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MEASUREMENT OF TANK GUN DYNAMICS IN SUPPORT OF A DYNAMIC MUZZLE REFERENCING SYSTEM

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA

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ABSTRACT

Experiments were conducted on a Leopard C1 main battle tank with a 105 mm gun to determine its non-firing, terrain-induced muzzle dynamics. The sensors included gyroscopes and accelerometers placed at the ends and the center of the gun barrel. The experiments were conducted in support of a Kalman filter design for a new tank Dynamic Muzzle Referencing System which is being developed by DND as a subsystem for a comprehensive Integrated Fire Control System for a future Main Battle Tank. Preliminary data analysis shows significant muzzle motion but most of this is attributed to gun stabilization system errors (1 to 2 milliradians). Some evidence of barrel bending was found (½ to 1½ mrad). The methods and results of the experiment are described.

RÉSUMÉ

Une expérience a été effectuée sur un char de battaille Leopard C1 avec un canon de 105 mm pour déterminer la dynamique du canon telle qu'induite par le mouvement au sol en l'absence de tir. Les senseurs se composaient de gyroscopes et d'accéléromètres installés aux bouts et au centre du canon. L'aboutissement de cette expérience a permis la conseption d'un filtre Kalman d'un nouveau système de référence dynamique en voie de développement au MDN comme sous-système pour un système intégré de contrôle de tir pour un futur char de battaille. L'analyse préliminaire des résultats indique la présence de mouvements notables du canon bien que ceux-ci sont en grande partie attribués aux erreurs du système de stabilisation du canon (de 1 à 2 millirads). De plus, ces résultats apporte d'évidence de flécchissement du canon (½ à 1½ mrad). La méthode et les résultats de l'expérience sont décrits.

EXECUTIVE SUMMARY

A Dynamic Muzzle Reference System (DMRS) is a proposed system of sensors, electronics and signal processing that will be used to measure and compensate for the high frequency, low amplitude motions of the stabilized gun of a main battle tank as the vehicle is driven over rough, uneven terrain. It has been suggested that the flexing of the gun barrel may cause muzzle displacement errors of several milliradians. The Department of National Defence and Ernst Leitz Canada Ltd. are currently developing a laser-based sensor and electronics system to attempt to measure these motions. The Defence Research Establishment Ottawa is developing advanced signal processing techniques to predict when the gun will be in its nominal position in order to set the precise firing instant.

This report describes a series of three data collection experiments that were conducted from October 1988 to May 1990 on a moving Leopard tank with a 105mm gun. The object of the experiments was to characterize the angular motions and deflections of the stabilized gun. Such a characterization is essential before the design of the predictive filtering algorithms and is also of use in the specification of the sensors for the DMRS. The measurements were made with externally mounted, rate-sensing gyroscopes on either end of the gun barrel. Other gyros and accelerometers were mounted both on the turret and on the gun. Most of the sensors were aligned to measure motions in the pitch (elevation) plane. The signals were digitally recorded on-board the tank and later analyzed in the laboratory.

The analysis of the data has shown some interesting characteristics as described in the report. With the particular tank used and the terrain chosen, significant barrel motion was detected. Most of this was sensed at both ends of the barrel, indicating large whole-barrel rotations. However, some runs showed significant barrel flex, on the order or 1½ to 2 milliradians. Errors of this magnitude are sufficient, if uncompensated, to induce a 2 meter miss distance at a nominal 1200m firing distance.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Table Title Page

1.0 INTRODUCTION

1.1 BACKGROUND

Accurate, long-range, fire-on-the-move ability is critical for Main Battle Tank (MBT) survivability on the modern battlefield. Current static hit probabilities are excellent but accuracy degrades rapidly when either the tank or its target is moving. Advances in sensors, computer hardware and signal processing will enable fire control engineers to include much more capability in future tank fire control systems.

DREO, as part of CRAD task DLAEEM 139, is conducting a feasibility study on the use of Kalman filters, a proven method of real-time signal processing, in various aspects of a next-generation Integrated Fire Control System (IFCS) for tanks. The areas of application currently being considered include muzzle referencing, target tracking, three-dimensional target trajectory prediction, battlefield navigation, and tank attitude and motion corrections for fire control solutions.

1.2 THE DYNAMIC MUZZLE REFERENCING PROBLEM

A Dynamic Muzzle Reference System (DMRS) is currently considered a high priority research area in tank fire control. It has been suggested that the barrel of the main gun of a mobile tank, even though it is stabilized in azimuth and elevation, still moves significantly when the tank is moving over rough terrain. This is due primarily to the terrain-induced motions experienced by the turret which, in turn, can affect the gun barrel as though it were a type of cantilevered beam. Significant decreases in the hit probability of a moving tank versus static targets compared to that of a stationary tank have been reported. Much of this additional error has been attributed to uncompensated barrel and muzzle motions. (Other sources of terrain-induced errors, such as those caused by the motion of the gunner, have also been identified and are being studied by other investigators.)

Most current muzzle reference systems accurately correct for static barrel droop and sight/gun misalignments but can operate only when the tank is stationary. A dynamic system, on the other hand, has two goals: 1) to allow the barrel droop/misalignments to be measured with the tank on the move, and 2) to allow for the fire control solution to account for high frequency (above the gun's stabilization system bandwidth) muzzle motions. The first goal may be achieved by operating the MRS at a high repetition rate and averaging the returns. The second requires a mathematical model of the dynamics of the gun system to predict future muzzle positions based on the returns from the MRS.

1.3 APPROACHES TO A SOLUTION

Currently there are several concepts being explored to help address the DMRS problem. A laser-based system, being developed by Leitz Canada, consists of a small laser transceiver mounted near the base of the gun barrel and a mirrored surface at the muzzle. As the barrel flexes, the position of the laser reflections from the mirror are detected. Another concept being advanced by the US Army's Ballistic Research Laboratory involves strain gauges placed at points along the gun to detect high frequency barrel vibrations in conjunction with an autocollimator-based static alignment system to detect barrel droop [1].

DREO briefly considered another approach to the DMRS based on inertial instrumentation, namely gyroscopes and accelerometers, placed both on the muzzle and inside the tank. Any instrumentation placed on the gun must be extremely durable to withstand firing shock and armoured to protect it from hits. Conventional gyros are far too fragile for such an environment. The gyros that show the greatest potential for this type of application are miniature fibre optic gyros, though they are still in the development stage. This idea has potential but is probably not feasible at present because of the lack of robust sensors. As well, the initial alignment of the muzzle-mounted instrumentation with the turret-mounted instrumentation to the required accuracies presents a significant problem. Static barrel droop could not be measured with such a system.

Regardless of the particular sensors used in an operational DMRS, the signals from them must be processed in some intelligent manner to correct for the barrel motions. The solution to this problem lies in the design of a prediction algorithm that would continually predict, in real-time, when the barrel would be passing through its nominal (static droop) position. This information, in principle, could then be used by the firing mechanism to determine the proper time to fire the shell. Research on these algorithms is on-going here and abroad and will benefit from the data collected in these field trials.

1.4 SCOPE OF THIS REPORT

This report describes three sets of preliminary data collection field trials in which it was attempted to characterize the form and extent of the muzzle motions. In Section 2, the experimental set-ups are described. In Sections 3, 4, and 5, the raw and processed data are presented. In Section 6 the results are summarized and some conclusions are drawn. Appendix A contains some approximate calculations to determine the expected dynamics of a simplified gun barrel. The design, simulation and evaluation of DMRS prediction filters are topics of current research.

2.0 EXPERIMENTAL EQUIPMENT AND PROCEDURES

The data collection experiments were conducted at the Land Engineering and Test Establishment (LETE) in Ottawa in October of 1988 (referred to as Set 1), in October of 1989 (Set 2), and in May of 1990 (Set 3). Gyros and accelerometers were placed on the gun and turret and the tank was driven over rough terrain with the gun in stabilized mode and with the gunner operating "hands-off" as much as possible. The outputs of the sensors were digitally sampled and recorded and returned to the laboratory for analysis. All sensors were recorded virtually simultaneously at a rate of 60 Hz with a 12 bit A/D converter in a small PDP-11 computer. The data was stored in non-volatile cartridge memory. The analog signals from each of the sensors were filtered through fourth-order, low-pass Butterworth (-6 dB at 30 Hz), anti-aliasing filters before sampling. A brief description of the experimental setup and some of the results follow. No firing was conducted during these experiments as the instrumentation placed on the gun would not withstand it.

2.1 THE SENSORS AND THE DATA RUNS FOR SET 1

For the first set of trials in October, 1988, seven inertial sensors were placed on the tank at various points as shown in Figure 2-1 and described in detail below. They were all oriented to measure motions in the pitch (elevation) plane. The channels as recorded are listed in Table 2-1.

