



NASA Contractor Report 159140

NASA-CR-159140
19800012550

HUMAN COMFORT RESPONSE TO RANDOM MOTIONS WITH A DOMINANT PITCHING MOTION

Ralph W. Stone, Jr.

RESEARCH LABORATORIES FOR THE
ENGINEERING SCIENCES
University of Virginia, Charlottesville, VA 22901

Contract No. NAS1-14908
February 1980

NASA

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665
AC 804 827-3966

A Report

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A DOMINANT PITCHING MOTION

Submitted to:

National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

Submitted by:

Ralph W. Stone, Jr.
Associate Professor

Department of Civil Engineering
SCHOOL OF ENGINEERING AND APPLIED SCIENCE
UNIVERSITY OF VIRGINIA
CHARLOTTESVILLE, VIRGINIA

Report No. UVA/528156/MAE-CE79/117

July 1979

Copy No. 1

N 80 - 21034 #

HUMAN COMFORT RESPONSE TO
RANDOM MOTIONS WITH A DOMINANT PITCHING MOTION

By Ralph W. Stone, Jr.

SUMMARY

The effects of random pitching velocities on passenger ride comfort response were examined on the NASA Langley Visual Motion Simulator. The effects of power spectral density shape and frequency ranges from 0 to 2 Hz were studied. This paper presents the subjective rating data and the physical motion data obtained in this study. No attempt at interpretation or detailed analysis of the data is made. There existed during this study motions in all degrees of freedom, as well as the intended pitching motion, because of the characteristics of the simulator. These unwanted motions may have introduced some interactive effects on passenger responses which should be considered in any analysis of the data.

INTRODUCTION

An increase in short-haul operations using short take-off and landing aircraft is expected (ref. (1)). Such operations, which are at low altitudes and with relatively low wing loading aircraft, will probably lead to conditions of flight where the ride quality will be degraded compared to that experienced in current jet aircraft operations. Accordingly, the consideration of ride comfort will probably become increasingly important. Understanding and defining the problems of passenger acceptance, and developing methods and systems for aircraft design that will allow for acceptable ride comfort, are encompassed in NASA programs described in references 2 and 3. These programs include the simultaneous measurement of subjective ride comfort responses and vehicle motions made on both scheduled airlines and simulators.

Much data has been obtained and ride comfort indices and acceptance ratings have been developed based on human exposures to the full six degrees of freedom motion of aircraft (refs. (4), (5), (6), (7), and (8) for example). The interactions of the various degrees of freedom of motion as they affect human comfort responses has been under study since 1975 but is not yet fully understood, especially for the frequencies of motion for aircraft. The nature of these interactions is important to the understanding of the total human comfort response to combined motions of two or more degrees of freedom in aircraft. In general data available for subjective comfort responses to single degree of freedom motions exist for sinusoidal and random oscillations but primarily at frequencies larger than those common to aircraft (refs. (9), (10), (11), (12), and (13) for example).

The influence of single degree of freedom motions having random oscillations typical of those aircraft in turbulence therefore is not fully understood. Typical airplane responses to turbulence have power spectra shapes with peak

power below 2 Hertz and often below 1 Hertz with rapid decreases in power beyond these frequencies. However, some response motions of airplanes (particularly the angular motions) have somewhat flatter power spectra shapes. Whether these different spectral shapes will have a significant influence on ride comfort is not clear. A program to measure human comfort responses in single degree of freedom random motions and the interactions of these motions, in two, three, and six degrees of freedom using two types of power spectra shapes and three frequency ranges was performed on the Visual-Motion Simulator at the NASA Langley Research Center (Figure 1). References (14), (15), (16), and (17) present the data obtained for the study of the subjective ride comfort response to random vertical, transverse, and longitudinal accelerations and rolling velocity, respectively. The present paper presents the subjective ride comfort response ratings obtained when using oscillations in the pitching degree of freedom.

SYMBOLS

R_s	ride comfort response
σ_{R_s}	standard deviation of ride comfort response
g	acceleration due to gravity
Hz	frequency, cps.

TESTS AND TEST CONDITIONS

Motion Stimuli

The investigation was initiated to measure human comfort response ratings to single degree of freedom motions and to multiple degree of freedom motions using random motions like those experienced in airplane flight. A program was developed using 14 separate simulator "flights," each flight consisting of 24 segments. Each of the segments consisted of either a single degree of freedom motion, a two-, three-, or six-degree of freedom motion. The segments for the six single degrees of freedom (vertical, transverse and longitudinal accelerations; and pitch, roll and yaw rates) were scattered throughout six flights. Any one single degree of freedom was contained within only two of the six flights. The various two degrees of freedom segments were similarly scattered throughout four flights. The various three degrees of freedom segments were scattered throughout two flights, and six degrees of freedom similarly in two flights.

As mentioned previously, typical airplane responses to turbulence have power spectra that decrease rapidly beyond 1 to 2 Hertz. However, some responses, particularly angular motions, have flatter power spectra. In order to investigate the effect of spectral shape and the frequency distribution of the response power on ride comfort, six power spectral density distributions were developed to drive the simulator. There were two general groups, the first termed "typical," having variations with frequency like those experienced on typical aircraft and the second termed "flat" with shallower decreases at the high frequencies. In each group, three distinct frequency distributions were used; the first with peak power centered between 0 and 1 Hz, the second between 0 and 2 Hz, and the third between 1 and 2 Hz.

The six power spectra shapes were tailored by filtering the output of a random number generator. The nominal shapes of these spectra are shown in Figure 2. In designing the spectra shapes to suit the simulator characteristics the "flat" spectra were not as flat as was intended and in Figure 2 appear to have more power in the 1 to 3 Hz range than the typical spectra for conditions with the same peak power. This increase in power, over the typical spectra, ranges from 35 percent for the 1 to 2 Hz spectra to 170 percent for the 0 to 1 Hz spectra.

The nominal spectra shown in Figure 2 are normalized to have a peak of 1. For the actual motions on the simulator the magnitude was raised for each spectra type by adjusting the gain of the input signal. Four magnitudes were examined for each of the six spectra shapes. Thus, the 24 flight segments were developed for use in the study.

Each "flight" of 24 segments was flown four or five times so that 8 to 10 subjects experienced each motion. As these "flights" were not precisely duplicated, the data discussed in the "Data" section of this paper are the average values of the four or five "flights" used. The standard deviation of the pitching velocities from the average values for the various segments in terms of percent of the average values is 9.76 percent. The maximum deviation was 30.02 percent. The actual output of the simulator for a test segment representing most nearly the average output for a given segment and, therefore, the motions essentially experienced by the subjects are presented in Figures 3 to 8. These figures include time histories for all six degrees of freedom, histograms of the pitching velocity and power spectral densities of the pitching velocities for the 24 segments of "flight" as follows:

Figure	Spectra Shape	Frequency Range
3	Typical	0-1 Hz
4	Typical	0-2 Hz
5	Typical	1-2 Hz
6	Flat	0-1 Hz
7	Flat	0-2 Hz
8	Flat	1-2 Hz

The four segments of motion in each figure are for progressively increasing values of pitching velocity.

Simulator

The Langley Visual-Motion Simulator (VMS) is primarily used for piloted flight, stability, control, and display studies, and does not contain a passenger compartment. The passengers used in this study sat in the pilot's compartment and rode passively, the controls and instruments being inoperative for these experiments. Figure 9 is an interior view of the cockpit. Two passengers rode each experimental "flight."

The normal operational envelope of motion frequencies and magnitudes of the VMS are presented in reference (2). The largest practicable input frequency is about 3 Hz. As noted in references (6) and (7), the major energy in aircraft motions is in the region of 2 Hertz and less.

The VMS is a large mechanical device with six hydraulically operated telescoping legs and associated switching valves. In order to obtain the desired motions without exceeding the mechanical limitations of the simulator, various controls and limiting systems are incorporated. The simulator, as a dynamic device, has its own natural frequencies and damping, and thus exerts an effect on the resulting motions. For precise development of a single degree of freedom, the six legs would have to move synchronously. Because of friction in the hydraulic systems and valves, and variations in the hydraulic pressure, it was not possible to produce the precise conditions necessary for one degree of freedom. Therefore, the motions developed by the simulator, when obtaining the data for this paper, had pitching velocity as the dominant motion with various lesser amounts of the other five degrees of freedom present. For these same reasons, the motions were not precisely duplicated even for identical computer inputs. As a result of the dynamic characteristics of the simulator, the actual motion power spectra experienced by the subjects was somewhat different than the nominal spectra used as input to the computer. The four different magnitudes previously mentioned were supposed to be the same for each of the six spectra shapes studied. However, because of the dynamic response characteristics of the simulator, different RMS values of the pitching velocities were obtained for the different spectra shapes.

The reference axis used was relative to the seated passengers and is shown in Figure 10. The pitching velocities used for this paper were along the pitching axis shown in Figure 10. The actual motions of the simulator, as experienced by the passengers, were measured by an inertial instrument package containing three linear accelerometers, one aligned with each axis, and three rate gyros also aligned with each axis.

Experimental Procedure

As noted previously, 24 segments of simulated flight were used in examining the pitching degree of freedom. These 24 segments were randomly scattered in two "flights." Each flight was 36 minutes long and consisted of 24, one-and-one-half minute segments. The subjects rated a 20-second portion in the center of each segment. A computer-driven buzzer system was used to identify this center portion of the segments. The subjects were instructed to consider only this 20 second segment of "flight" when making their comfort response rating. The subjects rated the segments on a seven-statement scale, as follows:

- Very comfortable
- Comfortable
- Somewhat comfortable
- Acceptable
- Somewhat uncomfortable
- Uncomfortable
- Very uncomfortable.

Many subjective ride comfort indices have been based on a five-point numerical scale (see refs. (5) and (8), for example). Accordingly, for analysis purposes the seven-statement rating scale was converted to numerical values for a five-point scale as follows:

- 1 = Very comfortable
- 2 = Comfortable
- 2½ = Somewhat comfortable
- 3 = Acceptable
- 3½ = Somewhat uncomfortable
- 4 = Uncomfortable
- 5 = Very uncomfortable

For the data presented herein, average numerical ratings for the 8 to 10 subjects based on this scale and standard deviations from these averages are used.

The subjects, in general, were supplied by the Hampton Institute and consisted of a relatively broad spectra of people. For the total program, 138 passenger "flights" were made using a total of 98 persons. No person rode the same flight twice. A general profile of the persons used on these "flights" is shown in Table I.

DATA

The mean RMS values for all six degrees of freedom of the four or five "flights" performed for each input segment along with the mean subjective ride comfort response ratings (R_s) are shown in Table II. The standard deviations of the response ratings for the passenger group on each "flight" segment are also shown in Table II. Cross correlation coefficients for the various motion components are shown in Table III. The four segments of motion on Tables II and III for each spectra shape are for progressively increasing values of RMS pitching velocity.

The data presented herein are for pitching motion inputs and as noted previously the existence of the other motion components in Tables II and III is the result of the simulator characteristics. Until data is available for each degree of freedom of motion and for combined motions, it will not be clear how significant the existence of the other motion components is in the subjective ride comfort responses presented in this paper. The RMS pitching velocity varied from 0.63 to 4.23 times the magnitude of the RMS rolling velocity, which ranged in magnitude from 1.12 to 2.19 degrees per second with a mean value of 1.47 degrees per second. According to reference (3) the threshold of sensation to rolling velocity may be about 0.874 degrees per second. It would seem that the existence of rolling to the passengers was known during these tests for pitching motion. It would further appear that the rolling stimulus if recognized may always have elicited comfortable responses on the bipolar scale used. The RMS pitching velocity varied from 1.17 to 9.28 times the magnitude of the RMS yawing velocity, which ranged in magnitude from 0.61 to 0.80 degrees per second with a mean value of 0.67 degrees per second. According to reference (2), the threshold of sensations in yawing may be about 0.72. The yawing motion therefore may always have been below threshold and thus had no influence on the response rating obtained. The angular motions can be compared in this fashion as they are similar types of stimulation to the pitching velocity. The linear RMS accelerations are however a different form of stimulation than the angular velocities, and no comparison as to their relative significance to RMS pitching velocity can be directly made. The values of linear acceleration range from

about 0.0067 to 0.0617 g, and have an average value of 0.02 g. These values generally exceed the values normally established as thresholds of perception for linear accelerations (see ref. (2) for example). Subjects exposed to these motions may therefore, have been cognizant of the existence of linear accelerations during this study. Whether these accelerations were sufficient to alter the subjective ride comfort ratings for pitching velocity will not be clear until the interactive effects of multiple degrees of freedom are understood. The magnitude of the linear accelerations experiences were such as to always be in the comfortable zone of the bipolar scale used.

The subjective ride comfort responses on Table II have an average standard deviation for all 24 segments of 0.727. This compares favorably with other experiences as, for example, the average standard deviation for the results of reference (8) is 0.758 units of response rating. The value of 0.727 for this pitching velocity study compares favorably with those for other motion components in references (14), (15), (16) and (17).

As expected, there is a progressive increase in response ratings with increasing pitching velocity. It appears that this variation (Table II) is not linear, especially when the peak power frequency is from 0-2 Hz and 1-2 Hz. The subjective ride comfort response ratings are plotted against the \log_{10} of the RMS pitching velocity for typical power spectra in Figure 11 and for flat power spectra in Figure 12. These plots do not show the relative linearity that was shown in similar plots for the linear accelerations and for rolling velocity (refs. (14), (15), (16) and (17)). This observation implies that comfort responses to RMS pitching velocities may have more complex relationships than do the other motions.

CONCLUDING REMARKS

A study has been made on the Langley Visual Motion Simulator to examine the influence of random pitching velocities on human subjective ride comfort responses. The effects of two general shapes of power spectral density of pitching velocity input for three frequency ranges in the 0 to 2 Hz region were examined. The data obtained in this study are presented in this paper. Although this study was made basically to examine the influence of random pitching velocities, because of the characteristics of the simulator there occurred in these data some amounts of motion in all other degrees of freedom. Analysis of these data must maintain cognizance of this fact. There appears to be no simple relationship between the response data and RMS pitching velocities.

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TABLE I - PASSENGER PROFILE FOR
VMS RIDE QUALITY PROGRAM

Total Passengers - 98 Persons

Sex Distribution

	Number	%
Males	47	48
Females	51	52

Age Distribution

	Number	%	Sex	
			Male	Female
18-25 yrs	55	56	44%	56%
26-45 yrs	30	31	47%	53%
46 + yrs	13	13	69%	31%

TABLE II - MEAN RMS VALUES OF MEASURED MOTION COMPONENTS WITH
PITCHING VELOCITY INPUTS AND MEAN RIDE COMFORT RESPONSES

Longitudinal acc. g	Transverse acc. g	Vertical acc. g	Pitching velocity deg/sec	Rolling velocity deg/sec	Yawing velocity deg/sec	R_s	σ_{R_s}
(a) Typical 0-1 Hz inputs							
0.0091	0.0093	0.0115	1.3765	1.2196	0.6881	2.188	0.741
0.0126	0.0101	0.0214	2.4391	1.2475	0.6466	2.438	0.496
0.0221	0.0134	0.0437	5.0500	1.4136	0.6545	3.750	0.534
0.0301	0.0158	0.0584	6.4297	1.5243	0.7166	4.188	0.704
(b) Typical 0-2 Hz inputs							
0.0078	0.0088	0.0079	0.7968	1.2047	0.6610	1.875	0.795
0.0103	0.0100	0.0162	1.0703	1.1617	0.5569	2.750	0.463
0.0199	0.0162	0.0362	2.0615	1.8173	0.6545	2.938	0.853
0.0340	0.0220	0.0617	3.0766	2.1941	0.7472	4.250	0.655
(c) Typical 1-2 Hz inputs							
0.0078	0.0093	0.0083	0.7976	1.2905	0.6781	1.688	0.795
0.0108	0.0107	0.0152	0.9663	1.2570	0.6196	2.625	0.518
0.0210	0.0160	0.0352	1.8359	1.6844	0.6756	3.562	0.320
0.0333	0.0218	0.0609	3.0231	2.1300	0.6993	4.375	0.518

TABLE II (concluded)

Longitudinal acc. g	Transverse acc. g	Vertical acc. g	Pitching velocity deg/sec	Rolling velocity deg/sec	Yawing velocity deg/sec	R_s	σ_{R_s}
(d) Flat 0-1 Hz inputs							
0.0087	0.0087	0.0118	1.2982	1.1179	0.6217	2.062	0.863
0.0096	0.0095	0.0132	1.3913	1.2759	0.6776	2.438	0.623
0.0248	0.0145	0.0483	4.6702	1.4978	0.6549	3.812	0.651
0.0294	0.0160	0.0598	6.3856	1.5236	0.6878	4.062	1.016
(e) Flat 0-2 Hz inputs							
0.0076	0.0088	0.0083	0.8037	1.2464	0.6542	2.062	1.084
0.0101	0.0098	0.0149	1.0122	1.1893	0.6192	2.312	0.651
0.0206	0.0137	0.0357	2.0152	1.5647	0.7013	3.375	0.641
0.0273	0.0164	0.0528	3.0080	1.8122	0.7162	4.188	0.704
(f) Flat 1-2 Hz inputs							
0.0067	0.0084	0.0075	0.7410	1.2517	0.6315	1.938	0.623
0.0108	0.0112	0.0158	0.9613	1.2774	0.6051	2.500	0.598
0.0225	0.0161	0.0366	1.9212	1.7564	0.8024	3.562	0.555
0.0273	0.0160	0.0461	2.3904	1.5947	0.6490	3.438	1.591

TABLE III - CROSS-CORRELATION COEFFICIENTS OF
MOTION COMPONENTS WITH PITCHING VELOCITY INPUTS

Longitudinal -Vertical	Longitudinal -Pitch	Transverse -Roll	Transverse -Yaw	Vertical -Pitch	Roll -Yaw
(a) Typical 0-1 Hz inputs					
0.6574	0.5034	0.7341	0.8564	0.3411	0.9202
0.7123	0.2755	0.4249	0.6677	0.1015	0.8293
0.7762	0.1634	0.2430	0.6010	0.0466	0.7367
0.7818	0.1583	0.2524	0.5922	0.0243	0.7515
(b) Typical 0-2 Hz inputs					
0.6836	0.8084	0.6217	0.8071	0.6842	0.8809
0.5236	0.5424	0.4617	0.7359	0.2327	0.8080
0.5134	0.3019	0.1144	0.5279	0.0425	0.6660
0.6228	0.3289	0.0692	0.5548	-0.0028	0.6040
(c) Typical 1-2 Hz inputs					
0.6978	0.8566	0.4990	0.7732	0.7490	0.8208
0.6526	0.6102	0.4257	0.7195	0.3650	0.7895
0.5708	0.3277	0.1943	0.5733	0.0591	0.6995
0.6874	0.3187	0.0408	0.5350	-0.0091	0.5822

TABLE III (concluded)

Longitudinal -Vertical	Longitudinal -Pitch	Transverse -Roll	Transverse -Yaw	Vertical -Pitch	Roll -Yaw
(d) Flat 0-1 Hz inputs					
0.6426	0.5035	0.6513	0.8337	0.3058	0.9112
0.7260	0.5748	0.7078	0.8587	0.4393	0.9288
0.7869	0.1664	0.1486	0.5577	0.0484	0.6837
0.7746	0.1970	0.2442	0.5820	0.0402	0.7698
(e) Flat 0-2 Hz inputs					
0.7685	0.8771	0.6788	0.8579	0.7659	0.9199
0.5481	0.5554	0.5156	0.7742	0.2662	0.8722
0.5467	0.3659	0.5208	0.6450	0.0712	0.7337
0.5546	0.2967	0.1415	0.5240	0.0185	0.7292
(f) Flat 1-2 Hz inputs					
0.8111	0.9360	0.6694	0.8774	0.8619	0.9106
0.6688	0.5255	0.2979	0.6703	0.3051	0.7940
0.6123	0.4918	0.4256	0.6974	0.1728	0.8348
0.5970	0.3225	0.0711	0.5135	0.0327	0.6409

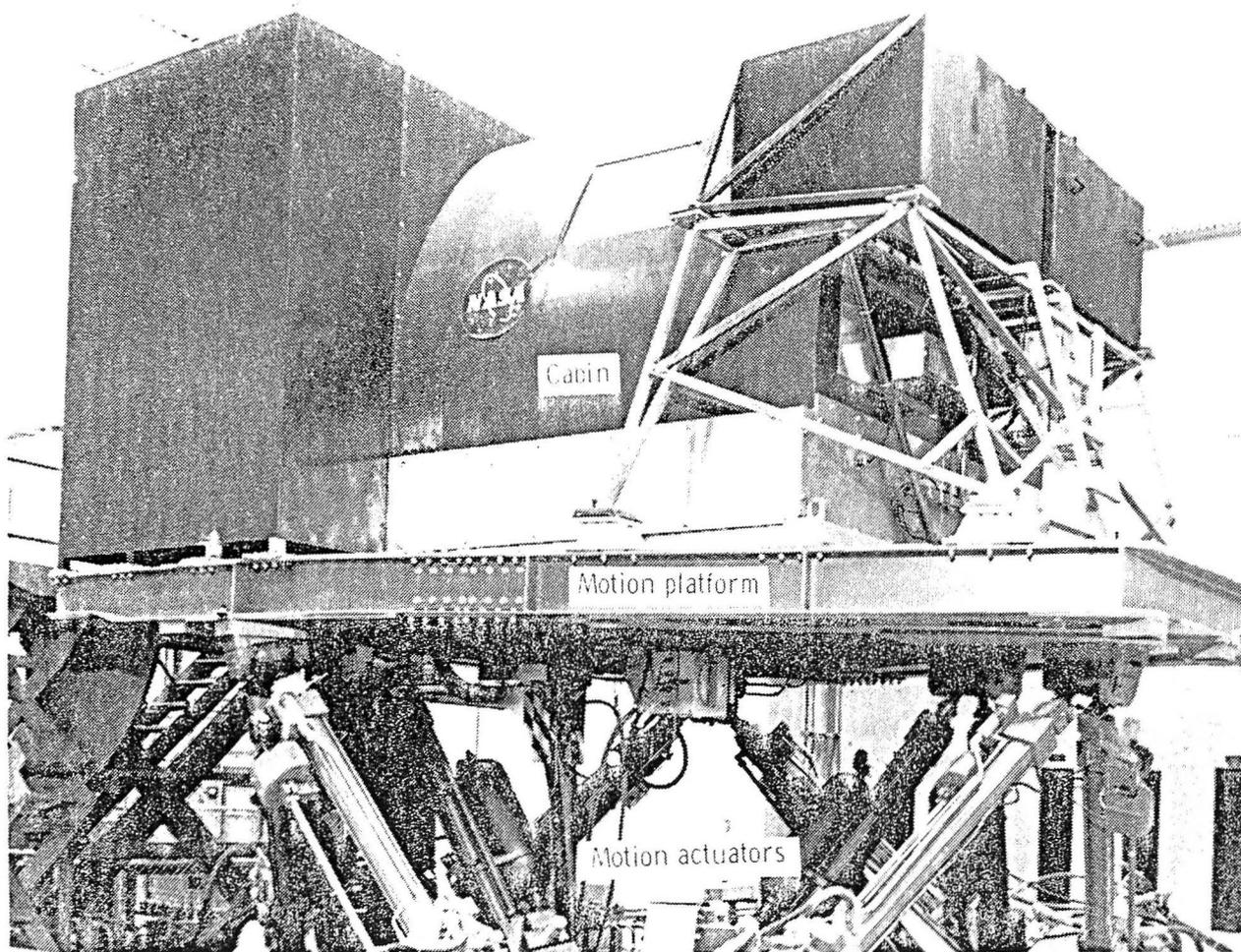
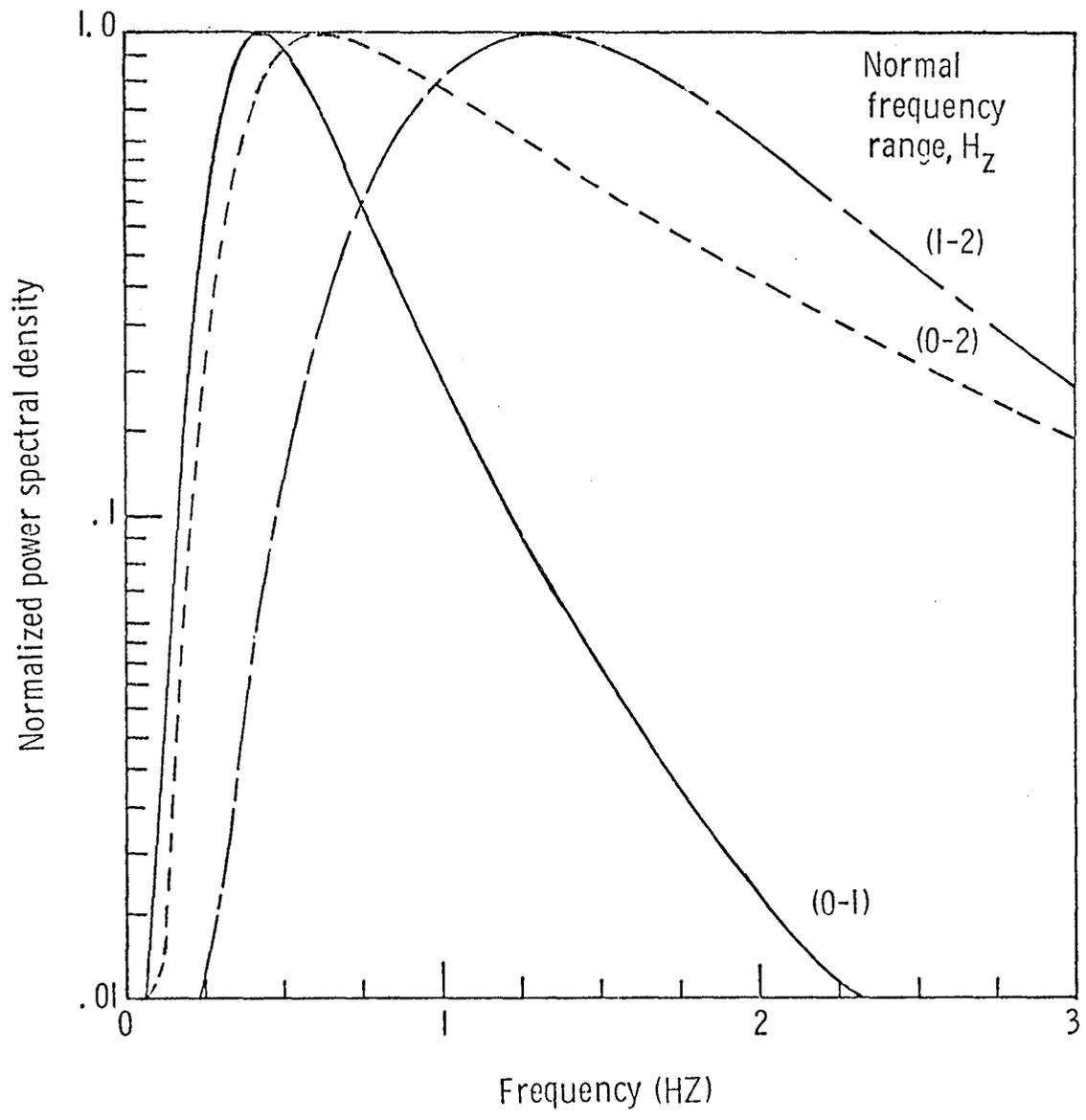
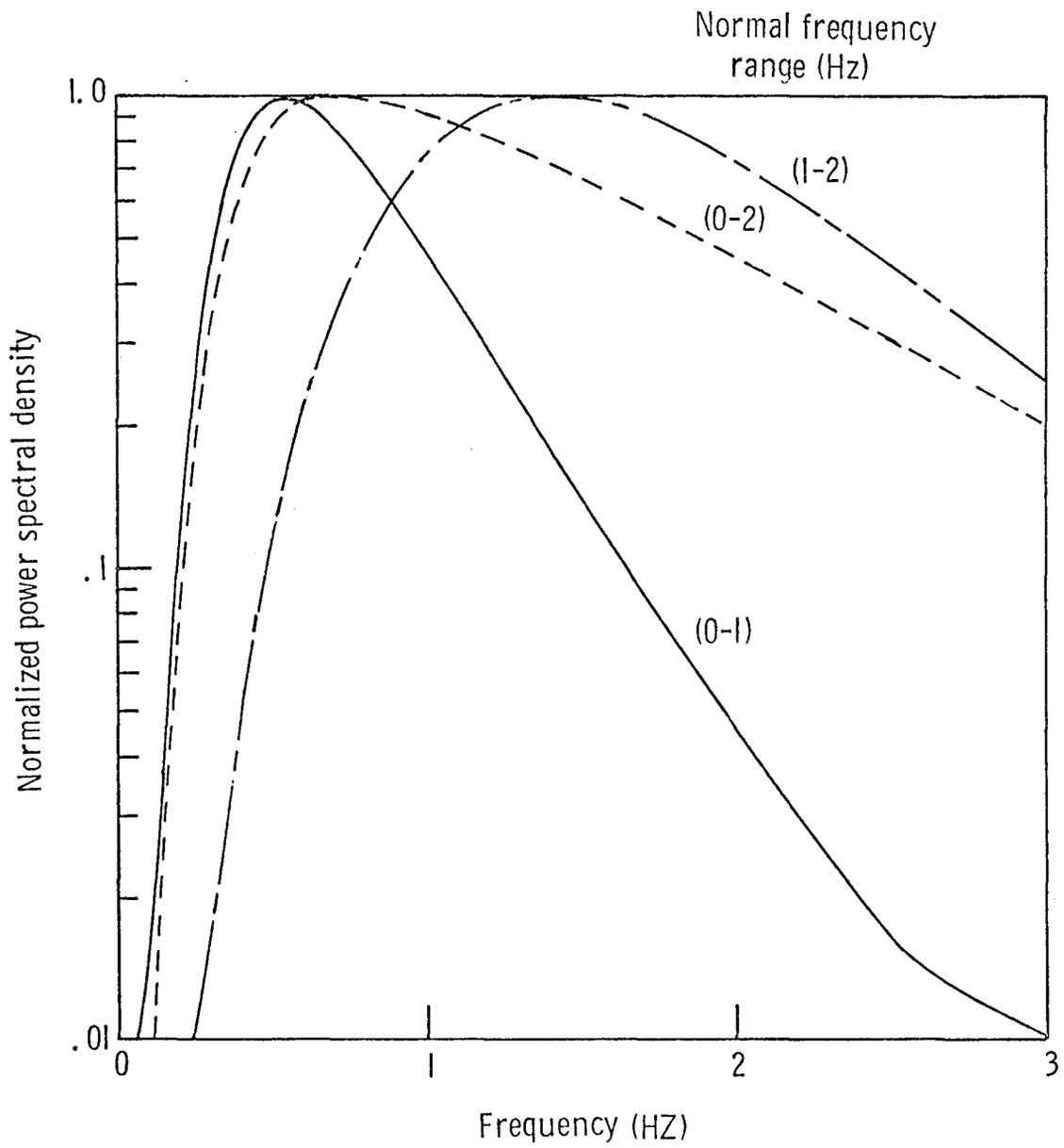


Figure 1 - Langley six-degree-of-freedom, vision motion simulator.



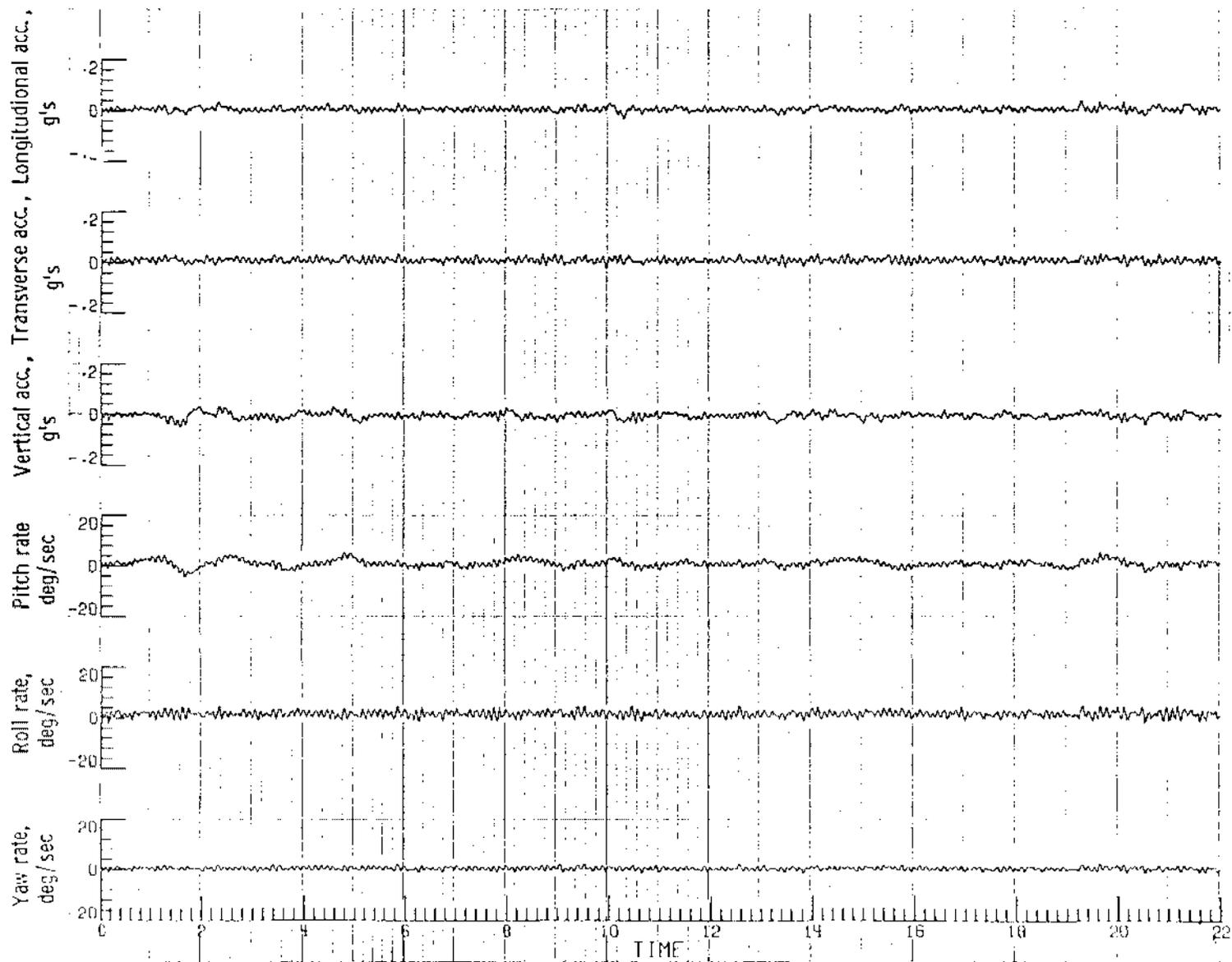
(a) Typical spectra.

Figure 2 - Nominal power spectra of motion components.



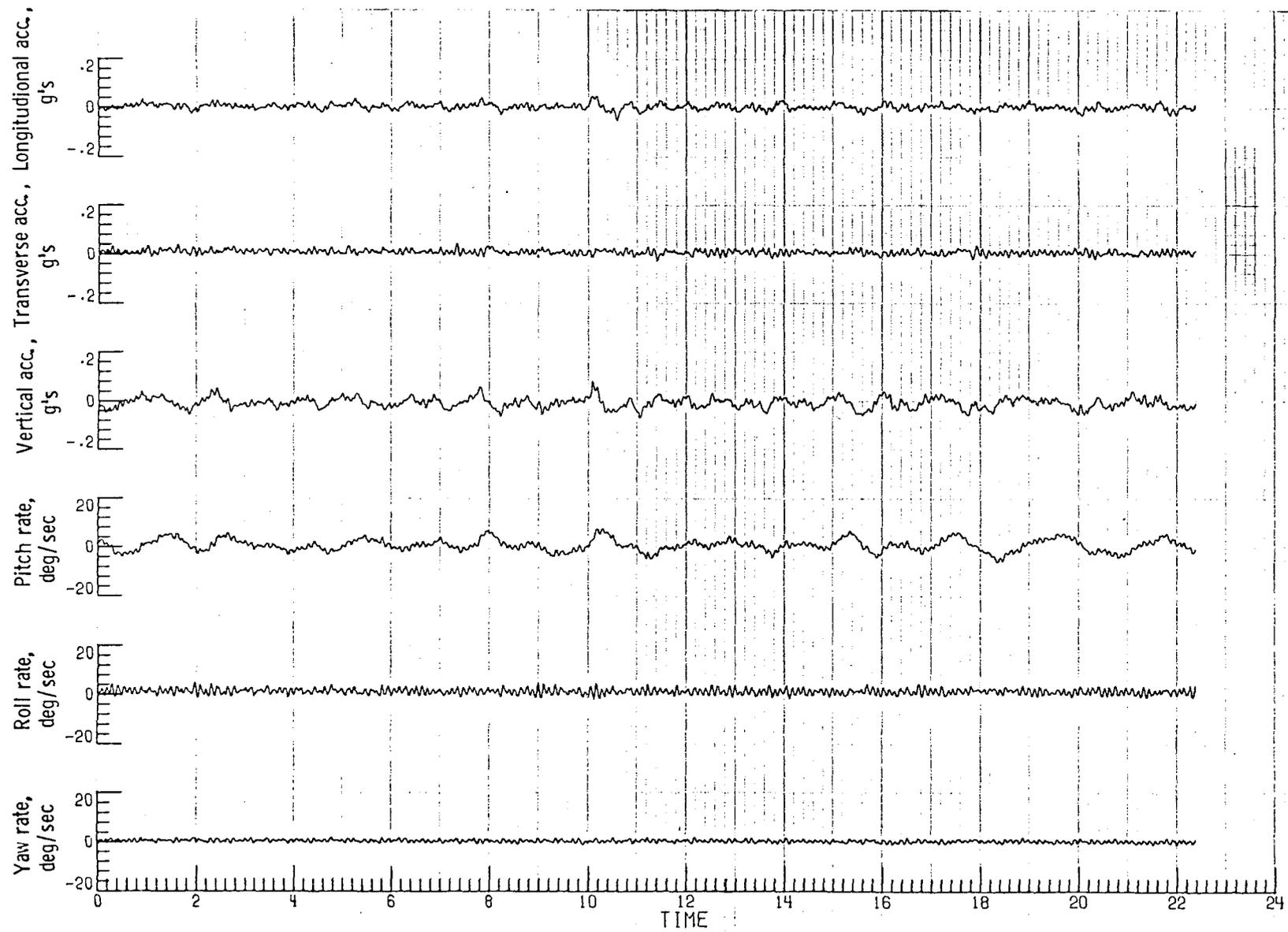
(b) Flat spectra

Figure 2 - Concluded.



