product can be close to zero, measuring to a fixed percentage of itself could be impossible under some conditions). The authors have found that unless the CG height is accurate to within 1%, it is generally impossible to get the roll and pitch moments of inertia to within 3%.

The machine is not required to measure tracked vehicles. In theory, tracked vehicles could be measured, but getting them on and off the machine would be difficult. The machine is required to measure tank turrets, if the turret is held within a stand. Measurements were to be done without vehicle disassembly, and the test was to be done in a few days (including set up time) by two technicians.

The weight and width requirements are beyond all current military wheeled vehicles (except a few, which will be discussed later) but the VIPER II was built with possible larger future vehicles in mind. There was no specification for CG height, but past testing showed that the maximum CG height was around 72 inches. The length specification of 600 inches does not translate directly into a machine dimension. Since the machine supports the wheels of the vehicle, the wheelbase is more of the limiting factor. The maximum length of the vehicle is limited by the size of the room. Since the vehicle is centered on the machine longitudinally, it is actually the CG-to-farthest axle dimension that dictates the size of the machine. For the VIPER II the half-length of the platform is 255 inches, so 245 inches is the maximum CG-to-farthest axle (allowing a margin on the end). Typically, military vehicles that are 600 inches long are trailers similar to the common 53-foot commercial trailers, and these have the axles well inside the maximum length of the trailer.

A few current military wheeled vehicles will not fit on the machine due to their excessive width. These are tank hauling trailers built to carry the very large M-1 tank. Tank hulls are not tested with this machine, partly due to their excessive weight and width, and partly because their tracks are not compatible with the drive-on ramps of the VIPER II. A few military trailers are lighter than 3000 lbs, and they can be tested, though with reduced accuracy.

DESIGN DETAILS

The weight of the vehicle must be known for measurement purposes, and the lateral and longitudinal CG location must be known in order to center the vehicle on the machine. These measurements are made by separate vehicle scales that are not part of the VIPER II.

A general distinction is made in inertia testing between stable pendulum methods and unstable pendulum methods. Stable pendulum methods are when the CG of the combined platform and vehicle is below the pivot, and unstable methods are when the CG is above the pivot and springs must be used to provide restoring torque and to keep the system oscillating in a stable manner. Based on good results obtained for many years on the VIMF it was decided to use a stable pendulum for CG height and pitch inertia, and an unstable pendulum for roll inertia. The stable pendulum CG height measurement method used by the VIPER II is one of the methods contained in ISO Standard 10392 (Reference 4). Yaw inertia is always measured using springs, since gravity does not provide a restoring torque about the yaw axis. The roll/yaw cross product is measured at the same time as the yaw moment of inertia.

A theoretical error analysis showed that the entire range of vehicle sizes could not be measured accurately using a single platform. For small vehicles, having a platform large enough for the largest vehicle would mean the inertia of the vehicle was tiny compared to that of the platform, and a platform appropriate for a small vehicle would not be strong enough for a heavy vehicle. Three platform options are used, short, long, and extra long. The short platform is made of aluminum and is 210 inches long, 102 inches wide, has a continuous top surface, and supports vehicles up to 30,000 lbs, or tank turrets in their stands of up to 60,000 lbs. The short platform is shown in Figure 1.

