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TURNAROUND BUMP REDUCTION IN A LINEAR HYDRAULIC ACTUATOR BY MECHANICAL MEANS

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The Vertical Motion Simulator at NASA Ames Research Center utilizes custom non-hydrostatic hydraulic actuators to drive its roll, pitch, yaw and longitudinal axis. These actuators have operated flawlessly with one exception; they exhibit a phenomenon that is detrimental to the motion fidelity called "Turnaround Bump" (TAB). TAB occurs in all hydraulic actuators with seals at the onset of motion (extending or retracting) when the friction on the seals changes from the higher static (no motion) to the lower dynamic (motion) friction. The sudden change in the friction force causes an acceleration spike that can be felt by the pilot thus giving a false motion cue. In order to reduce TAB without going to costly hydrostatic actuators, a cost effective mechanism was designed that constantly rotates the piston rod end of the actuator so that the piston rod never stops moving relative to the seals even when the actuator stops moving in the linear direction.

Nomenclature

α	=	rotational acceleration of yaw axis
A_1	=	pressure area of hydraulic actuator
D_C	=	perpendicular distance from center of rotation to the center line of hydraulic actuator
F_{ACT}	=	weight of yaw actuator
F_{NFS}	=	total normal force on hydraulic seals caused by the weight of the actuator, assumed constant
F_{SR}	=	radial force on hydraulic seals due to compression
I	=	rotation inertia of yaw axis
P_{SPIKE}	=	difference between P_{START} and P_{STOP}
P_{START}	=	differential pressure in hydraulic actuator required to start motion
P_{STOP}	=	minimum differential pressure required to keep in motion
R_1, R_2	=	reaction forces at end of yaw actuator
μ_{KS}	=	coefficient of kinetic friction in hydraulic seals
μ_{SS}	=	coefficient of static friction in hydraulic seals
μ_R	=	coefficient of rolling friction in yaw bearing
ω	=	rotational velocity of yaw axis
W_{CAB}	=	weight of simulator cab

I. Introduction

The Vertical Motion Simulator (VMS) at NASA Ames Research Center has been in operation since the mid 1970's. The VMS is a one-of-a-kind simulation research and development facility. It offers unparalleled capabilities for conducting experiments involving some of the most challenging aerospace disciplines. The VMS, shown in Fig. 1, is a very large, six-degrees-of-freedom electro-mechanical/electro-hydraulic servo system. It is located in and partially supported by a specially constructed 73-foot-wide by 36-foot-deep by 120-foot-high tower,

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whose entire interior volume is available for the operation of the motion system. The motion platform consists of a 40-foot long beam, which can travel up to ±30 feet vertically. On top of the beam is the lateral carriage that traverses the 40-foot length of the beam. Then, on top of the carriage is a longitudinal carriage and gimbal system that can simultaneously provide ±4 feet longitudinal, ±18 degrees pitch, ±18 degrees roll, and ±24 degrees yaw (see Fig. 1).

In addition to its size, another unique feature of this facility is that it can simulate the physical cueing environment of a large range of vehicles. Five cabs representing the cockpits of a variety of vehicles - each with its own instruments, controls, visual display and audio cueing systems - can be placed on the motion cueing system of the VMS[1] (see Fig. 2).

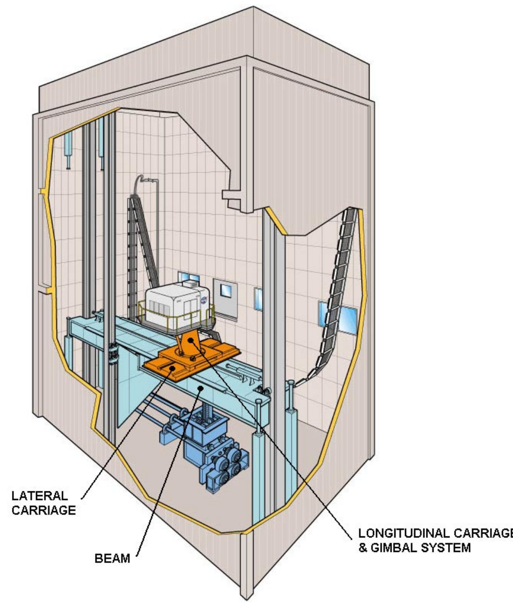

Figure 1: Vertical Motion Simulator Complex.

