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A study is presented of a 430 gun installed in a AH-1G helicopter and firing GAU-8 ammunition. The weight of the system limits ammunition capacity to less than 100 rounds. The forces on the helicopter limit the burst length to only a few rounds due to the stability augmentation limits of the helicopter. Concepts are generated which address the gun mount control system. Electric versus hydraulic servo drives are discussed. The effects of fire rate on servo bandwidth are studied as are the effects of angular base motion of the helicopter.

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SUMMARY

The system identified in this study is intended mainly as a test vehicle that would verify feasibility, and provide data for further development of this concept.

A trainable gun concept with limited field of fire is presented that weighs about 1100 lbs, and is located aft of the 20-mm turret occupying the former ammunition compartment. Ammunition capacity is less than 100 rounds. Power for the system would come from a stored energy source such as an accumulator. The field of fire is ±10° azimuth, +6° and -10° in elevation, for short bursts only, depending on the gun elevation. The servo system utilizes linear hydraulic actuators connected to elevation and azimuth gimbals and a balanced gun cradle. Elevation and azimuth servos are essentially the same. Each servo has electronic tach and position loops. Loop bandwidths were selected to attenuate the instantaneous torques generated by the vertical and horizontal gun support loads. This approach reduces weight and power consumption. Dynamic pointing accuracy is maintained by having a balanced gimbal, low inertia drive system and incorporating rate feed forward into the servo system.

INTRODUCTION

There is an interest in some quarters for arming an attack helicopter with a gun system capable of defeating armored targets. This study is the result of a proposal by the General Electric Company to analyze the requirements of such a high impulse gun system, and perform tradeoff studies to identify a suitable turret design.

A contract was awarded to GE in August 1979 to study the effects of loads and torques on the helicopter airframe and turret.

This study addresses the concepts specifically outlined in the Statement of Work, and further separates them into two general categories of Mechanical Systems and Servo Design Considerations. The work done under this contract was accomplished by analysis of system performance and functional requirements, and identification of a system configuration compatible with those requirements.

The GAU-8 ammunition considered in this study is a high impulse round (125-150 lb-sec), with an effective antiarmor projectile (APIT). The GE 430 gun used as a test vehicle in this concept is a 4-barrel, 30-mm gatling gun developed by General Electric, and currently used in the GEPOD 30.

The objective of the study was to determine if GAU-8/A ammunition could be successfully fired in a GE 430 gun from the AH-1G helicopter. The conclusion of the study is, that while it is feasible, only a few rounds could be fired in a burst, due to stability augmentation limits of the helicopter. Further study is needed to determine the effectiveness against the intended target.

Future studies should include detail simulations of the helicopter airframe and gun servos. These simulations would provide information on the helicopter airframe vibrations as a result of firing the GE 430. This would be done with various firing rates, burst length, recoil systems and gun control systems.

TECHNICAL DISCUSSION

MECHANICAL SYSTEMS

Helicopter Weight and C.G. Limitations

This concept is based on the assumption that the weight of the HIGAD installation aboard the AH-1G should not exceed the fully loaded XM97 system weight (1002 lbs), and the c.g. should be no further forward than the c.g. of the fully loaded XM97 (F. STA 101.5). (See Appendix A.)

This weight and c.g. limitation locates the gun in the aircraft, and has a significant impact on the structure, ammunition capacity, gun drives, servo actuators, and recoil system. The center of gravity of the gun and cradle should be located as near as possible to the fuselage station 101.5 (the c.g. of a loaded XM97 system), while allowing clearance for maximum recoil motion between the aft end of the gun, and the bulkhead at fuselage station 138.7. The HIGAD gun would occupy the ammunition compartment space on the AH-1G, Figure 1. The structure will have to be an efficient, lightweight design to meet the weight limitation. Since there is no space available at the aft end of the gun, ammunition storage will have to be at the side or bottom of the gun. This concept allows a closed loop of ammunition of less than 100 rounds for test purposes. The tradeoff of gun drives will be made largely on space and weight. If there is insufficient electrical or hydraulic power available to drive the 430 gun (6 hp at steady state - 6 times the XM197 power), then the power will come from a stored energy source; accumulator, batteries or compressed gas located near the helicopter c.g. A dc motor drive and battery pack were included in the weight and c.g. analysis. The tradeoff study of gun drives and energy storage should be the subject of future analysis.

Static and Dynamic Loading in the Mounting Area AH-1G Structural Limitations.

The only structural portion of the XM97 turret that might be applicable in a HIGAD installation is the upper support and azimuth bearing. There is not enough depth or clearance in the lower support to contain a 430 gun and cradle (saddle). Since the upper support has inadequate fatigue life for peak recoil loads exceeding 2000 lbs at the present XM197 location, it is unlikely that the upper support would be structurally adequate for a 430 HIGAD installation.[1] The average (rms) recoil force for both active and passive recoil attenuators will be 1680 lbs at 720 spm, however, the active system could reduce the peak-to-peak forces, resulting in a lower maximum recoil force. (See Appendix A.) The maximum vertical forces at the gun supports will be approximately the same for either recoil system, due to the fact that both systems set back and dither approximately the same. The firing barrel location relative to the structure and azimuth bearing, results in significantly larger stresses of the upper support and bearing. A new structure should be designed which would allow a mounting area interface with the AH-1G large enough to dissipate the recoil loads and moments safely, and minimize local deflections of structure which may affect accuracy. In addition, extensive modifications of the bulkhead aft of the existing turret would be required for clearance of the gun which extends aft of the bulkhead.