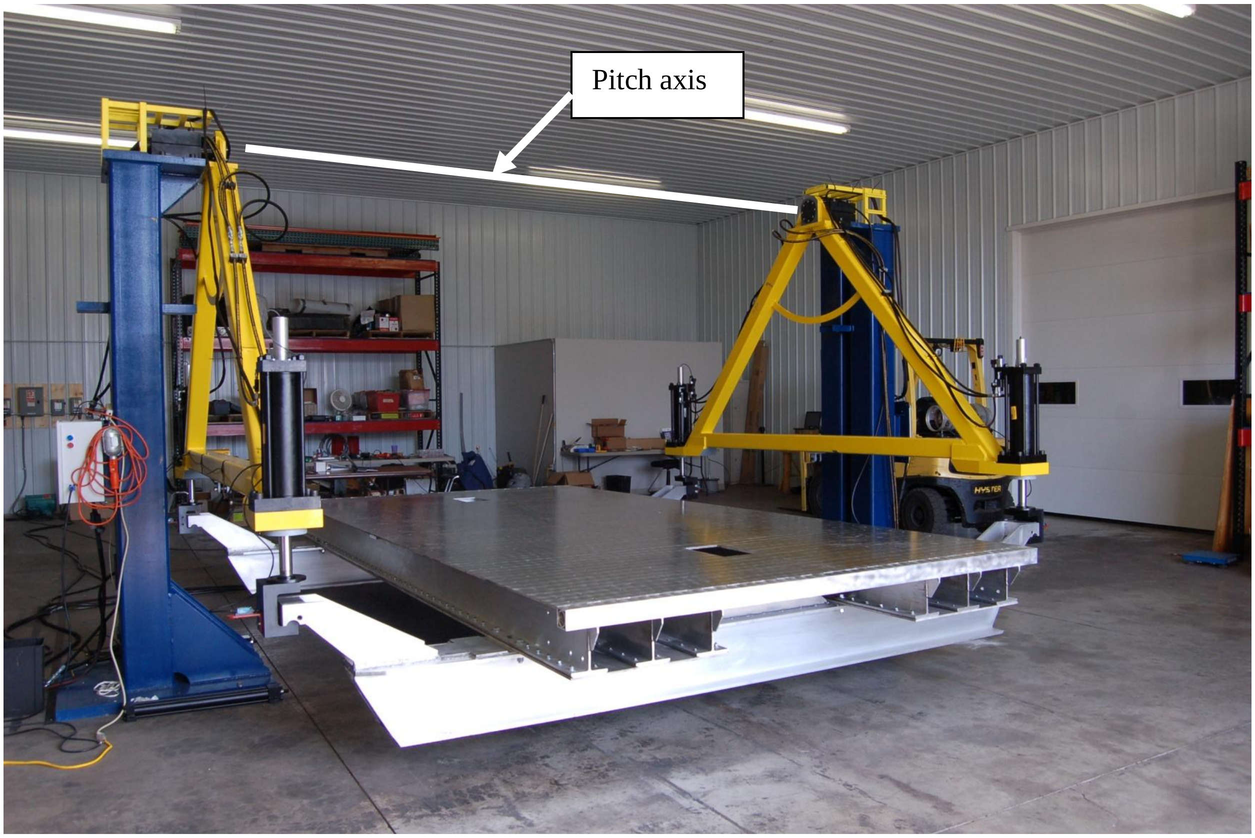

Figure 1: The small platform (aluminum) fixed pylons (blue) and swing arms (yellow).

The long platform is 350 inches long and is made of steel. It has a sectional top with three different width settings to accommodate a range of track widths up to 110 inches. Light aluminum extensions can be added to the long platform to make the extra long platform which is 510 inches long.

The platform is limited by its deflection more than by its strength. Preliminary calculations showed that platform deflections lead to large errors in the measurements. The aluminum platform is very flat, while weld warpage produced considerable curvature in the long steel platform. This curvature was mapped using a surveying instrument and the curvature is included in the calculations of CG height. The deflection of the platform is also calculated based on the individual axle weights, and this is included in the CG calculation.

The CG test is done by measuring the hand angle of the platform with the vehicle, then by hanging accurately known weights on each end of the platform and measuring the change in hang angle. This is done at two different angles in both the positive and negative direction, giving a total of four CG measurements which are averaged. A very accurate inclinometer is attached to the pivot, and the bearings that allow pitch motion are high quality roller bearings.

Figure 1 shows the VIPER II with the small platform in the CG/Pitch configuration, with the location of the pitch axis indicated, 80 inches above the platform. The platform lifts 14 inches with the action of the four hydraulic cylinders at the corners of the swing arms. Figure 2 shows the machine during a CG test of a HMMWV.

