FaAA-85-4-1
QRCEI

TORSIOGRAPH TESTS OF EMERGENCY DIESEL GENERATORS, DIVISIONS 1 AND 2, AT PERRY NUCLEAR POWER PLANT--UNIT 1

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TABLE OF CONTENTS

1.0 INTRODUCTION

The purpose of the torsiograph test of the emergency diesel generator was to measure the angular displacements of the forward end of the crankshaft. These displacements were then used in conjunction with a dynamic torsional analysis of the crankshaft to assess the maximum stresses in the crankshaft. Torsiograph tests were performed on diesel generators Unit 1 Division 1 (U1D1) and Unit 1 Division 2 (U1D2) at Perry Nuclear Power Plant. Data were obtained during both steady-state and transient (startup and coastdown operation) conditions.

2.0 INSTRUMENTATION

The instrumentation generally consisted of an HBM Torsiograph, Signal Conditioner, Data Tape Recorder, Frequency Analyzer, Oscilloscope, Multimeter, and assorted interconnecting cables. The specific instrumentation used is shown in Table 2.1.

3.0 PROCEDURE

The torsiograph, which was attached to the front end of the crankshaft through an adapter plate supplied by the Perry plant, was used to measure angular displacements of the crankshaft relative to its mean rotational speed. The angular displacement signal from the signal conditioner was recorded on magnetic tape for further analysis to determine angular displacement components for each order. Tests were conducted at several speeds under no-load conditions, and at several loads at operating speed. In addition, fast starts were performed with predetermined crankshaft positions. The torsiograph data was recorded continuously from startup through coastdown. The spectrum analyzer was used to verify data integrity by determining harmonic components for each test condition.

The test was carried out for each diesel engine in the following five stages:

1. Calibration and instrumentation run-in.
2. Variable speed tests at 0% load.
3. Variable load tests at rated speed.
4. Startup and coastdown tests.
5. Post test calibration.

3.1 Calibration and Instrumentation Run-in

The torsiograph was mounted on the front end of the crankshaft using a rigid adapter plate. The torsiograph was connected to the signal conditioner and the signal conditioner to the instrumentation recorder with the designated cables. The signal conditioner was also connected to the spectrum analyzer and oscilloscope to monitor the torsiograph signals.

The following steps were completed to calibrate the instrumentation before and after testing:

1. The recording equipment and cabling was calibrated by introducing a known signal into the signal conditioner connection and recording the signal.

2. The calibration signal was verified by playing back the calibration recording.

3. A field calibration of the torsiograph was completed following the manufacturer's instructions [1]. The field calibration signal was recorded.

4. The field calibration signal was played back for verification.

After the calibration procedure was completed, the diesel engine was operated at no load for approximately two to ten minutes while data was recorded. The engine was then shut down while the recorded data was examined to verify the instrumentation and recording system operation.

The test documentation information in Table 3.1 was logged.

3.2 Variable Speed, 0% Load Tests

The engine was operated for two to five minutes at rated speed and no load. The speed was then adjusted using the mechanical governor to operate at speeds between 400 and 470 rpm. The engine was operated at each speed for two to ten minutes while the torsiograph output was recorded. The output speeds and tape footage were recorded (Table 3.2).

3.3 Variable Load, Operating Speed Tests

The engine was brought to operating speed. The load was adjusted successively to operate at the following load conditions for five to ten minutes: 25%, 50%, 75%, 100%. The load, current, speed, and tape footage were recorded (Table 3.3).

3.4 Startup and Coastdown Tests

Transient data was recorded for each engine at four different startup positions and the four coastdowns from 450 rpm. The startup and coastdown conditions monitored are the normal procedural fast starts and coastdowns in use at Perry.

The fast starts were performed with predetermined initial crankshaft positions at 180 degree intervals of crankshaft rotation to cover the full 720 degree firing cycle. The positions are described in Table 3-4. Once at the operating speed of 450 rpm the engine was allowed to coastdown. No load was applied to the engine during this test. The tape footage and run I.D.'s were recorded (Table 3.5).

3.5 Post Test Data Verification and Calibration

Selected data records were played back to verify proper measurement and recording. The calibration procedure outlined above was repeated and the signals recorded.

4.0 RESULTS

4.1 Calibration Data

The pre and post test static calibration data are shown in Tables 4.1 and 4.2. The torsiograph sensitivity was calculated as follows:

$$\text{Torsiograph Sensitivity, } \frac{mV/V}{\text{degree}} = \frac{\begin{pmatrix}\text{Teac}\\ \text{Output, V}\end{pmatrix}\begin{pmatrix}\text{Amp. Range} & \frac{mV/V}{10V}\\ \text{Setting,} & \end{pmatrix}}{(\text{Input, degrees})\begin{pmatrix}\text{Tape Deck}\\ \text{Gain, } V_{out}/V_{in}\end{pmatrix}}$$

The multiplication factors used in data reduction were calculated as follows:

$$\begin{matrix}\text{Vibration}\\ \text{Amplitude}\\ \text{(degrees-pk)}\end{matrix} = \frac{\begin{pmatrix}\text{Tape Deck*}\\ \text{Output, Vpk}\end{pmatrix}\begin{pmatrix}\text{Amp. Range} & \frac{mV/V}{10Vpk}\\ \text{Setting,} & \end{pmatrix}}{\begin{pmatrix}\text{Torsiograph}\\ \text{Sensitivity, } \frac{mV/V}{\text{degree}}\end{pmatrix}\begin{pmatrix}\text{Tape Deck}\\ \text{Gain, } V_{out}/V_{in}\end{pmatrix}}$$

where Amp. Range Setting = $20 \frac{mV/V}{10\ Vpk}$

Tape Deck Range Setting = 0.1 V_{out}/V_{in} Ch. 1

0.2 V_{out}/V_{in} Ch. 2

Unit 1 - Division 1

From Table 4.1 for Channel 1,

$$\text{Torsiograph Sensitivity} = \frac{(1.424)\left(\frac{20}{10}\right)}{(.1)\ (6)} = 4.747\ \frac{mV/V}{\text{degree}} \pm 0i14\%$$

* For out put in V_{RMS} (as in spectral plots) multiply by $\sqrt{2}$.

and for Channel 2,

$$\text{Torsiograph Sensitivity} = \frac{(1.426)\left(\frac{20}{10}\right)}{(.1)\ (6)} = 4.753\ \frac{\text{mV/V}}{\text{degree}} \pm 0.14\%$$

The sensitivities for the post test calibration were found to be 4.750 and 4.730 $\frac{\text{mV/V}}{\text{degree}}$ for channels 1 and 2 respectively.

