SEVENTH EUROPEAN ROTORCRAFT AND POWERED LIFT AIRCRAFT FORUM

Paper No. 52

REVIEW OF HELICOPTER MAST MOUNTED SIGHT (MMS) BASE MOTION ISOLATION AND LINE-OF-SIGHT (LOS) STABILIZATION CONCEPTS

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September 8 - 11, 1981

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ABSTRACT

Incorporation of a MMS or any precision stabilized pointing system on a helicopter is a complex and interesting dynamic design problem which combines automatic control through a servomechanism with vibration reduction techniques. Generally, the helicopter disturbance inputs to the MMS must be accomodated by a stiffer MMS structure and servo-system. However, weight and cost are usually critical and many benefits could be derived from incorporation of a lightweight vibration isolator. There are important design considerations on both sides of the interface, the airframe and the MMS. A review of these design considerations and several vibration isolation concepts will be presented. The need for adequate simulation modeling of this complex dynamic environment will also be discussed.

1. Introduction

Military tactics for helicopter scout missions require the helicopter crew to detect, recognize, and designate targets while keeping the helicopter hidden behind low terrain features. Laser designation of targets is also a requirement when requested for attack helicopters or other laser guided weapon launches. While an existing electro-optical system such as the Target Acquisition Designation System (TADS) mounted on the nose of the Advanced Attack Helicopter (AAH) could fulfill this role there are distinct advantages for the scout helicopter to have a lighter weight electro-optical system mounted above the helicopter rotor disk. These advantages consist primarily of enhanced survivability due to the fact that the helicopter, excluding the mast mounted sight (MMS), can remain masked behind low terrain features. Verification of this enhanced survivability has been obtained through operational and engineering flight testing of several prototype MMS's on several different helicopters. In order to take advantage of this enhanced operational capability the US Army has initiated a program to upgrade some of its scout helicopters by incorporating a MMS and improving overall mission capability.[1] An artist concept is depicted in Figure 1.

While there are many areas to address when integrating a complex electro-optical system on a helicopter the electro-mechanical interface is the most interesting and also one of the most important. This paper will not address specific helicopter - MMS configurations but will attempt to address how MMS base motion (mechanical) excitations are a function of helicopter configuration parameters and how line-of-sight (LOS) stabilization (electrical) concepts are influenced by mechanical excitations both external and internal to the MMS.

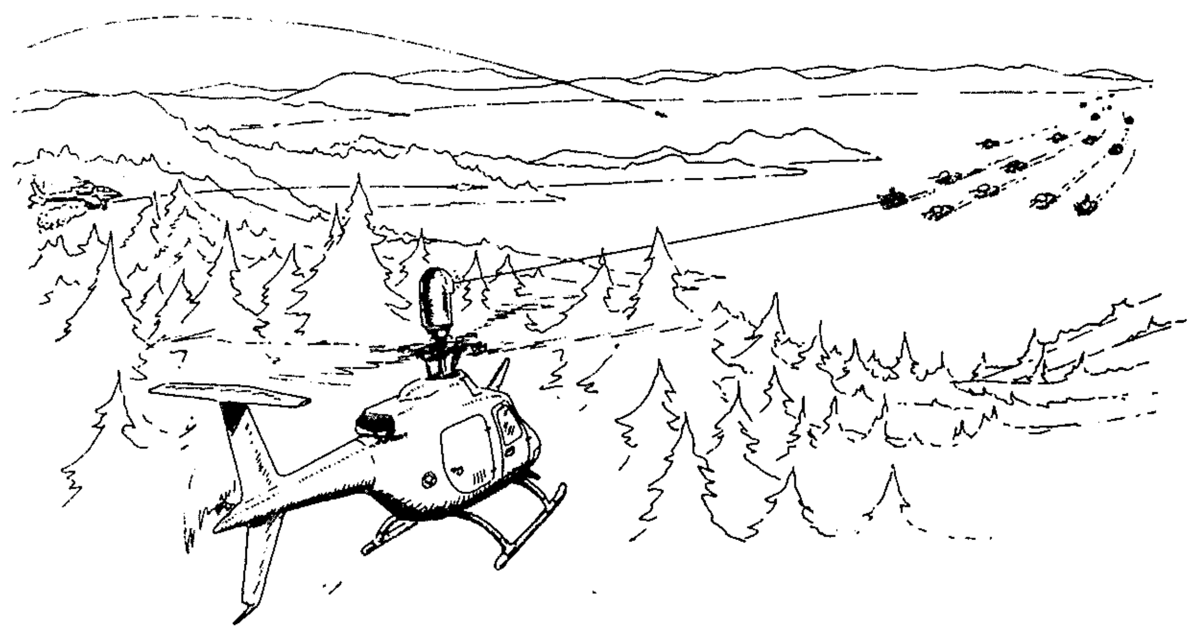

FIGURE 1 - SCOUT HELICOPTER MMS CONCEPT

2. Airframe Integration Design Considerations

Modification of existing helicopters to accept a MMS is difficult because the vibration environment above the rotor is due to a combination of complex aerodynamic and inertial loadings, the rotating rotor shaft inside diameter (ID) is usually small, and the rotor support is often soft mounted to reduce the vibratory loads being transmitted into the airframe. Some helicopters are more difficult to modify than others due to rotor configuration (teetering, articulated, or hingeless), number of blades, and rotor diameter. Necessary airframe integration design considerations for a MMS are the sight vibration environment (translational and angular), rotor, hub and mast loads (steady and oscillatory), aeromechanical stability, rotating to stationary mast clearance (rotor shaft ID to MMS standpipe OD), fuselage vibration characteristics, handling qualities, performance (aerodynamic drag), and weight and balance. Of these considerations the MMS and fuselage vibration environments and rotor, hub, and mast loads appear to be most crucial and the most difficult to analyze.

