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METHODOLOGY ISSUES CONCERNING THE ACCURACY OF KINEMATIC DATA COLLECTION AND ANALYSIS USING THE ARIEL PERFORMANCE ANALYSIS SYSTEM

Robert P. Wilmington

Contract NAS9-17900

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Prepared for
Lyndon B. Johnson Space Center

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ACRONYMS AND ABBREVIATIONS

ABL	Anthropometry and Biomechanics Laboratory
APAS	Ariel Performance Analysis System
CPM	Continuous Passive Motion
LESC	Lockheed Engineering & Science Company
NASA	National Aeronautics and Space Administration

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EXECUTIVE SUMMARY

Kinematics, the study of motion exclusive of the influences of mass and force, is one of the primary methods used for the analysis of human biomechanical systems as well as other types of mechanical systems. The Anthropometry and Biomechanics Laboratory (ABL) in the Crew Interface Analysis section of the Man-Systems Division performs both human body kinematics as well as mechanical system kinematics using the Ariel Performance Analysis System (APAS). The APAS supports both analysis of analog signals (e.g. force plate data collection) as well as digitization and analysis of video data.

The current evaluations address several methodology issues concerning the accuracy of the kinematic data collection and analysis used in the ABL.

This document describes a series of evaluations performed to gain quantitative data pertaining to position and constant angular velocity movements under several operating conditions. Two-dimensional as well as three-dimensional data collection and analyses were completed in a controlled laboratory environment using typical hardware setups. In addition, an evaluation was performed to evaluate the accuracy impact due to a single axis camera offset.

Segment length, positional data, exhibited errors within 3% when using three-dimensional analysis and yielded errors within 8% through two-dimensional analysis (Direct Linear Software). Peak angular velocities displayed errors within 6% through three-dimensional analyses and exhibited errors of 12% when using two-dimensional analysis (Direct Linear Software).

The specific results from this series of evaluations and their impacts on the methodology issues of kinematic data collection and analyses are presented in detail. The accuracy levels observed in these evaluations are also presented.

1.0 INTRODUCTION

The Anthropometry and Biomechanics Laboratory (ABL) in the Man-Systems Division's Crew Interface Analysis section performs both human body kinematics as well as mechanical system kinematics using the Ariel Performance Analysis System (APAS). Three categories of evaluations have been performed, including: two-dimensional data collection and analysis, three-dimensional data collection and analysis, and a two-dimensional single axis camera offset data collection and analysis.

This series of evaluations was performed to gain quantitative data pertaining to position and constant angular velocity movements under several operating conditions. Two-dimensional as well as three-dimensional data collection and analyses were completed in a controlled laboratory environment using typical hardware setups. In addition, an evaluation was performed to evaluate the accuracy impact due to a single axis camera offset. Two-dimensional as well as three-dimensional data collection methodologies were addressed. Two-dimensional data analysis was performed using two different software packages within the APAS, Direct Linear and Multiplier. Three-dimensional data analysis was performed using the Direct Linear method software.

2.0 METHOD

2.1 Apparatus

The LIDO Multi-Joint II system is a dynamometer designed for rehabilitation and force measurement of isolated joints (see Figure 1). The upper extremity extension and arm hardware were used for the greatest torque arm length (see Figure 2). The LIDO software was used for the left arm while the actuator was on the right side of the table but turned 180° to point out away from the table. Note: At the time of these evaluations, the LIDO system in the laboratory was experiencing a minor vibration artifact in the arm motion. This vibration artifact may have caused slight variations in the range of motion or the angular velocity of the torque arm but did not drastically alter these variables.

Three 3.81 cm diameter retroreflective balls were placed on the torque arm (see Figure 3). One was placed on the actuator shaft, a second was placed 40.64 cm out on the arm, and a third was placed 80.01 cm out on the arm. The upper extremity extension and arm attachments were covered in black cloth to gain contrast between the retroreflective balls and the silver coloring of these attachments. In addition, a black cloth was draped over two laboratory camera stands as the background for the evaluations.

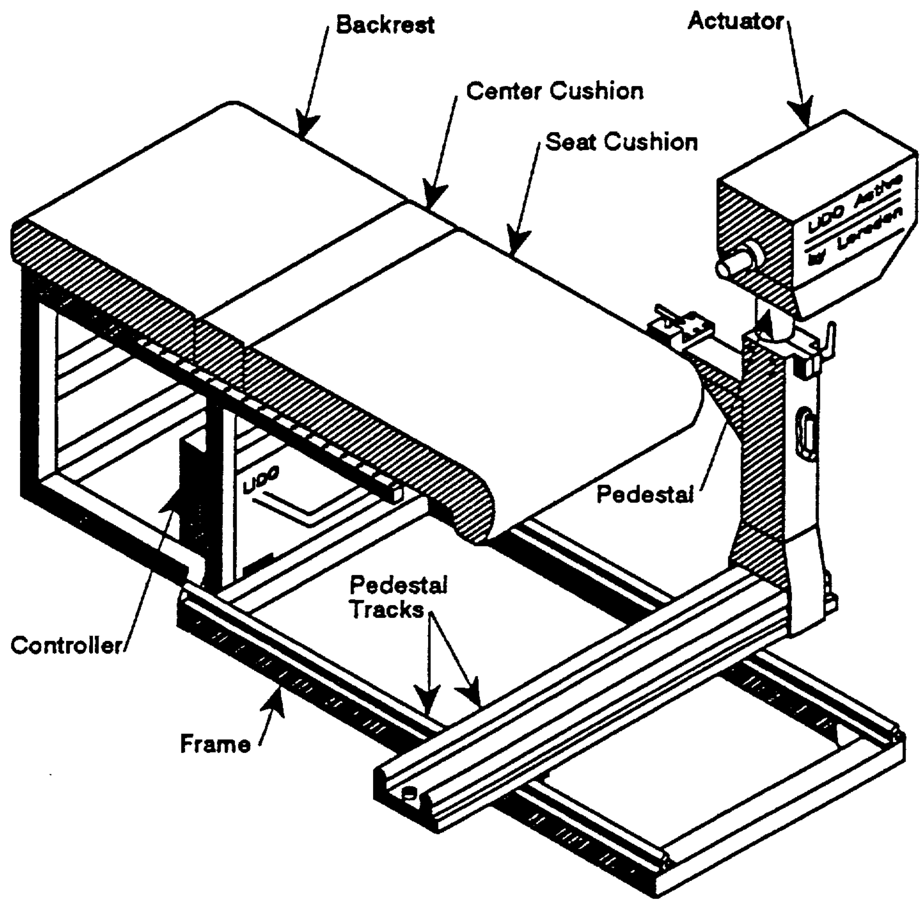

Figure 1. LIDO Multi-Joint II System
Note: Figure obtained from LIDO Multi-Joint II Users' Guide

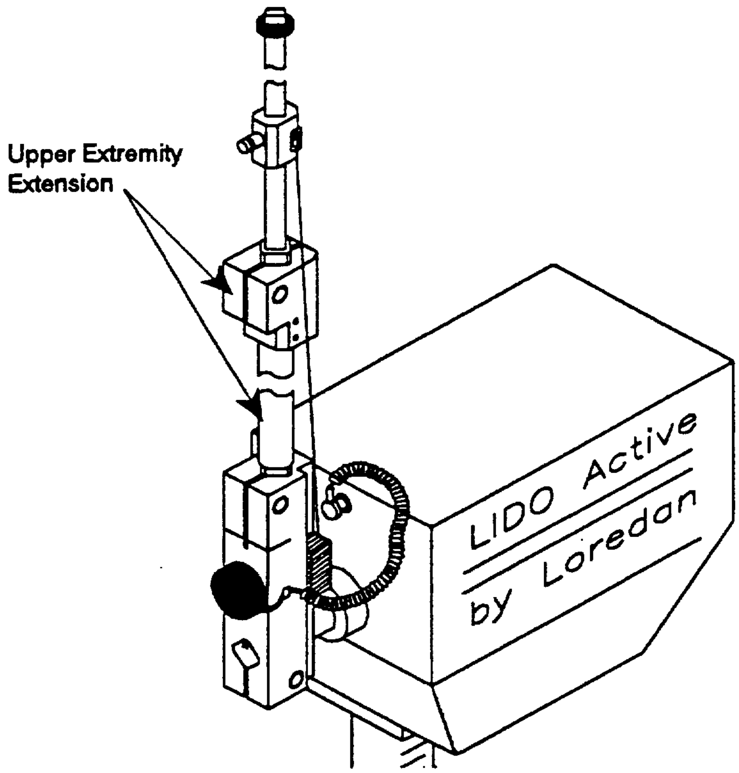

Figure 2. Upper Extremity Extension and Arm
Note: Figure obtained from LIDO Multi-Joint II Users' Guide

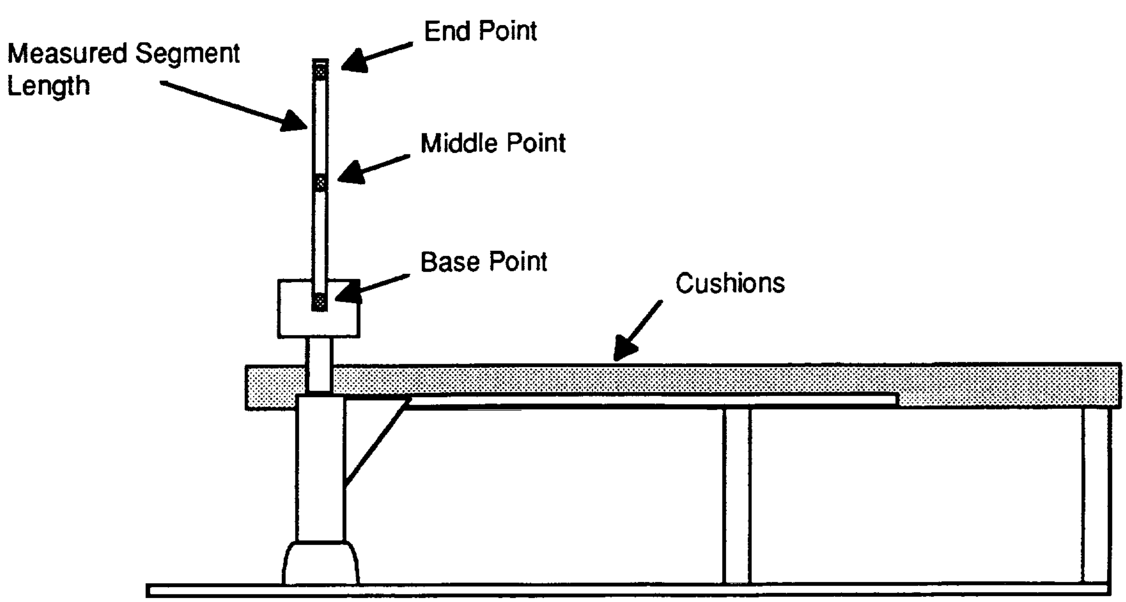

Figure 3. Experiment Setup

A Panasonic camcorder (model PV-530) and a Quasar camcorder (model VM-37) were used for all the video recordings at a film speed of 30 frames/second. Wide angle lenses (.5X) were used in all of the evaluations. A flash was used for synchronizing the cameras in the three-dimensional analysis.

A reference frame constructed of PVC pipe was used in the evaluations. The frame has a 91.44X91.44 cm base and a height of 183 cm. The calibration reference frame has markings on the four vertical struts every 45.7 cm.

2.2 Procedure

For these evaluations, the LIDO Multi-Joint II system was set up in the shoulder mode in the supine position. This system allows the operator to designate the range of motion of the torque arm as well as the angular velocity. In all of the evaluations, the LIDO Multi-Joint II system was set up with the appropriate parameters and then set into motion using the continuous passive motion (CPM) mode. The CPM mode is used to warm up a subject's muscles prior to data collection by having the muscle group of interest passively moved through the range of motion in which the data collection will be performed. Data were collected after the torque arm had performed at least two full repetitions of motion because of the built-in ramp up time in the software.

2.2.1 Two-Dimensional Analysis

A two-dimensional analysis was performed with a single camera placed ten feet away from the plane of motion. A standard Panasonic camcorder was used with a wide angle lens (.5X). The LIDO Multi-Joint II system was set up at 30, 60, 90 and 120 degrees/second angular velocity settings with a range of motion of 200 degrees (± 100 from a torque arm center-up position perpendicular to the LIDO cushion). In addition, it should be noted that since the entire length of the upper extremity extension and the arm is 80.0 cm, the 200° range of motion takes the end point 34.3 cm out of the calibration reference frame area. The video data collected in this evaluation was digitized and analyzed using two different software methods within the APAS-Direct Linear and Multiplier. The Direct Linear method uses four control points and the Multiplier method uses two control points. The two control points used in the Multiplier method software were placed along the X (horizontal) axis. All data were taken for 10 seconds with a skip factor of 4. The skip factor indicates the number of frames that are intentionally left undigitized for every digitized frame. Thus with the video being recorded at 30 frames/second, a skip factor of 4 correlates to 6 frames/second digitized (frame 1 digitized and frames 2 - 5 skipped, frame 6 digitized and frames 7-10 skipped, etc.). The skip factor is used to reduce the amount of time required in the digitization process.

2.2.2 Three-Dimensional Analysis

Three-dimensional analysis was performed with two camcorders placed on a line parallel to the plane of motion. The parallel line was at a distance of 9 feet from the LIDO, and the cameras were each displaced at 45° from perpendicular to the actuator. The LIDO Multi-Joint II system was set up at a 60 degrees/second angular velocity setting with a range of motion of 120 degrees. All data were taken for 6 seconds with a skip factor of 4.

2.2.3 Two-Dimensional Analysis Addressing a Single Axis Camera Offset

A two-dimensional analysis was performed with a single camera placed nine feet away from the plane of motion. A standard Panasonic camcorder was used with a wide angle lens. The LIDO Multi-Joint II system was set up at a 60 degrees/second angular velocity setting with a range of motion of 120 degrees (60° clockwise and 60° counterclockwise from a torque arm center up position perpendicular to the LIDO Multi-Joint II table). The camera was then displaced along a line parallel to the plane of motion at 0, 5, 20, 25, 30, 35, 40, and 50 degrees. After each displacement of the camera, the camcorder was adjusted to place the torque arm motion to the center of the viewing screen. All data were collected for 6 seconds with a skip factor of 4.

2.3 Analysis

The analyses presented in the following sections address five characteristics: segment length, peak velocity, velocity range, velocity range average, and angular displacement. The resultant characteristics are based on the placement of the retroreflective balls on the torque arm. One retroreflective ball was placed on the actuator shaft and is referred to as base point. A second retroreflective ball placed 40.64 cm out on the torque is termed the middle point. The retroreflective ball placed 80.01 cm out on the torque arm is termed the end point (see Figure 3).

All data presented in this report went through a cubic spline smoothing process at a smoothing value of 1.0 unless specifically stated otherwise. The smoothing value is an indication of the amount of smoothing used in the selected units. A smoothing value of 0.1-0.3 would closely represent the raw data, whereas 1.0 represents an intermediate smoothing value. The APAS defaults to a smoothing value of 1.0 but allows the operator to determine the appropriate smoothing value to use depending on the amount of noise in the data collected.

The torque arm segment length has been calculated based on the distance between the middle point and the end point (measured value 39.37 cm).

Peak velocity was taken as the highest absolute value over the range of recorded data. The percent peak error was calculated based on the angular velocity setting of the LIDO Multi-Joint II system. The velocity range is the measurement of the dispersion of values equal to the difference of the greatest velocity and smallest velocity within the constant angular velocity interval of the angular velocity curve (see Figure 4). The constant angular velocity interval is the portion of the velocity curve after the torque arm has ramped up and reached the operator preset angular velocity and extends until the torque arm begins to slow down at the end of the range of motion. For the purposes of this evaluation the arm was considered going into the constant angular velocity interval when the angular velocity was within ≈ 3 degrees/second or greater than the preset constant angular velocity. The torque arm was considered to be leaving the constant angular velocity interval when the value was below ≈ 3 degrees/second of the preset angular velocity. The angular velocity average is calculated based on the constant angular velocity interval.

The angular displacement is presented as the full range of motion of the torque arm. The smoothing value used in the data reduction was observed to have an effect on the measurement of the angular displacement. Thus, the angular displacement data will be presented using smoothing values of 1.0 and 0.1. In addition, it should be noted that for this experiment if angular displacement is of primary concern, a skip factor of 0 should be used to minimize any errors due to the high angular velocity changes experienced at the extremes of the range of motion.