Multiplication factors for time domain response:

Ch 1.

$$\text{Input, degrees-pk} = (\text{Output, Vpk}) \left(4.213\ \frac{\text{degrees-pk}}{\text{Vpk}}\right)$$

Ch 2.

$$\text{Input, degrees-pk} = (\text{Output, Vpk}) \left(2.104\frac{\text{degrees-pk}}{\text{Vpk}}\right)$$

and for frequency domain response:

Ch 1.

$$\text{Input, degrees-pk} = (\text{Output, } V_{RMS}) \left(5.958\ \frac{\text{degrees-pk}}{V_{RMS}}\right)$$

Ch 2.

$$\text{Input, degrees-pk} = (\text{Output, } V_{RMS}) \left(2.975\ \frac{\text{degrees-pk}}{V_{RMS}}\right)$$

<u>Unit 1 - Division 2</u>

From Table 4.1 for Channel 1,

$$\text{Torsiograph Sensitivity} = \frac{(1.425)\left(\frac{20}{10}\right)}{(0.1)\ (6)} = 4.750\ \frac{\text{mV/V}}{\text{degree}} \pm 0.2\%$$

and for Channel 2,

$$\text{Torsiograph Sensitivity} = \frac{(1.419)\left(\frac{20}{10}\right)}{(.1)\ (6)} = 4.730\ \frac{\text{mV/V}}{\text{degree}} \pm 0.2\%$$

The sensitivities for the post test calibration were found to be 4.747 and 4.727 $\frac{\text{mV/V}}{\text{degree}}$ for channels 1 and 2 respectively.

Multiplication factors for time domain response:

Ch 1.

$$\text{Input, degrees-pk} = (\text{Output, Vpk})\left(4.211\ \frac{\text{degrees-pk}}{\text{Vpk}}\right)$$

Ch 2.

$$\text{Input, degrees-pk} = (\text{Output, Vpk})\left(2.114\ \frac{\text{degrees-pk}}{\text{Vpk}}\right)$$

and for frequency domain response:

Ch 1.

$$\text{Input, degrees-pk} = (\text{Output, } V_{RMS})\left(5.955\ \frac{\text{degrees-pk}}{V_{RMS}}\right)$$

Ch 2.

$$\text{Input, degrees-pk} = (\text{Output, } V_{RMS})\left(2.990\ \frac{\text{degrees-pk}}{V_{RMS}}\right)$$

4.2 Variable Speed Results

The variable speed test was performed to determine the frequency of the first mode of the crankshaft torsional system. The results of this test are shown in Table 4.3. Figures 4.1 and 4.2 show that the 4th order critical speed is reached at about 436 rpm for each crankshaft. Thus, the first natural frequency is 29.1 Hz. This is in good agreement with the Holzer calculation of 29.2 Hz made by Delaval [2].

The amplitude of nominal shear stress may be estimated from the amplitude of free-end vibration by assuming that the shaft is vibrating in its first mode. Under these conditions, the nominal shear stress in the number 8 crankpin journal and the number 9 main journal is 8596 psi per degree of free-end vibration [2]. Thus, the maximum amplitude of nominal shear stress during the variable speed test was 2923 psi for each crankshaft.

4.3 Variable Load Results

The variable load test at rated speed was performed to determine the amplitude of vibration and estimate the nominal shear stress as a function of load. The results of this test are shown in Table 4.4. Figures 4.3 and 4.4 show that the amplitude of vibration increases with load to a maximum of 0.54 degrees at 7000 kW. The figures also show the response of the other major orders.

The amplitude of nominal shear stress may be estimated from the amplitude of free-end vibration by assuming that the shaft is vibrating in its first mode. Under these conditions, the nominal shear stress in the number 8 crankpin journal and the number 9 main journal is 8596 psi per degree of free-end vibration [2]. Thus, the amplitude of nominal shear stress at full load is as follows:

Diesel Generator	Nominal Torsional Stress at Full Load (7000 kW)	
	Single Order	Combined Order
Unit 1 - Division 1	1891 psi	4659 psi
Unit 1 - Division 2	2020 psi	4642 psi
DEMA [3] allowable	5000 psi	7000 psi

4.4 Startup/Coastdown Results

Coastdown

For the coastdowns monitored, the response of the crankshaft was found to be repeatable in both shape and magnitude. The maximum peak-to-peak amplitude recorded was found to be 0.96 degrees and occurs at the 8th order critical speed of approximately 218 rpm. The approximate length for a coastdown is 80 seconds.

An analytical model to predict the stress as a function of time during coastdown at each shaft section as well as the free-end rotational vibration was performed for the crankshaft at Perry. The analysis was performed using a cold compression curve with a peak pressure of 450 psi. It was found that with a damping of 1.5 percent of critical modal damping in each mode, the maximum peak to peak response was 0.93 degrees which is in good agreement with that measured in the torsiograph test.

The maximum amplitude of nominal stress was found to be 3970 psi and occurred between cylinders No. 7 and No. 8 based on the analysis. A comparison of the predicted and measured free-end amplitude time histories is shown in Figure 4-5. The good comparison of dynamic features is readily apparent in these plots. The time occurrence of some features are shifted due to the assumed linear change of angular velocity with time in the analysis.

Startup

The maximum peak-to-peak response for each of the four conditions tested in each engine is shown in Table 4.5 The mean maximum peak-to-peak response is 1.89 degrees for Unit 1 Division 1 and 1.84 degrees for Unit 1 Division 2. For each engine the maximum peak-to-peak response for each condition tested varied within 9% of the mean maximum peak-to-peak response (except for the one start that had a poor quality signal). The duration of a fast start was found to be 6 seconds.