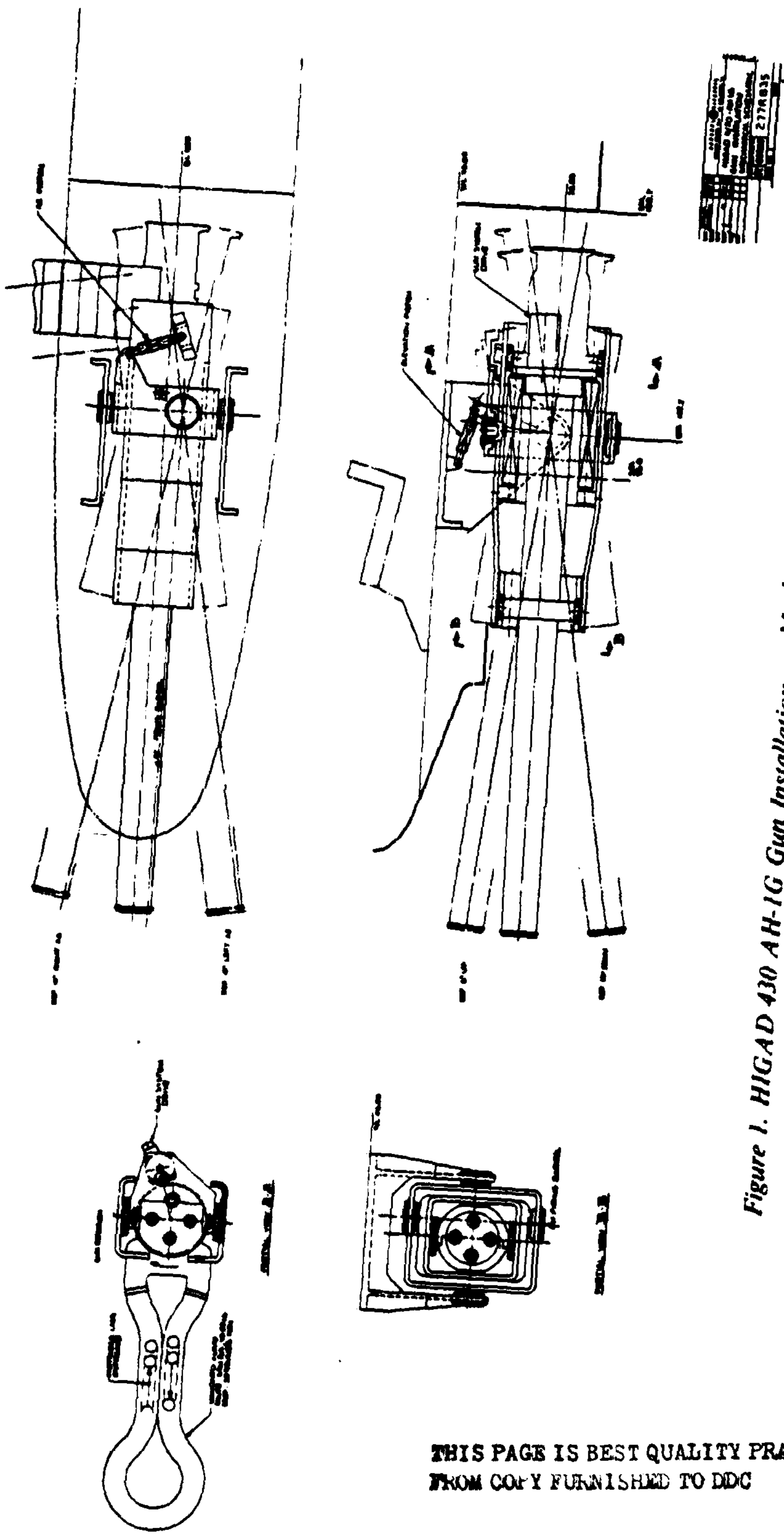


Figure 1. HIGAD 430 AH-1G Gun Installation — Mechanical Schematic

One method of reducing the structural loads is by the use of a muzzle brake which could reduce the recoil loads by about 20%. Such a muzzle brake device is currently in use on the GE 30-mm pod. These devices tend to aggravate gun gas flash and pressures in the vicinity of the muzzle, and may not be suitable for this application.

Limited Turret Field of Fire

It will be assumed that the HIGAD turret field of fire will be limited by the AH-1G rotor torque capability to correct for moments about the c.g. of the helicopter. Those rotor torques are:

Roll	4400 ft-lbs	
Pitch	2500 ft-lbs	These numbers were obtained from Bell Helicopter
Yaw	8900 ft-lbs	

This assumption is based on steady state continuous firing using average recoil loads.