Figure 2: VMS Simulator Cab.

The roll, pitch, yaw and longitudinal axes rely on custom hydraulic actuators to drive their motion. These axes exhibit a phenomenon known as “Turnaround Bump”. “Turnaround Bump” occurs when the hydraulic actuator comes to a stop and then tries to move again. As the axis travels through zero velocity a disturbance force is introduced in the opposite direction of the hydraulic actuator motion. The disturbance force is caused by friction, also known as “stiction”, in both the actuator’s hydraulic seals and axis bearings.

When the force caused by the differential pressure in the actuator becomes less than the force due to kinetic friction minus the inertial force due to the simulator cab, the actuator stops. The minimum differential pressure required to keep the actuator moving is expressed in Eq. (1), using the yaw axis of the VMS as an example (See Fig. 3 and 4).

$$P_{STOP} < \mu_{KS}(F_{SR} + F_{NFS})/A_1 + (\mu_R W_{CAB})/A_1 - I\alpha/(A_1 D_C) \quad (1)$$

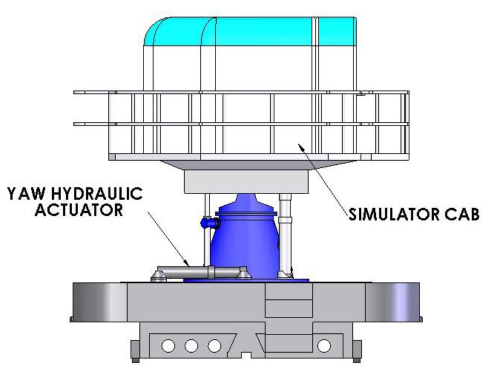

Figure 3: Yaw actuator layout, side view.

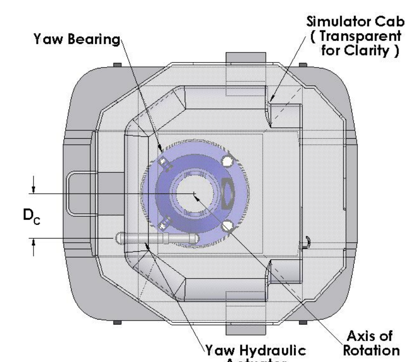

Figure 4: Yaw actuator layout, top view.

In order for the actuator to start moving again the force caused by the differential pressure in the actuator must be greater than the static friction in the actuator and bearings as expressed in Eq. (2):

$$P_{START} > \mu_{SS}(F_{SR} + F_{NFS})/A_1 + (\mu_R W_{CAB})/A_1 \text{ when } \alpha = 0 \text{ and } \omega = 0 \quad (2)$$

The differential pressure to start the actuator moving must also be greater than the minimum required pressure to keep the actuator moving. The difference between the differential pressure to start the actuator moving and the minimum pressure to keep the actuator moving is what causes the "Turnaround Bump". This pressure spike can be expressed by subtracting Eq. (2) from Eq. (1) with $\alpha = 0$ and ω=0 :

$$P_{SPIKE} = \mu_{SS}(F_{SR} + F_{NFS}) / A_1 + \mu_R W_{CAB} / A_1 - \mu_{KS}(F_{SR} + F_{NFS}) / A_1 - \mu_R W_{CAB} / A_1 \quad (3)$$

Which can be simplified to:

$$P_{SPIKE} = ((F_{SR} + F_{NFS}) / A_1)(\mu_{SS} - \mu_{KS}) \quad (4)$$

The pressure spike expressed in Eq. (4) is the minimum pressure spike that would occur due to the seals regardless of the control system driving the hydraulic actuator. The VMS yaw axis control system drives the position, so when the control system commands a new position from a stop the pressure must build up to P_{START} as described in Eq. (2). As the pressure builds up the control system is also building up error so when the hydraulic actuator does break loose from the "stiction" the control system will cause the differential pressure to overshoot and cause a greater pressure spike.