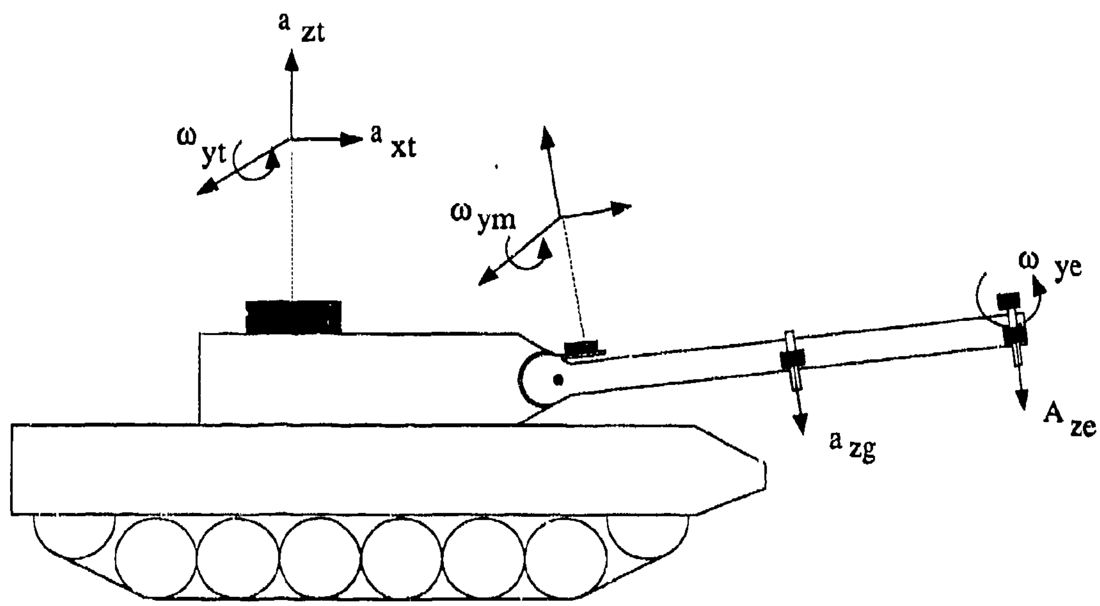

Fig. 2-1: Sensor Placement - Set 1

Table 2-1: Recorded Sensors - Data Set 1

Channel	Sensor
ω_{yt}	Turret Pitch Rate Gyro
ω_{ye}	End of Barrel Pitch Rate Gyro
ω_{ym}	Mantlet Pitch Rate Gyro
a_{ze}	End of Barrel Vertical Accelerometer
a_{zg}	Gun-Center Vertical Accelerometer
a_{zt}	Turret Vertical Accelerometer
a_{xt}	Turret Forward Accelerometer

2.1.1 External Rate Gyros for Set 1

Three single-axis rate gyros from a disassembled aircraft-grade Inertial Measurement Unit (IMU) were installed on the tank as shown in Figure 2-1. One was placed on the turret roof to measure the pitch rate experienced by the turret. A second gyro was placed on the gun mantlet as close as possible to the elevation axis of the gun. It would have been preferable to mount this gyro directly on the gun at its elevation axis but this point was not readily accessible due to the gun cradle. This gyro would read zero if the gun stabilization were perfect; however any motions outside the bandwidth of the stabilization loops would be sensed by this gyro. The third gyro was placed on the muzzle at the very tip of the barrel, again to measure angular rates about the elevation axis. If the gun stabilization were perfect, any rates sensed by this gyro could only be a result of barrel flexing. The difference between the signal from this gyro and that from the one on the mantlet should give a reasonable indication of barrel flex. A loss of precision is expected here, though, due to slackness in the cradle-to-gun fitting. The restrictions on the placement of the gyros meant that more than just barrel flex was measured. The effects of imperfect servo loops and slack gun fittings on dynamic muzzle pointing errors would also be sensed. All have an effect on muzzle motion and all affect hit probabilities when firing on the move.

Table 2-2: Summary of Data Runs - Set 1

Run	Course	Terrain	Duration (sec)	MaxSpeed (m/s)	Data File
1	1-Out	Grass/ Dirt Road	30	11	O07CTA1
2	1-Back	"	40	11	O07CTA2
3	1-Out	"	35	9	O07CTB1
4	1-Back	"	40	9	O07CTB2
5	2-Out	Soft Field	35	11	O07CTC
6	2-Out	"	30	9	O07CTD
7	2-Out	"	25	10	O07CTE

2.1.2 External Accelerometers for Set 1

Four accelerometers were also used. Two were in the IMU on the turret roof to measure vertical and forward acceleration. A third external accelerometer was placed on the muzzle and a fourth about midway along the gun. It was hoped the signals from these latter two accelerometers, though noisy and difficult to process, could be subtracted and numerically integrated to give an indication of the angular velocity at the muzzle to compare with the information from the muzzle gyro. This differencing was done analog before sampling. Hence the two channels recorded were actually "vertical muzzle acceleration" and "midgun minus muzzle vertical acceleration".

2.1.3 The Data Runs of Set 1

For Set 1, the tank was driven cross-country through level, grassy fields at speeds of 30-40 km/h. All tests were conducted with stabilization on and the main gun level and pointing straight ahead at the start of the run. The gunner was instructed not to move the gun during the runs. With the tank stationary, the recording system was started. Then the tank was accelerated up to speed for a straight run of about one half-minute. The tank was decelerated and stopped and the recording was stopped. This was repeated 7 times on two different courses. A summary of the runs is shown in Table 2-2.

2.2 THE SENSORS AND THE DATA RUNS FOR SET 2

For the Runs of Set 2 conducted in October 1989, the configuration of the inertial sensor suite was changed to that shown in the schematic of Figure 2-2 and Table 2-3. The sensors that were previously mounted on the turret roof were moved to the mantlet to allow a more complete characterization of the gun stabilization system. As well the accelerometers were not installed on the gun barrel due to disappointing results from the first set of trials.

Table 2-3: Recorded Sensors - Data Set 2

Channel	Sensor
ω_{xm}	Mantlet Roll Rate Gyro
ω_{ye}	End of Barrel Pitch Rate Gyro
ω_{ym}	Mantlet Pitch Rate Gyro
a_{xm}	Mantlet Forward Accelerometer
a_{ym}	Mantlet Lateral Accelerometer
a_{zm}	Mantlet Vertical Accelerometer

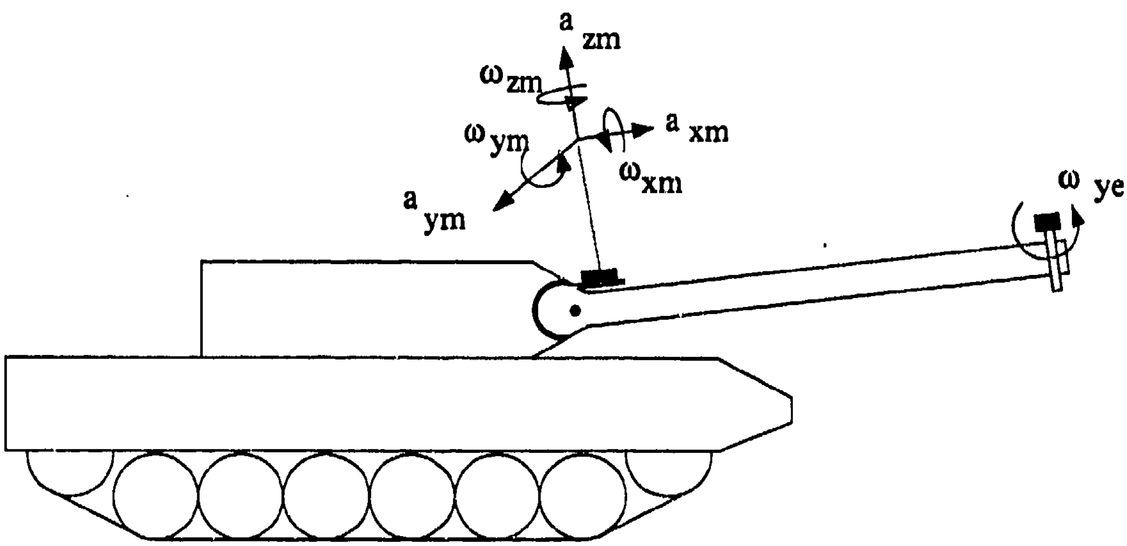

Fig. 2-2: Sensor Placement - Set 2

2.2.1 External Rate Gyros for Set 2

The rate gyros included the three in the inertial measurement unit on the mantlet which measured mantlet roll, elevation and azimuth angular rates, as well as a remote gyro on the muzzle to measure muzzle elevation rate.

2.2.2 External Accelerometers for Set 2

The three accelerometers in the IMU measured mantlet forward, vertical and lateral accelerations. No barrel accelerometers were installed.

2.2.3 The Data Runs of Set 2

For Set 2, the tank was driven through a variety of terrain, some of which was significantly more severe than the previous set, at speeds of 30-40 km/h. Again, all tests were conducted with stabilization on and the main gun level and straight ahead at the start of the run. The gunner was instructed not to move the gun in elevation during the runs. However, some azimuth control was required on runs through wooded areas. A summary of the runs is shown in Table 2-4.

Table 2-4: Summary of Data Runs - Set 2

Run	Course	Terrain	Duration (sec)	MaxSpeed (m/s)	Data File
1	1-Out	Grass/ Dirt Road	43	3	GUNSTABA
2	1-Back	"	35	8	GUNSTABB
3	1-Out	"	35	10	GUNSTABC
4	3-Out	Cobbles	65	4	GUNSTABD
5	4-Out	Rocky	44	7	GUNSTABE
6	4-Back	"	33	8	GUNSTABF
7	4-Out	"	27	11	GUNSTABG

2.3 THE SENSORS AND THE DATA RUNS FOR SET 3

For the Runs of Set 3 conducted in May 1990, the configuration of the inertial sensor suite was identical to that of Set 2 (Fig. 2-2) except the muzzle mounted gyro was not installed since these runs were conducted primarily to satisfy another requirement.

2.3.1 External Rate Gyros for Set 3

The rate gyros were exactly the same as for Set 2 except for the absence of the muzzle gyro. The sensitivity of the A/D converters was also increased for these runs.

