HWIL Testing of Smart Weapon Systems

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ABSTRACT

The increase in sophistication of shoulder and gun launched smart weapon systems have increased the demands placed on the flight motion simulator. The high spin rate and accelerations seen during launch drastically exceed the capability of the roll axes on today's motion simulators. Improvements are necessary to the bearing and drive system to support these requirements.

This paper documents the requirements, design, and testing of a flight motion simulator produced to meet these challenges. This design can be incorporated into a new flight motion simulator, or as this paper describes, can be retrofitted into an existing flight motion simulator to improve its capability.

Keywords: Flight Motion Simulator, Smart Weapon Systems, HWIL

1. INTRODUCTION

The importance of HWIL testing during the development phases of a missile program have long been established and cannot be overstated. The purpose of this paper is not to re-establish this fact, but to highlight the unique design challenges to the flight motion simulator developer that have recently come about with the advent of the smart weapon systems, and to present the test results of a flight motion simulator developed for smart weapon system testing.

2. MOTIVATION FOR SMART WEAPON SYSTEMS

For the purpose of this paper we will consider two smart weapon systems, the **A**dvanced **P**recision **K**ill **W**eapon **S**ystem/**L**ow **C**ost **P**recision **K**ill (APKWS/LCPK) and the **P**recision **G**uided **M**ortar **M**unition (PGMM) programs.

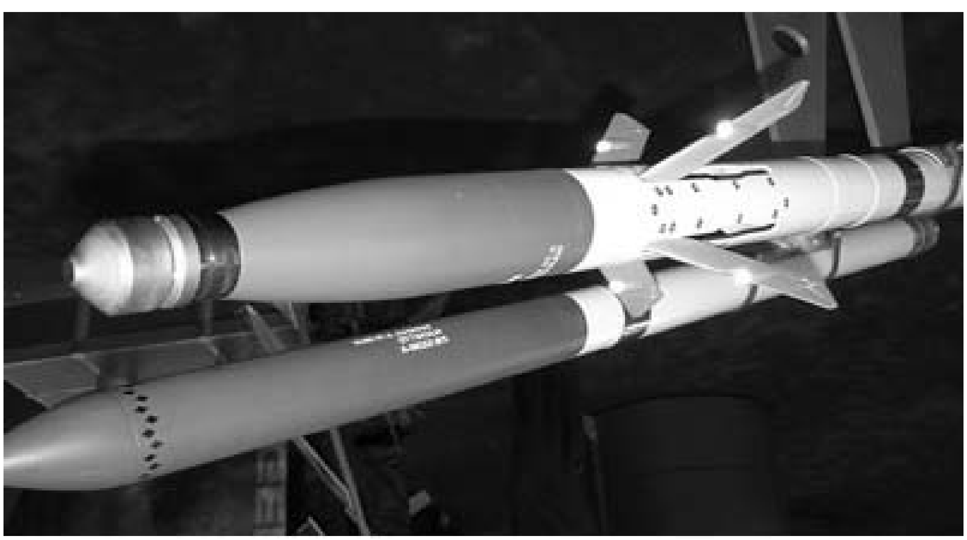

Figure 2-1: Photograph of General Dynamics APKWS[1]

During investigations of Desert Storm it was determined that a large number of HELLFIRE engagements were made against non-tank point targets that could have been killed by a smaller weapon.[2] In 1996, the U.S. Army formulated a requirement for an APKWS to close the gap in capability and cost between the unguided HYDRA-70 rockets and the sophisticated AGM-114 HELLFIRE anti-armour guided missile. The Army needed a small and accurate weapon against non-hardened point targets especially in environments with a high risk of collateral damage, e.g. in urban warfare.[3] APKWS adds a low cost, accurate (1-m CEP) guidance and control package for the 2.75-inch HYDRA-70 rocket that provides a standoff range (> 6 km) capability against specified non-tank point targets. This capability will provide for a high single shot probability of hit (pH> 0.7) against the long range target, exceeding the current unguided 2.75-inch rocket baseline by 1 or 2 orders of magnitude and thereby providing a 4 to 1 increase in stowed kills at one third the cost per kill compared to current guided missiles.[4]