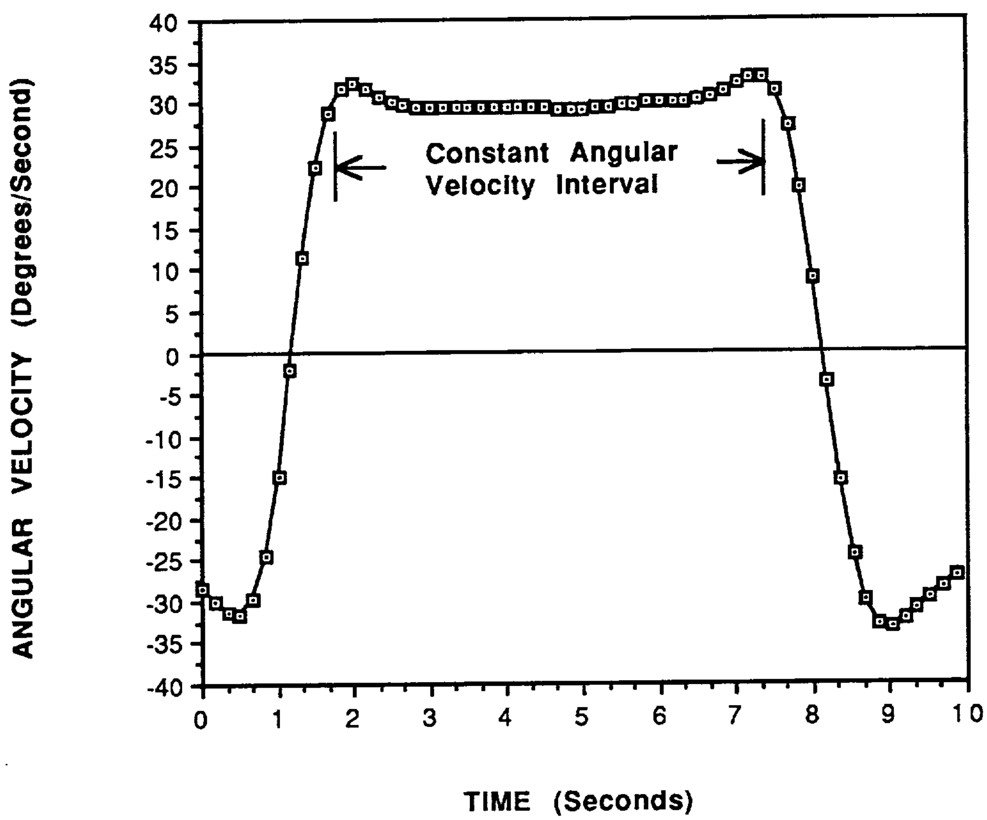

Figure 4. Angular Velocity Sample Curve - 30 Degrees/Second

3.0 RESULTS AND DISCUSSION

3.1 Two-Dimensional Analysis Results

The Direct Linear and the Multiplier software analysis methods were both performed on the same video recordings. The results are presented in the following sections.

3.1.1 Direct Linear Method Software

3.1.1.1 Segment Length

The linear distance results using the Direct Linear method software are summarized in Table 1 and Table 2. The X axis measurements were taken with the torque arm at 90° rotations. The Y axis measurements were taken with the torque arm at 0°. The percent error in the segment length as taken when along the X axis was between 2.13% and 7.92% corresponding to segment length errors of .84 cm to 3.12 cm. Segment length percent error as taken when along the Y axis was between 3.87% and 8.74% corresponding to length errors of 1.53 cm to 3.44 cm.

Table 1. Two-Dimensional Direct Linear Distances Based on the X-Axis

Angular	Middle Point Location		End Point Location		Segment	% Length
Velocity	X	Y	X	Y	Length	Error
30	58.54	-12.56	98.69	-14.65	40.21	2.13
60	58.72	-8.02	101.16	-10.11	42.49	7.92
90	60.01	-10.69	102.05	-13.73	42.15	7.06
120	59.91	-11.81	101.77	-15.07	41.98	6.63

Table 2. Two-Dimensional Direct Linear Distances Based on the Y-Axis

Angular	Middle Point Location		End Point Location		Segment	% Length
Velocity	X	Y	X	Y	Length	Error
30	17.18	30.56	15.94	71.66	41.12	4.45
60	18.46	29.54	18.37	70.44	40.90	3.87
90	18.16	28.59	17.68	71.40	42.81	8.74
120	21.50	26.58	24.40	68.86	42.38	7.65

3.1.1.2 Angular Velocity

The angular velocity results using the Direct Linear method software are summarized in Table 3. The data reveal that for the angular velocities tested in this evaluation, peak errors were between 6.9% and 11.8%. The percentage in peak errors was also shown to be consistent (variation < 1.4%) between the middle and end points. The range averages are very close to the set values of the LIDO Multi-Joint II system but fairly high variations in the angular velocity were present in the constant angular velocity interval. The velocity curve graphs for the two-dimensional analysis using the Direct Linear method software are presented in Appendix A.

Table 3. Two-Dimensional Direct Linear Angular Velocities

	Middle Point Velocity				End Point Velocity			
Angular Velocity	Variation	Interval Average	Peak Value	% Peak Error	Variation	Interval Average	Peak Value	% Peak Error
30	4.45	29.94	32.76	9.20	3.93	30.05	33.09	10.30
60	13.25	59.27	67.10	11.80	10.26	60.17	67.02	11.70
90	20.55	87.25	97.87	8.70	12.12	89.71	96.61	7.30
120	23.34	113.49	129.1	7.60	15.97	118.25	128.3	6.90

3.1.1.3 Angular Displacement

Angular displacement results using the Direct Linear method software at smoothing values of 1.0 and 0.1 are summarized in Table 4 and Table 5. The angular displacements tested using a smoothing value of 1.0 in this evaluation exhibited errors between 1.9% and 9.74%. The angular displacements were consistently lower than the 200° angular displacement that was set up through the LIDO Multi-Joint II software. The angular displacements exhibited errors between 0.12% and 1.94% using a smoothing value of 0.1. Notice that the errors exhibited by all conditions when smoothed at a value of 0.1 were reduced.

Table 4. Two-Dimensional Angular Displacements Using Direct Linear Method (Smoothing Value 1.0)

Angular Velocity	Middle Point Angular Displacement	End Point Angular Displacement	% Error Middle	% Error End
30	191.57	196.20	4.22	1.90
60	180.53	189.76	9.74	5.12
90	186.45	194.00	6.78	3.00
120	191.39	197.31	4.31	1.35

Table 5. Two-Dimensional Angular Displacements Using Direct Linear Method (Smoothing Value 0.1)

Angular Velocity	Middle Point Angular Displacement	End Point Angular Displacement	% Error Middle	% Error End
30	200.98	201.71	.49	.86
60	198.49	200.24	.76	.12
90	201.02	202.07	1.94	1.43
120	202.11	201.67	1.06	.84

3.1.2 Multiplier Method Software

3.1.2.1 Segment Length

The linear distance results using the Multiplier method software are summarized in Table 6 and Table 7. The data shown in the tables are presented under the conditions that the torque arm is parallel to the X-axis (horizontal axis) or parallel to the Y-axis (vertical axis). The percent error in the segment length when parallel to the X-axis were between 2.31% and 8.61% corresponding to length errors of .91 cm to 3.39 cm. The percent errors exhibited in the segment length when parallel to the Y-axis were between 34.77% and 36.22% corresponding to 13.39 cm and 14.26 cm. Thus, using the multiplier software based on only two control points, slight distortions were observed on the X-axis and very pronounced distortions were exhibited along the Y-axis. The two control point locations used in this evaluation were placed along the X-axis.

Table 6. Two-Dimensional Multiplier Method Linear Distances Based on the X-Axis

Angular	Middle Point Location		End Point Location		Segment	% Length
Velocity	X	Y	X	Y	Length	Error
30	210.01	202.19	250.26	200.58	40.28	2.31
60	209.74	201.40	252.24	196.68	42.76	8.61
90	211.11	198.71	253.51	194.01	42.66	8.36
120	211.04	197.50	253.56	191.71	41.12	4.45

Table 7. Two-Dimensional Multiplier Method Linear Distances Based on the Y-Axis

Angular	Middle Point Location		End Point Location		Segment	% Length
Velocity	X	Y	X	Y	Length	Error
30	168.78	253.74	166.56	306.99	53.30	35.38
60	167.31	252.68	164.43	305.66	53.06	34.77
90	170.90	251.97	171.53	305.15	53.18	35.08
120	171.98	251.54	173.93	305.13	53.63	36.22

3.1.2.2 Angular Velocity

The angular velocity results using the Multiplier software are summarized in Table 8. The data reveal that for the angular velocities tested in this evaluation peak errors were between 21.60% and 38.90%. The range averages were shown to have fairly large variations from the set values of the LIDO Multi-Joint II system. Extremely high variations in the angular velocity were present in the constant angular velocity interval. The velocity curve graphs for the two-dimensional analysis using the Multiplier method software are presented in Appendix B.

Table 8. Two-Dimensional Multiplier Method Angular Velocities

	Middle Point Velocity				End Point Velocity			
Angular Velocity	Variation	Interval Average	Peak Value	% Peak Error	Variation	Interval Average	Peak Value	% Peak Error
30	19.89	27.42	39.54	31.80	20.38	30.63	41.76	38.90
60	38.56	55.57	76.74	27.90	39.15	54.11	81.22	35.37
90	52.03	82.58	111.3	23.68	48.92	84.58	113.3	25.86
120	62.21	108.98	142.5	18.71	60.00	113.15	145.9	21.60

3.1.2.3 Angular Displacement

Angular displacement results using the Multiplier method software at smoothing values of 1.0 and 0.1 are summarized in Table 9 and Table 10. It should be noted that both extremes of the range of motion are only 10 degrees beyond being parallel to the X-axis. The angular displacements analyzed at a smoothing value of 1.0 were shown to have errors between 0.3% and 8.51%. The angular displacement errors for the middle point tended to be much higher than those exhibited for the end point. The angular displacements analyzed at a smoothing value of 0.1 exhibited errors between 1.82% and 4.34%. Notice that the overall magnitude of the error was reduced from 8.51% to 4.34% but several of the individual percent error values were increased.

Table 9. Two-Dimensional Angular Displacements Using Multiplier Method (Smoothing Value 1.0)

Angular Velocity	Middle Point Angular Displacement	End Point Angular Displacement	% Error Middle	% Error End
30	182.98	193.21	8.51	3.40
60	187.00	196.78	6.50	1.61
90	191.49	200.60	4.26	.30
120	196.75	203.78	1.63	1.89

Table 10. Two-Dimensional Angular Displacements Using Multiplier Method (Smoothing Value 0.1)

Angular Velocity	Middle Point Angular Displacement	End Point Angular Displacement	% Error Middle	% Error End
30	203.63	206.03	1.82	3.02
60	205.91	208.06	2.96	4.03
90	207.25	208.68	3.63	4.34
120	207.66	208.43	3.83	4.21

3.2 Three-Dimensional Analysis Angular Velocity

3.2.1 Segment Length

Table 11 and Table 12 summarize the linear distance results found in the three-dimensional analysis based on the X-axis (horizontal axis) and the Y-axis (vertical axis). The percent errors in the segment length when compared to the X-axis was between 1.63% and 2.67% corresponding to length errors of .64 cm to 1.05 cm. The percent errors in the segment length when taken with the segment parallel to the Y-axis were between .33% and 1.27% corresponding to 0.13 cm and 0.5 cm. Thus, the linear distance errors exhibited through the three-dimensional analysis were found to be small.

Table 11. Three-Dimensional Analysis Distances X-Axis

Angular	Middle Point Location			End Point Location			Segment	% Length
Velocity	X	Y	Z	X	Y	Z	Length	Error
30	78.38	76.06	60.73	110.0	77.73	82.36	38.32	2.67
60	78.40	76.55	59.71	110.1	78.19	81.48	38.52	2.16
90	78.97	76.86	58.79	111.2	78.49	79.48	38.34	2.62
120	81.43	76.20	58.25	113.9	77.69	79.27	38.73	1.63

Table 12. Three-Dimensional Analysis Distances Y-Axis

Angular	Middle Point Location			End Point Location			Segment	% Length
Velocity	X	Y	Z	X	Y	Z	Length	Error
30	46.27	76.57	77.66	43.78	78.60	116.4	38.87	1.27
60	46.09	76.47	76.43	44.67	78.34	115.6	39.24	.33
90	40.91	76.43	75.61	33.82	78.02	114.5	39.56	.48
120	41.75	76.37	75.23	35.56	79.42	114.2	39.58	.53

3.2.2 Angular Velocity

The angular velocity results using the three-dimensional Direct Linear method software are summarized in Table 13. The data reveals that for the angular velocities tested in this evaluation peak errors were between 0.73% and 5.90%. The percentage in peak errors were also shown to be consistent (variation < 2.25%) between the middle and end points. The range averages are very close to the set values of the LIDO Multi-Joint II system and the variations in the angular velocity were low over the constant angular velocity interval. The maximum range was 4.63 degrees/second. The velocity curve graphs for the three-dimensional analysis using the Direct Linear method software are presented in Appendix C.

Table 13. Three-Dimensional Analysis Angular Velocities Using the Direct Linear Method

	Middle Point Velocity				End Point Velocity			
Angular Velocity	Range	Range Average	Peak Value	% Peak Error	Range	Range Average	Peak Value	% Peak Error
30	2.53	29.30	31.20	4.00	2.95	28.59	31.77	5.90
60	4.63	60.26	61.71	2.90	2.43	60.40	60.44	.73
90	1.70	89.94	89.33	.85	3.42	89.71	92.79	3.10
120	2.82	116.59	118.01	1.60	4.57	120.67	122.90	2.40

3.2.3 Angular Displacement

Angular displacement results using the Direct Linear method software at smoothing values of 1.0 and 0.1 are summarized in Table 14 and Table 15. The angular displacements tested using a smoothing value of 1.0 in this evaluation exhibited errors between 1.96% and 7.13%. The angular displacements were consistently lower than the 120° angular displacement that was set up through the LIDO Multi-Joint II software. The angular displacements exhibited errors between 0.87% and 3.00% using a smoothing value of 0.1. Notice that the errors exhibited in all but one of the angular velocity conditions were reduced at a smoothed value of 0.1 rather than 1.0.

Table 14. Three-Dimensional Angular Displacements Using Multiplier Method (Smoothing Value 1.0)

Angular Velocity	Middle Point Angular Displacement	End Point Angular Displacement	% Error Middle	% Error End
30	108.22	111.44	9.82	7.13
60	108.33	112.30	9.73	6.42
90	111.17	115.11	7.36	4.08
120	116.02	117.65	3.32	1.96

Table 15. Three-Dimensional Angular Displacements Using Multiplier Method (Smoothing Value 0.1)

Angular Velocity	Middle Point Angular Displacement	End Point Angular Displacement	% Error Middle	% Error End
30	116.78	116.40	2.69	3.00
60	117.36	116.49	2.20	2.93
90	117.04	116.83	2.47	2.64
120	118.96	117.38	.87	2.18

3.3 Two Dimension Analysis Camera Offset

The Direct Linear method software was used for data analysis of the video recordings. The LIDO Multi-Joint II system was set up at a 60 degrees/second angular velocity setting with a range of motion of 120 degrees (60° clockwise and 60° counterclockwise from a torque arm center up position perpendicular to the LIDO table).

3.3.1 Segment Length

Linear distance results using the Direct Linear method software are summarized in Table 16 and Table 17. The data presented in the tables are presented in terms of being closest to parallel to the X-axis (horizontal axis) and parallel to the Y-axis (vertical axis). The percent errors in the segment length when parallel to the X-axis was between 1.10% and 6.38% corresponding to length errors of 0.43 cm to 2.51 cm. The percent errors exhibited in the segment length when parallel to the Y-axis were between 2.92% and 7.92% corresponding to 1.15 cm and 3.12 cm.

Raw data taken with respect to the X-axis does reveal that the Y values for the middle and end points are very consistent but the X values are skewed as the camera is offset. In a similar manner, when comparing data with respect to the Y-axis, the Y values are again very consistent while the X values are skewed with the camera offset. One should note that the offset of the camera was performed only in the X direction. A skewing effect along the axis of the camera offset was observed but did not skew the Y-axis. Thus, although an absolute shift in raw data was observed along the X-axis, it does not appear to drastically alter the relative distances between the two points over this range of motion.

