The Effect of Sensor Location on the Control of Turret/Gun Systems

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THE EFFECT OF SENSOR LOCATION ON THE CONTROL OF TURRET/GUN SYSTEMS

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ABSTRACT

The problem of sensors location and its effect on the gun servo system is discussed. Direct measurements both in time and frequency domain are give. Modeling and simulation results are presented and reveal good agreement to actual measurements.

INTRODUCTION

A tank can be regarded as a powerful heavy combat weapon manipulator. Basically, there are two main objectives to the turret/gun servo control. The first one is to achieve a very accurate inertial positioning of the gun to within 1-2 tenths of the angular mil (1 angular mil = 10^{-3} radian) even in the presence of major ground velocity disturbances. The second control objective is to enable the gunner to drive the system in very low velocities in spite of the existence of frictions, unbalance moments and ground disturbances moments. This servo control combined with the fire control system must achieve a first-shot hit for survival capability. Only two degree of freedom of the tank gun, the elevation angular axis and the traverse angular axis, are mechanically driven .

The elevation of the gun relative to the turret can be effected by a helical transmission system. Its servo system loop consists of a power amplifier which drives a direct current brush motor. The inertial velocity control of the gun is based on a gyro signal.

The traverse servo system loop can consist of two power amplifiers, two DC brush motors and a gear box mounted on the turret that moves the turret on the hull ring by a pinion gear. The inertial velocity control of the turret is based on a gyro signal. The gyro is mounted on the turret. In another mode of operation the turret/gun velocity is controlled by using the signals of tachometers mounted on the motors' shafts.

The servo controls of a turret/gun in a tank and the control of a robotic manipulator are essentially similar. Controllers of robotic systems are quite complex and are subject of a large number of papers.

Only few papers, however, investigate the drive control problems (the power amplifiers, d.c. motors and the gear box) and the importance of the sensors' positioning and load resonances. Good et al. [2] investigated these subjects both theoretically and experimentally.

Scheib [1] gives a detailed description on the control design of current loop for a power amplifier and on the modelling of turret/gun dynamics and on an adaptive controller based on Lyapunov theory. Klittich [4] presents an excellent investigation on gear drive dynamical model for simulation. It emphasizes the importance of the material type selection for the construction of a gear box in order to achieve nonresonative drive. In Follinger's book [3] an exact analysis is given of a velocity control servo system.

In this paper we focus on the question of the location of sensors and their effects on the turret/gun control.

PROBLEM FORMULATION

Sensors are the main feedback component for closing control loops. The performance of a tracking system is checked by the rate of the tracking error. This error is calculated by the difference between the command signal value and the relevant sensor output. The location where the sensor is placed in the system determine the mechanical component that is controlled. At times, due to technological difficulties, the location for the sensor is selected in a component different then the one that must be controlled. In robots, for example, a definite preference for controlling the robot's joints rather than the end-effectors since it is no convenient to locate a sensor at that end. At the joints it is easier to locate and protect the sensors.

It is necessary to fully understand the consequences of locating the sensor that way. Figure 1 shows an electrical driven gun/turret of a tank. The elevation drive system consists of a power amplifier that drives a DC motor with suitable current commands. A tachometer (denoted by T), that measures the rotation of the shaft relative to the breech block, is connected to the motor shaft. Tachometers are inexpensive components and are usually supplied together with the motors. The motor is connected to a helical screw transmission with high efficiency in both directions. The transmission gear is connected to the gun's breech block and amplifies the moments supplied by the motor. A two-axis gyro, denoted by G, connected to the bottom of the gun's breech block, measures the inertial velocity of the gun in the elevation and the breech block axes. A gyro is a sensitive and expensive component and is attached to a region that is subject to shocks of the gun. Many efforts must be made to protect the gyro.

For a stationary tank, the output of the gyro is not different, in principle, from that of the tachometer. The ratio is that of the transmission gear ratio. When the tank is moving the output of the tachometer is indicative of the instantaneous relative velocity during elevation between the barrel and the turret while the output of the gyro is he instantaneous relative velocity during elevation between the barrel and the earth.