The yaw and roll moments due to firing the 430 gun at 720 spm in the 10° maximum train position are 2430 and 1170 ft-lbs respectively, well within the control limits of the helicopter. However, the average pitch moment due to firing the 430 at the 720 spm rate exceeds the 2500 ft-lbs allowable, except at depression angles of 17° and lower. (See Appendix A.) Those large depression angles are beyond the scope of this study, and would require other concepts of mounting and controlling the gun. At a reduced firing rate of 360 spm the gun may be depressed to 7° and lower without exceeding the control limit. Another helicopter control factor to be considered is the total thrust aft if the rotor is used to its maximum pitch correction while the gun is firing. At the high rate of fire this thrust amounts to 1680 lbs from the gun, which added to the compensating rotor thrust would amount to a significant deceleration of the helicopter.

These high loads and moments nearly preclude firing continuously, and the length of burst would be limited by the controllability of the helicopter and maintaining accuracy of the gun within the limitations of the sight and gun control systems. If the gun is fired at depression angles less than 17° the length of burst is limited by the gun reaching the maximum elevation position (+6°) as the helicopter pitches down. (See Appendix A.)

Gun Recoil Loads - Recoil System Design

The gun recoil peak-to-peak loads should be kept to a minimum to minimize the disturbance of firing to the aircraft which may affect gun pointing accuracy.

In general, the recoil forces are higher at higher rates, but the ratio of peak-to-peak forces is less. For instance, the Honeywell active recoil system varies from a peak of 1760 lbs at 720 spm to only 960 lbs at 360 spm, while the maximum peak to minimum peak ratio of recoil forces varies from

1.21 at 720 spm to 1.52 at 360 spm. The GE passive recoil system has a maximum peak of 3300 lbs and peak-to-peak ratio of 4.71.

While an active recoil system has potential in improving accuracy and increasing structure fatigue life by reducing peak-to-peak loads, it will add considerable weight and cost to the system. Peak hydraulic flow rates of approx: ately 47 gpm (1500 psi - 3 inch stroke) will be required, which will require a power supply to deliver more than 20 hp. Since there is insufficient hydraulic power available on the AH-1G, an energy reservoir system must be included, such as an hydraulic accumulator. The size, weight, and placement of these components have not been included in this analysis, but should be included in future tradeoff studies of a recoil system design.

The size and weight of a typical low force, passive ring spring recoil system were included in this analysis. Our experience with similar turreted systems on XM97 and EX-83 indicates that such recoil systems provide adequate peak-to-peak force reduction at significant savings of weight and cost.

The effect of the moment due to the offset between the firing barrel and the center of gravity of the guns' recoiling mass can best be improved by optimizing the supporting stiffness in the plane of the moment. This can allow more gun motion in this plane, reducing the forces and the resulting disturbance on the servo control system.

A major factor affecting location of the firing barrel and the center of gravity of the recoiling mass is the type of ammunition feed chuting and its location. A rigid chuting mounted outboard of the gun will be accelerated more than 100 g's with each round fired, will be subjected to very high stresses, and will adversely affect the c.g. of the recoiling mass and create higher transverse forces due to the moment induced by gun longitudinal accelerations. A flexible ammunition chuting which allows less rounds and chuting to move through the entire gun range of motion will reduce stresses on gun, feeder, and chuting and have less adverse effect on the c.g. and transverse forces. The location of the firing barrel will be determined by the size and flexibility of the chuting. The weight and c.g. limitations dictate that less than 100 rounds can probably be stored directly opposite the gun feeder, to either side of or below the gun.

Gun Mount Balance

The average disturbance torques should be kept low by locating the fore-aft c.g. and the firing barrel as close as possible to the gimbal axes.

SERVO DESIGN CONSIDERATIONS

The primary function of the gun servo system is to keep the gun aligned with the commanded position from the fire control system in the presence of torque disturbances and dynamic motion of the helicopter. The following considerations were addressed in this study.

Electric Versus Hydraulic Servo Drives

For the limited field of fire of ±10° in azimuth and +6, -10° in elevation; linear actuators provide an efficient package. Hydraulic actuators were selected because hydraulic systems are capable of producing larger torque than electrical equipment of equivalent sizes or weights. As detailed later, the maximum flow required is estimated at 5 gpm at 1500 psi.

Torque Response Requirements

The 430 gun is a 30-mm 4-barrel Gatling gun. With this type of design, the center of gravity of the recoiling parts is approximately in the geometry center of the circle formed by the four barrels. The 430 has its firing barrel 2.8 inches from the center of gravity of the recoiling parts. Firing the gun will produce moment impulses within the recoiling parts. The major concern is not pointing errors or dispersion due directly to the firing disturbance. These are normally insignificant with proper gun mounting (firing barrel on axis). The cyclic gun position error signals due to the firing disturbance is not a true measure of the gun pointing error (i.e. where the bullets will go). The fundamental component of the errors is the firing frequency. Thus, for a constant firing rate, the gun error is approximately the same at each instant the round is fired. For this reason it is not required to have the servos respond to the firing instantaneous disturbance. If the servos were to respond and try to keep the gun from moving, the servo power consumption, during firing, would be significantly increased. Tracking performance can be reduced because available power was reduced in overcoming these disturbances. Thus, in order to keep the servo components small and lightweight and minimize power consumption, it is desirable to design the servo control so that it does not respond to the instantaneous firing disturbances.