Steady and vibratory loads at the main rotor hub are a combination of complex individual rotor blade aerodynamic and inertial loadings. Difficulties in predicting and measuring rotor hub loads are well recognized.[2] Figure 2 represents the total combination of steady and vibratory loads that could be experienced at the rotor hub. Depending on the type of rotor system, i.e., hingeless, articulated, or teetering, all or some of these loads will be transmitted to the MMS and airframe. For instance, for a hingeless rotor each blade is, in essence, a cantilevered beam so that both moments and shears are transmitted to the hub. Figure 3 illustrates how a four bladed hingeless rotor transmits all six forces and moments to the hub. Also illustrated is the fact that the rotating blade loads occur not only at n/revolution (rev), where n is the number of blades, but also at n-1 and n+1 per rev. For an articulated or hinged rotor each blade is individually hinged (pinned) at a slight offset from the center of rotation to provide an additional source of control power. Blade lag dampers are usually required to insure freedom from mechanical instability. Figure 4 summarizes the major source of hub shaking forces on a four bladed hinged rotor. For a teetering rotor the blades are usually mounted as a single unit on a"see-saw" or "teetering" hinge. The usual teetering rotor configuration consists of two opposite blades that flap and bend together about the central hinge in a symmetric or antisymmetric pattern as depicted in Figure 5. Therefore, both a pinned and cantilevered boundary condition exist at the center of rotation. A combination of forces and moments are transmitted into the hub and since, in the rotating system, they are occurring at n, n-1 and n+1 per rev, where n is equal to two, they are the first three harmonics of shears and moments and can thus be quite large.

POSITIVE SIGN AND VECTOR CONVENTIONS FOR FORCES ACTING ON THE HELICOPTER

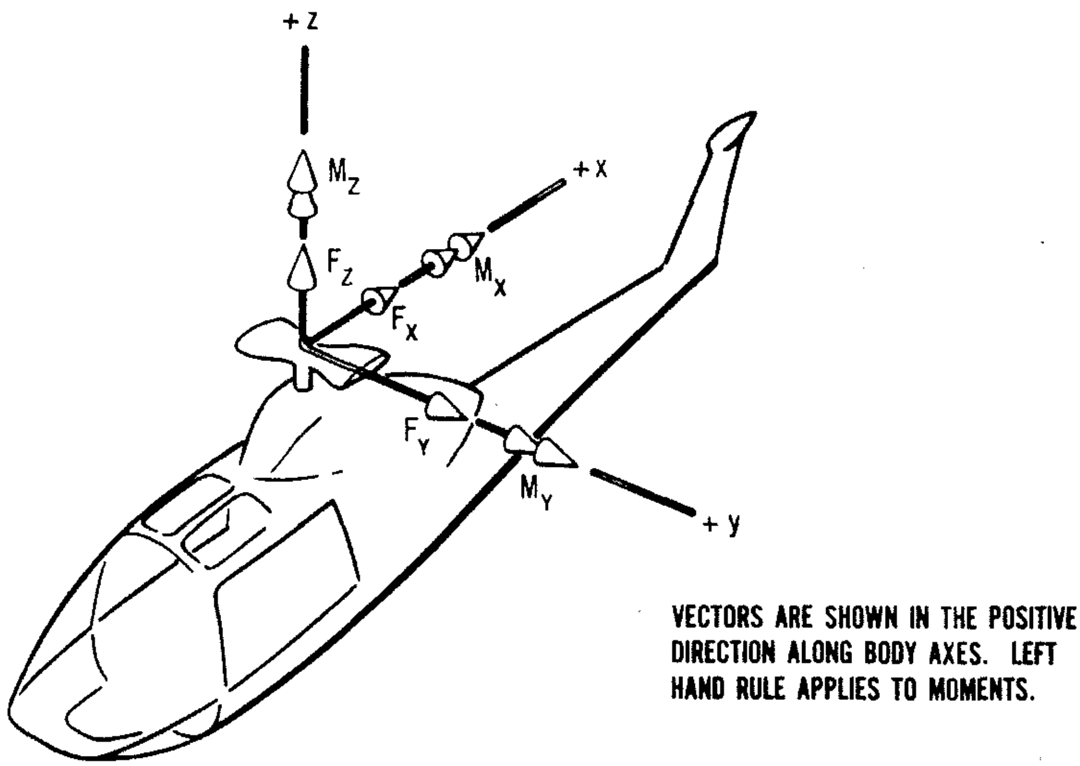

FIGURE 2 - TOTAL COMBINATION OF STEADY AND VIBRATORY LOADS

HINGELESS ROTOR (4 BLADES)

SOURCE OF 4/REV HUB SHAKING FORCES

ROTATING BLADE LOADS (SHEARS AND MOMENTS)			HUB SHAKING FORCES (FIXED SYSTEM)					
			F_X LONG	F_Y LAT	F_Z VERT	M_X ROLL	M_Y PITCH	M_Z YAW
FLAP	**SHR**	**MOM**						
3/REV	X	X				X	X	
4/REV	X				X			
5/REV	X	X				X	X	
CHORD								
3/REV	X	X	X	X				
4/REV	X	X					X	
5/REV	X	X	X	X				