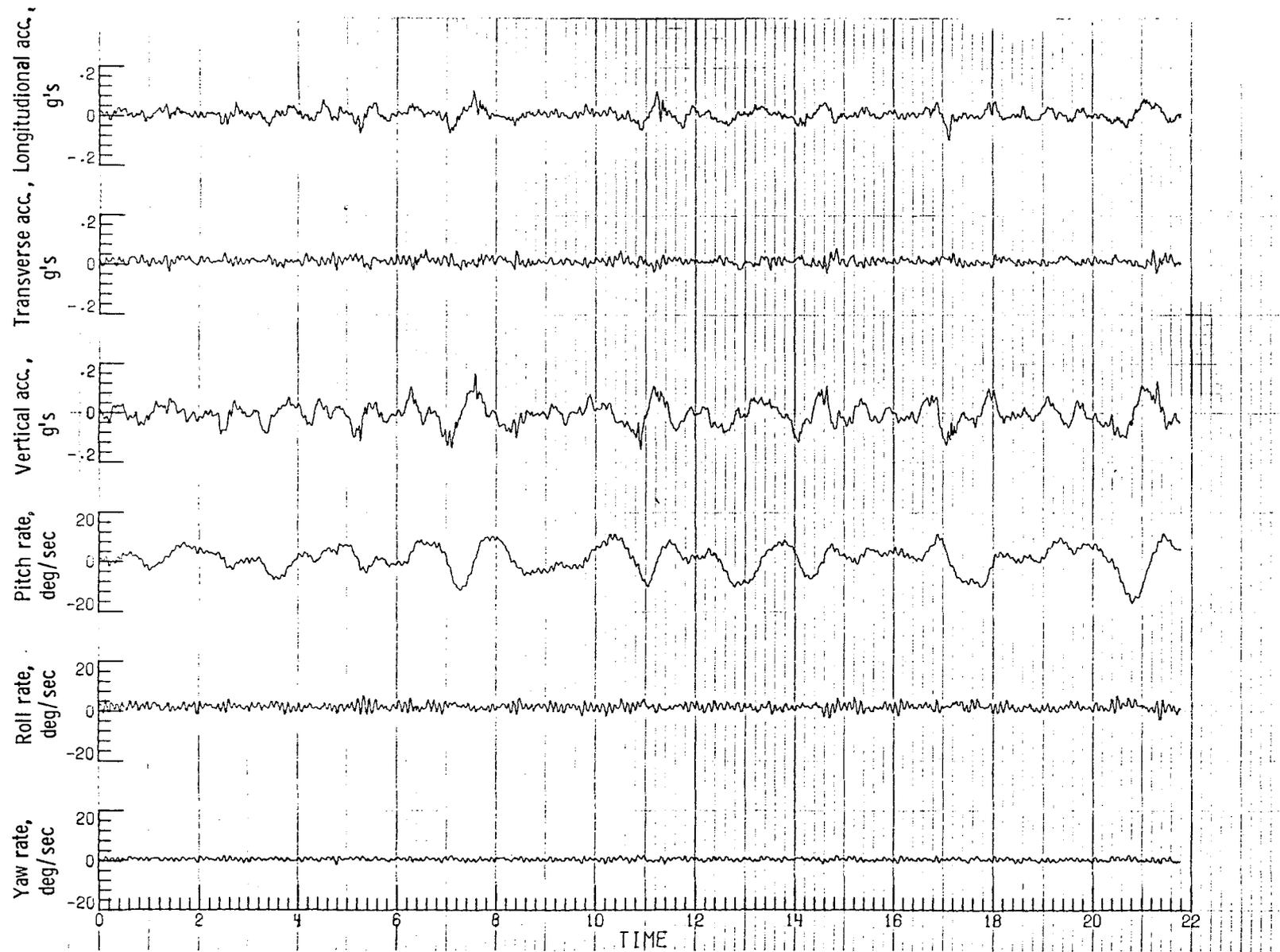
(a) Time histories (RMS pitching velocity 1.376 deg/sec).

Figure 3. Measured motion characteristics using pitching velocity with typical 0-1 Hz inputs.



(a) Time histories (RMS pitching velocity 2.439 deg/sec).

Figure 3. - Continued.



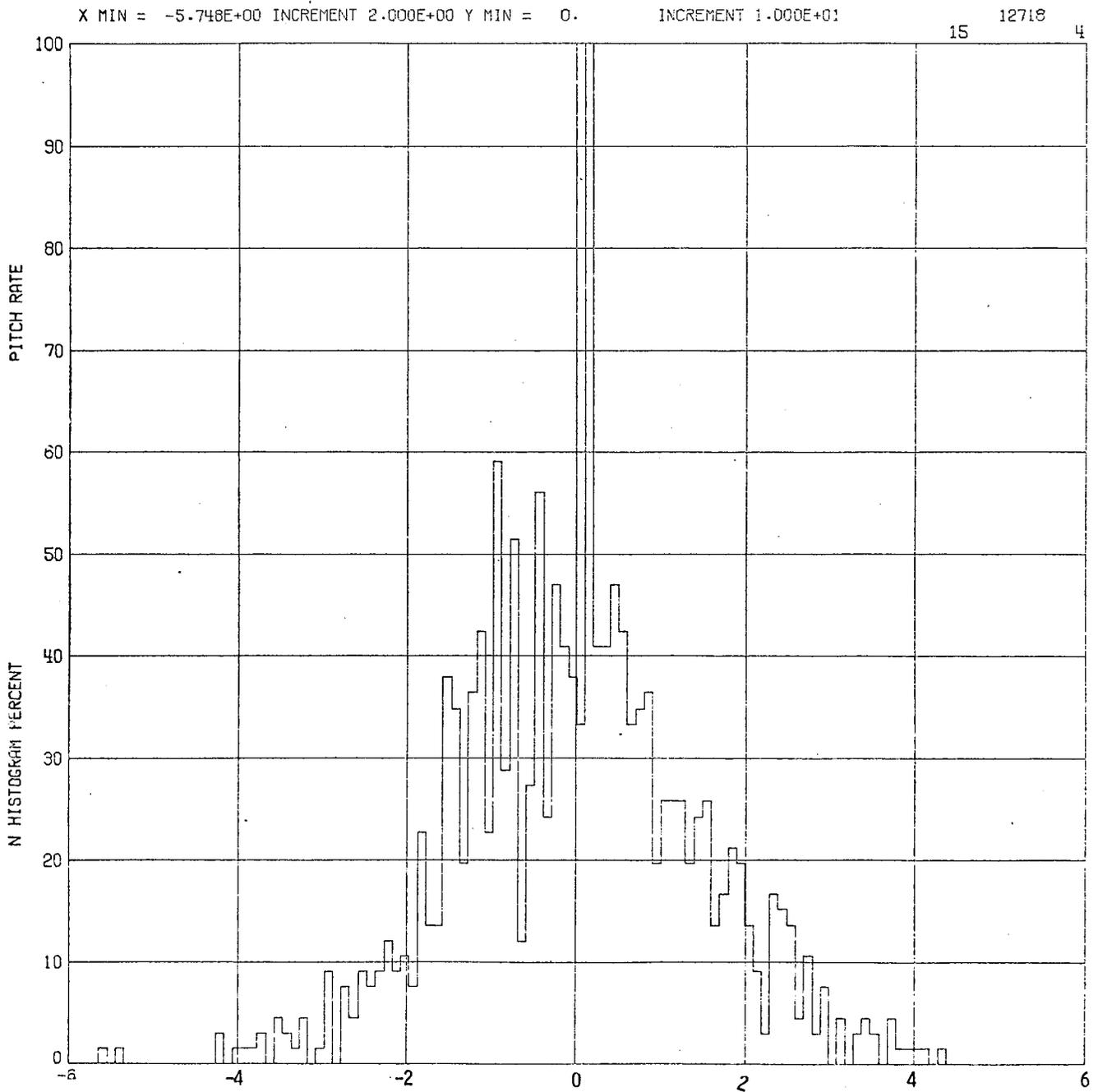
(a) Time histories (RMS pitching velocity 5.050 deg/sec).

Figure 3. - Continued.



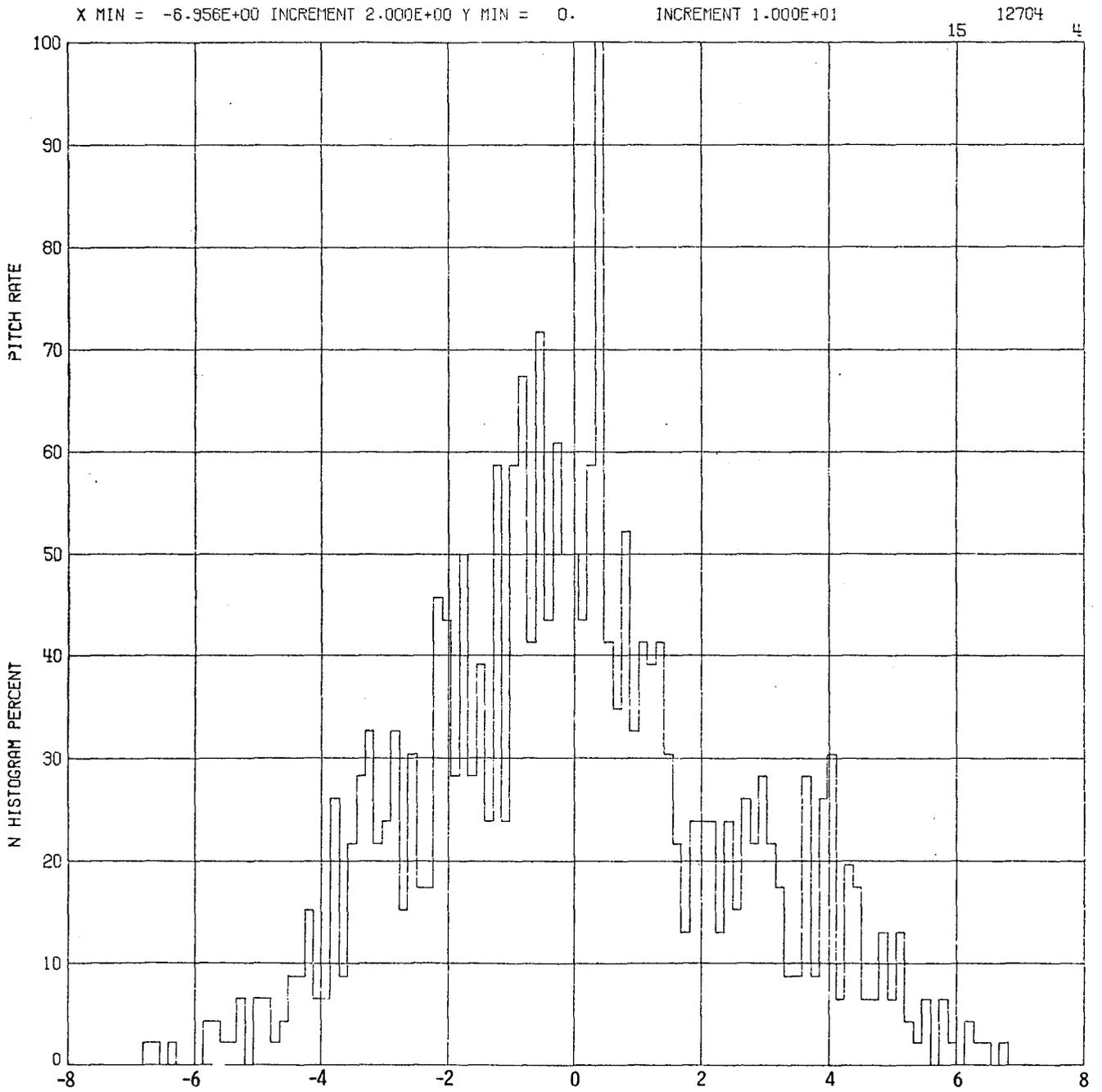
(a) Time histories (RMS pitching velocity 6.430 dea/sec).

Figure 3.- Continued.



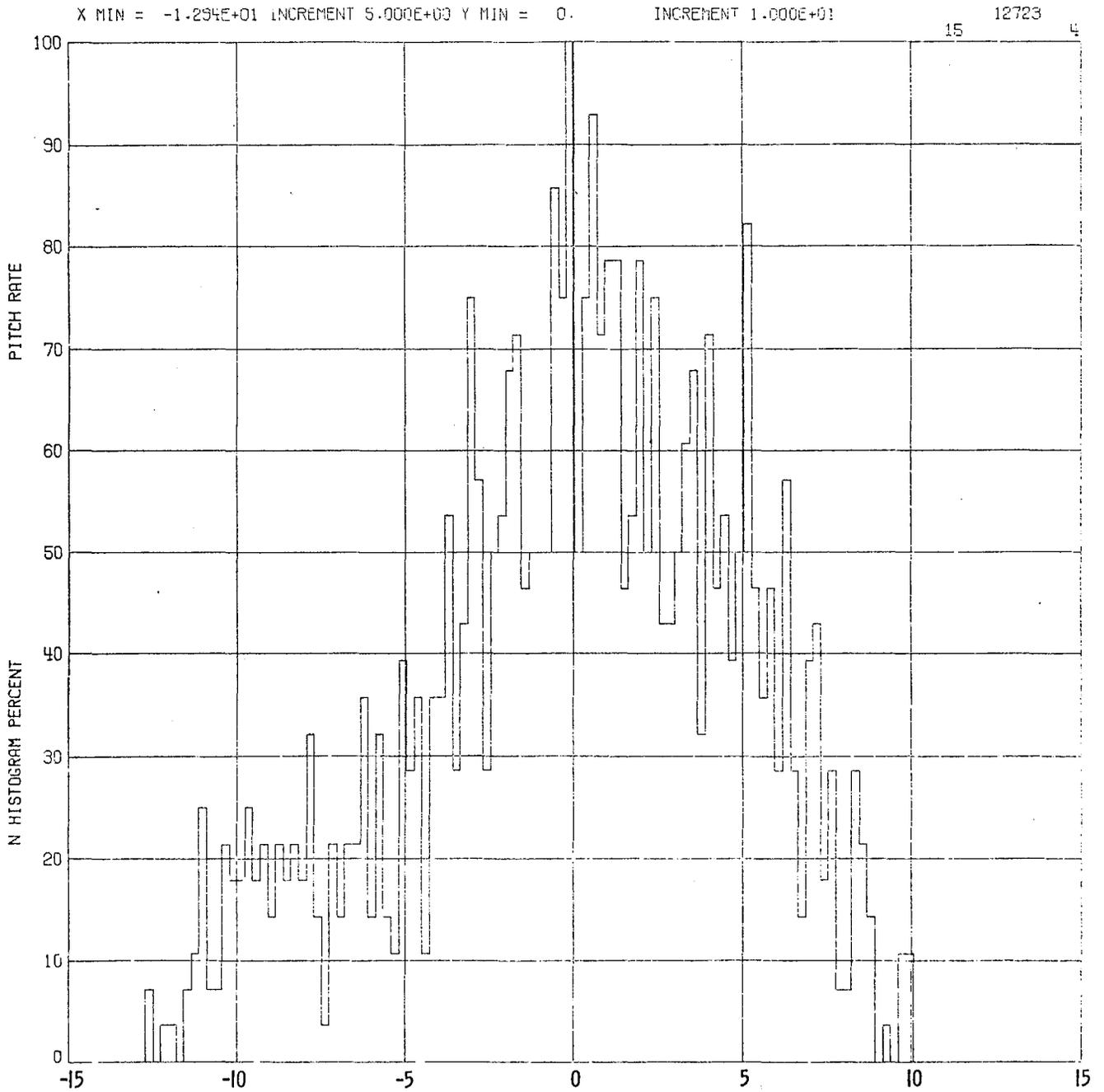
(b) Pitching velocity histograms (RMS pitching velocity 1.376 deg/sec).

Figure 3, - Continued.¹



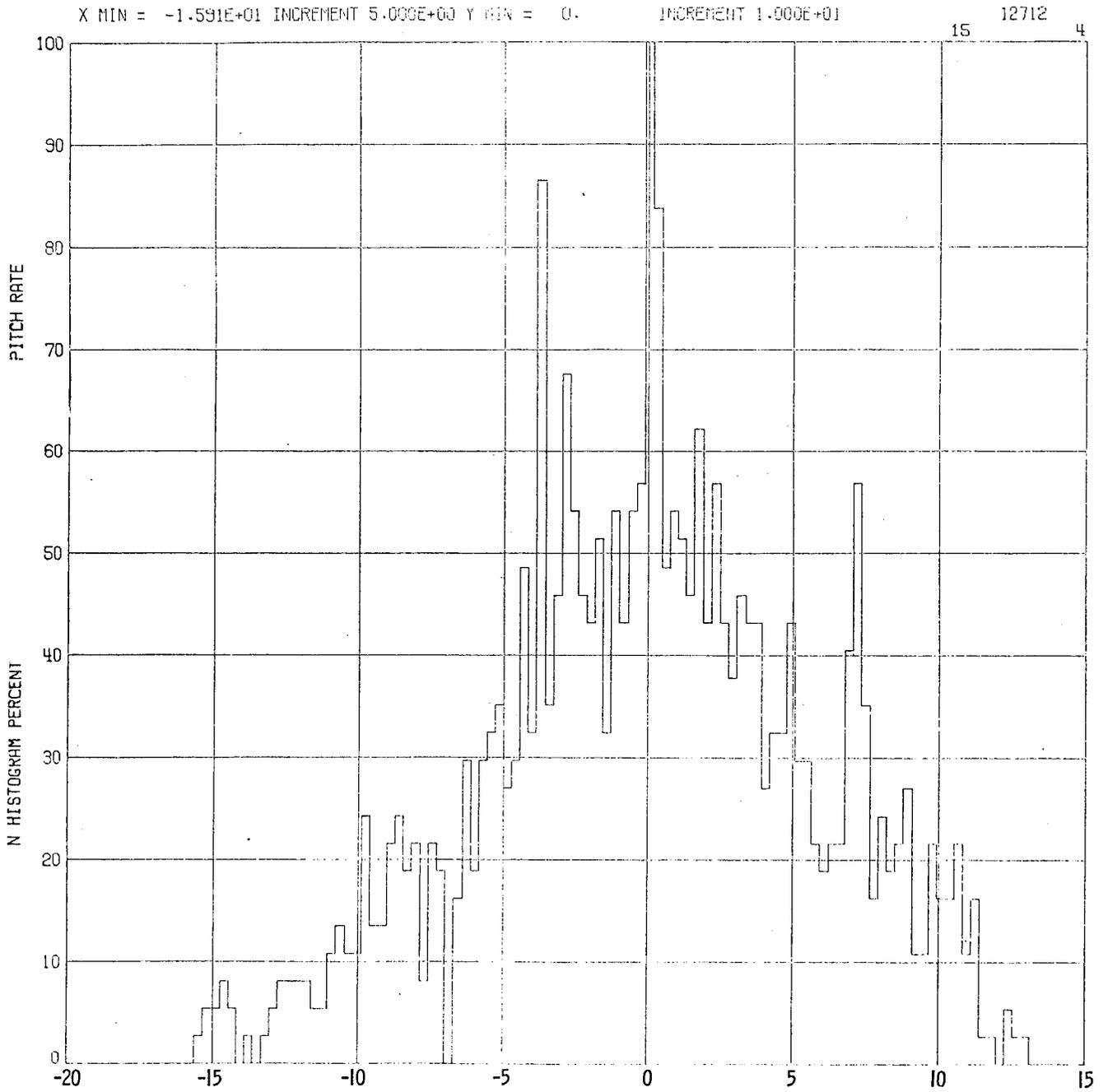
(b) Pitching velocity histograms (RMS pitching velocity 2.439 deg/sec).

Figure 3. - Continued.



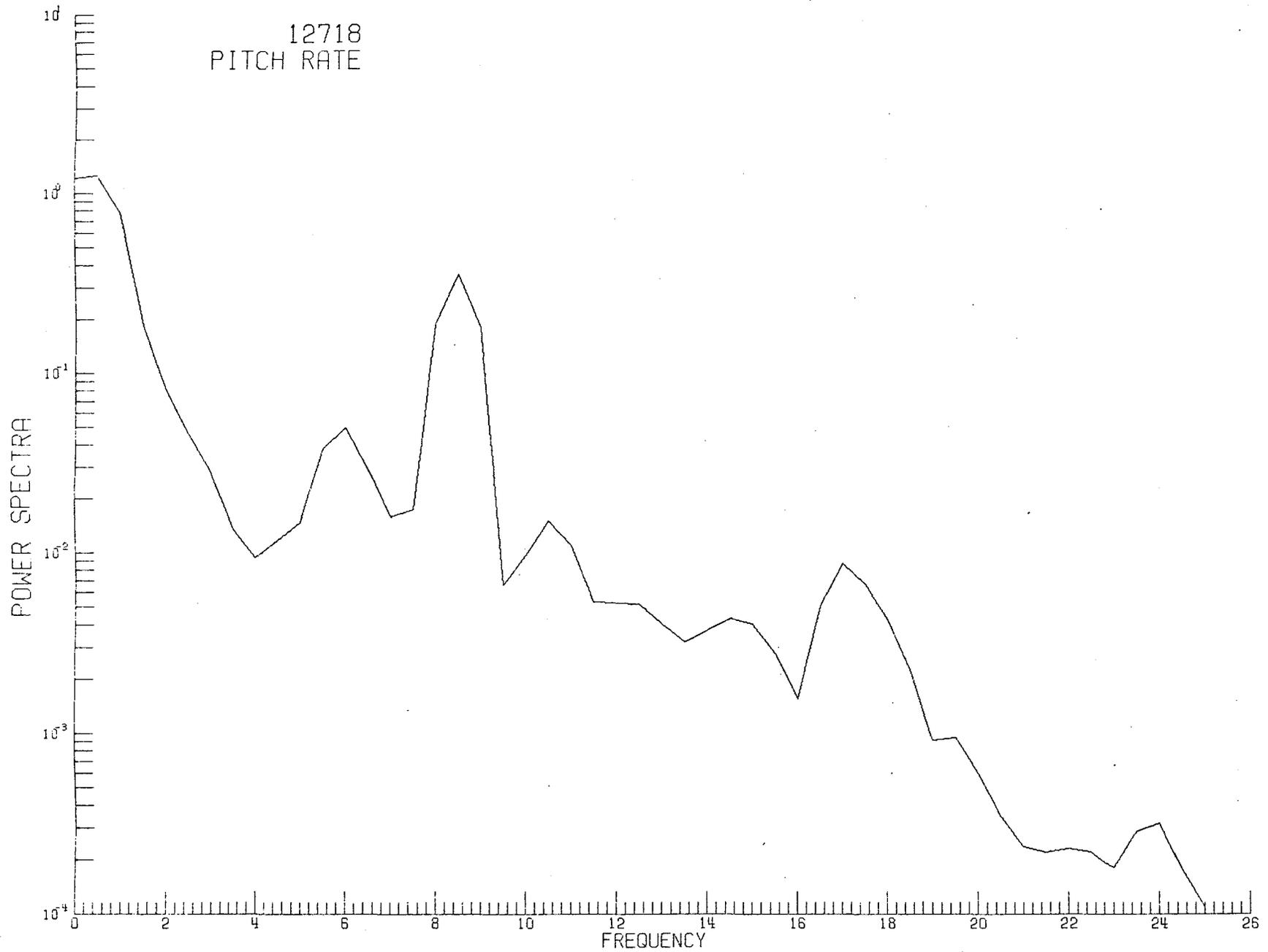
(b) Pitching velocity histograms (RMS pitching velocity 5.050 deg/sec).

Figure 3 - Continued.



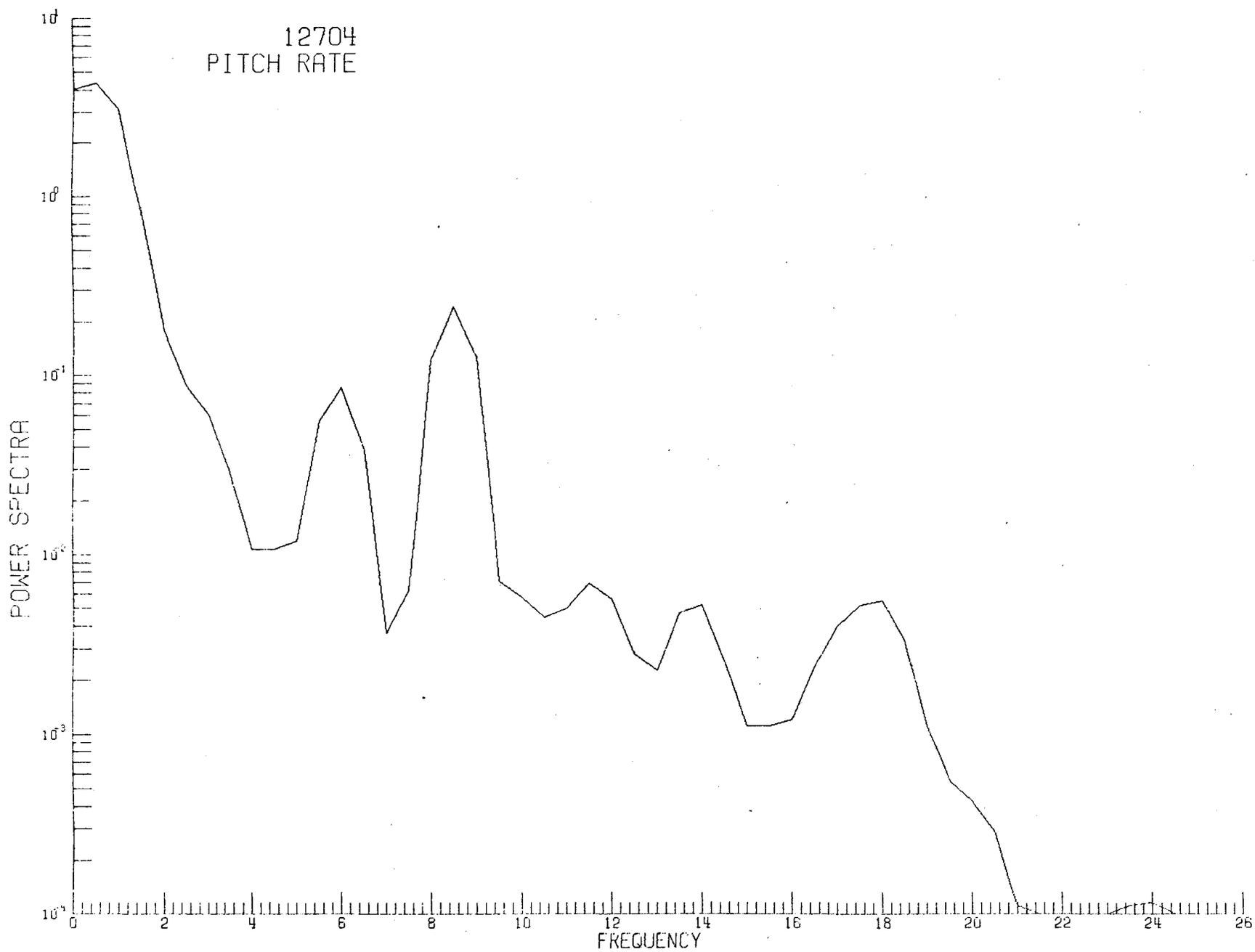
(b) Pitching velocity histograms (RMS pitching velocity 6.430 deg/sec).

Figure 3. - Continued.



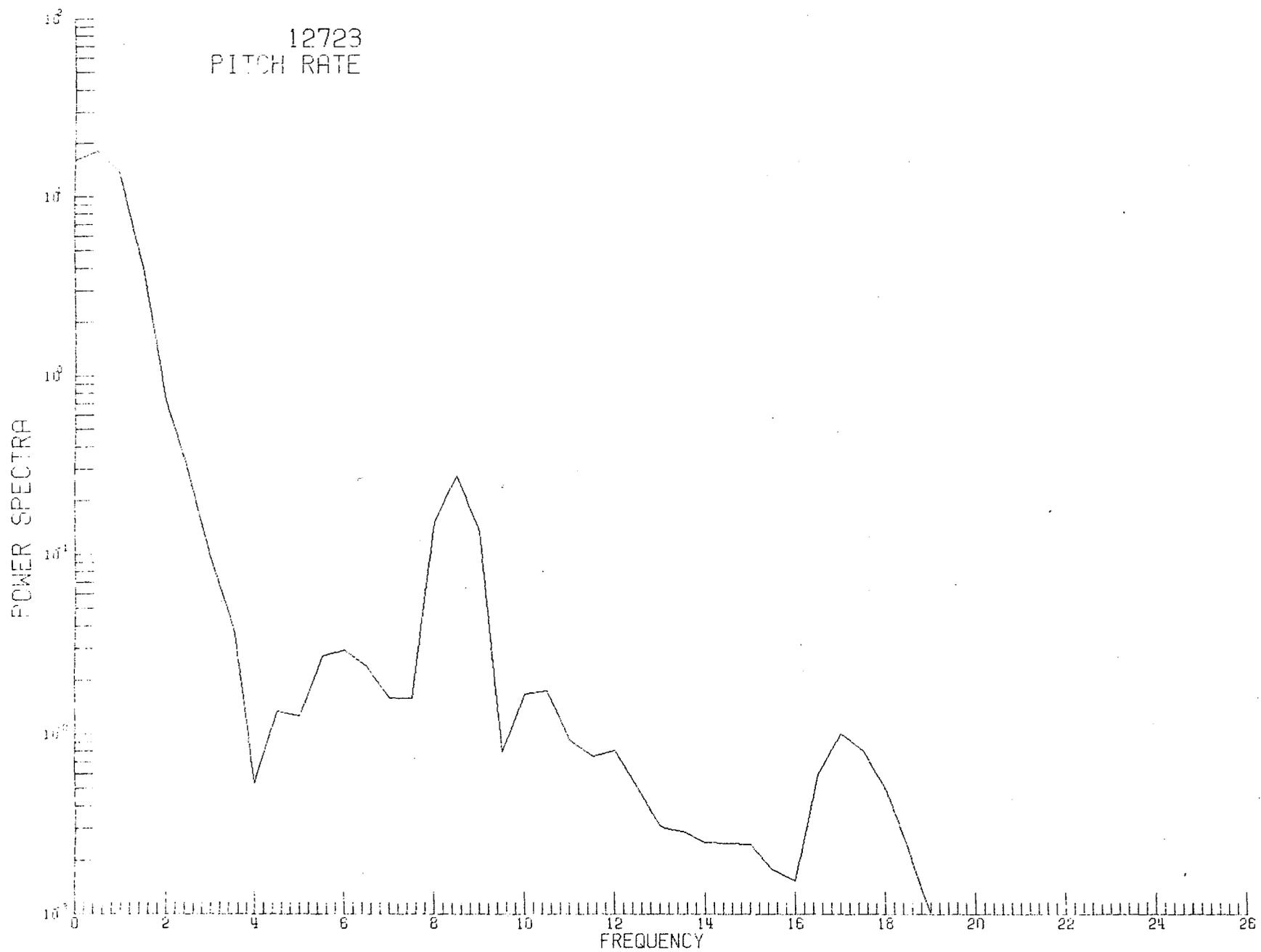
(c) Pitching velocity power spectrum (RMS pitching velocity 1.376 deg/sec).

Figure 3. - Continued.



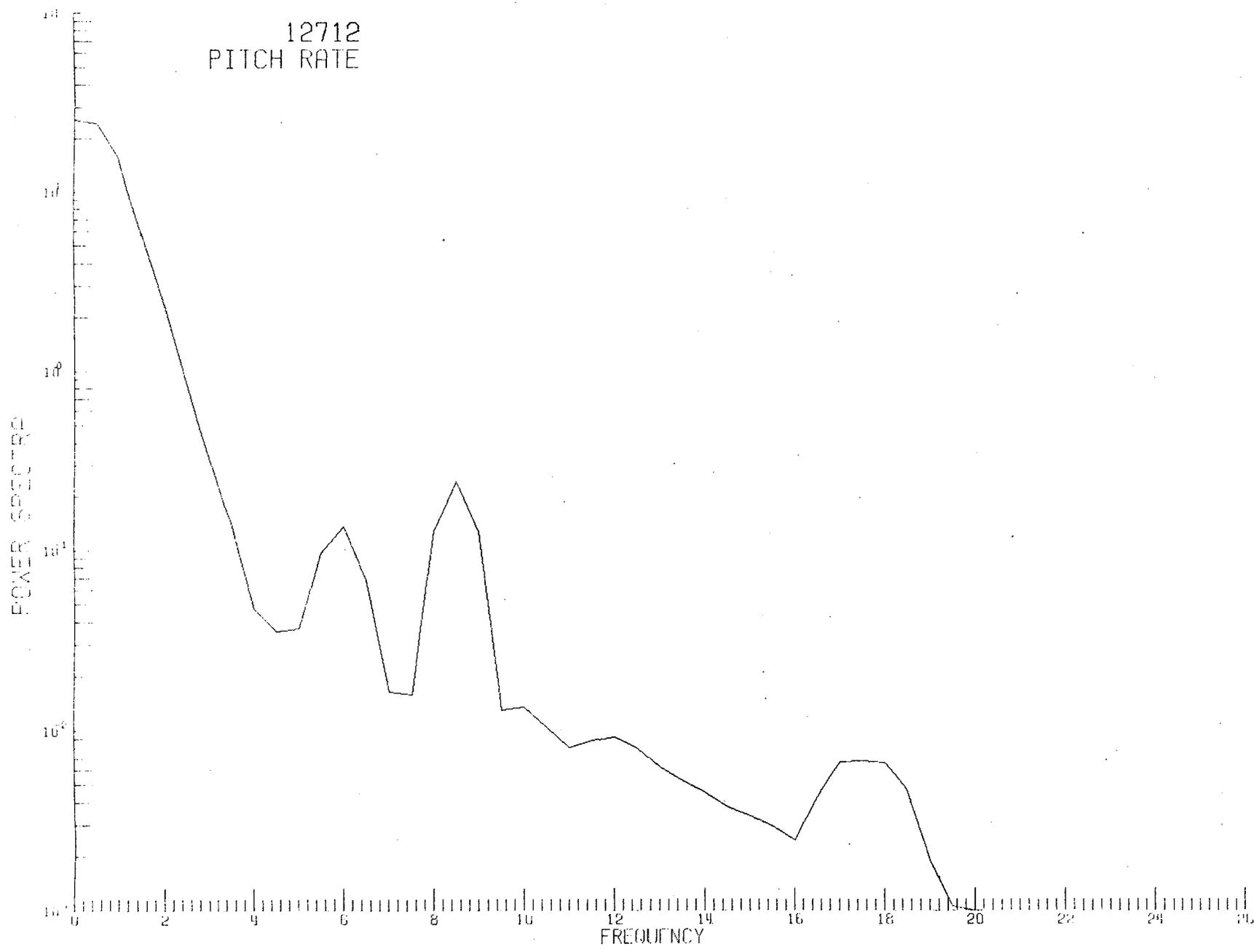
(c) Pitching velocity power spectrum (RMS pitching velocity 2.439 deg/sec).

Figure 3. - Continued.



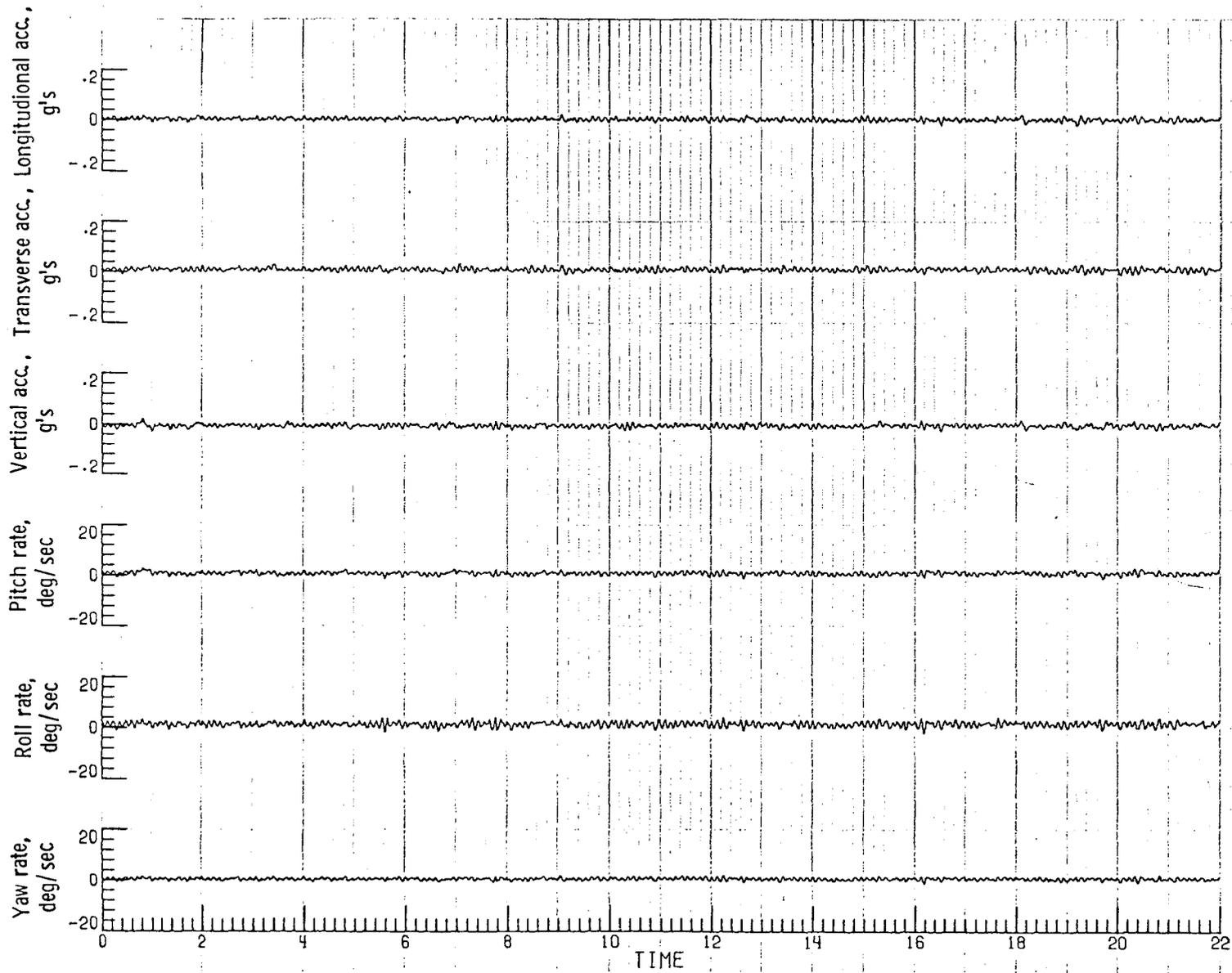
(c) Pitching velocity power spectrum (RMS pitching velocity 5.050 deg/sec).

Figure 3, - Continued.



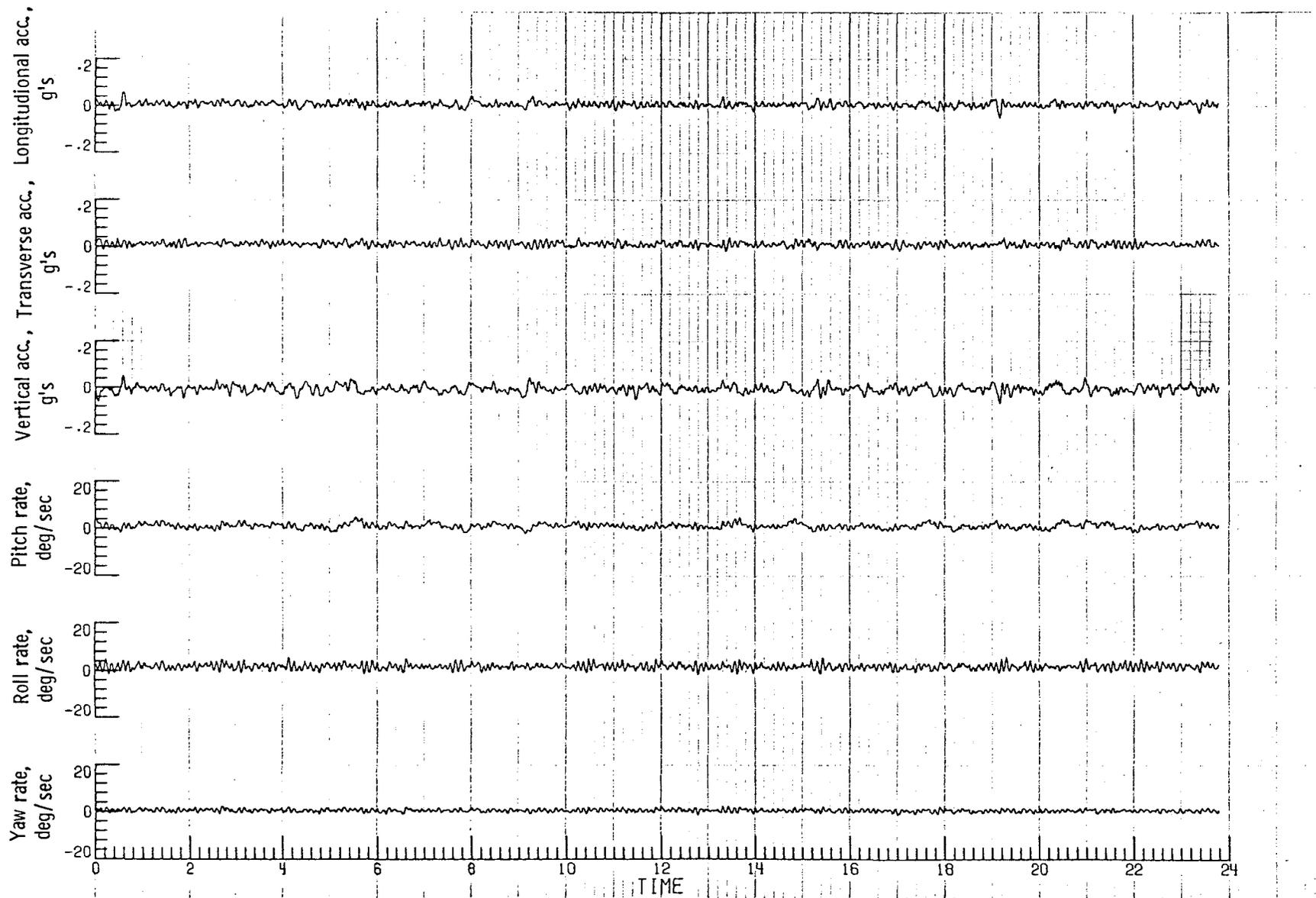
(c) Pitching velocity power spectrum (RMS pitching velocity 6.430 deg/sec).