Table 16. Two-Dimensional Camera Offset Linear Distances Based on the X-Axis

Camera	Middle Point Location		End Point Location		Segment	% Length
Offset	X	Y	X	Y	Length	Error
0°	70.57	19.42	101.71	45.75	40.78	3.58
5°	68.84	19.65	100.22	46.49	41.29	4.88
20°	65.15	19.15	96.07	45.52	40.64	3.23
25°	63.13	19.10	92.68	45.76	39.80	1.10
30°	59.56	18.94	91.04	46.48	41.83	6.25
35°	57.83	19.28	88.67	46.04	40.83	3.71
40°	58.34	19.50	88.70	46.47	40.61	3.15
50°	52.41	19.45	83.41	47.61	41.88	6.38

Table 17. Two-Dimensional Camera Offset Linear Distances Based on the Y-Axis

Camera	Middle Point Location		End Point Location		Segment	% Length
Offset	X	Y	X	Y	Length	Error
0°	45.12	27.90	47.33	70.33	42.49	7.92
5°	45.94	28.00	50.95	69.93	42.23	7.26
20°	39.96	28.27	43.03	70.18	42.02	6.73
25°	37.04	27.71	36.79	68.23	40.52	2.92
30°	33.95	27.77	34.85	69.35	41.59	5.64
35°	30.44	27.98	29.81	68.73	40.75	3.51
40°	27.51	28.41	23.45	69.57	41.36	5.05
50°	24.32	27.98	21.74	69.73	41.83	6.25

3.3.2 Angular Velocity

The angular velocity results are summarized in Table 18. For the operator set 60 degree/second angular velocity tested in this evaluation, the data revealed peak errors ranging between 0.20% and 7.90%. The magnitude of the peak velocities, as well as the range average velocity, consistently decreased as the camera displacement increased. The peak values were also shown to be fairly consistent between the middle and end points. The range averages are close to the set values of the LIDO Multi-Joint II system and exhibit the same decease in magnitude as the camera offset was increased. Relatively low variations (maximum range 5.27°) were present in the constant angular velocity interval. The velocity curve graphs for the camera offset analysis are presented in Appendix D.

Table 18. Camera Offset Angular Velocities

	Middle Point Velocity				End Point Velocity			
Angular Velocity	Variation	Range Average	Peak Value	% Peak Error	Variation	Range Average	Peak Value	% Peak Error
0°	4.93	61.66	64.74	7.90	4.73	61.66	63.99	6.70
5°	2.25	62.22	63.50	5.80	2.20	61.96	62.96	4.90
20°	2.06	59.74	61.27	2.10	1.87	60.76	61.97	3.20
25°	3.50	59.70	62.39	4.00	3.70	59.98	61.93	3.20
30°	2.61	59.40	61.19	2.00	3.77	59.80	61.64	2.70
35°	3.47	59.43	61.05	1.70	4.54	60.01	62.00	3.30
40°	4.71	57.78	61.18	2.00	4.10	60.6	62.35	3.90
50°	5.27	56.92	58.84	5.50	3.15	58.61	60.06	.20

3.3.2 Angular Displacements

Angular displacement results collected in the camera offset testing at smoothing values of 1.0 and 0.1 are summarized in Table 19 and Table 20. The angular displacements tested in this evaluation at a smoothing value of 1.0 exhibited errors between 9.67% and 22.78%. The angular displacements are consistently lower than the 120° angular displacement that was set up through the LIDO Multi-Joint II software. The angular displacement errors exhibited while using a smoothing value of 0.1 were between 1.43% and 7.36%. Hence, the errors in angular displacement were smaller when using the smoothing value of 0.1.

Table 19. Two-Dimensional Camera Offset Angular Displacements Using Direct Linear Method (Smoothing Value 1.0)

Angular Velocity	Middle Point Angular Displacement	End Point Angular Displacement	% Error Middle	% Error End
0°	98.57	108.40	17.86	9.67
5°	98.33	107.34	18.06	10.55
20°	97.02	106.39	19.15	11.34
25°	95.99	105.60	20.01	12.00
30°	96.53	105.97	19.56	11.69
35°	95.58	105.37	20.35	12.19
40°	96.48	106.02	19.60	11.65
50°	92.66	103.10	22.78	14.08

Table 20. Two-Dimensional Camera Offset Angular Displacements Using Direct Linear Method (Smoothing Value 0.1)

Angular Velocity	Middle Point Angular Displacement	End Point Angular Displacement	% Error Middle	% Error End
0°	116.49	118.29	2.92	1.43
5°	116.88	117.60	2.60	2.00
20°	116.22	117.19	3.15	2.34
25°	114.13	116.19	4.89	3.18
30°	115.15	116.20	4.04	3.17
35°	114.92	115.66	4.23	3.62
40°	114.64	116.11	4.67	3.24
50°	111.17	113.00	7.36	5.83

3.4 Summary

3.4.1 Segment Length

A summary of the segment length results found in two-dimensional and three-dimensional analyses is presented in Table 21. The results using the direct linear method software indicate that the worst error exhibited in two-dimensional analysis was 8.74% while the worst error shown through three-dimensional analysis was 2.67%.

The two-dimensional Multiplier method displayed errors only slightly larger than the two-dimensional Direct Linear method when taken with respect to the X-axis, but exhibited large errors with respect to the Y-axis. The Multiplier method had a maximum segment length error of 36.22% with respect to the Y-axis.

Table 21. Segment Length Error Summary

	Segment Length % Error X-Axis			Segment Length % Error Y-Axis		
Angular Velocity	2D Direct Linear	2D Multiplier	3D Direct Linear	2D Direct Linear	2D Multiplier	3D Direct Linear
30	2.13	2.31	2.67	4.45	35.38	1.27
60	7.92	8.61	2.16	3.87	34.77	.33
90	7.06	8.36	2.62	8.74	35.08	.48
120	6.63	4.45	1.63	7.65	36.22	.53

3.4.2 Angular Velocity Errors Summary

Angular velocity results from the two-dimensional and three-dimensional analyses are presented in Table 22 and Table 23. The peak angular velocity results using the direct linear method software indicate that the worst error exhibited in two-dimensional analysis was 11.80% and the worst error shown through three-dimensional analysis was 5.90%. The variation of the data was also much higher in the two-dimensional analysis as compared to the three-dimensional analysis.

The two-dimensional Multiplier method displayed peak angular velocity errors significantly higher than those observed in either condition using the Direct Linear method software. The Multiplier method had a maximum error of 38.90% and exhibited approximately two to five times greater variation than that observed using the Direct Linear method software.

Table 22. Peak Angular Velocity Percent Error Summary

	Middle Point Velocity Percentage Peak Error			End Point Velocity Percentage Peak Error		
Angular Velocity	2D Direct Linear	2D Multiplier	3D Di[illegible] Linear	2D Direct Linear	2D Multiplier	3D Direct Linear
30	9.20	31.80	4.00	10.30	38.90	5.90
60	11.80	27.90	2.90	11.70	35.37	.73
90	8.70	23.68	.85	7.30	25.86	3.10
120	7.60	18.71	1.60	6.90	21.60	2.40

Table 23. Variation Summary

	Middle Point Velocity Variation			End Point Velocity Variation		
Angular Velocity	2D Direct Linear	2D Multiplier	3D Direct Linear	2D Direct Linear	2D Multiplier	3D Direct Linear
30	4.45	19.89	2.53	3.93	20.38	2.95
60	13.25	38.56	4.63	10.26	39.15	2.43
90	20.55	52.03	1.70	12.12	48.92	3.42
120	23.34	62.21	2.82	15.97	60.00	4.57

3.4.2 Angular Velocity Errors Summary

Results from the angular displacement analyses of both two-dimensional and three-dimensional data are presented in Table 24 and Table 25. The maximum percent error in angular displacement using the Direct Linear method was and Multiplier method software packages with a smoothing value of 1.0 was 9.82% while the results using a smoothing value of 0.1 displayed a maximum percent error of 4.34%. In addition, the angular displacement error values observed in most conditions when using a smoothing value of 0.1 were substantially lower than those observed when using a smoothing value of 1.0. Hence, a smoothing value of 1.0 appears to be to high for the analysis of the angular displacement data. It should be noted that both extremes of the range of motion in the analysis using the Multiplier method software are only 10 degrees beyond being parallel to the X-axis.

Table 24. Angular Displacement Summary (Smoothing Value 1.0)

	Middle Point Angular Displacement			End Point Angular Displacement		
Angular Velocity	2D Direct Linear	2D Multiplier	3D Direct Linear	2D Direct Linear	2D Multiplier	3D Direct Linear
30	4.22	8.51	9.82	1.90	3.40	7.13
60	9.74	6.50	9.73	5.12	1.61	6.42
90	6.78	4.26	7.36	3.00	.30	4.08
120	4.31	1.63	3.32	1.35	1.89	1.96

Table 25. Angular Displacement Summary (Smoothing Value 0.1)

	Middle Point Angular Displacement			End Point Angular Displacement		
Angular Velocity	2D Direct Linear	2D Multiplier	3D Direct Linear	2D Direct Linear	2D Multiplier	3D Direct Linear
30	.49	1.82	2.69	.86	3.02	3.00
60	.76	2.96	2.20	.12	4.03	2.93
90	1.94	3.63	2.47	1.43	4.34	2.64
120	1.06	3.83	.87	.84	4.21	2.18

4.0 CONCLUSIONS

This series of evaluations performed to gain quantitative data pertaining to position and constant angular velocity movements under several operating conditions. Two-dimensional as well as three-dimensional data collection and analyses were completed in a controlled laboratory environment using typical hardware setups. These evaluations addressing several methodology issues concerning the accuracy of the kinematic data collection and analysis performed in the ABL indicate that three-dimensional data collection achieves greater accuracy that two-dimensional data collection. Results also indicate that the multiplier method software performs adequately along the axis of the calibration points but should not be used for two-dimensional analysis.

Segment length, positional data, exhibited errors within 3% when using three-dimensional analysis and yielded errors within 8% through two-dimensional analysis (Direct Linear Software).

Peak angular velocities displayed errors within 6% through three-dimensional analyses and exhibited errors of 12% when using two-dimensional analysis (Direct Linear Software).

In addition, an evaluation was performed to evaluate the accuracy impact due to a single axis camera offset. The analyses revealed that the offset of the camera in only one axis did cause a shift in the position of the motion with respect to the reference frame but did drastically alter the linear distances of the torque arm segment even with the 50° camera offset. A slight reduction in the peak angular velocities was observed as the camera offsets were increased. Additional evaluations should be performed to evaluate camera offsets in one axis in greater detail as well as two axes camera offsets.

APPENDIX A

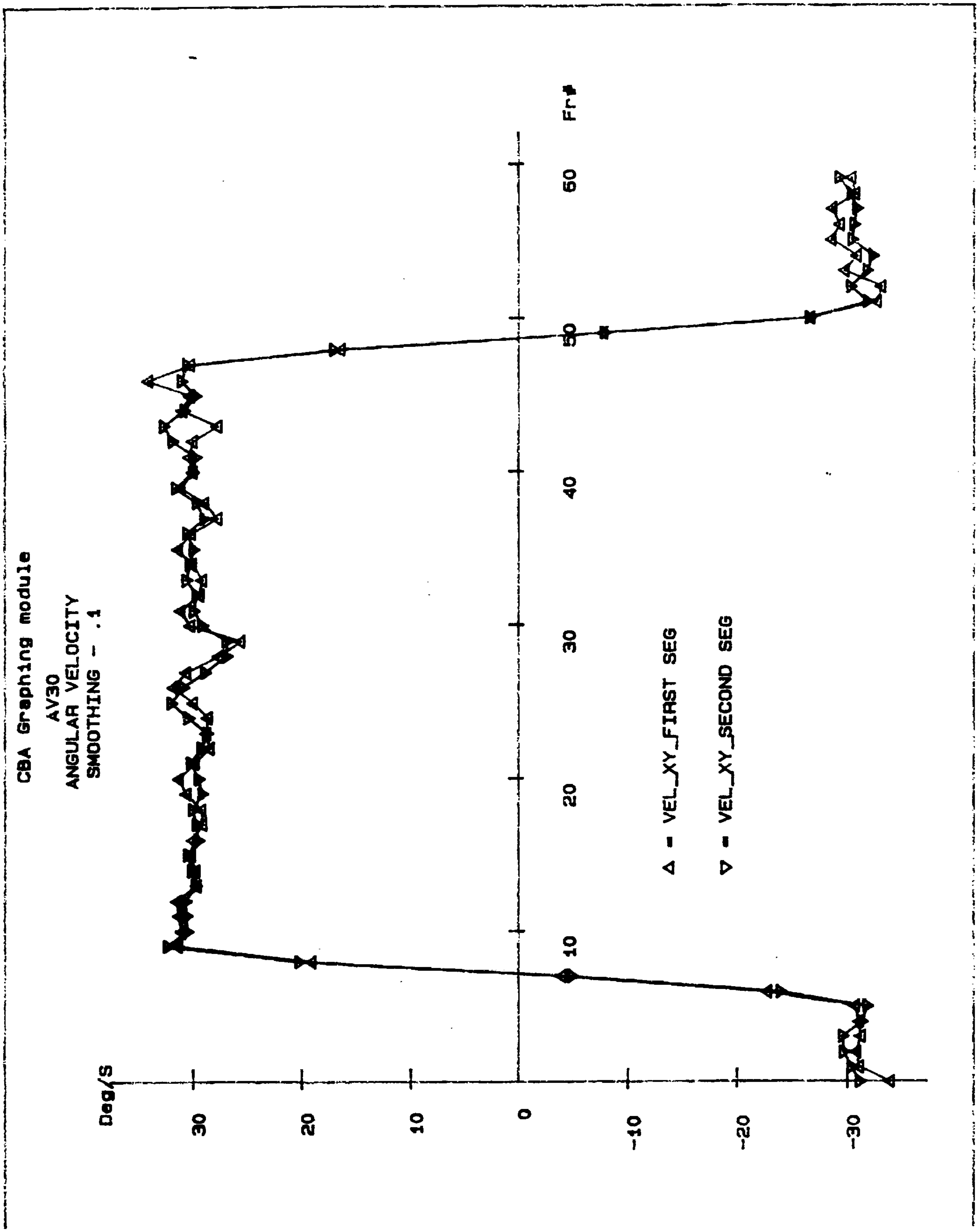

Figure A-1. Two-Dimensional Angular Velocity 30 Degrees/Second - Direct Linear Software Method (Smoothing 0.1)

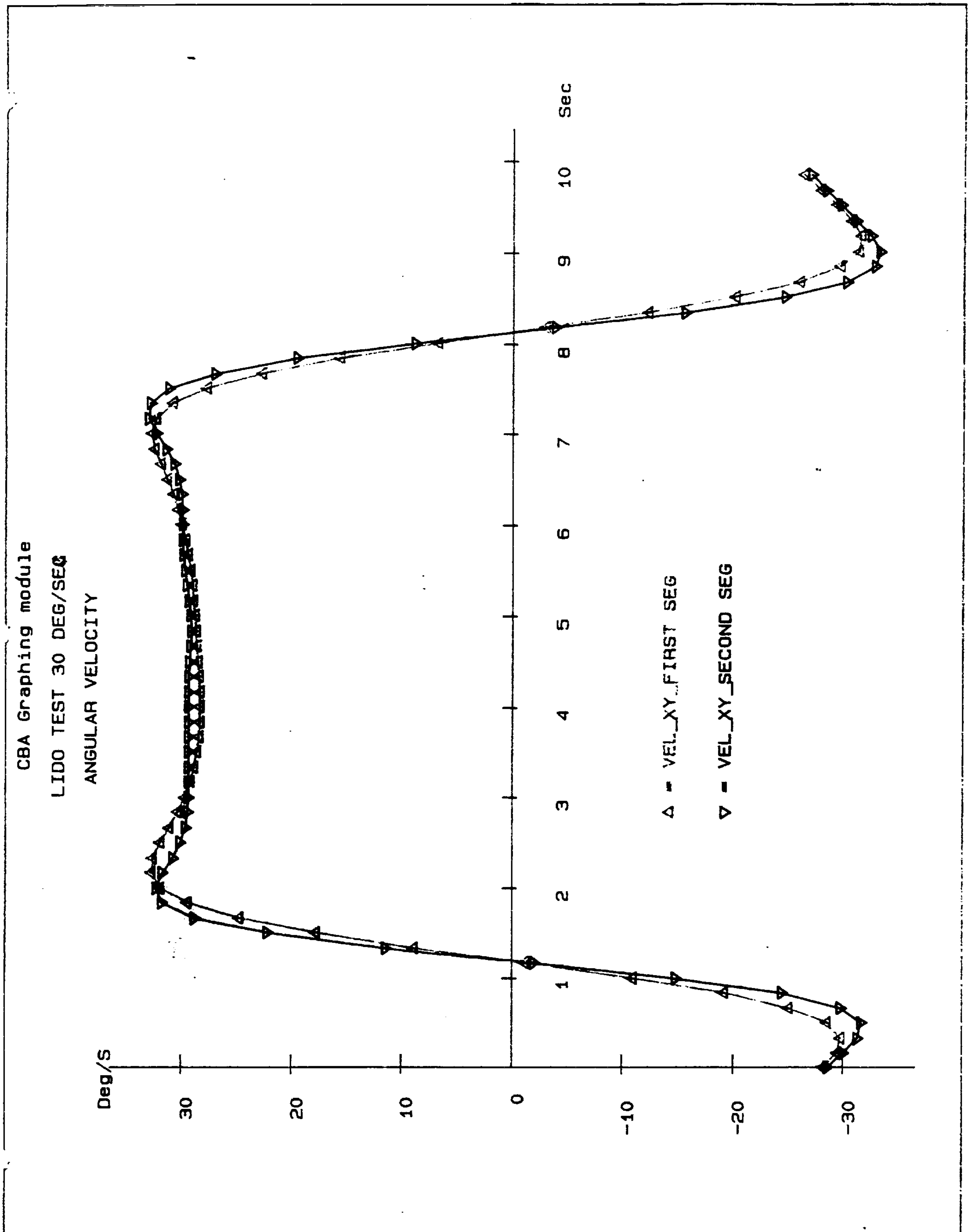

Figure A-2. Two-Dimensional Angular Velocity 30 Degrees/Second - Direct Linear Software Method