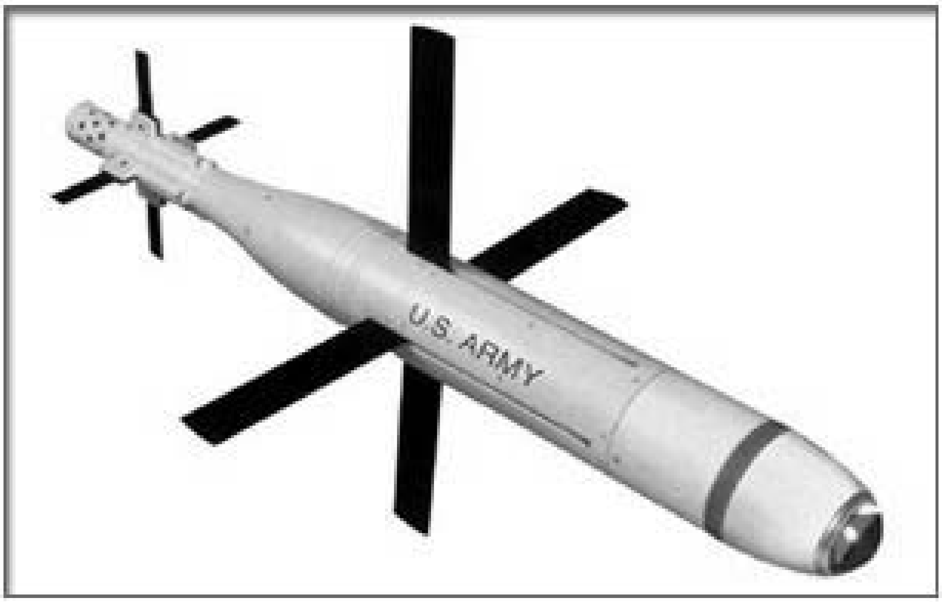

Figure 2-2 Photograph of ATK PGMM[5]

The **Precision Guided Mortar Munition (PGMM)** is a laser-guided 120 mm mortar with extended-range glide capability. It adds a new dimension to the battlefield by extending range and precision strike capability. This significantly improves the survivability of friendly forces, reduces collateral damage, increases the lethality of the Army's lift capability and streamlines the logistics tail, which is critical to rapid deployment. The use of PGMM requires no modification to the force structure since it is launched from standard 120mm mortar tubes on existing plat forms, and the single-shot lethality of PGMM makes it very cost effective. PGMM will provide dramatic increases in the survivability of friendly forces. Today, targets behind protective cover must be destroyed by hand-emplaced explosives or direct fire, often requiring a costly assault. The new capability provided by PGMM will defeat these targets without requiring a close-range attack.[6,7]

3. FLIGHT MOTION SIMULATOR REQUIREMENTS FOR TESTING OF SMART WEAPON SYSTEMS

The primary attributes of these smart weapon systems that affect the design of a flight motion simulator are the cost, the size and the dynamics to be reproduced. Table 3-1 summarizes the most important characteristics:

Specification	APKWS	PGMM
Diameter	2.75 inch (70 mm)	4.92 inch (120 mm)
Weight	~ 22.5 lbm	~ 40 lbm
Cost	< $10,000	< $15,000
Roll Rate	>38 Hz	>6 Hz
Range	6 km	12 km

Table 3-1: Comparison of APKWS and PGMM Specifications [8,9,10,11]

The relatively small size of the payloads would not dictate anything other than a standard flight motion table design. However, the very high spin rates are atypical of standard flight motion simulators. Because these high spin rates are typically developed during the initial launch (<100 msec typical) very high accelerations are also required. The combination of high rates and high accelerations represent a design challenge to the flight motion table manufacturer. Furthermore, the low cost targets for the smart weapon systems mandates a cost effective testing solution.

4. DEVELOPMENT OF FLIGHT MOTION SIMULATOR FOR TESTING OF SMART WEAPON SYSTEMS

To address the cost target, the development effort was focused not on a new flight motion simulator design, but instead on new roll drive design (AC130HS) that could be incorporated as a retrofit onto existing flight motion simulators as well as future systems. This roll drive is shown in Figure 4-1.

