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HUMAN COMFORT RESPONSE TO RANDOM MOTIONS WITH COMBINED YAWING AND ROLLING MOTIONS

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A Report

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HUMAN COMFORT RESPONSE TO RANDOM MOTIONS

COMBINED YAWING AND ROLLING MOTIONS

By Ralph W. Stone, Jr.

SUMMARY

The effects of random yawing and rolling velocities on passenger ride comfort responses were examined on the NASA Langley Visual Motion Simulator. The effects of power spectral density shape and frequency ranges of peak power 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 other degrees of freedom as well as the yawing and rolling motions, 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 (refs. (2) and (3)). This program includes 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 airplane motions. An extensive amount of data exists which documents subjective comfort response to single degree of freedom motion for sinusoidal and random oscillations (refs. 9-13, for example). However, these data apply to vibrations with spectral content greater than 2 Hz. Consequently, there is a need for detailed information about this type of response for vibrations with energy below 2 Hz.

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), (17) and (18) present the data obtained for the study of subjective ride comfort responses to random vertical, transverse, and longitudinal accelerations and to random rolling and pitching velocities, respectively. The present study was to measure the subjective ride comfort response ratings obtained when using oscillations in the yawing degree of freedom. The simulator however responded with both yawing and rolling motions when a yawing motion was input to the simulator. These two motions were highly correlated because of the dynamic characteristics of the simulator. These data, herein, are presented therefore as responses to combined highly correlated yawing and rolling motions.

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 motions, 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.

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 3 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. The motions developed by the simulator, when obtaining the data for this paper, were intended to be dominantly a yawing motion, but as noted previously because of these peculiar simulator characteristics a dominant rolling motion also existed that was of similar and often larger magnitude than the yawing motion. Therefore, these data must be considered as having dominant combined yawing and rolling motions. Also lesser amounts of the other four degrees of freedom were 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 were somewhat different than the nominal spectra used as input to the computer. The four different magnitudes of power in the spectra previously mentioned were supposed to be the same for each of the six spectra shapes studied. However, because of the dynamic response characteristics and limits of the simulator, different RMS values of the yawing velocities were obtained for the different spectra shapes.

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, as just noted, the data discussed in the "Data" section of this paper are average values of the four or five "flights" used. The standard deviation of the yawing velocities from the average values for the various segments in terms of percent of the average values is 11.71 percent. The maximum deviation was 32.46 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 Figure 4 to 9. These figures include time histories for all six degrees of freedom, histograms of the yawing velocity and power spectrum of the yawing and rolling velocities for the 24 segments of "flight" as follows:

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

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

The reference axis used was relative to the seated passengers and is shown in Figure 10. The yawing velocities used for this paper were along the yaw axis shown in Figure 10. Of course, the corresponding rolling velocities that occurred along with the yawing velocities were along the roll axis. The actual motions of the simulator, as experienced by the passengers, and shown in Figures 4 to 9, were measured by an inertial instrument package containing three linear accelerometers, one alined with each axis, and three rate gyros also alined with each axis.

Experimental Procedure

As noted previously, 24 segments of simulated flight were used in examining the combined yawing and rolling motions of this paper. These 24 segments were randomly scattered in two "flights," each of which also had dominant motions in other degrees of freedom which have previously been presented. 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 portion of the "flight" when making their comfort response ratings. 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 and peak power frequency range are for progressively increasing values of RMS yawing velocity. As noted previously there was a significant rolling motion accompanying each input yawing motion. The RMS rolling velocities are highly correlated with the RMS yawing velocities. The RMS rolling velocities also are larger than what could be construed as threshold values from reference (17). The results herein are therefore construed to be subjective ride comfort responses to highly correlated yawing and rolling motions.

In addition to the yawing and rolling motions, there existed components of motion along the other degrees of freedom, Tables II and III. Until data is adequately analyzed for these other degrees 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 yawing velocity varied from 0.86 to 7.44 times the magnitude of the RMS pitching velocity, which ranged in magnitude from 0.446 to 1.530 degrees per second with a mean value of 0.960 degrees per second. According to reference (3), the threshold of sensation to pitching velocity maybe about 0.3025. It would seem that the existence of pitching to the passengers possibly was known during these tests. It would further appear that the pitching stimulus if recognized may always have illicited comfortable responses on the bipolar scale used. The effects of pitching angular motions can be compared to the yawing motions in this fashion as they are similar types of stimulation. The values of linear acceleration range from 0.0053 to 0.0899 g and have an average value of 0.026 g. These values generally exceed the values normally established as thresholds of perception for linear accelerations (see ref. (3) for example). Subjects exposed to these motions therefore, may have been cognizant of the existence of linear accelerations during this study. Whether these accelerations were sufficient to alter the subjective ride comfort response ratings for the combined yawing and rolling velocities will not be clear until the interactive effects of multiple degrees of freedom are understood. The magnitudes of the linear accelerations experienced 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 0.619. This compares favorably with other experience as, for example the average standard deviation for the results of reference (8) is 0.758 units of response rating. The value of 0.619 for this combined yawing and rolling velocity study compares favorably with those for other motion components in references (14), (15), (16), (17) and (18).