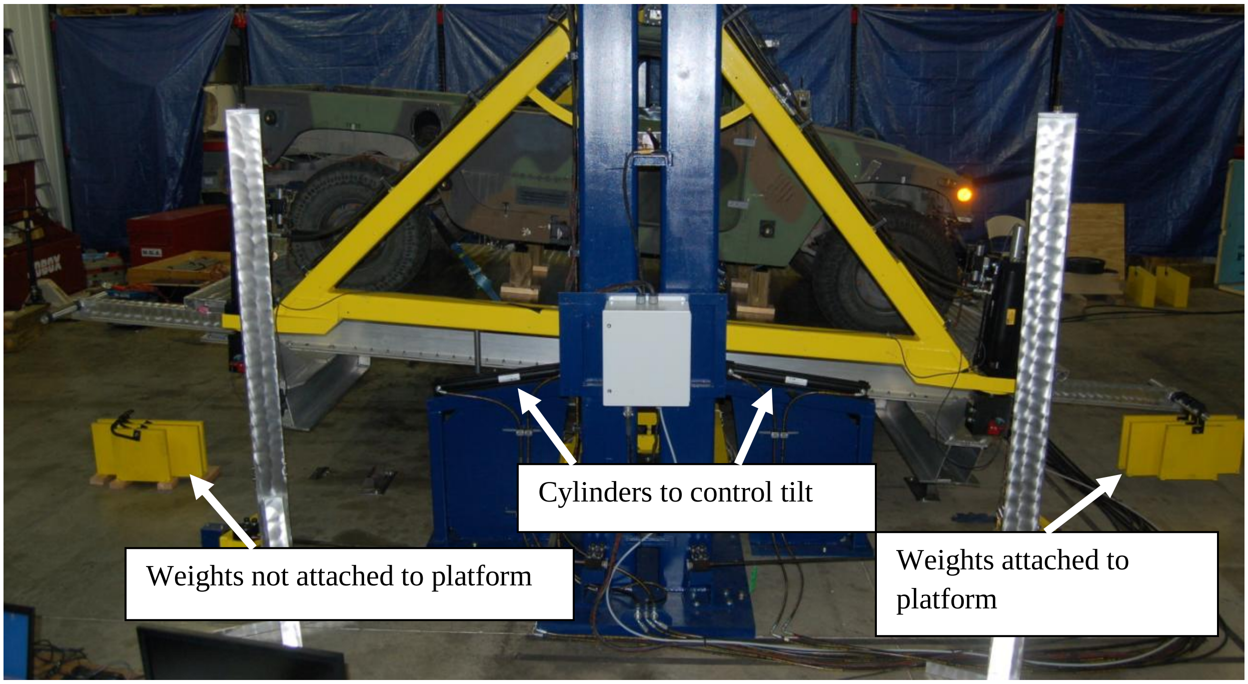

Figure 2: A CG test of a HMMWV.

After the vehicle is driven onto the platform and centered it is tied to the platform using a system of restraints. These restraints constrain vehicle motion relative to the platform, typically to less than 0.1 inches during the tests. Calculations show that even these small motions can affect the results, so a pair of motion transducers is used to measure the vehicle motion relative to the platform in each of the tests. Motion of the fuel in the fuel tank can also affect the results, so these tests are typically done when there is almost no fuel, or when the tank is completely full and there is little fluid motion. The weights of the restraints can be significant, so the weights and location of all the restraint components are measured and added analytically to the platform.

To attach the weights to each end, the platform is tilted to a given angle by a pair of hydraulic cylinders, seen in Figure 2. There are about 2000 lbs of weight on each end of the platform sitting at specific locations on the floor. Small hooks on the weights are swung up and hooked on a bar attached to the corner of the platform. In Figure 2, the weights are yellow and the hooks are black. The hydraulic cylinders then allow the platform to tilt back toward the neutral angle, lifting the weights off the floor. Once the system has come to equilibrium the new static hang angle is measured and a CG height value is computed. This is done with two different amounts of weight on each end of the platform, giving a total of four CG measurements that are averaged.

The use of the hydraulic cylinders and hooks on the weights means the weights never have to be lifted, except by the platform during the test. When the platform tilts back to its extreme angle the weights go back to their initial positions on the floor. The weights never have to be moved except when changing between the long and short platforms. Tilt angles of 3-4° are optimal. There are a total of 12 weights on each end of the machine, and any combination of the 12 can be used that gives the correct angle for that vehicle.

The tests can be done in any order, but typically the CG test is done first, followed by the pitch inertia test. For the pitch test, the weights and weight hanger bars are removed and the platform is allowed to oscillate by gravity in pitch. The oscillations are started by hand, and typically are typically between +/- 3°. The angle of oscillation does not matter as long as the small angle approximation is valid, such that the gravitational restoring torque is proportional to the angle. The period of oscillation is measured using the same high accuracy inclinometer as used in the CG test. Vehicle motion relative to the platform, while small, is measured and a two degree of freedom model is used to calculate the inertia, with one degree of freedom being the pitch motion and the other being the linear motion of the vehicle relative to the platform. This model requires a high separation of the eigenvalues, in other words it requires that the period of oscillation in pitch (typically 3-4 seconds) is much different from the period of oscillation of the vehicle within the restraints (much faster than 1 second). See Reference 2 for details of this model.

At least three trials are done for each vehicle, and the software calculates the results and checks for possible errors, such as too large a swing angle, excessive vehicle motion relative to the platform, motion transducers not set up properly, and many others. At the end of the pitch test the platform is lowered onto the roll/yaw pivot assembly shown in Figure 3, and the yellow swing arms are detached from the platform by retracting some air cylinders.