FIGURE 3

HINGED ROTOR (4 BLADES)

SOURCE OF 4/REV HUB SHAKING FORCES

ROTATING BLADE LOADS (SHEARS AND MOMENTS)			HUB SHAKING FORCES (FIXED SYSTEM)					
			F_X LONG	F_Y LAT	F_Z VERT	M_X ROLL	M_Y PITCH	M_Z YAW
FLAP	**SHR**	**MOM**						
3/REV	(2)					(2)	(2)	
4/REV	X				X			
5/REV	(2)					(2)	(2)	
CHORD								
3/REV	X	(1)	X	X				
4/REV	X	(1)					X	
5/REV	X	(1)	X	X				

(1) LAG DAMPER (2) HINGE OFFSET

FIGURE 4

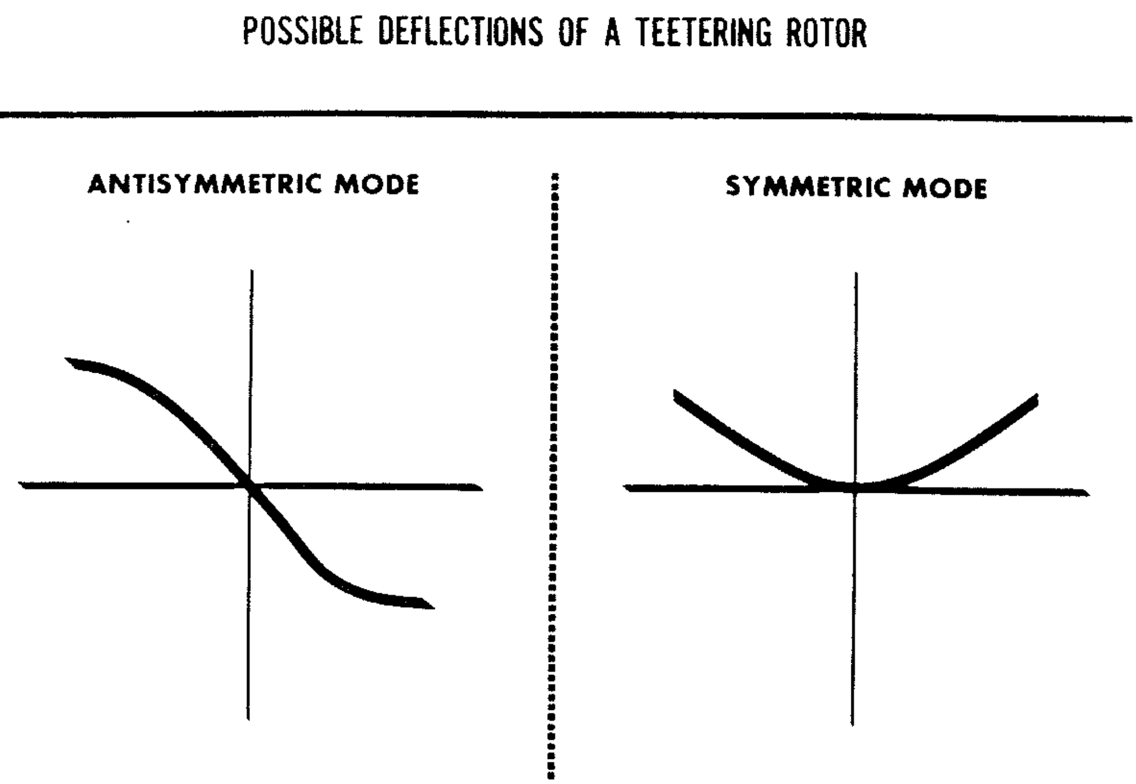

FIGURE 5

The base motion that the MMS will experience can consist of a combination of forces and moments which are strongly dependent on the type rotor system. These forces and moments in the fixed system will principally be at n times the rotational speed and multiples of n, except when blades are not balanced or tracked properly, then any harmonic of rotational speed can occur. In addition to determining the forces and moments at the hub the type rotor system will also determine how much influence the weight of the MMS will have on rotor, hub and mast loads. The MMS will change the rotor hub impedance which can have a big influence on rotor, hub, and mast loads depending on the type rotor system. For teetering and hingeless rotors the influence is quite large due to the moment transfer between hub and blades. Most teetering rotors require soft mounting of the MMS to keep the first blade chordwise bending frequency from approaching the rotor rotational speed.

Another important helicopter configuration parameter influencing the MMS and fuselage vibration environment is rotor support stiffness. Many helicopters have rotor isolation systems incorporated between the rotor and airframe. One such system, pylon focal mounting, is illustrated in Figure 6 which has been used quite successfully to isolate fore and aft and lateral forces from the airframe on two bladed teetering rotors.[3] As can be seen the hub is allowed to oscillate to force a node at the pylon or on the fuselage. Obviously, incorporation of a MMS with stringent vibration requirements to meet line-of-sight (LOS) performances will be influenced by this hub motion as will the location of the node points and hence fuselage vibration due to the mass of the MMS. Some compromise may be required if rigid mounting of the MMS is desired.