The minimum pressure spike that can be expected from a position driven controls system is expressed by Eq. (4), but depending on the control system, this pressure can be much higher. An example of the performance of a position driven hydraulic actuator can be seen in Fig. 5.

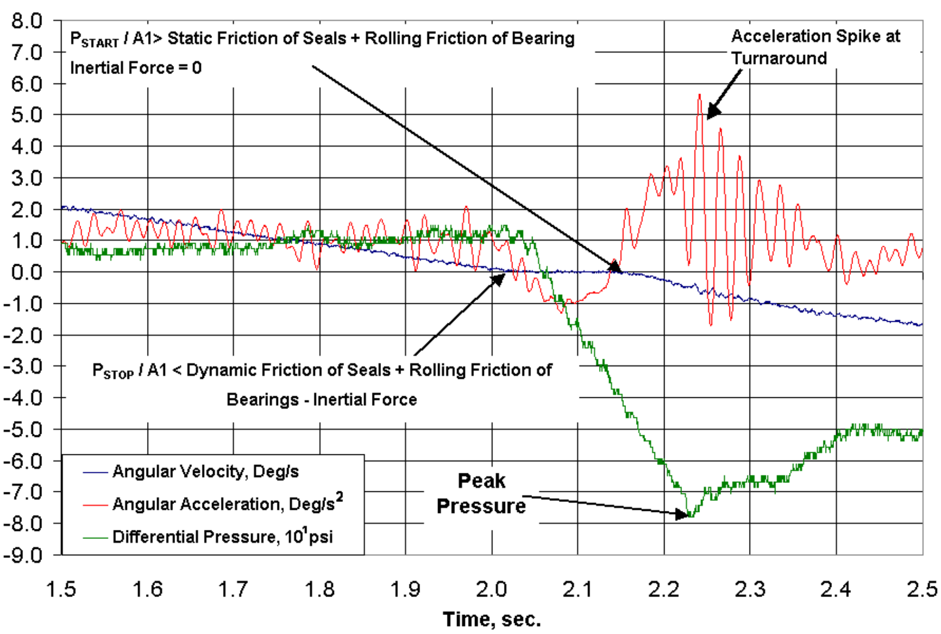

Figure 5: "Turnaround Bump" at zero angular velocity.

II. Design Solution

In order to reduce the "Turnaround Bump" in the yaw axis of the VMS, a mechanism was designed to eliminate the static friction in the yaw hydraulic actuator. The Turnaround Bump Reduction Mechanism (TABRM) constantly rotates the piston rod end of the yaw hydraulic actuator so that the piston rod end of the actuator is always moving relative to the housing, because of this, the seals inside the actuator never transition from kinetic to static friction (see Fig. 6 and 7). A similar mechanism has been designed and patented[2] though the TABRM was developed independently.

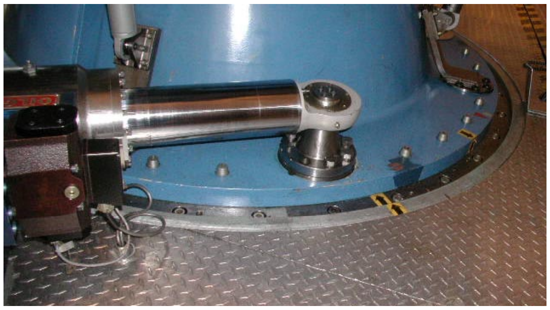

Figure 6: Yaw actuator with existing rod end.