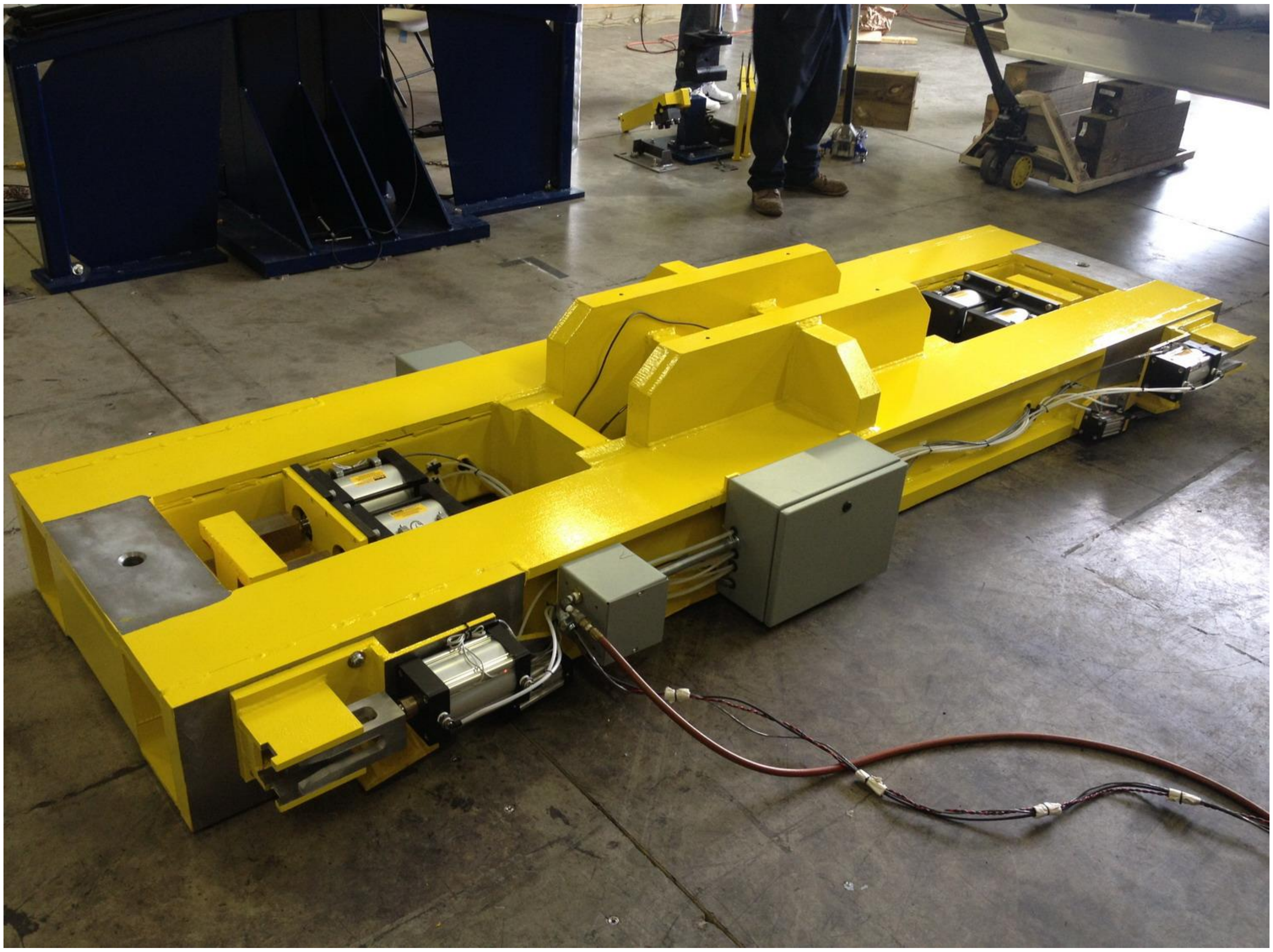

Figure 3: The yaw base containing the yaw bearing and the roll bearing mounting surfaces.