The analytical model was used to determine the stresses in the crankshaft during startup for each of the four conditions tested. The analysis was performed using pressure-time data recorded during a fast start at another plant [Ref. (4)], and using damping of 2.5 percent of critical modal damping in each mode. The analysis confirms that the effect of initial crankshaft position on the maximum peak-to-peak response is small.

The analysis indicates that the maximum amplitude of nominal stress for a typical fast start is 7650 psi and occurs between cylinders No. 7 and No. 8. A comparison of the predicted and measured free-end amplitude time histories for a typical fast-start is shown in Figure 4-6.

5.0 CONCLUSIONS

The following conclusions are made:

- the first natural frequency of the torsional system for each engine was found to be approximately 29.1 Hz, and is in good agreement with Delaval Holzer calculations [2]. Thus the 4th order critical speed is 436 rpm.
- for both Unit 1 diesel generators, the stresses in the crankshaft are below DEMA's [3] allowables for both single order and combined order response at full load (7000 kW) for steady-state operation.
- The coastdown transient response is repeatable and has a maximum peak-to-peak amplitude of approximately 0.96 degrees, which produces a maximum amplitude of nominal stress of 3970 psi.
- A typical startup transient response produces a maximum peak-to-peak response of 1.86 degrees. Such a startup has a maximum amplitude of nominal stress of 7650 psi. This stress amplitude exists for only a few cycles on each startup.
- The results of the torsiograph test indicate that the crankshafts are adequate for their intended service at Perry nuclear Power Plant.

References

1. HBM Operating Manual for Rotary Vibration Transducer, 160.03-1.0-1.0e.

2. Yang, Roland, "Torsional and Lateral Critical Speed, Engine Numbers 75051/54 Delaval-Enterprise Engine Model DSRV-16-4, 7000 kW/9734 BHP at 450 RPM for Cleveland Electric Illuminating Co.," Delaval Engine & Compressor Division, Oakland, California.

3. Standard Practices for Low and Medium Speed Stationary Diesel and Gas Engines, Diesel Engine Manufacturers Association, 6th ed., 1972.

4. "Evaluation of Transient Conditions on Emergency Diesel Generator Crankshafts at San Onofre Nuclear Generating Station Unit 1," FaAA 84-12-14, Revision 1.0, April 1985.

Table 2.1: EQUIPMENT LIST

Equipment Manufacturer	Equipment Description	Model No.	Serial No.	FaAA ID No.
HBM	Rotary Vibration Transducer	BD 5	701	n/a
HBM	5KHz Carrier Frequency Amp.	KWS 7073	72984	n/a
Teac	Cassette Data Recorder	MR-30	116404	00138
B&K Precision	Sweep/Function Generator	3020	89-11576	00119
B&K Precision	Dual Trace 40MHz Oscilloscope	1540P	11400731	00118
Hewlett Packard	Dual Channel FFT Analyzer	3582A	L039823	
HBM	cable (connect transducer to amplifier)	n/a	n/a	n/a
n/a	cable (connect amplifier to tape deck)	n/a	n/a	n/a
n/a	cable (connect tape deck monitor to Spectrum analyzer or oscilloscope)	n/a	n/a	n/a
Fluke	Digital Multimeter	8060A	8396137	00128
Hewlett Packard	Dual Channel FFT Analyzer	5423A	2040A00345	00124
Hewlett Packard	Plotter	7225B	1206A01534	00122

Table 3.1: TORSIOGRAPH TEST DOCUMENTATION

Job Name:	Perry Torsiograph Test	Date:	
Job Number:	QRCEI	Div. 1:	3/27/85
Location:	Perry Nuclear Power Plant Cleveland Electric Illuminating Co.	Div. 2:	3/28/85

Engine Description:

Unit 1, Div. 1	Unit 1, Div. 2
Transamerica Delaval Inc.	Transamerica Delaval Inc.
DSRV-16-4	DSRV-16-4
Serial No. 75051	Serial No. 75052

Notes:

Test Personnel:

Steve Riess	FaAA
Paul Johnston	FaAA
Tony Pusateri	CEI
Mark Hickman	CEI

Table 3.2: TORSIOGRAPH VARIABLE SPEED TEST

Test Personnel:	Steve Riess, FaAA	Date:	
	Paul Johnston, Fa[illegible]	Div. 1:	3/27/85
	Tony Pusateri, C[illegible]	Div. 2:	3/28/85
	Mark Hickman, C[illegible]		

Unit 1 - Division 1

Tape I.D.	[illegible]tage	Test Speed (RPM)
	[illegible]44	400
	[illegible]-161	410
	[illegible]-175	420
	[illegible]9-190	430
QRCEI-1	193-204	435
TORSIOGRAPH	207-216	440
TEST	222-230	450
	242-250	460
	262-271	470
	278-289	425

Unit 1 - Division 2

Tape I.D.	Tape Footage	Tape Speed (RPM)
QRCEI-2	177-186	400
TORSIOGRAPH	192-200	410
TEST	204-210	420
	215-233	425
	226-232	430
	236-242	435
	245-253	440
	255-265	445
	268-275	450
	278-287	460
	304-312	470

Table 3.3: TORSIOGRAPH VARIABLE LOAD TEST

Test Personnel: Steve Riess, FaAA
Paul Johnston, FaAA
Tony Pusateri, CEI
Mark Hickman, CEI

Date:
Div. 1: 3/27/85
Div. 2: 3/28/85

Test Speed: 450 rpm

Unit 1 - Division 1

Tape I.D.	Tape Footage	Load (kW)
QRCEI-1 Torsiograph Test	410-418	1750 (25%)
	427-435	3500 (50%)
	442-448	5250 (75%)
	460-510	7000 (100%)

Unit 1 - Division 2

Tape I.D.	Tape Footage	Load (kW)
QRCEI-2 Torsiograph Test	361-369	1750 (25%)
	379-387	3500 (50%)
	397-405	5250 (75%)
	423-432	7000 (100%)

Table 3-4: PREDETERMINED INITIAL CRANKSHAFT POSITIONS FOR STARTUP TESTS

Run I.D.	Crankshaft Rotation w.r.t. 1 LB TDC Firing (degrees)
1 LB TDC firing	0°
7 LB TDC firing	180°
8 LB TDC firing	360°
2 LB TDC firing	540°