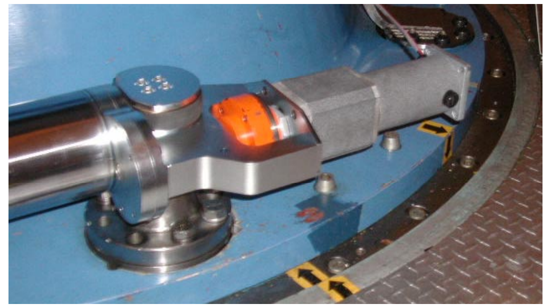

Figure 7: Yaw actuator with TABRM installed.

The TABRM has a 24V DC motor that rotates the rod end at approximately 10 rpm. The motor turns a shaft that rotates a gear train (1:1 gear ratio) located in the gear housing that in turn rotates the rod end that is screwed into the piston rod of the yaw actuator. A clutch is inserted in the TABRM to insure that the motor cannot be overloaded (see Fig. 8).

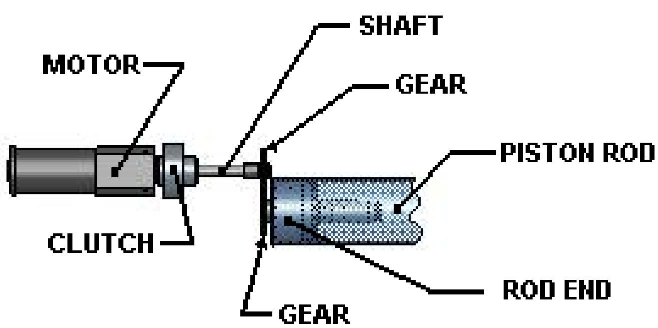

Figure 8: Turnaround Bump Reduction Mechanism (TABRM) design.

With the TABRM installed, the pressure required to start the hydraulic actuator can be expressed by Eq. (5), which replaces the coefficient of static friction from the seals with the coefficient of kinetic friction from Eq. (1).

$$P_{START} > \mu_{KS}(F_{SR} + F_{NFS}) / A_1 + \mu_R W_{CAB} / A_1 \text{ when } \alpha = 0 \text{ and } \omega = 0 \tag{5}$$

The pressure spike with the TABRM installed can be expressed by Eq. (6), which replaces the coefficient of static friction from the seals with the coefficient of kinetic friction from Eq. (4).

$$P_{SPIKE} = 0 \tag{6}$$

Eq. (8) shows that with the TABRM installed there should be no additional pressure spike due to the sudden change in friction from static to kinetic on the seals. The yaw axis position driven control system on the VMS will still have a pressure spike because $P_{START} > 0$ due to the kinetic friction on the seals and the rolling friction of the yaw bearing.

III. TABRM Testing

Sine sweeps were performed on the yaw axis of the VMS ranging from .125 Hz to .500 Hz while the commanded position, position feedback, velocity, acceleration, and the differential pressure were recorded with and without the TABRM installed. The friction in the yaw bearing was determined by using a load cell to measure the amount of force required to move the yaw axis with the yaw actuator disengaged.

IV. TABRM Testing Results

Subtracting the friction force in the yaw bearing (see Table 2) from the force required to move the yaw axis from a stop gives the static friction force in the hydraulic actuator (see Table 3). The TABRM reduced the static friction in the hydraulic actuator by 47.2% when retracting and 51.7% when extending (see Table 3). The overall static friction in the yaw axis was reduced by 42.3% when retracting and 45.8% when extending (see Table 1).