One method for achieving this torque response, is to have the servo bandwidth lower than the firing rate. Disturbance torques become more of a problem at low firing rates. In this study, the maximum firing rate of the GE 430 is primarily determined by the stabilization capabilities of the helicopter during firing. The rate loop bandwidth is set at approximately 40 rd/sec to reduce the response to the firing disturbance at 75 rd/sec.

Base Motion Response Requirements

Helicopter base motion will disturb the servo system as "($S\theta$) helicopter" shown as the servo block diagram. Both low frequency (less than 1 Hz) motion due to evasive maneuvering or air turbulence and high frequency motion resulting from vibrations are present. Normally, the low frequency motion is the significant base motion disturbance. It is assumed that the servo position command signal will be stabilized but the errors required to drive the rate loop would be appreciable in trying to follow this motion. This is especially true since the servo bandwidths were reduced in order to obtain the desired torque response. To effectively eliminate the errors due to base motion, rate feed forward would be used. This signal is now available on the AH-1G Multi-Weapon Fire Control System helicopter. The required gyros were added for the air-to-air gun application tests which were recently completed.

The helicopter length results in a large moment of inertia about the pitch axis, thereby minimizing the disturbances and accelerations about this axis. The average pitch acceleration at 0°

gun elevation is -0.3 rd/sec² (See Appendix A). There will be alternating peaks about this mean, with the maximums and minimums determined by the type of recoil system and the amount of force attenuated by the turret structure. The disturbance is at the firing frequency (12 Hz). Other disturbances can result from local deflections at the turret/helicopter interface and may have higher frequency components.[2]

Servo Loop Design

Figure 2 is a model of the first order effect of the gun and cylinder interaction. The gun inertia is shown as J2 and the stiffness of the gun and support structure is shown as k.

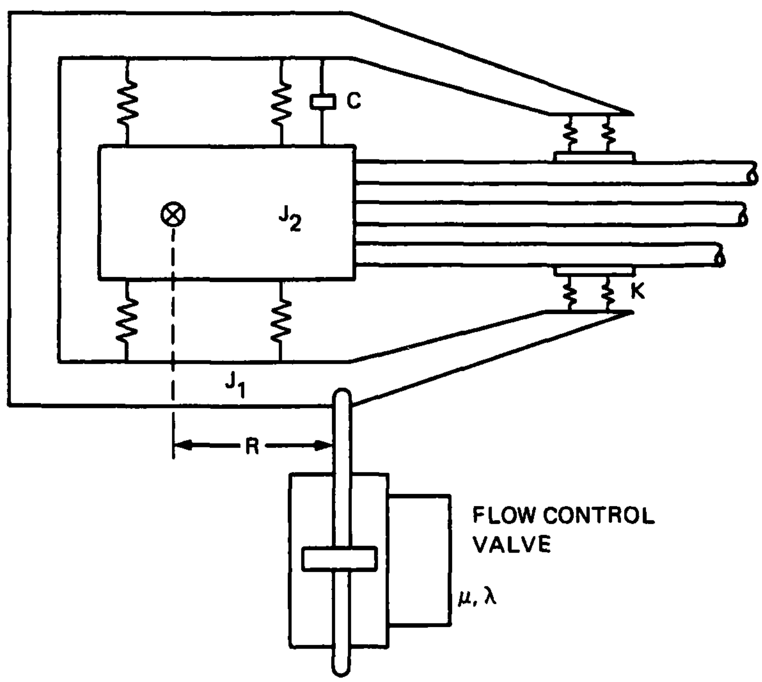


Figure 2. First Order Effect of the Gun and Cylinder Interaction

The gimbal inertia is shown as J1 which is driven with a double-ended hydraulic cylinder controlled by a flow control valve. Test data on the GE 430 gun shows that J2 and k give a natural frequency of 18 Hz. The compressibility of the hydraulic fluid in the cylinder along with the aircraft structure is another spring in the system. The compressibility of the hydraulic fluid together with the cylinder design will give a linear stiffness of approximately 285,000 lbs/in. The aircraft structure is assumed to have a stiffness of 50,000 lbs/in. The total compliance (λ) is 23.5×10^{-6} lb/in. This design will allow the closure of a 40 rd/sec tachometer loop and provide the desired torque response. This design approach (balanced gimbal-train and elevation, plus firing barrel aligned with gimbal axis) minimizes the need for a high gain (bandwidth) torque response loop.

Both elevation and azimuth servos are essentially the same. The cylinders are supplied with hydraulic fluid from a flow control valve. The valve armature is driven by an electronic current loop of high bandwidth (greater than 500 Hz). The servo-valve transfer function is represented in the servo block diagram by a simple first order expression. This expression is adequate for the frequency range of interest, i.e. to about 70 Hz.