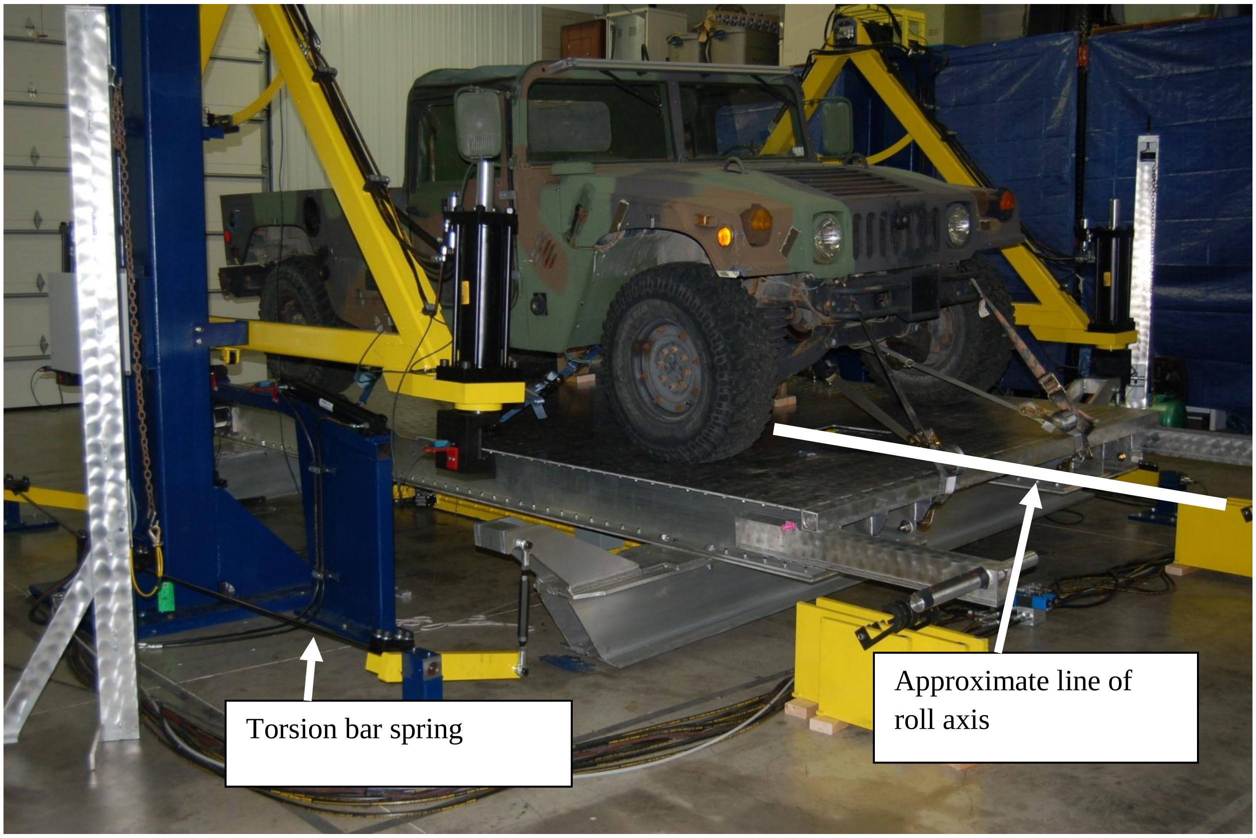

Figure 4: Roll test. The roll axis is shown. One of the four torsion bar springs is shown, and these are connected to the platform via a crank linkage mechanism.

For the roll test four torsion bar springs are attached to the platform. Figure 4 shows the roll test. There are two sets of torsion bar springs with about a 4:1 range of stiffness. The stiff set is used for heavy vehicles and/or high CG, and the softer set is used for lighter vehicles and/or low CG. The effective stiffness of the springs is a function not only of their physical stiffness but also of the CG height and weight of the platform and vehicle. Typically the roll inertia results are the least accurate of the results, partly because the calculated roll inertia is a strong function of the CG height. Thus, CG height must be measured very accurately to get good roll inertia accuracy.

The period of oscillation is measured using a rotary encoder attached to the moving end of one of the torsion springs. The angle of oscillation does not matter as long as the small angle approximation is valid. Vehicle motion is again measured relative to the platform and again a two degree of freedom model is used to calculate roll inertia. The roll axis is about two inches below the top deck of the platform. Having the roll axis as high as possible increases accuracy and minimizes the roll stiffness needed in the springs. The army requested a flat upper deck on the platform, hence the roll axis can not be higher than the platform deck.

Barely visible in Figure 4 is the yaw base under the platform. This assembly contains the bearings that define the roll axis, the bearing that defines the yaw axis test, and many other pieces.

For the yaw test the weight of the vehicle and platform is supported by a thrust bearing under the center of the yaw base. Extension springs are contained within the aluminum towers seen in Figure 4 and are attached to the corners of the platform via a cord and pulley. Motion of the vehicle relative to the platform is again measured and incorporated into a two degree of freedom model. Since CG height, gravity, and platform deflection do not come into play during the yaw test, the yaw test is the simplest of all the tests. Yaw angle is measured with a rotary encoder.

During the yaw test the roll/yaw cross product is measured. Roll motion is prevented by using two load cells, oriented vertically and offset from the roll axis by a fixed dimension. A force will be produced in these load cells that is proportional to the cross product. The force is also proportional to the yaw acceleration at any moment. A damped sine wave curve is fitted to the yaw angle data, and a damped sine wave curve is fitted to the roll torque that comes from the load cells. The ratio of the amplitudes of these curves gives the roll/yaw cross product. Typically, frictional effects are the largest during the yaw test, with most of the friction coming from the pulleys over which the yaw spring cords pass. For this reason, a damped sine wave functions must be used, and the damping is assumed to be linear (damping force proportional to velocity). Measuring the cross product by this method gives a direct measurement of the cross product, as opposed to other methods that rely on differences in moment of inertia about different axes.

Typically, the total time for the test is 1-2 hours, and the set up of the vehicle is about a day, depending on the vehicle size. Much of the test is automated, and various safety checks are built into the computer control. Commercial vehicles can also be tested on this system.

CONTROLS

VIPER II control and data acquisition is performed by an embedded realtime programmable automation controller. The controller has an FPGA (Field Programmable Gate Array) for hardware timing and signal conditioning and a processor running a realtime operating system for high level tasks such as control, data acquisition and communications. The PC (a Windows computer) acts as a host to the realtime controller via Ethernet communication. The host sends motion, data acquisition and other actuation commands to the realtime controller over TCP/IP. Test setup, data processing, and databases are handled by the PC.

An important function of the VIPER II controller is to maintain tight tolerance between the vertical position of the four hydraulic lift cylinders controlling the height of the platform. This is accomplished by a master-slave control scheme and a 2000 Hz pulse width modulation (PWM) signal to the hydraulic proportional valves.

Various sensors and actuators on the VIPER II are connected over a CAN network to provide a robust and reliable system with simplified wiring. Besides the hydraulic cylinder position sensors and angular encoders, the pneumatic actuators that control various locks, and machine status switches are also networked over CAN.