The correlation between the RMS yawing and rolling velocities previously discussed in this paper are shown in Figure 11. Exceptional correlation exists within a given peak frequency range but appears not to be related with the general power spectra shape, typical or flat. The cross-correlation coefficients for roll-yaw shown in Table III are for zero lag and do not show the correlation of the RMS values shown in Figure 11. It is clear from Figure 11 that rolling velocities even greater than the input yawing velocities were often experienced. In Figures 4, 5, 6, 7, 8 and 9 are shown the power spectrum of both the yawing and rolling motions. The yawing spectra show peak power frequencies between 0 and 2 Hz as intended by the input signals to the simulator. The rolling spectra, which occurs from the dynamic response of the simulator generally have flatter spectra with peak power frequencies around 8 Hz. It is interesting to note that similar power peaks occur in the rolling velocity spectra presented in reference (17).

As expected, there is a progressive increase in the response ratings with increasing yawing or rolling velocity (Table II). It appears that this variation is not linear. The subjective ride comfort response ratings are plotted against the $\log_{10}$ of the RMS yawing and rolling velocities for typical power spectra in Figure 12 and for flat power spectra in Figure 13. It should not be construed by these figures that a Weber-Fechner psychophysical model is proposed as representing these data, however there is a reasonable linearity shown in Figures 12 and 13 which allows some observations relative to the data. In Figures 12(b) and 13(b) are shown in solid lines the best fit linear regression for the current data. Also shown on these figures are best fit lines from reference (17) for dominant rolling motions. It appears that the presence of yawing velocities with rolling velocities ameliorates the effects of rolling velocity on ride comfort responses. Results shown in reference (3) also show such amelioration. The effects of yawing motions alone are not evident from these data.

Figures 14, 15 and 16 present the same data but as a function of peak power frequency range rather than power spectral density shape as in Figures 12 and 13. In Figures 14, 15 and 16, the subjective response data are ploted against RMS yawing and rolling velocities for peak power frequency ranges of 0 - 1 Hz, 0 - 2 Hz, and 1 - 2 Hz, respectively. Best fit lines are shown. In Figures 14(b), 15(b) and 16(b), there is also shown best fit lines from reference (17) for data with dominant rolling motions alone. It appears that the previously mentioned ameliorating effect of yawing velocity on responses to rolling velocity is influenced by the peak power frequency range. The results in Figure 14(b), for the peak power range from 0 - 1 Hz, indicate that the presence of a yawing motion with a rolling motion tends to cause more unfavorable subjective ride comfort responses than for rolling motions alone. For higher peak power frequency ranges (0 - 2 Hz and 1 - 2 Hz) however, the ameliorating effect is apparent (Figures 15(b) and 16(b). From Figure 11, the data shows larger yawing velocities and smaller rolling velocities for the peak power frequency range from 0 - 1 Hz than for the other ranges of 0 - 2 Hz and 1 - 2 Hz. The following table lists the slopes of rolling velocity as a function of yawing velocity for the various peak power frequency ranges shown in Figure 11.

Peak Power Frequency Range	Slope
0 - 1 Hz	0.286
0 - 2 Hz	2.480
1 - 2 Hz	1.463

The ameliorating effect or unfavorable effect previously noted may therefore be related to the relative magnitudes of the two angular velocities as well as the peak power frequency range.

CONCLUDING REMARKS

A study has been made on the Langley Visual Motion Simulator to examine the influence of random yawing velocities combined with highly correlated random rolling velocities on human subjective ride comfort responses. The effects of two general shapes of power spectral density of the yawing velocity input for three frequency ranges in the 0 - 2 Hz region were examined. The data obtained in this study are presented in this paper. Although this study was made to examine the influence of random yawing velocities alone, because of the characteristics of the simulator, there occurred in this study, rolling motions of significant magnitude and some amounts of motion in all other degrees of freedom. As the rolling motion was significant the data are considered as the influence of combined yawing and rolling velocities on subjective ride comfort responses. Analysis of these data must maintain cognizance of the existance of the motions in all other degrees of freedom. There appears to be a complex relationship between the rolling and yawing velocities and the response data. Peak power frequency ranges and relative velocity magnitudes may influence this relationship.