Gimbal rate relative to the helicopter is sensed by a tachometer and summed into the servo electronics. Within the tachometer servo loop electronics is an integrator to allow closure of the loop around the non-linear actuator loop. Also included is a velocity/position limit function for braking at the end of travel. The gimbal position relative to the helicopter is sensed by a position transducer. Within the forward part of the position loop electronics there is an integrator-lead function in addition to synchronizing circuits. The position loop bandwidth would be approximately 1 Hz. The function of the integrator-lead function is to ensure zero static position errors in response to steady-state torque disturbances such as wind load. The static error is then a function of transducer accuracy, servo deadband and amplifier offsets.

It can be shown by block diagram (Figure 3) manipulation that the effective position bandwidth with rate feed forward is the product of the two loop bandwidths. For this preliminary design, the effective position loop bandwidth for command inputs is 6 x 40 = 240 rd/sec. This high effective bandwidth will allow the gun servo to follow command inputs to less than one milliradian.

The position and rate feed forward command signals may be digital or analog. Digital inputs would be converted to analog voltages with standard D/A modules.

The torque requirements for the GE 430 servo are conservatively estimated to be 1440 ft-lbs. This will provide approximately the same peak acceleration capability as the present XM97 turret. The limited field of fire (10°) compensates for the larger area of the GE 430 so that the maximum wind load is about the same as the XM97 turret. A pistor area of 2.0 in.^{2} and a one foot lever arm were selected. With a supply pressure of 1500 psi, the normal load pressure will be less than a half of the supply pressure. This will help linearize the rate loops. A Moog series 32 servo valve was selected. With this valve, a hydraulic flow rate of 18.8 in.^{3}/sec. (5 gal/min) will drive the gun system at 45°/sec.

The servo bandwidths were determined primarily from two factors: the maximum firing rate is set by the helicopter torque limits; and the tach loop bandwidth must be less than the firing frequency in order to reduce the response to firing torques.

The preliminary design has a tach loop bandwidth of 6 Hz which is set with the gain term K_2K_V. The position loop bandwidth is 1 Hz, set with K_1.