Figure 3. Concluded.



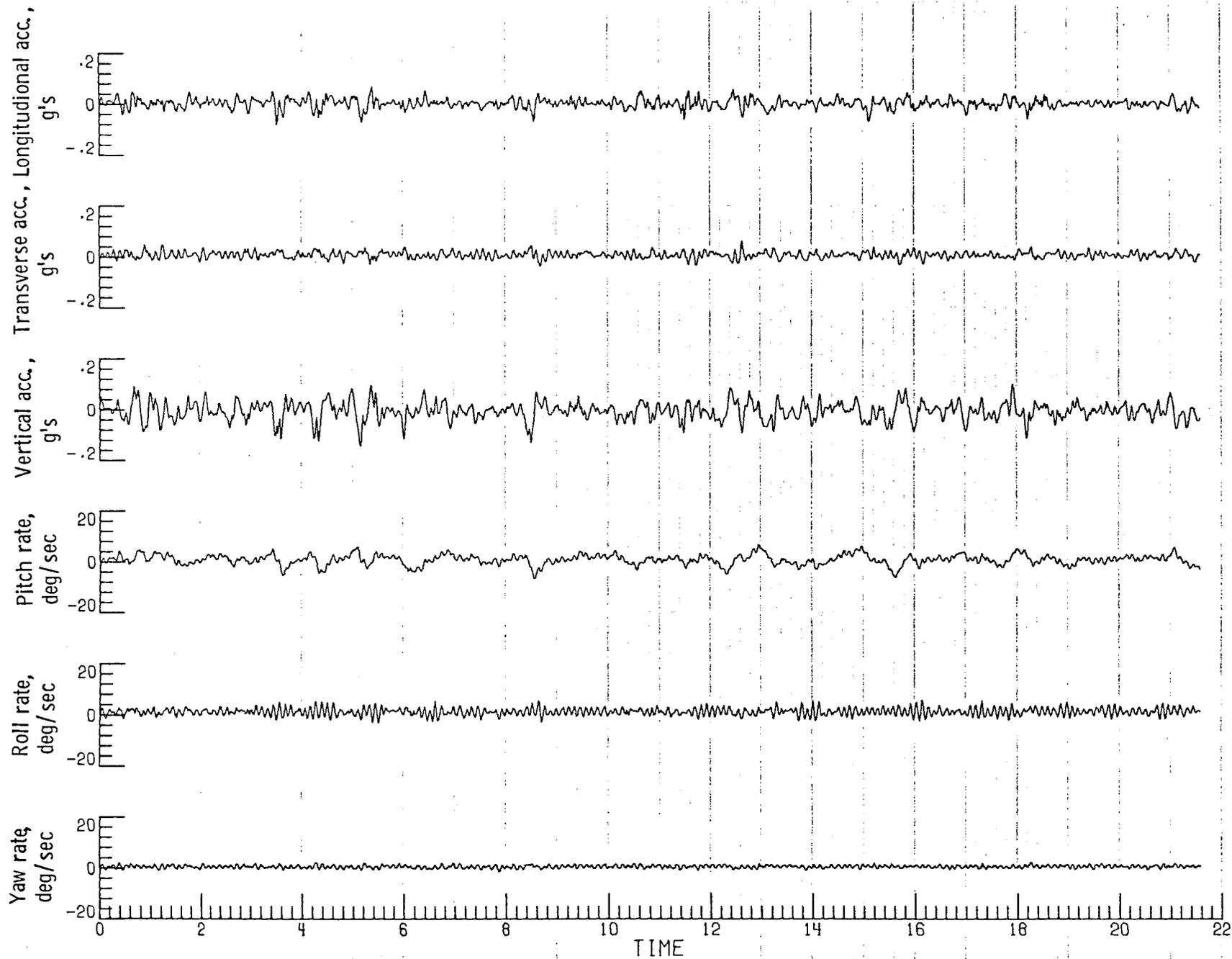
(a) Time histories (RMS pitching velocity 0.797 deg/sec).

Figure 4. - Measured motion characteristics using pitching velocity with typical 0-2 HZ inputs.



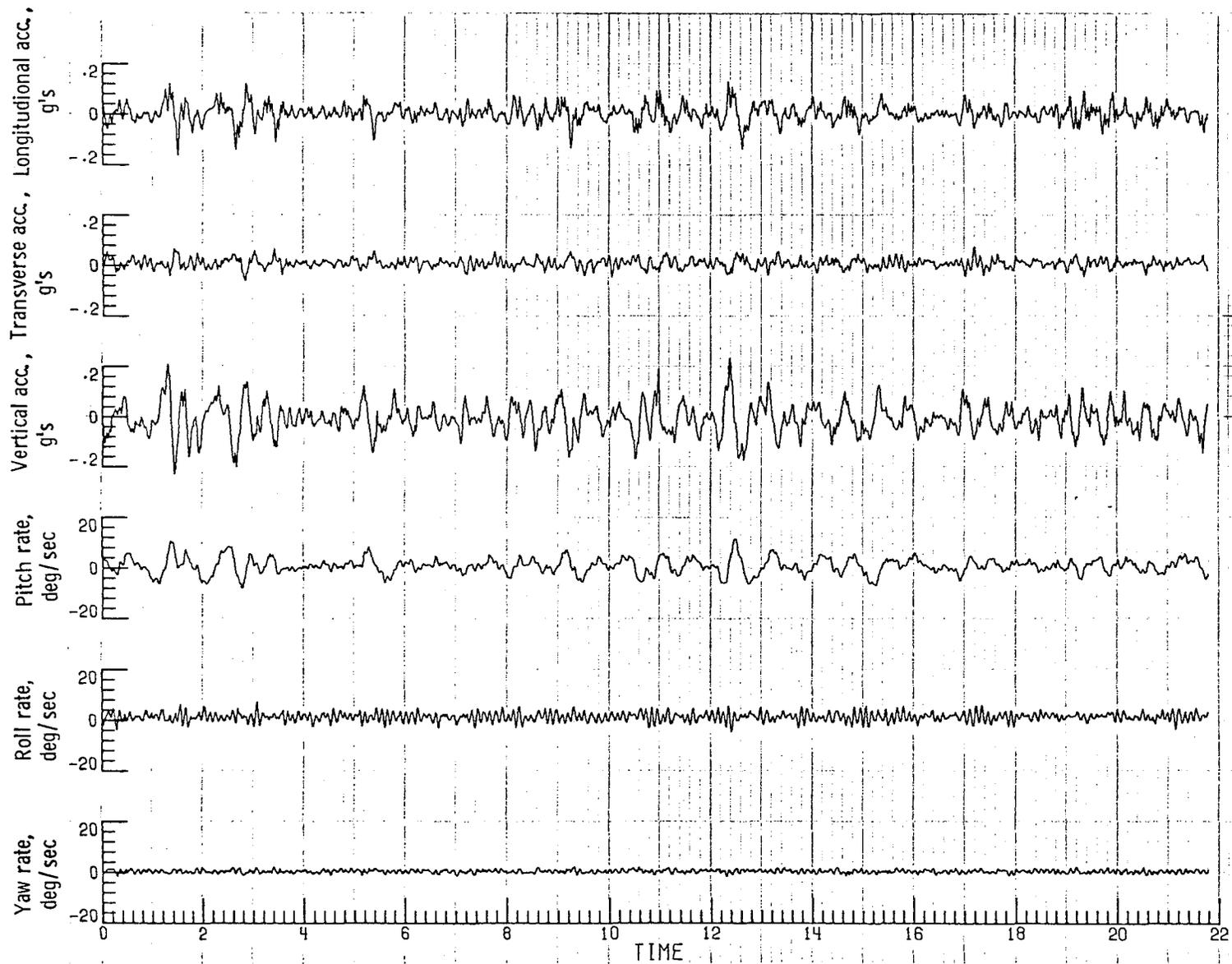
(a) Time histories (RMS pitching velocity 1.070 dea/sec).

Figure 4. - Continued.



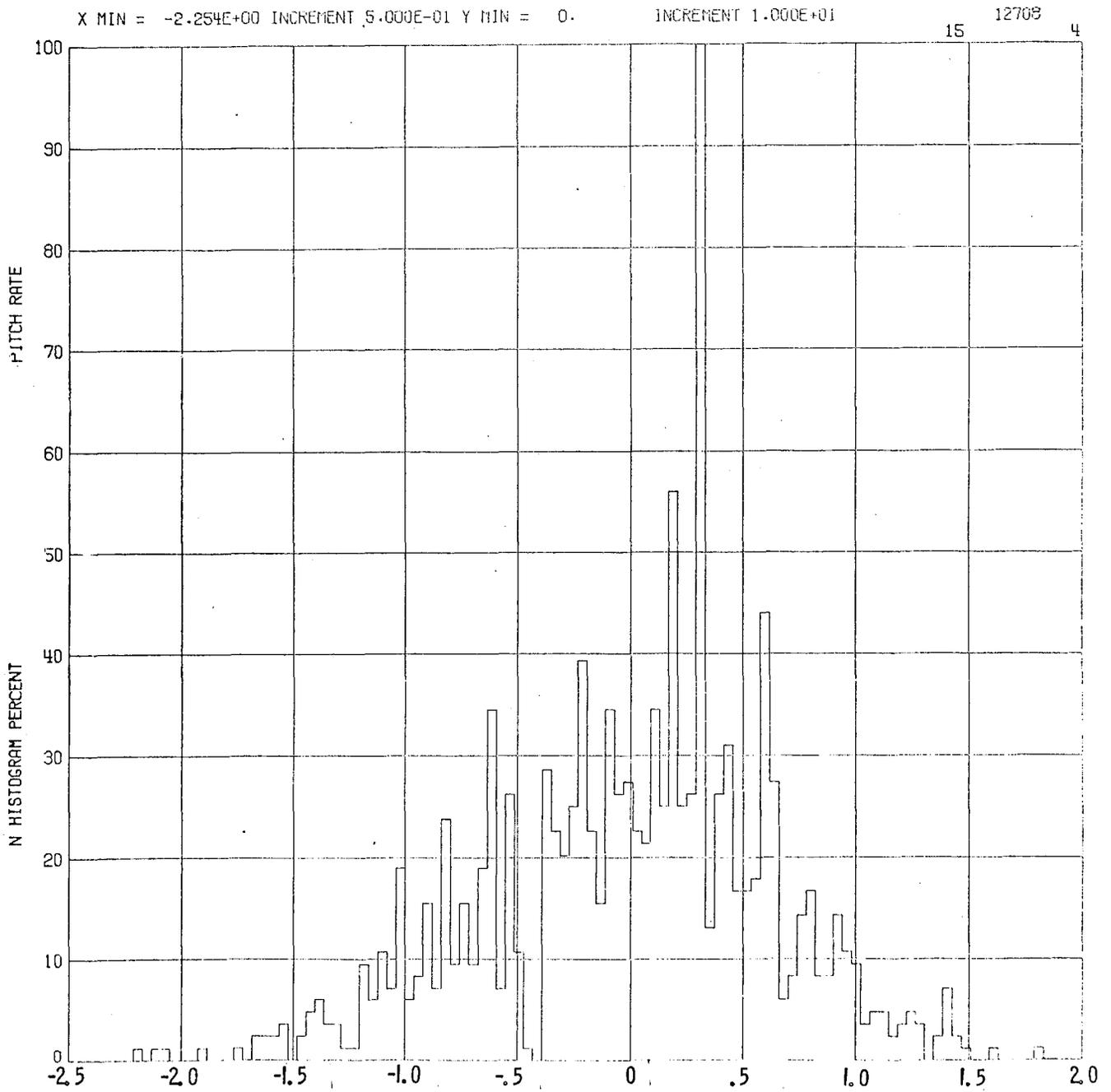
(a) Time histories (RMS pitching velocity 2.061 deg/sec).

Figure 4, -Continued.



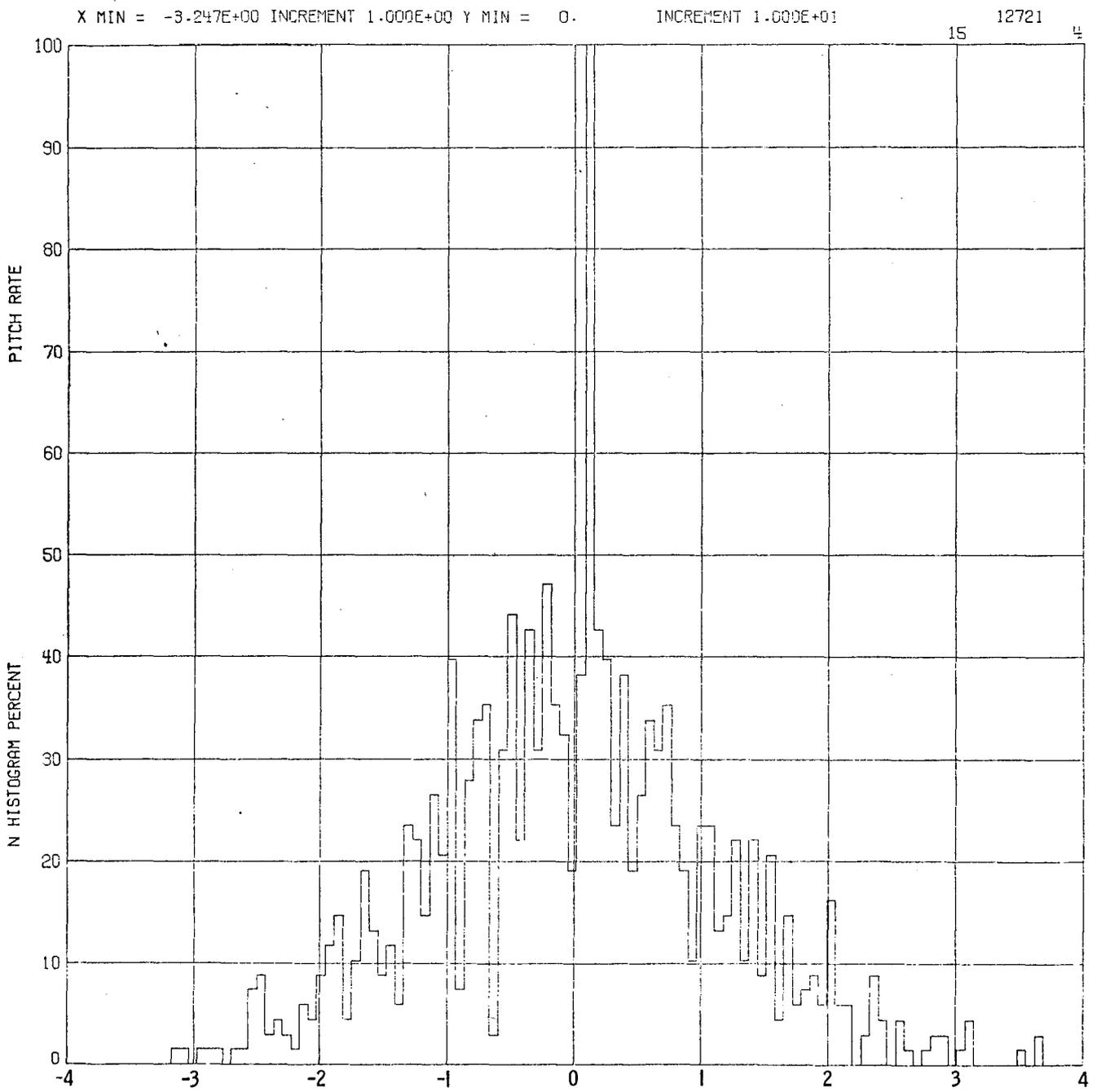
(a) Time histories (RMS pitch rate velocity 3.077 deg/sec).

Figure 4. - Continued.



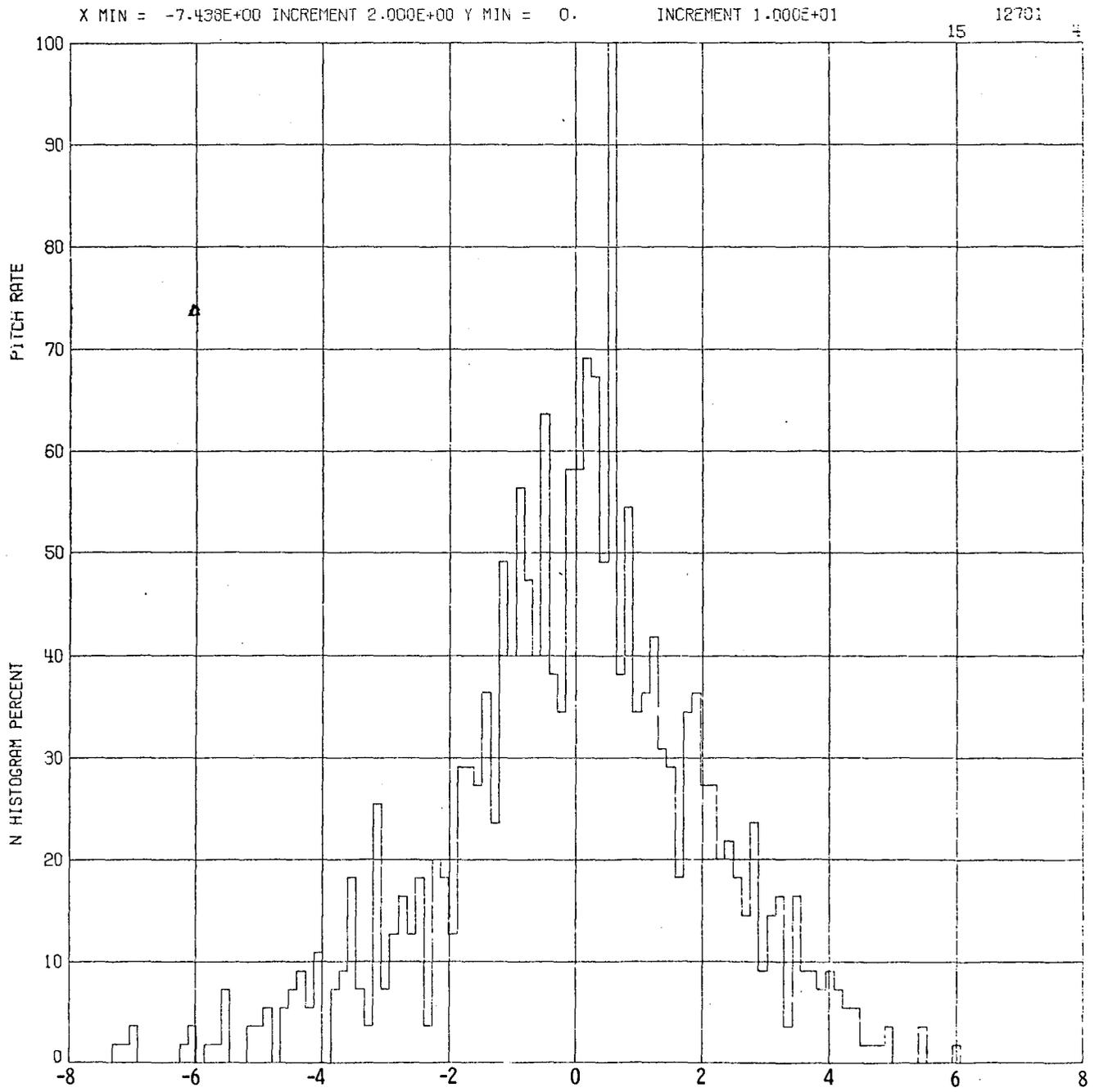
(b) Pitching velocity histograms (RMS pitching velocity 0.797 deg/sec).

Figure 4. - Continued.



(b) Pitching velocity histograms (RMS pitching velocity 1.070 deg/sec).

Figure 4. - Continued.



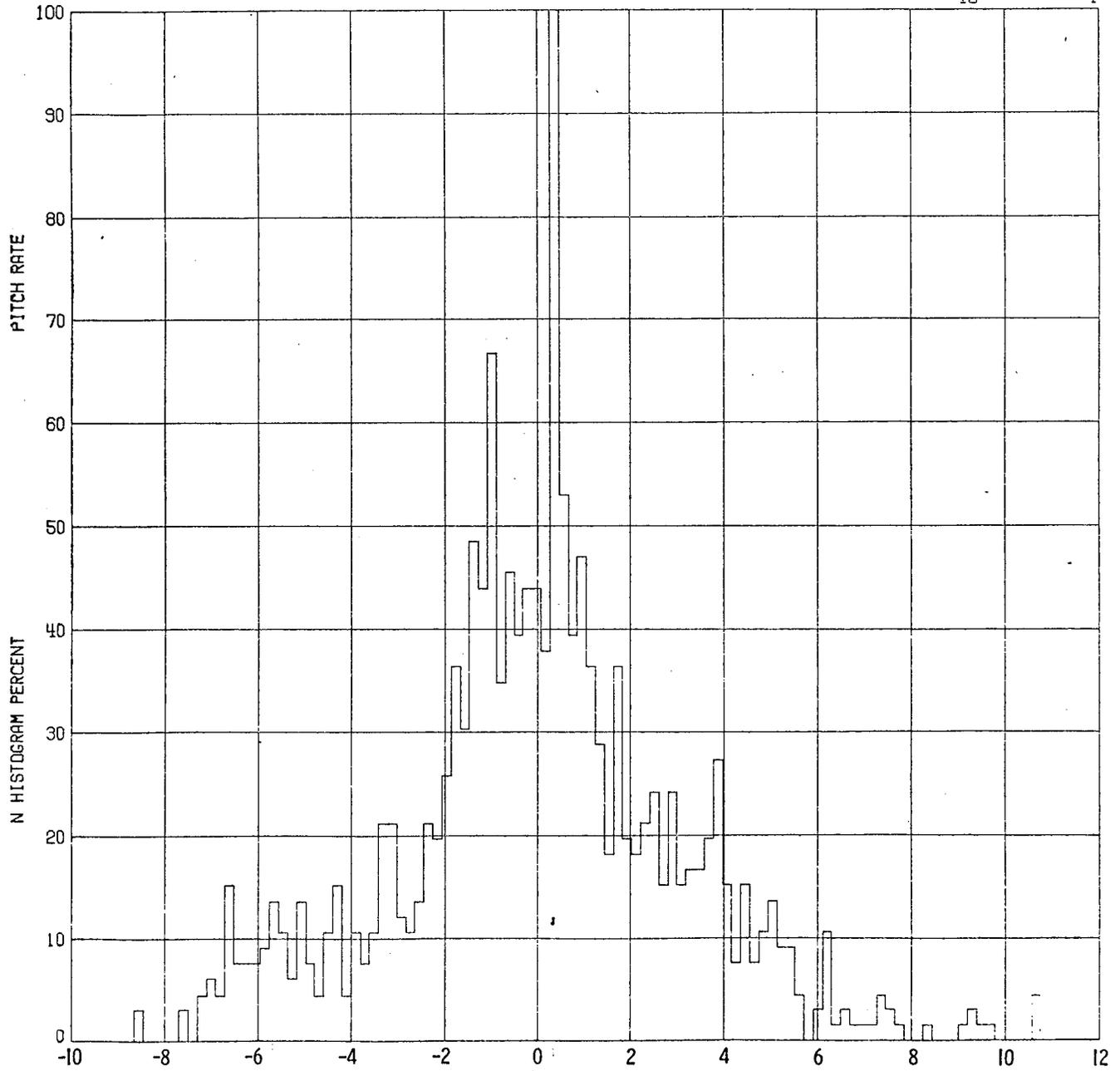
(b) Pitching velocity histograms (RMS pitching velocity 2.061 deg/sec).

Figure 4. - Continued.

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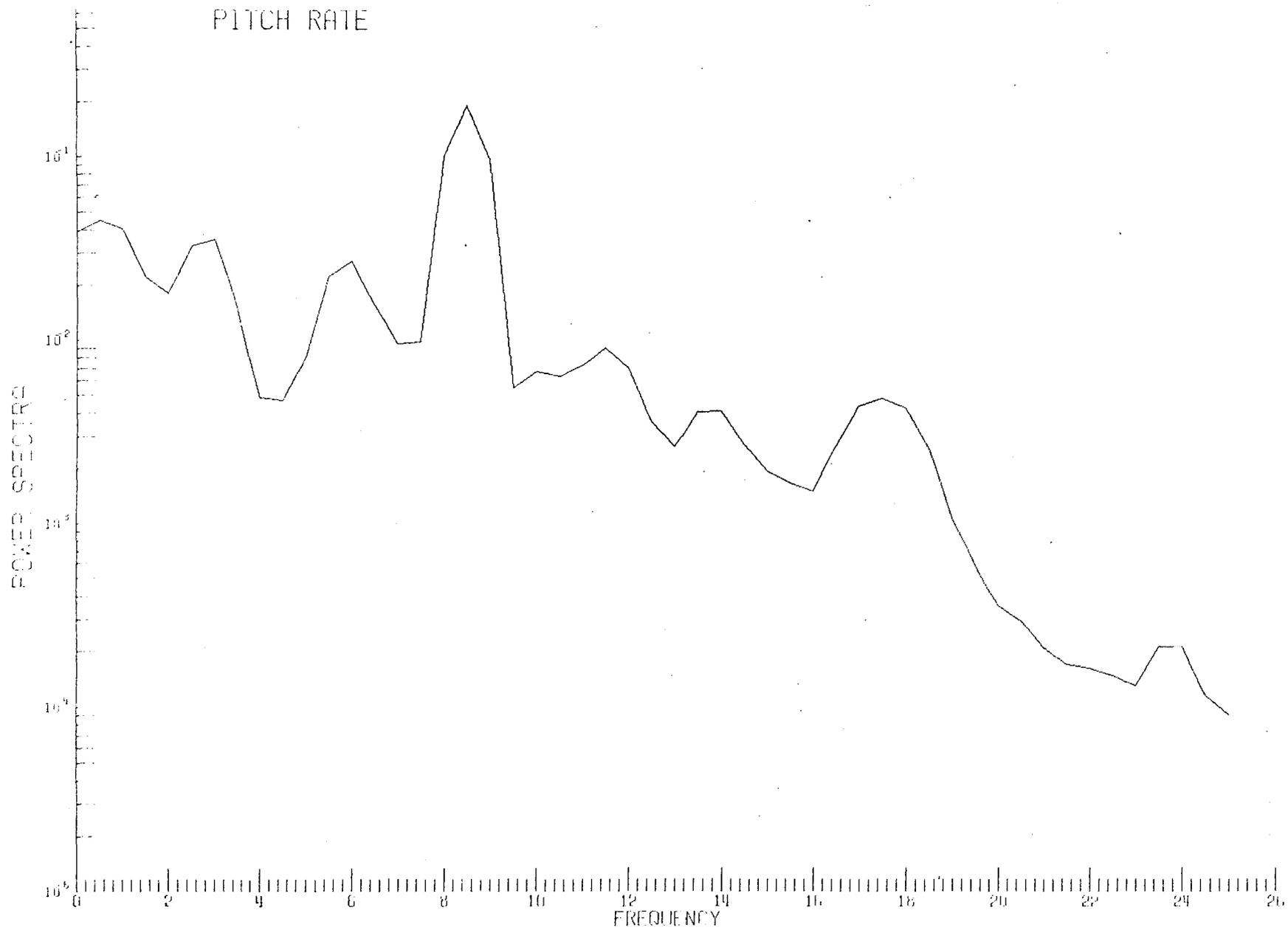
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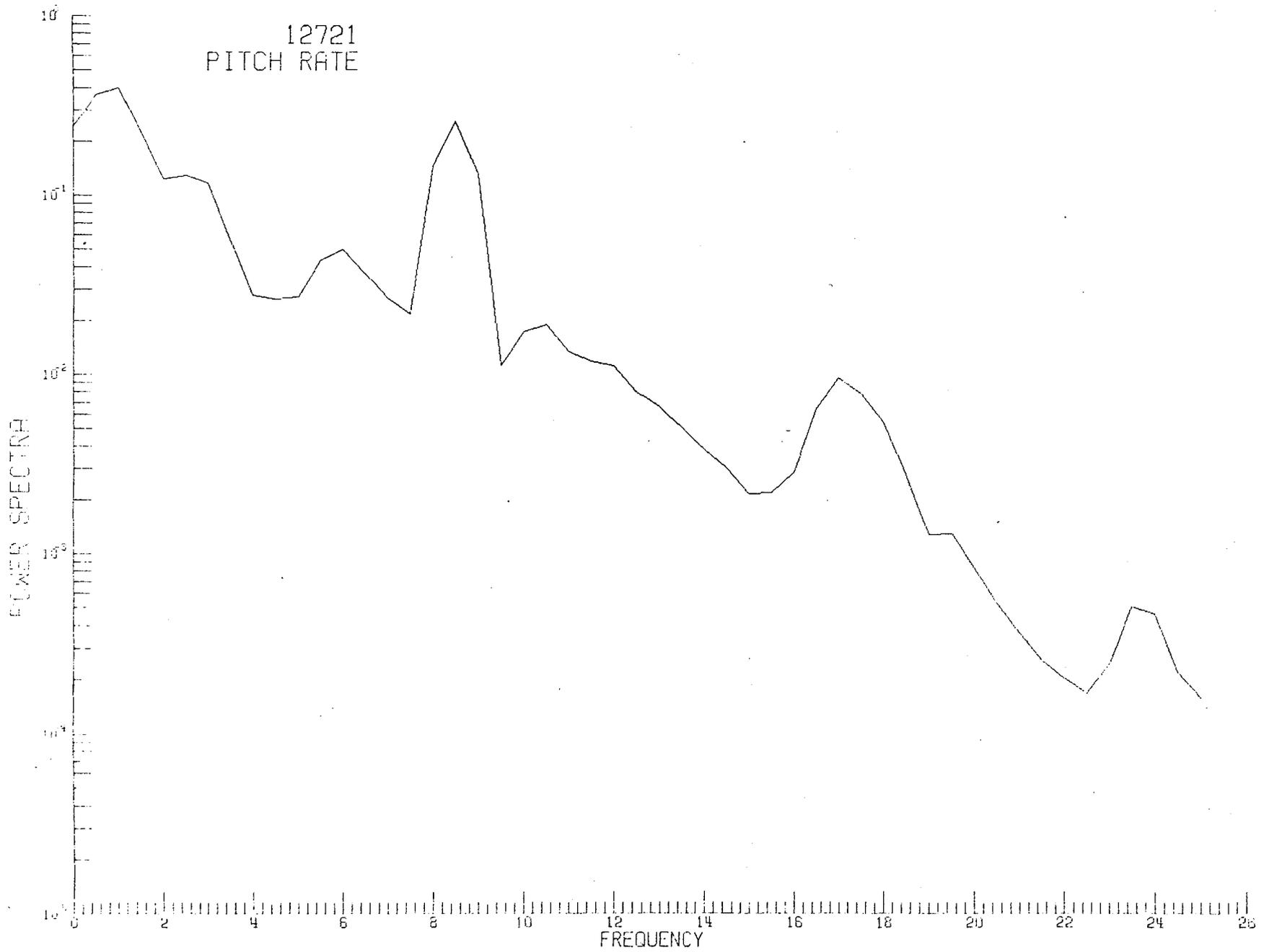
Pitching velocity histograms (RMS pitching velocity 3.077 deg/sec).

Figure 4.- Continued .



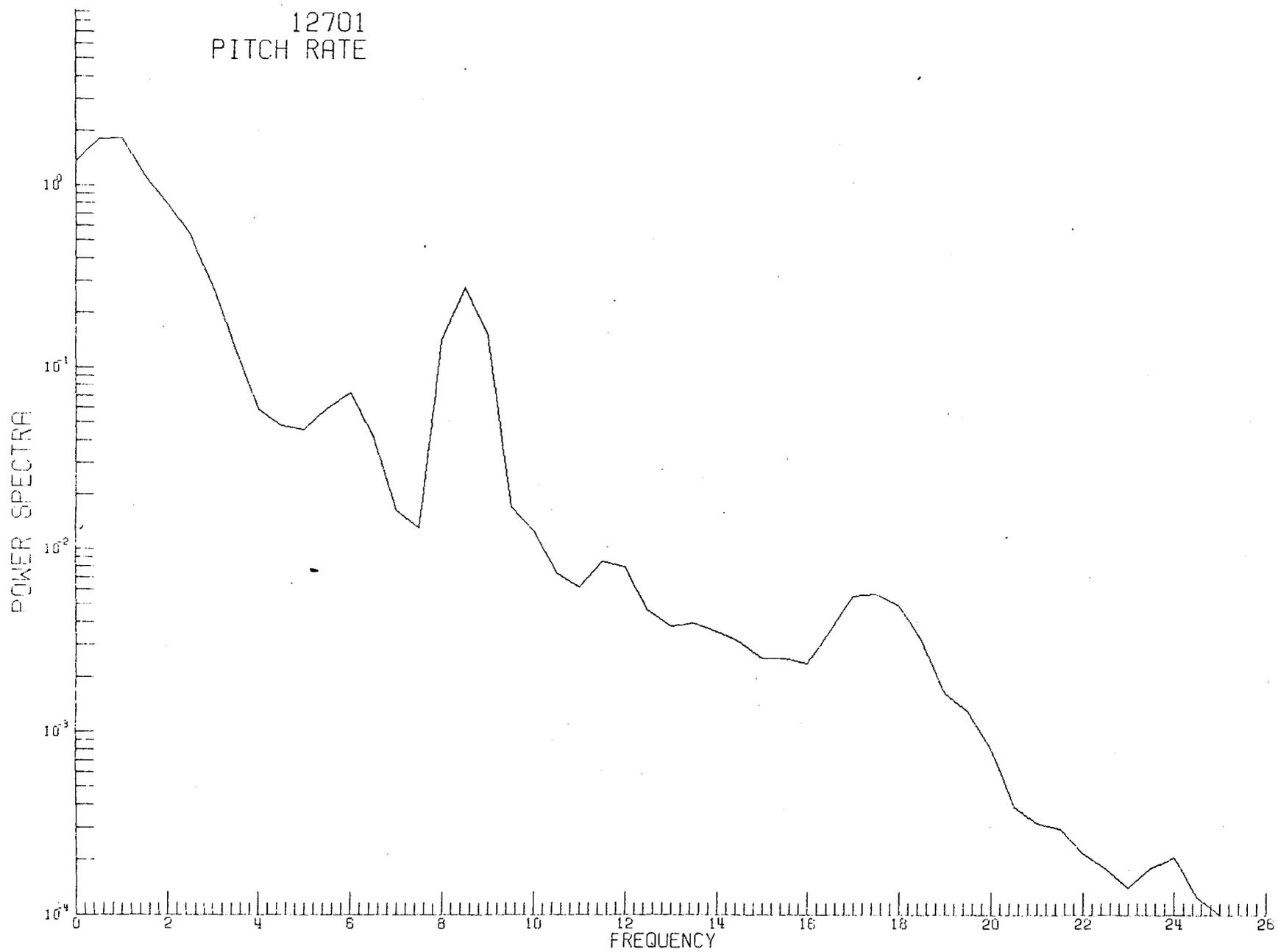
(c) Pitching velocity power spectrum (RMS pitching velocity 0.797 deg/sec).

Figure 4. - Continued.



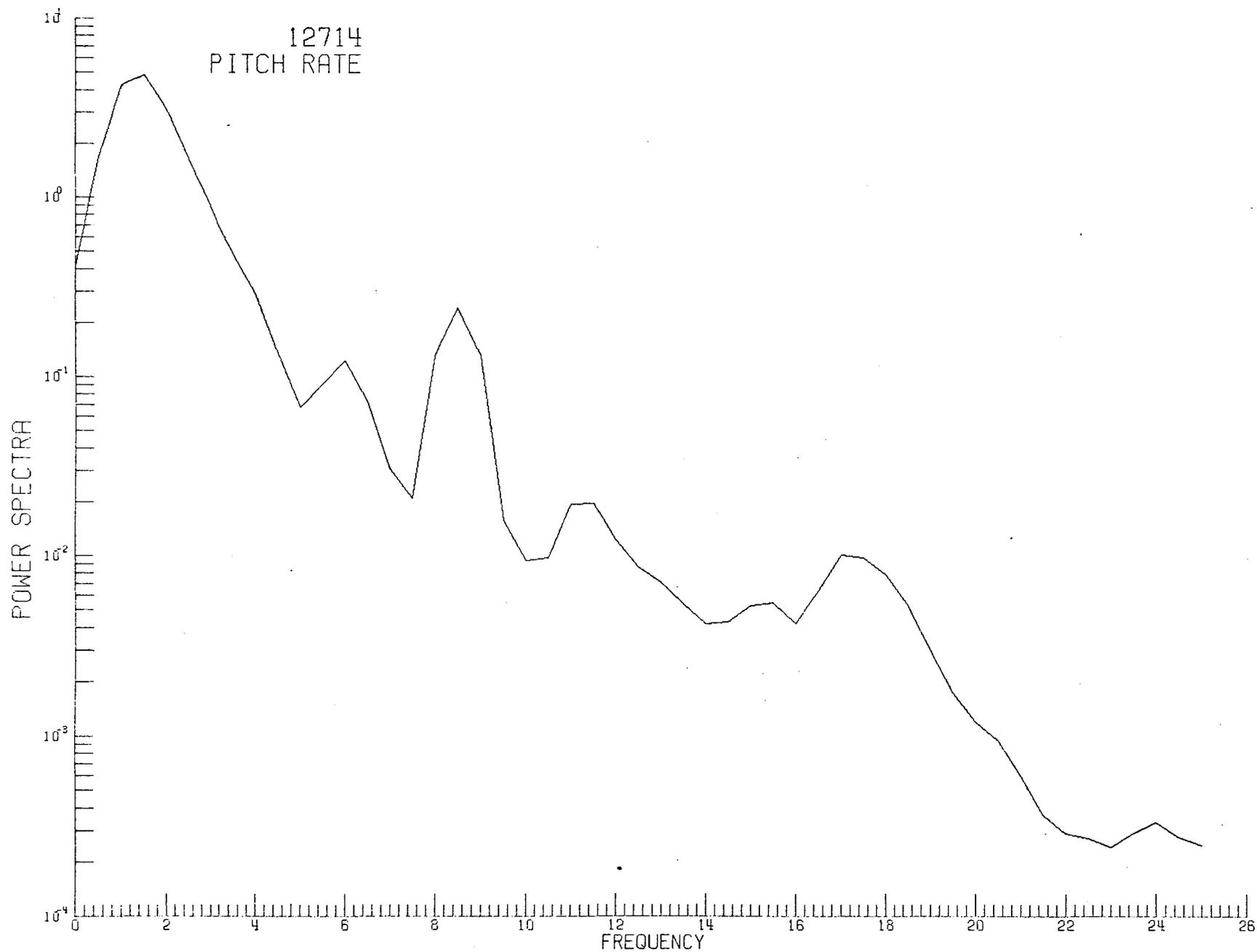
(c) Pitching velocity power spectrum (RMS pitching velocity 1.070 deg/sec).