FOCAL PYLON ISOLATION SYSTEM PRINCIPLE

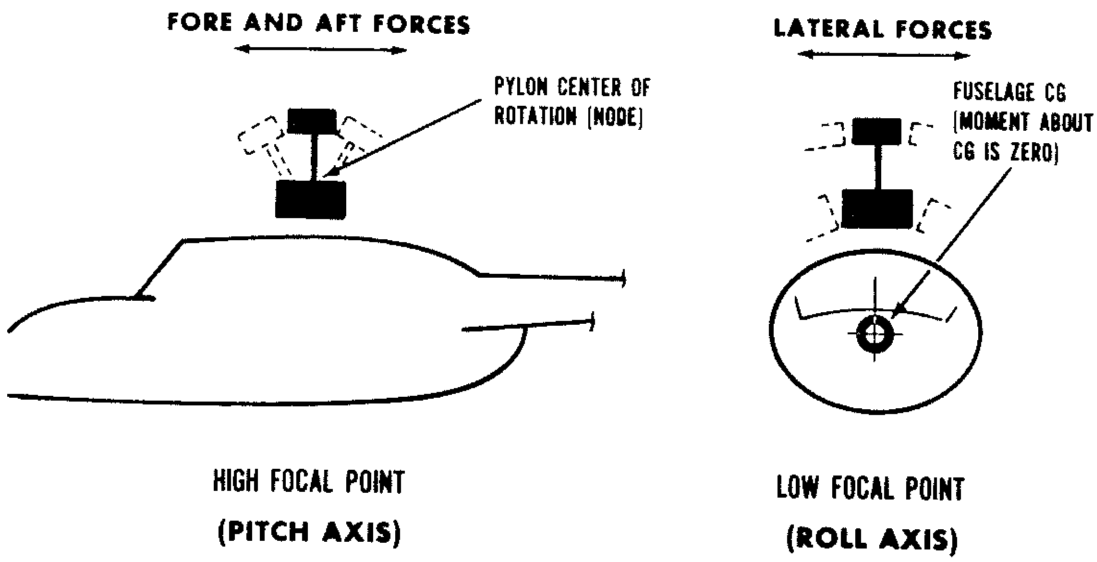

FIGURE 6

3. <u>MMS Integration Design Considerations</u>

There are many MMS integration design considerations. Some of these deal with electrical power requirements to operate the sensors, wire routing techniques, boresighting and sensor cooling requirements. Figure 7 is a schematic of possible MMS concepts for a day/night system with laser range-finder/designation (LRF/D) capability.[1] Also depicted in Figure 7 is a box called Stabilization and LOS Gimbals which will be the principal topic of discussion. Two types of MMS Concepts are usually employed. These are stabilized mirror or stabilized platform. The internal payload of the MMS must be precision stabilized to minimize sight line jitter and retain system resolution without image blur, and enhance system reliability. The purpose of the stabilization system is to actively correct the various disturbances to the payload i.e., the acquisition sensors mounted on an optical bench plus the mirror (if included). The impact of LOS stabilization on recognition range for television (TV) and forward looking infrared (FLIR) systems can be seen on the trend plot of Figure 8. The limiting parameters on recognition range with zero stabilization error are system resolution which is primarily a function of TV and FLIR aperture size, field of view, noise and boresight errors. As can be seen reductions in stabilization error can greatly increase standoff range and therefore enhance survivability.