2.3.2 External Accelerometers for Set 3

The accelerometers for Set 3 were the same as Set 2.

2.3.3 The Data Runs of Set 3

The runs of Set 3 were restricted by other requirements. The terrain was smooth level asphalt. Some runs included a short segment over a temporary bump course set up on the road. The bumps consisted of 4 sets of wood blocks approximately 20 cm high and 1 meter long (with ramps) placed under each track followed by another set of equivalent blocks arranged in a staggered pattern so that only one track was on a bump at a time. These bumps were intended to induce simulated cross-country disturbances. A summary of the runs of Set 3 is given in Table 2-5.

Table 2-5: Summary of Data Runs - Set 3

Run	Course	Terrain	Duration (sec)	MaxSpeed (m/s)	Data File
1	5-Out	Smooth Pavement	80	8	LETE9AM1
2	5-Out	"	80	8.5	LETE9AM2
3	5-Out	"	80	10	LETE9AM3
4	5-Out	"	90	10	LETE9AM5
5	5-Out	Pavement/ Wooden Bumps	100	8	LETE9AM4
6	5-Out	"	110	9	LETE8AM7
7	5-Out	"	90	8.5	LETE8PMA2

3.0 DATA ANALYSIS - DATA SET 1

The raw sensor data was returned to the laboratory and transferred to a VAX computer for analysis. Preliminary data analysis included application of sensor scale factors, low-pass digital filtering, numerical integration, and estimation of power spectral densities and autocorrelations. A modular, menu-driven analysis package called DATAGUN [2] was developed to perform this basic signal analysis and plot the results in this report. The next three sections present the main results for the three data sets.

3.1 The Raw Data - Set 1

Figures 3-1 through 3-7 show the raw data from all seven sensors from Run 5 (file O07CTC). The data from the other 6 runs are very similar.

The turret roof gyro (Figure 3-1) shows the largest signal levels as expected. The two gyros on the gun (Figures 3-2 and 3-3) show much lower signal levels, due to the effect of the stabilization system. However, it is evident there is still significant motion registered by these sensors. A visual comparison of the signals from the muzzle gyro (Figure 3-2) and the mantlet gyro (Figure 3-3) indicates, on average, more motion at the muzzle. This is to be expected due to bending or vibration at the end of the barrel.

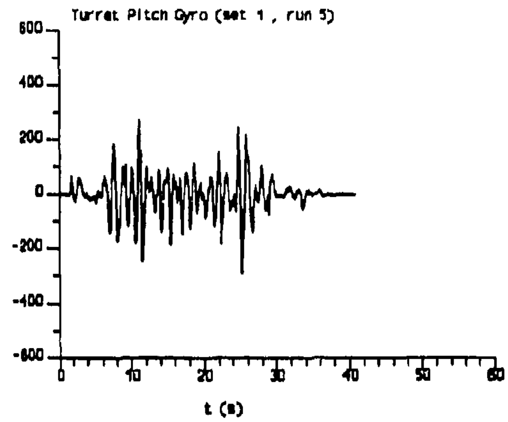

Fig. 3-1: Turret Pitch Gyro

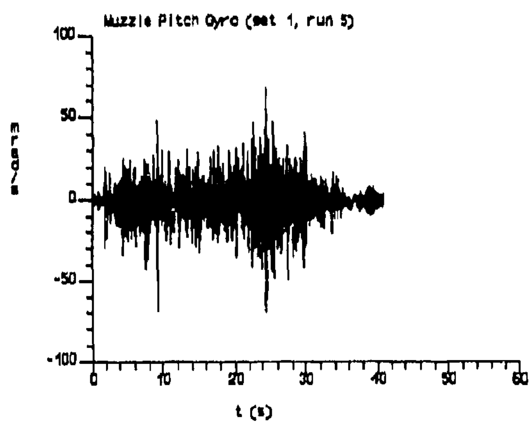

Fig. 3-2: Muzzle Pitch Gyro

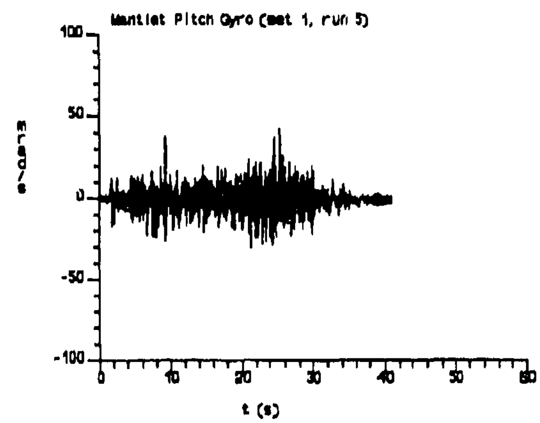

Fig. 3-3: Mantlet Pitch Gyro

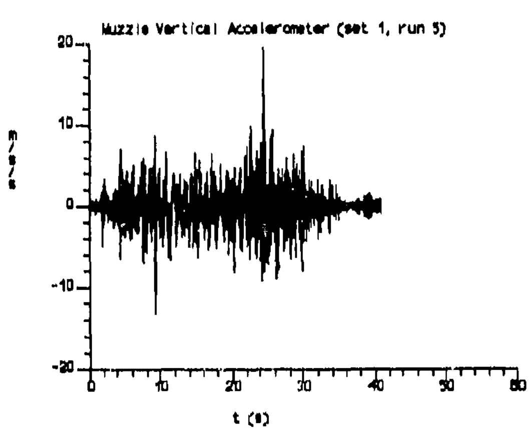

Fig. 3-4: Muzzle Vert. Accelerometer

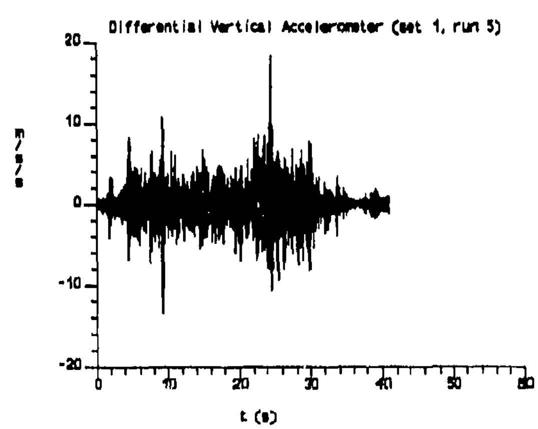

Fig. 3-5: Midgun-Muzzle Vert. Acc.

Figure 3-4 is the data from the accelerometer at the muzzle. Figure 3-5 is the data from the differential accelerometer (i.e., the analog difference of the mid-gun minus the muzzle accelerometer).

Figures 3-6 and 3-7 are signals from the vertical and forward accelerometers on the turret roof. The forward accelerometer allows accurate calculation of tank speed. These measurements can by processed with the information from the turret roof gyro to yield approximate vertical and forward acceleration in stabilized coordinates. In this run the tank reached a maximum speed of 11 m/s (40 km/h) at t=20s.

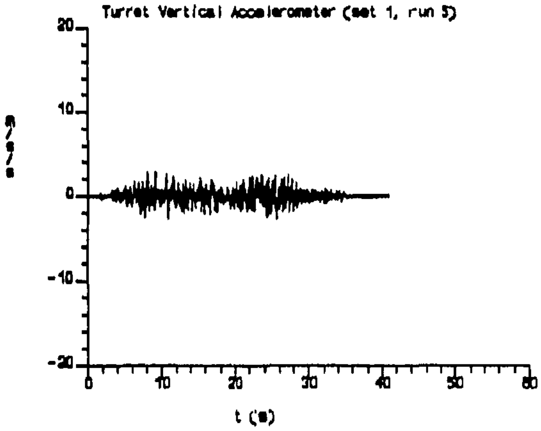

Fig. 3-6: Turret Vertical Accelerometer

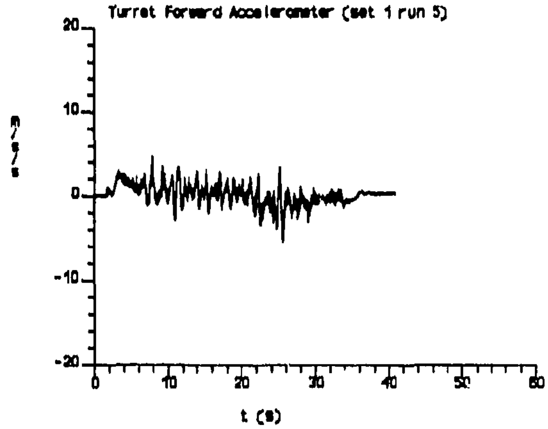

Fig. 3-7: Turret Forward Accel.

3.2 Integrated Gyro Data - Set 1

A simple numerical integration algorithm was applied to the raw sensor data. Since the gyros measure angular rate, the integral yields angular position. Figure 3-8 shows the turret pitch angle and muzzle and mantlet elevation angles for the initial 20 seconds of Run 5. The turret angle (solid line) is much larger than the other angles (which appear as one dashed line near zero) because most of the turret pitching motion is removed by the gun's stabilization system.

Figure 3-9 is a blow-up of the same two integrated gun gyro signals of Figure 3-8, with the mantlet angle shown as a solid trace and the muzzle shown as dashed. This figure demonstrates very graphically how the stabilization system performed. The mantlet elevation angle varies somewhat, but remains bounded within about ±1 milliradians. The stabilization system can have only a finite bandwidth so some motion is expected. The power spectral density plots, in Section 3.1.4, will show this bandwidth to be around 5 Hz. Any turret angular motion above this frequency will be directly transferred to the gun.