Figure 4 - Continued.



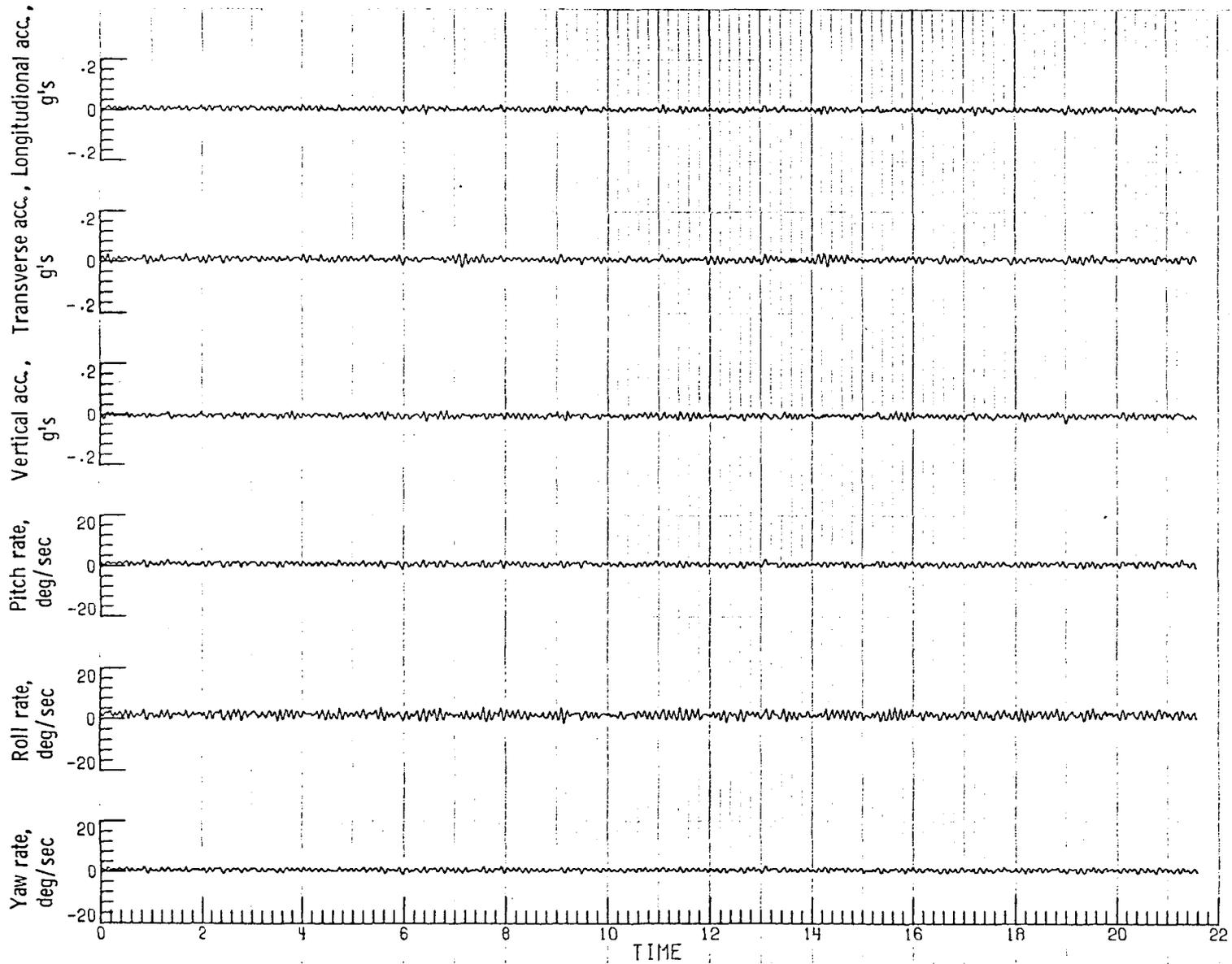
(c) Pitching velocity power spectrum (RMS pitching velocity 2.061 deg/sec).

Figure 4. - Continued.



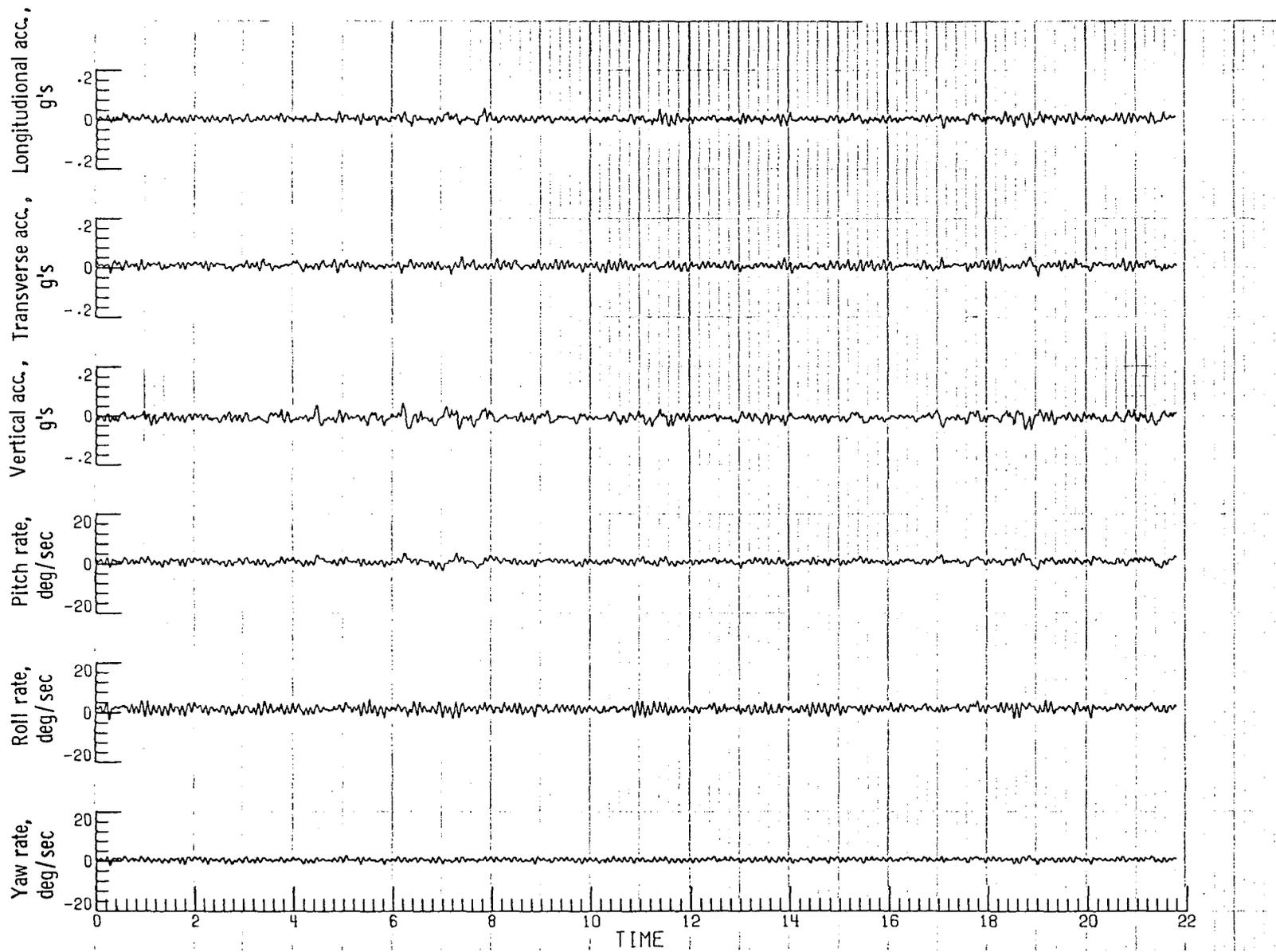
(c) Pitching velocity power spectrum (RMS pitching velocity 3.077 deg/sec).

Figure 4. - Concluded.



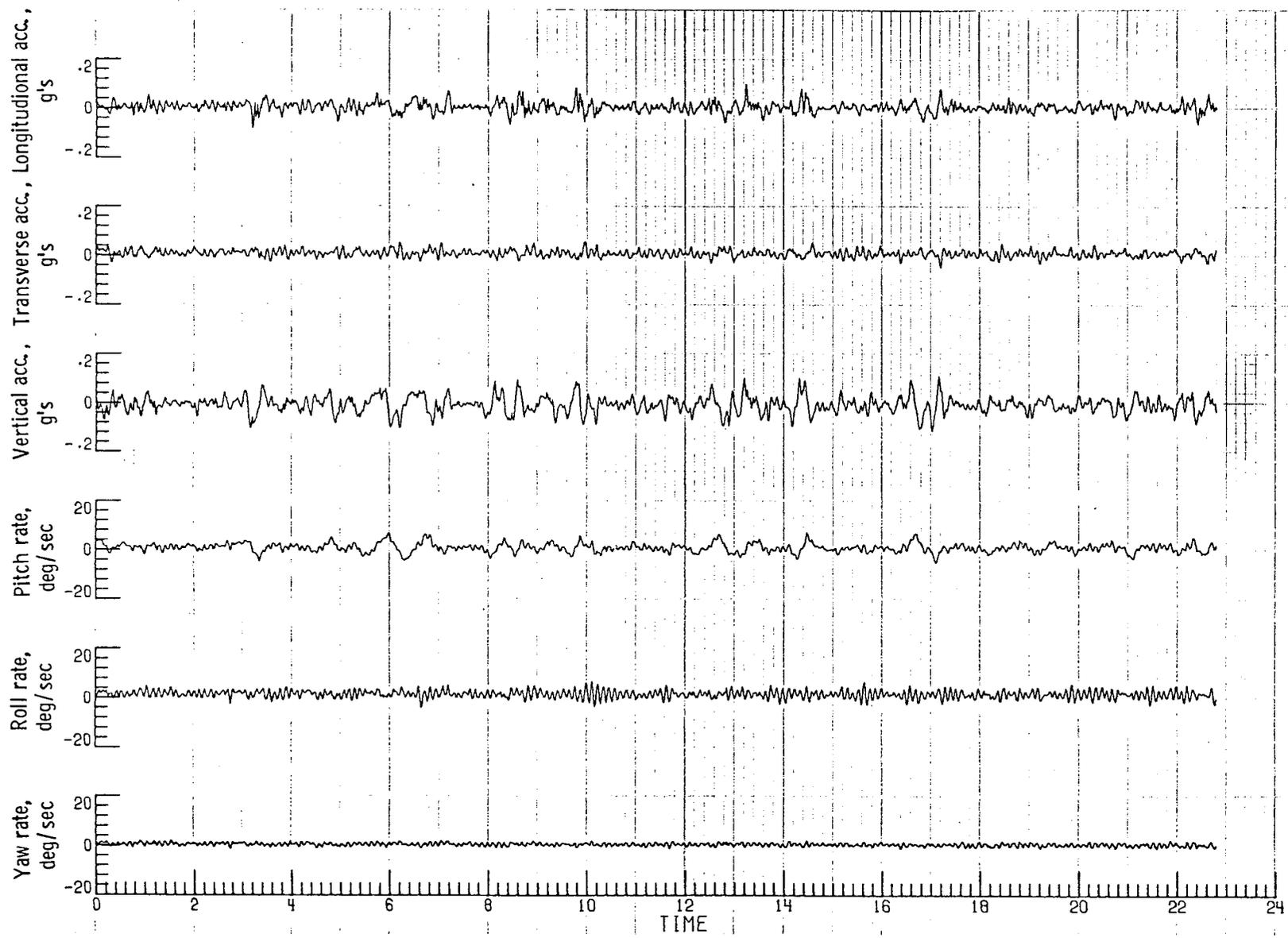
(a) Time histories (RMS pitching velocity 0.798 deg/sec).

Figure 5. - Measured motion characteristics using pitching velocity with typical 1-2 HZ inputs.

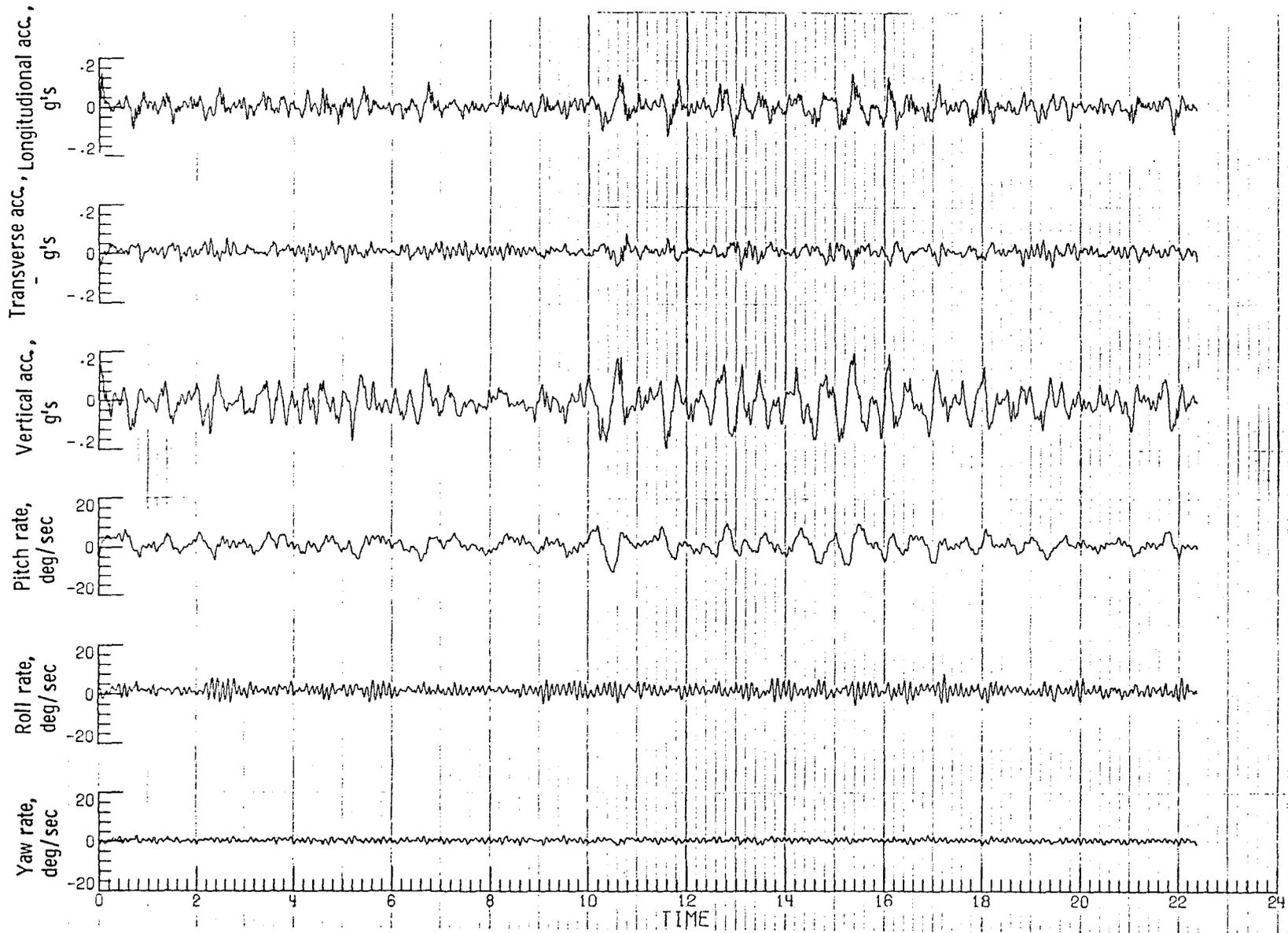


(a) Time histories (RMS pitching velocity 0.966 deg/sec).

Figure 5. - Continued.

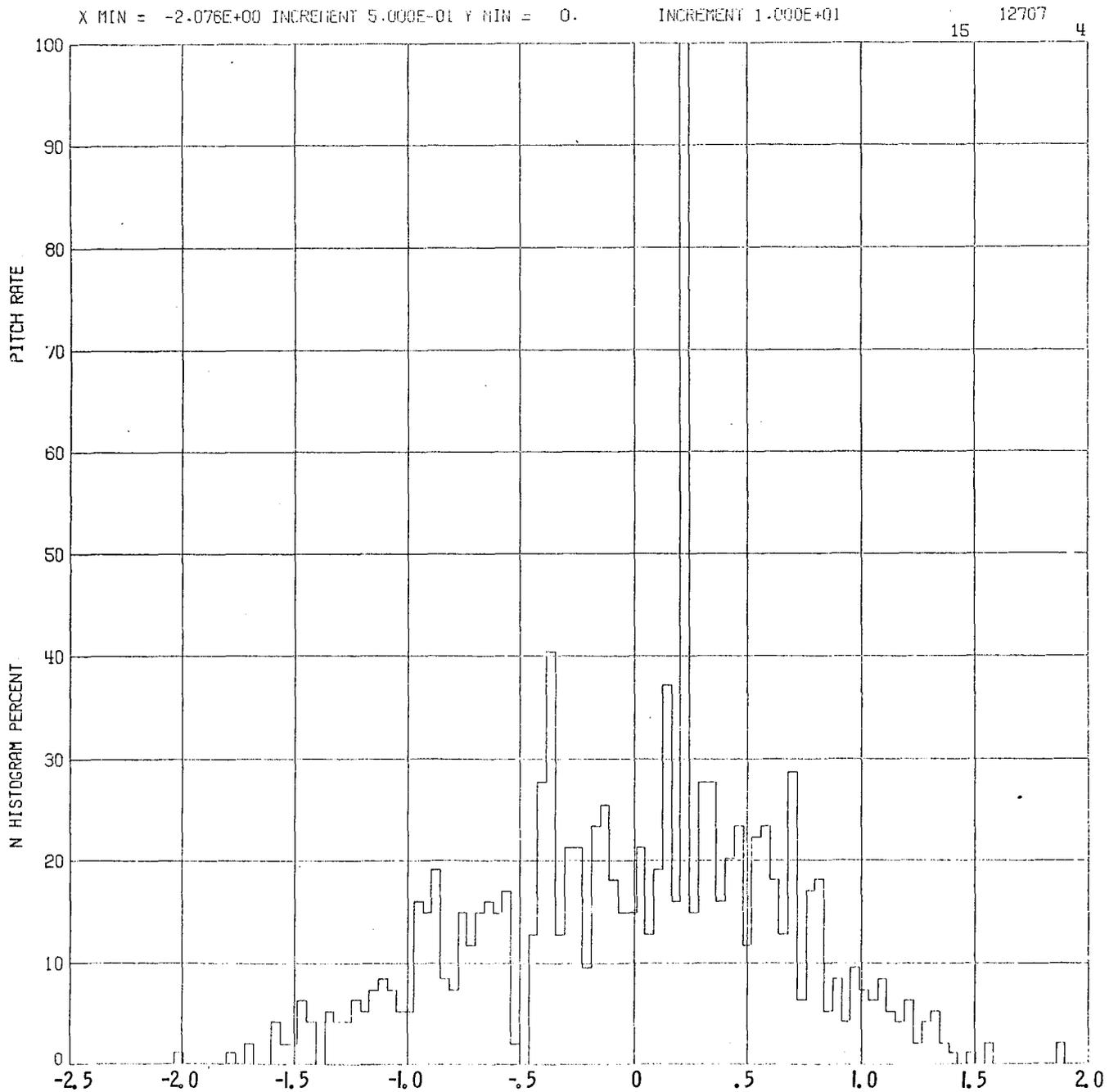


(a) Time histories (RMS pitching velocity 1.836 deg/sec).



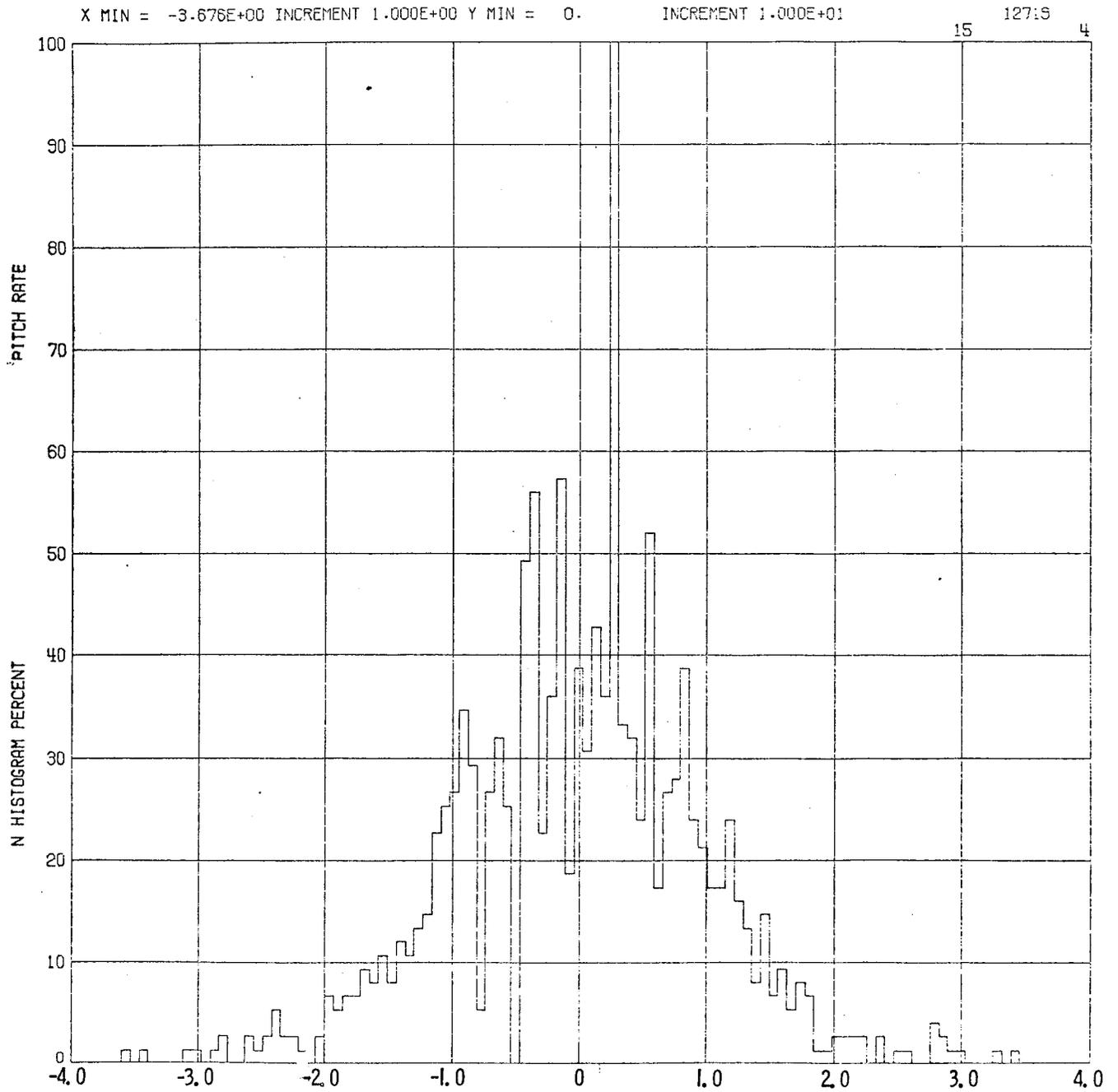
(a) Time histories (RMS pitching velocity 3.023 deg/sec).

Figure 5. - Continued.



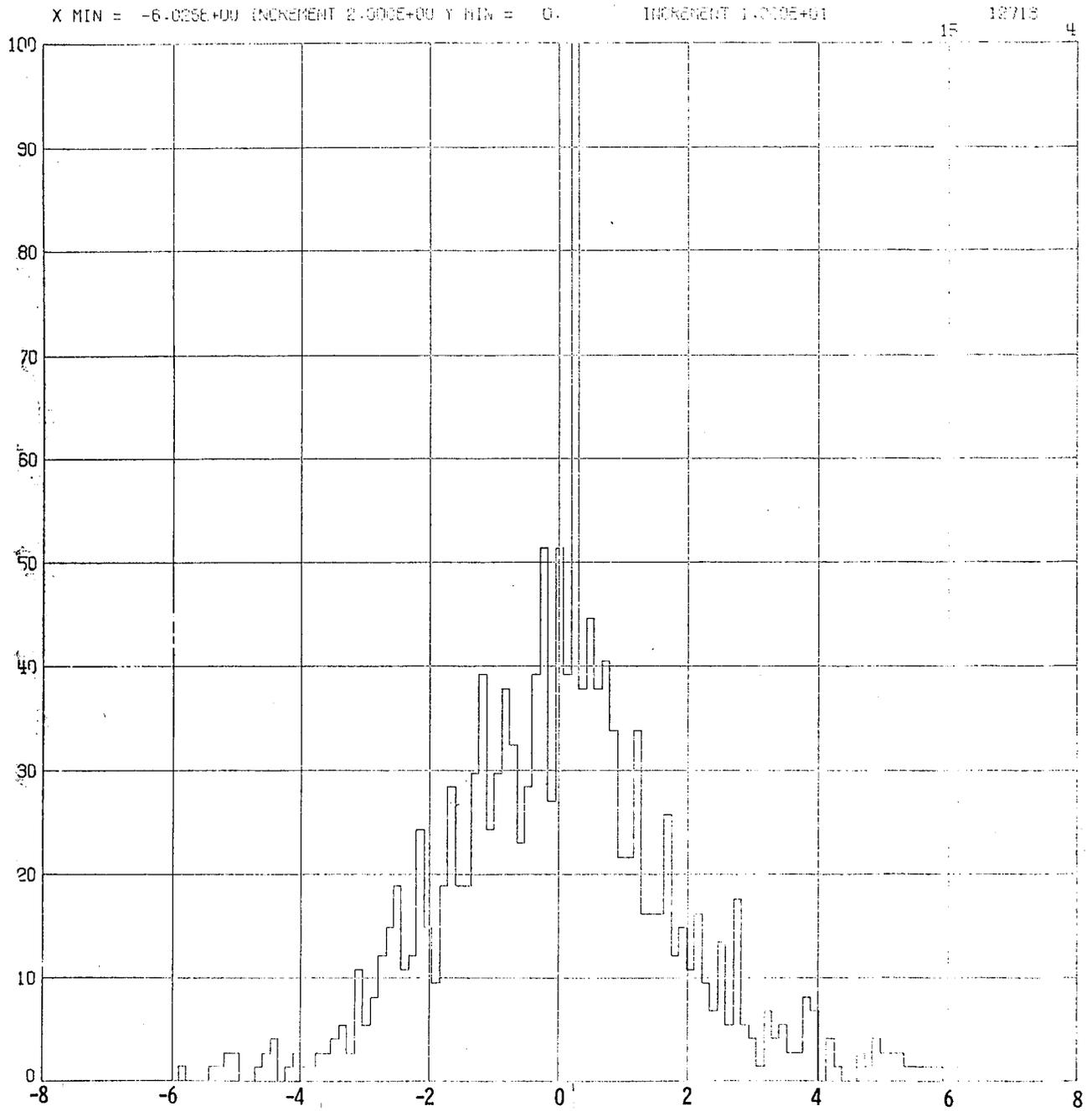
(b) Pitching velocity histograms (RMS pitching velocity 0.798 deg/sec).

Figure 5. - Continued.



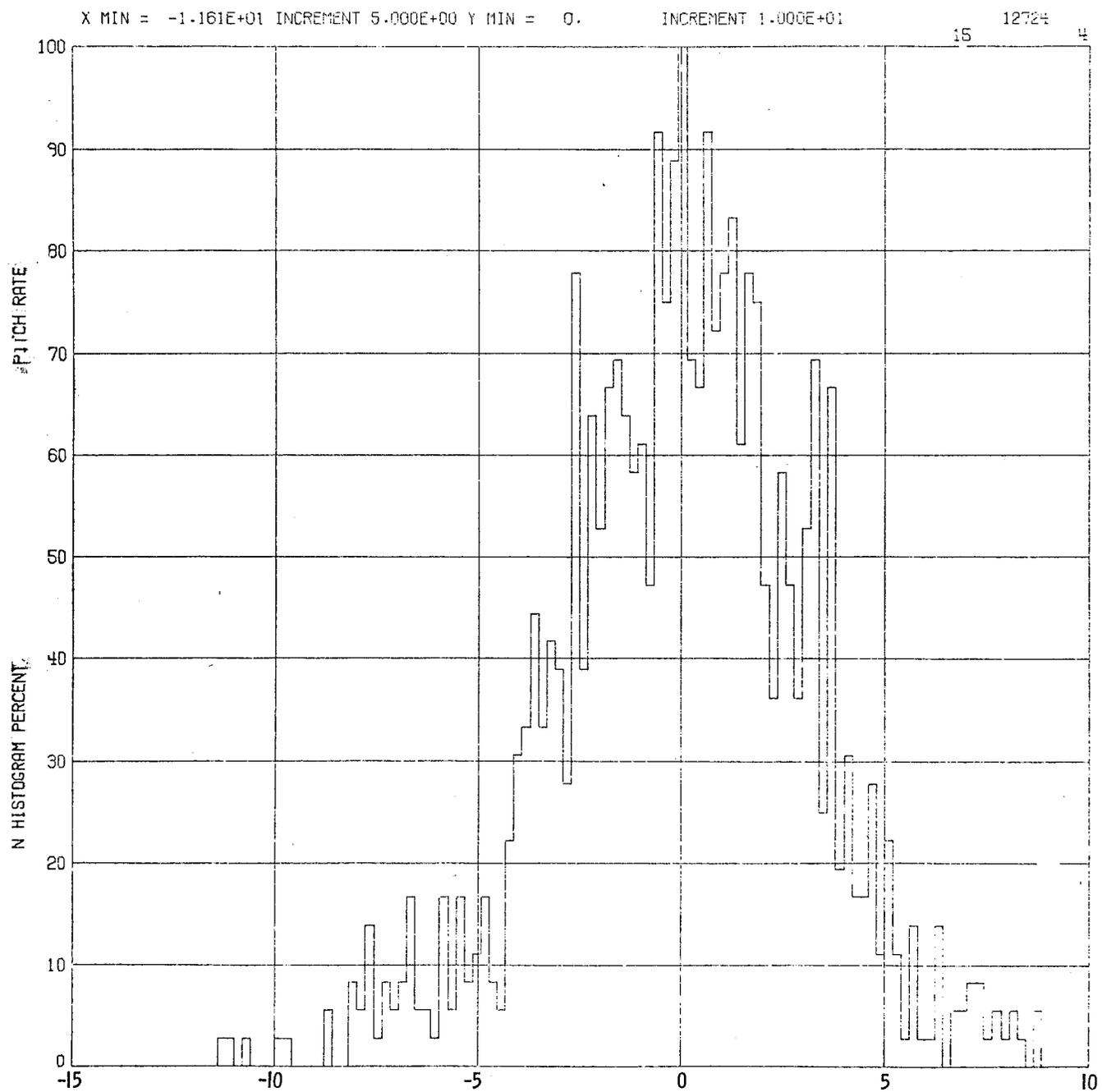
(b) Pitching velocity histograms (RMS pitching velocity 0.966 deg/sec).

Figure 5. - Continued.



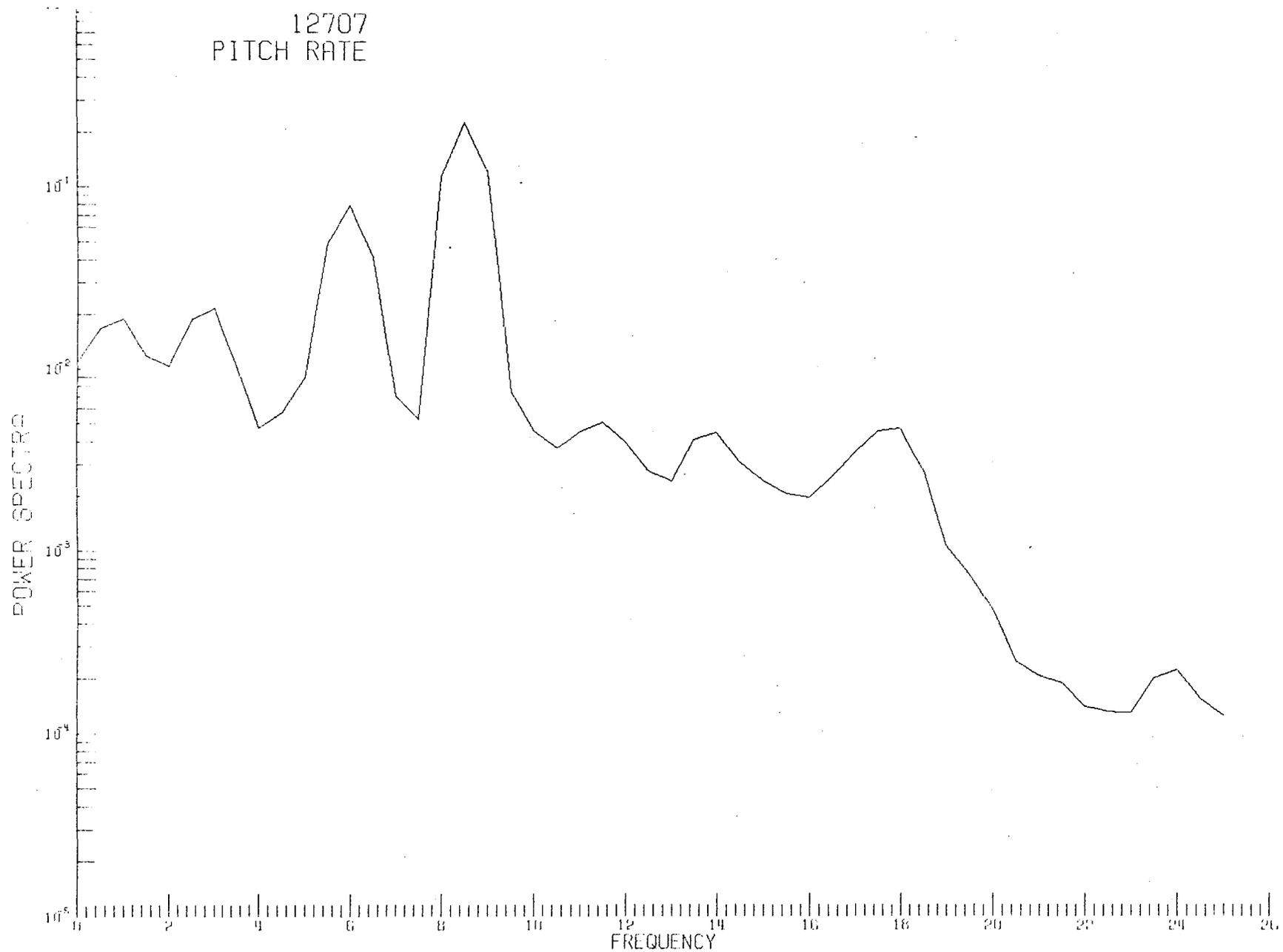
(b) Pitching velocity histograms (RMS pitching velocity 1.836 deg/sec)

Figure 5.- Continued.

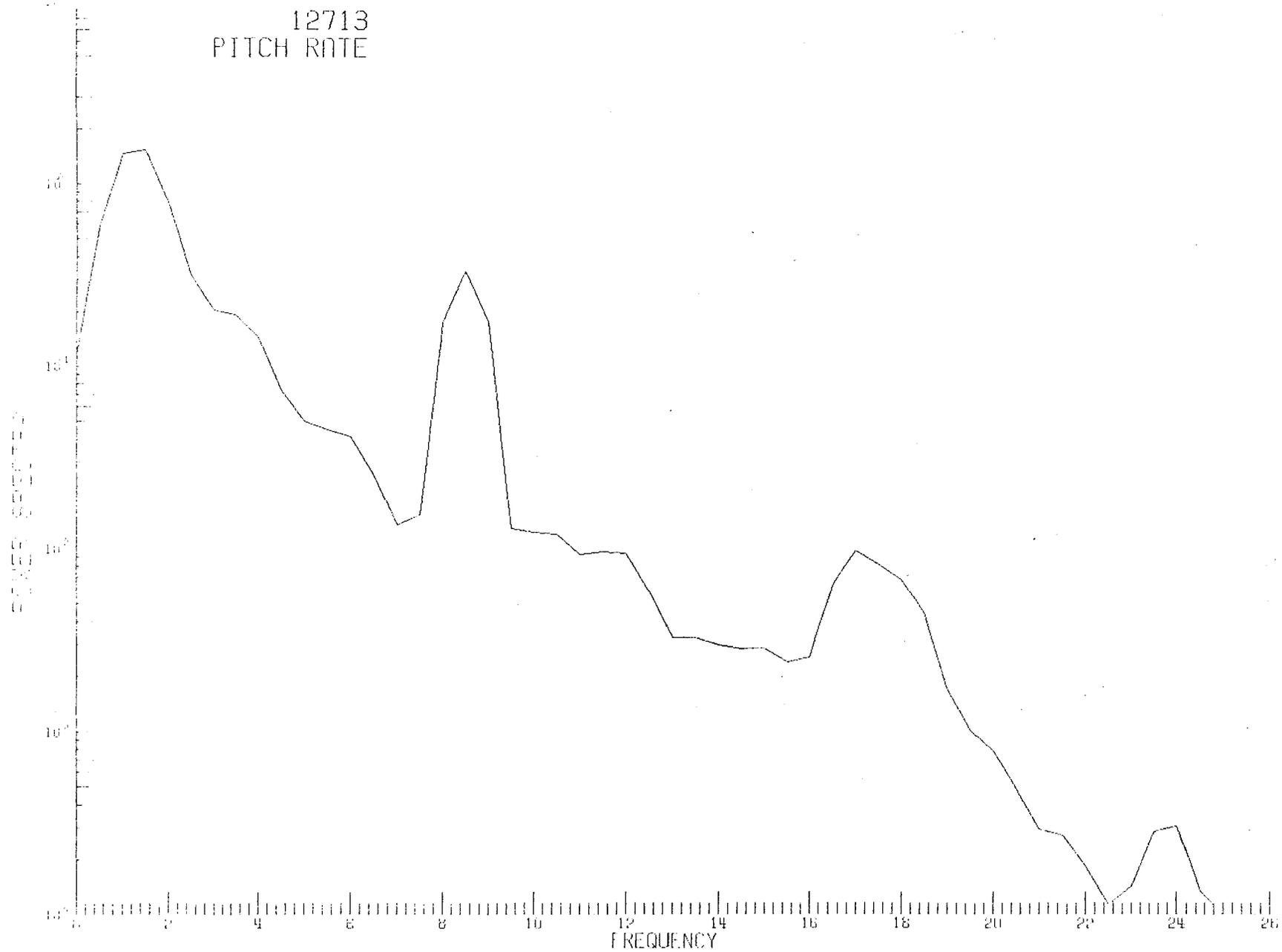


(b) Pitching velocity histograms (RMS pitching velocity 3.023 deg/sec).

Figure 5. - Continued.