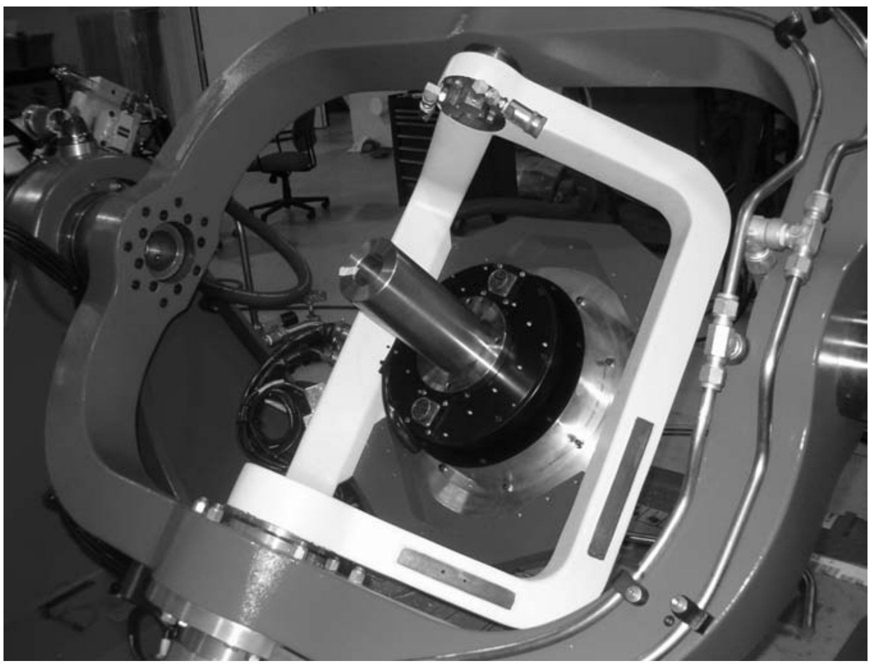

Figure 4-1: AC130HS High Speed Roll Drive Mounted to a Carco S450 Flight Motion Simulator

The following goals were developed from the PGMM and the APKWS specifications:

- Speed: 60 rev/sec maximum
- Torque: 25 ft-lbf nominal, 50 ft-lbf peak
- Torque vs. Speed: Peak torque available to 30 rev/sec

- Frequency Response: Minimal Gain/Phase Errors Below 10 Hz
- UUT Access: 60 circuit minimum

4.1. Torque Actuation

Several options were considered for the torque actuation. Analysis showed that both the high velocities and high accelerations required were achievable for a reasonable cost. The only method which could deliver the required dynamics and achieve the size constraints of the existing flight motion simulators was a direct drive brushless torque motor.

Three important considerations went into the selection of the torque motor:

- Pole Count. A low pole count motor is necessary because of the high commutation rate (pole count x rev/sec).
- High Speed Operation. A high commutation rate requires a very efficient stator lamination design to prevent excessive heating at peak speeds. Additionally, the rotor must have special treatments (banding) due to the centrifugal forces exerted on the magnets.
- Windings. To achieve the peak speed, a low BackEMF constant and a very low winding impedence is necessary.

In order to constrain the costs of the motor, it was determined that some torque rolloff with speed would be acceptable. Figure 4-2 shows the torque vs. speed curve for the AC130HS High Speed Roll Drive Option. Four curves are shown:

- Peak Torque developed by the combination of motor and power amplifier (Tpeak)
- Continuous torque output of the motor and amplifier (Tcont)
- Torque required to meet acceleration specification (Treq)
- Torque limit from the Acutrol3000 Motion Controller (Tlim)

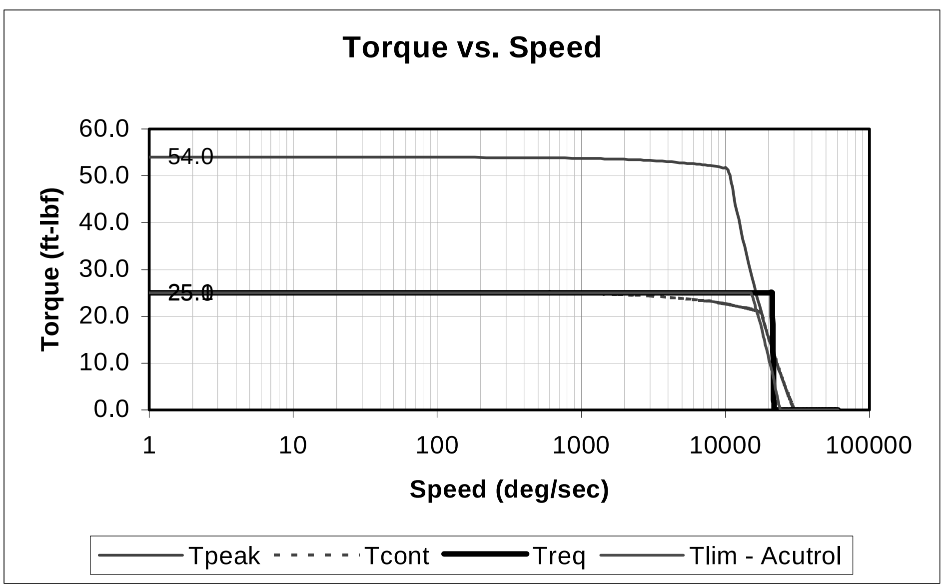

Figure 4-2: Torque vs. Speed Curve for AC130HS High Speed Roll Drive Option

The torque reduction at high speeds is clearly visible. At the peak speed of 60 rev/second only10 ft-lbf is available.