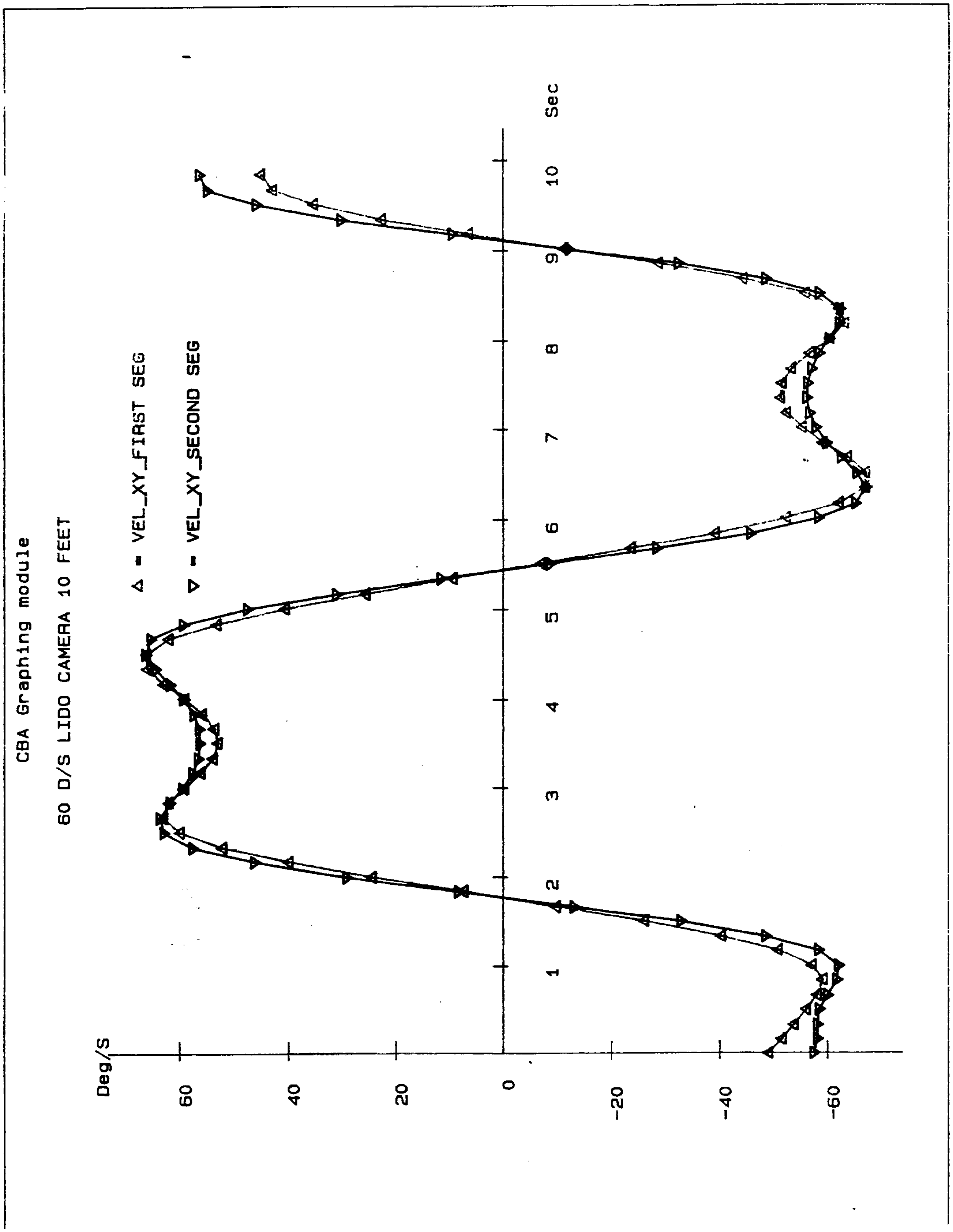

Figure A-3. Two-Dimensional Angular Velocity 60 Degrees/Second - Direct Linear Software Method

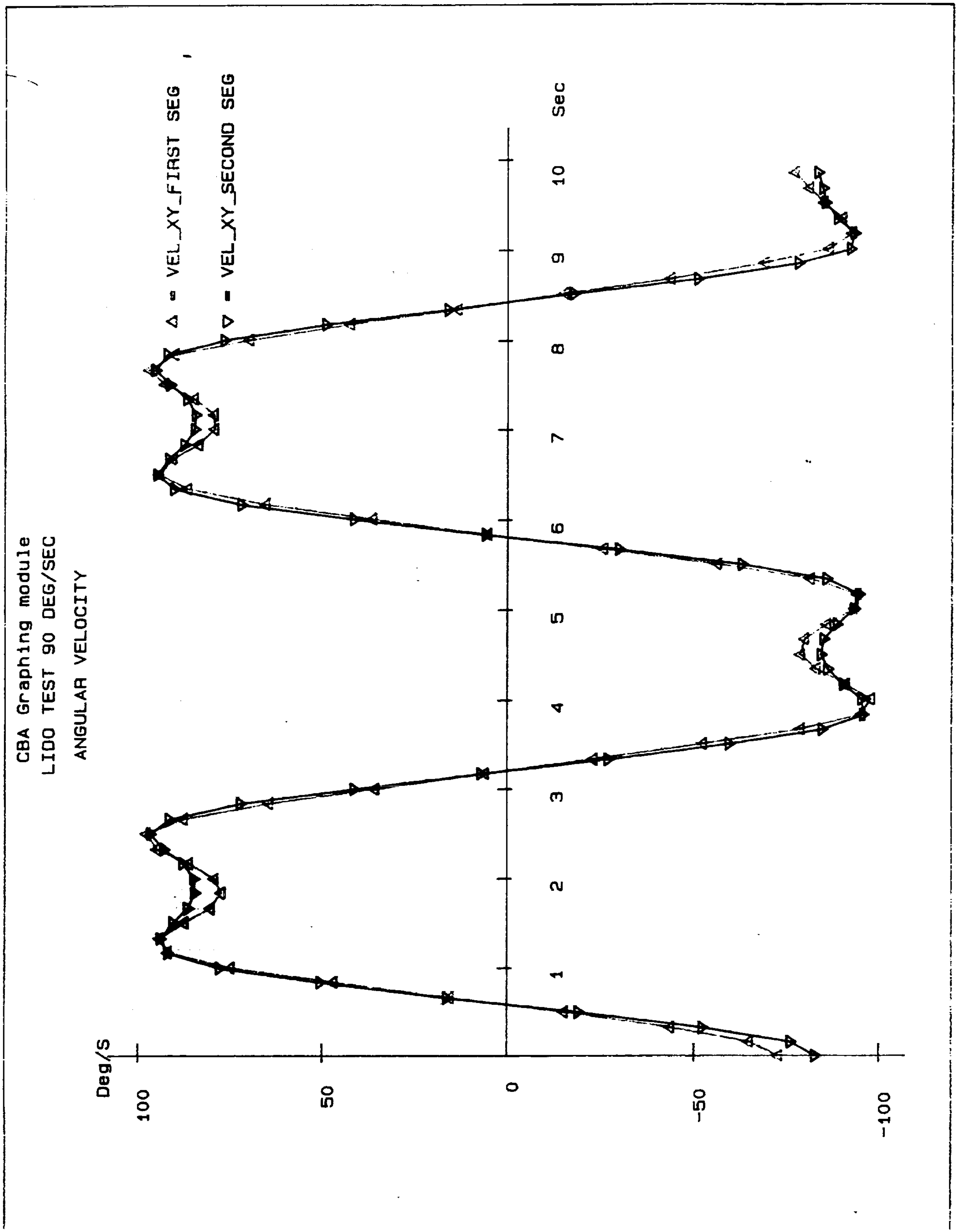

Figure A-4. Two-Dimensional Angular Velocity 90 Degrees/Second - Direct Linear Software Method

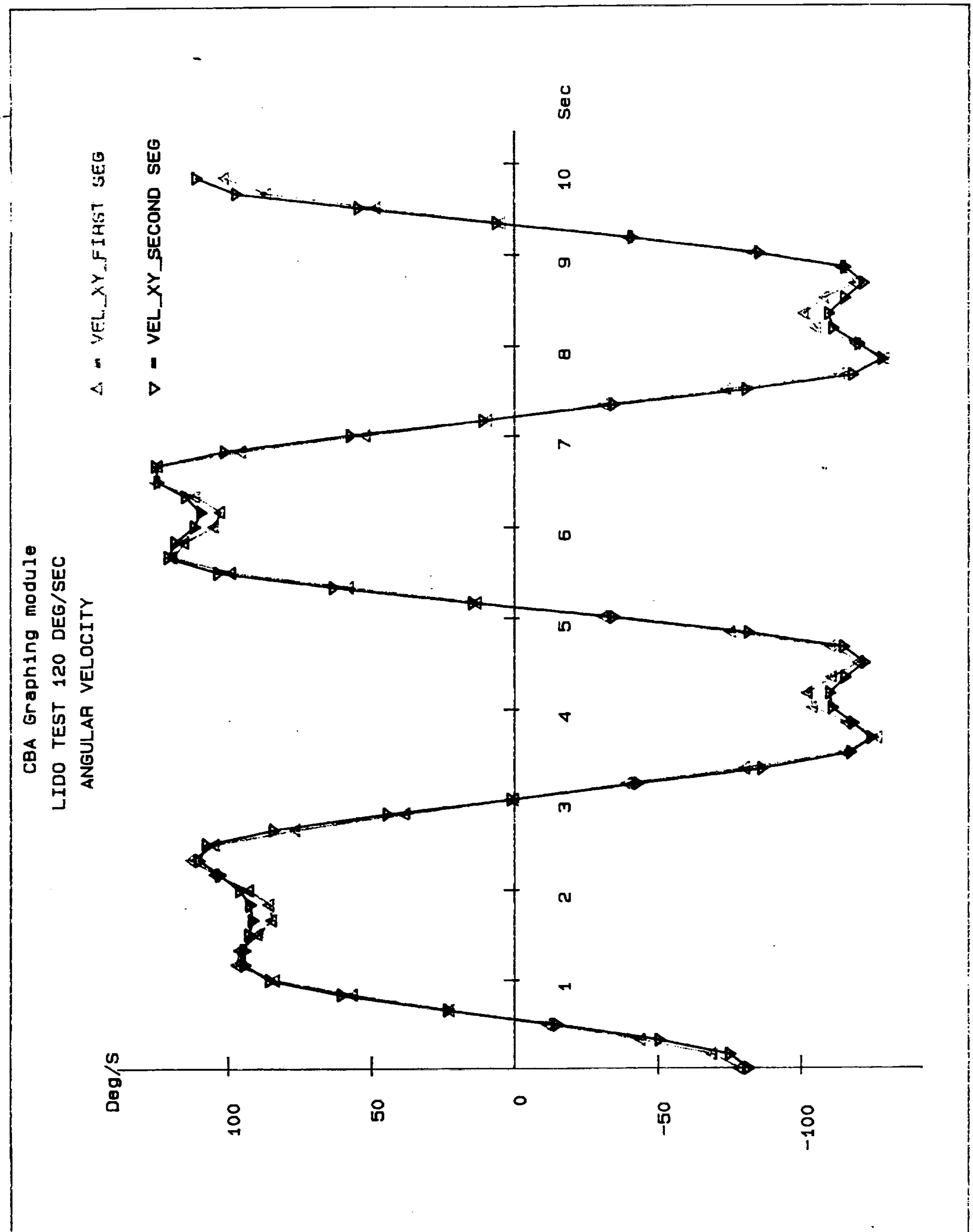

Figure A-5. Two-Dimensional Angular Velocity 120 Degrees/Second - Direct Linear Software Method

APPENDIX B

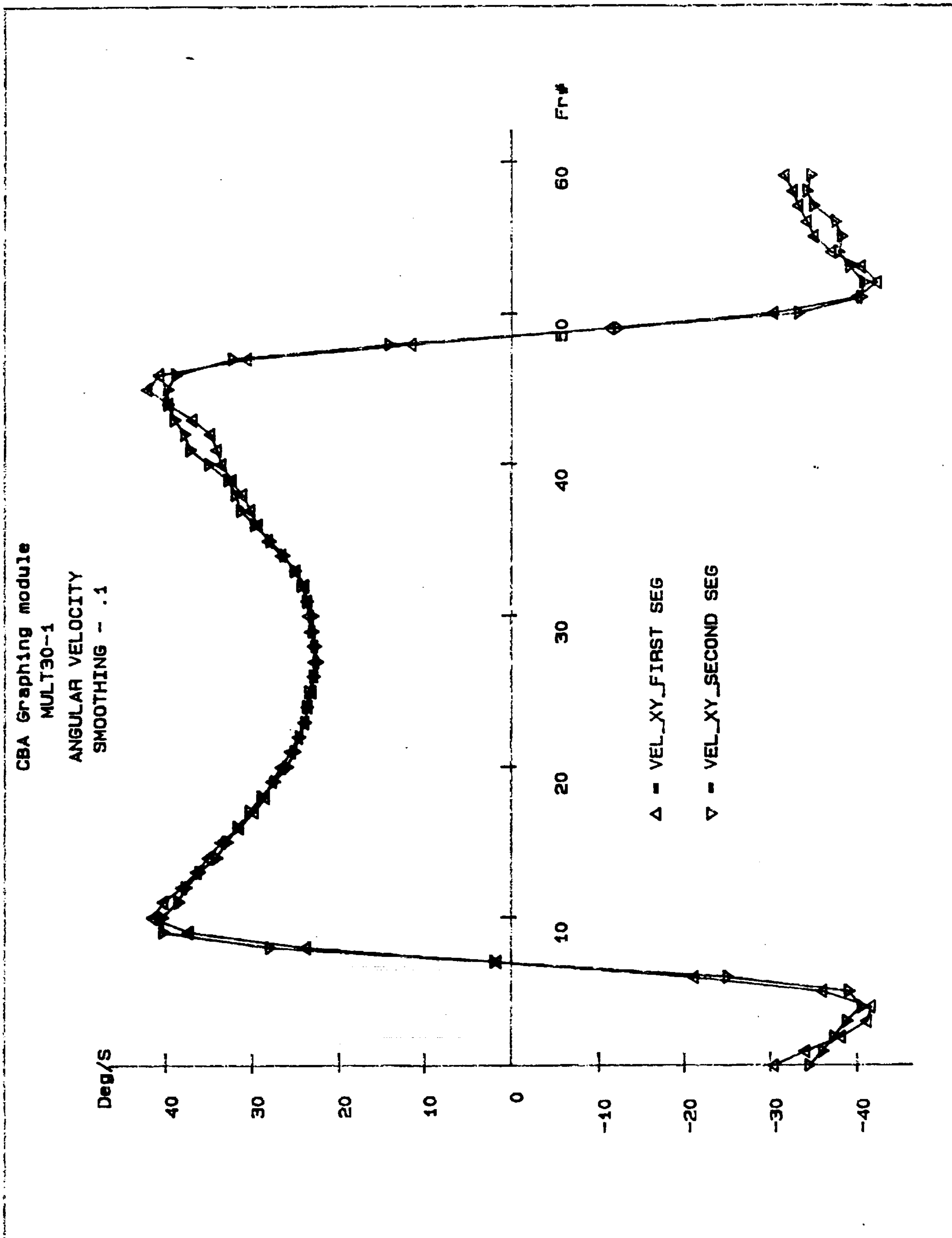

Figure B-1. Two-Dimensional Angular Velocity 30 Degrees/Second - Multiplier Software Method (Smoothing 0.1)