Table 1: Force and Pressure Required by Hydraulic Actuator to Move Yaw Axis from a Stop

Direction of Motion	Existing System		System with TABRM		% Change
	Diff. Pressure (psi)	Force (lbs)	Diff. Pressure (psi)	Force (lbs)	
Extending	-44.5	-874.4	-24.1	-473.6	45.8%
Retracting	48.2	947.3	27.8	546.5	42.3%

Table 2: Rolling Friction in Yaw Bearing

Direction of Motion	Force (lbs)
Extending	-98.7
Retracting	98.7

Table 3: Friction Force in Hydraulic Actuator Required to Overcome to Start Motion

Direction of Motion	Existing System (lbs)	System with TABRM (lbs)	% Change
Extending	-775.71	-374.94	51.7%
Retracting	848.58	447.81	47.2%

The TABRM was most effective when used during maneuvers that slowly approach and depart zero velocity, such as a low frequency sine wave. When comparing the performance of the yaw axis with the existing system (see Fig. 9) against the performance with the TABRM engaged (see Fig. 10), there are obvious differences.

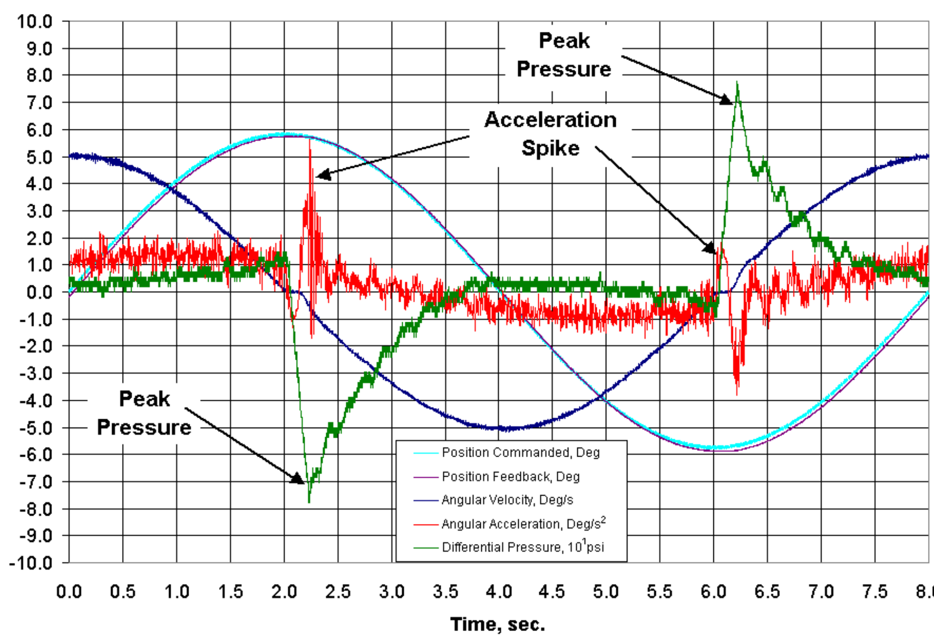

Figure 9: Existing System (Before TABRM, .125 Hz)