Both the tachometer and the gyro measure velocities. The transfer function between the electric current to the motor and the velocity outputs should be a pure integration. Measured transfer functions of the tachometer and the gyro vs.the electric motor current, shown in Fig. 2, indicate, however, that only for low frequencies, below 3 Hz, they both behave like integrators. For higher frequencies they exhibit large differences in their behavior.

Main points that worth mentioning are that both exhibit anti-resonance and resonance behavior but at different frequencies. Also, the phase angle of the tachometer is generally above -90°, while the phase angle of the gyro drops to -180° for frequencies over 20 Hz. Models to explain this behavior are presented here.

MODELS

The gun and its elevation drive system are shown schematically in Fig. 3. Two control options are available. One based on the tachometer output as a feedback and the other on the output of the gyro. The feedback is processed by a control electronic unit (CEU) and is translated as an input to the power amplifier which provide the current for the drive motor. The moment of the motor is amplified by a transmission and a helical gear to provide the moment required for the elevation of the gun. The transmission is characterized by its gear teeth stiffness and damping coefficients. The gun is modeled as a breech block and a barrel, each with its characteristic inertia connected to each other by appropriate stiffness and damping coefficients.

A complete block diagram that describe the mathematical relations of the gun-drive, including models for the power amplifier and motor, for the transmission and for the gun, is given in Fig. 4. A brief description of this diagram follows.

The model for the power amplifier and motor is shown in Fig 5. It features an electric motor controlled by a PWM (pulse width modulation) amplifier. The motor is described by the following equations:

$$V = L\frac{dI_m}{dt} + RI_m + K_e\omega_m \tag{1}$$

$$J_m\frac{d\omega_m}{dt} = T_m - T_q sgn(\omega_m) - T_v \tag{2}$$

$$T_m = I_m K_T \tag{3}$$

The equations of the current controller are, according to Scheib[1] are

$$R(I_c - I_m) + \frac{R^2}{L}\int (I_c - I_m)dt = V \tag{4}$$

Based on the above equations it can be easily shown that

$$I_M(S) \cong \frac{1}{1+\tau_s S} I_o(S) \tag{5}$$

It is recommended to select $\tau_s = 0.1\tau_e = 0.1(L/R)$ and τ_e is the electric pole of the motor.

The current feedback allows the reduction of the system sensitivity to changes in resistance and reluctance of the motor. Also, for a wide range of frequencies, $I_c \sim I_m$, which offers a direct control of the motor's current and load acceleration. The amplifier acts as a high efficiency current amplifier due to the PWM technique.

Analog simulations of transmissions were carried out at AEG by Klittich[4].He focused on transmissions of gears, as shown in Fig. 6, that relate the moments of inertia of the load and the drive. A block diagram of that system is given in Fig 7 with the following terminology: J_m is the moment of inertia of the motor and the transmission, J_L is the moment of inertia of the load, Tql and Tqm are the Coulombic friction moments of the Motor/transmission and the load, respectively, K_k the rigidity of the transmission, K_v is the elastic damping coefficient of the transmission and K_s is a self locking coefficient. Viscous frictions were ignored for simplicity.

Klittich showed that a transmission can be viewed as a second order system with a typical polynomial

$$P(S) = S^2 + \frac{K_v}{J^*}S + \frac{K_k}{J^*} \qquad (6)$$

whose natural frequency is $\omega_n = \sqrt{K_k/J^*}$

and the damping coefficient $\zeta = \dfrac{K_v}{2\sqrt{K_k J^*}}$

where $$J^* = \frac{J_m J_L}{J_m + J_L} \qquad (7)$$

Control considerations require high values of ω_n to facilitate transfer of moments in a wide range of frequencies, that can be achieved by selecting the motor and transmission with low inertia and high rigidity of the transmission . It also requires damping ratios close to 1 to prevent resonance which can be achieved by selecting materials of low restitution coefficients. Presence of backlash in the transmission complicates the control since there are periods of times where the drive and the load are practically not connected.