Table 3.5: STARTUP AND COASTDOWN TESTS

Test Personnel: Steve Riess, FaAA
Paul Johnston, FaAA
Tony Pusateri, CEI
Mark Hickman, CEI

Date:
Div. 1: 3/27/85
Div. 2: 3/28/85

Unit 1 - Division 1

Tape ID	Tape Footage	Startup/Coastdown ID
	555-566	Cylinder 1LB TDC Firing
QRCEI-1	566-581	Cylinder 7LB TDC Firing
Torsiograph Test	581-595	Cylinder 8LB TDC Firing
	595-611	Cylinder 2LB TDC Firing

Unit 1 - Division 2

Tape ID	Tape Footage	Startup/Coastdown ID
QRCEI-2	469-485	Cylinder 1LB TDC Firing
Torsiograph Test	485-500	Cylinder 2LB TDC Firing
	500-517	Cylinder 7LB TDC Firing
	517-534	Cylinder 8LB TDC Firing

Table 4.1: PRE TEST STATIC CALIBRATION

Unit 1 - Division 1

Static Input (degrees)	Voltage Output (Vdc)		Teac Range Setting (V/V)		HBM Signal Cond. Setting	
	Ch. 1*	Ch. 2*	Ch. 1	Ch. 2	(mV/V) / 10 V	U_B (V)
0	.005	.009	.1	.1	20	5
+3	.719	.726	.1	.1	20	5
0	.005	.010	.1	.1	20	5
-3	-.705	-.700	.1	.1	20	5
0	.003	.008	.1	.1	20	5
+3	.719	.726	.1	.1	20	5
0	.004	.010	.1	.1	20	5
-3	-.705	-.700	.1	.1	20	5
0	.002	.008	.1	.1	20	5

Unit 1 - Division 2

Static Input (degrees)	Voltage Output (Vdc)		Teac Range Setting (V/V)		HBM Signal Cond. Setting	
	Ch. 1*	Ch. 2*	Ch. 1	Ch. 2	(mV/V) / 10 V	U_B (V)
0	.004	.008	.1	.1	20	5
+3	.722	.721	.1	.1	20	5
0	.009	.013	.1	.1	20	5
-3	-.703	-.698	.1	.1	20	5
0	.006	.009	.1	.1	20	5
+3	.722	.721	.1	.1	20	5
0	.009	.010	.1	.1	20	5
-3	-.704	-.697	.1	.1	20	5
0	.006	.009	.1	.1	20	5

* ± .002 Vdc

Table 4.2: POST TEST STATIC CALIBRATION

Unit 1 - Division 1

Static Input (degrees)	Voltage Output (Vdc) Ch. 1*	Ch. 2*	Teac Range Setting (V/V) Ch. 1	Ch. 2	HBM Signal Cond. Setting (mV/V) / 10 V	U_B (V)
0	.011	.018	.1	.1	20	5
+3	.727	.730	.1	.1	20	5
0	.012	.020	.1	.1	20	5
-3	-.698	-.689	.1	.1	20	5
0	.011	.019	.1	.1	20	5
+3	.727	.730	.1	.1	20	5
0	.015	.021	.1	.1	20	5
-3	-.697	-.689	.1	.1	20	5
0	.012	.019	.1	.1	20	5

Unit 1 - Division 2

Static Input (degrees)	Voltage Output (Vdc) Ch. 1*	Ch. 2*	Teac Range Setting (V/V) Ch. 1	Ch. 2	HBM Signal Cond. Setting (mV/V) / 10 V	U_B (V)
0	.014	.022	.1	.1	20	5
+3	.729	.733	.1	.1	20	5
0	.015	.022	.1	.1	20	5
-3	-.695	-.685	.1	.1	20	5
0	.014	.021	.1	.1	20	5
+3	.730	.734	.1	.1	20	5
0	.016	.024	.1	.1	20	5
-3	-.695	-.686	.1	.1	20	5
0	.013	.020	.1	.1	20	5

* ± .002 Vdc

Table 4.3: VARIABLE SPEED RESPONSE

Unit 1 - Division 1

Order	Amplitude of free-end vibration (millidegrees) for given speed (rpm)									
	403	412	423	428	434	438	443	454	463	474
0.5	6	11	9	6	10	13	11	11	9	12
1.0	2	2	2	2	1	0	1	1	1	1
1.5	39	40	40	40	40	40	40	41	41	41
2.0	6	7	8	8	9	11	12	13	14	16
2.5	55	56	57	58	58	59	60	62	64	65
3.0	2	2	2	3	2	2	1	2	2	3
3.5	39	42	46	49	52	56	61	74	93	130
4.0	37	55	99	153	240	211	140	80	57	43
4.5	68	43	31	27	23	20	19	15	13	10
5.0	2	2	2	2	22	2	2	2	2	2
5.5	9	8	7	6	6	5	5	4	4	5
6.0	4	5	6	7	8	7	5	3	3	3
Total	170	170	210	260	340	290	240	230	230	240

Unit 1 - Division 2

Order	Amplitude of free-end vibration (millidegrees) for given speed (rpm)										
	400	410	420	425	431	435	439	445	451	460	470
0.5	5	6	4	4	5	5	5	7	6	6	5
1.0	1	1	1	1	2	2	2	2	2	3	3
1.5	38	39	39	38	38	38	39	39	39	39	40
2.0	6	6	7	8	8	9	11	12	12	14	15
2.5	57	59	60	60	60	61	62	64	64	66	68
3.0	3	3	4	4	4	3	3	4	4	5	5
3.5	36	40	43	45	48	51	56	61	66	81	107
4.0	26	40	66	96	151	232	186	122	89	48	43
4.5	91	50	34	29	25	22	20	18	16	13	10
5.0	2	1	1	1	1	2	2	2	2	2	2
5.5	10	8	7	7	7	6	5	5	4	4	4
6.0	5	5	5	6	7	8	6	4	4	3	3
Total	185	165	160	200	255	340	270	235	215	205	230