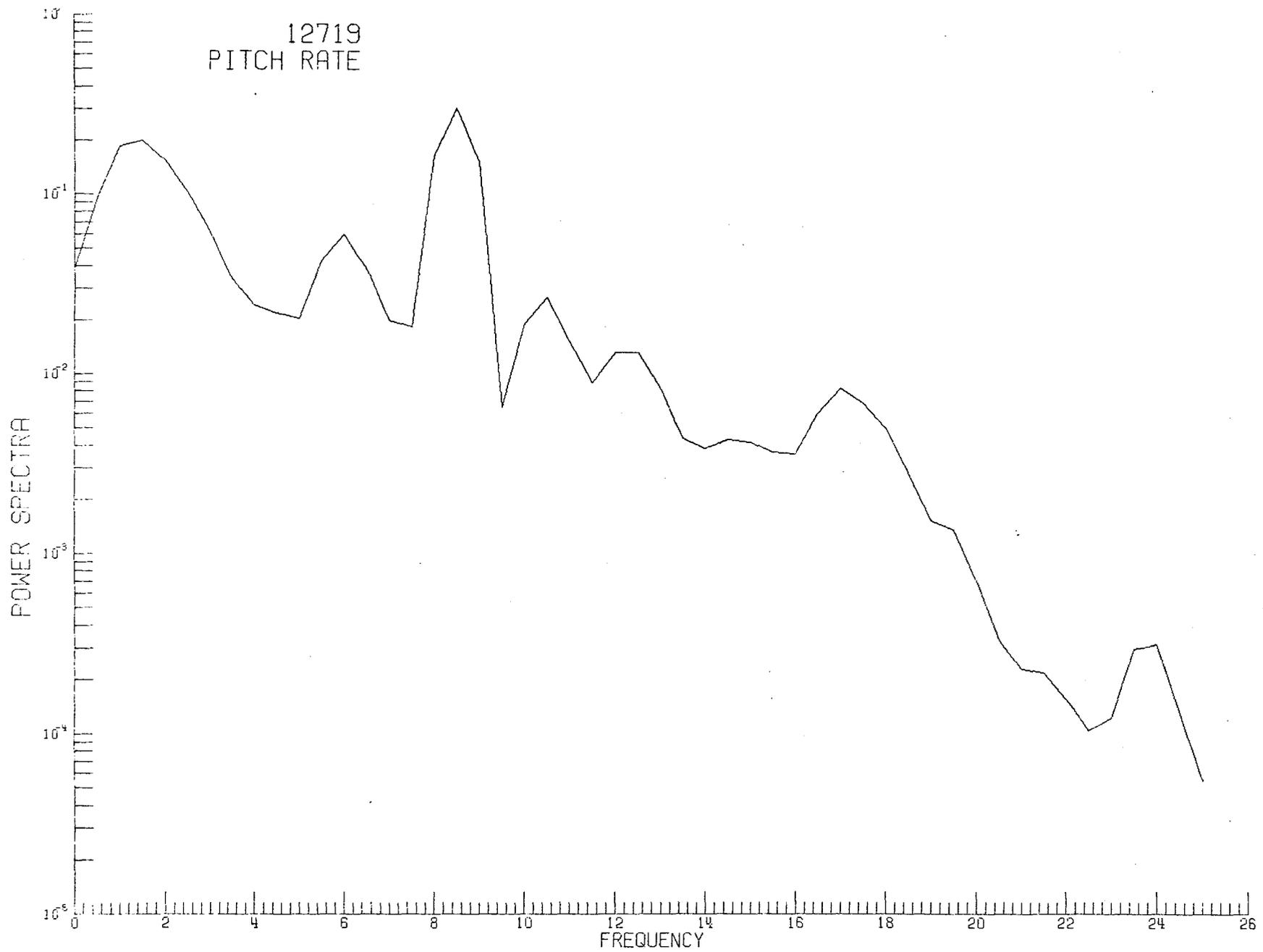


(c) Pitching velocity power spectrum (RMS pitching velocity 0.798 deg/sec).

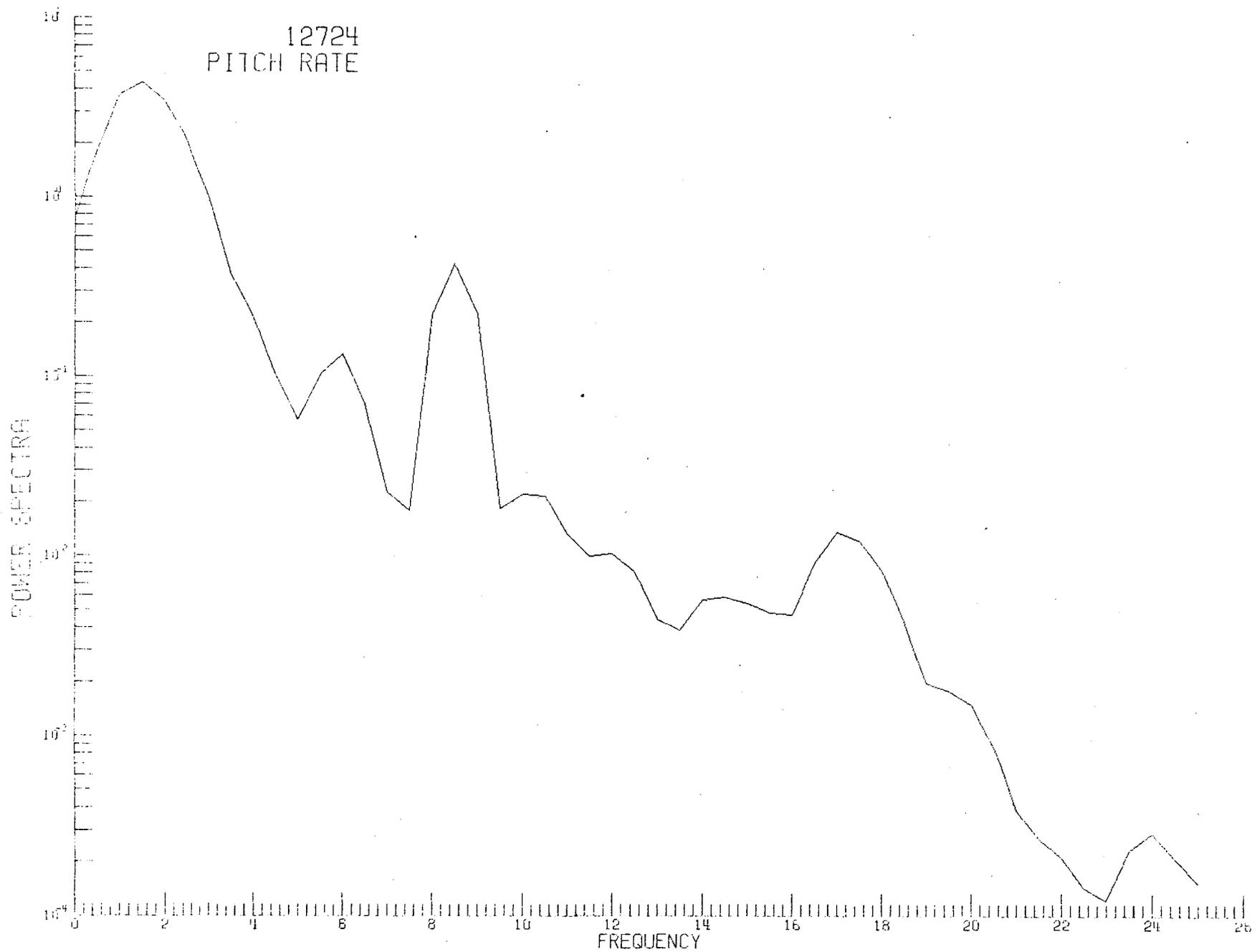


(c) Pitching velocity power spectrum (RMS pitching velocity 1.836 deg/sec).

Figure 5. - Continued.

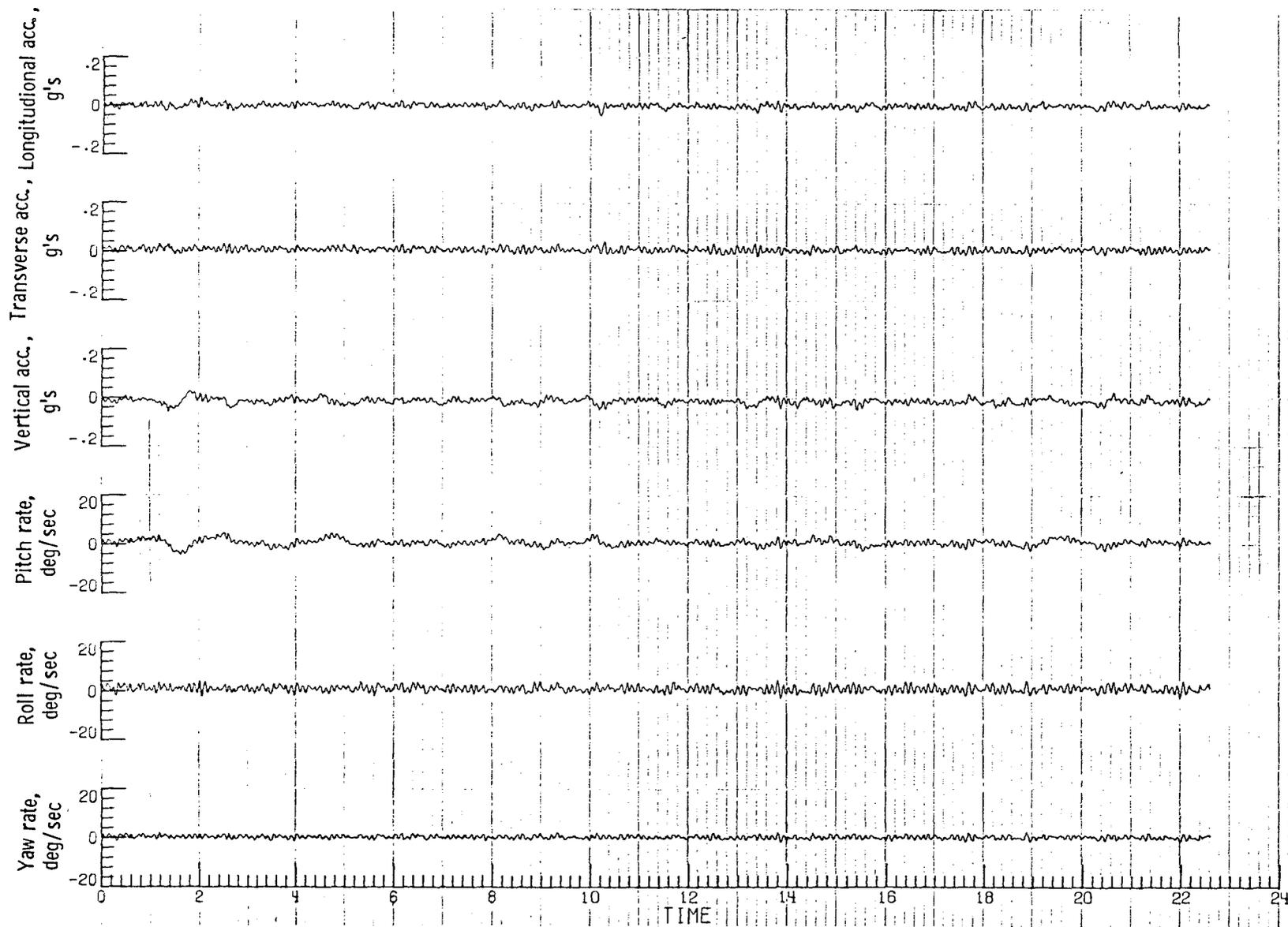


(c) Pitching velocity power spectrum (RMS pitching velocity 0.966 deg/sec).



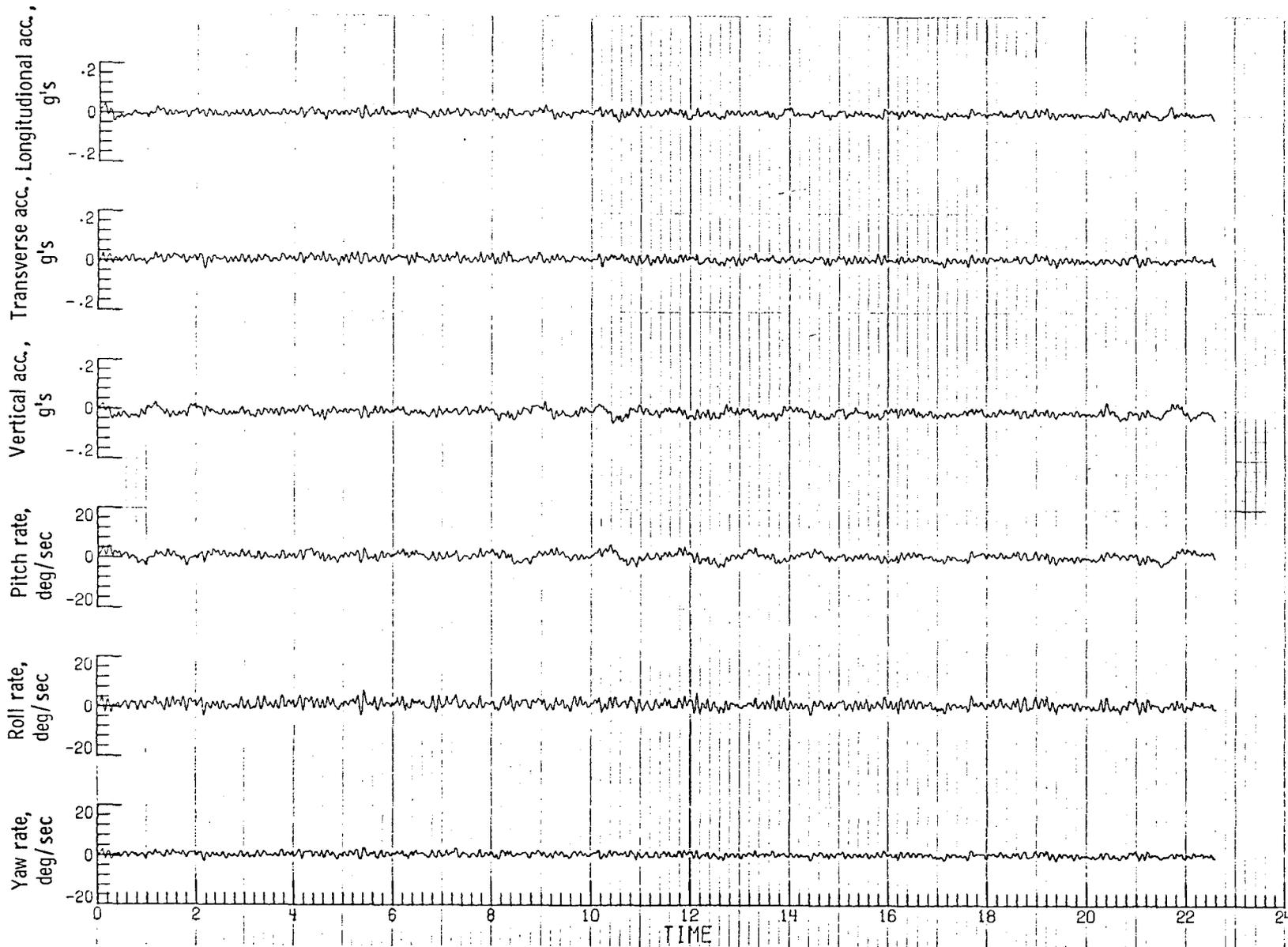
(c) Pitching velocity power spectrum (RMS pitching velocity 3.023 deg/sec).

Figure 5. - Concluded.



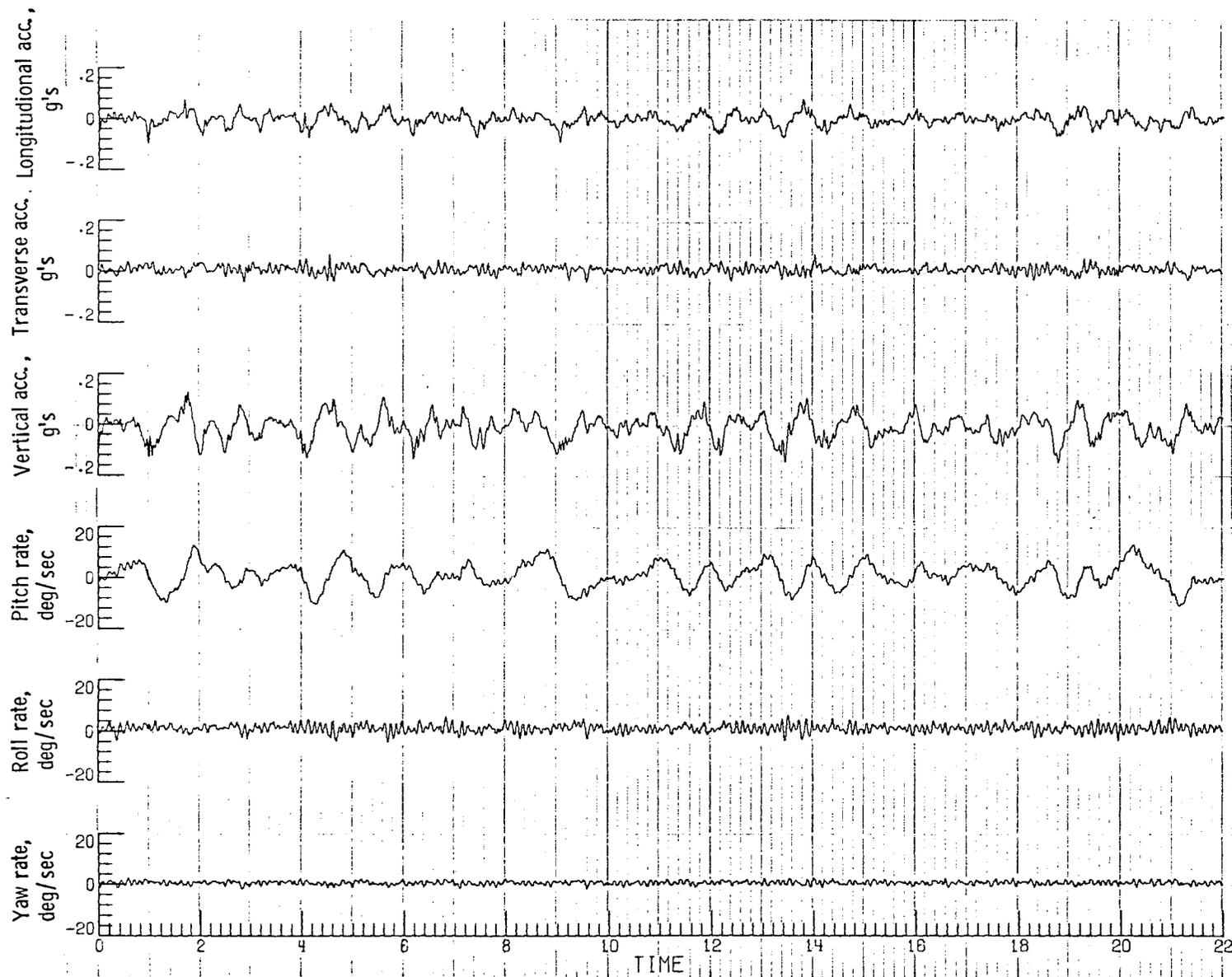
(a) Time histories (RMS pitching velocity 1.298 deg sec).

Figure 6. - Measured motion characteristics using pitching velocity with typical 0-1 HZ inputs.



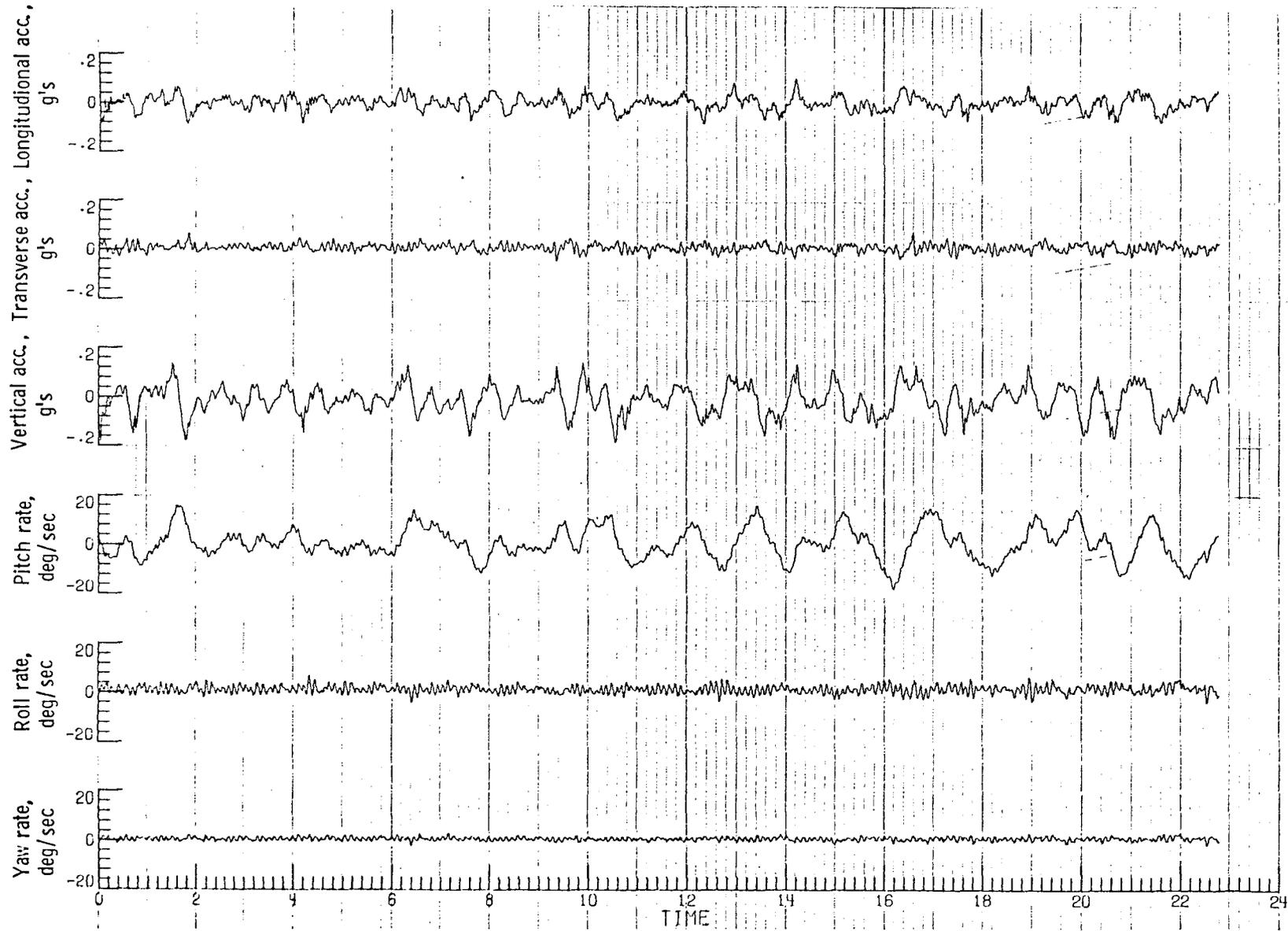
(a) Time histories (RMS pitching velocity 1.391 deg/sec).

Figure 6. - Continued.



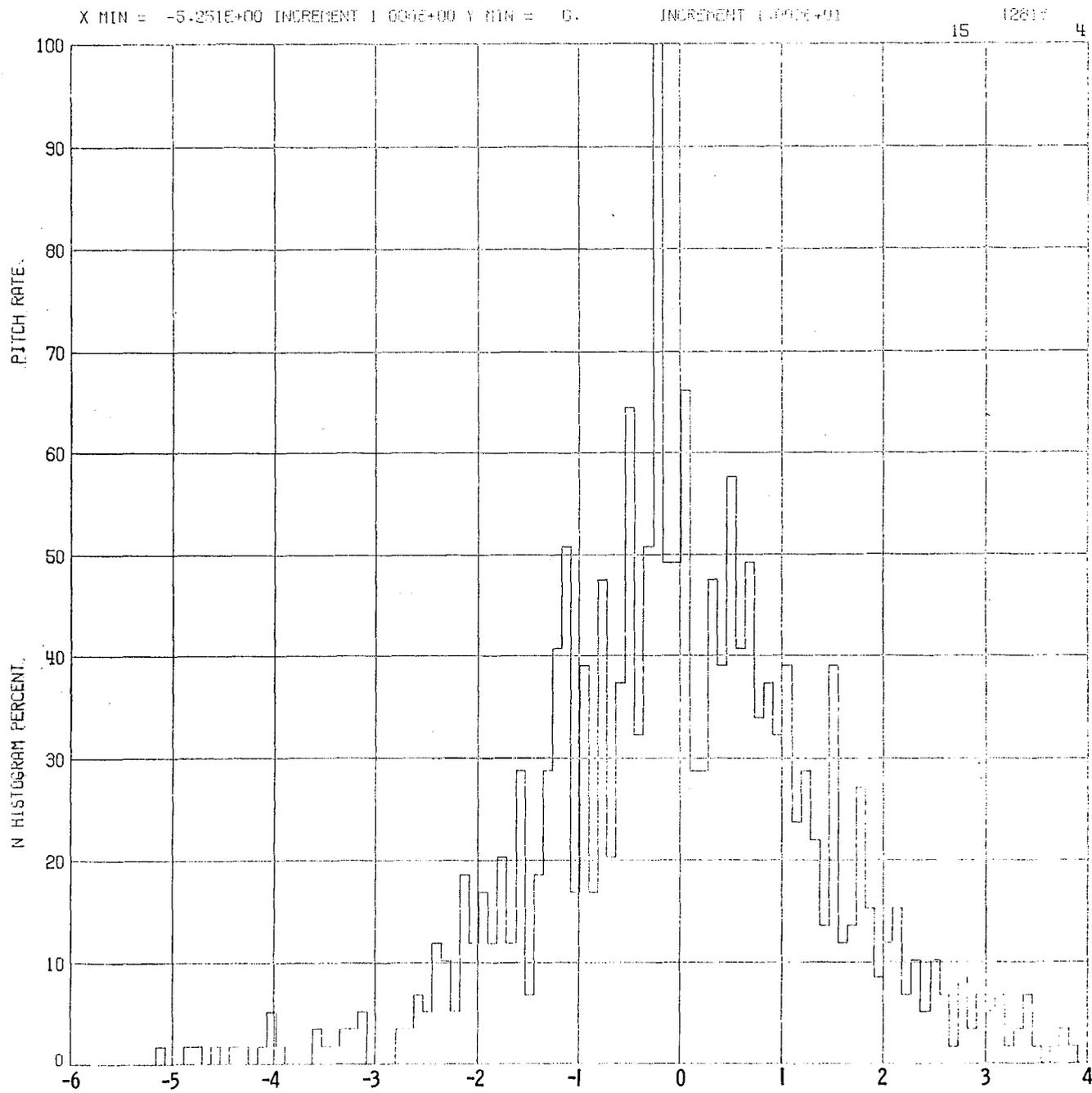
(a) Time histories (RMS pitching velocity 4, 670 deg/sec).

Figure 6 - Continued.



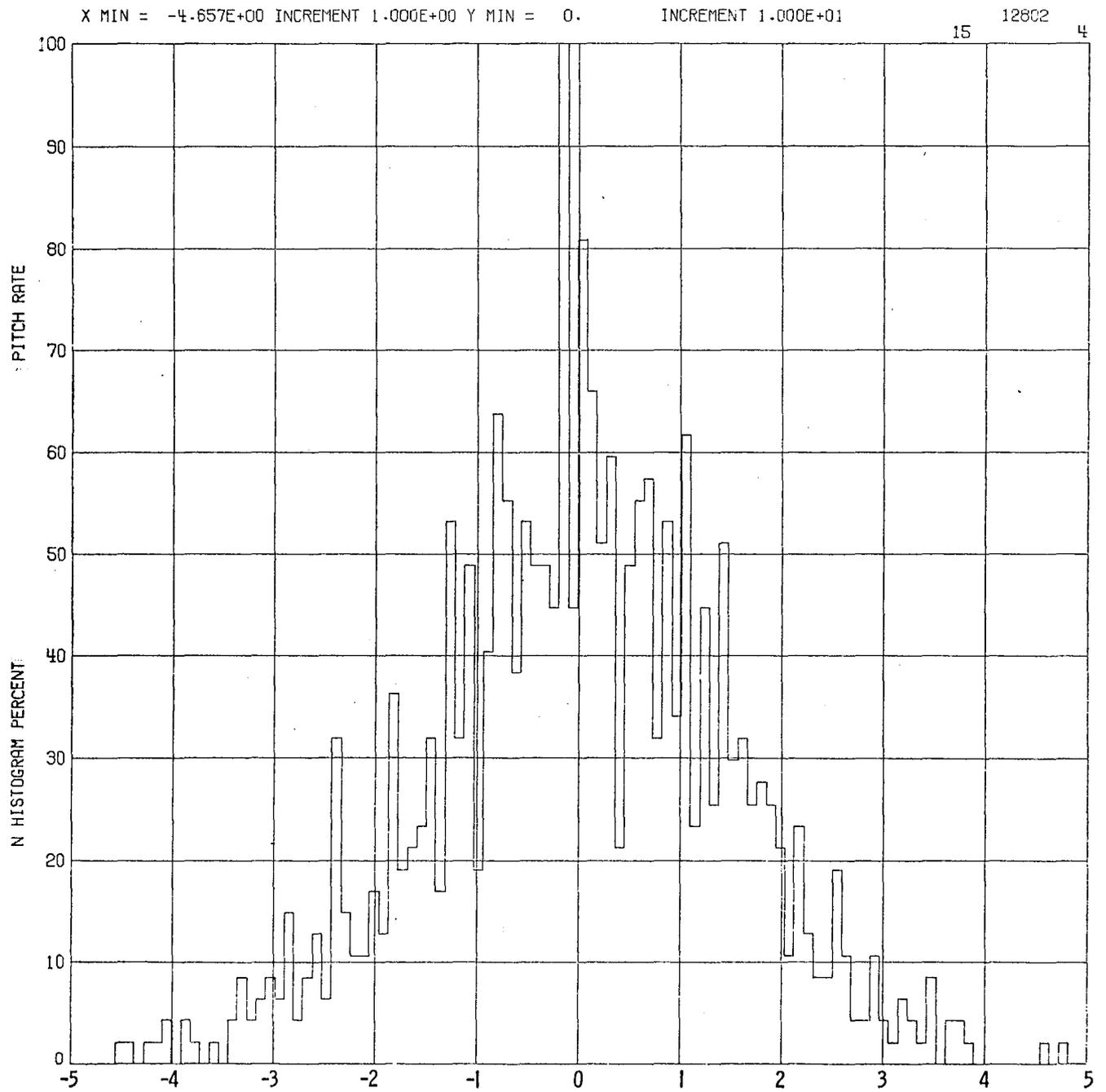
(a) Time histories (RMS pitching velocity 6.386 dwg/sec).

Figure 6. - Continued.



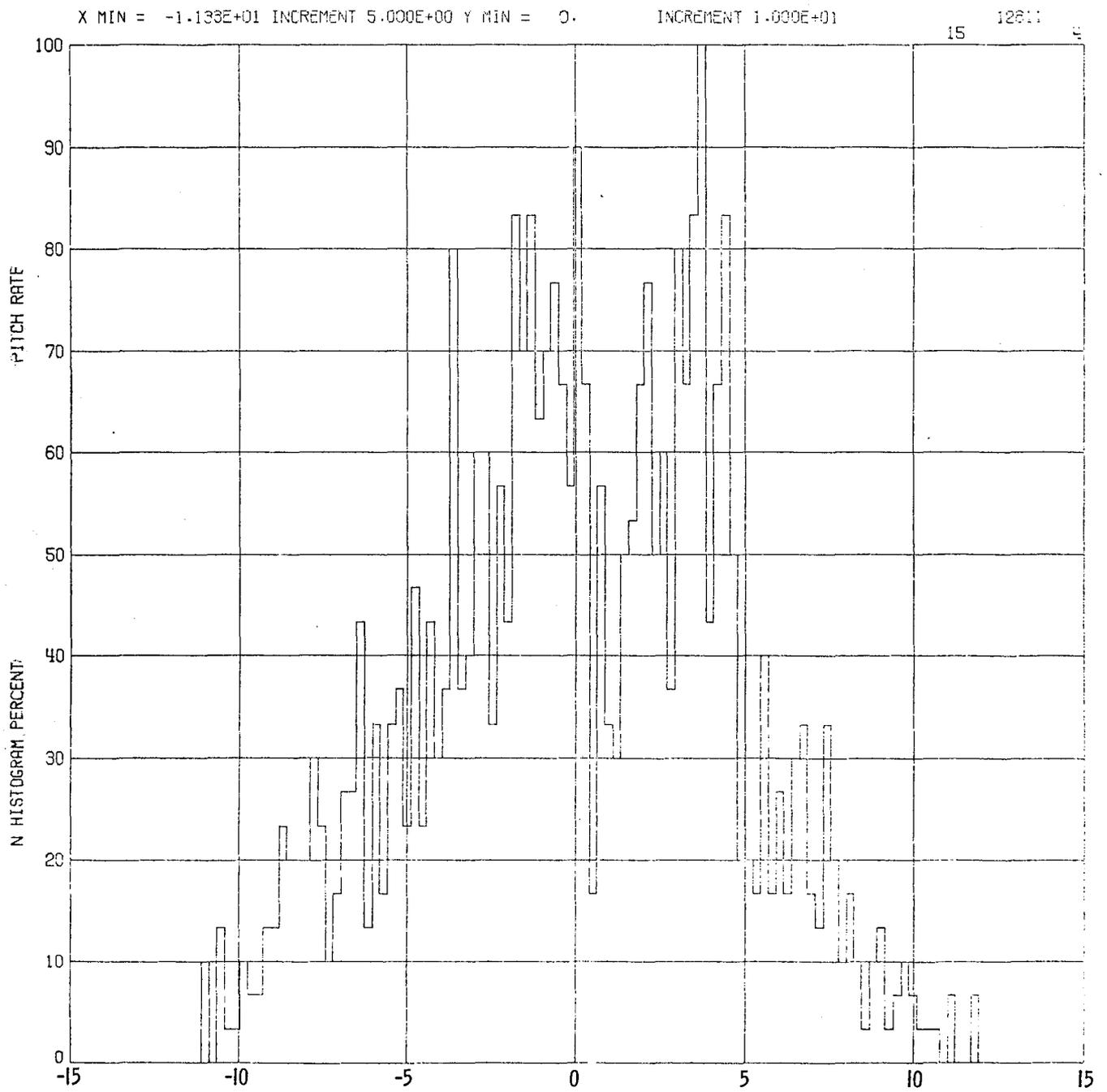
(b) Pitching velocity histograms (RMS pitching velocity 1.298 deg/sec).

Figure 6. - Continued.



(b) Pitching velocity histograms (RMS pitching velocity 1.391 deg/sec).

Figure 6. - Continued.



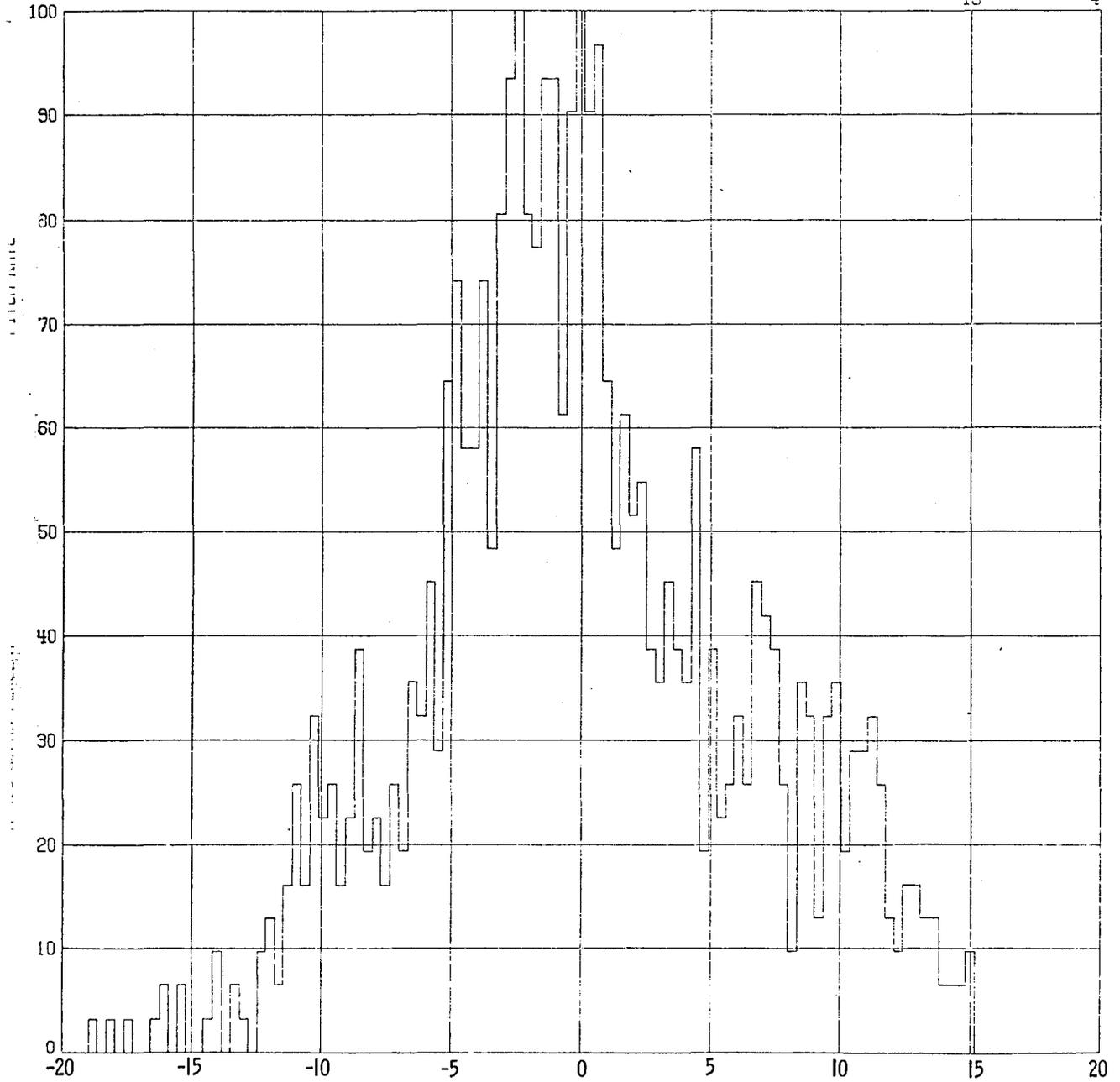
(b) Pitching velocity histograms (RMS pitching velocity 4.670 deg/sec).

Figure 6. - Continued .