What is most interesting about Figure 3-9, and perhaps is the primary observation of this data set, is that the muzzle angle almost exactly tracks the mantlet angle. This indicates that very little, if any, barrel bending was measured. The differences in the traces of the figure, which are in the order of 0.2 mrad, could be due to at least three effects: bending, random gyro noise, or gun-cradle fitting slackness. Recall that these runs were conducted on soft grassy fields (a realistic operational scenario) rather than a bump course. The turret pitch angle RMS (root mean square) was only about 30 mrad (1.7 degrees). The RMS of the mantlet angle was found to be about 0.6 mrad so the stabilization system was operating within its specified performance range of ±1 mrad. A histogram of the mantlet angular position in Figure 3-10 shows, in effect, an approximation of the probability density function of the stabilization system error as recorded by the mantlet gyro. This histogram is actually the sum of the histograms of the mantlet elevation angle of all data runs of Set 1. The vertical axis of the histogram indicates the percentage of mantlet elevation angle data points that fall within the corresponding "bin" (which is defined as a quantized range of 0.04 mrad in angle).

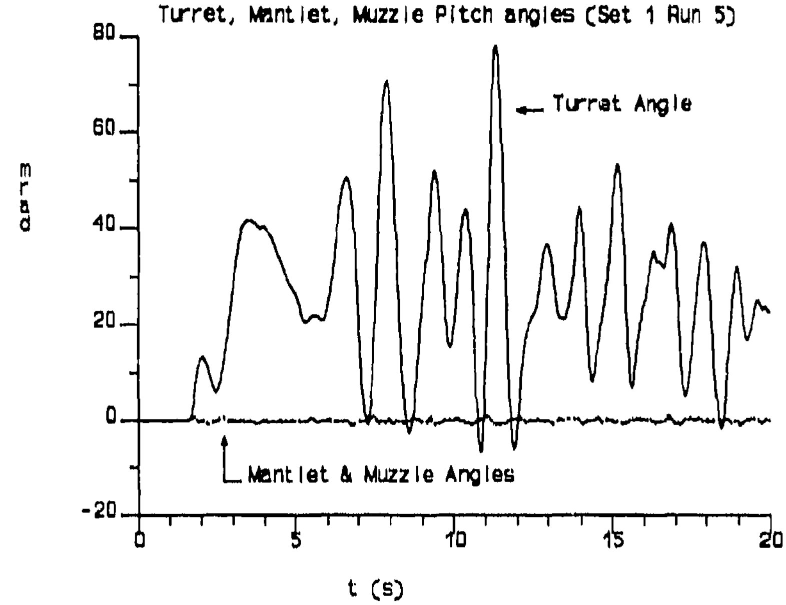

Fig. 3-8: Turret, Mantlet, Muzzle Elev. Angles

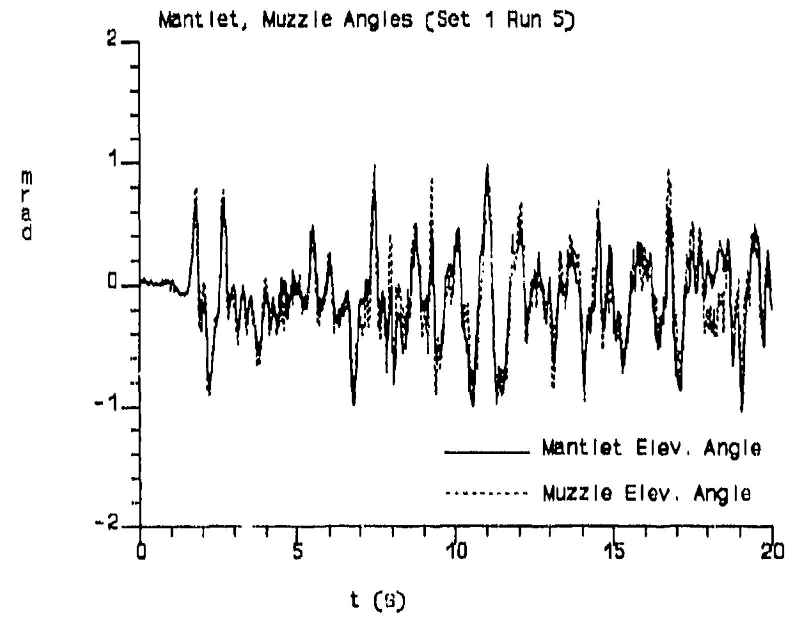

Fig. 3-9: Mantlet, Muzzle Elev. Angles

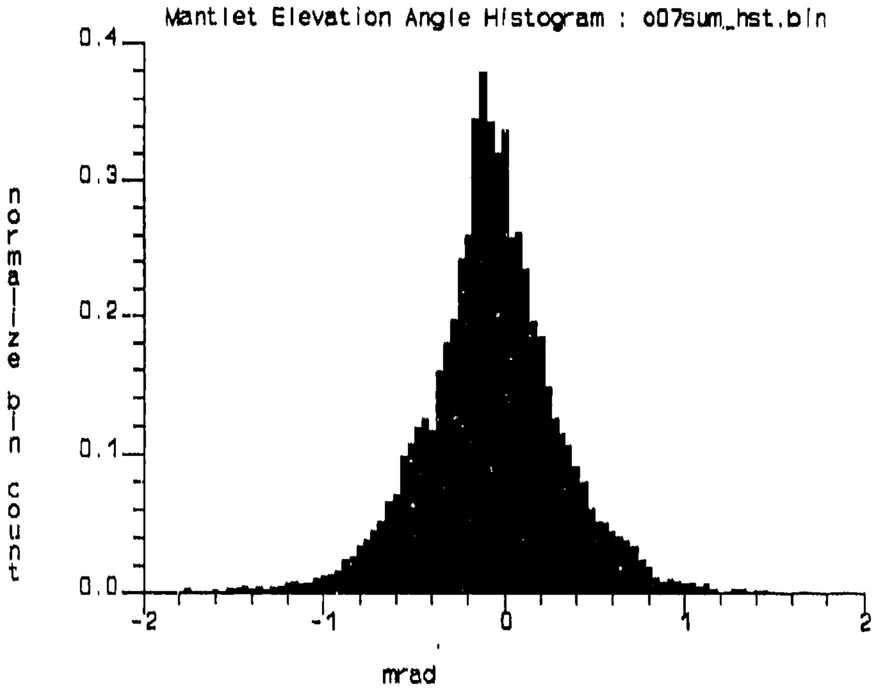

Fig. 3-10: Mantlet Elevation Angle Histogram (Set 1, All Runs)

3.3 Integrated Accelerometer Data - Set 1

The signals from the accelerometers mounted on the gun present several difficulties when processing. They tend to be very noisy so simple numerical integration often results in displacements with unrealistically large drifts. The acceleration due to gravity must also be accurately removed before integrating. This requires knowledge of the time-varying orientation of the accelerometers with respect to the vertical. The orientation of the turret-mounted accelerometers was determined by integrating the turret gyro signals which in turn allowed the data from the accelerometers to be resolved in a locally level coordinate frame. (This could only be done about the elevation axis, however, since the turret roll and heading angles were not measured in this set.) The acceleration due to gravity could then be removed from each vertical accelerometer signal. Then a mild high-pass filter was applied to all signals but the forward accelerometer. This was a first order filter with a -3 db frequency of 0.1 Hz. The filtered data retains the important dynamic information but any slowly changing biases are removed. Thus numerical integration will not lead to unrealistic drifts.

The purpose of mounting a pair of accelerometers on the gun barrel was to see if they could be used to provide similar information as the muzzle-mounted rate gyro. The justification being that if durable and inexpensive accelerometers could be used to sense the angular position of the muzzle to sufficient accuracy, they would be a viable candidate for an operational dynamic muzzle referencing system. Since the barrel mounted accelerometers were differenced in analog before sampling, the first integral of the signal coming from this differential accelerometer should look like that from the muzzle-mounted rate gyro. However, after thoroughly examining all the data from this set, this was not found to be the case, in general. The best correspondence that could be found appears in the following figures. In Figure 3-11, the first 5 seconds of raw data (Run 5 of Set 1) from the muzzle elevation gyro and the integrated differential accelerometer (Fig. 3-12) show the same general characteristics. However, integrating both channels again to yield angular position (Figures 3-13 and 3-14) shows little, if any, correspondence.

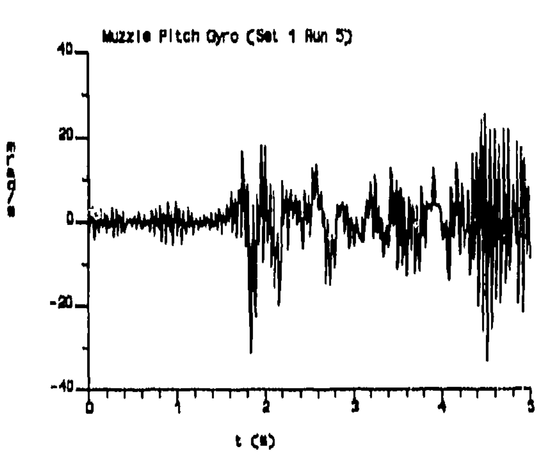

Fig. 3-11: Muzzle Gyro (first 5 sec)

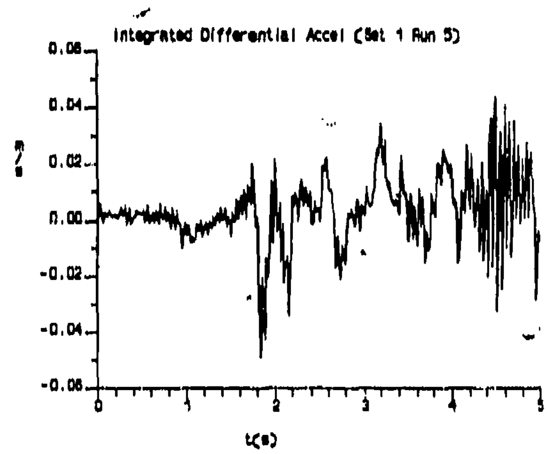

Fig. 3-12: Integrated Differential Accel.