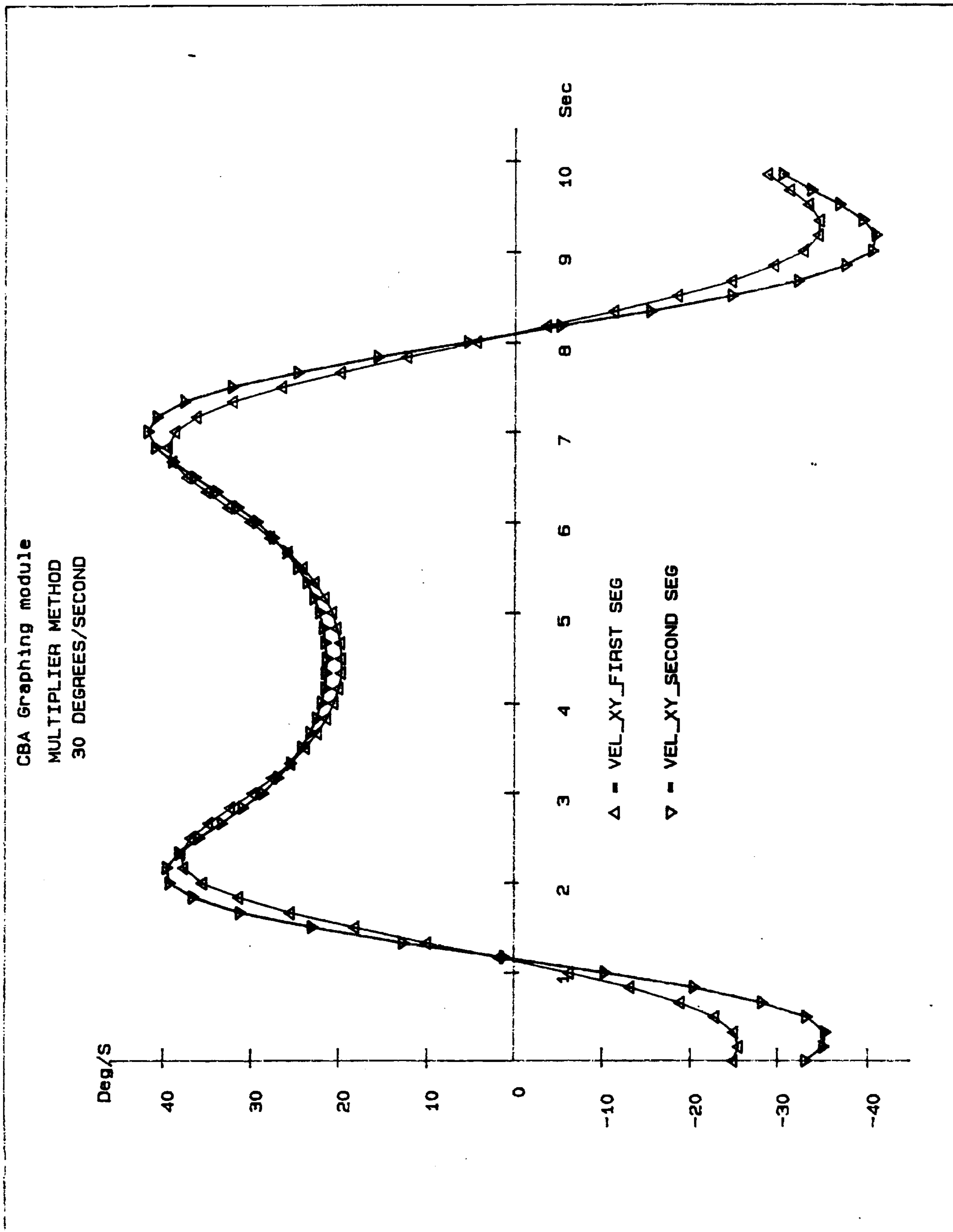

Figure B-2. Two-Dimensional Angular Velocity 30 Degrees/Second - Multiplier Software Method

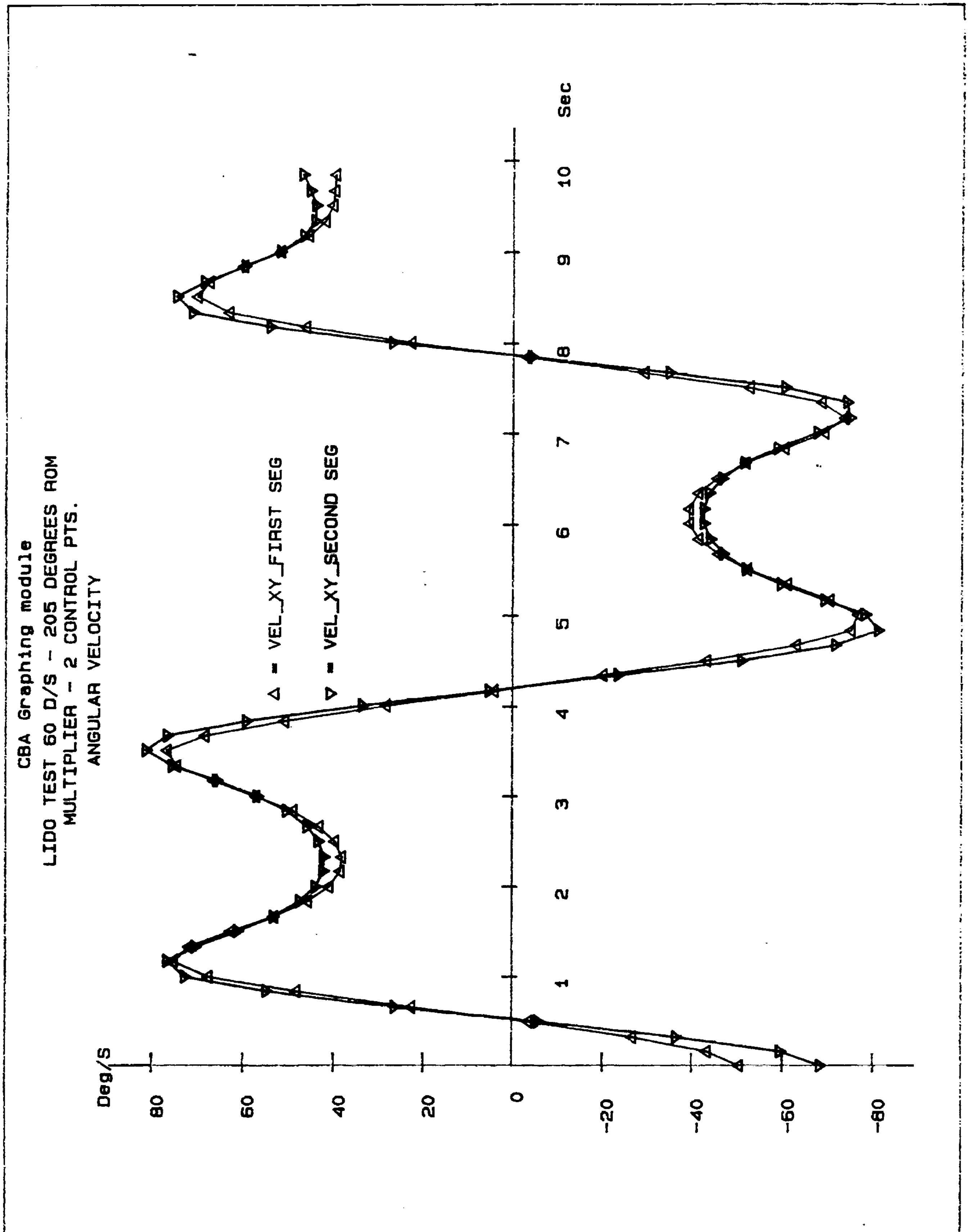

Figure B-3. Two-Dimensional Angular Velocity 60 Degrees/Second - Multiplier Software Method

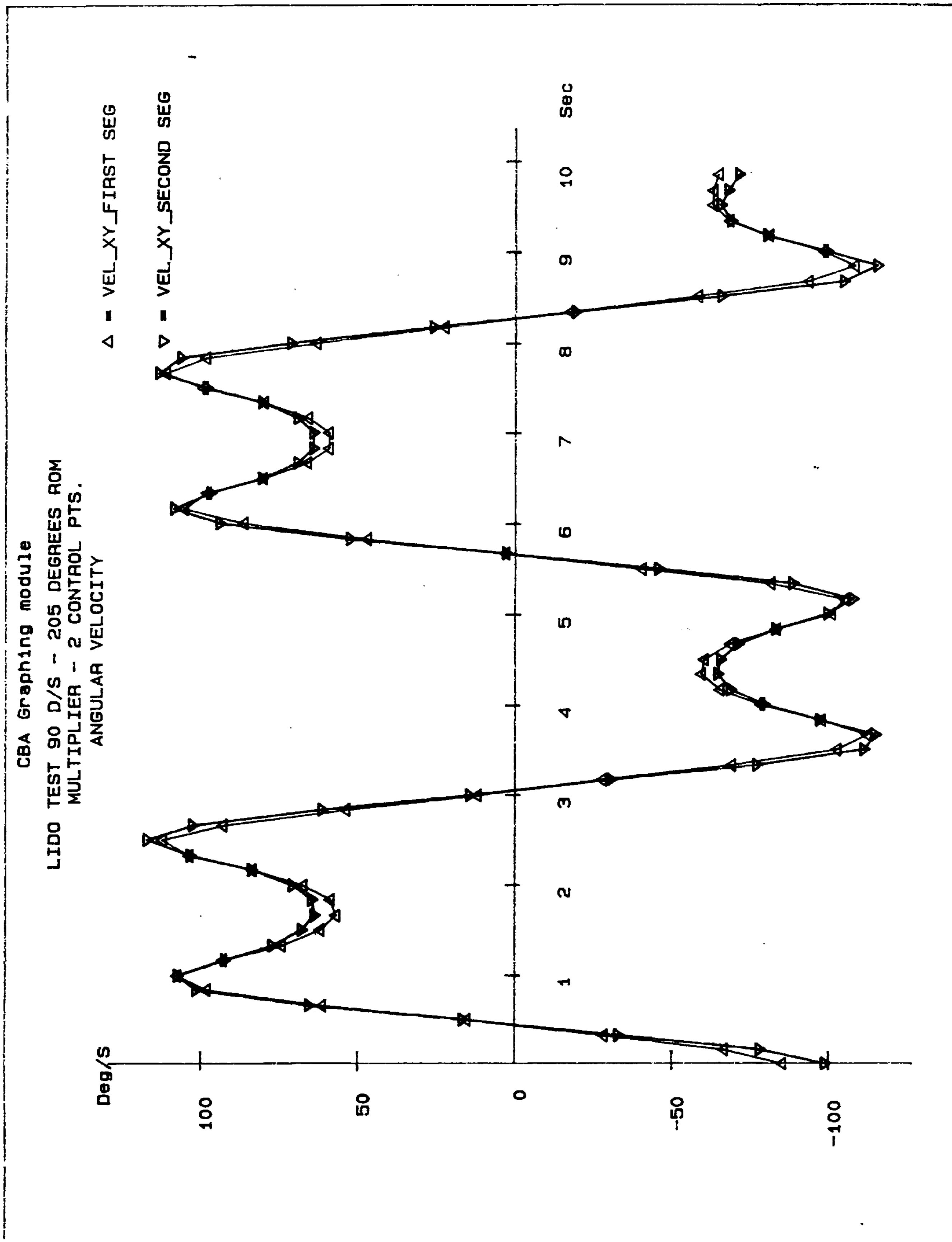

Figure B-4. Two-Dimensional Angular Velocity 90 Degrees/Second - Multiplier Software Method

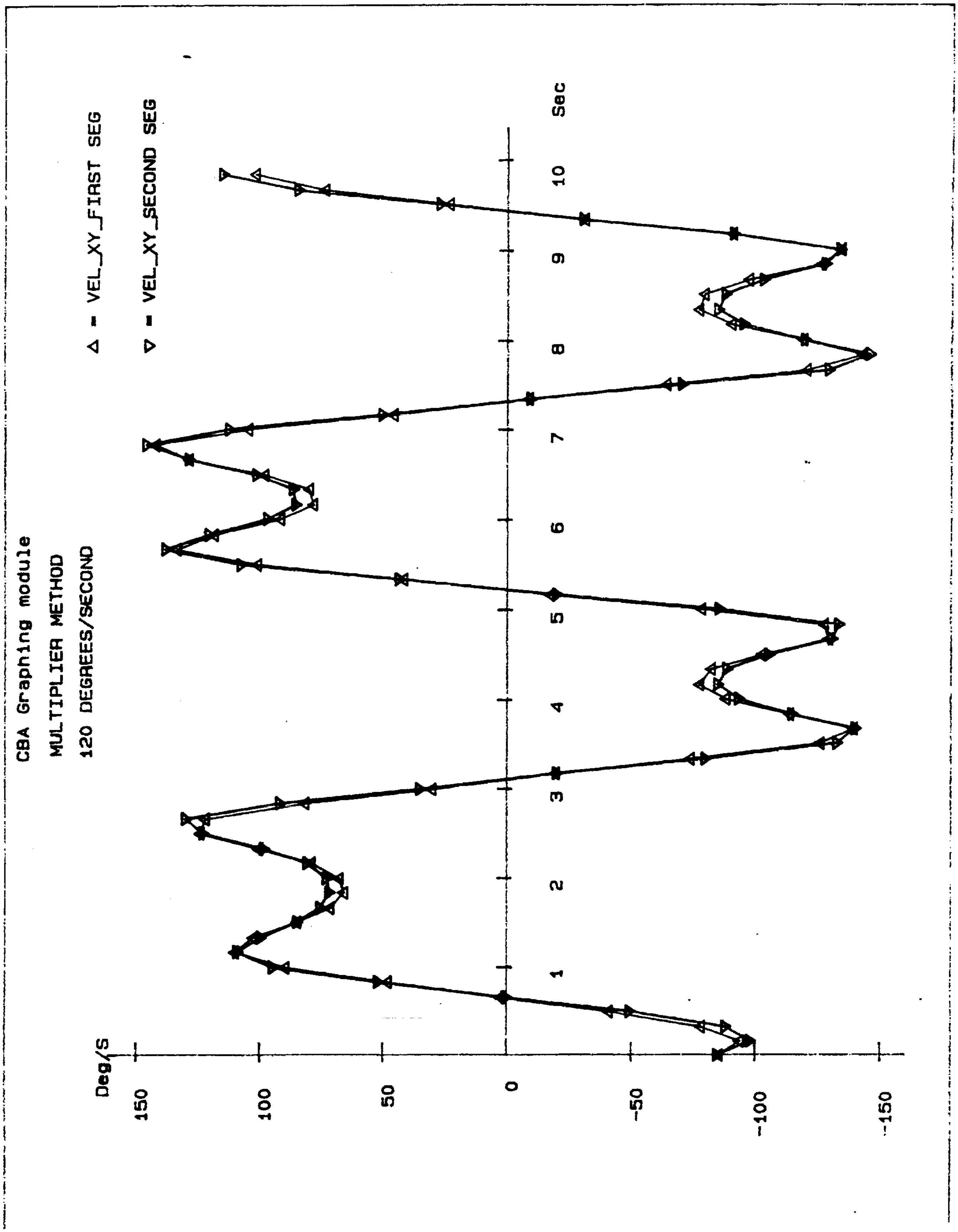

Figure B-5. Two-Dimensional Angular Velocity 120 Degrees/Second - Multiplier Software Method