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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 YAWING 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							
0.0053	0.0143	0.0058	0.4460	0.8238	1.0703	1.550	0.497
0.0072	0.0150	0.0072	0.7007	1.1008	1.3279	1.650	0.669
0.0151	0.0540	0.0176	1.1433	2.2371	4.5249	2.950	0.896
0.0178	0.0684	0.0198	1.1367	2.7912	6.9070	3.400	0.699
(b) Typical 0 - 2 Hz inputs							
0.0081	0.0123	0.0089	0.8236	1.3542	0.7574	1.350	0.474
0.0103	0.0258	0.0147	0.9094	2.0109	1.0800	1.900	0.699
0.0199	0.0584	0.0341	1.4098	4.7902	2.2626	2.950	0.804
0.0275	0.0862	0.0544	1.5301	8.0852	3.0464	3.150	0.709
(c) Typical 1 - 2 Hz inputs							
0.0090	0.0110	0.0093	0.9303	1.4673	0.8133	1.150	0.338
0.0101	0.0276	0.0150	0.8776	1.9587	1.0643	1.950	0.559
0.0161	0.0550	0.0254	1.0870	3.2233	1.9477	2.700	0.823
0.0262	0.0812	0.0364	1.4119	4.7640	3.0970	3.350	0.914

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							
0.0063	0.0170	0.0070	0.5876	0.9865	1.1344	1.550	0.599
0.0077	0.0169	0.0081	0.7652	1.2062	1.2474	1.600	0.699
0.0162	0.0654	0.0176	0.8951	2.1200	4.7582	3.100	0.460
0.0197	0.0796	0.0190	0.8571	2.2128	6.3740	4.000	0.782
(e) Flat 0 - 2 Hz inputs							
0.0066	0.0107	0.0075	0.6637	1.1118	0.6072	1.400	0.699
0.0083	0.0240	0.0124	0.6745	1.4914	0.9182	2.100	0.615
0.0165	0.0561	0.0273	1.0784	3.6768	2.0582	3.050	0.438
0.0250	0.0838	0.0420	1.4194	6.0600	2.9974	3.400	0.994
(f) Flat 1 - 2 Hz inputs							
0.0073	0.0102	0.0080	0.7726	1.2114	0.6624	1.000	0
0.0089	0.0270	0.0144	0.7266	1.6664	0.9757	2.000	0.471
0.0167	0.0578	0.0264	0.9679	3.1814	1.8609	3.450	0.497
0.0242	0.0899	0.0348	1.2194	4.8222	3.0956	3.900	0.516

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

Longitudinal -Vertical	Longitudinal -Pitch	Transverse -Roll	Transverse -Yaw	Vertical -Pitch	Roll -Yaw
(a) Typical 0 - 1 Hz inputs					
0.7406	0.7729	0.1469	0.0708	0.7239	0.2097
0.8692	0.8734	0.3538	0.1321	0.8722	0.3324
0.4084	0.4175	0.0096	-0.0454	0.4500	-0.1087
0.3283	0.1770	-0.0931	-0.0668	0.2475	-0.2006
(b) Typical 0 - 2 Hz inputs					
0.6677	0.8764	0.4328	0.5028	0.7548	0.7472
0.1321	0.3690	-0.2046	-0.0162	0.3501	0.1052
-0.0430	0.2934	-0.2092	0.0303	0.2960	0.0334
-0.2978	-0.2947	-0.3273	-0.0697	-0.0139	-0.1475
(c) Typical 1 - 2 Hz inputs					
0.9139	0.9761	0.7999	0.8400	0.9409	0.9559
0.4138	0.7189	0.0838	0.1680	0.5152	0.3524
0.1164	0.1988	-0.1638	-0.0334	0.1590	-0.1348
0.0475	0.1734	-0.1946	-0.0326	0.1557	-0.1360