INSTRUMENTS

There are two strain gage load cells of 1000-lb capacity for the short platform, and two similar load cells of 3000-lb capacity for the long platform. A single inclinometer is used in the CG and pitch tests. A rotary encoder is used for the roll motion. For the pitch and roll tests, accurate measurement of the angle is not needed, the only requirement is to get a sine wave function of the correct period.

A rotary encoder is used to get the yaw angle. This encoder is used to give the period of oscillation but also needs to give the yaw angle accurately for cross product calculations. Two linear potentiometers are attached to stands to measure the vehicle motion relative to the platform in each test. The potentiometers are set at the estimated CG height before the test.

CALIBRATION SYSTEM

To calibrate and test the accuracy of the machine, a dedicated calibration system was built. This consists of a central frame made of steel tubing weighing nominally 5000 lbs, plus 40,000 lbs of additional weights in the form of concrete filled steel tubes. The base frame is shown in Figure 5, and the complete fixture is shown in Figure 6.

Previous experience with the VIPER I showed that setting up a calibration system of this size from a collection of test weights, bars, and other structures was very time consuming and gave rise to uncertainties about the true inertia of the calibration system. The current system, by contrast, was designed to be easy to set up and precise and repeatable in its dimensions. The central frame bolts to any of the platforms in one location only, and the weights bolt to the central frame in one location only. There are various pins and tabs to locate the weights. While the number of added weights is up to the user, their location is fixed. A spreadsheet was written to calculate the inertia properties for any number of added weights.

The base frame represents the inertia properties and weight of a light vehicle, the base frame with end weights represents a medium vehicle of about 25,000 lbs, and the complete frame represents a large vehicle of 45,000 lbs. While vehicles much heavier than 45,000 lbs can be tested on the VIPER II, it was decided that this was as heavy as the calibration frame needed to be.