Table 4.4: VARIABLE LOAD RESPONSE

Unit 1-Division 1

Order	Amplitude of free-end vibration (millidegrees) for given load (kw) 0	1750	3500	5250	7000
0.5	22	55	95	72	93
1.0	2	4	5	5	5
1.5	43	67	103	137	181
2.0	12	9	6	4	1
2.5	64	89	130	173	220
3.0	2	2	2	5	8
3.5	72	94	133	173	201
4.0	94	85	95	92	130
4.5	16	18	27	38	26
5.0	2	3	3	4	5
5.5	5	6	9	12	14
6.0	3	5	7	9	10
Total	225	273	368	417	542

Unit 1 - Division 2

Order	Amplitude of free-end vibration (millidegrees) for given load (kw) 0	1750	3500	5250	7000
0.5	7	6	13	34	55
1.0	3	3	3	3	1
1.5	41	64	98	138	184
2.0	11	8	5	5	7
2.5	68	96	138	185	235
3.0	4	7	8	7	4
3.5	69	93	129	172	205
4.0	88	69	80	133	141
4.5	15	19	29	41	52
5.0	1	1	1	2	1
5.5	5	6	10	12	14
6.0	4	6	8	11	12
Total	215	240	330	445	540

Table 4.5: STARTUP RESPONSE

Fast Start ID	Maximum Peak-to-Peak Free-End Vibration (degrees)	
	Unit 1 Division 1	Unit 1 Division 2
1 LB TDC Firing	2.39*	1.90
7 LB TDC Firing	1.80	1.68
8 LB TDC Firing	1.61	1.76
2 LB TDC Firing	1.75	2.00

* Torsiograph data for this test was determined from a noisy signal.

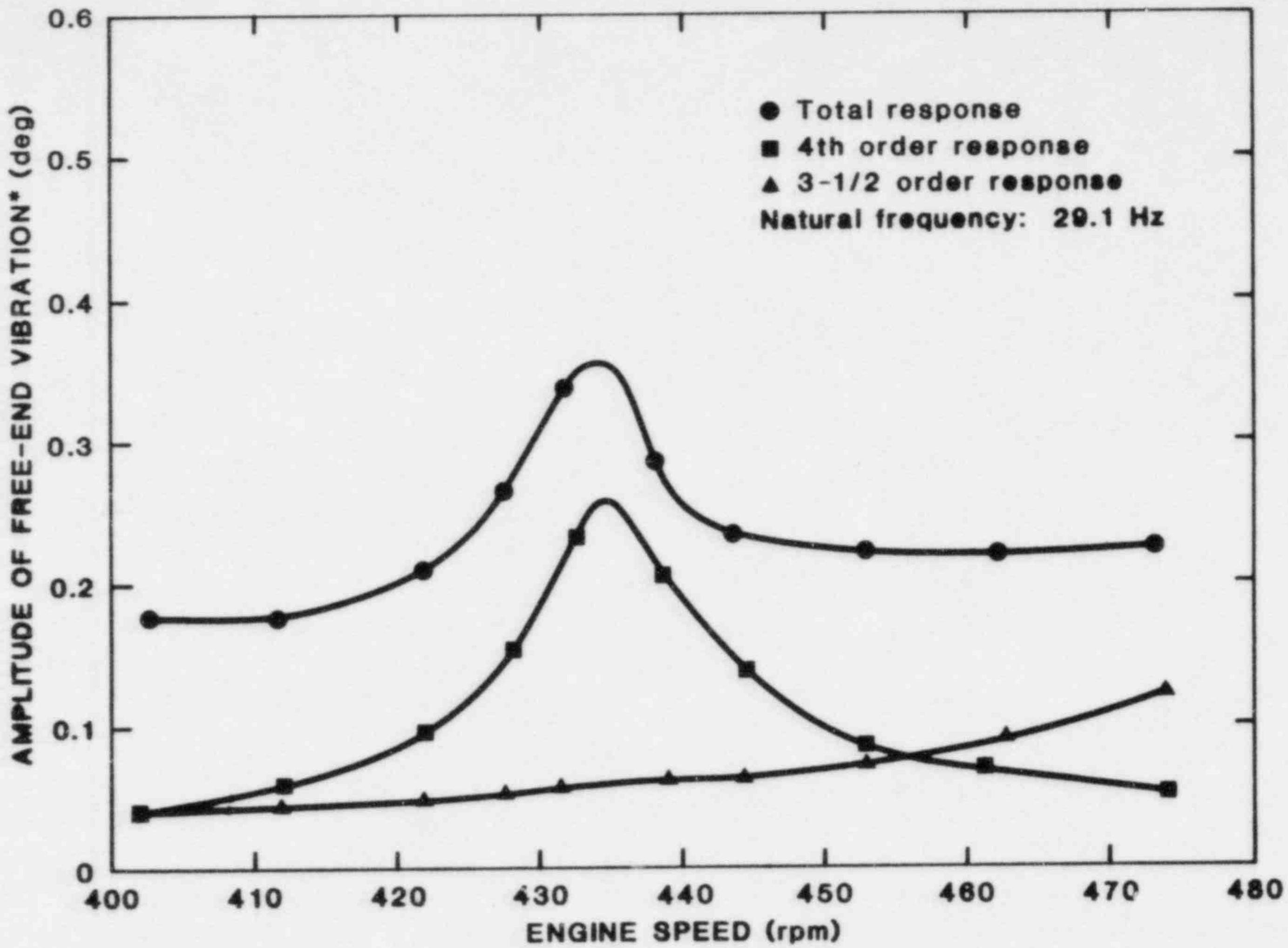

Figure 4-1. Variable speed response of Unit 1, Division 1.
*Amplitude of nominal shear stress is 8596 psi/degree of free-end vibration, assuming the shaft is vibrating in its first mode.