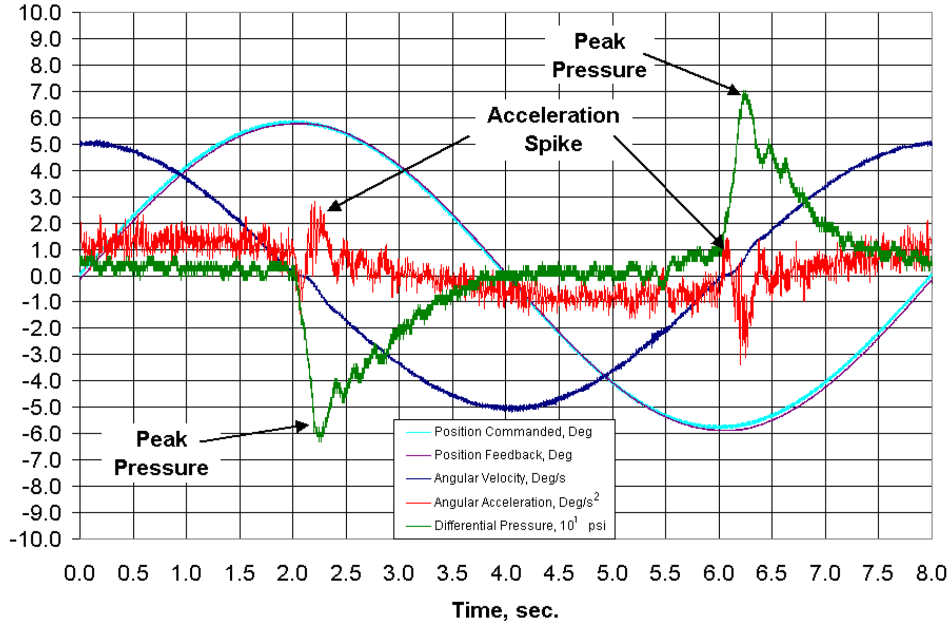

Figure 10: TABRM Engaged (.125 Hz)

With the TABRM engaged and the hydraulic actuator oscillating at .125 Hz, the acceleration spike is reduced as much as 36.6% and the peak differential pressure is reduced by as much as 19% as compared to the existing system. Also, with the TABRM engaged, the amount of time the hydraulic actuator is stuck at zero velocity is reduced by approximately 50% (see Fig. 11).

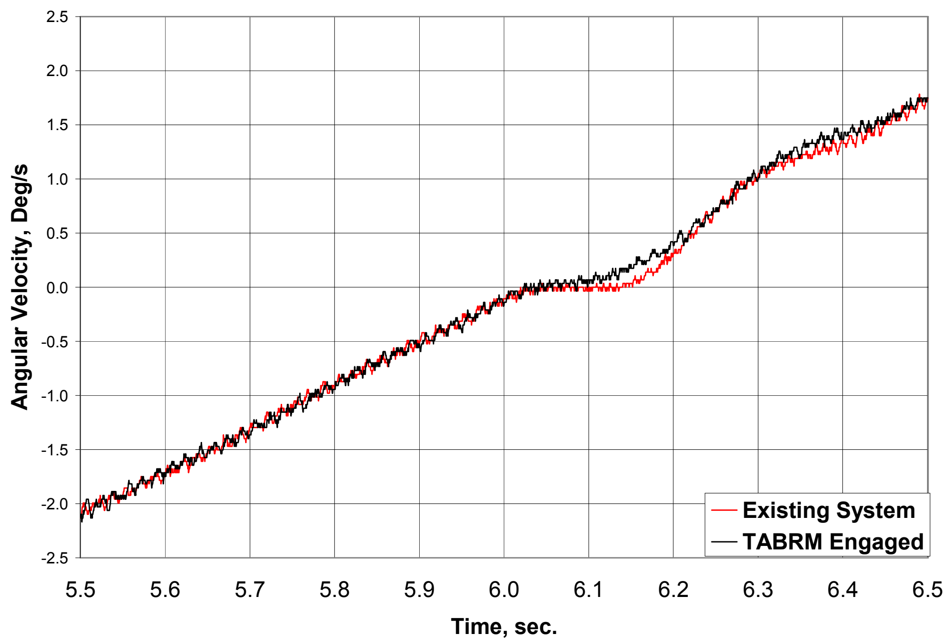

Figure 11: Angular velocity with and without the TABRM (.125 Hz)

The TABRM is less effective during more aggressive maneuvers such as higher frequency sine waves. Comparing the performance of the yaw axis with the existing system (see Fig. 12) to that with the TABRM engaged (see Fig. 13), the differences are less obvious.