MAST MOUNTED SIGHT SCHEMATIC

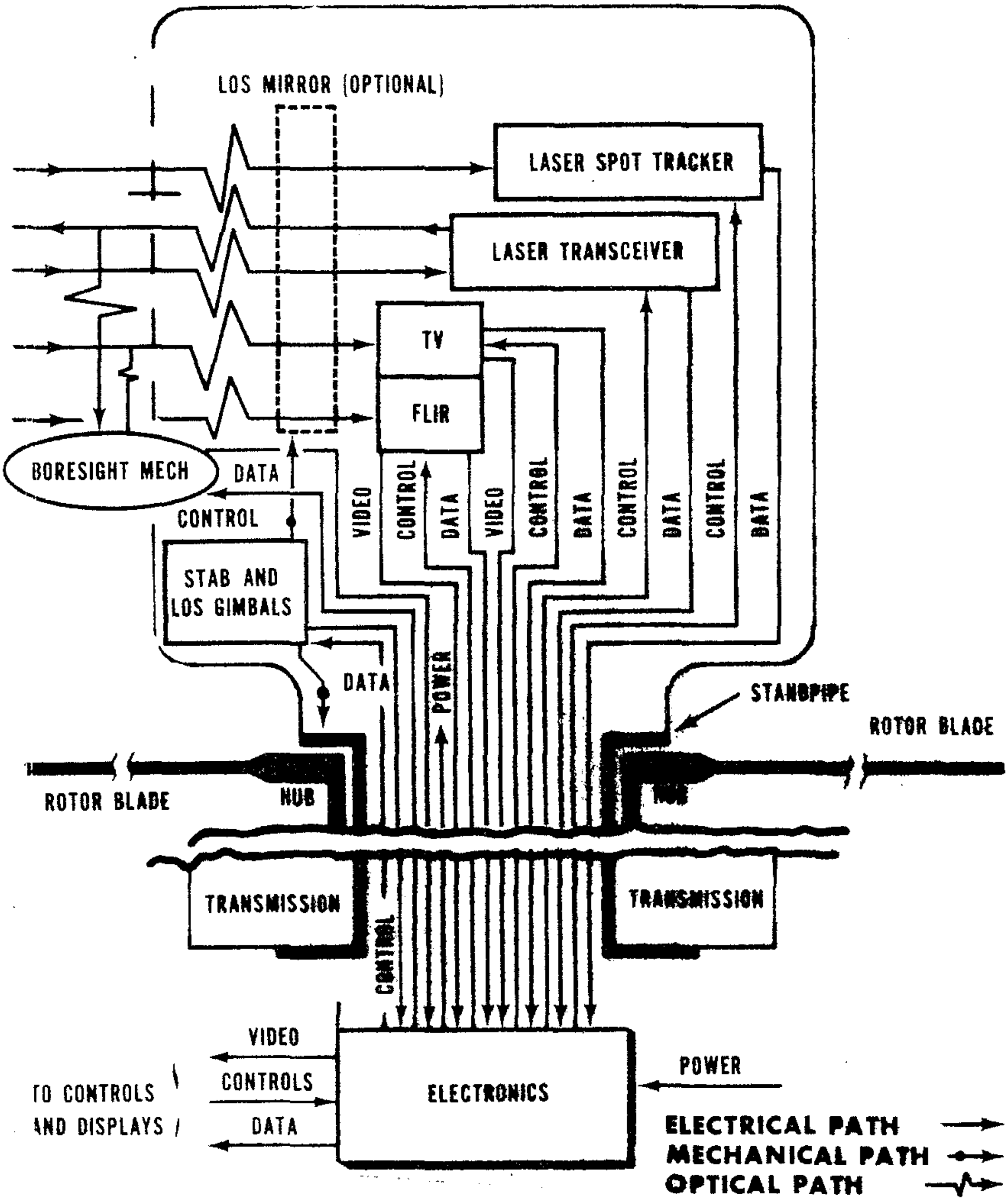

FIGURE 7

RECOGNITION RANGE SENSITIVITY TO LOS STABILIZATION

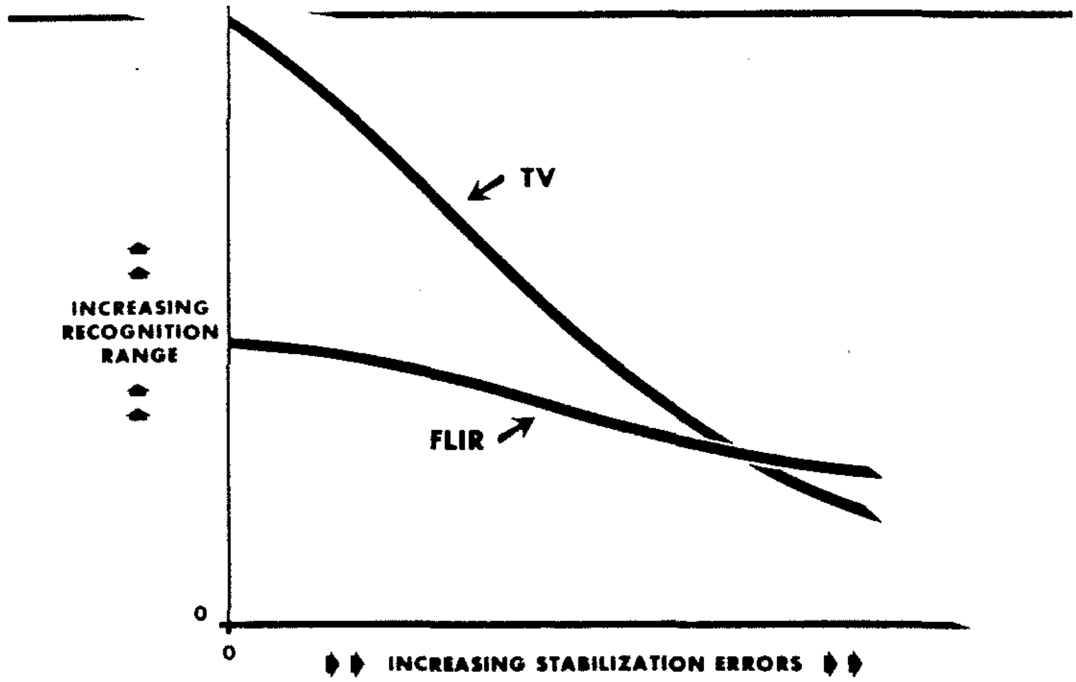

FIGURE 8

Stabilization errors are produced by many sources such as torque disturbances, geometric and kinematic coupling, gyro misalignments, and gyro imperfections. The torque disturbances occur due to brush and bearing friction, cable torques, mass unbalance, and wind loading. The geometric coupling occurs primarily because the system is usually stabilized in only two axes, pitch and yaw. Kinematic coupling can occur due to the dynamic relationships between the gimbal assembly inertias and the total system angular rates and accelerations. Gyro misalignments about their output axes can couple angular motion about the line sight into the stabilized axes. Finally, gyro imperfections such as translation acceleration sensitivity and noise can also limit the stabilization accuracy by producing an error source.