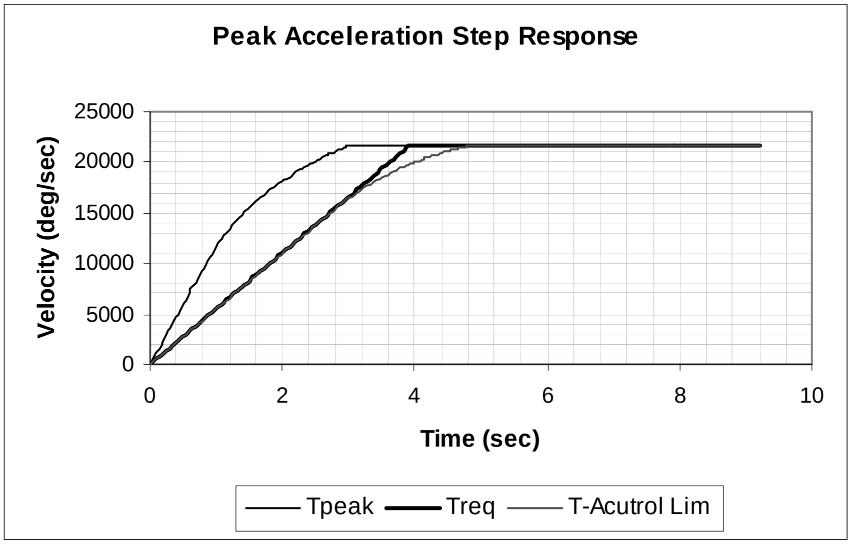

Figure 4-3: Peak Acceleration Step Response for AC130HS High Speed Roll Drive Option

Because of the highly non-linear torque speed curve, saturation of the servo control loops during large transients would be inevitable without some form of trajectory control that incorporated knowledge of a torque vs. speed curve. The trajectory generator built into the Acutrol3000 Motion Controller has a feature that allows for a non-square torque speed curve (See Figure 4-4). This produces the torque vs. speed curve shown in Figure 4-2 as "Tlim-Acutrol". The net result is the axis can be driven to the edge of its peak capability while still preventing servo saturation and thus ensuring minimal settling time. This also results in an increased time to achieve peak speed as shown in Figure 4-3.

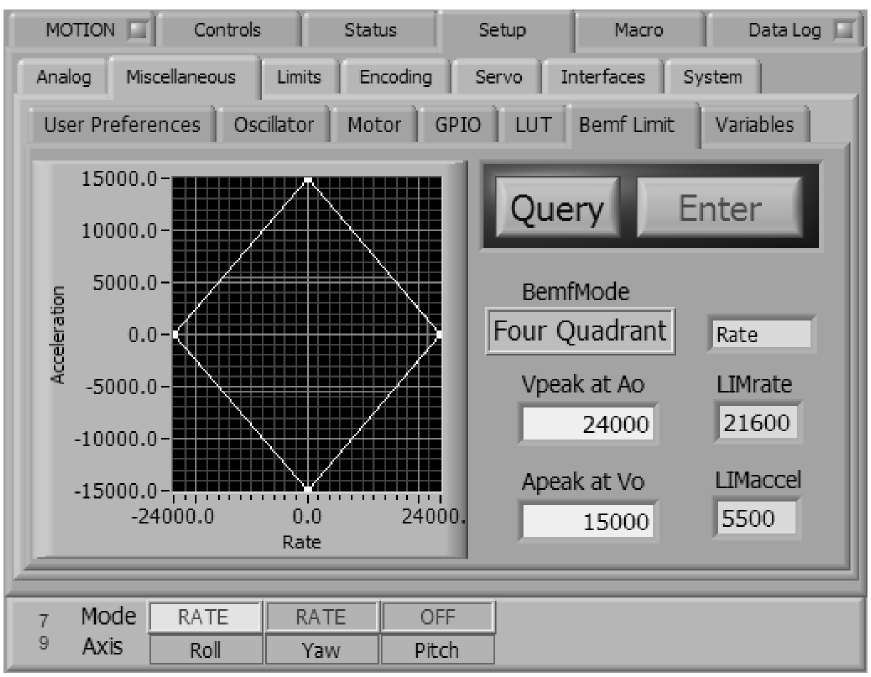

Figure 4-4: Acutrol3000 Torque vs. Speed Limitations for Trajectory Generation

4.2. UUT Signal Access

To handle the high speed rotation, sliprings that incorporated silver/graphite rings/brushes were chosen. This technology offers the longest life operation at these high speeds, because of the graphite is self-lubricating. This self-lubrication feature not only minimize wear, but also reduces the likelihood of brush chatter due to vibrations induced by the brush-ring sliding contact.

4.3. Gyroscopic Torque Disturbances

Figure 4-5 shows the coordinate convention for a typical flight motion simulator. Because of the high angular rate of the roll axis, gyroscopic torques can be considerable. Because of the symmetry of the test article and because both Yaw and Pitch axes obtain the same peak rate, the peak gyroscopic torques induced into the Yaw and Pitch Axes will be the same. However, since the middle (yaw) axis of a flight motion simulator has much less torque than the outer (pitch) axis, the effect of the gyroscopic torque on the middle axis will be greater.