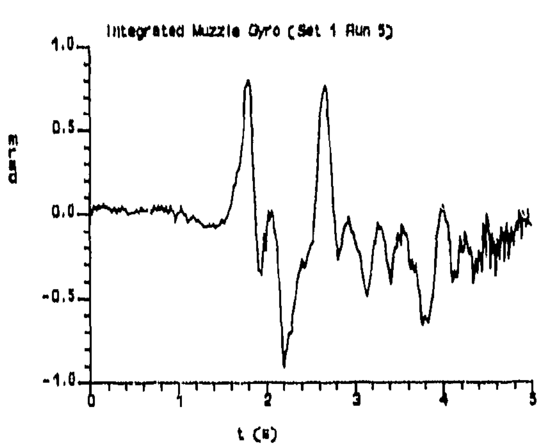

Fig. 3-13: Integrated Muzzle Gyro

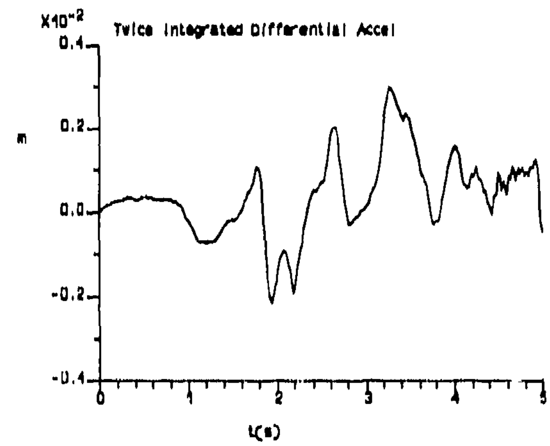

Fig. 3-14: Double Integrated Diff'l Accel

It appears the accelerometers used in these trials were inherently too noisy to allow two numerical integrations to provide the accuracy that would be required for a DMRS. For this reason, the gun-mounted accelerometers were not used on subsequent trials.

3.4 Power Spectral Densities - Set 1

A frequency domain analysis, in the form of power spectral densities (PSD), was performed on all the recorded data. Since the spectrum of an individual data record was in general very noisy, the PSD's shown in this section are actually averages of several PSD's from different runs. An assumption of stationarity has to be made for this analysis. This is not exactly true because one cannot guarantee the tank was moving over the same terrain at the same constant speed on every run. However, since circumstances were replicated as nearly as possible for each run, the stationary assumption should not be too unreasonable for preliminary PSD estimates.

Sections of data 20 seconds long from each of the seven runs were selected. The PSD of each sensor from each section was calculated (with Fast Fourier Transforms and 50% overlapping Hanning windowing techniques [3]) and then the resulting PSD's for each sensor were obtained from a simple arithmetic average of the PSD's for that sensor. The resulting averaged PSD was normalized so that the area under the averaged PSD was equal to the average of the powers of the individual time series that were used to compute the PSD.

Since the data sampling rate was 60 Hz, the maximum frequency information obtainable from the PSD's is 60/2 = 30 Hz. The smallest frequency information is a function of the length of the data records, 1/(20 sec) = 0.05 Hz in this case.

Figures 3-15 through 3-22 show the results of the PSD analysis for each of the integrated sensors. The units of the PSD's of the integrated gyro sensors are $mrad^2/Hz$ and for the integrated accelerometer sensors, $(m/s)^2/Hz$. The vertical scale can be converted to dB's by multiplying the exponent of 10 on the graph by 10.

The turret gyro PSD (Figure 3-15) has one dominant broadband peak around 1 Hz. This is the frequency of the rocking motion experienced by the turret induced by the terrain. Note that the level at this frequency is about 30 dB. The next two figures, 3-16 and 3-17 are the muzzle and mantlet gyro PSD's respectively. Most of the broadband peak around 1 Hz has been removed, down to a level of -10 dB, but it is still noticeable. The elevation stabilization system is responsible for the reduction of the magnitude of this peak. If one "divides" the PSD of Figures 3-17 (mantlet) by that of Figure 3-15 (turret), the resulting "Disturbance Rejection Ratio" (Fig. 3-18) shows the bandwidth of the stabilization system to be about 5 hertz.

The information in Figures 3-16 and 3-17 between 4 and 30 Hz is most interesting. Both figures show a very dominant peak around 20 Hz. This is likely the first bending mode of the gun (see Appendix A for some estimates of the fundamental frequency modes and modal shapes of the 105 mm gun barrel). The muzzle has a rather sharp peak at 8 Hz. It is difficult to say exactly what is causing this. It could be a bending mode but it seems rather low for such a stiff gun. It is more likely an effect of the cradle-to-gun fitting slackness that allowed the gun to vibrate within its sleeve at 8 Hz.

Figure 3-19, the muzzle accelerometer PSD, shows the turret heave being registered at the muzzle (1 Hz), the possible vibration at 8 Hz and the possible bending mode at 20 Hz. The differential accelerometer PSD, Figure 3-20, does not show the heave at 1 Hz, since it is common to both accelerometers, but it does show the other two peaks. For completeness, the PSD's of the turret roof accelerometers are shown in Figures 3-21 and 3-22.

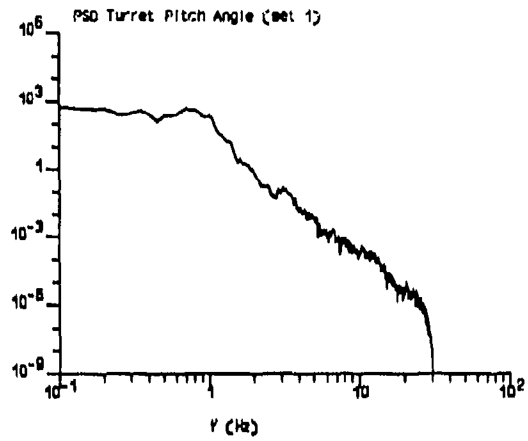

Fig. 3-15: Power Spectral Density - Turret Pitch Angle (Units are $mrad^2/Hz$)

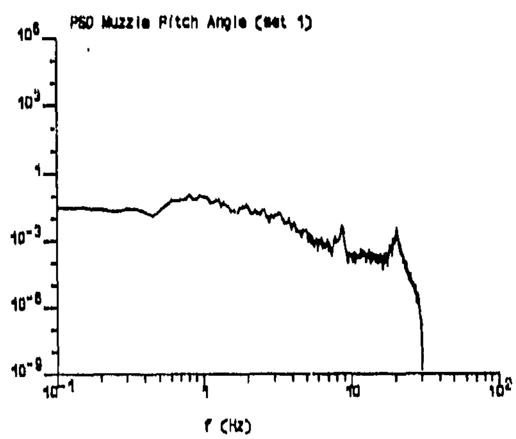

Fig. 3-16: PSD - Muzzle Elev. Angle

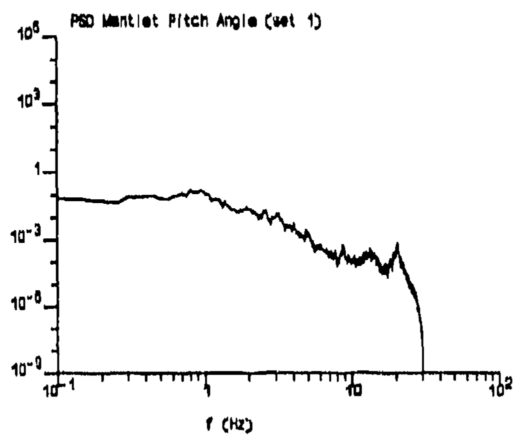

Fig. 3-17: PSD - Mantlet Elev. Angle

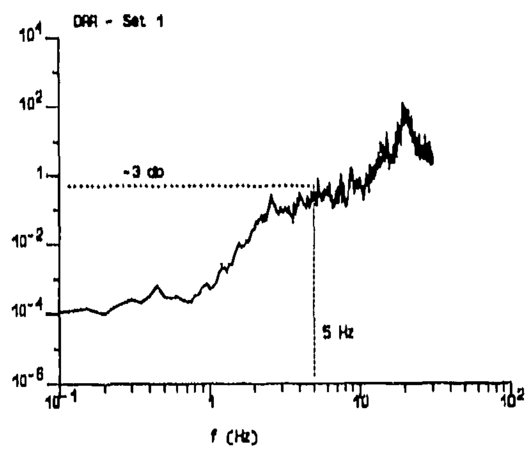

Fig. 3-18: Disturbance Rejection Ratio - Elevation Servo System (Set 1)