The gun of a tank is modeled in Fig 8. In this model J_S is the moment of inertia of the breech block, J_G is the moment of inertia of the gun barrel, K_{k1} and K_{v1} are the spring and damping coefficient connecting the breech block and the barrel. Here too the moment depends on the difference in angles and angular velocities of the load (gun barrel) and the drive (motor). The mathematical equations describing this relationship are:

$$\frac{d\omega_G}{dt} = \frac{T_B}{J_G} \qquad (8)$$

$$\frac{d\omega_G}{dt} = (\omega_S - \omega_G)K_{v1} + K_{k1}\int (\omega_S - \omega_G)dt \qquad (9)$$

$$\frac{d\omega_S}{dt} = \frac{T_{\text{gear}} - T_{fr} + K_{k1}}{J_S} \qquad (10)$$

$$T_{fr} = T_{f0}sgn(\omega_S) \qquad (11)$$

SIMULATIONS

Figure 4 shows the complete gun elevation system that includes the drive motor, the power amplifier, the transmission and the gun barrel. Fitting the theoretical model to the measured results requires the identification of the parameters such as the equivalent moments of inertia, rigidities,and friction and friction moments.

One can calculate from these the transfer functions

$$\frac{\text{Tachometer output}}{\text{Control current}} \text{ and } \frac{\text{Gyro output}}{\text{Control current}}.$$

Figure 9a&b shows measurements and simulation results. The tachometer output shows good agreement for all frequencies while the agreement for the gyro is good for frequencies below 30 Hz.

EFFECT OF LOCATION OF SENSORS ON CONTROL

Control based on two possible of sensor locations are to be compared here. Systems where the control is based on sensing the speed of the motor shaft is simpler to perform but gives inferior control relative to that based on sensing directly the speed of the gun barrel.

The measured frequency response of the tachometer output in the open loop was shown in Fig. 2. In this situation, since the phase is generally higher than -90°, there is no problem to synthesize a simple P&I high gain controller for achieving a large bandwidth over 100Hz without the running into a danger of instability. The frequency response of the tachometer in closed loop using such high gain controller is given in Fig. 10.

It can be seen that the bandwidth at -90° is 250 Hz. That implies a good control of the velocity of the motor's shaft. Also, even though the measured response to a step function is fast with only small overshoot, it does not describe well the response of the gun barrel as measured by the gyro, Fig 11. It can be seen that the latter is quite resonative. On the other hand it is possible to get a better response to a step function if a smaller bandwidth controller is carefully selected taking in consideration the resonances of the gun barrel. Figures 12 and 13 show the much smoother response in this case.

The open loop response of the gyro indicates a dangerous resonance of the gun barrel, at frequencies between 12 and 20 Hz, expressed by the sharp drop of the phase to near -180°. A high gain controller may bring about instabilities in the system. Such resonances may be attenuated by using suitable notch filters. Figure 14 give an example of a controller combined with suitable filters where the resonances are greatly attenuated, thus allowing the use of a high gain controller.

The closed loop response, shown in Fig. 14 and 15, indicate that a bandwidth of 4 Hz is achieved without getting into a resonative condition as a result of a step input.

CONCLUSIONS

A comparison between simulations and measured results of the performance of a tank that included an all-electric drive system in the elevation axis was presented. A detailed mathematical model was presented and it was shown that it describes well directly measured results in a tank.

A substantial difference exists between the measured transfer functions from the motor shaft and from the gun barrel. That is due to the flexibilities between the rigid bodies contained in the system.This difference affect the control as follows:

It is seems relatively easy to obtain a rigid control with high amplification based on output of the motor shaft velocity, due to the excess positive phase. On the other hand that may cause resonance in the gun barrel. This resonance, however, can be somewhat eliminated by careful design of the control taking in consideration the resonance frequency of the load. Still even precise tracking on the motor shaft may not guarantee, because of the flexibilities in the links, similar tracking on the gun.