APPENDIX C

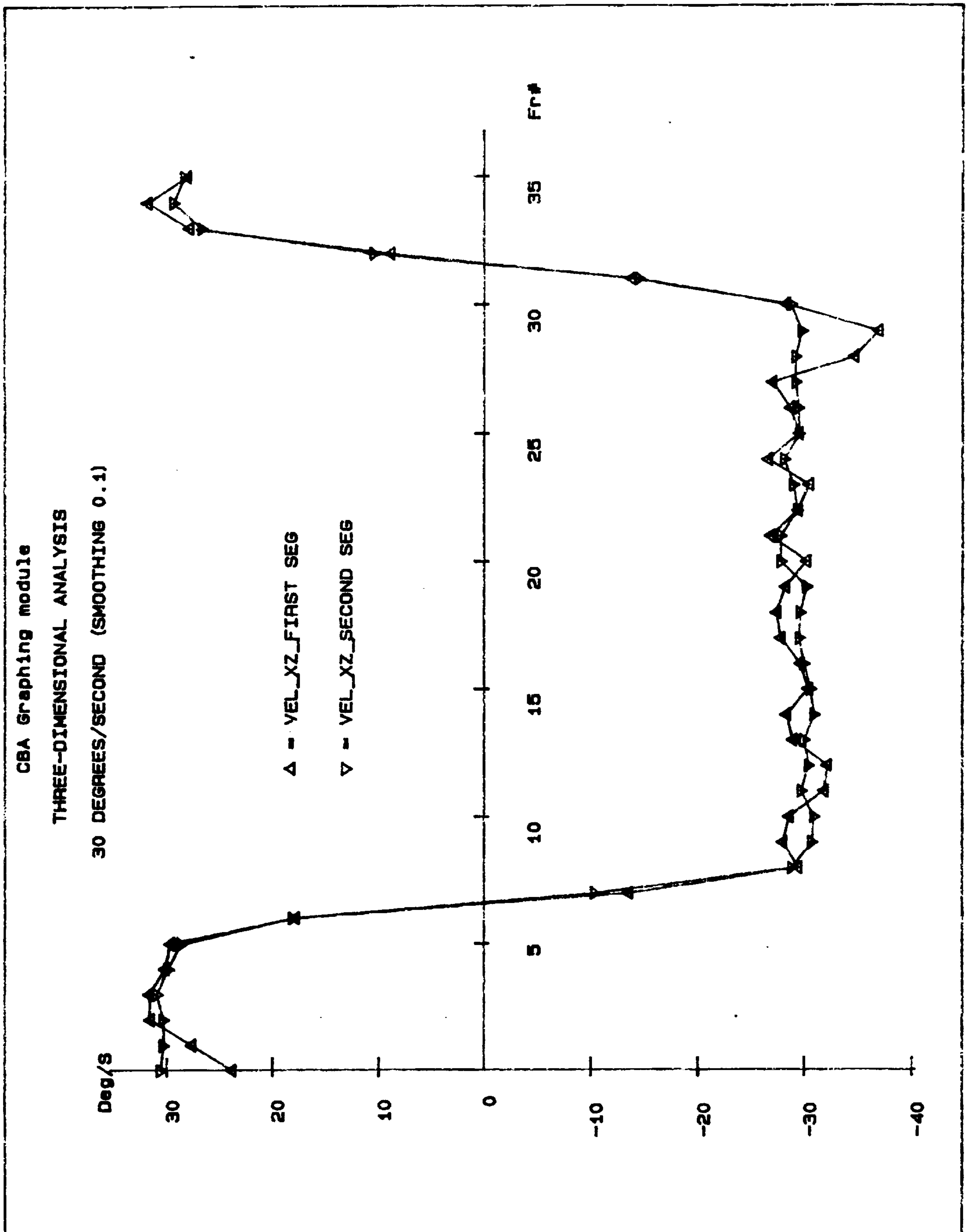

Figure C-1. Three-Dimensional Angular Velocity 30 Degrees/Second (Smoothing 0.1)