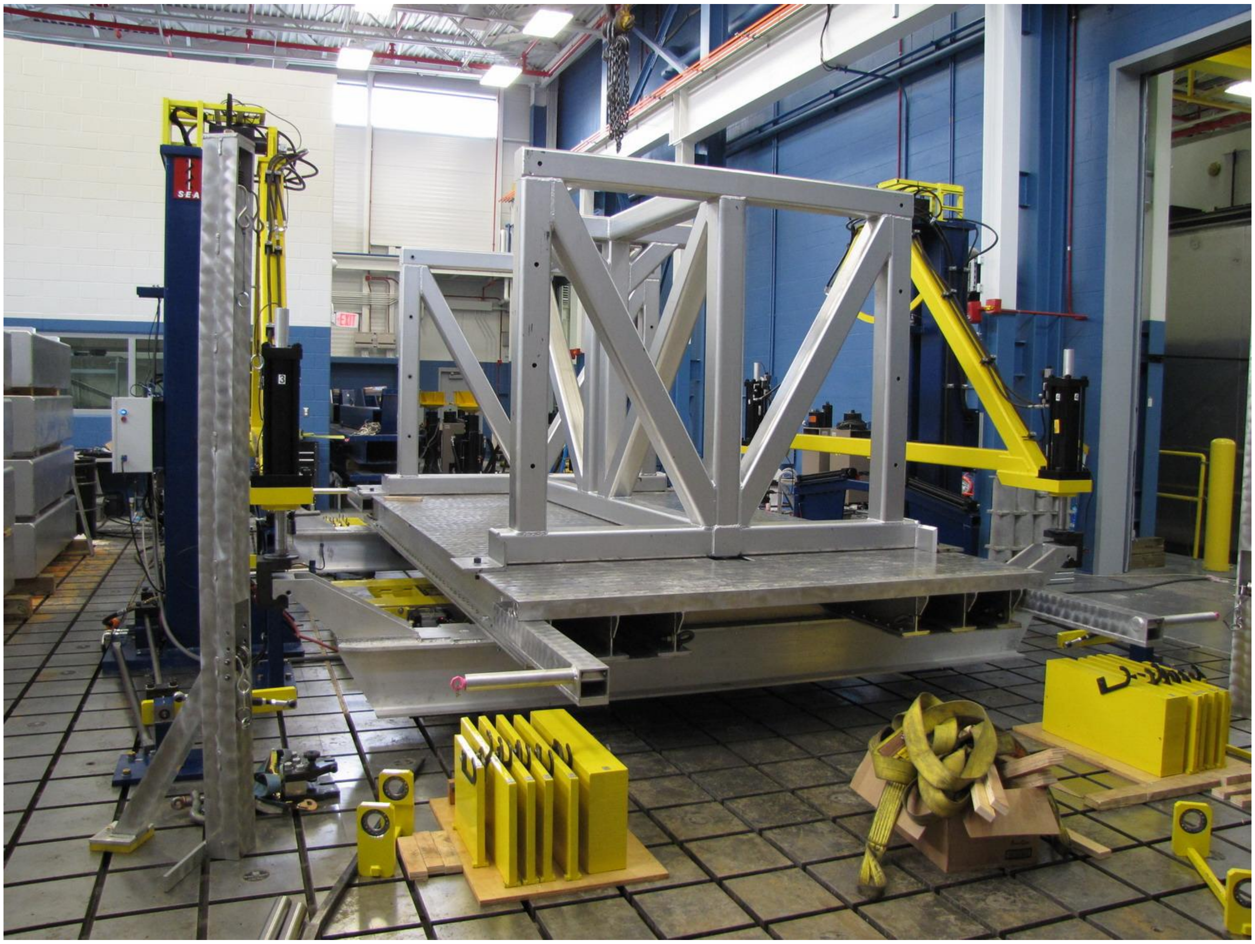

Figure 5: The central frame of the calibration fixture on the short aluminum platform.

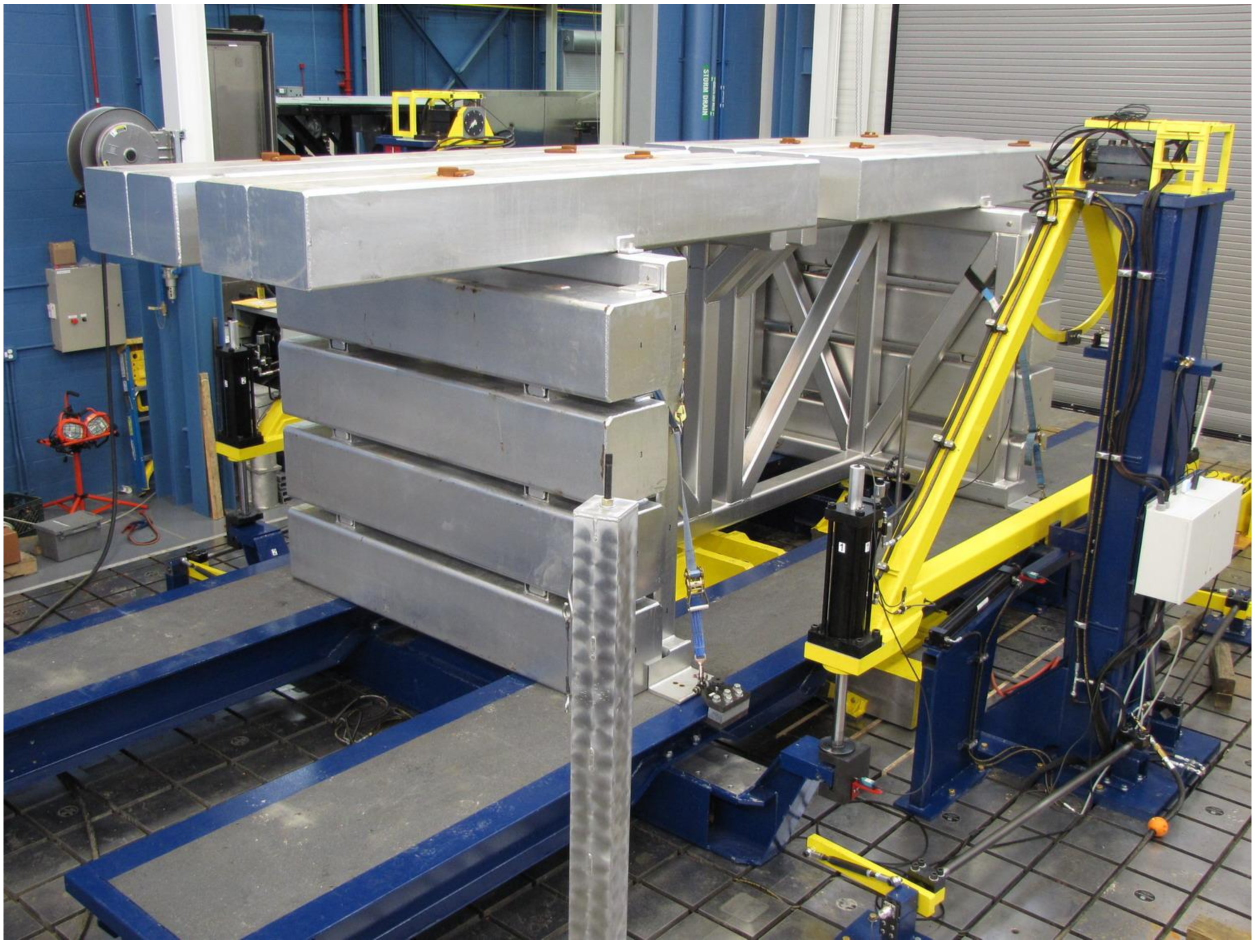

Figure 6: The entire calibration system on the long steel platform.

RESULTS

The machine was installed in March, 2014. Tables 1-6 give the results of the validation tests. The CG height is given in inches, the inertia values are in ft-lb_f-sec^2, the percent errors for the cross product are the percentage of the smallest moment of inertia.