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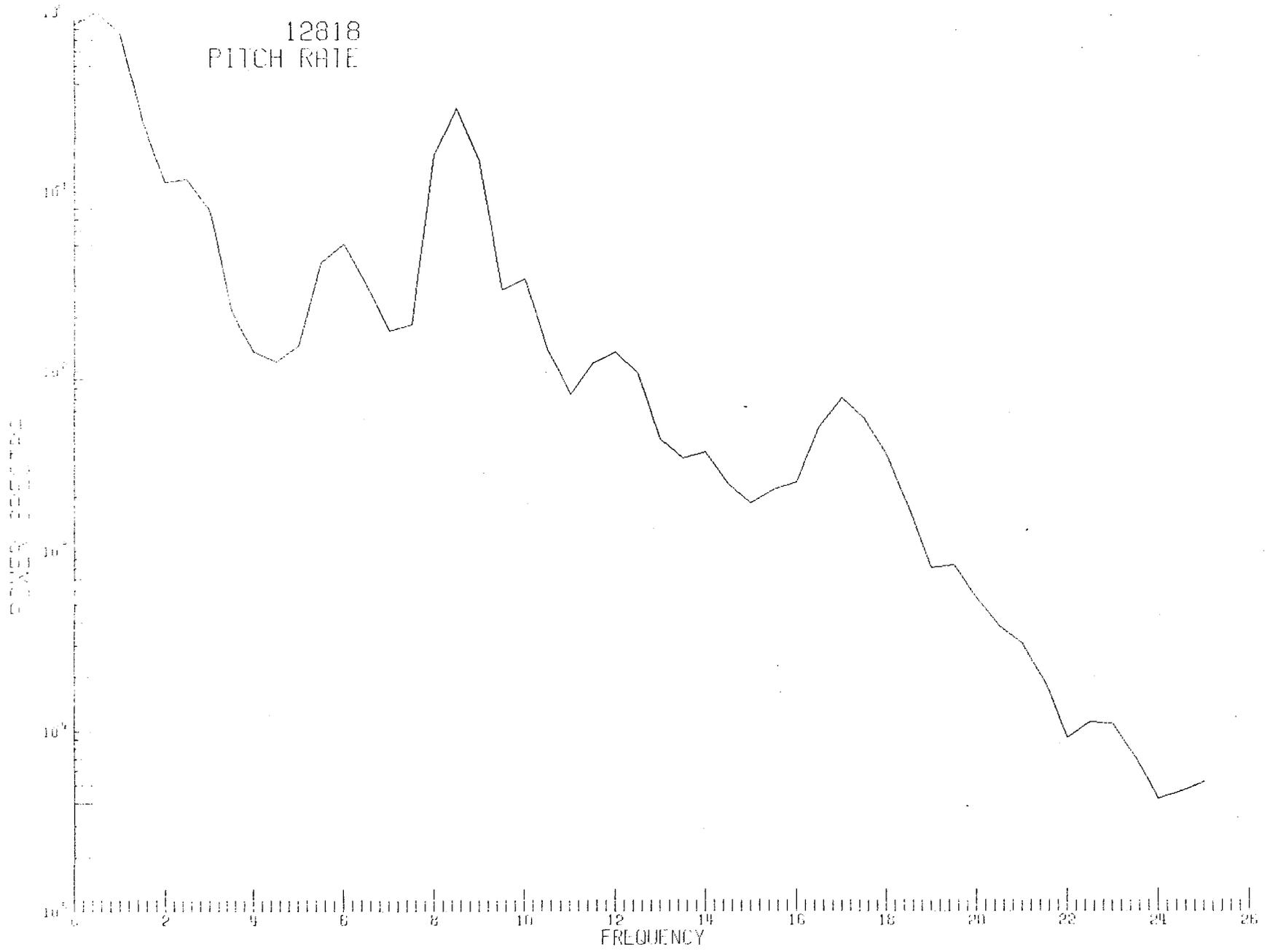
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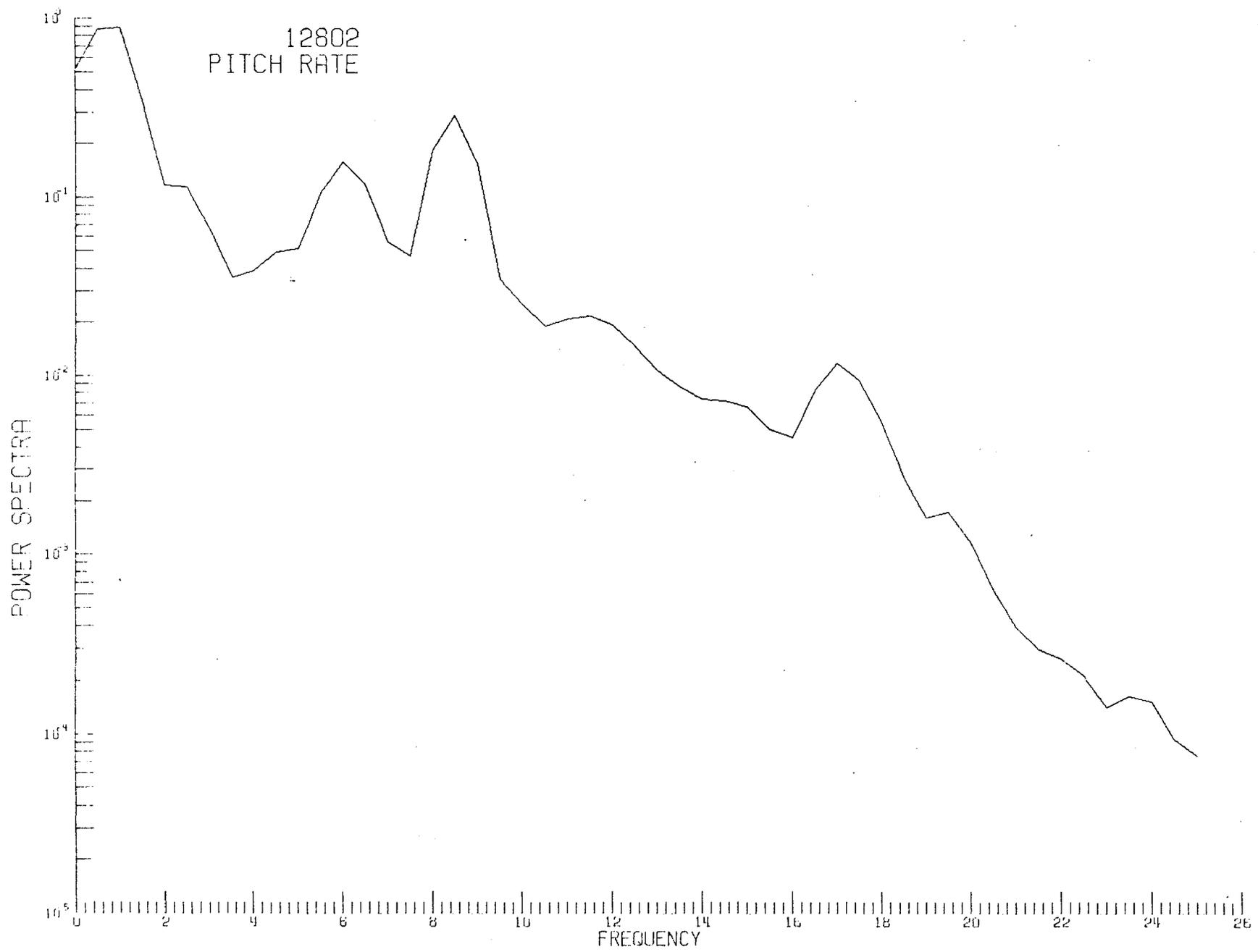


(b) Pitching velocity histograms (RMS pitching velocity 6.386 deg/sec).

Figure 6. - Continued.

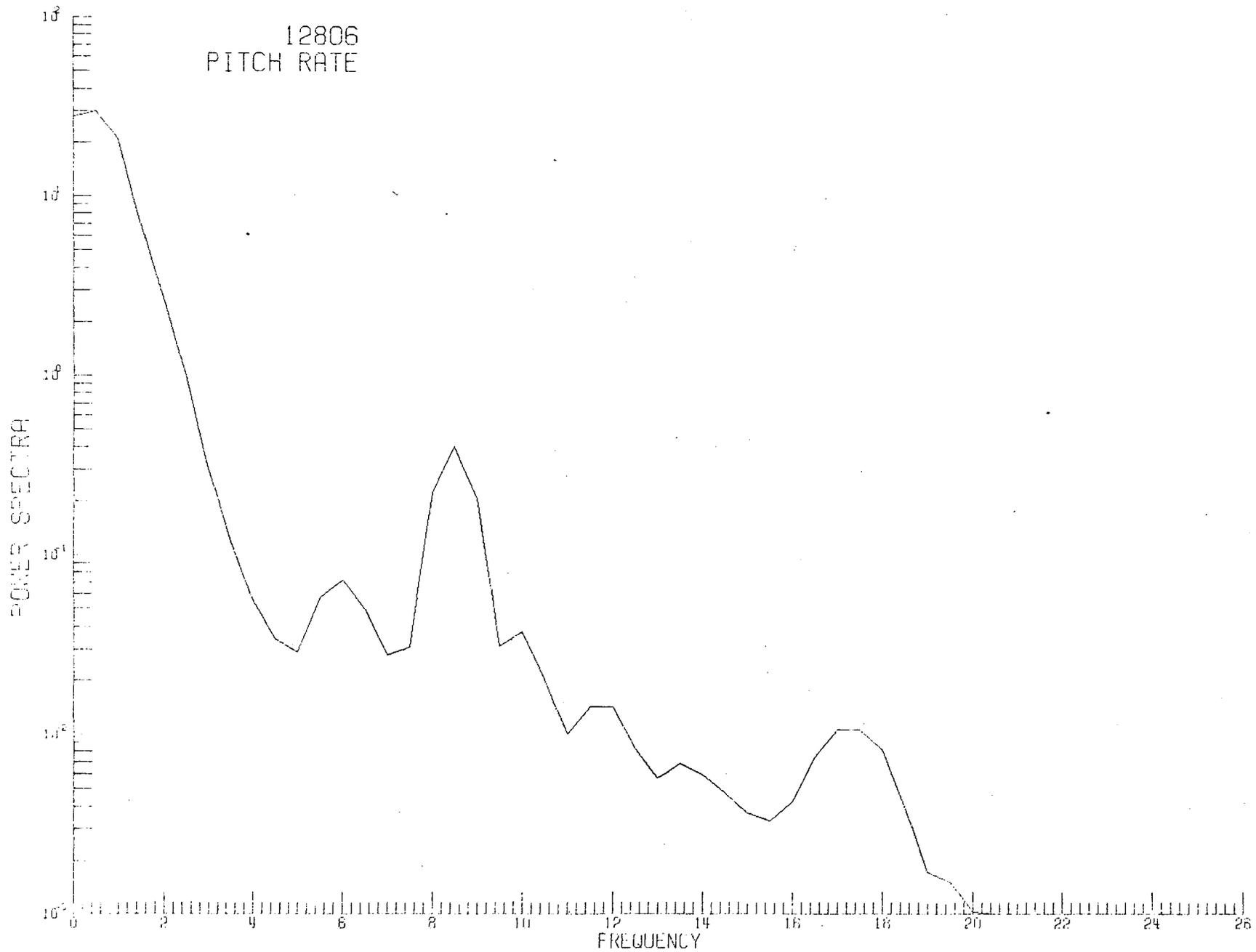


(c) Pitching velocity power spectrum (RMS pitching velocity 1.298 deg/sec).



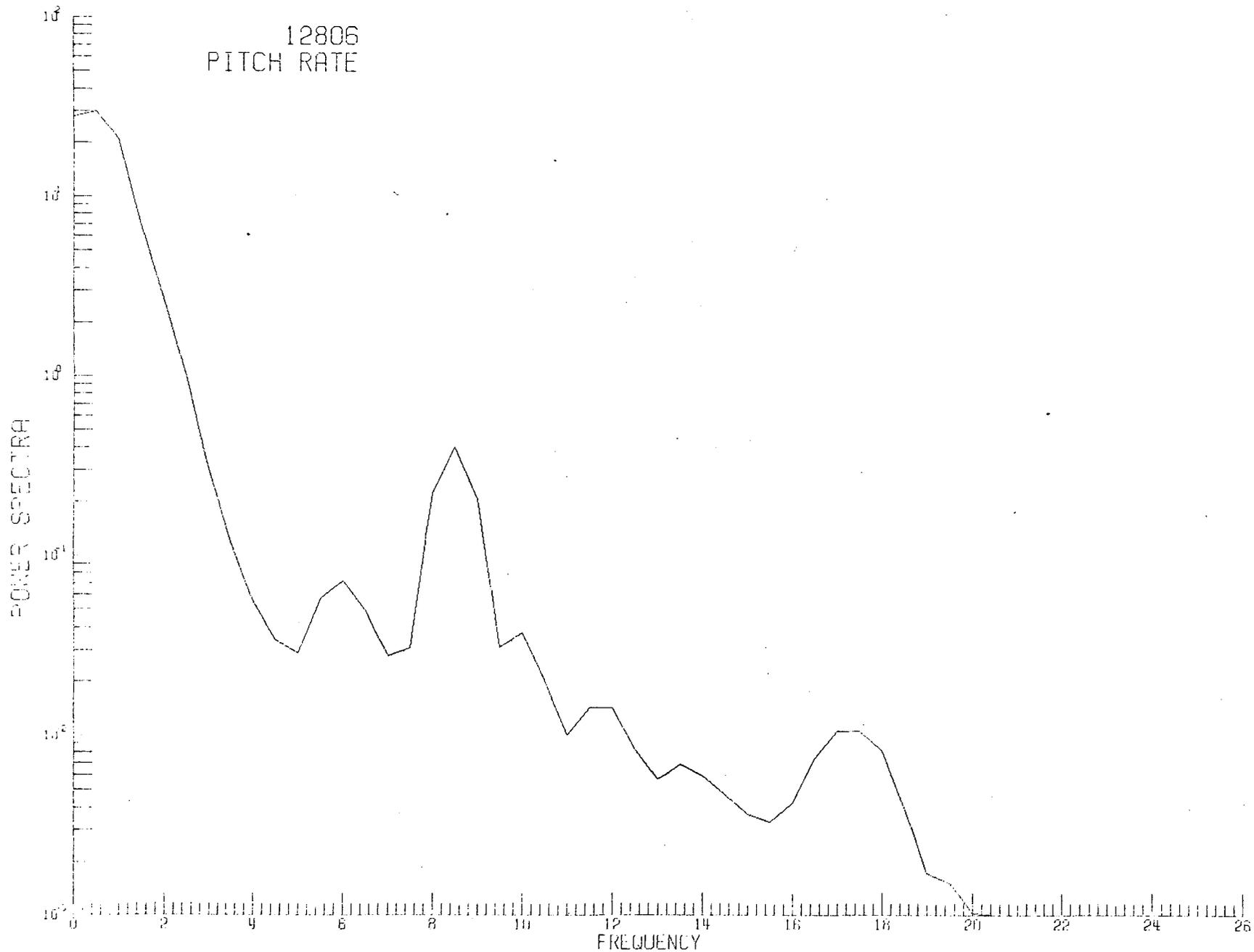
(c) Pitching velocity power spectrum (RMS pitching velocity 1.391 deg/sec).

Figure 6 - Continued.



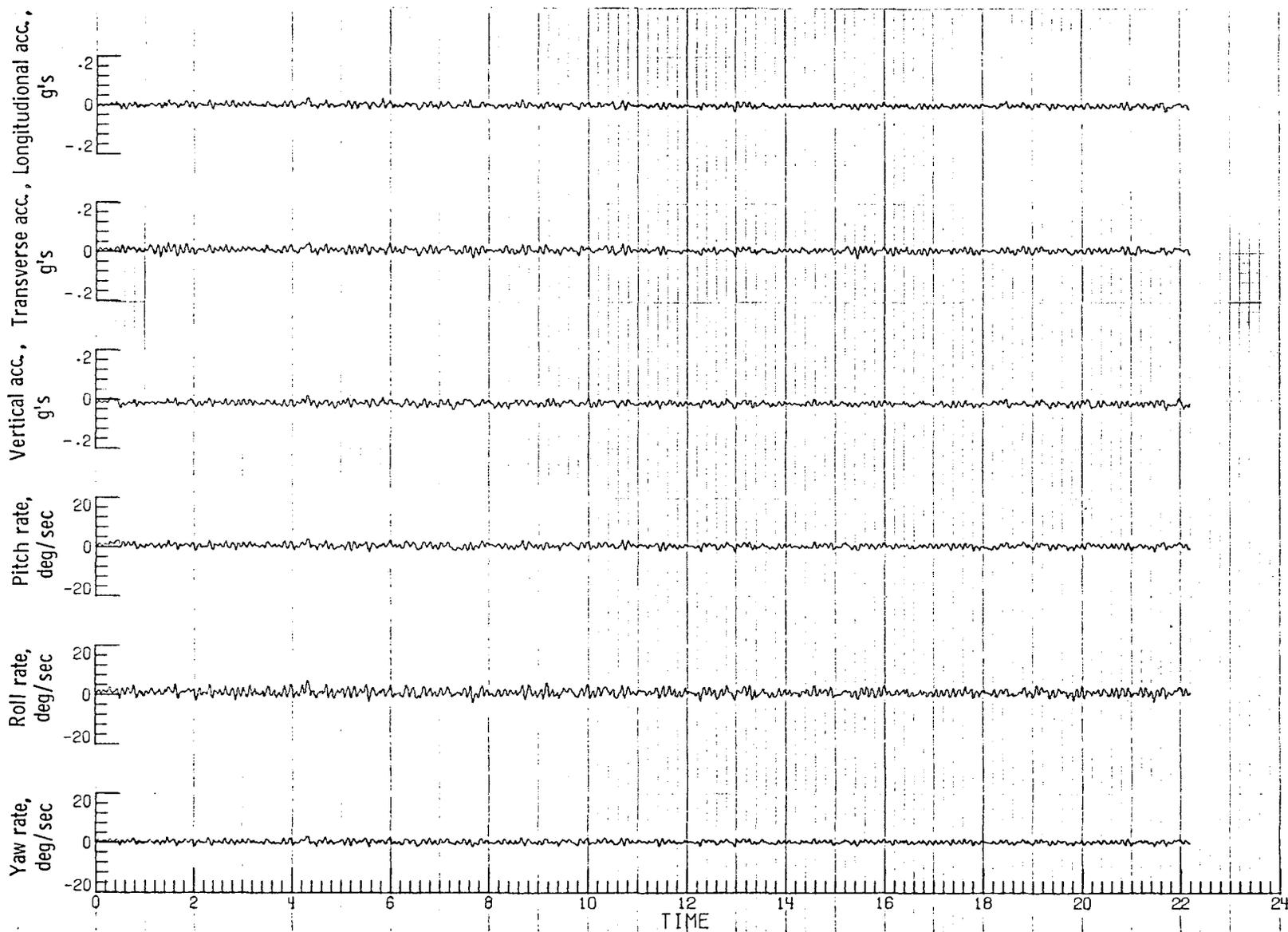
(c) Pitching velocity power spectrum (RMS pitching velocity 6.386 deg/sec).

Figure 6. - Concluded.



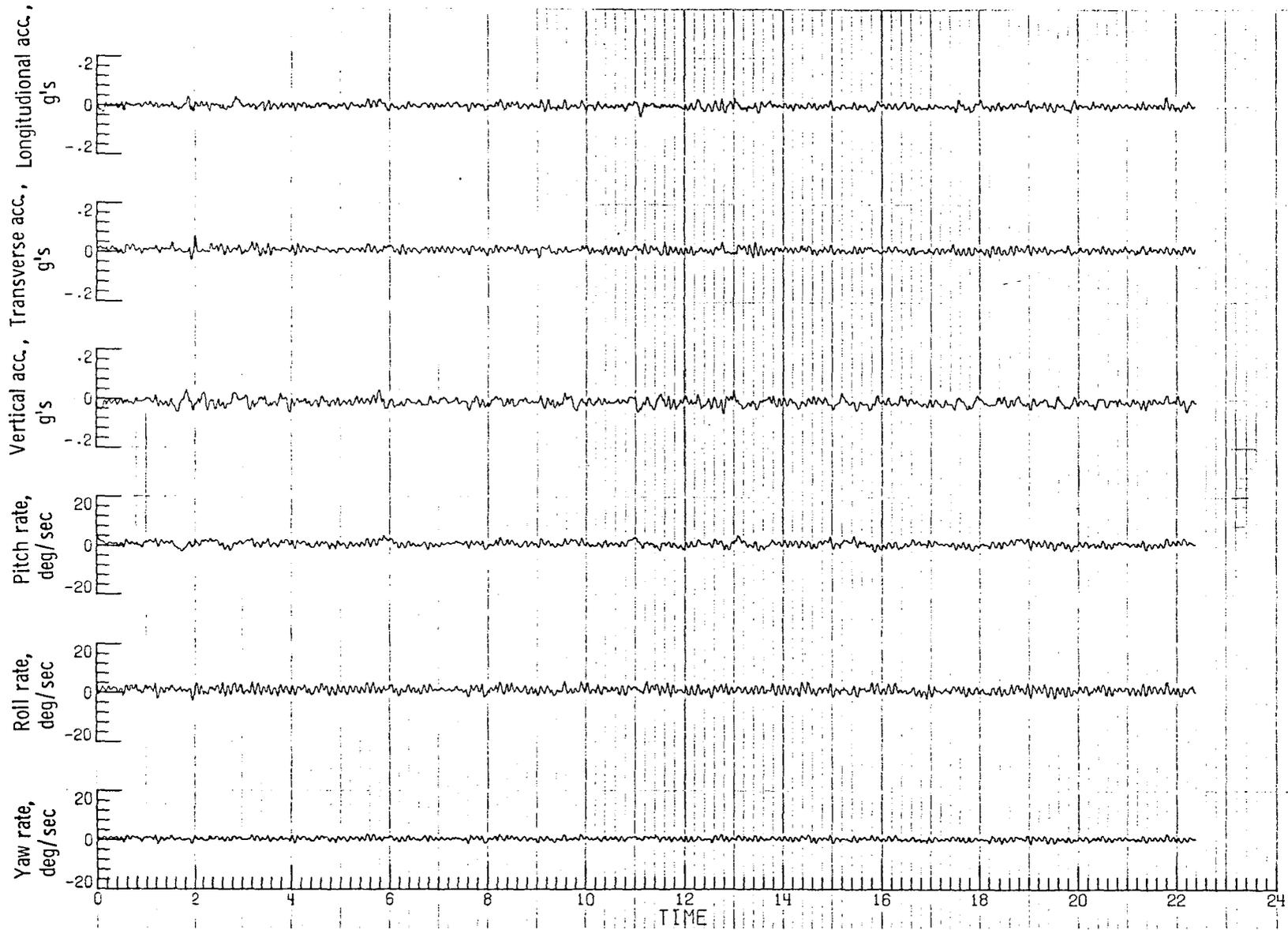
(c) Pitching velocity power spectrum (RMS pitching velocity 6.386 deg/sec).

Figure 6. - Concluded.



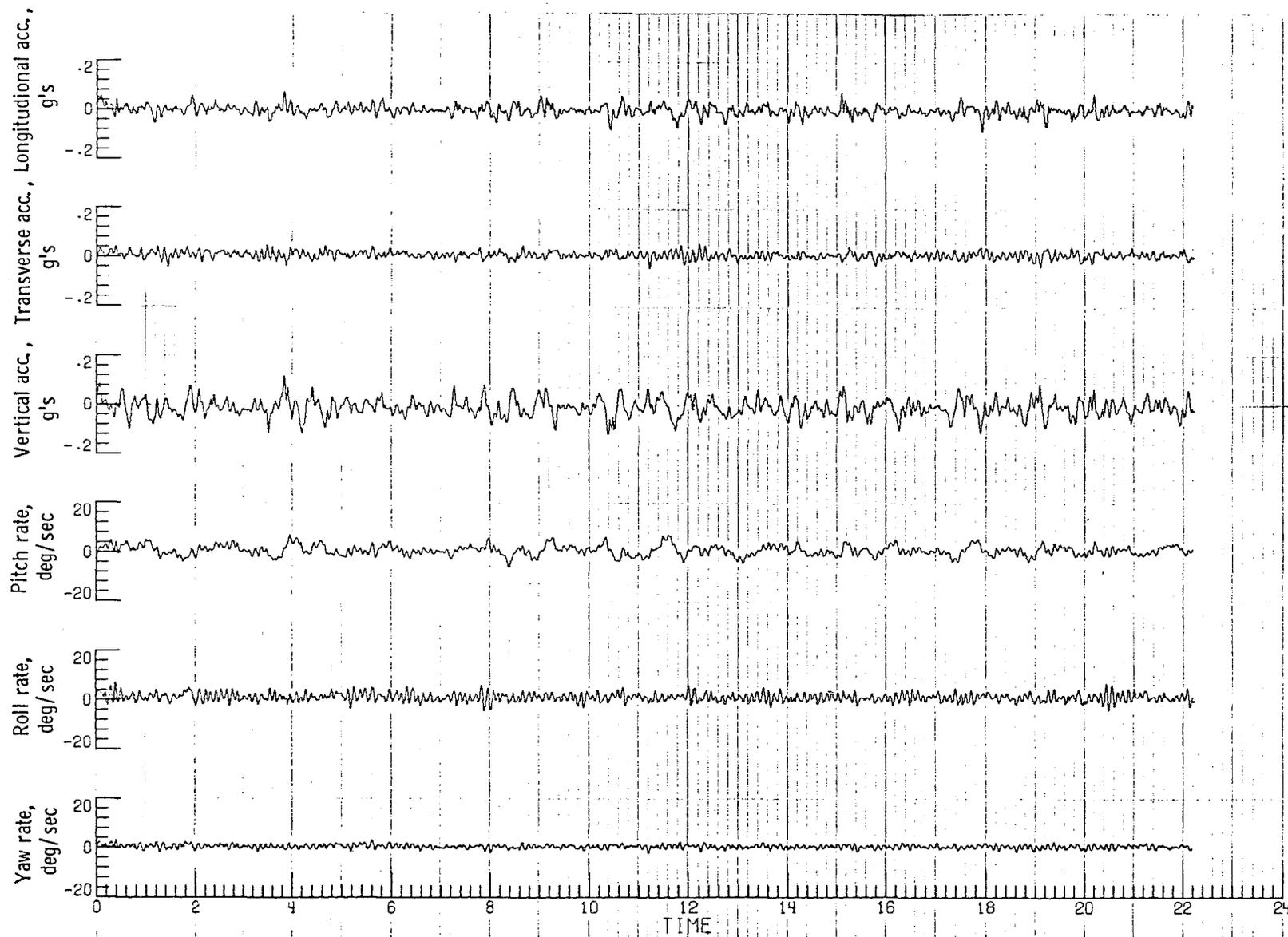
(a) Time histories (RMS pitching velocity 0.804 deg/sec).

Figure 7. - Measured motion characteristics using pitching velocity with typical 0-2 HZ inputs.



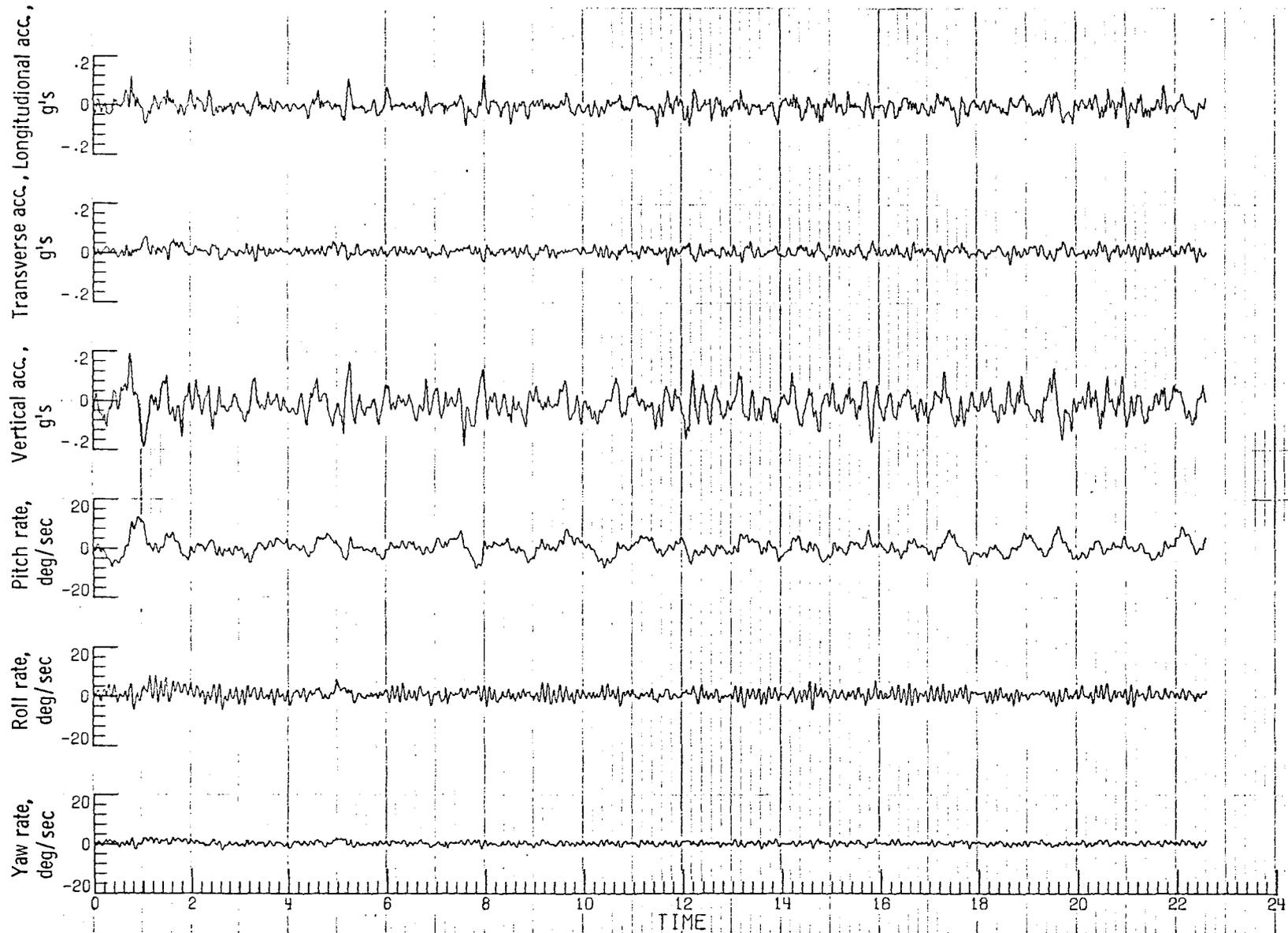
(a) Time histories (RMS pitching velocity 1.012 deg/sec).

Figure 7. - Continued.



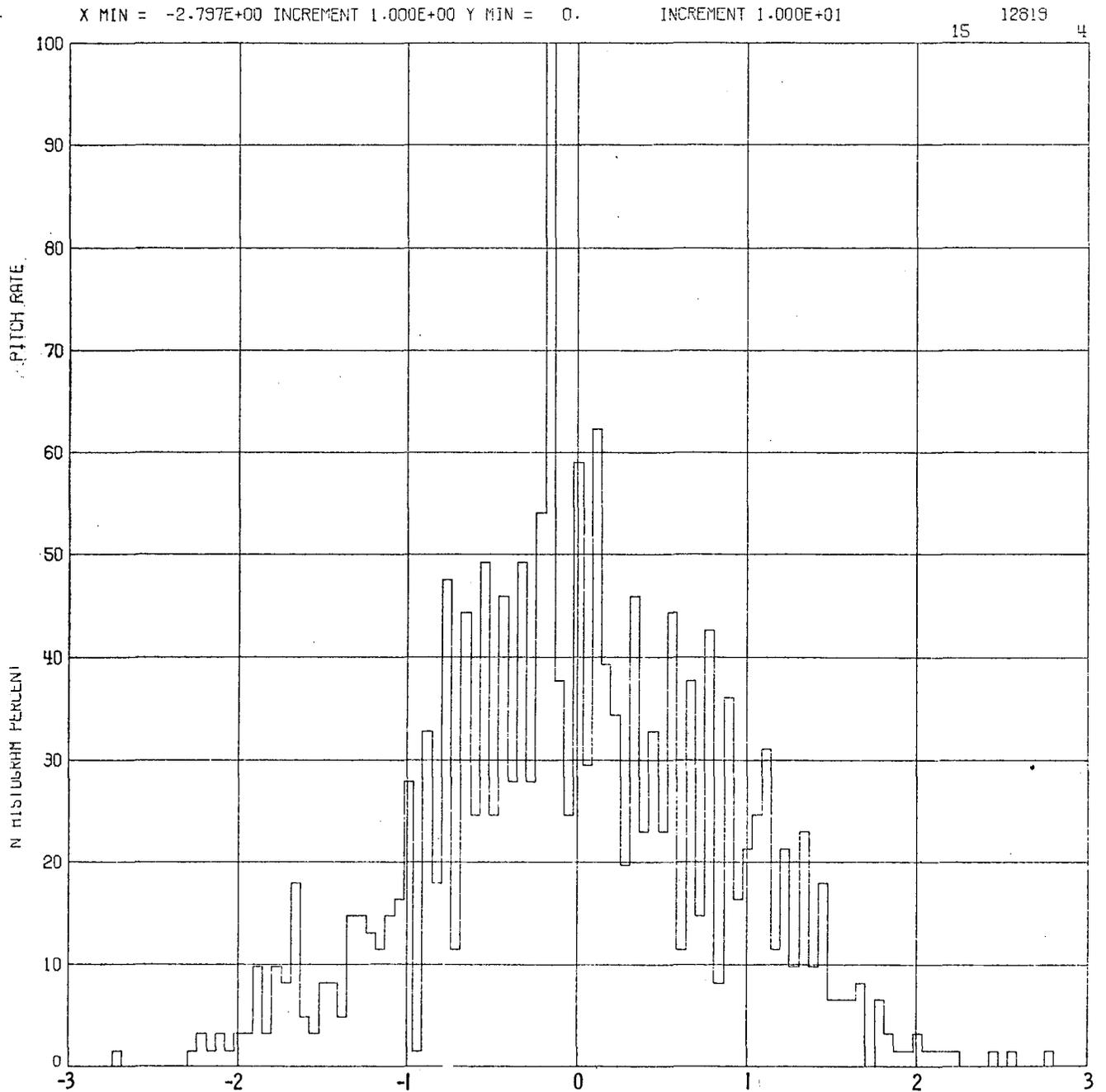
(a) Time histories (RMS pitching velocity 2.015 deg/sec).

Figure 7. - Continued.



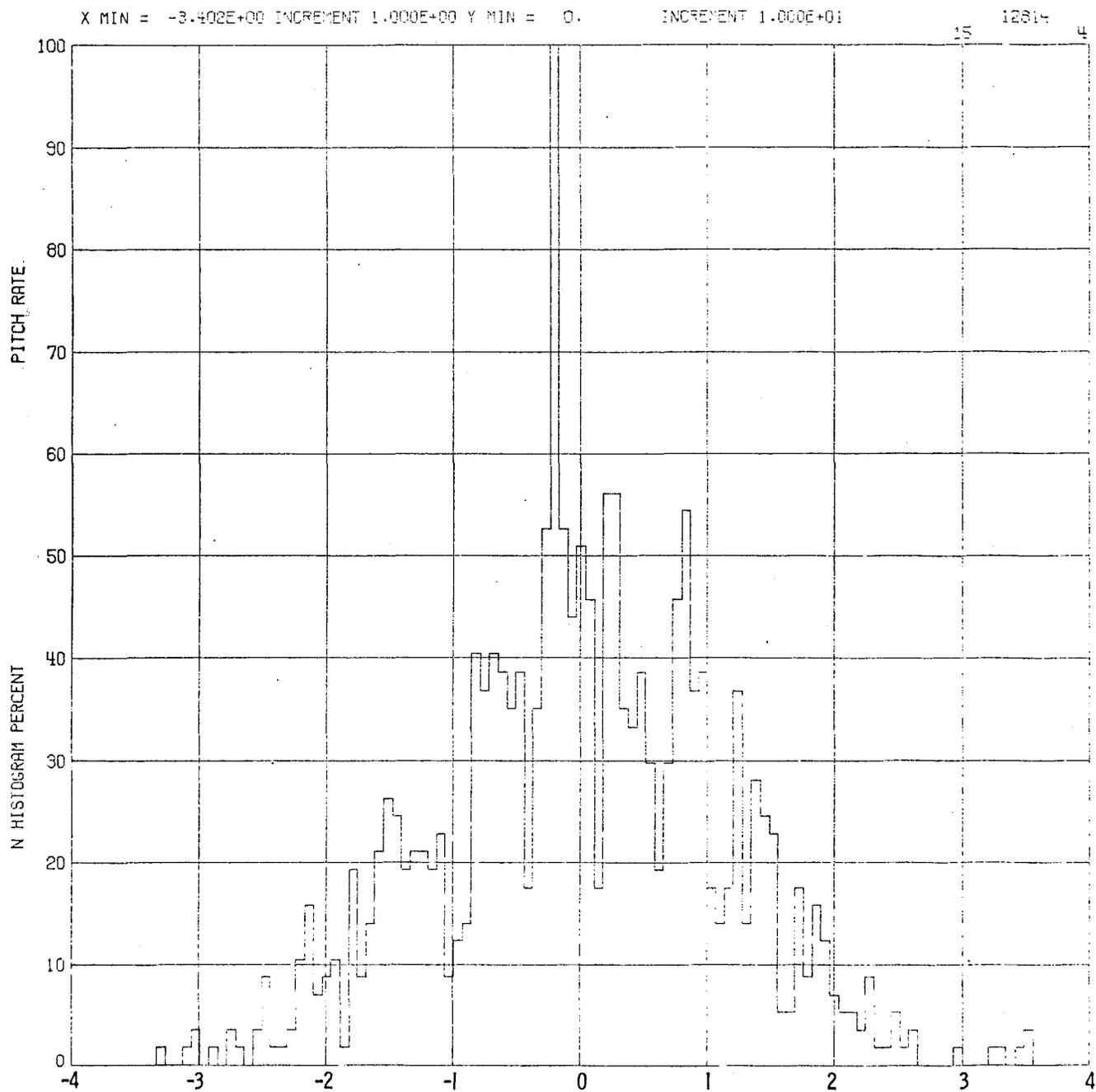
(a) Time histories (RMS pitching velocity 3.008 deg/sec).

Figure 7. - Continued.



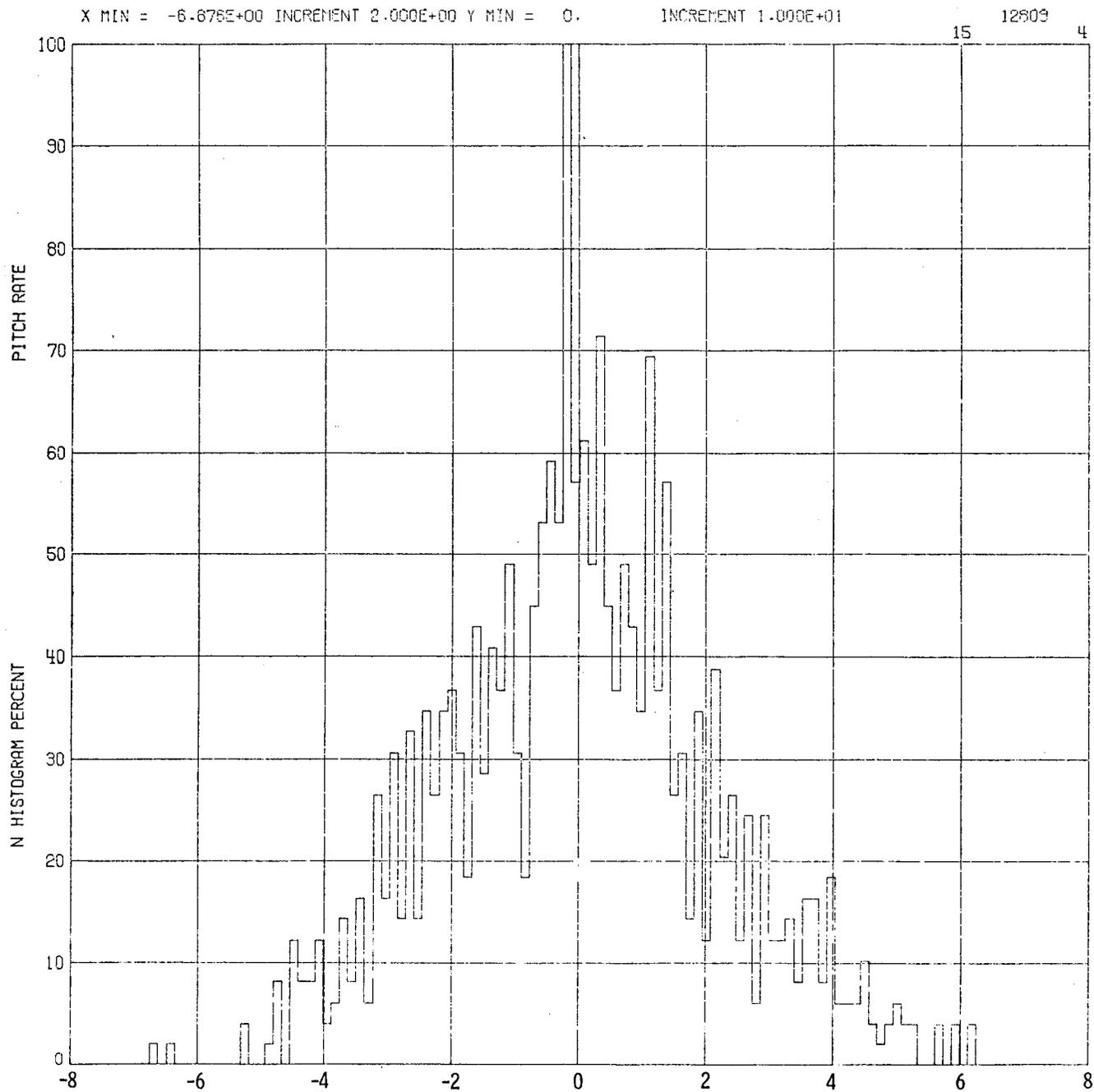
(b) Pitching velocity histograms (RMS pitching velocity 0.804 deg/sec).