Direct sensing of the gun breech block speed allows direct control of the gun. This control is more difficult to accomplish due to the lack of phase margin and the occurrence of resonances. Using it requires development of special filters to prevent the resonances.

LITERATURE

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2. M.C. Good, L.M. Sweet and K.L. Stroble, Dynamic models for control systems design and integrated robot and drive systems", ASME J. Dynamic Syst. Meas. Cont. Vol. 107/53, 1985.
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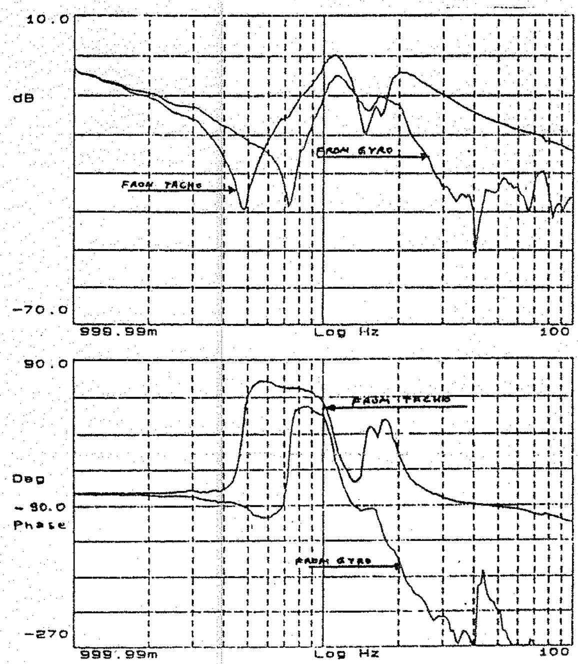

Figure 2: Measured Bode diagrams of tachometer and gyro vs current command transfer functions.

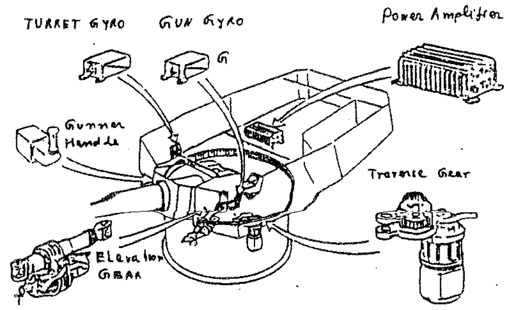

Figure 1: An all electric gun/turret drive system (after Scheib [1])