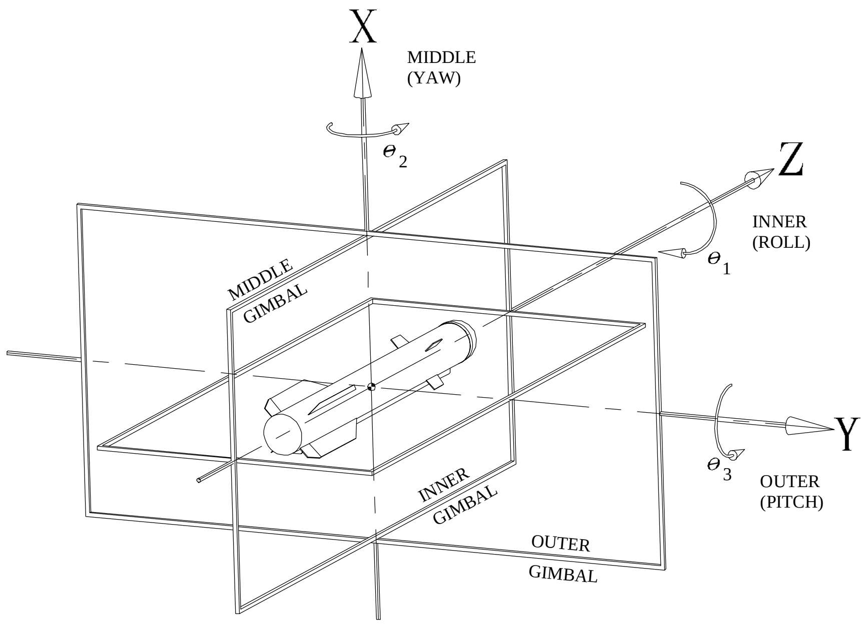

Figure 4-5: Coordinate Convention for Flight Motion Simulator

The total torque to the middle (yaw) axis is given by:

$$T_{\theta 2} = \left(I_{20} + I_{11}\sin^2(\theta_1) + I_{12}\cos^2(\theta_1)\right)\ddot{\theta}_2 + \frac{1}{2}\left(I_{11} - I_{12}\right)\sin(2\theta_1)\cos(\theta_2)\ddot{\theta}_3$$
$$+\frac{1}{2}\left[-\left(I_{21} - I_{22}\right) - I_{10} + \left(I_{11}\cos^2(\theta_1) + I_{12}\sin^2(\theta_1)\right)\right]\sin(2\theta_2)\dot{\theta}_3^2$$
$$+\left(I_{11} - I_{12}\right)\sin(2\theta_1)\dot{\theta}_1\dot{\theta}_2 + \left[\left(I_{12} - I_{11}\right)\cos(2\theta_1) + I_{10}\right]\cos(\theta_2)\dot{\theta}_1\dot{\theta}_3$$
$$-\frac{1}{2}\left(I_{12} - I_{11}\right)\sin(2\theta_1)\sin(\theta_2)\dot{\theta}_2\dot{\theta}_3$$

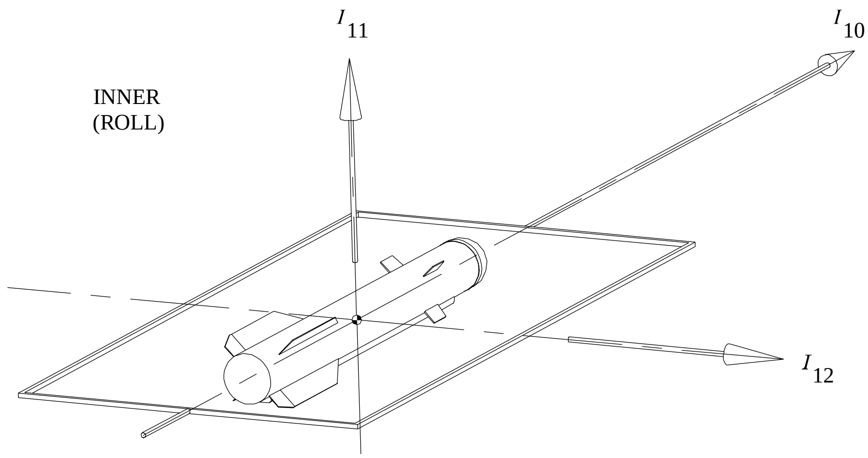

Figure 4-6: Inertia Definition for Inner (Roll) Axis

The inertia components are defined in Figure 4-6 through Figure 4-8. This can be simplified with the following assumptions:

- The yaw axis is stationary $\left(\dot{\theta}_2 = 0, \ddot{\theta}_2 = 0\right)$
- The test article is symmetric $\left(I_{11} = I_{12}\right)$
- Pitch and Yaw axes are orthogonal $\left(\theta_2 = \theta_3 = 0\right)$