In some tables the same weight was measured twice but in different cross product configurations. This would typically involve some end weights high in the front and low in the rear on the negative cross product test, and vice versa in the positive cross product test. Since the individual weights are not all exactly the same weight, the CG height and inertia values will change slightly between the positive and negative cross product tests.

Table 1: 4716 lb central frame on short platform

Item	Theory	Measured	% Difference
CG Height	39.02	39.03	0.03
Roll Inertia	1248	1255	0.56
Pitch Inertia	4047	4080	0.82
Yaw Inertia	3834	3829	-0.13
Cross Product	0	36	2.88

Table 2: 24,476 lb test fixture on short platform (results from 2 tests)

Item	Theory	Measured	% Difference
CG Height	27.13 27.11	27.25 27.30	0.44 0.70
Roll Inertia	5432 5433	5381 5340	-0.94 -1.71
Pitch Inertia	36,469 36,470	36,803 36,799	0.92 0.90
Yaw Inertia	38,207 38,207	38,217 38,303	0.03 0.25
Cross Product	846 -840	731 -964	-2.12 -2.28

Table 3: 4714 lb central frame on long platform

Item	Theory	Measured	% Difference
CG Height	39.02	39.01	0.03
Roll Inertia	1248	1240	-0.64
Pitch Inertia	4047	4076	0.72
Yaw Inertia	3834	3866	0.83
Cross Product	0	35	2.80

Note that for the test given in Table 3 the test subject is very light but is being tested on the long platform, which is not the optimum situation. The accuracy is still good.

Table 4: 9630 lb test fixture on long platform

Item	Theory	Measured	% Difference
CG Height	23.26	23.29	0.13
Roll Inertia	2534	2532	-0.06
Pitch Inertia	11,594	11,703	0.94
Yaw Inertia	11,621	11.477	-1.24
Cross Product	1	33	1.25

Table 5: 24,476 lb test fixture on long platform

Item	Theory	Measured	% Difference
CG Height	27.11 27.09	27.15 27.28	0.15 0.70
Roll Inertia	5435 5434	5588 5514	2.82 1.47
Pitch Inertia	36,890 36,888	37,084 37,010	0.53 0.33
Yaw Inertia	38,624 38,624	38,609 38,704	-0.04 0.21
Cross Product	867 -852	707 -883	-2.94 -0.57

Table 6: 44,847 lb test fixture on long platform

Item	Theory	Measured	% Difference
CG Height	57.33	57.67	0.59
Roll Inertia	13,102	12,855	-1.89
Pitch Inertia	67,941	67,898	-0.06
Yaw Inertia	65,160	64,641	-0.80
Cross Product	0	-294	-2.24

It can be seen that the machine is within the 3% accuracy specification under all conditions tested. In many cases the machine is well within specification, particularly pitch inertia and CG height. The roll inertia is often the least accurate moment of inertia. The roll/yaw cross product is measured to within 3% of the roll inertia. All of these are similar to past results on the VIMF and much better than the original VIPER I.

MEASUREMENT OF SPRUNG MASS PROPERTIES

The system measures the inertia properties of the entire vehicle, but in addition it may be desirable to know the properties of the sprung mass (vehicle without suspensions) separately. One method of estimating the sprung mass properties is to disassemble the suspensions, weigh the parts, and subtract out their mass properties analytically, generally assuming the major suspensions parts are point masses. For some suspensions, particularly independent suspensions, some of the significant parts are not truly part of the sprung mass nor are they truly part of the unsprung mass. Another method is to disassemble the suspensions but keep the sprung mass on the platform (usually in a different longitudinal location so that the sprung mass is centered on the platform) and then its properties can be directly measured, but this whole process is very time consuming.

Another method is possible if the CG measurements are accurate enough. The theoretical background of this method and some results are in Reference 5. The basic idea is that the CG height and weight of the sprung mass is calculated by doing three CG tests at three ride heights. The vehicle restraint system usually consists of jacks and straps, which allow the vehicle to be pulled down or jacked up to any ride height desired. The static load radius of the tire is also measured. This method directly gives the sprung mass and its CG height. Some hand calculations are necessary to estimate the other properties, but the big advantage of this method is that the vehicle does not need to be disassembled. Reference 5 gives a comparison of the results by this method to the results based on direct measurements.

CONCLUSION

A system for accurately measuring the inertia properties of large vehicles has been developed. The system was designed for military wheeled vehicles between 3000 and 100,000 lbs, and up to 150 inch total vehicle width to accommodate the Army's MRAP vehicles. Commercial vehicles can also be tested. The machine measures CG height; roll, pitch, and yaw moments of inertia; and roll/yaw cross product of inertia. It has been checked against a calibration system and found to be accurate in all measurements. Testing time is one to two hours, with set up time around one day. Other details about the design of the VIPER II are given in Reference 6, including a mathematical analysis of the effects of platform deflection.

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