There are three basic stabilized payload concepts that have been used on precision stabilized electro-optical platforms. These concepts are illustrated in Figure 9. The concept in Figure 9a is a rigid or hard-mounted gimbal arrangement in a one-axis version. The payload is mounted in a gimbal shaft which rests in bearings that are rigidly attached to the rotor hub or a coarse drive. The torquer, torquing actuator, is mounted across the bearing inner and outer races. A block diagram of this concept is illustrated in Figure 10. The bearing acts on the relative displacement between the output pointing angle and the input angle. The output of the bearing is a torque which is a function of both input amplitude and frequency. The purpose of the stabilization system is to reduce this error torque by the feedback loop via the torquer before it is applied to the payload inertia. As stated earlier there are many stabilization error sources. The interaction between base motion translational vibration and payload mass unbalance creates a coupling torque which can be broadband in frequency and will be fed directly to the payload unless actively attenuated by the servomechanism. This error source is depicted in Figure 10. The servo frequency bandwidth becomes critical with respect to which error disturbances are actively attenuated. In theory the wider the servo bandwidth the larger frequency range of disturbances are actively attenuated. In practice there are other concerns that limit servo frequency bandwidth such as structural resonance and loop stability.

COMPARISON OF GIMBAL CONCEPTS

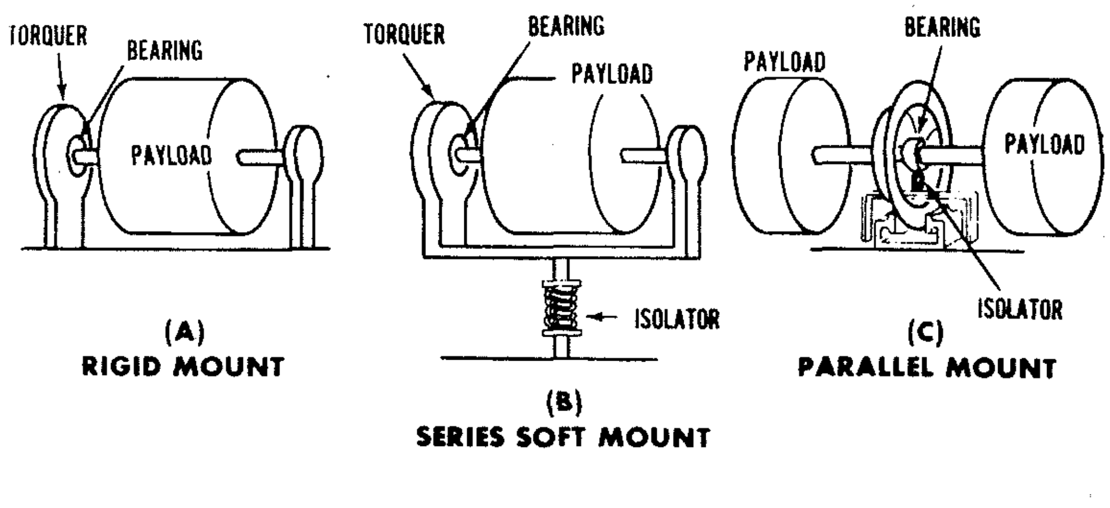

FIGURE 9

RIGID MOUNT GIMBAL BLOCK DIAGRAM

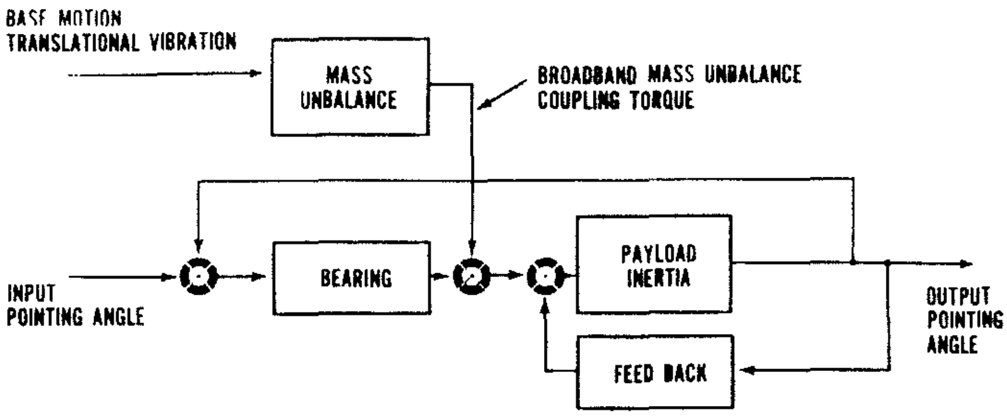

FIGURE 10

Of all the effects that can limit the achievable servo frequency bandwidth, structural resonance is often one of the most severe. In order to maintain good stability in a rate loop servomechanism it has been shown that it is often impossible to have a servo frequency bandwidth greater than one-third of the structural natural frequency for a control system closed around the structure.[4]

For the rigid or hard-mounted gimbal there are fundamental limitations on the performance of a precision stabilized system. The gimbal structure must be very stiff to keep from deflecting under the influence of shock and vibration. This generally results in gimbal structures which are heavy and expensive and not always compatible with airborne applications. Another limitation is the high sensitivity to mass unbalance coupled torques since translational vibrations are not attenuated. The payload structure or bench must also be very stiff which usually requires gusseting to keep structural resonances approximately three times higher than the servo bandwidth which must be quite wide to accomodate all major torque disturbances which can be transmitted through the rigid amount. Finally, because the payload will be subject to a hard ride due to shock and unattenuated vibrations the mean-time-between-failure (MTBF) and mean-time-between removal (MTBR) of the payload sensors and bearings can be low resulting in poor system reliability.