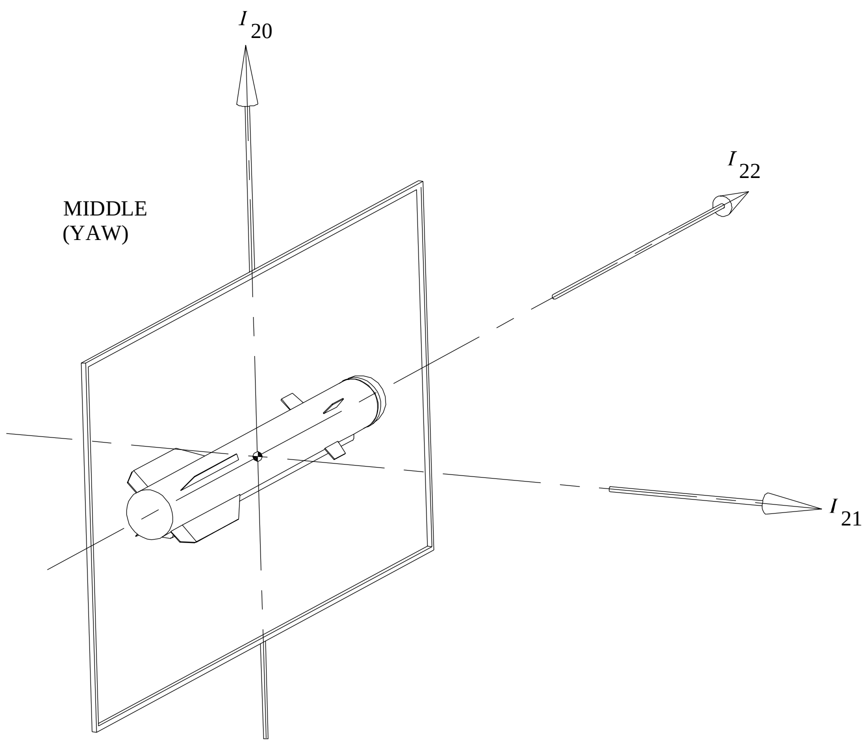

Figure 4-7: Inertia Definition for Middle (Yaw) Axis

The middle axis torque is then given by $T_{\theta 2} = [I_{10}]\dot{\theta}_1\dot{\theta}_3$. Assuming an axis inertia of 0.15 ft-lbf-sec^2, a peak roll rate of 21,600 deg/sec (60 rev/sec), and a peak pitch rate of 200 deg/sec, we find the peak gyroscopic torque to be 197 ft-lbf.

Note that this can be a significant amount of the axis peak torque and can introduce significant position error into the yaw and pitch axes.

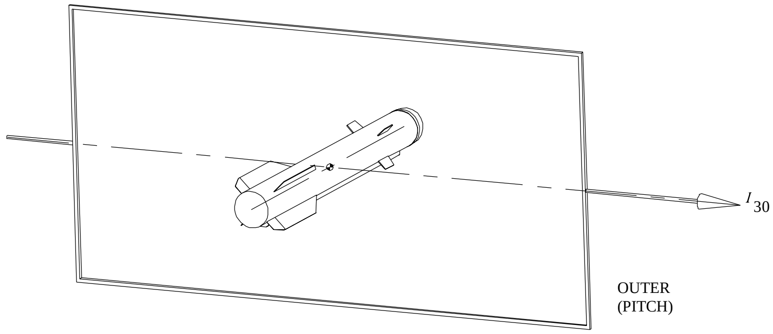

Figure 4-8: Inertia Definition for Outer (Pitch) Axis

The static case listed above would not cause a significant position disturbance provided torque saturation is avoided. The dynamic gyroscopic torque can cause much higher position disturbances. Figure 4-9 shows the position disturbance on the pitch axis when the roll axis is operated at 10,000 deg/sec and the yaw is oscillated at 1 Hz with a 15 deg peak amplitude