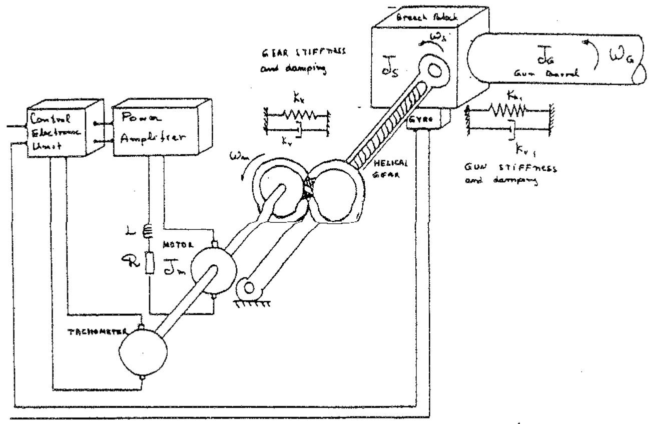

Figure 3: An electromechanical model of the elevation servo system

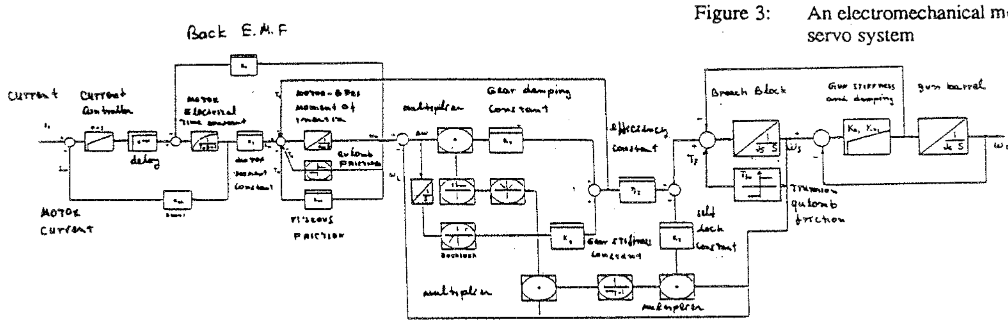

Figure 4: A block diagram of the complete elevation system

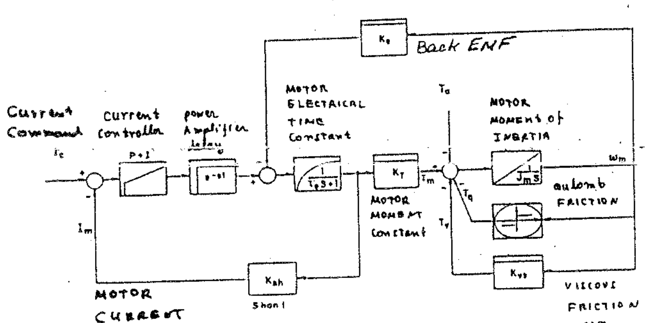

Figure 5: A block diagram of the power amplifier and the DC motor

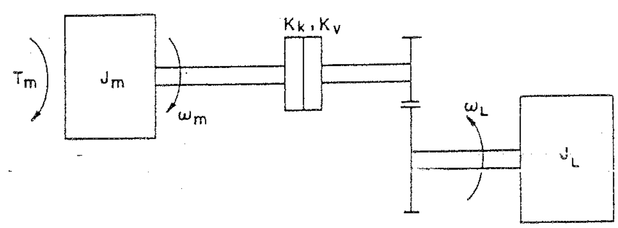

Figure 6: Gear description (after Klittich [4])

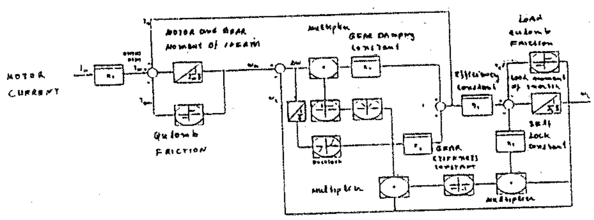

Figure 7: A block diagram of the gear (after Klittich [4])

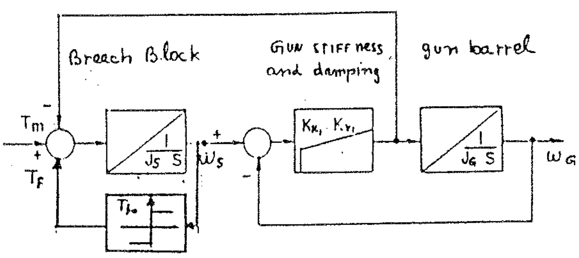

Figure 8: A block diagram of the breech block and the gun barrel

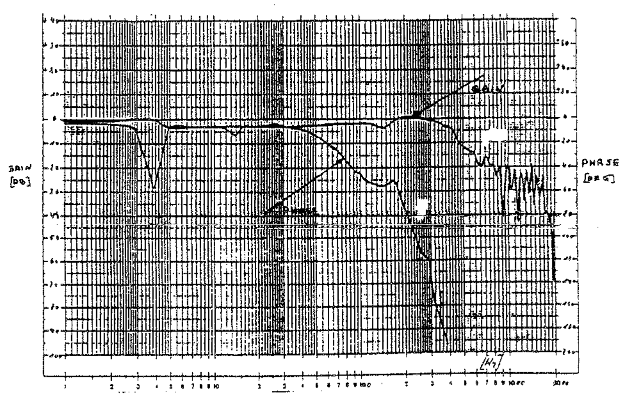

Figure 10: Measured tachometer closed loop Bode diagram with high gain P&I controller