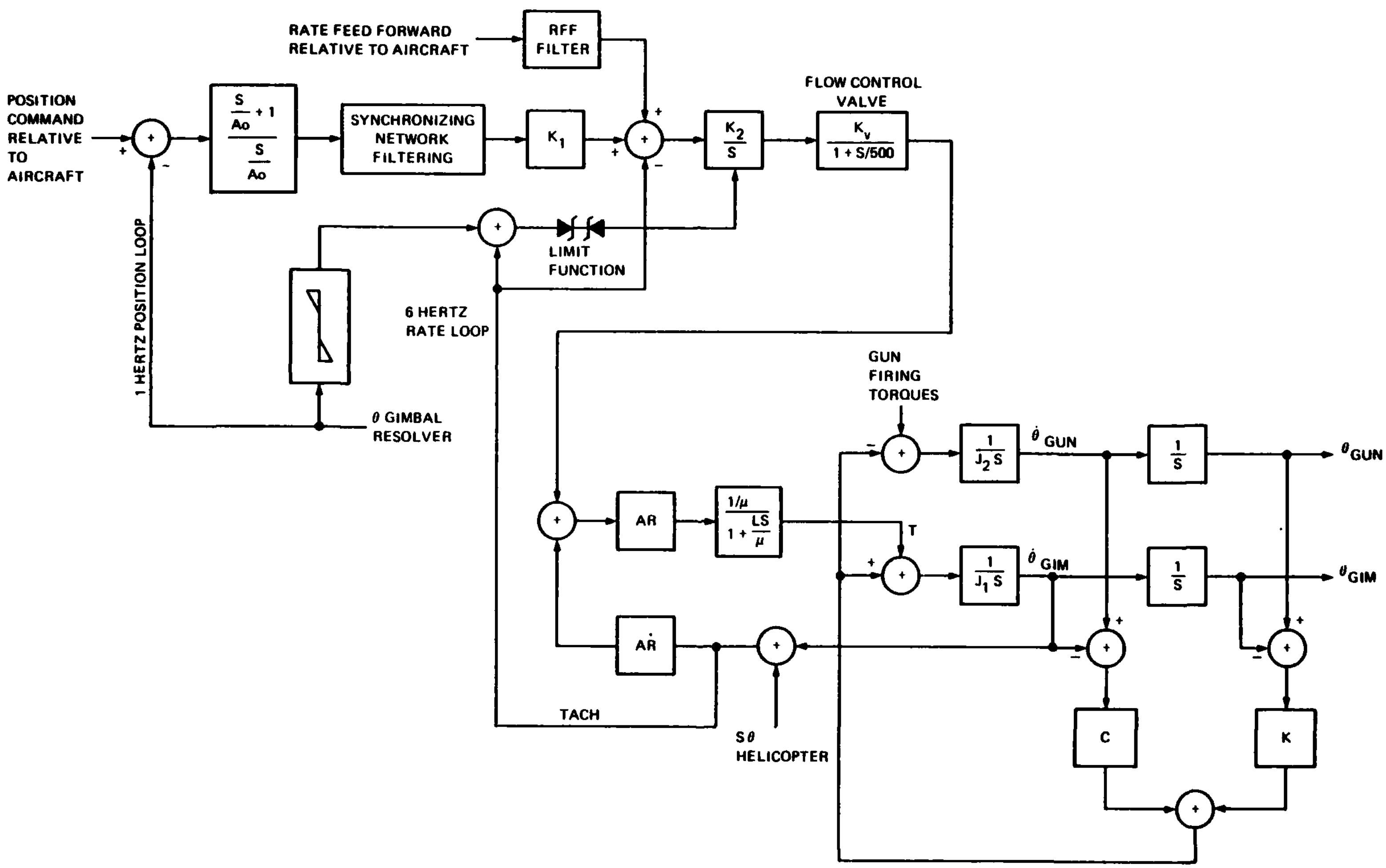


Figure 3. Hydraulic Servo Block Diagram

ESTIMATED SERVO LOOP PARAMETERS

J_1	GIMBAL INERTIA	11 SLUG FT^2
J_2	GUN INERTIA	61 SLUG FT^2
K	GUN STIFFNESS	800,000 FT-LB/RAD
C	GUN DAMPING	4000
A	PISTON AREA	2 IN.^{2}
R	LEVER ARM	1 FT
μ	FLOW/PRESSURE GRADIENT	0.13 CIS/PSI MAX.
L	$\lambda * A^2$	
λ	HYDRAULIC & STRUCTURE COMPLIANCE	23.5×10^{-6} IN/LB
K_2K_V	TACH LOOP GAIN	SET FOR BANDWIDTH OF 6 HZ
K_1	POSITION LOOP GAIN	SET FOR BANDWIDTH OF 1 HZ

CONCLUSIONS AND RECOMMENDATIONS

This study concludes that the concept of a high impulse gun firing from a helicopter is feasible with limitations on burst length and requiring extensive structural modification. Further analysis is required to determine the adequacy of the system effectiveness.

The dynamic gun pointing errors should be determined from a simulation of the recoil forces on the helicopter airframe and gun servos.

The design configuration will require further analysis and tradeoff studies for recoil system, drive, power supply and structural design.

REFERENCES

1. D.H. Spawn, *Advanced Turret Study*, Technical Information Series No. 79APB509, Burlington: General Electric Armament Systems Department, 9 January 1979.

2. T.D. Hutchings and A.R. Zak, *The Investigation of Dynamic Gun Pointing Errors for Helicopter Mounted Automatic Cannon Systems*, Rock Island: GEN Thomas J. Rodman Laboratory, 2 November 1976.