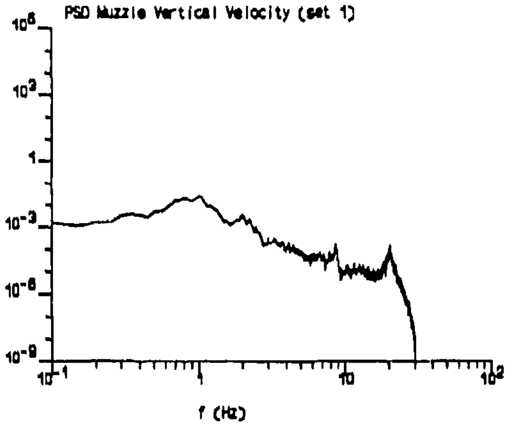

Fig. 3-19: PSD - Muzzle Vertical Velocity

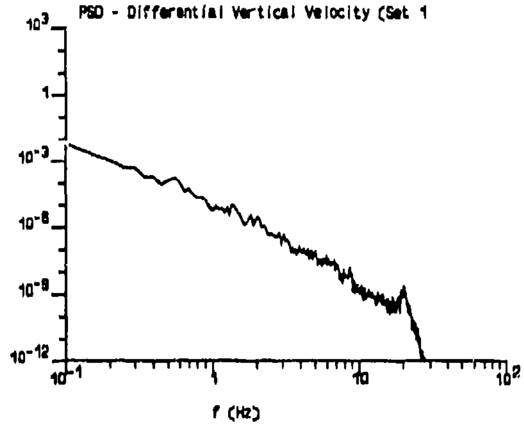

Fig. 3-20: PSD- Differential Vertical Velocity

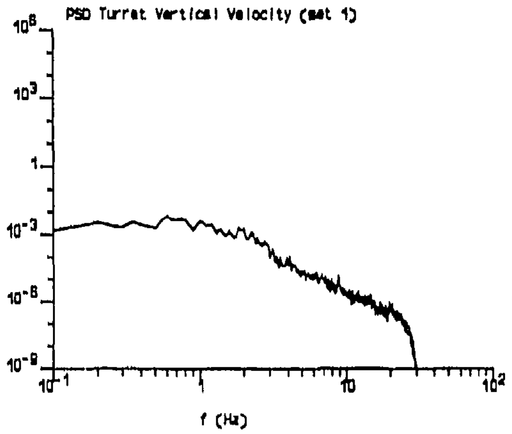

Fig. 3-21: PSD - Turret Vertical Velocity

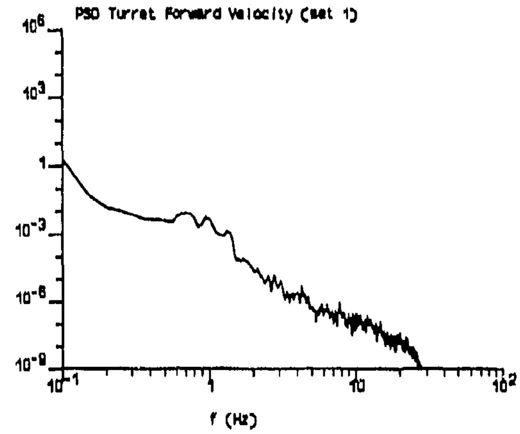

Fig. 3-22: PSD - Turret Forward Velocity

4.0 DATA ANALYSIS - DATA SET 2

The sensor configuration and brief descriptions of the data runs of Data Set 2 were summarized in Section 2.2. The primary sensors were the two rate gyros mounted at either end of the gun barrel to measure differences in barrel elevation angular rates. The terrain was primarily rough, rocky roads through light brush. Tank speeds were roughly 40 km/h. The purpose of these runs was to quantify the barrel flex measurable by these methods under very severe terrain conditions.

4.1 The Raw Data - Set 2

Since the raw data appears very similar to that collected for Set 1 (Section 3.1.1) and provides little new information, it is not shown.

4.2 Integrated Gyro Data - Set 2

This section shows some of the most significant results in this report. These runs were over very rough ground so the stabilization system was fully taxed. The gun was exhibiting substantial residual motion that was discernible to an observer. The signals from the two elevation rate-sensing gyros at opposite ends of the gun were numerically integrated and analyzed. Figures 4-1 and 4-2 show these signals from run 7 (see Table 2-4) which was the most severe run of these trials. Mantlet stabilization errors are seen to be kept within 1 mrad, as expected, by the stabilization system. The muzzle angle shows a larger signal which occasionally exceeds 2 mrad. Closer looks at two segments of this run are shown in Figures 4-3 and 4-4. These figures indicate that the muzzle angle can exceed the mantlet angle by as much as 1 1/2 mrad over the harshest bumps. This is the most direct evidence that was seen that indicated that the magnitude of the barrel flex was comparable to the errors produced by the stabilization systems. The sensor configuration's angle measurement error was found to be on the order of 0.1 to 0.2 mrad, based on pre-trial lab tests.

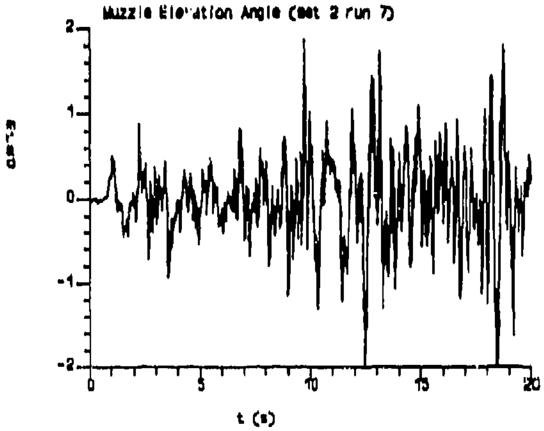

Fig. 4-1: Muzzle Elevation Angle

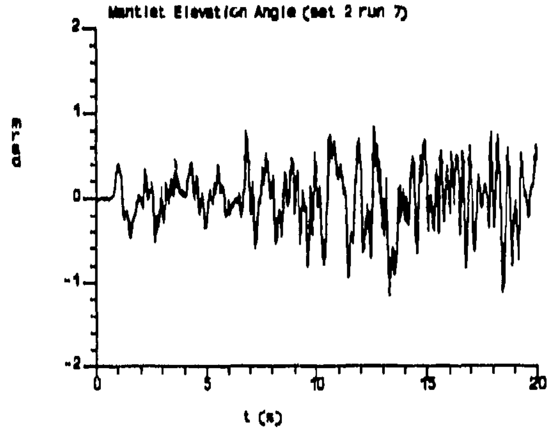

Fig. 4-2: Mantlet Elevation Angle

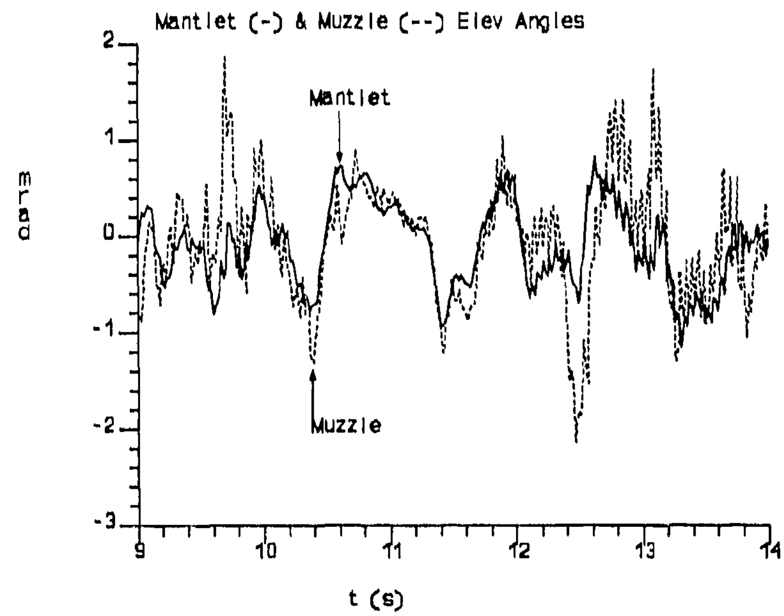

Fig. 4-3: Expanded Section of Gun Barrel Elevation Angular Excursions (Set 2 Run 7). This figure shows some of the largest barrel flexing recorded in these trials.

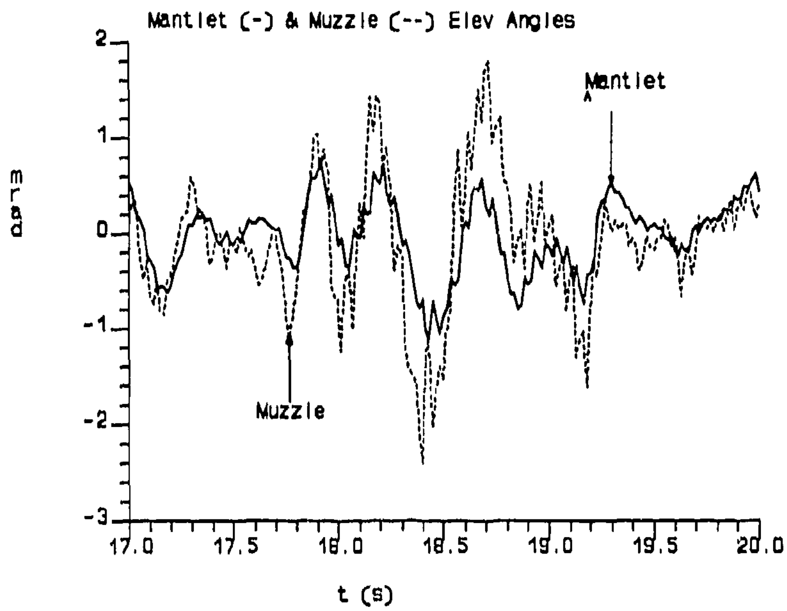

Fig. 4-4: Another Expanded Section (Set 2 Run 7)

4.3 Power Spectral Densities - Set 2

Spectral estimates of the mantlet and muzzle elevation angles were computed from several 20 second segments of runs 5, 6 and 7 with the same techniques as outlined in Section 3.4. These are shown in Figures 4-5 and 4-6.