FaAA-86-4-1

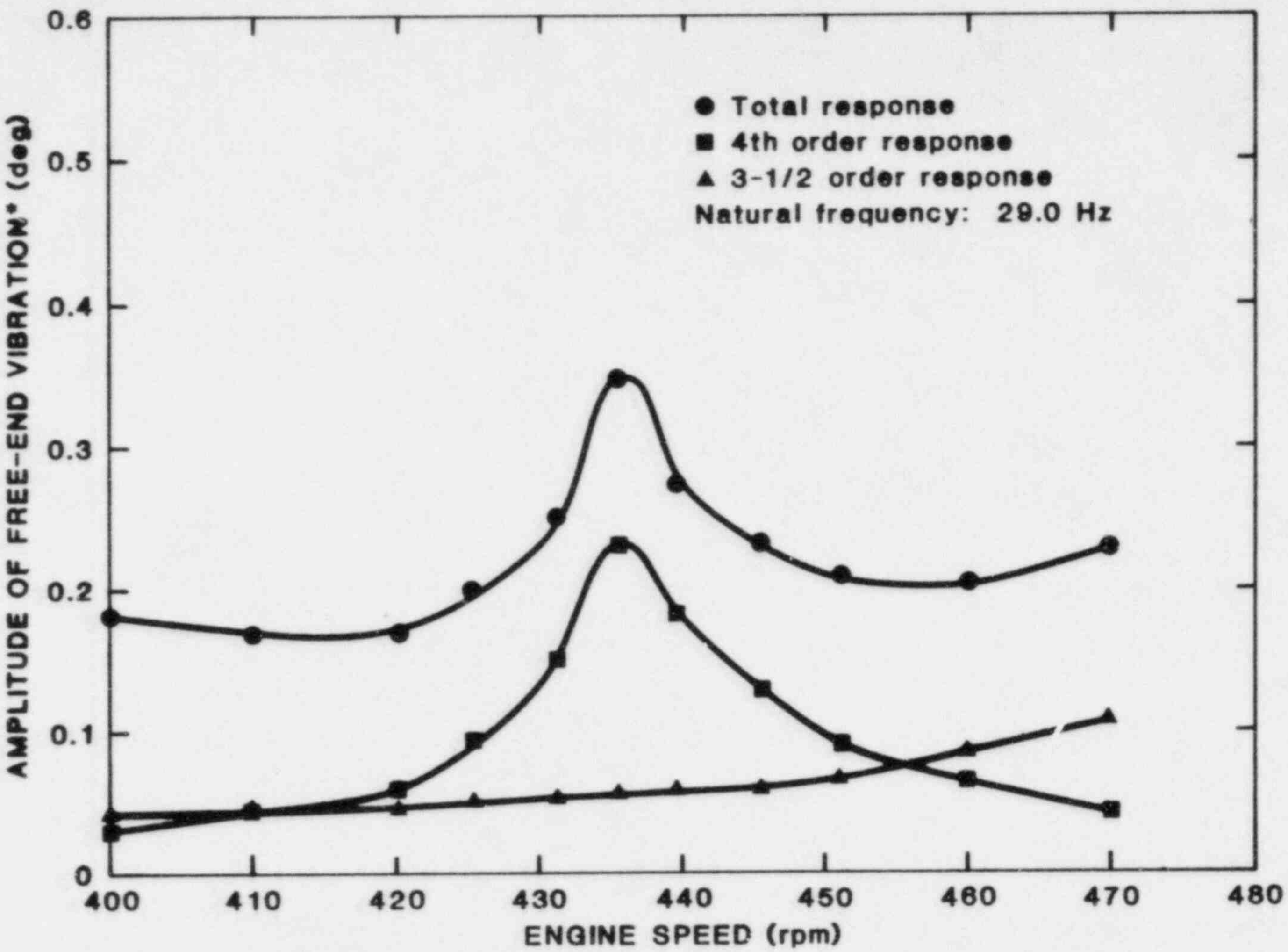

Figure 4-2. Variable speed response of Unit 1, Division 2.
*Amplitude of nominal shear stress is 8596 psi/degree of free-end vibration, assuming the shaft is vibrating in its first mode.

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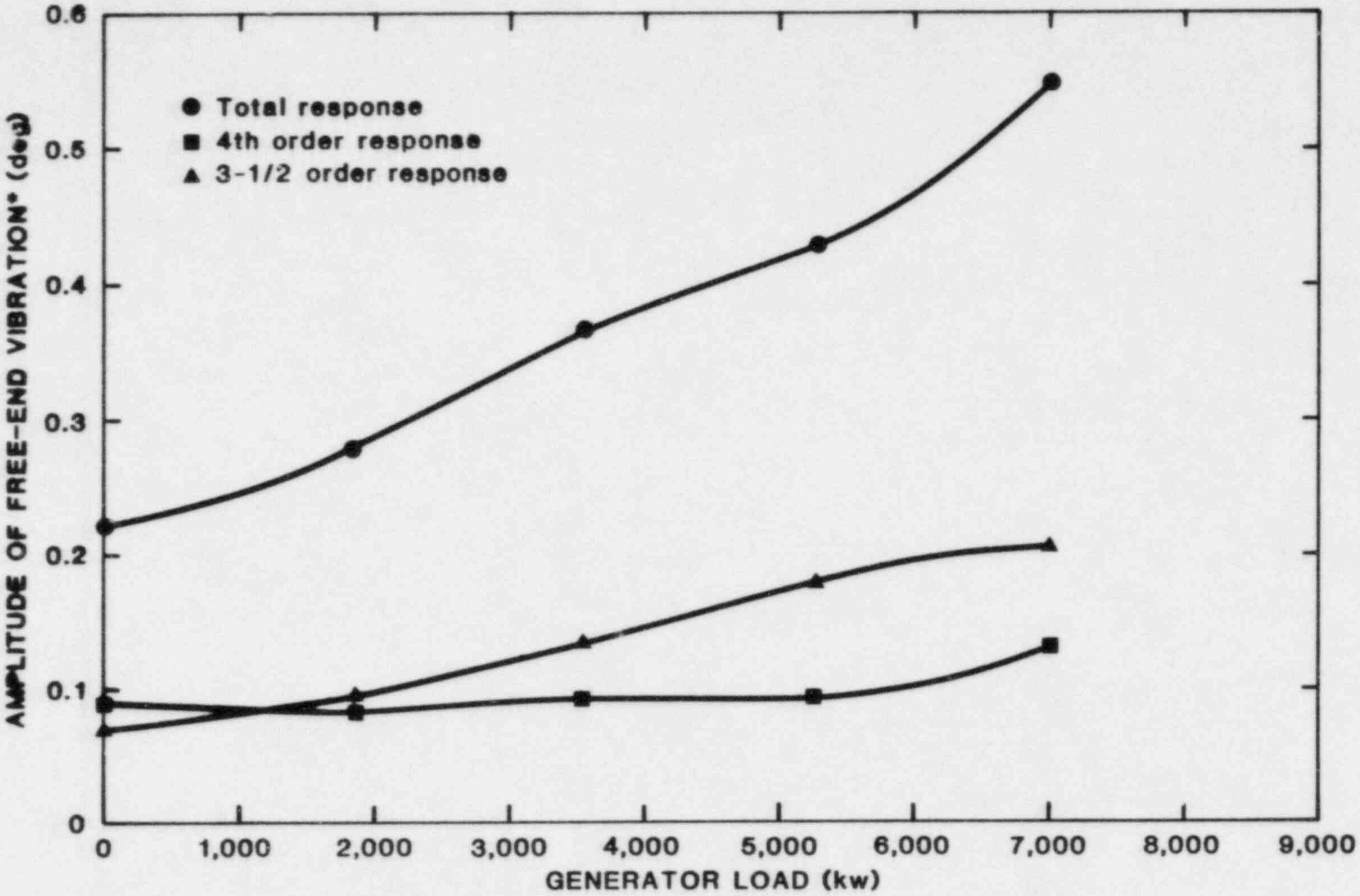