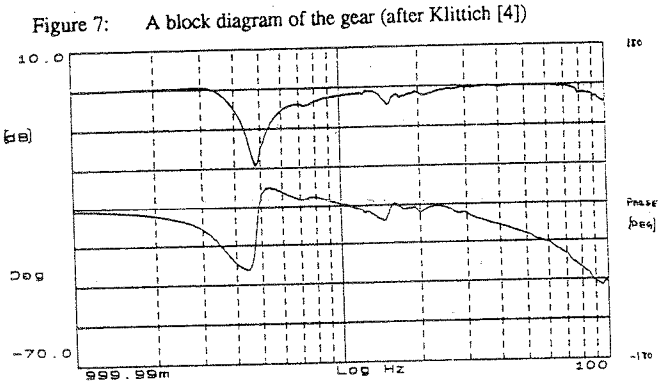

Figure 12: Measured tachometer closed loop Bode diagram with P&I controller

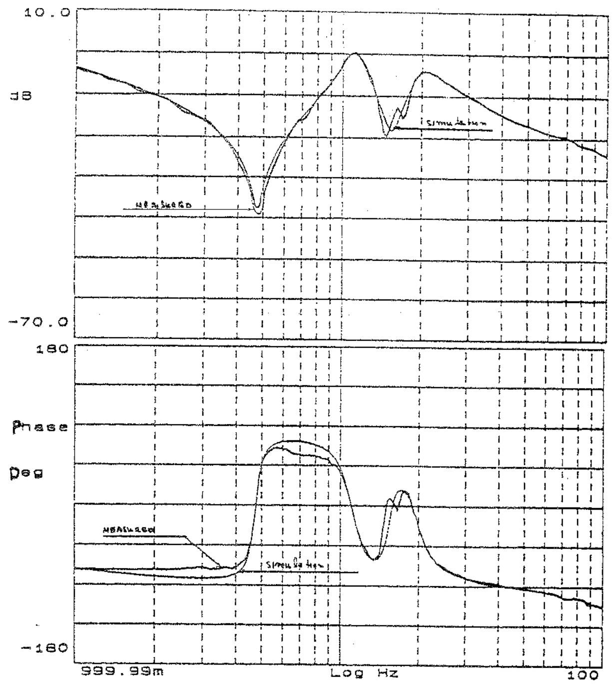

Figure 9a: Measured and simulated Bode diagrams of tachometer vs current command.