Figure 7 - Continued.



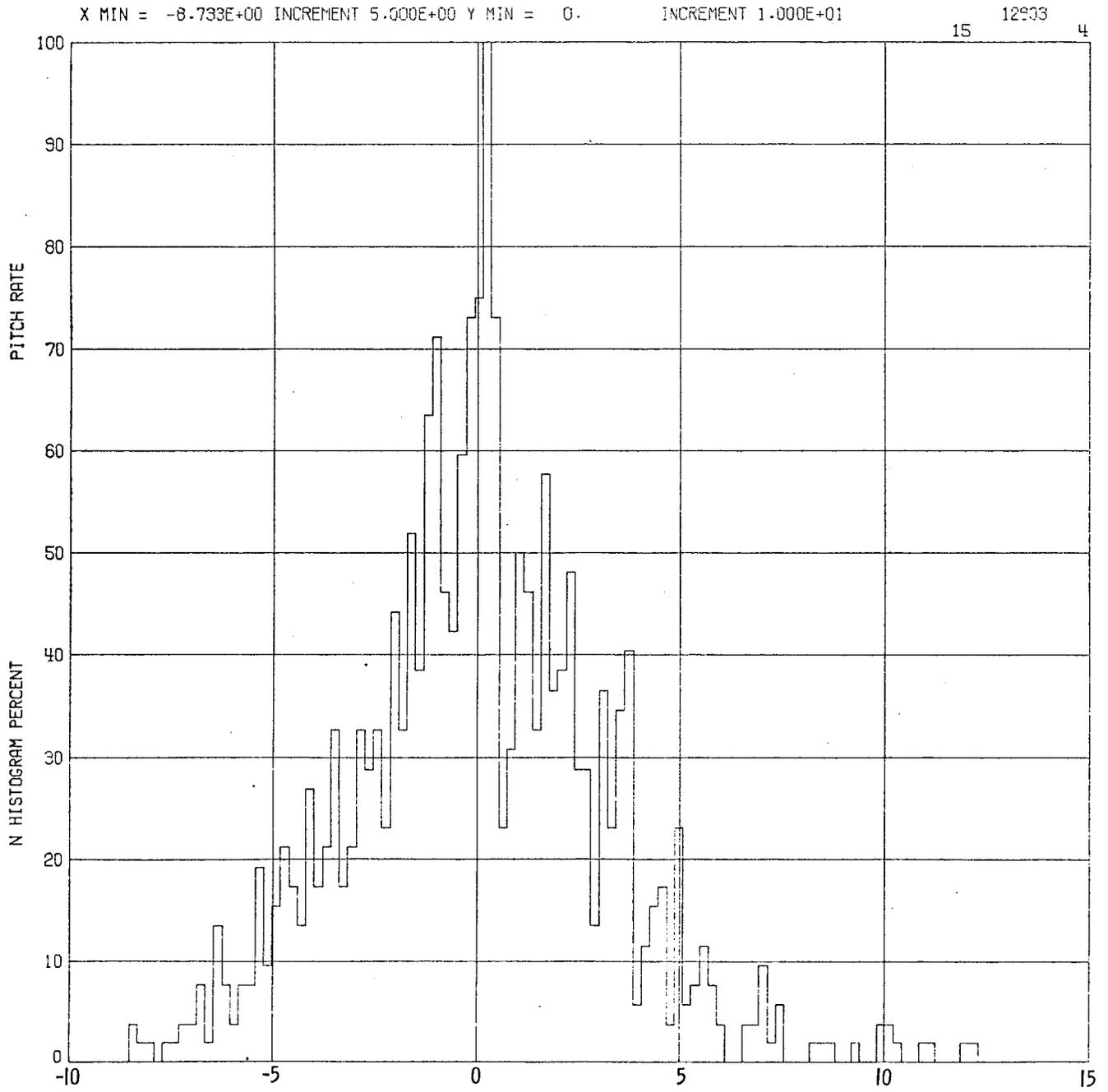
(b) Pitching velocity histograms (RMS pitching velocity 1.012 deg/sec).

Figure 7. - Continued.



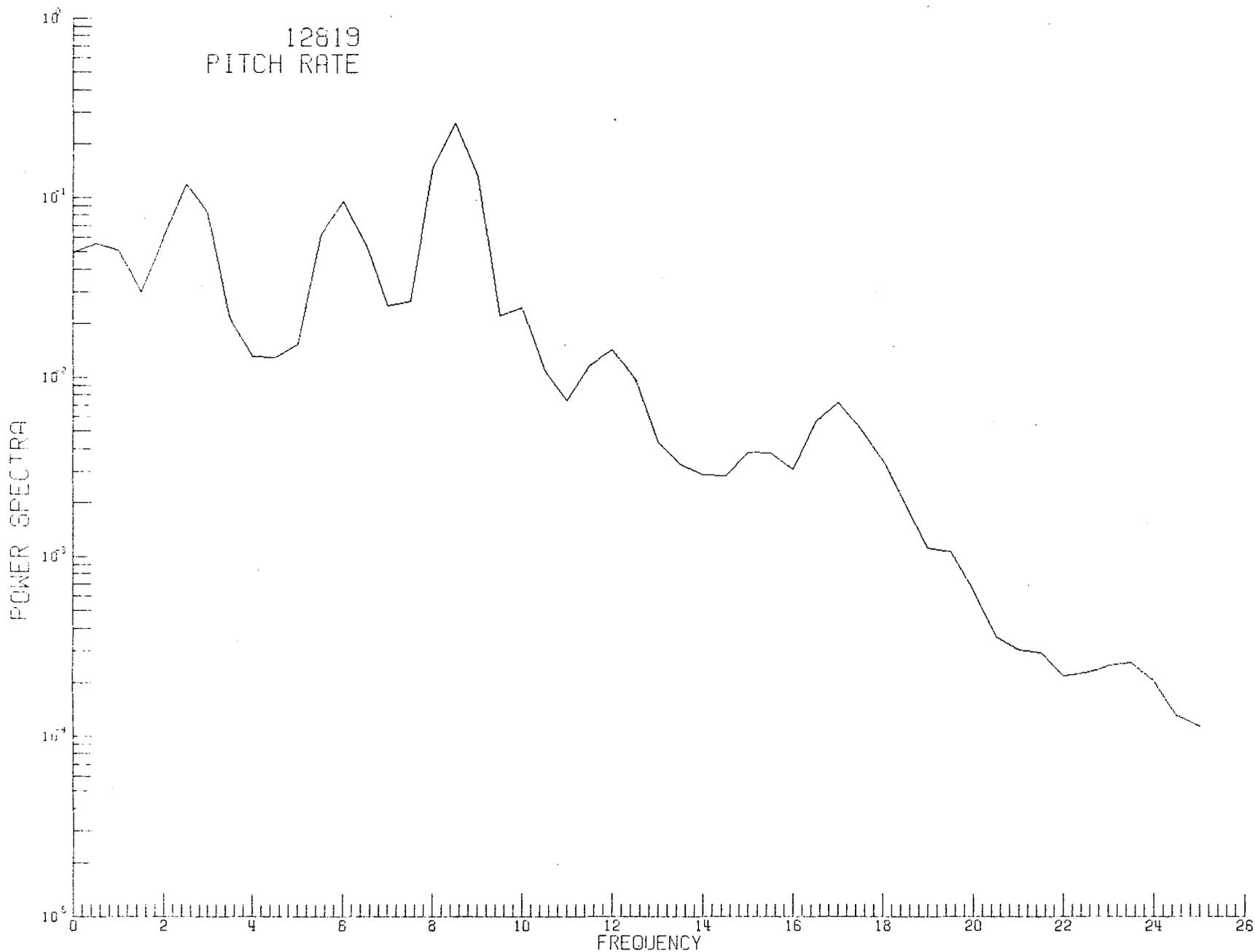
(b) Pitching velocity histograms (RMS pitching velocity 2.015 deg/sec).

Figure 7. - Continued.



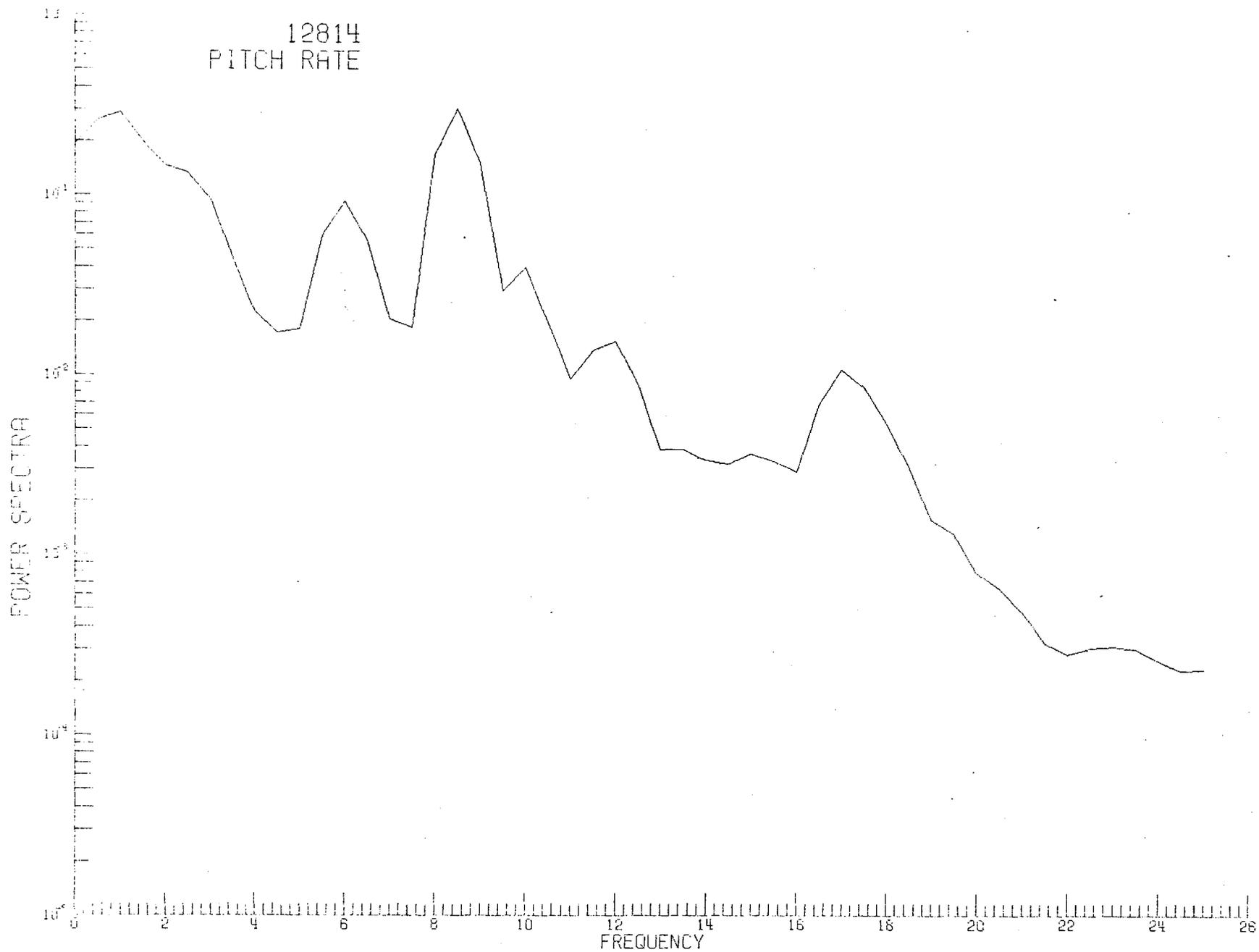
(b) Pitching velocity histograms (RMS pitching velocity 3.008 deg/sec).

Figure 7.- Continued.



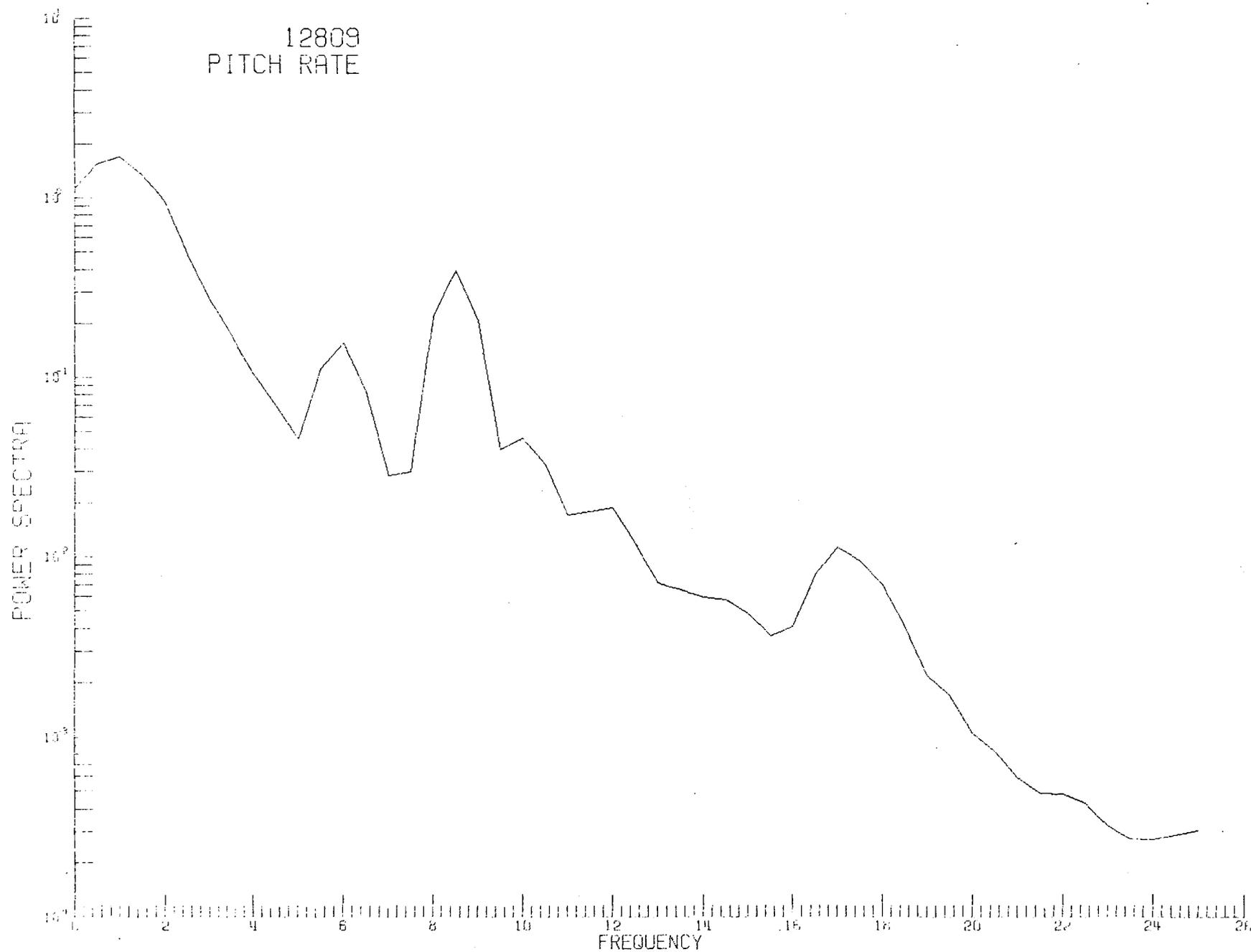
(c) Pitching velocity power spectrum (RMS pitching velocity 0.304 deg/sec).

Figure 7. - Continued.



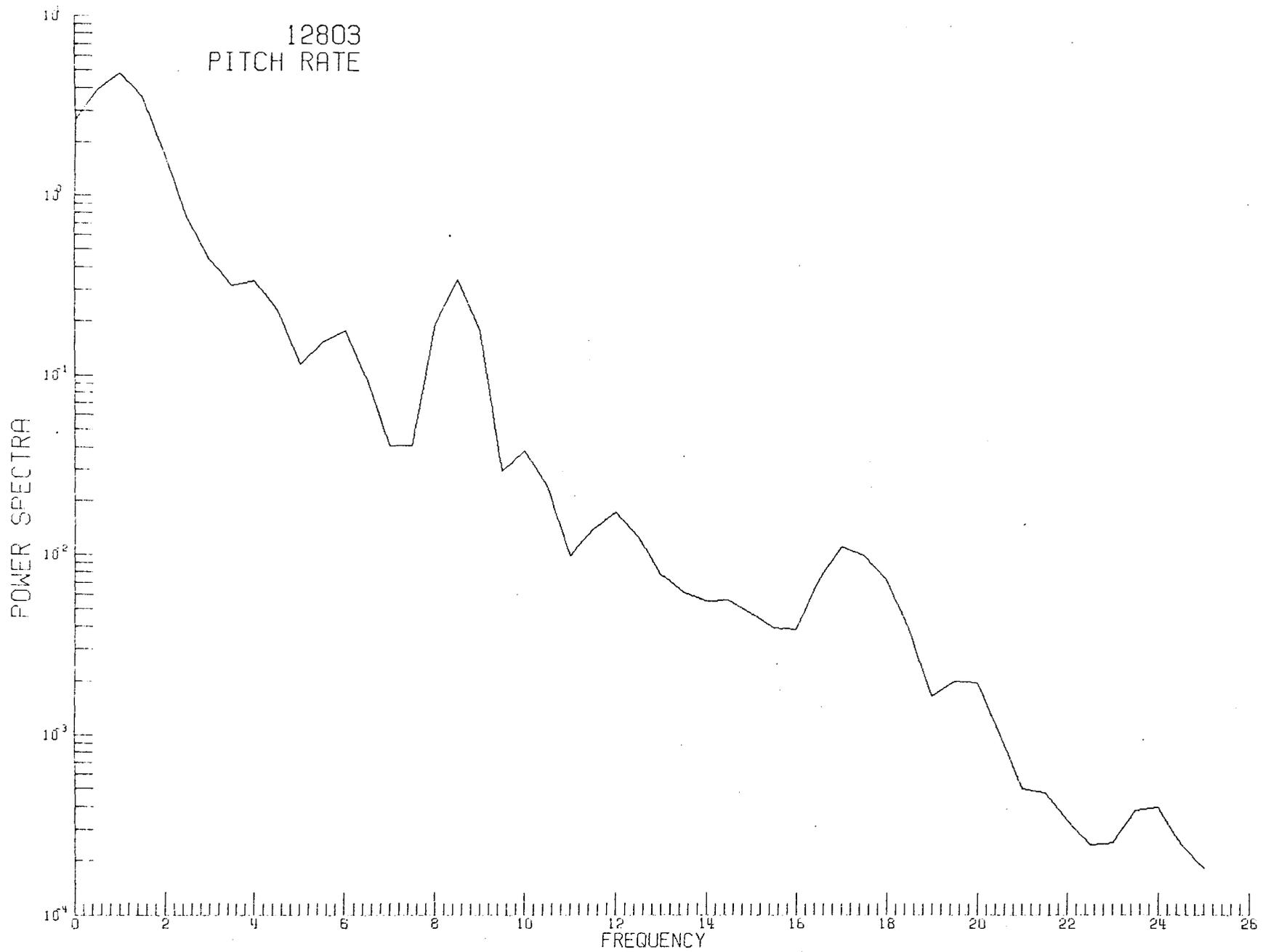
(c) Pitching velocity power spectrum (RMS pitching velocity 1.012 deg/sec).

Figure 7. - Continued.



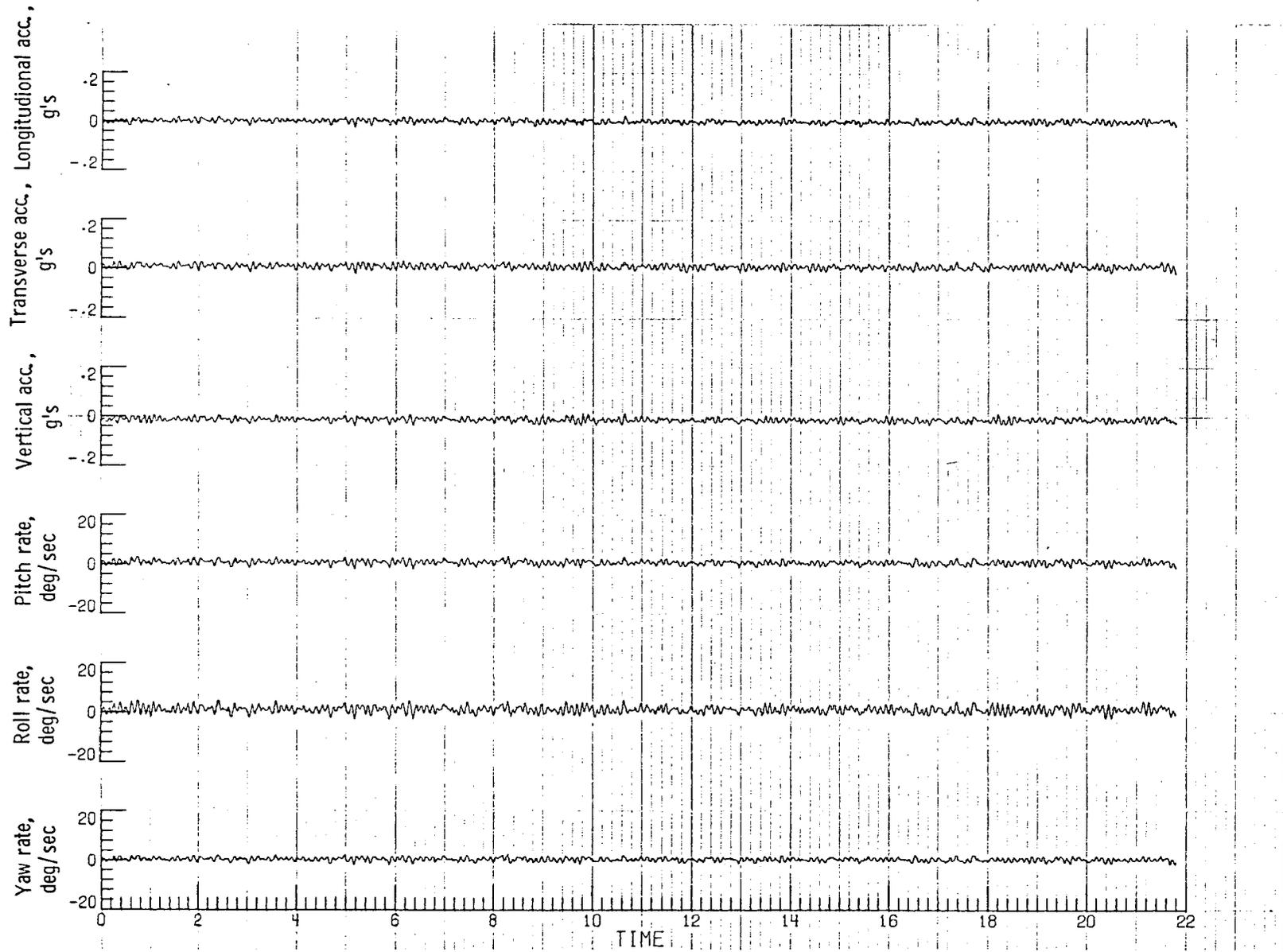
(c) Pitching velocity power spectrum (RMS pitching velocity 2.015 deg/sec).

Figure 7. - Continued.



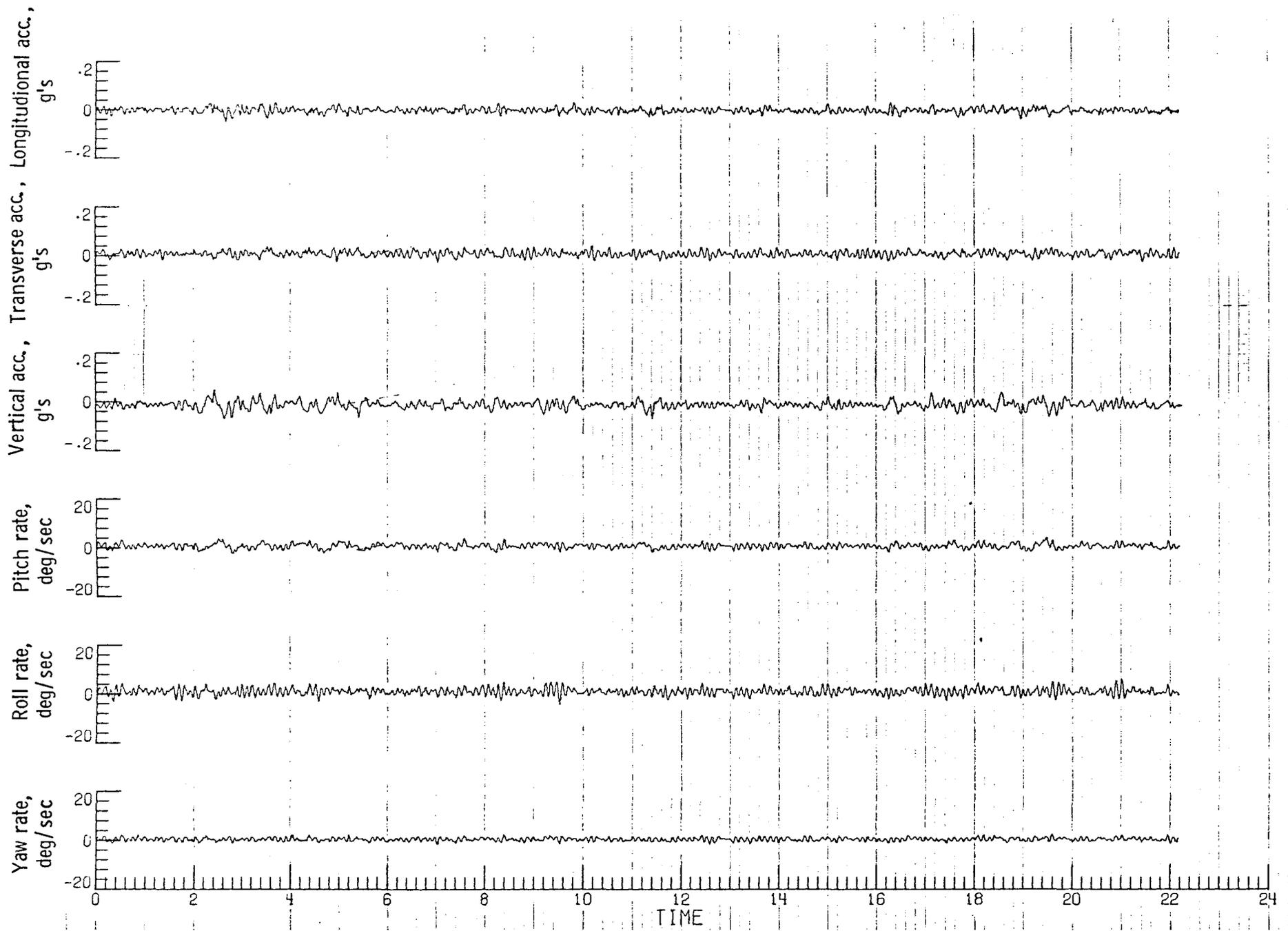
(c) Pitching velocity power spectrum (RMS pitching velocity 3.008 deg/sec).

Figure 7. - Concluded.



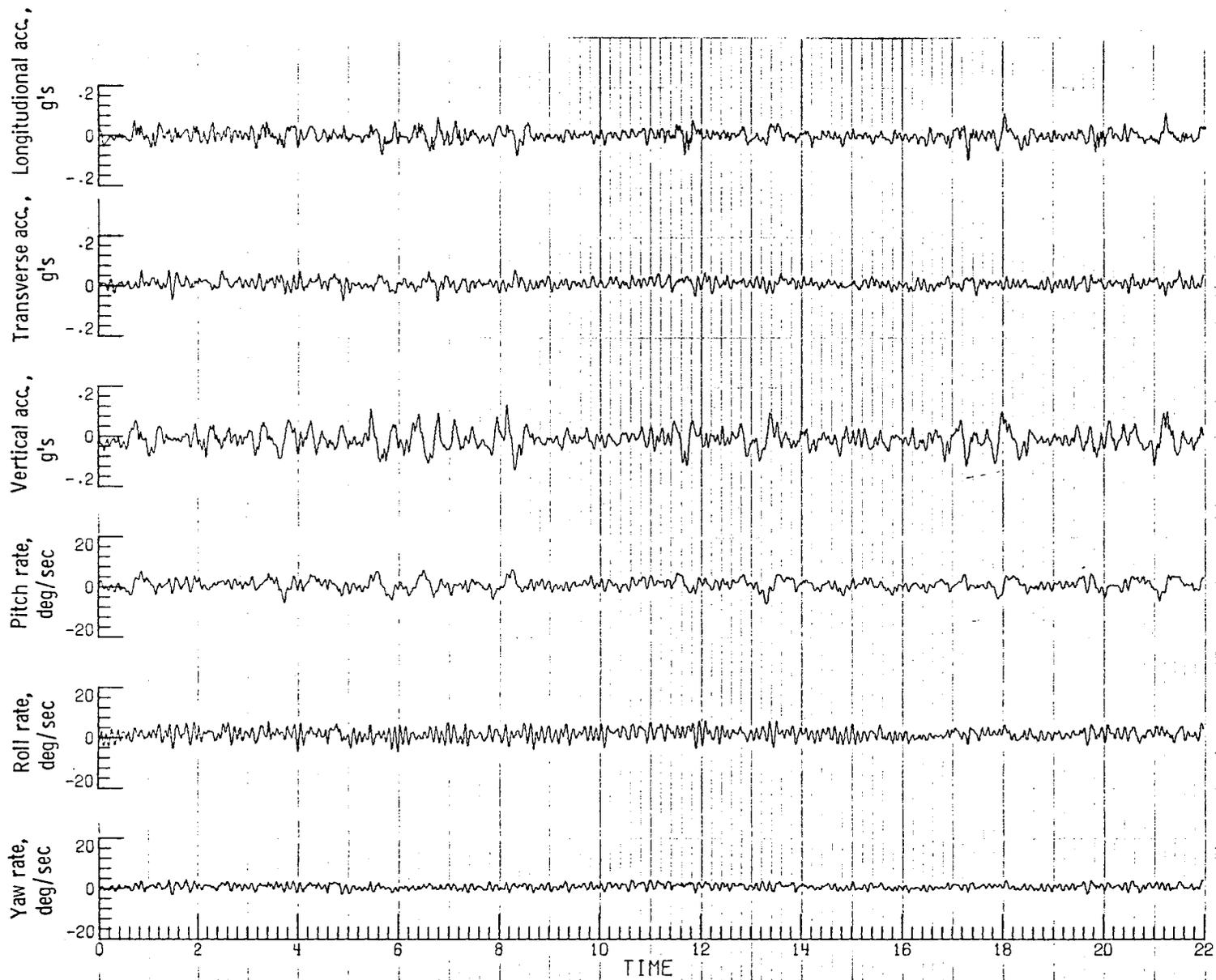
(a) Time histories (RMS pitching velocity 0.741 deg/sec).

Figure 8 - Measured motion characteristics using pitching velocity with typical 1-2 HZ inputs.



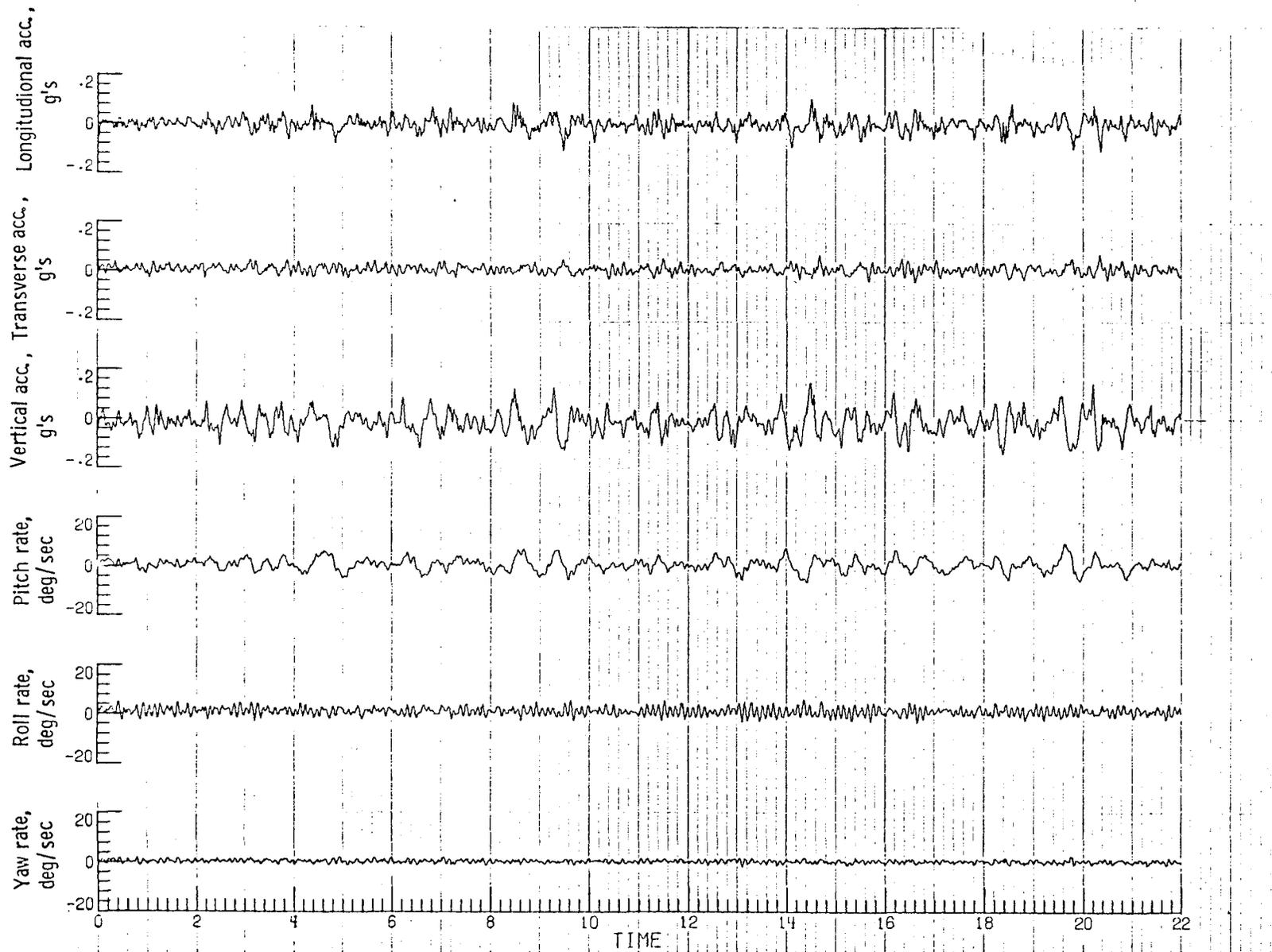
(a) Time histories (RMS pitching velocity 0.961 deg/sec).

Figure 8. - Continued.



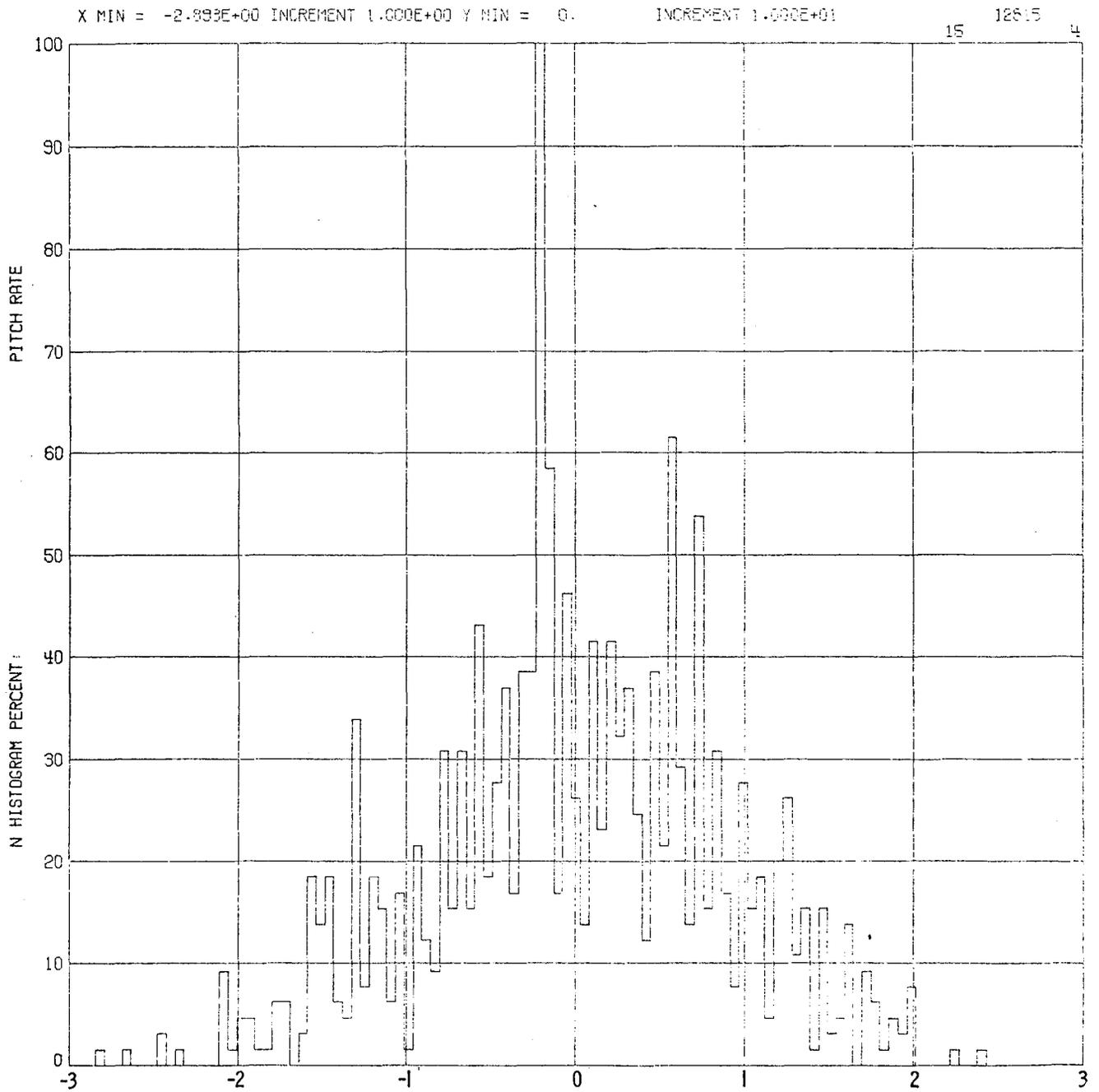
(a) Time histories (RMS pitching velocity 1.921 deg/sec).

Figure 8. - Continued.