The concept illustrated in Figure 9b is a conventional soft mount isolated gimbal. In this case the payload is mounted in a gimbal set with the torquer (motor) across the bearing assembly as in the rigid mounted case, except the total system is mounted on a passive isolator. While passive isolation is quite effective on many systems because it keeps high frequency vibration, above the isolator frequency, from being transmitted into the structure it has distinct limitations on a servo-controlled isolation system. On these systems one of the most important factors in achieving a satisfactory isolation system is the determination of dynamic stability of the system. In the concept of Figure 9b the isolator is in series with the torquer so that the motor pushes on the isolator to stabilize the payload and the reaction torques wind up the isolator. With the isolator resonance within the servo bandwidth the system can become unstable if the dimensionless gain of the servo control element for this particular system becomes larger than twice the damping ratio.[5]

Another consideration of a system with the isolator in series with the torquer is the introduction of a second order resonance in positive feedback with the actuator torquing loop. This factor places a lower bound on the isolator natural frequency which becomes a limitation on the effectiveness of the isolator as a vibration and shock attenuator. Therefore, for a given isolator natural frequency, the servo bandwidth will be limited such that the isolator resonance does not cause a servo loop instability. By placing the isolator and torquer in series the translational and angular motions are coupled so that a tradeoff exists between angular disturbance rejection capability and translational shock and vibration attenuating capability.

In order to decouple the torquer from the isolator a parallel mounting system such as illustrated in Figure 9c can be utilized. In this concept an angular decoupling device, bearing, and a low natural frequency isolator are in series and both mounted in parallel with a torquing actuator to give simultaneous angular stabilization and passive translational vibration isolation. In this concept the problems of servo bandwidth limitation and isolator natural frequency selection discussed previously can be eliminated. The parallel arrangement is achieved by arranging the torquing actuator with its armature tied to the payload on one side and its stator pushing on the vehicle or rotor hub base on the other side. In this manner the isolator supports the payload and is not coupled with the torquing actuator.

This concept of parallel mounting of the isolator and spherical bearing with the torquing actuator has been developed for the Army by McDonnell-Douglas Astronautics Corporation to introduce passive isolation into stabilized gimbal platforms.[6] The concept has been given the name IBSSU which stands for Internal Bearing Stabilized Sighting Unit. The exploratory development program has been under the sponsorship of the Army Advanced Concepts Team and directed by the Guidance and Control Directorate of the US Army Missile Laboratory, US Army Missile Command (MICOM), with support from the Army Aviation Research and Development Command (AVRADCOM). The exploratory development has included generation of the equations of motion for use in digital computer simulation,[7] evaluation of stabilization performance in laboratory vibration tests,[8] and flight test evaluation on the nose station of the AH-1G Cobra helicopter.[9] Results of this program have been very promising with the achievement of excellent stabilization peformance.[10]

4. MMS Computer Simulation Modeling

Too often the management approach taken to a complex dynamic system is to give up on computer simulation modeling in lieu of only hardware development and trial and error testing. Reasons often given are cost; that the system is too complex to effectively model on the computer; and that correlation is seldom achieved between predicted and test results. While computer simulation modeling is no substitute for MMS laboratory and flight testing it is a very important element in the design evolutionary process. It will more than pay for itself in initiating a good preliminary design as well as identifying critical laboratory and flight testing and as an aid in troubleshooting the source of problems encountered.

For the MMS, computer simulation is very important to study system performance in the harsh above the rotor helicopter environment. Careful modeling of gimbal, sensor and controller components as well as noise and disturbance effects will enhance the believability[10] of performance predictions for a proposed MMS. Under a MICOM Contract[10] with AVRADCOM support mathematical modeling of a generic precision pointing and tracking (PP&T) system has been accomplished. An effort was made to retain model flexibility to insure efficiency in the application of the model as a test bed for validation of new technical approaches to PP&T systems. Existing Army PP&T systems such as the Stabilized Platform Airborne Laser (SPAL), the Target Acquisition and Designation System (TADS), the MICOM Stabilized Mirror System (MSMS), the Airborne Target Acquisition and Fire Control System (ATAFCS), and the Internal Bearing Stabilized Sighting Unit (IBSSU) were reviewed to provide a broad background for generic modeling. Three gimbal/sensor categories were identified and initialized by their stabilization platform: the basic platform, the isolated platform and stabilized mirror. The basic platform model is illustrated in Figure 11. Four gimbals are shown and are composed of two coarse positioning gimbals (elevation and azimuth) and two fine positioning gimbals (pitch and yaw). The fine positioning gimbals lie within the coarse positioning gimbals and are meant to move through only small angles relative to the coarse gimbals. The other two gimbal/sensor categories are the isolated platform model and the stabilized mirror model. The isolated platform model is based on the parallel mount concept already discussed. The stabilized mirror model is depicted in Figure 12. In this system only the mirror is precision stabilized to maintain alignment of the optical axes from the undesirable effects of helicopter vibrations, maneuvers, and environmental accelerations. The physical representation is characterized by an inertial wheel, a mirror, and an inertial platform all mounted inside an outer gimbal frame. As illustrated in Figure 12 four types of motion are indicated: coarse elevation and azimuth and fine elevation (pitch) and fine azimuth (yaw). The mirror and the counter inertia wheel are mounted on axes parallel to the platform pitch axis.