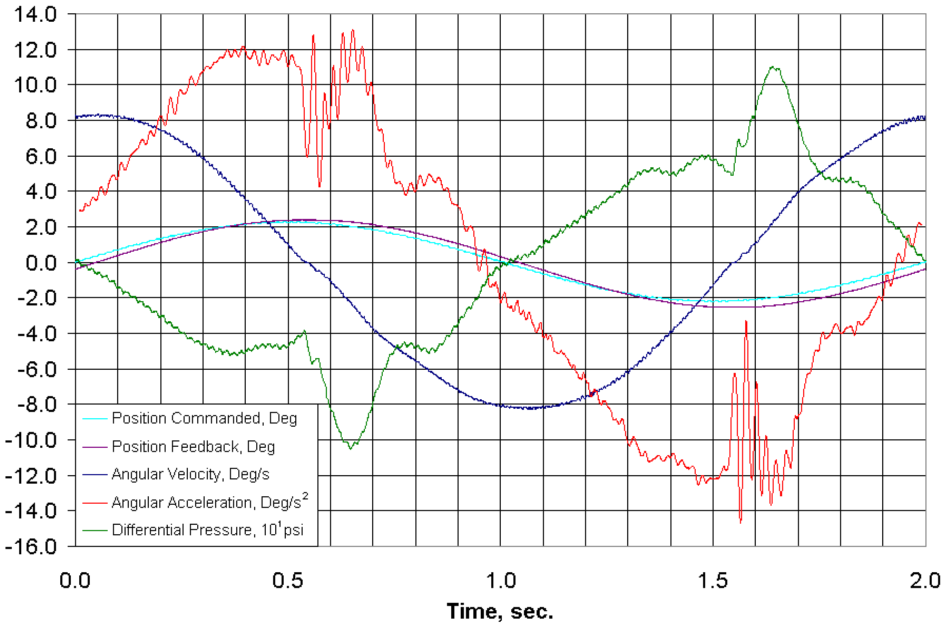

Figure 12: Existing System (Before TABRM, .50 Hz)

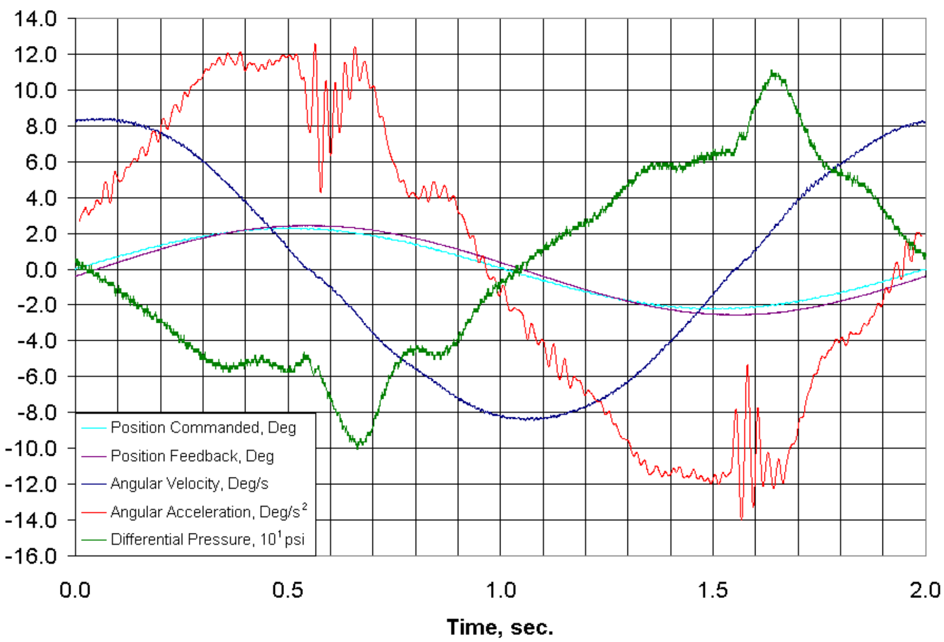

Figure 13: TABRM Engaged (.50 Hz)

With the TABRM engaged and the hydraulic actuator oscillating at .50 Hz, the highest acceleration spike is only reduced by 9.3%, and the highest differential pressure spike is only reduced by 4.3% as compared to the existing system.