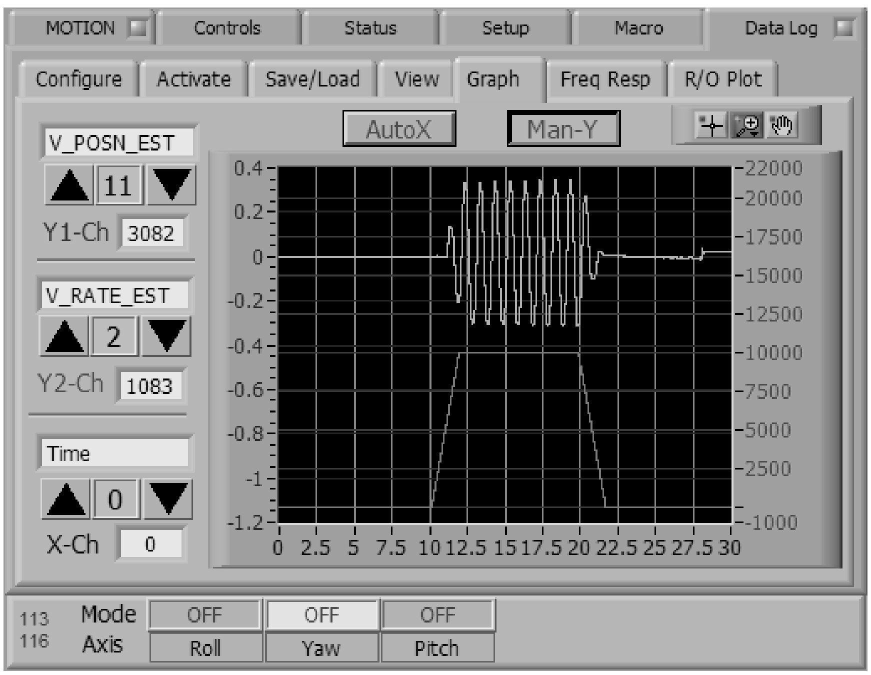

Figure 4-9: Position Disturbance On Pitch Axes Caused By Gyroscopic Torques

4.4. Imbalance Torque Disturbances

The AC130HS High Speed Roll Drive is essentially a high-G centrifuge mounted to a flight motion simulator. Consider that with a tabletop diameter of 12.00 inches, the surface speed at the edge of the tabletop is 2262 in/sec (128.5 mph). The connectors are located at a 9.5 inch bolt circle and experience 1750-g acceleration.

Balancing of the test article is paramount to minimize the torque disturbances. For example, a 1.6 oz mass at a radius of 4 inches will prouduce a sinusoidal torque of 31 lbf peak at 27.77 Hz when the roll axis is operated at 10,000 deg/sec.

This produces a disturbance torque to the yaw and pitch axes of 252 in-lbf (8 inch moment arm). With a yaw axis inertia of 300 in-lbf-sec^2, a disturbance of 0.01 deg can be measured on the yaw axis. See Figure 4-10.

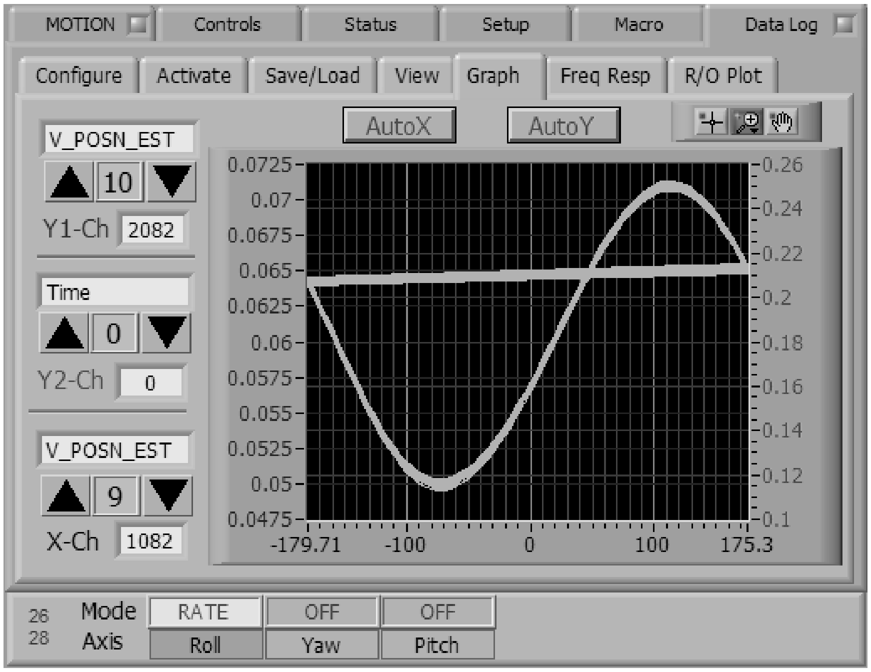

Figure 4-10: Yaw Axis Position Disturbance When Roll Is Operated At 10,000 Deg/Sec And An Imbalance Of 1.6 Oz At 4.0 In Is Attached To The Tabletop

The datalogging feature of the Acutrol3000 Motion Controller allows realtime measurement and display of the position disturbances. Using the datalogging, the user can intuitively balance the axis for minimum position disturbance.

5. RESULTS

The actual test results of the AC130HS High Speed Roll Drive were quite impressive. Figure 5-1 shows the frequency response of the roll drive. Below 10 Hz there is virtually no phase or gain error. At 30 Hz there is a gain error of ~1 dB and a phase error of only 0.25 deg, while at 100 Hz there is only a gain error of ~ 2dB and a less than 25 degrees of phase lag. Such impressive performance is characteristic of a direct drive brushless motor coupled to a high bandwidth power amplifier.