Once the physical characteristics of a system are modeled the fundamental modeling differential and difference equations can be written. For servo system components the differential equations are the same for all three gimbal/sensor categories. The only difference among components and across concepts is the constant coefficients in the equations. The differences between physical concepts or categories is indicated mathematically in the algebraic and trigonometric coupling of block diagram concepts.[10]

PLATFORM CONCEPT GIMBALS AND SERVO/SENSOR COMPONENTS

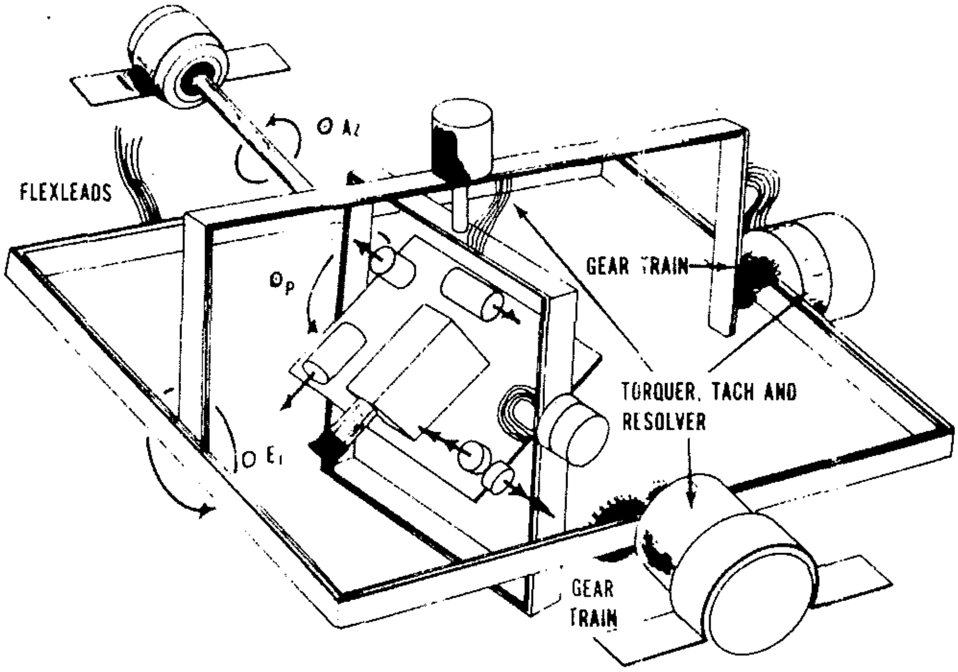

FIGURE 11

STABILIZED MIRROR CONCEPT GIMBALS AND SERVO/SENSOR COMPONENTS

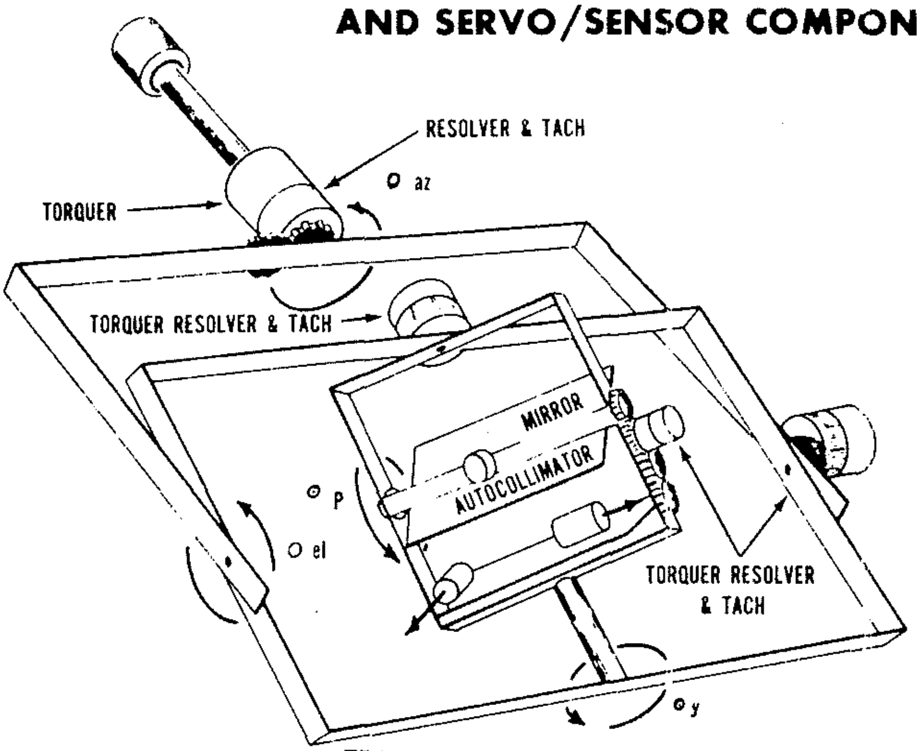

FIGURE 12

5. Summary

The incorporation of a MMS on a helicopter represents an interesting and complex dynamic problem to both the helicopter and MMS manufacturers. To successfully integrate such a system requires an understanding of the design considerations on each side of the interface. This paper has attempted to review some of these design considerations with special emphasis placed on MMS base motion vibration and how it impacts MMS LOS stabilization concepts. From the airframe integration design considerations it was illustrated how the type rotor system and rotor support method strongly influence MMS base motion vibration. From the MMS integration design considerations it was illustrated how stabilization concepts can greatly influence LOS performance. The benefits of MMS computer simulation modeling which includes system dynamics, structural characteristics, passive isolation and active controllers were discussed and its importance in a successful design evolutionary process addressed.

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