APPENDIX A
SYSTEM ANALYSES

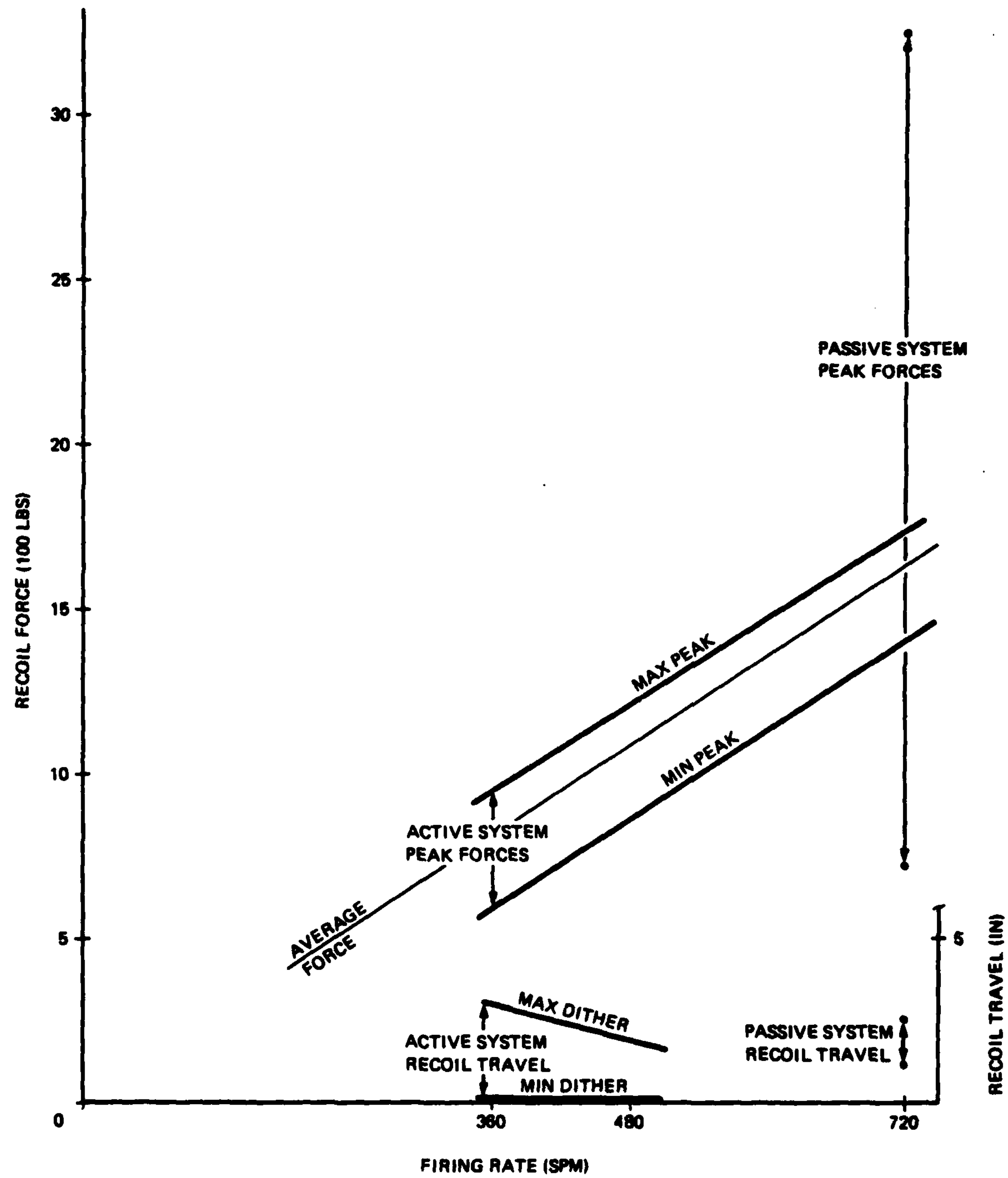
WEIGHT AND C.G. ANALYSIS HIGAD VS XM97

XM-97	Component	Weight (lbs)	c.g. from AZ axis STA 75.5 $\overline{X}$ (in.)
	XM197 Gun	179	–3.45 (meas.)
	Turret Assembly	175	
	Feed System	93	+43.2 (est.)
	750 Rounds 20-mm Ammo	421	
	750 Links	106	
	Control Electronics	29	+16 (est.)
	Loaded System	1003	+26 STA 101.5
	Empty System	582	+13.5 STA 89

430 HIGAD	Component	Weight (lbs)	c.g. from recoil attachment (in.)
	430 Gun & Feeder	360 (meas)	–11.2
	Drive Motor & Gearbox	27 (est)	–11.2
	Servo Actuators	9	
	Recoil Adapters	25	
	Gun-Servo Control Electronics	29	
	Structure (cradle, Az & El yoke & drive support)	369	35% of volume in steel
	GAU-8 Ammunition 80 rds	120	+16
	Ammunition Conveyor & Storage	64	
		1003	–6.2
	Gun Drive Battery Pack	80	Assumed located at c.g. of helicopter

if 430 gun c.g. is at STA 101.5 locate recoil attachment at STA 101.5 +6.2 or STA 106.7

HIGAD RECOIL LOAD ANALYSIS
PREDICTED DATA



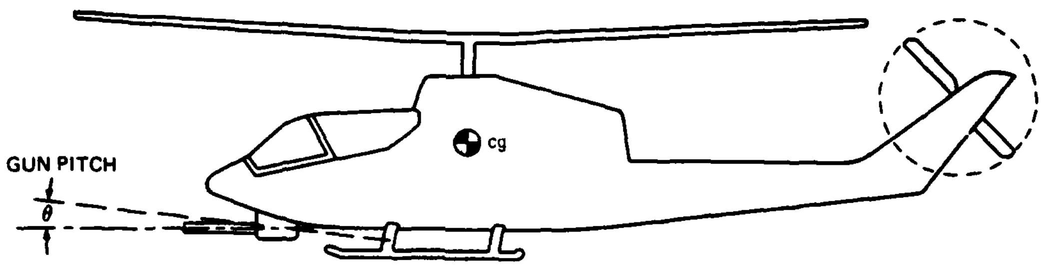
HIGAD RECOIL LOAD ANALYSIS

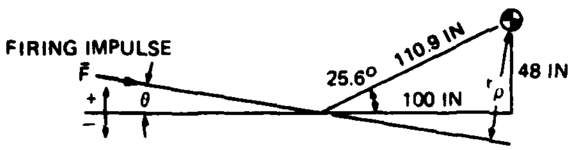
PITCH, ROLL, AND YAW MOMENTS ABOUT cg OF AH-1G

ASSUME IMPULSE OF GAU-8 30-MM I = 140 LB-SEC

AVERAGE RECOIL LOAD = AT 720 SPM $\bar{F}_{720} = \frac{720.140}{60} = 1680$ LBS

AT 360 SPM $F_{360} = 840$ LBS





r = MOMENT ARM FROM FIRING BARREL TO cg

$= 110.9 \text{ SIN } (25.6^\circ + \theta)$

$r_{\rho\ max}$ WHEN $\theta = +6^\circ$, $r_{\rho\ max} = 58$ IN

<u>MAX PITCH MOMENT</u> $M_p = \bar{F}_{720}\, r_{max} = 1680 \text{ LBS } \frac{58.2 \text{ FT}}{12} = 8146$ FT-LBS

AT $\theta = +6^\circ$ $r = 58.2$ IN

AT 360 SPM $M = 840 \text{ LBS} \times \frac{58.2}{12}$ FT = 4073 FT-LBS

<u>SAFE GUN ELEVATION</u> WHEN $M_{SCAS} = 2500$ FT-LBS $r_{safe} = \frac{2500 \text{ FT-LBS}}{1680 \text{ LBS}} = 1.5$ FT