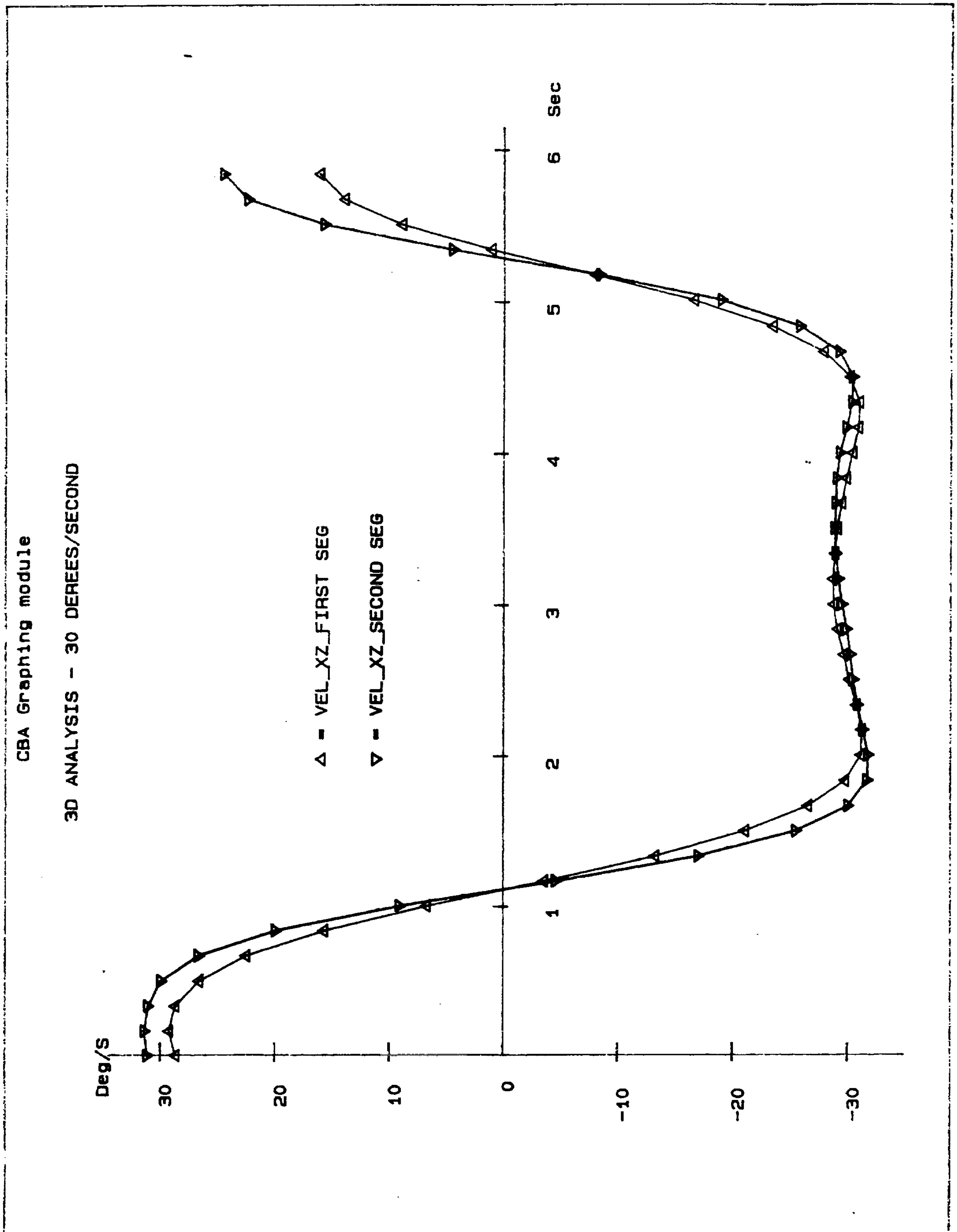

Figure C-2. Three-Dimensional Angular Velocity 30 Degrees/Second

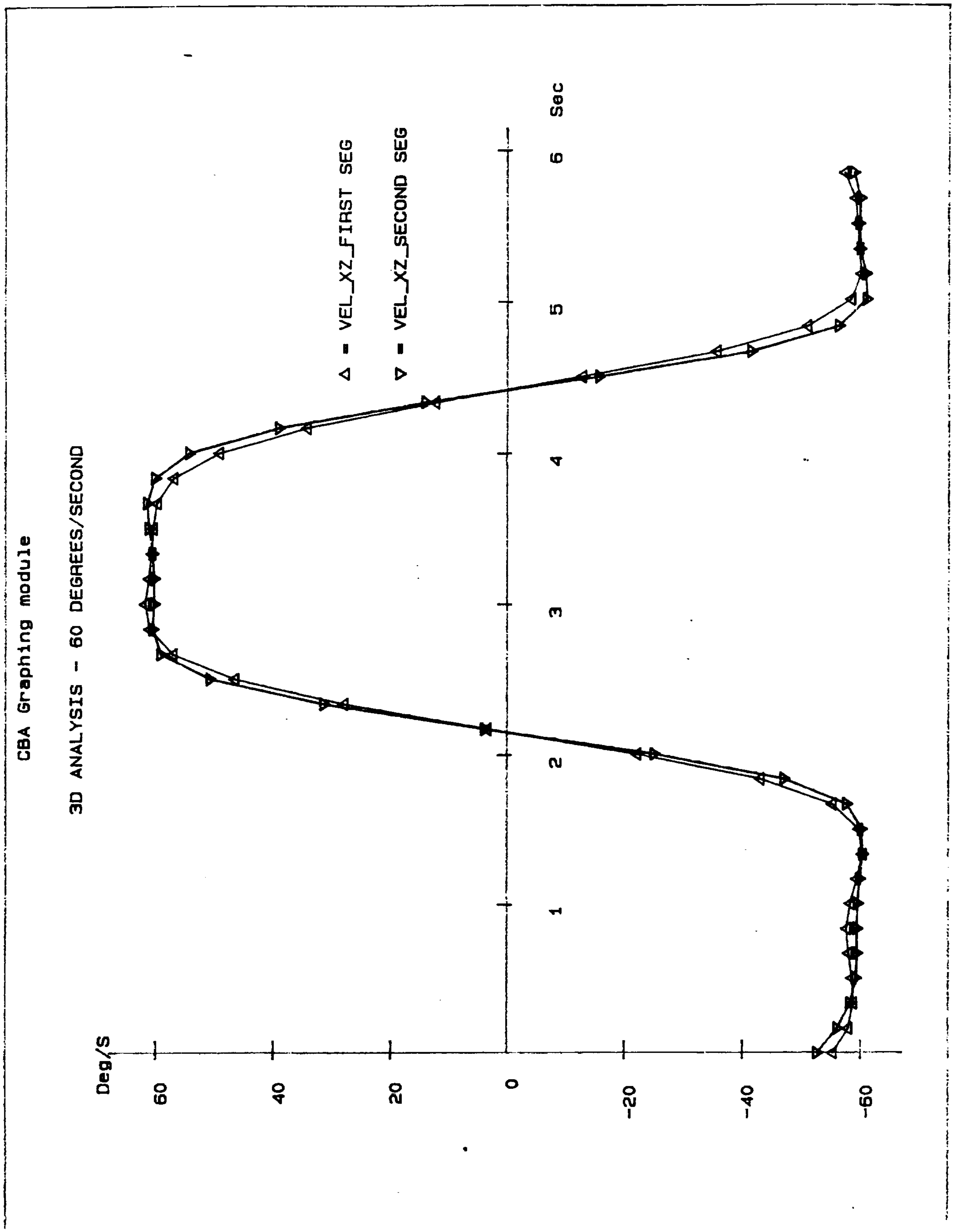

Figure C-3. Three-Dimensional Angular Velocity 60 Degrees/Second

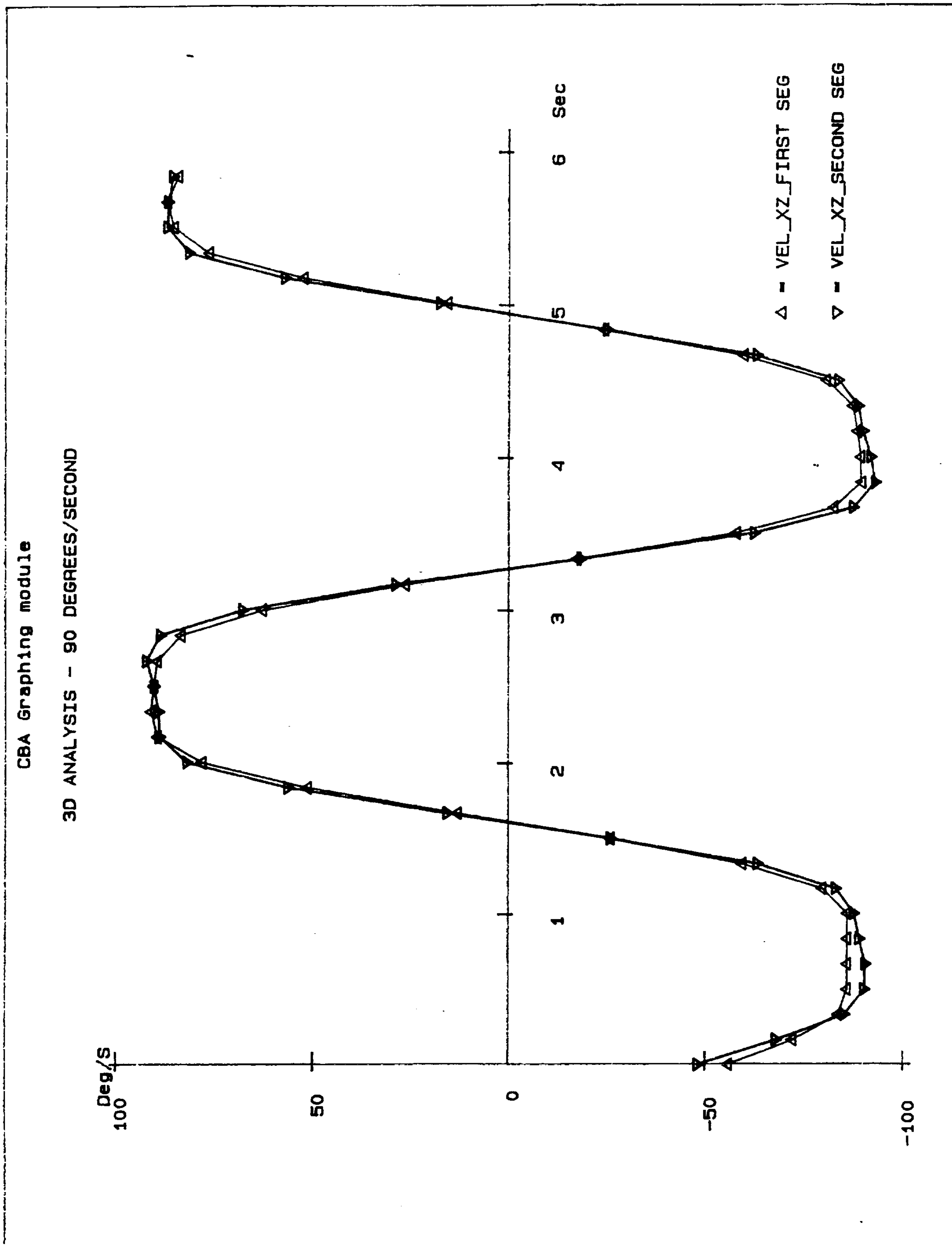

Figure C-4. Three-Dimensional Angular Velocity 90 Degrees/Second

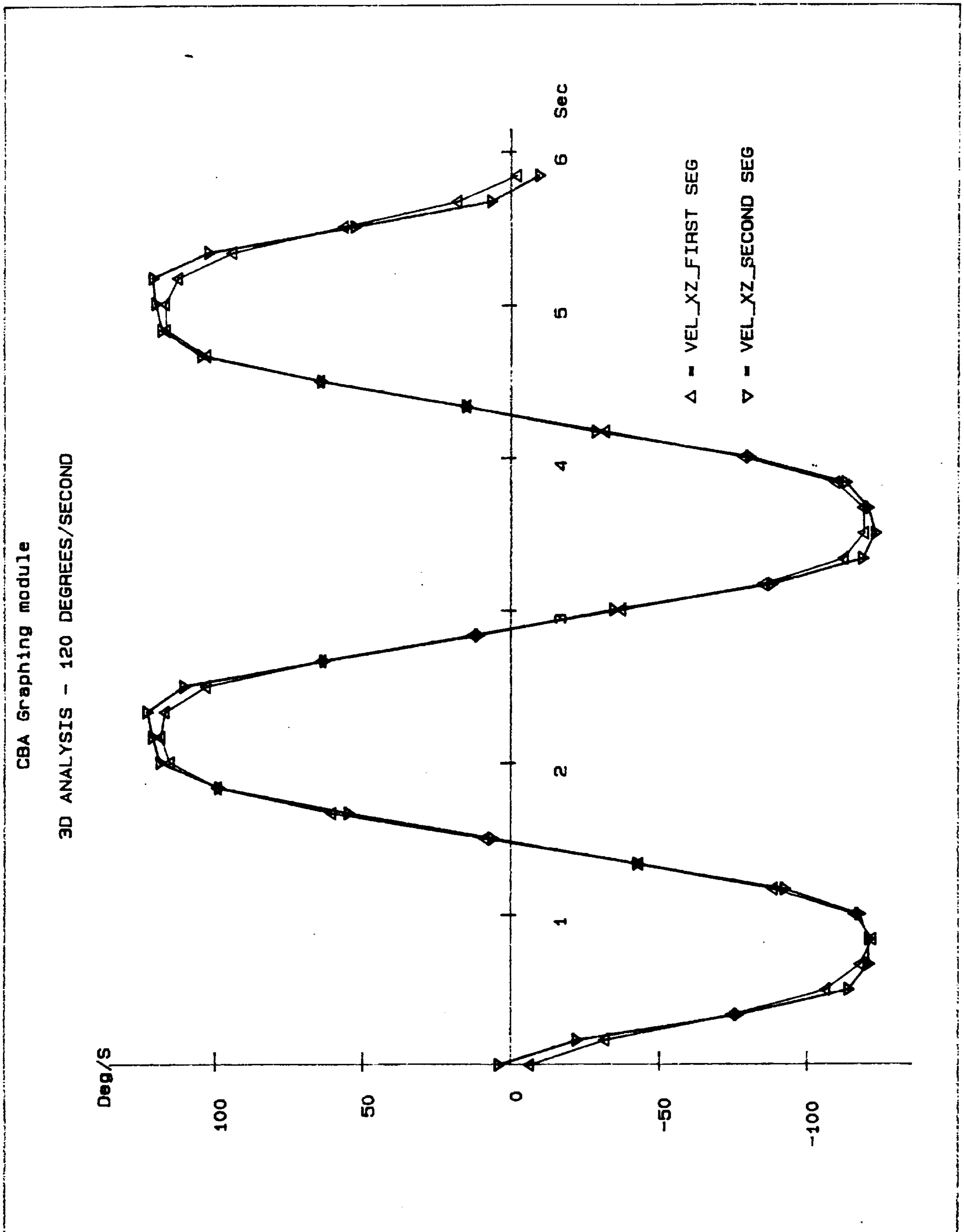

Figure C-5. Three-Dimensional Angular Velocity 120 Degrees/Second

APPENDIX D

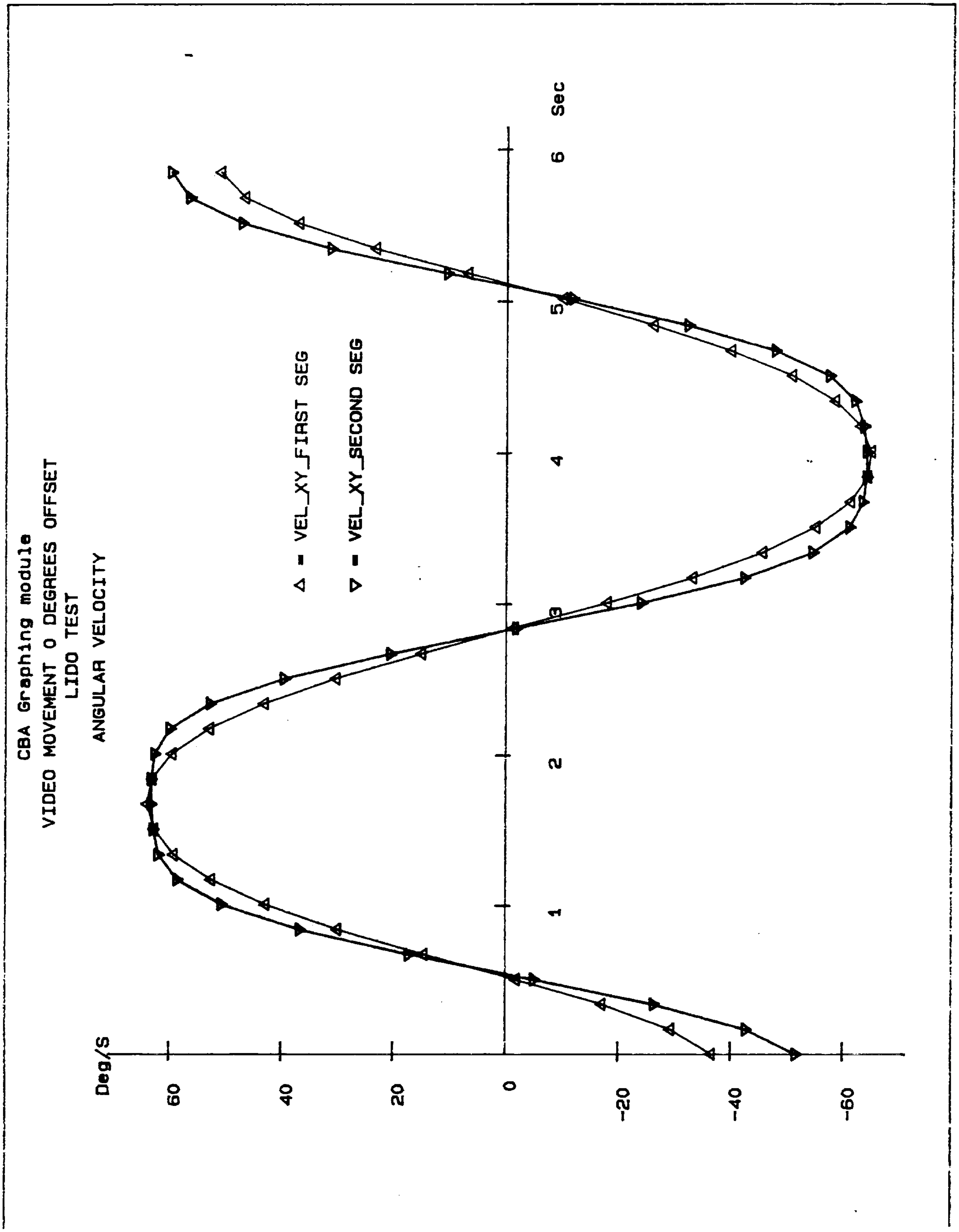

Figure D-1. Two-Dimensional Angular Velocity 60 Degrees/Second - Camera Offset 0°

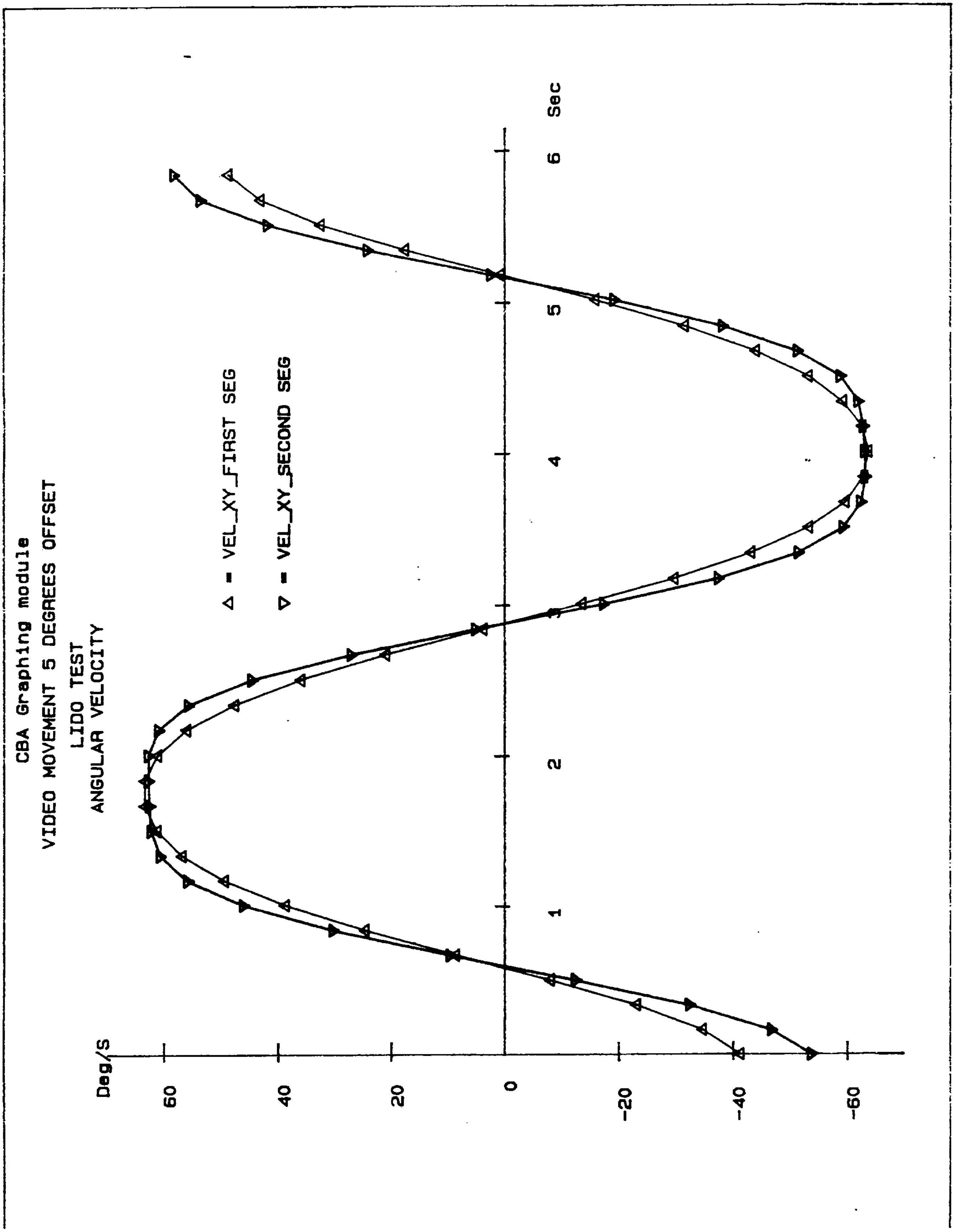

Figure D-2. Two-Dimensional Angular Velocity 60 Degrees/Second - Camera Offset 5°

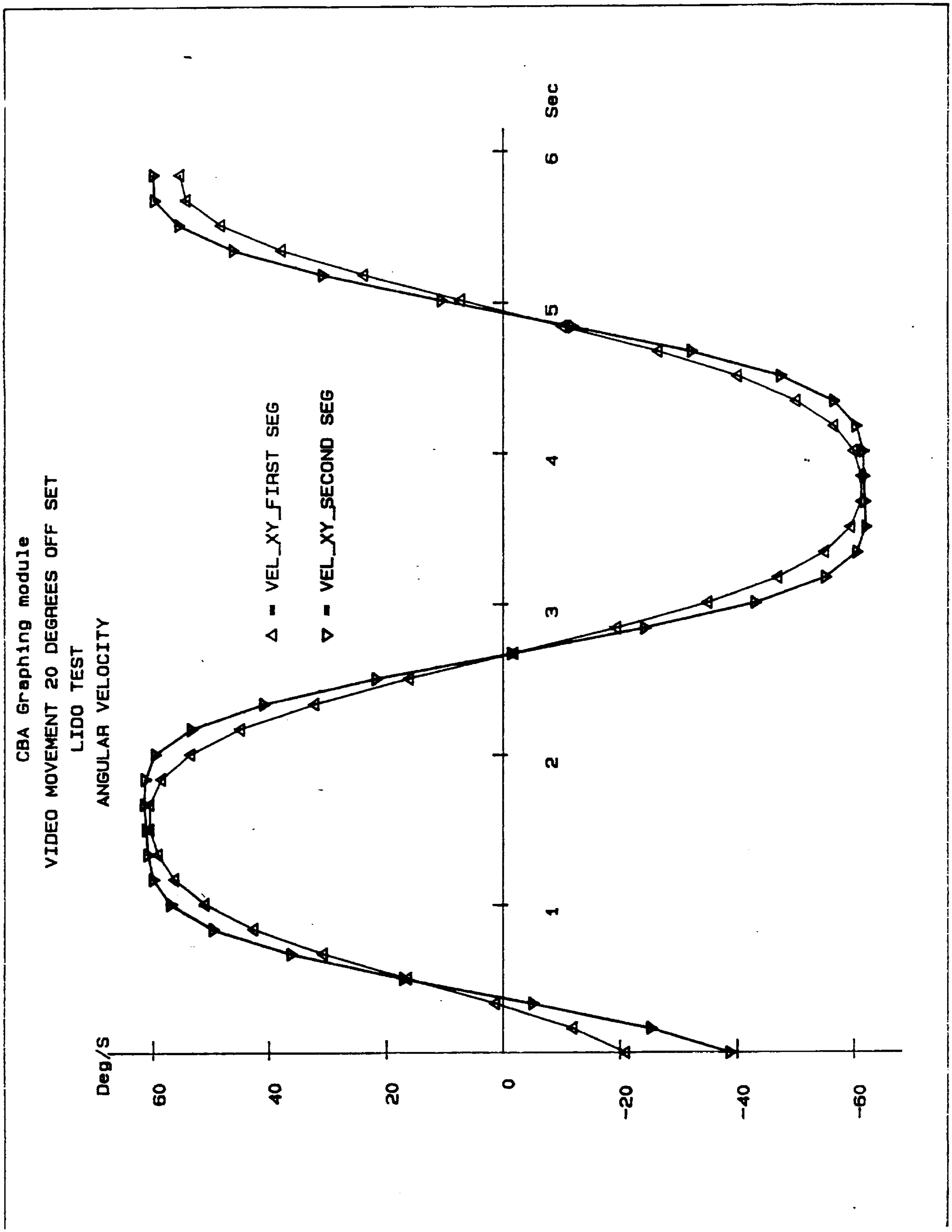

Figure D-3. Two-Dimensional Angular Velocity 60 Degrees/Second - Camera Offset 20°

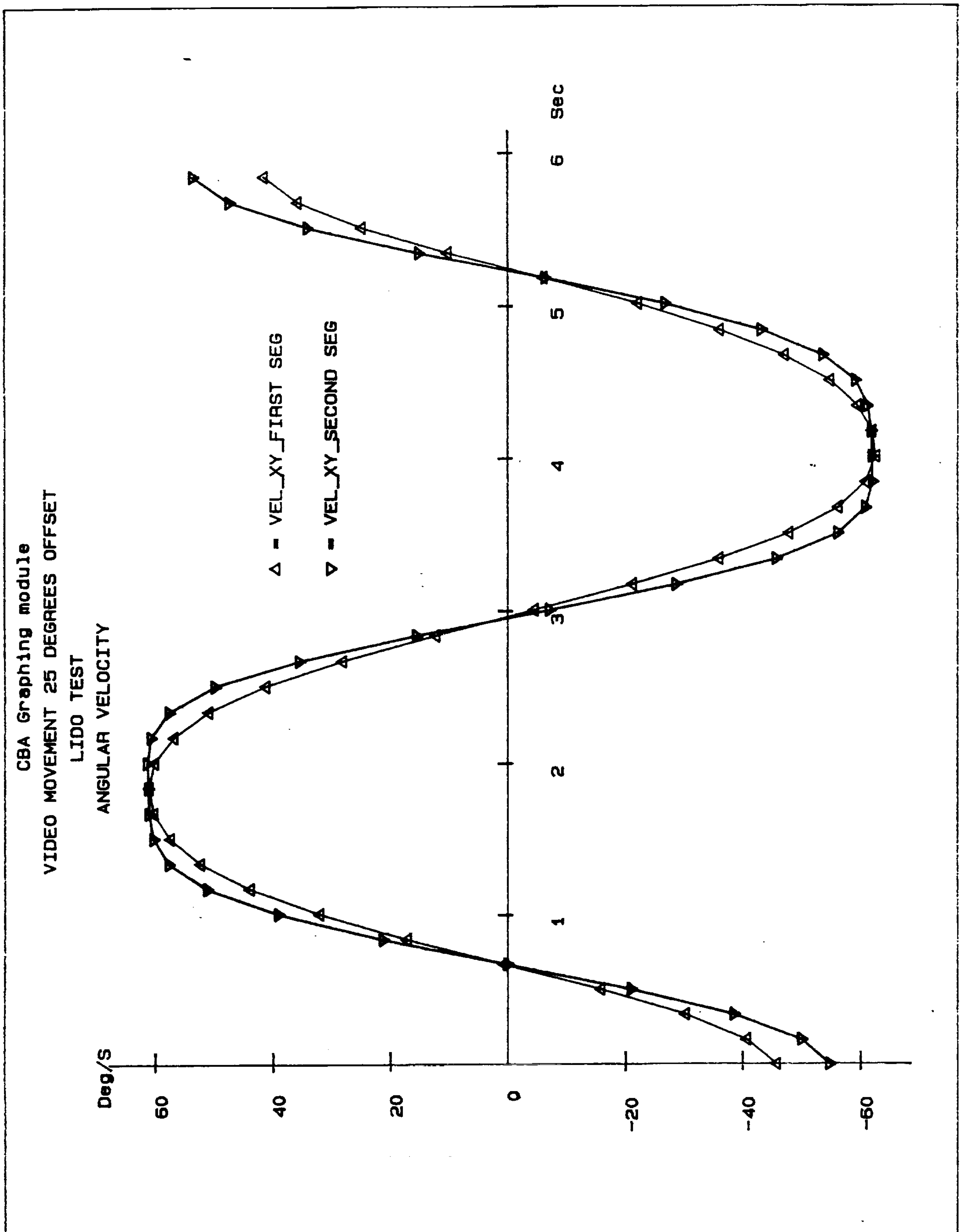

Figure D-4. Two-Dimensional Angular Velocity 60 Degrees/Second - Camera Offset 25°