FaAA-85-4-1

Figure 4-3. Variable load response of Unit 1, Division 1.
*Amplitude of nominal shear stress is 8596 psi/degree of free-end vibration, assuming the shaft is vibrating in its first mode.

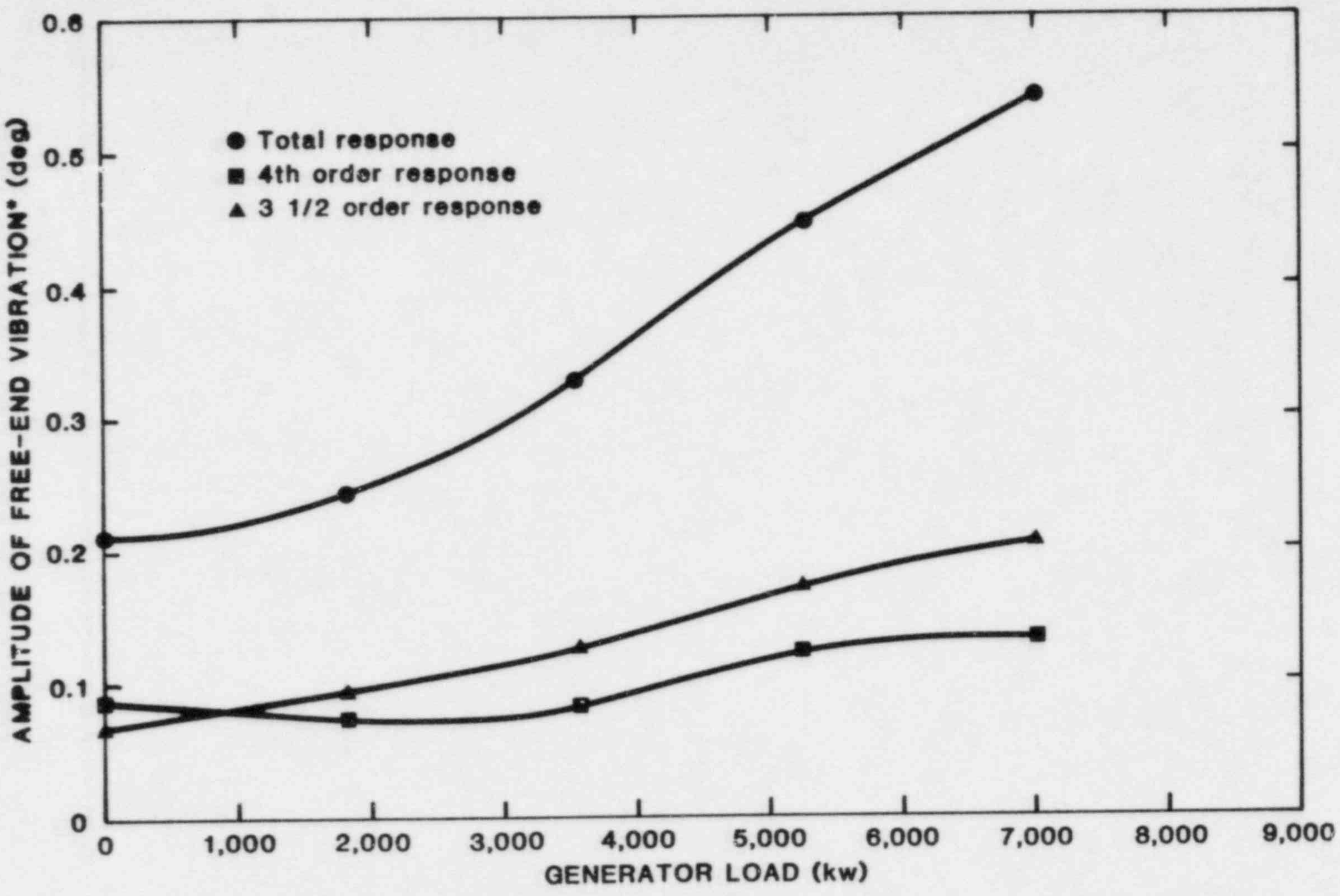

Figure 4-4. Variable load response of Unit 1, Division 2.
*Amplitude of nominal shear stress is 8596 psi/degree of free-end vibration, assuming the shaft is vibrating in its first mode.