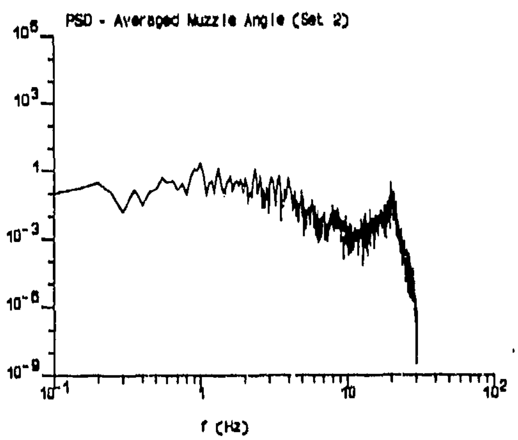

Fig. 4-5: PSD - Muzzle Elev. Angle

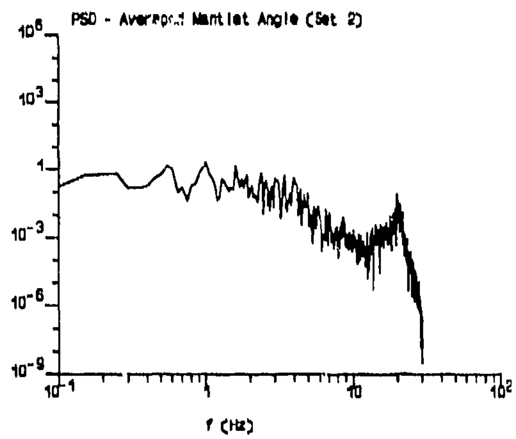

Fig. 4-6: PSD - Mantlet Elev. Angle

These spectra are quite similar to those obtained in Set 1 (Figs. 3-16 and 3-17) but with slightly higher power levels due to more severe terrain, and with a little more noise due to the fact that only 5 segments were a .raged instead of 7. In spite of this, it is evident that the peak at 20 Hz is still in dominance but the peak at 8 Hz is significantly reduced. It should be noted that this data set was collected on a different tank than was used for Set 1 and had

had its gun control system tuned up prior to these trials. This may account for the lack of the 8 Hz vibration that was most likely a result of some slackness in the gun cradle or hydraulic system.

5.0 DATA ANALYSIS - DATA SET 3

5.1 Integrated Gyro Data - Set 3

The runs of Set 3, as described in Section 2.3.3, were conducted primarily for stabilization system performance measurements to provide data for another requirement. The conditions were quite benign (over pavement) so little barrel flex was expected. For this reason, the gun barrel was not instrumented. The data gathered from these runs of primary interest to this report are the signals recorded from the 3-axis inertial unit on the mantlet while the tank was driven over the wooden bumps.

Figures 5-1 to 5-3 show the mantlet roll, azimuth and elevation angles respectively for Run 5 of this set. The unstabilized roll axis shows the largest excursions even over the pavement (t=0 to t=60 sec). From t=60 to t=65 sec, the first four bumps (in-phase) cause little roll disturbance. The four staggered bumps (t=65 to t=70 sec) cause the large roll angles shown. The performance of the azimuth stabilization system (Fig. 5-2) is quite good. In general, azimuth errors are kept within 1 mrad since the bumps could not fully tax the azimuth control system. Note however the regular oscillation of the azimuth loop even over smooth ground, as if the system is in a limit cycle. This appears throughout the azimuth data collected on the Leopard. The elevation angle (Fig. 5-3) is maintained within ±1 mrad until the four in-phase bumps (t=60 to t=65) cause mantlet elevation errors of about ± 4 mrad. The 4 staggered bumps between 65 and 70 seconds cause lesser elevation errors.

5.2 Integrated Accelerometer Data - Set 3

The integrated mantlet accelerometer data from the same run are shown in Figs. 5-4 to 5-6. The forward velocity profile show the tank acceleration, gear changes, bumps and deceleration. Vertical and lateral velocities are shown for completeness.

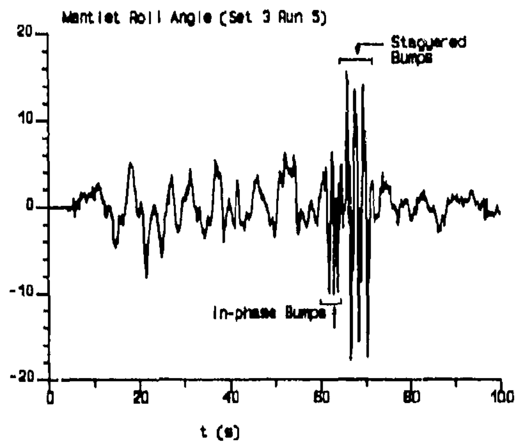

Fig. 5-1: Mantlet Roll Angle - Set 3 Run 5

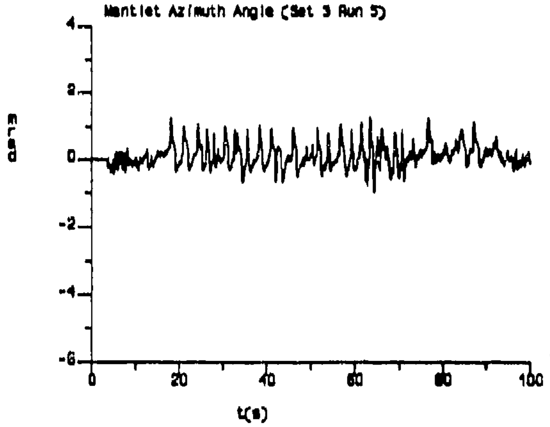

Fig. 5-2: Mantlet Azimuth Angle

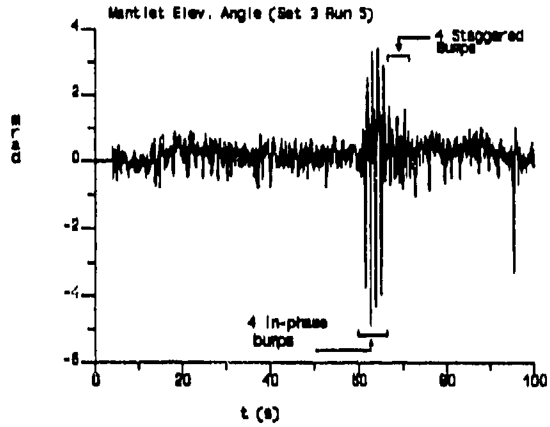

Fig. 5-3: Mantlet Elev Angle

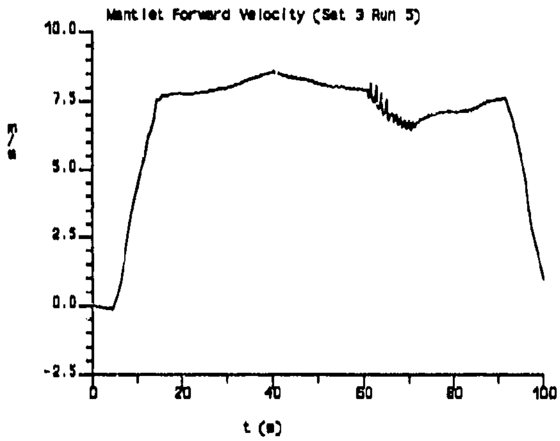

Fig. 5-4: Mantlet Forward Velocity (from integrated accelerometer) - Set 3 Run 5

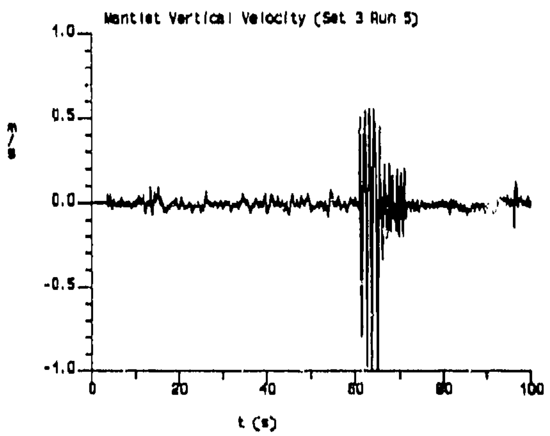

Fig. 5-5: Mantlet Vert. Velocity

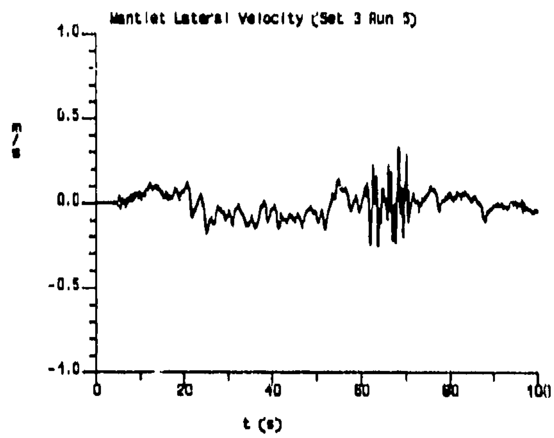

Fig. 5-6: Mantlet Lateral Velocity

6.0 CONCLUSIONS

The purpose of these trials was to measure and characterize the time characteristics and power spectra of terrain-induced gun barrel motions in order to design predictive filtering algorithms for future fire control systems. In summary, it can be stated that there is significant muzzle motion that is induced by rough terrain. The roughest bumps produced gun pitch plane bending angles of as much as 1½ mrads as observed in Section 4.2. Gun elevation stabilization errors are of comparable magnitudes, typically within 1 mrad but occasionally as large as 3 or 4 mrad. Azimuth stabilization performance was similar. Azimuth barrel flex was not measured. It should be similar or perhaps somewhat less than elevation bending.