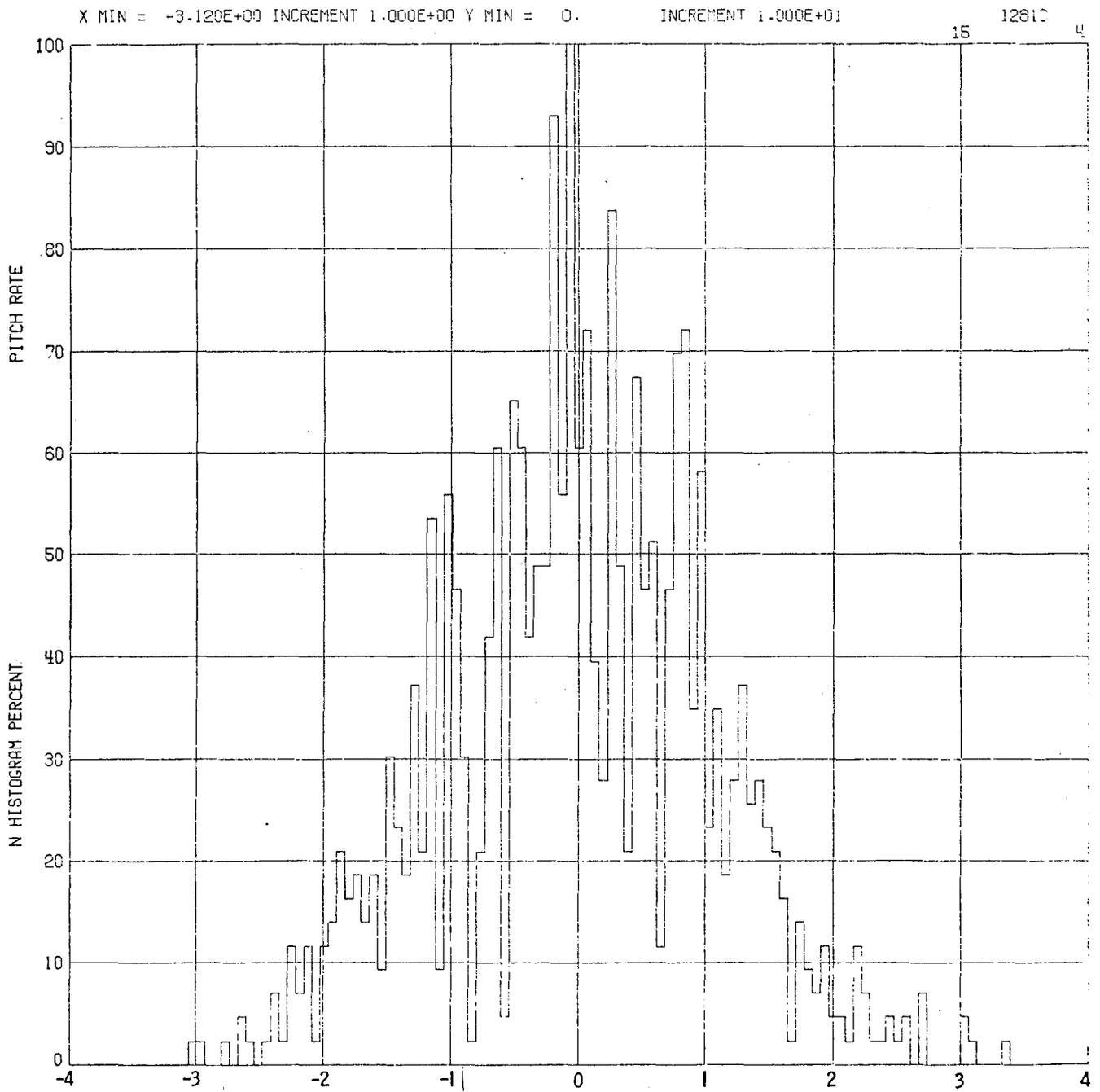
(a) Time histories (RMS pitching velocity 2.390 deg/sec).

Figure 8. - Continued.

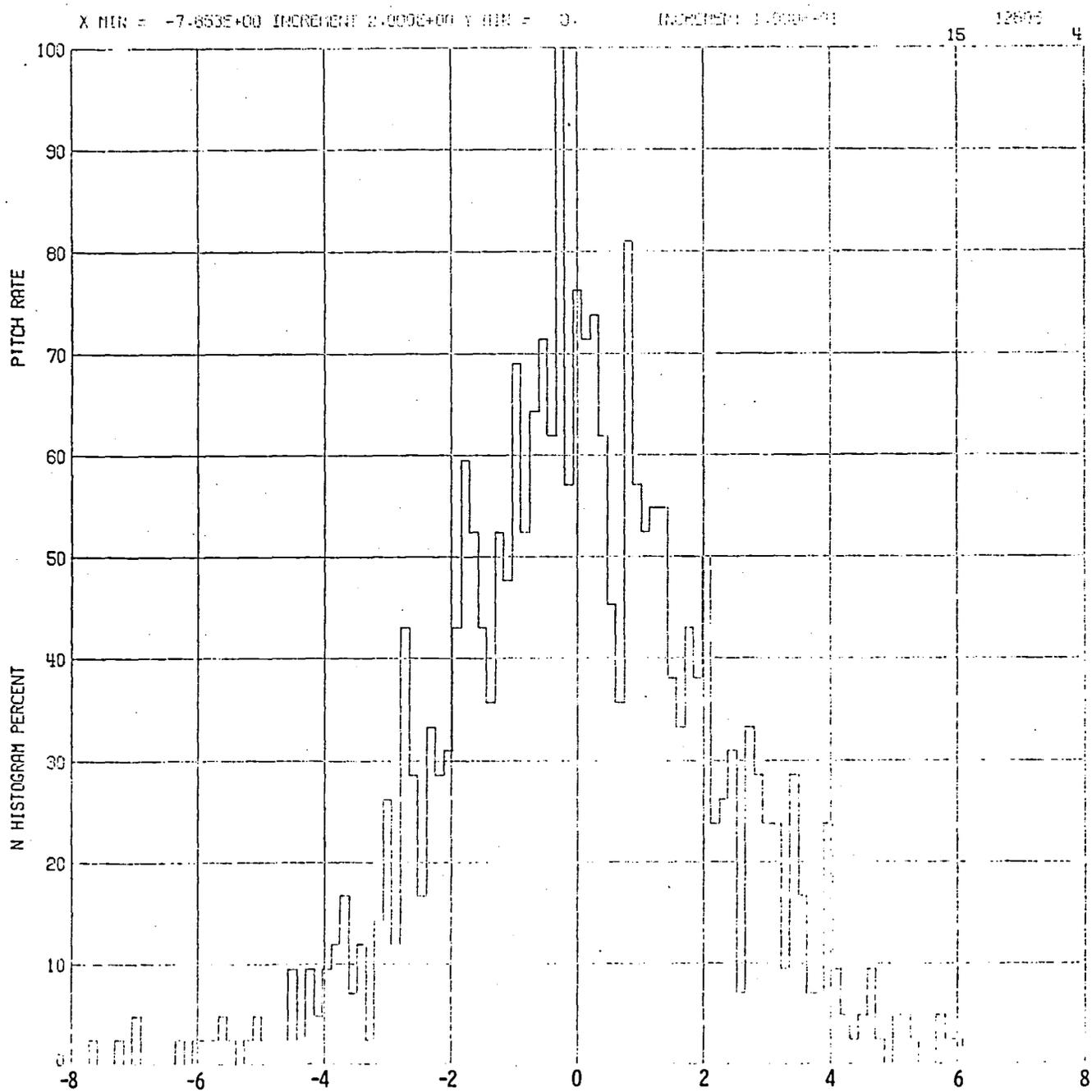


(b) Pitching velocity histograms (RMS pitching velocity 0.741 deg/sec).

Figure 8. - Continued.

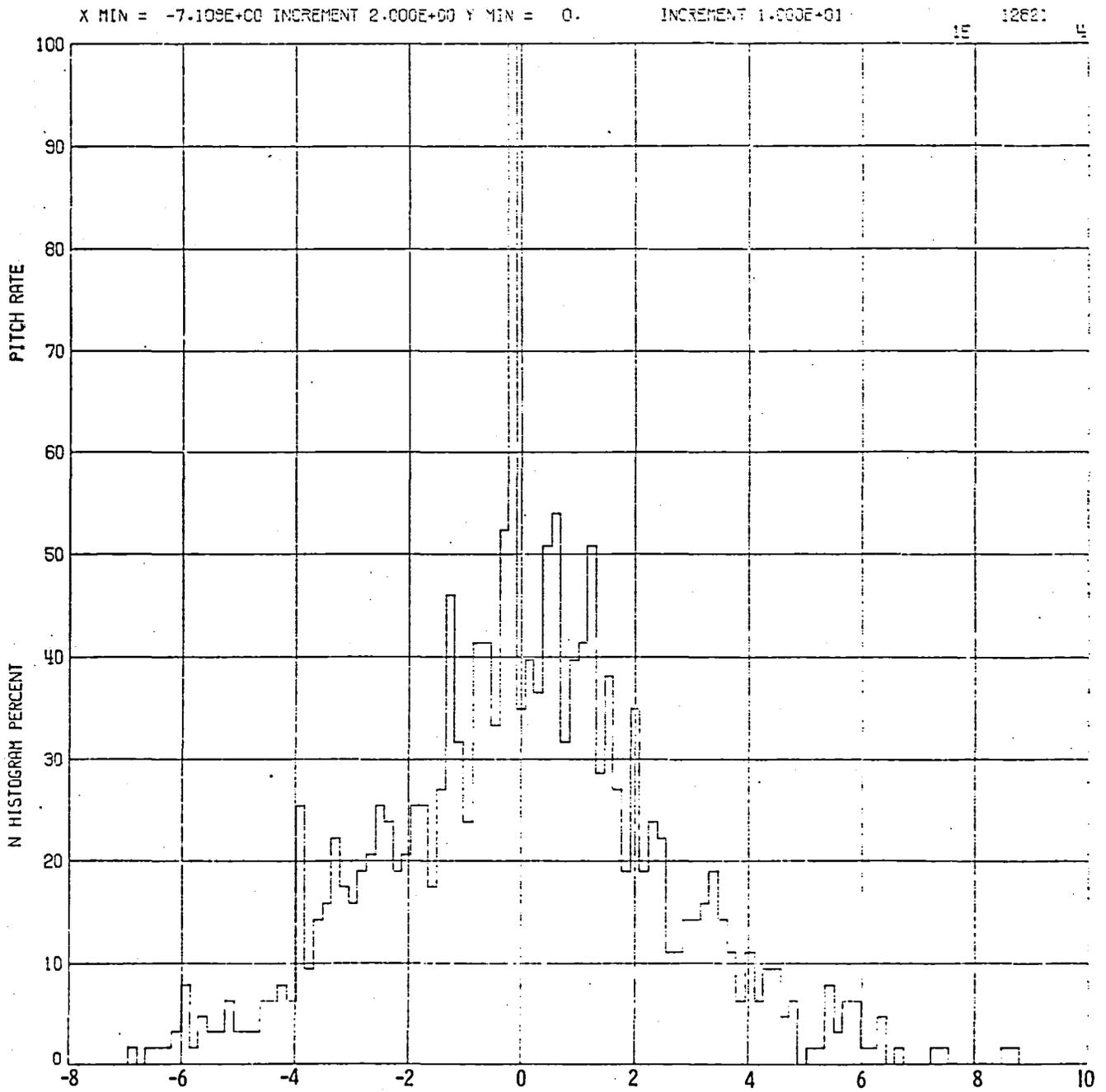


(b) Pitching velocity histograms (RMS pitching velocity 0.961 deg/sec).
Figure 8- Continued.



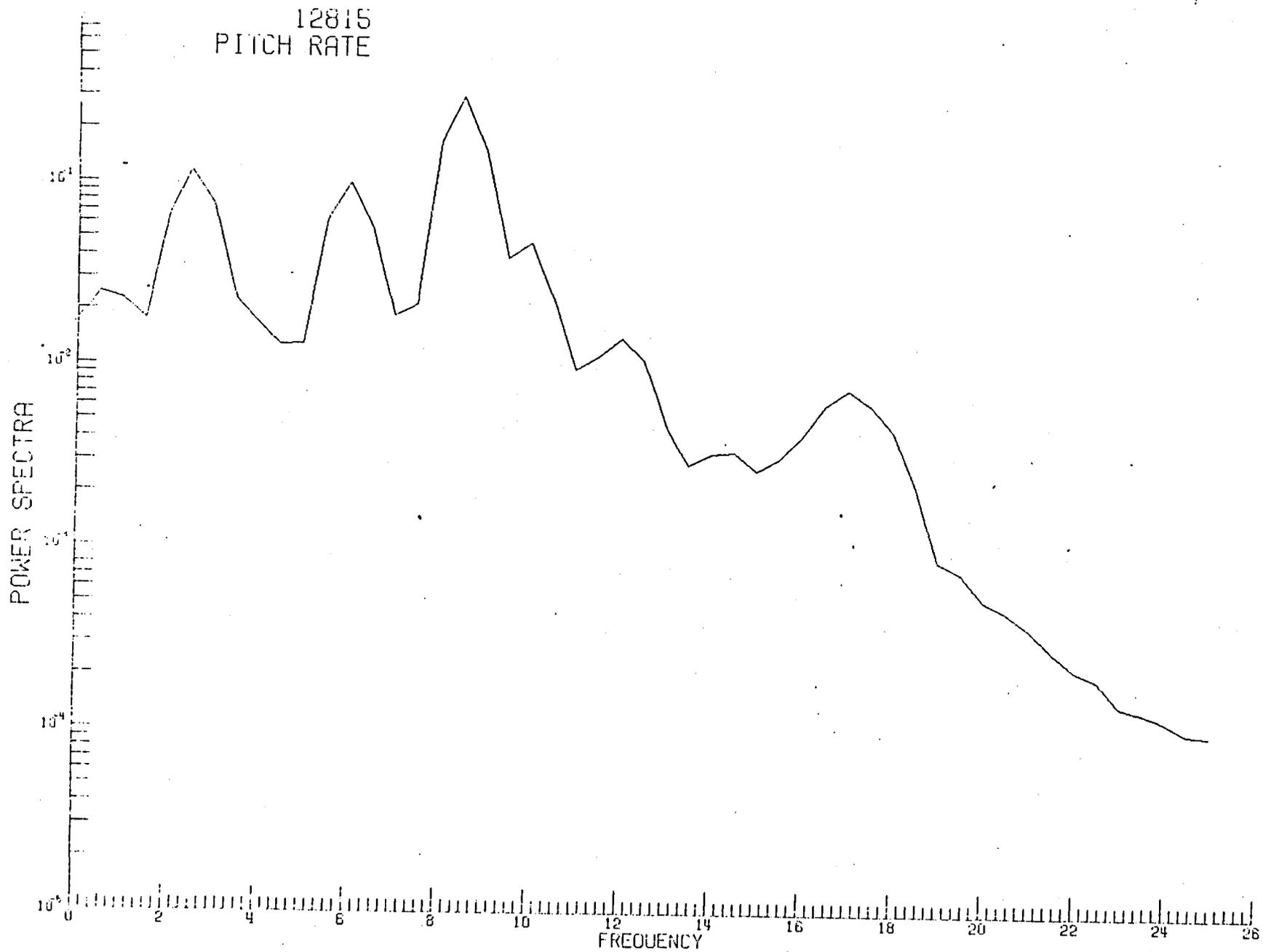
(b) Pitching velocity histograms (RMS pitching velocity 1.921 deg/sec).

Figure 8 - Continued.



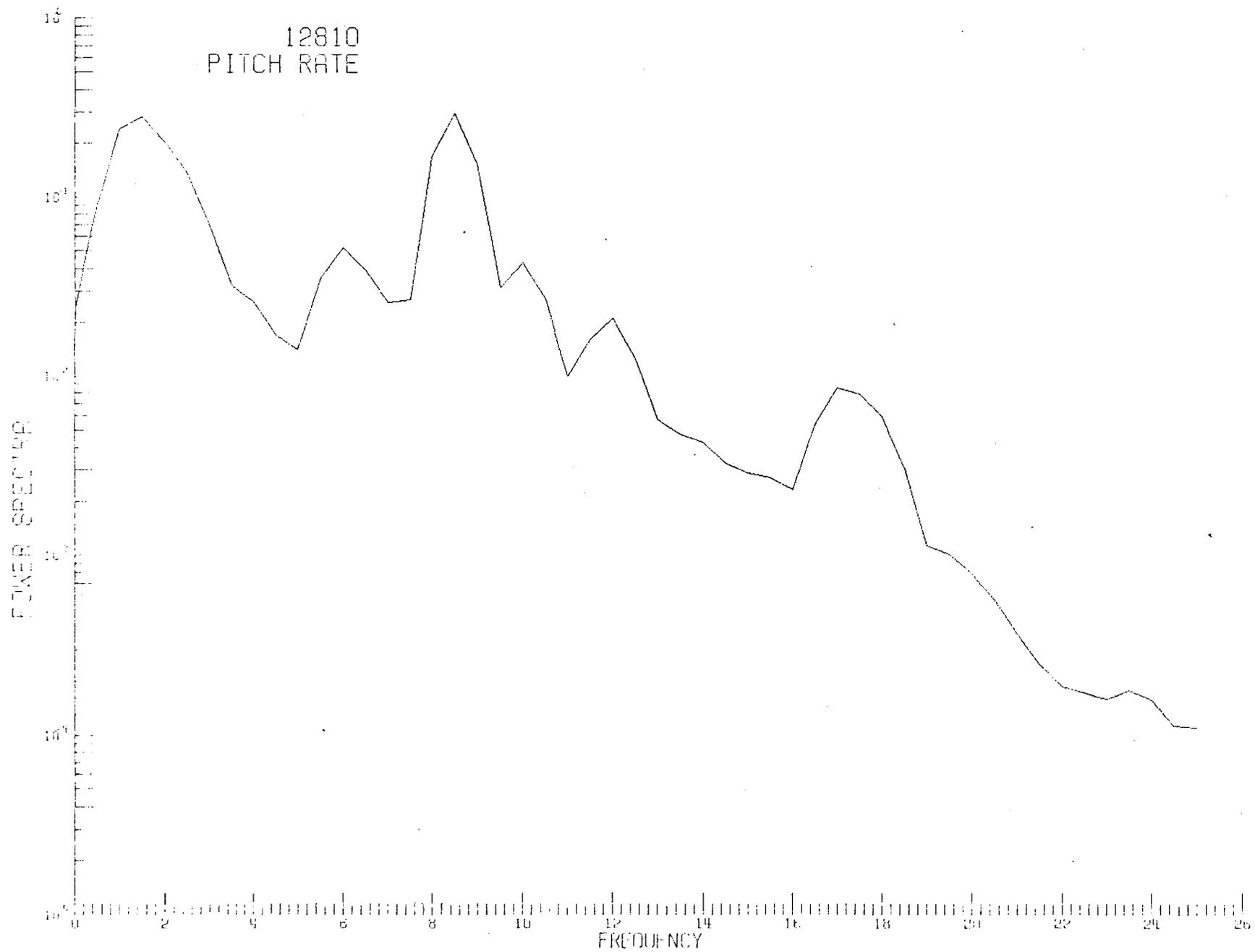
(b) Pitching velocity histograms (RMS pitching velocity 2.390 deg/sec).

Figure 8 - Continued.



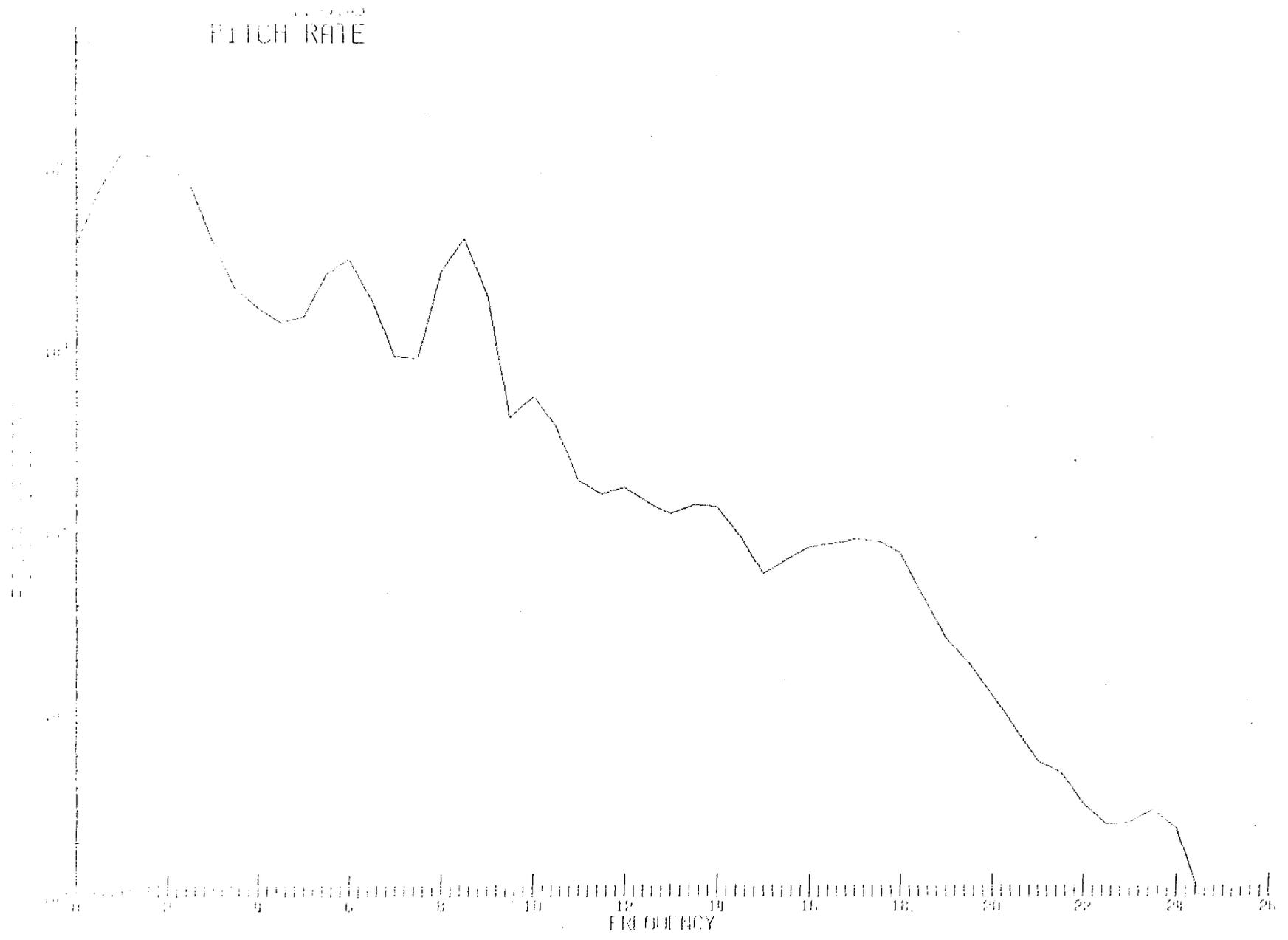
(c) Pitching velocity power spectrum (RMS pitching velocity 0.741 deg/sec).

Figure 8. - Continued.



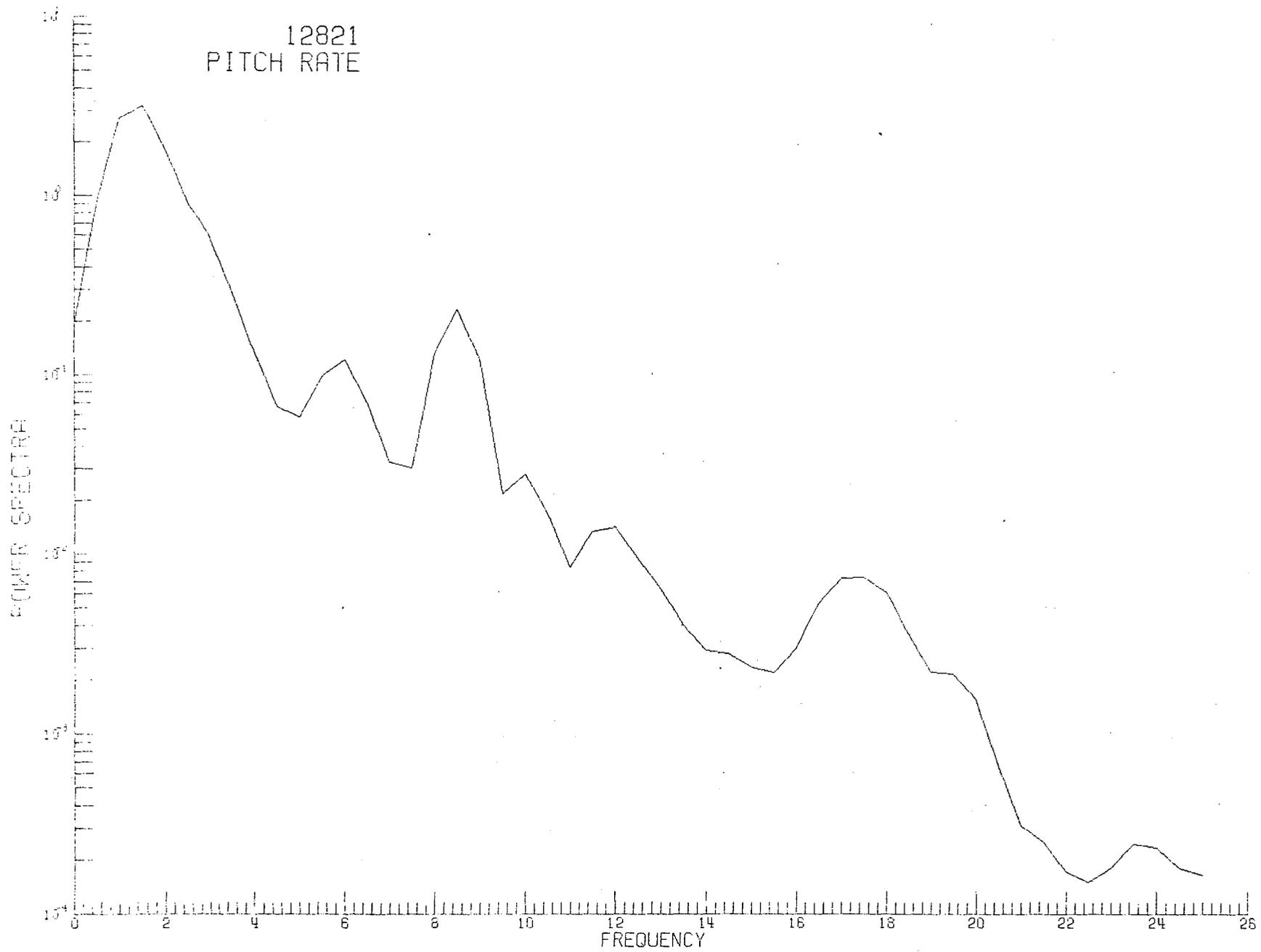
(c) Pitching velocity power spectrum (RMS pitching velocity 0.961 deg/sec).

Figure 8, - Continued.



(c) Pitching velocity power spectrum (RMS pitching velocity |. 92| deg/sec).

Figure 8. - Continued.



(c) Pitching velocity power spectrum (RMS pitching velocity 2,390 deg/sec).

Figure 8. - Concluded.

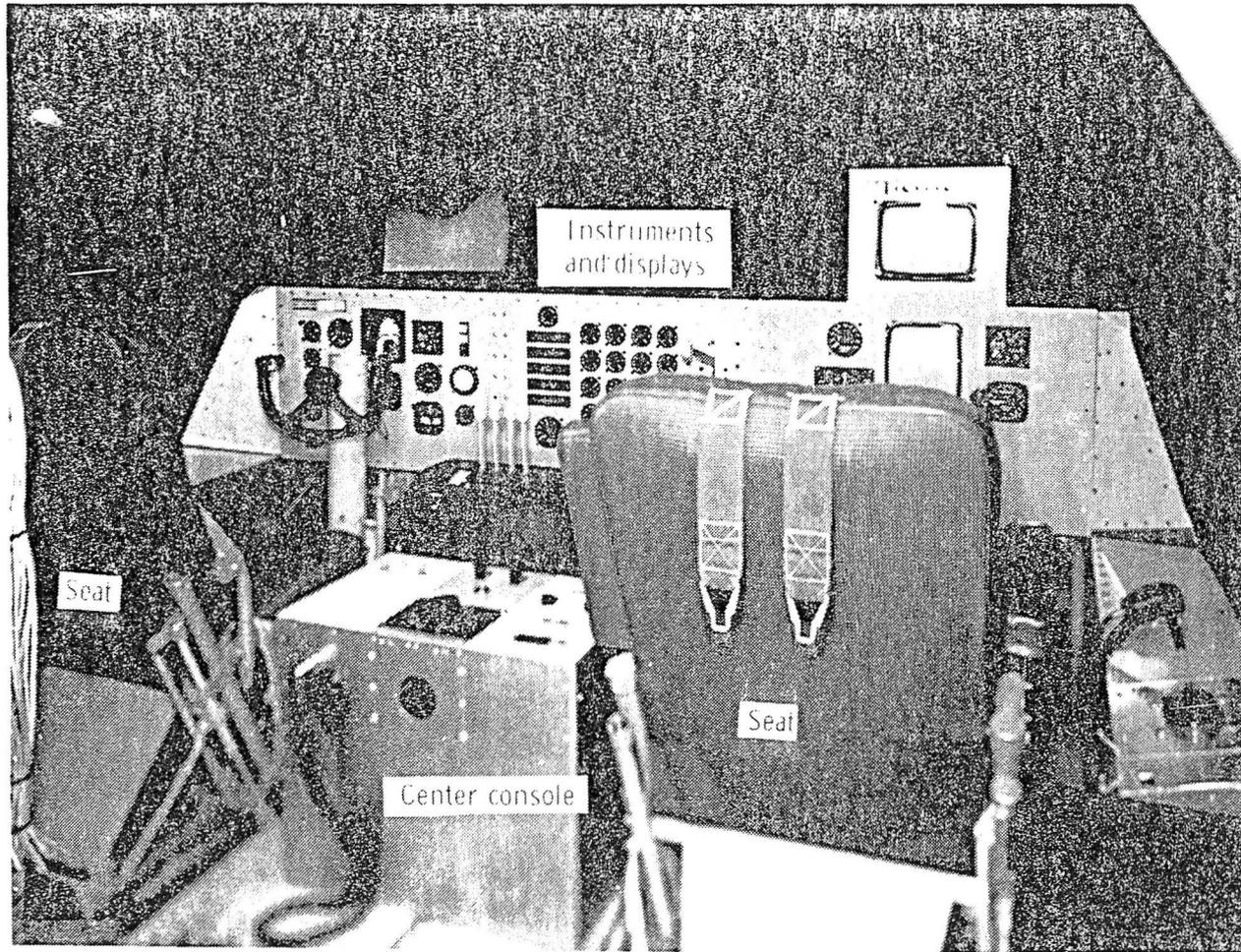


Figure 9 - Interior of the Langley six-degree-of-freedom vision motion simulator.

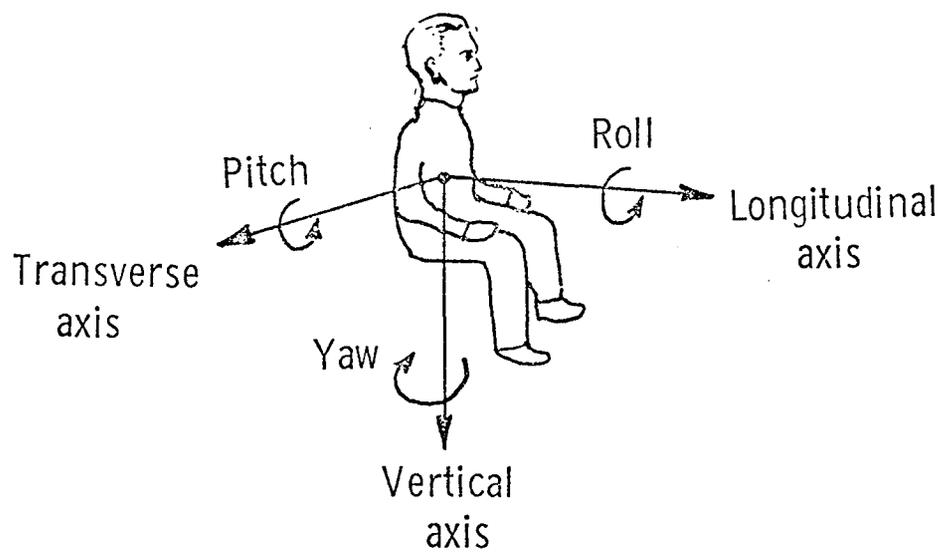


Figure 10- Reference axes.

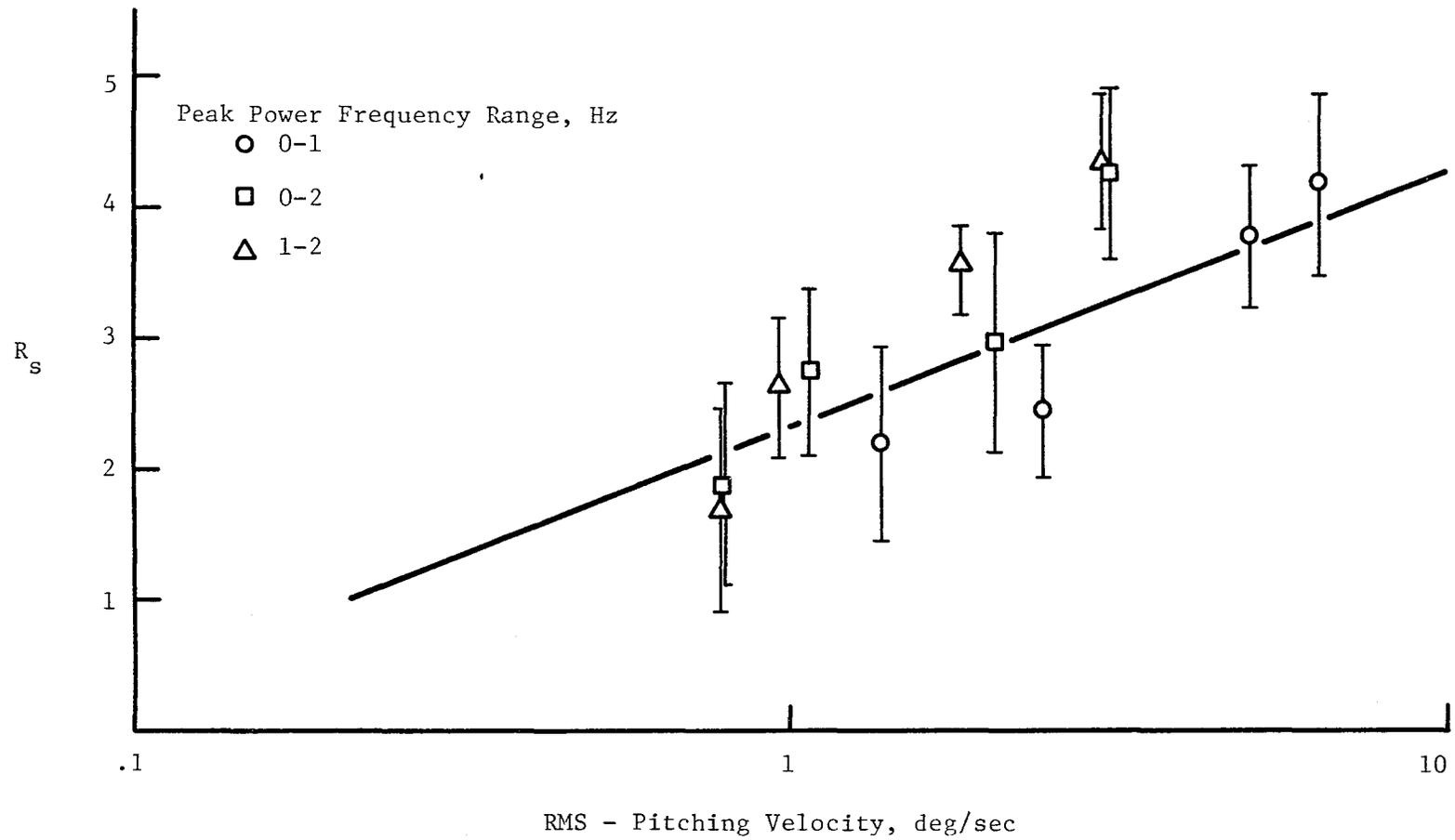


Figure 11 - Variations of ride comfort response with RMS - pitching velocities having typical power spectra.

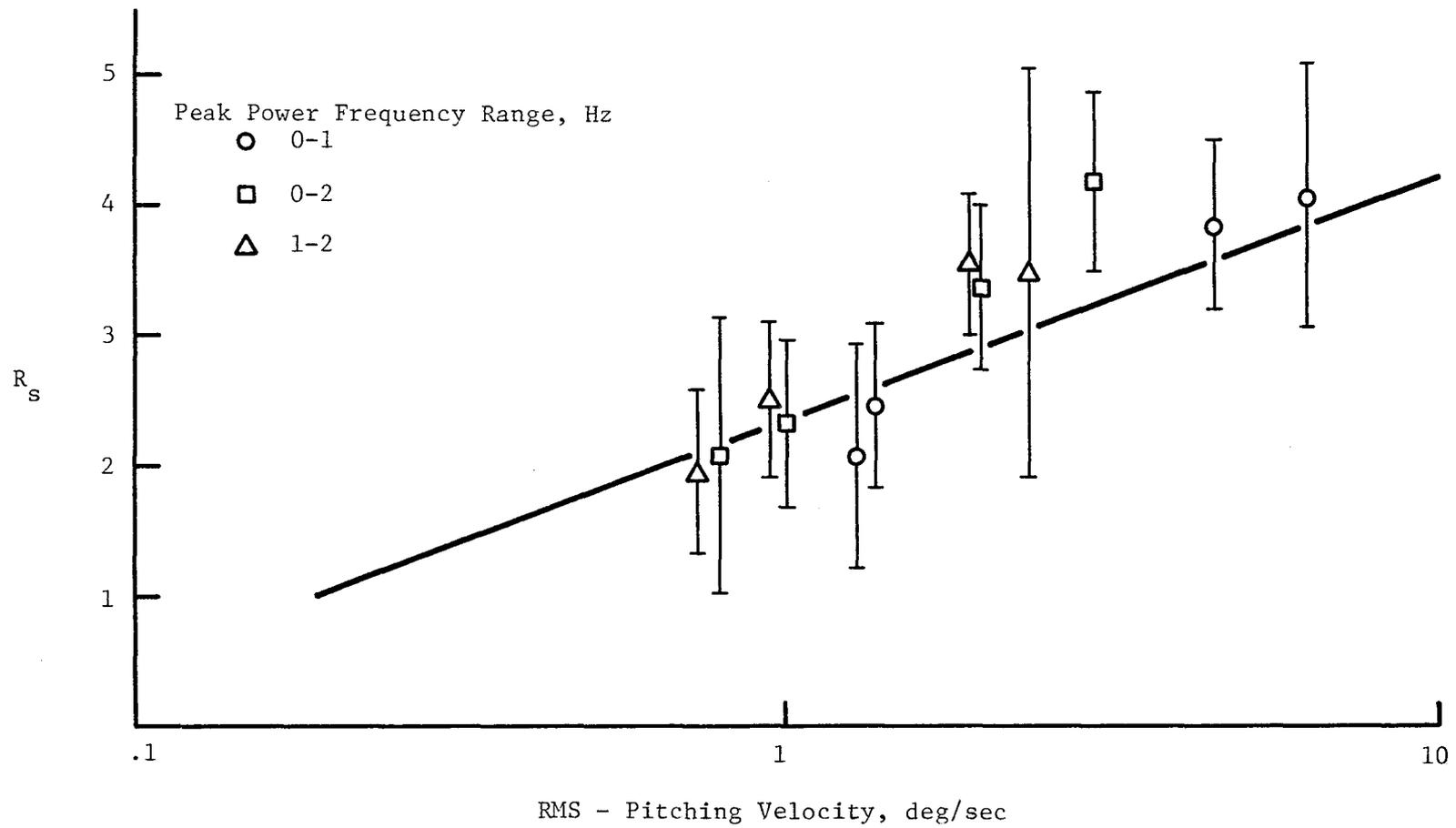


Figure 12 - Variations of ride comfort response with RMS - pitching velocity having flat power spectra.

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