The TABRM becomes less of a factor when the differential pressure in the actuator is greater than the differential pressure required to overcome the static friction at zero velocity. The differential pressure at zero velocity when the yaw axis is oscillating at .125 Hz (see Fig. 10) is much lower than the differential pressure when the yaw axis is oscillating at .50 Hz (see Fig. 13) because the higher differential pressure is needed to slow the yaw axis down from the more aggressive maneuver. When the differential pressure is greater than the pressure required to overcome the static friction, the hydraulic actuator will start to move almost instantaneously, rather than pausing slightly at zero velocity, as seen in Fig. 11.

V. Future Turnaround Bump Reduction Efforts

The TABRM greatly reduces the static friction but does not affect the kinetic friction. The yaw actuator on the VMS is mounted horizontally and the center of gravity (CG) is located between the two mounting points. The weight of the hydraulic actuator causes a high normal force on the seals due to the racking between the piston rod end and the housing (see Fig. 14).

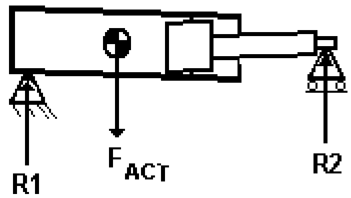

Figure 14: Free Body Diagram of Unbalanced Yaw Actuator

Adding an external moment at the pivot point can reduce the kinetic friction (see Fig. 15). The optimum normal force on the seals is when the external moment eliminates the racking between the piston rod end and the actuator housing. Ideally, the moment would change such that the actuator housing is always fixed with reference to the piston rod end.

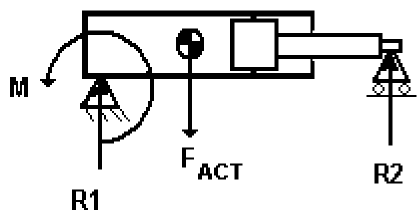

Figure 15: Free Body Diagram of Actuator with External Moment

In application it is difficult to apply a moment that exactly counters the change in the location of the piston rod end with respect to the housing. Currently, a spring-loaded mechanism is being tested on the VMS that is experimentally adjusted to best approximate the required moment to obtain the lowest starting pressure.

VI. Conclusion

Turnaround bump cannot be avoided with a hydraulic actuator that has seals. Turnaround bump is not just a phenomenon of the VMS but is prevalent in many applications that use hydraulic actuators such as hexapod motion systems and robotic applications. There will always be friction from the seals, so there will always be a disturbance force introduced into the control system when the hydraulic actuator tries to move from a stop. There are two ways to try and reduce the turnaround bump; one is to reduce the friction in the system, and the second is to change the control system.

The control system has a large affect on the turnaround bump. Typically, the better response a control system has the worse it handles disturbances. There is a balance that must be met between response and disturbance rejection when tuning the control system. If the control system is tuned to reduce the turnaround bump then the response will be more sluggish. If the system is tuned for maximum performance then the effect of the turnaround bump will be more prominent.

Regardless of the control system, every effort should be made to reduce the friction from the seals so that the control system can be as responsive as possible. The TABRM does not eliminate the turnaround bump but reduces it enough such that it is unnoticeable by the pilot.

References

[1]Giovannetti, D.P., "High-Fidelity Motion Simulator Rapid Cockpit Implementation Demonstrated Using a Blackhawk Configuration", *American Institute of Aeronautics and Astronautics (AIAA), 2002-4795*

[2]Sheldon, P., Sheldon/Van Someren, Inc., Wauwatosa, Wi, U.S. Patent for a "Actuator Cylinder with Mechanism to Reduce Stiction" Patent No. 5,727,445 Issued Mar. 17, 1998