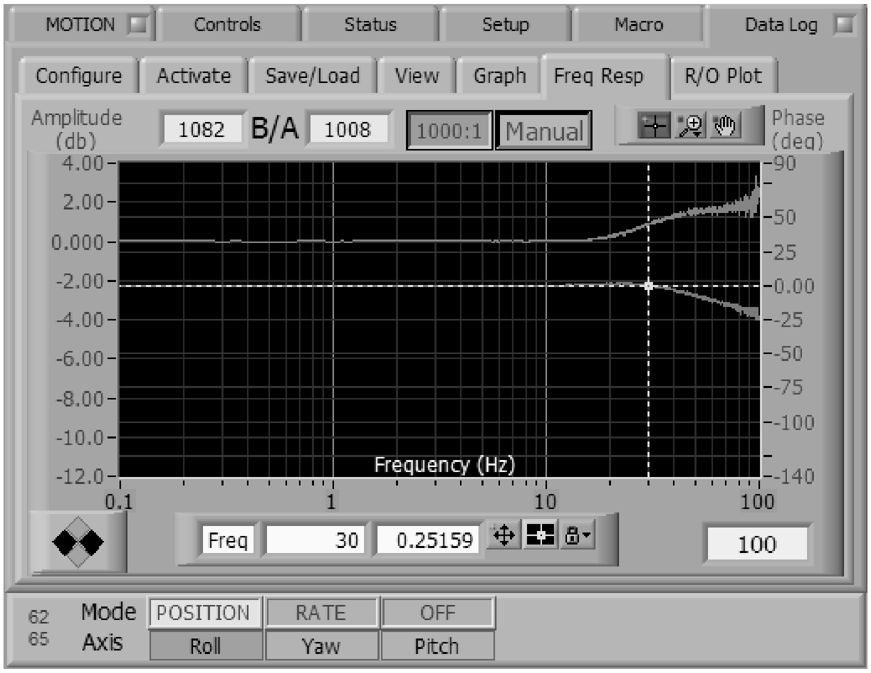

Figure 5-1: Frequency Response of AC130 HS High Speed Roll Drive showing only 2 dB of Gain and 25 deg of Phase Lag at 100 Hz

Figure 5-2 shows the maximum velocity capabilities of the AC130HS. The roll drive can accelerate to +/-60 rev/sec with zero overshoot on the actual rate. The effect of the torque vs. speed limitation of the trajectory generator are clearly visible in the velocity command.

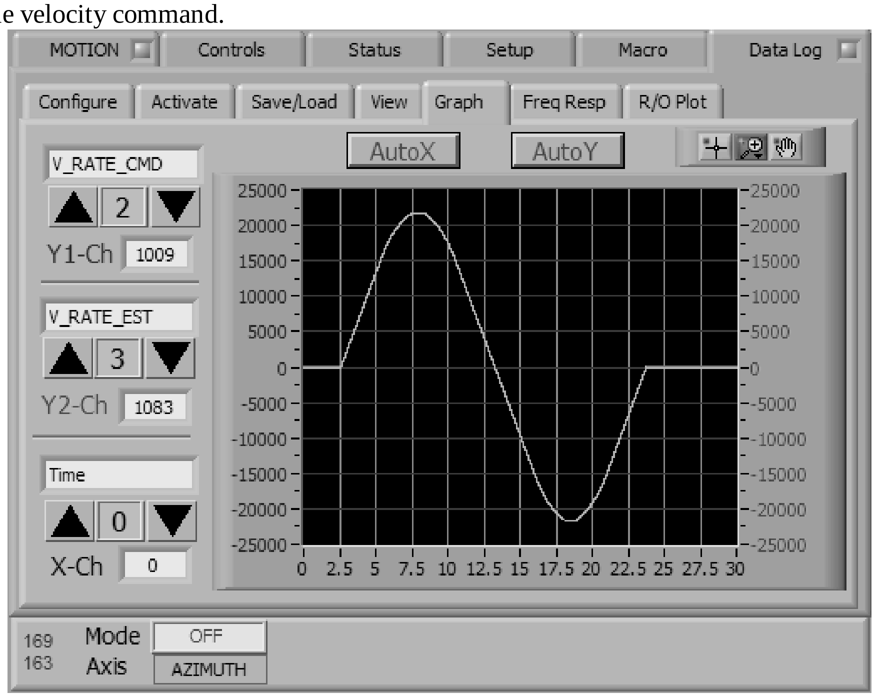

Figure 5-2: Peak Speed Measurement of AC130HS High Speed Roll

6. SUMMARY

The simulation requirements of the new smart weapon systems exceed the capability of prior flight motion systems. The information presented in this paper demonstrates not only the feasibility of meeting these simulation requirements, but also presents a method for incorporating these capabilities into existing flight motion simulators.

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