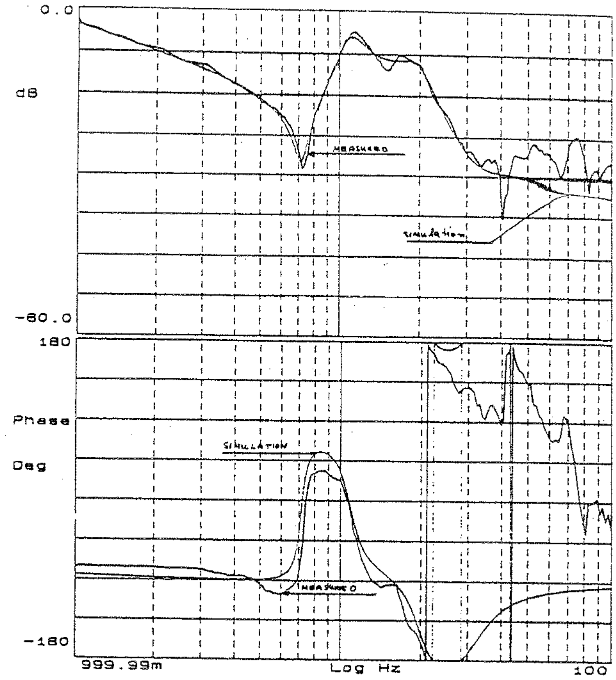

Figure 9b: Measured and simulated Bode diagrams of gyro vs current command

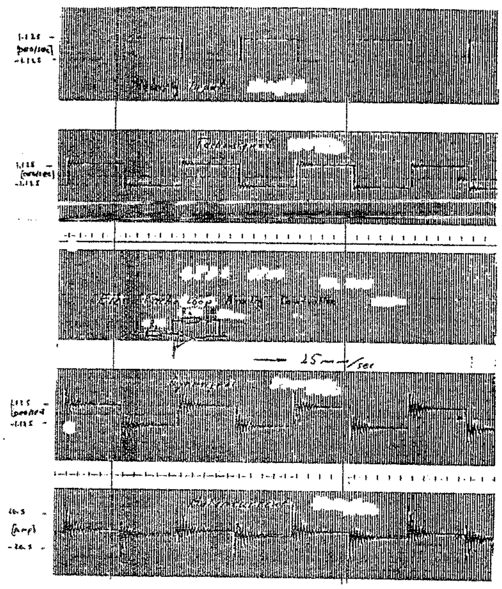

Figure 11: Measured tachometer closed loop step response with high gain P&I controller

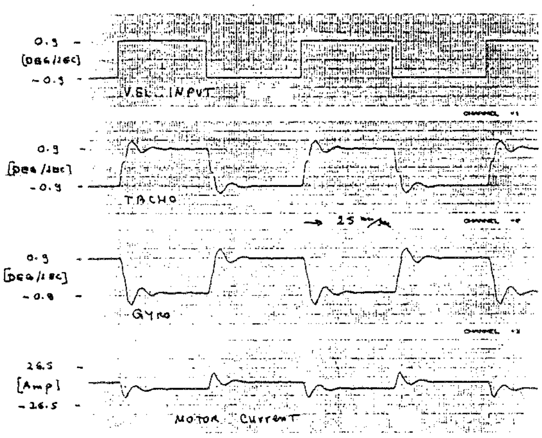

Figure 13: Measured tachometer closed step response with P&I controller

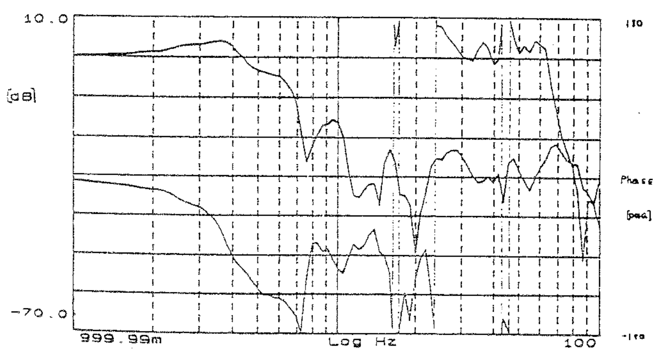

Figure 14: Measured gyro closed loop Bode diagram

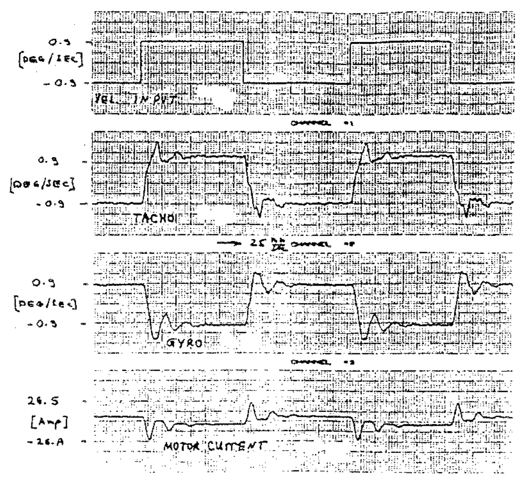

Figure 15: Measured gyro closed loop step response