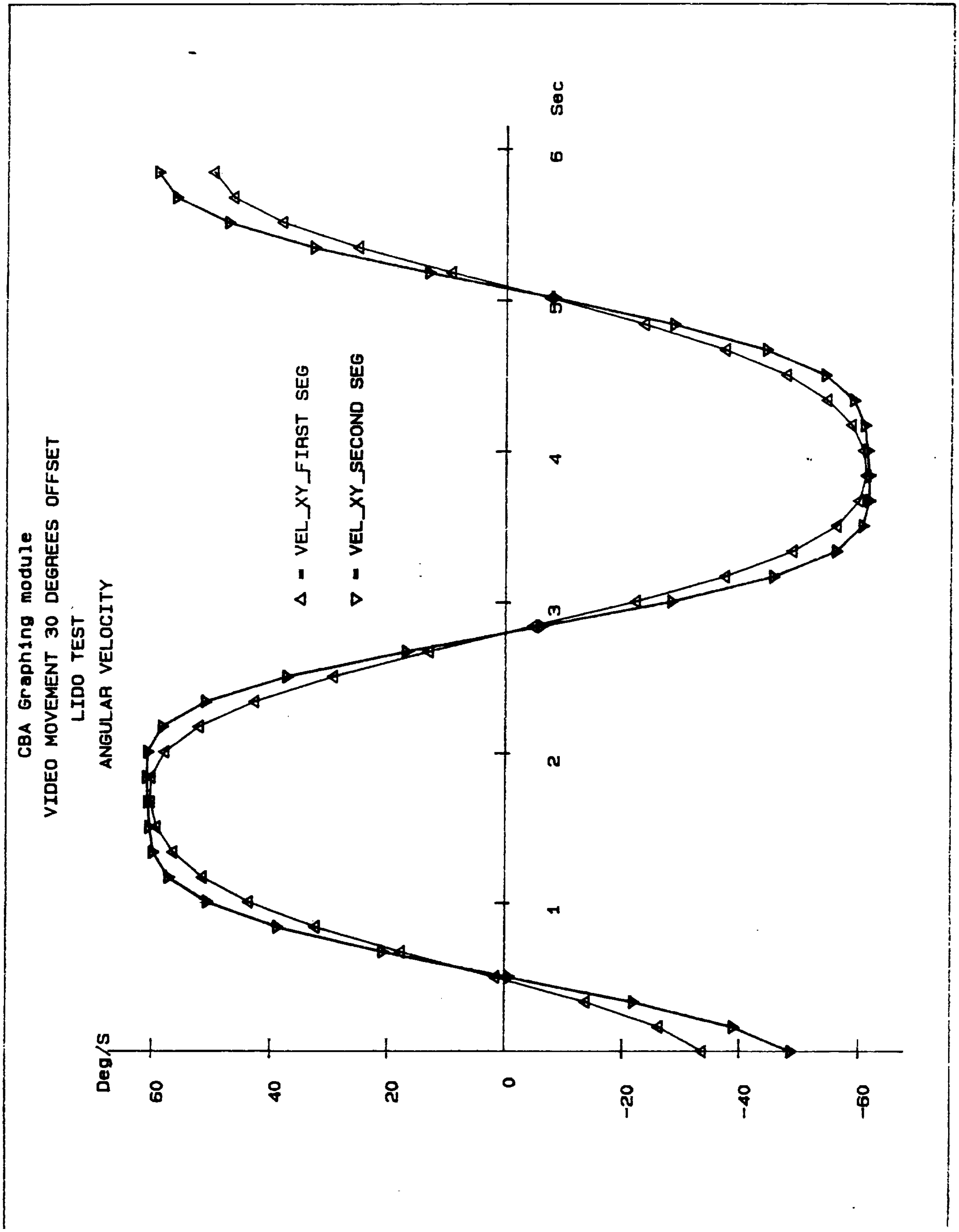

Figure D-5. Two-Dimensional Angular Velocity 60 Degrees/Second - Camera Offset 30°

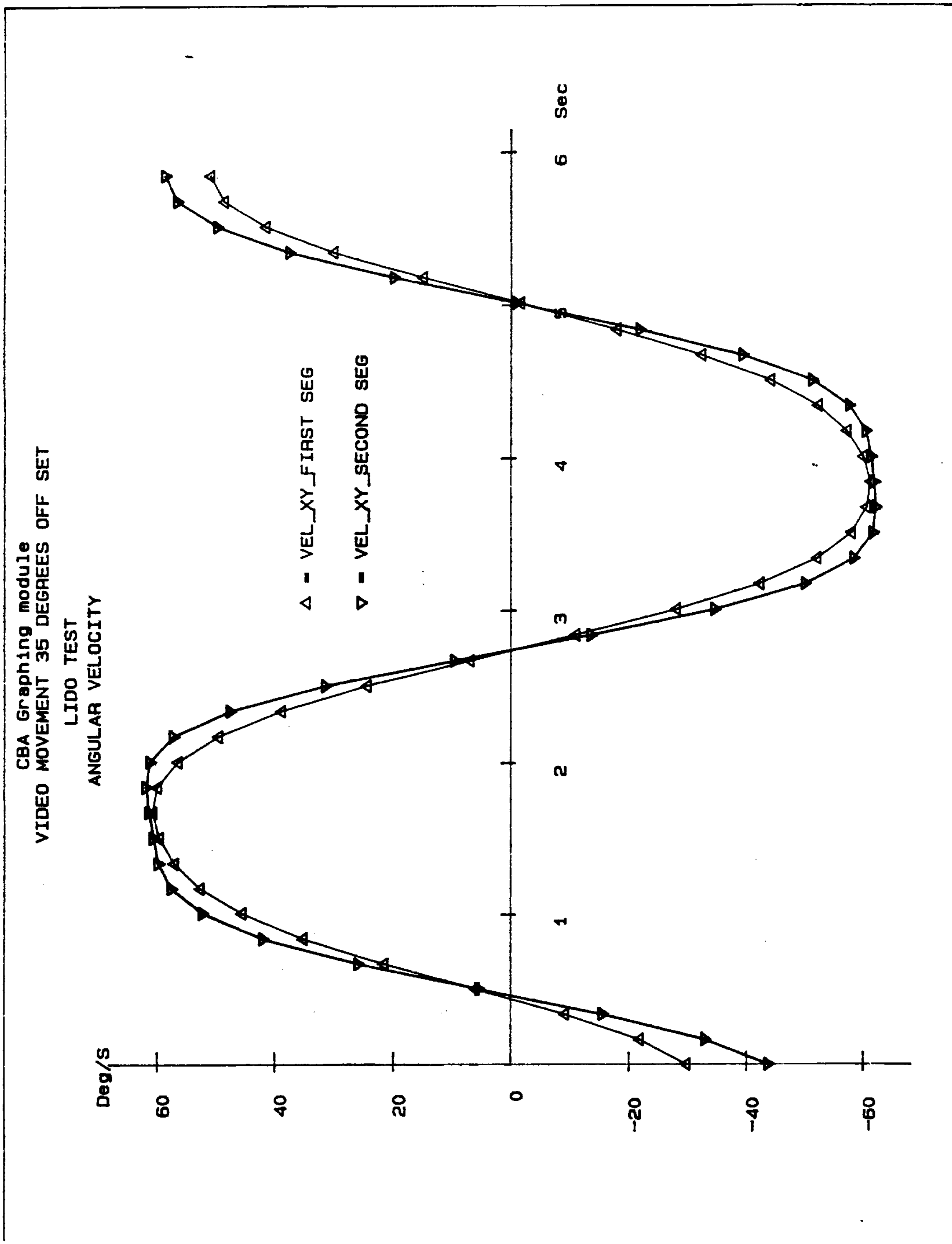

Figure D-6. Two-Dimensional Angular Velocity 60 Degrees/Second - Camera Offset 35°

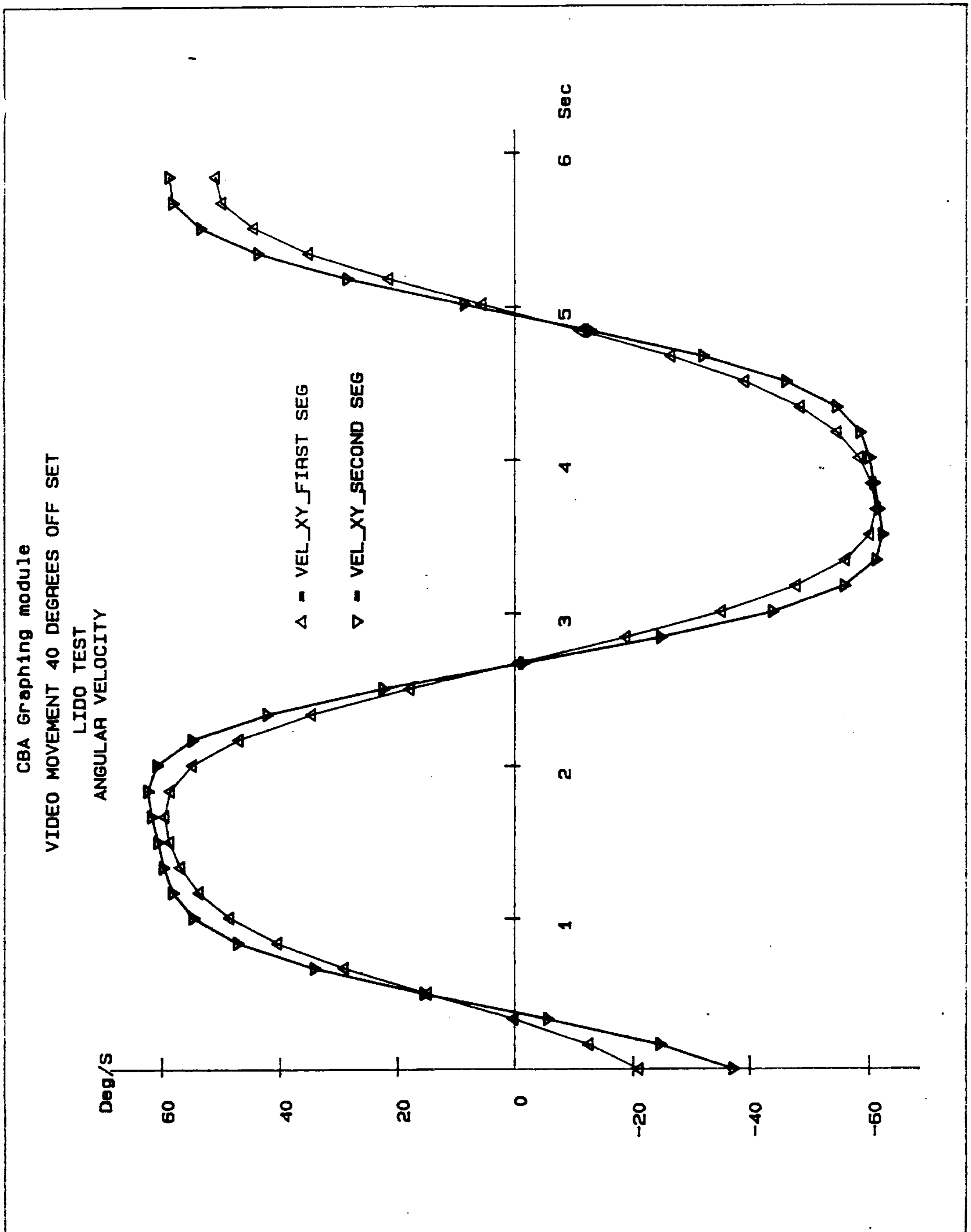

Figure D-7. Two-Dimensional Angular Velocity 60 Degrees/Second - Camera Offset 40°

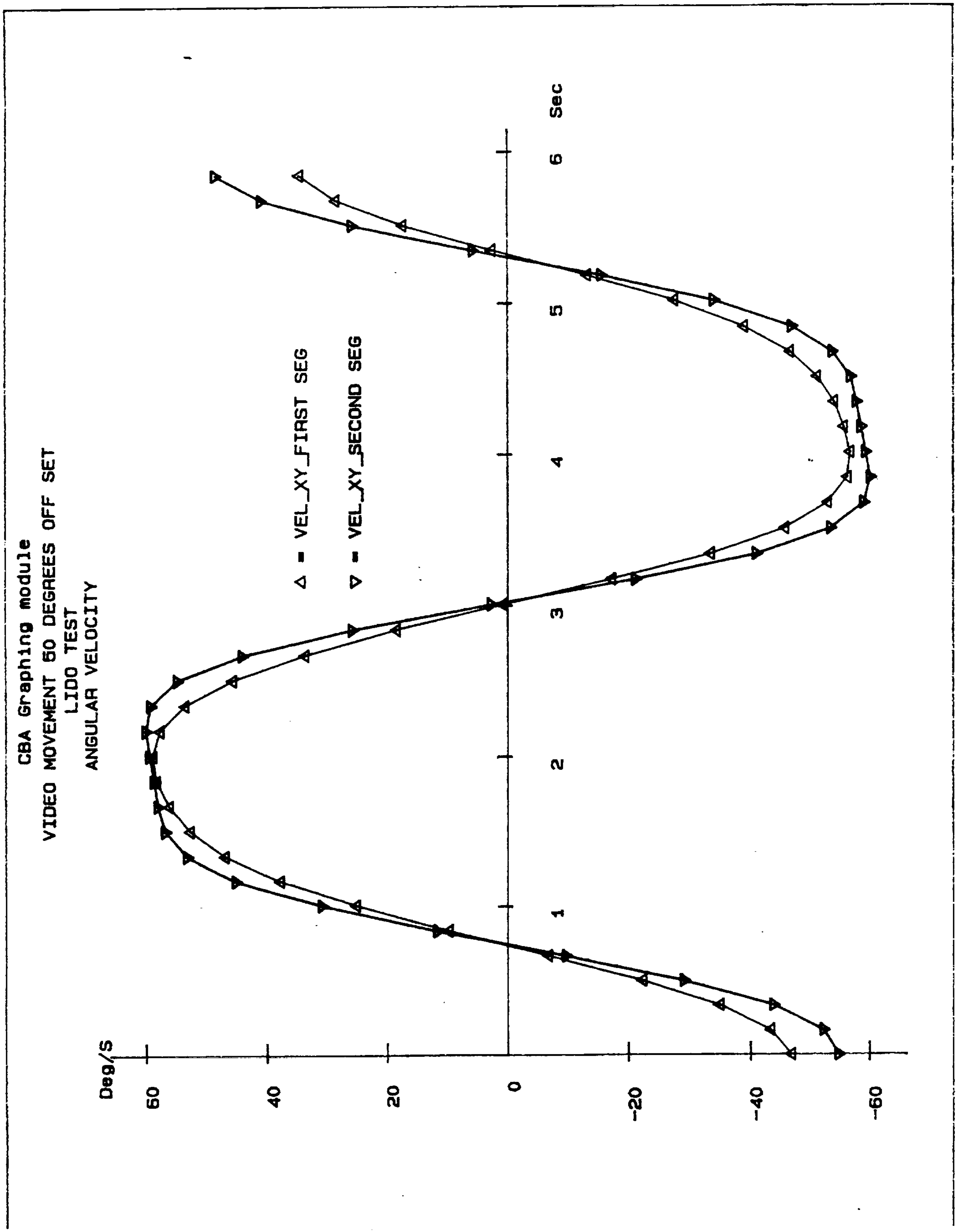

Figure D-8. Two-Dimensional Angular Velocity 60 Degrees/Second - Camera Offset 50°

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13. ABSTRACT *(Maximum 200 words)* Kinematics, the study of motion exclusive of the influences of mass and force, is one of the primary methods used for the analysis of human biomechanical systems as well as other types of mechanical systems. The Anthropometry and Biomechanics Laboratory (ABL) in the Crew Interface Analysis section of the Man-Systems Division performs both human body kinematics as well as mechanical system kinematics using the Ariel Performance Analysis System (APAS). The current evaluations address several methodology issues concerning the accuracy of the kinematic data collection and anlaysis used in the ABL. This document describes a series of evaluations performed to gain quantitative data pertaining to position and constant angular velocity movements under several operating conditions. Two-dimensional as well as three-dimensional data collection and analyses were completed in a controlled laboratory environment using typical hardware setups. In addition, an evaluation was performed to evaluate the accuracy impact due to a single axis camera offset. The specific results from this series of evaluations and their impacts on the methodology issues of kinematic data collection and analyses are presented in detail. The accuracy levels observed in these evaluations are also presented.

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