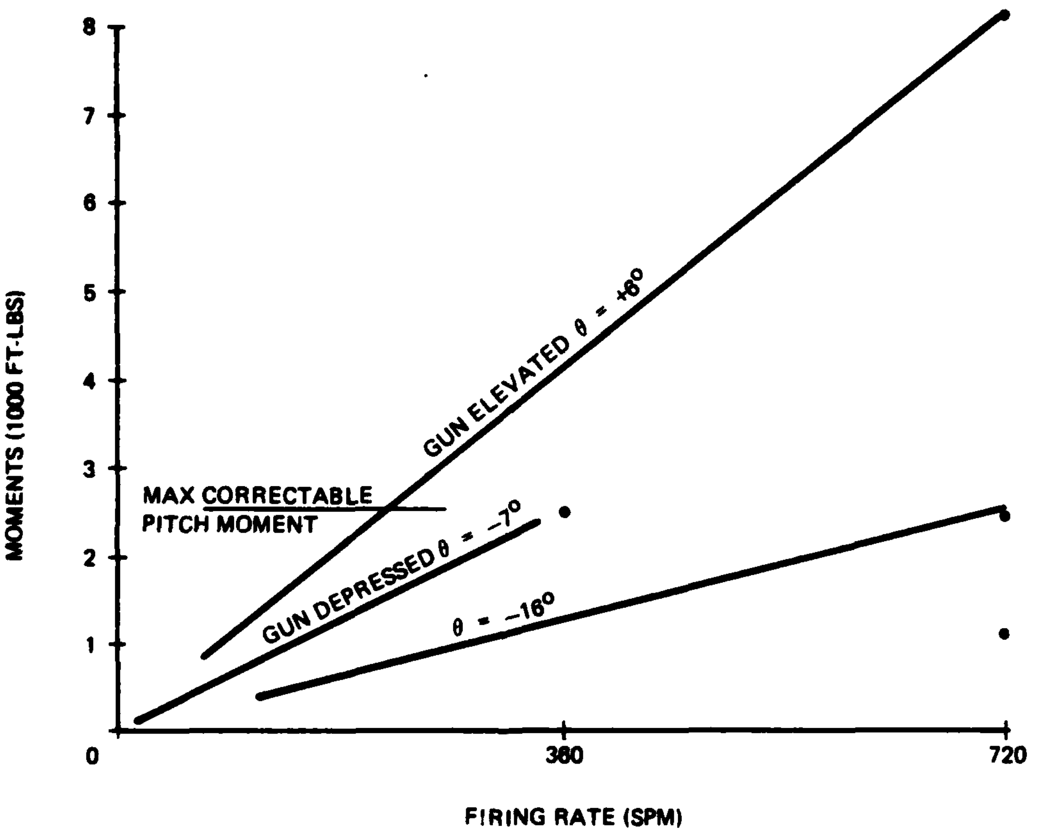
$\theta_{safe} = -25.6^\circ + \text{SIN}^{-1}\left(\frac{r}{110.9}\right)$ $\theta_{safe} = -16.4^\circ$

AT 360 SPM $\theta_{safe} = -25.6^\circ + \text{SIN}^{-1}\left(\frac{2500/840}{110.9/12}\right) = -6.8^\circ$

<u>MAX ROLL MOMENT</u> $M_R = \bar{F}_{720}\, r_R \text{ SIN } 10^\circ = 1680 \text{ LBS } \frac{48 \text{ FT}}{12} \text{ SIN } 10^\circ = 1167$ FT-LBS

<u>MAX YAW MOMENT</u> $M_Y = \bar{F}_{720}\, r_Y \text{ SIN } 10^\circ = 1680 \ \frac{100 \text{ FT}}{12} = 2431$ FT-LBS

PITCH MOMENTS AT VARIOUS GUN ELEVATIONS AND FIRING RATES



AH-1G RESPONSE TO HIGAD

J_{PITCH} = 14,000 SLUG FT^2 (FT-LBS SEC^2)

TORQUE FROM FIRING GUN AT A CONSTANT 0^o ELEVATION $\qquad r_\rho = 4$ FT, $\bar{F}_{720} = 1680$

$T_\rho = -6720$ FT-LBS

SCAS $T_{SCAS} = +2500$ FT-LBS

HELICOPTER PITCH ACCELERATION $\quad \alpha_\rho = \frac{T}{J_\rho} = \frac{-6720 + 2500 \text{ FT-LBS}}{14{,}000 \text{ FT-LBS SEC}^2} = \frac{-0.3 \text{ RAD}}{\text{SEC}^2} = -17.3\,^o/\text{SEC}^2$

$$\omega_\rho = \omega_o + \alpha_\rho t, \quad \theta_\rho = \omega_o t + \tfrac{1}{2}\alpha_\rho t^2$$

WITH SCAS

AT 1 SEC $\quad \omega_\rho = -17.3^o \times 1 = -17.3^o$/SEC. $\quad \theta_\rho = \tfrac{1}{2}\, 17.3^o/\text{SEC}^2 \times 1^2 = -8.65^o$

AT 2 SEC $\quad \omega_\rho = -34.6^o$/SEC $\quad \theta_\rho = -34.6^o$

GUN WOULD HIT ELEVATION STOP AT +6° ELEVATION IF IT REMAINED TRAINED ON TARGET.