FaAA-85-4-1

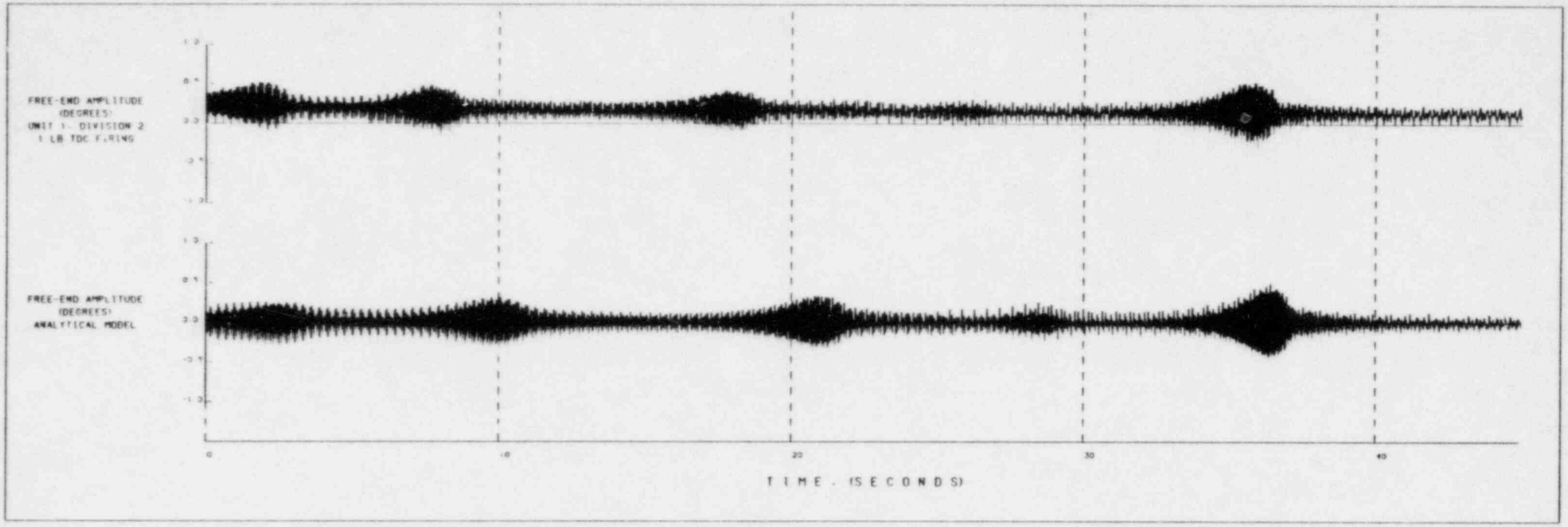

Figure 4-5. Comparison of predicted and measured free-end amplitudes during a typical coastdown.

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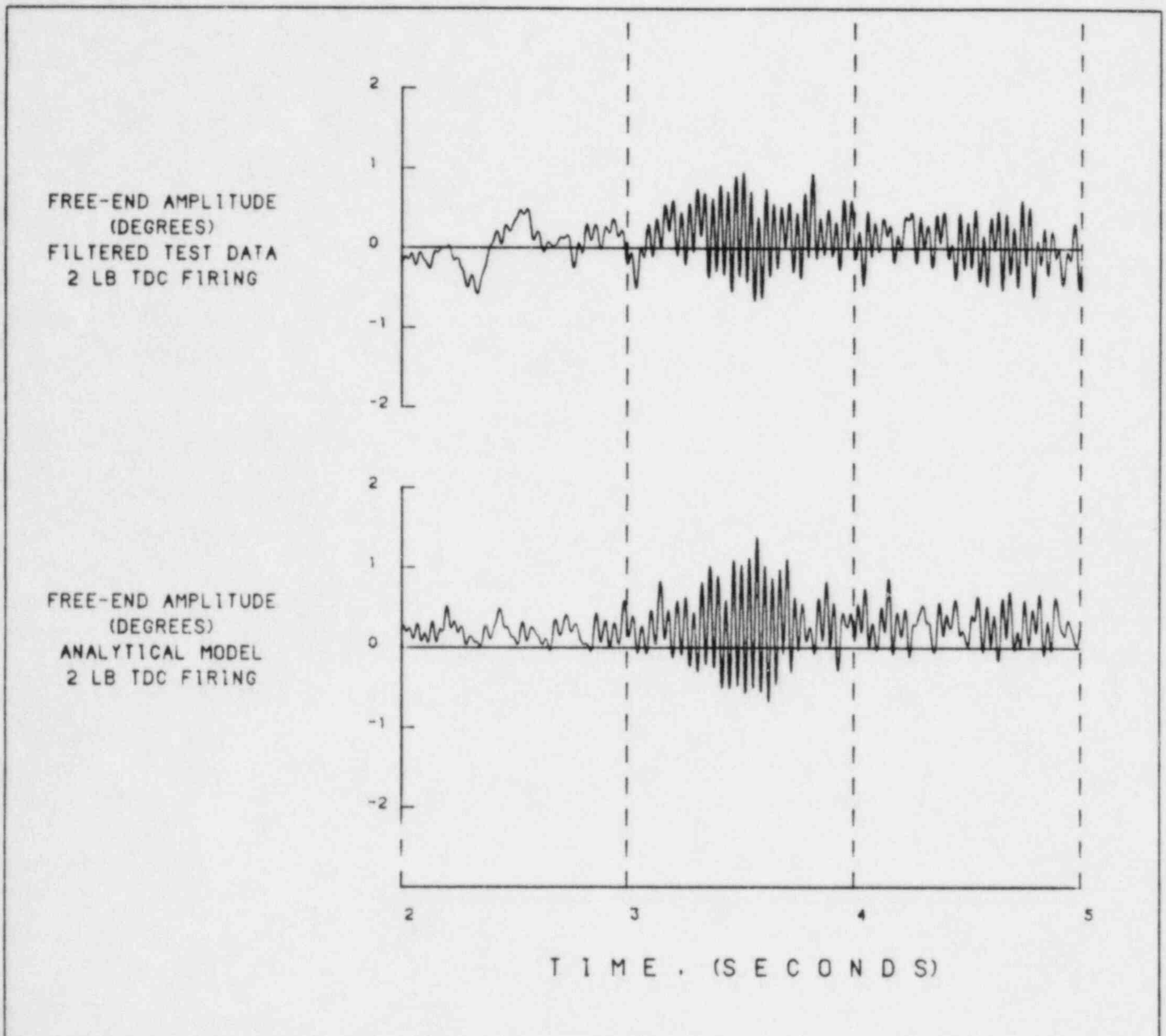

Figure 4-6. Comparison of predicted and measured free-end amplitudes.