Spectral analysis of the recorded data indicated the fundamental bending mode to be at roughly 20 Hz. Higher frequency, but presumably much less significant modes could not be observed due to limitations of the sensor systems. These results agree with preliminary modal frequency estimates.

REFERENCES

1. Brosseau, T.L., M.D. Kregel, and A.F. Baran, Autonomous Accuracy Enhancement System, Proceedings of the 6th US Army Symposium on Gun Dynamics, 1990.

2. Bird, J.S., and T. Nguyen, DATAGUN: Dynamic Tank Gun Analysis Utility - Software User's Manual, DREO Technical Note 89-27, September 1989.

3. Bendat, J.S., and A.G. Piersol, *Random Data - Analysis and Measurement Procedures,* Wiley & Sons, New York, 1986

4. Harris, C.M., and C.E. Crede, *Shock and Vibration Handbook - Volume 1*, McGraw-Hill, New York, 1961

5. Craig, R.R. Jr., *Structural Dynamics - An Introduction to Computer Methods*, Wiley & Sons, New York, 1981

APPENDIX A - ESTIMATED BENDING MODES

The theory of vibration of uniform beams is a well-studied area. In general, however a gun barrel is not uniform. It has several different cross sections along its length and is very often tapered at some points. Closed form solutions for the modal shapes and frequencies are not known in general and require extensive modelling and numerical simulation efforts to approximate.

For the purposes of this report, however, it will suffice to assume the gun barrel can be modelled as a uniform hollow tube hinged at one end and free at the other. In this case, any number of classical mechanics reference texts can be used to compute the modal shapes and frequencies (e.g. the tables in Appendix I of [4]).

For a uniform hollow tube of length l, outer diameter d_o, inner diameter d_i, density ρ, and elastic modulus E, the first four modal frequencies are:

$$\omega_i = k\, A_i$$

where

$$A_1 = 15.4$$
$$A_2 = 50.0$$
$$A_3 = 104$$
$$A_4 = 178$$

and

$$k = [(EI)/(\rho A l^4)]^{1/2}$$

with

E = Elastic modulus of steel = 2.068×10^{11} N/m^2
I = Cross-sectional moment of inertia = $(\pi/64)(d_o^4 - d_i^4)$
A = Cross-sectional area = $(\pi/4)(d_o^2 - d_i^2)$
ρ = Density of steel = 8000 kg/m^3
l = Length of barrel = 5m
d_o = Outer diameter = 0.15m
d_i = Inner diameter = 0.105m

Upon substitution, we get

$$k = 9.3 \text{ sec}^{-1}$$

which results in the first four modal frequencies being

$$\omega_1 = kA_1 = (9.3)(15.4) = 143 \text{ rad/s} = 22.8 \text{ Hz}$$
$$\omega_2 = kA_2 = (9.3)(50) = 465 \text{ rad/s} = 74 \text{ Hz}$$
$$\omega_3 = kA_3 = (9.3)(104) = 967 \text{ rad/s} = 155 \text{ Hz}$$

$$\omega_4 = kA_4 = (9.3)(178) = 1655 \text{ rad/s} = 263 \text{ Hz}$$

The corresponding modal shapes, $V_i(x)$, are in general nonlinear combinations of hyperbolic and trigonometric functions which depend on the end conditions. For the beam in question, these work out to be (see e.g. [4], [5]):

$$V_i(x) = \sin(B_i x/l) + r_i \sinh(B_i x/l),\ 0 \leq x \leq l$$

where

$$r_i = \sin(B_i)/\sinh(B_i)$$

with

$$B_1 = 3.9226$$
$$B_2 = 7.06858$$
$$B_3 = 10.21018$$
$$B_4 = 13.35177$$

These mode shapes are sketched in Figure A-1.

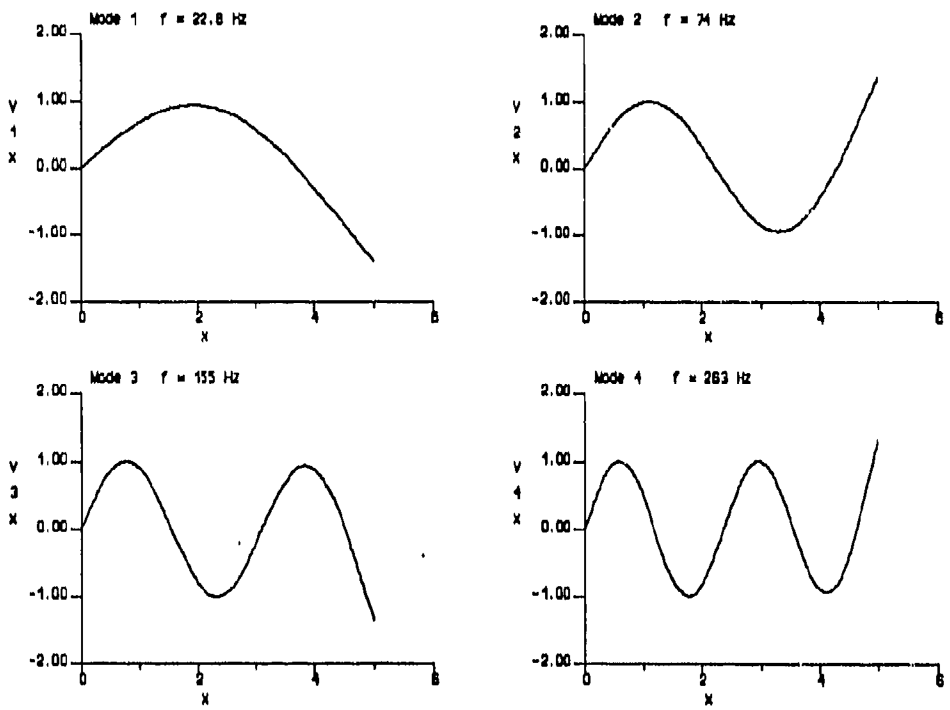

Fig. A-1: Modal Shape Functions of Hinged-Free Hollow Tube

The time-varying, relative magnitudes of the various modes are dependent on the initial conditions and input forcing function. Computer simulations were conducted on the above barrel model with a small initial condition (a 1 cm tip displacement) and no other input function. The simulation uses the Bernoulli-Euler theory of transverse beam vibrations (see [5], for example) and assumes the spatial and temporal components of the solution can be separated so that a numerical solution to the time varying portion, $e_i(t)$, of the following equation can be computed:

$$(EIv'')'' + \rho A(\partial^2 v/\partial t^2) = 0 \qquad \text{(where } v' \text{ denotes } \partial v/\partial x)$$

where the complete temporal/spatial solution to the beam vibrations has the assumed form (for *n* modes)

$$v(x,t) = \Sigma\, V_i(x)\, e_i(t), \quad i=1,\ldots,n$$

The power spectral density function of the resulting tip displacement is shown in Figure A-2. A sampling frequency of 600 Hz was used in the simulation so the response of all modes could be observed. Mode 1 is by far dominant, being at least 40 db higher than mode 2. Higher modes are even less significant.

Even if this simulation is within only an order of magnitude of the behavior of the real gun barrel, it seems to give justification to the assumption that the initial bending mode at 20-25 Hz is the only one of significance. The PSD of this simulation is quite similar to that obtained from the muzzle-mounted gyro on the gun barrel in Figure 4-5, at least up to the 30 Hz frequency limit of the real data, and if one ignores the low frequency (< 5 Hz) effects of the stabilization system that were not simulated.

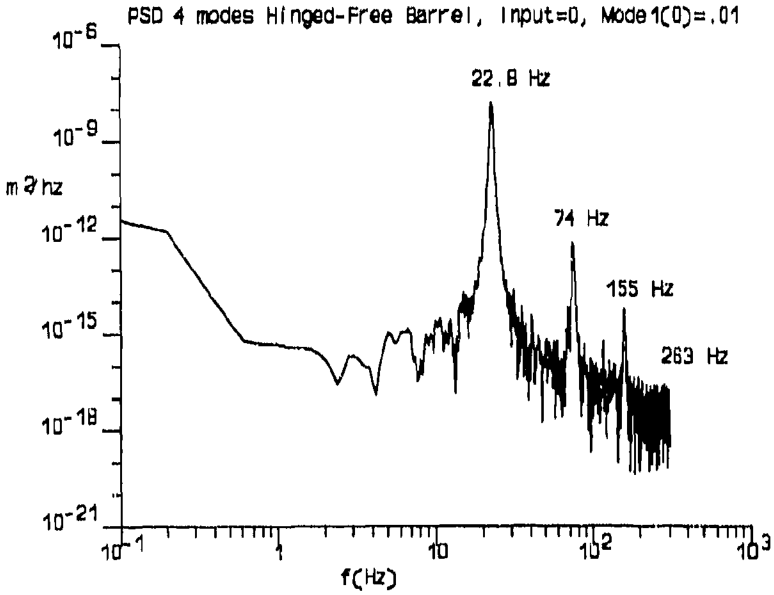

Fig. A-2: PSD of Simplified Simulated Gun Barrel

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