TABLE III - CONCLUDED

Longitudinal -Vertical	Longitudinal -Pitch	Transverse -Roll	Transverse -Yaw	Vertical -Pitch	Roll -Yaw
(d) Flat 0 - 1 Hz inputs					
0.5960	0.8181	0.1955	0.1060	0.6879	0.2721
0.7879	0.9117	0.4172	0.2953	0.8467	0.4837
0.3304	0.3818	-0.0882	-0.0288	0.3382	-0.1528
0.3076	0.0710	-0.1469	-0.0533	0.1348	-0.2866
(e) Flat 0 - 2 Hz inputs					
0.6596	0.9067	0.4666	0.5781	0.7895	0.7613
0.2617	0.6689	-0.0206	0.1356	0.4973	0.1981
-0.1510	0.2653	-0.2340	-0.0137	0.2859	0.0954
-0.2792	-0.1451	-0.3074	-0.0508	0.0848	-0.2408
(f) Flat 0 - 2 Hz inputs					
0.8358	0.9630	0.7206	0.8198	0.8972	0.9078
0.2586	0.7020	-0.0584	0.1439	0.4793	0.2168
0.0084	0.2767	-0.2244	-0.0328	0.2369	-0.1846
-0.1750	-0.1324	-0.2779	-0.0566	0.0135	-0.2370

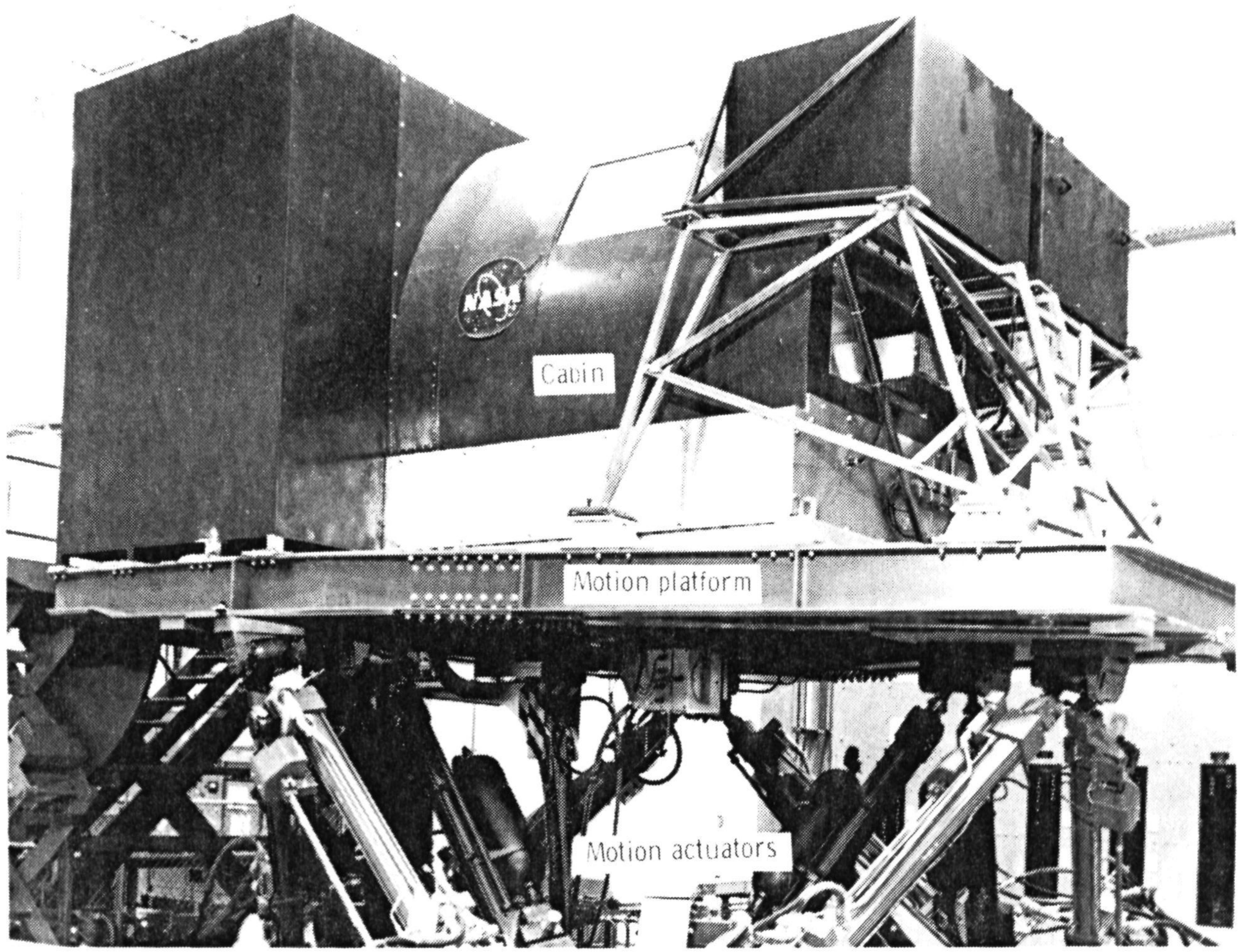
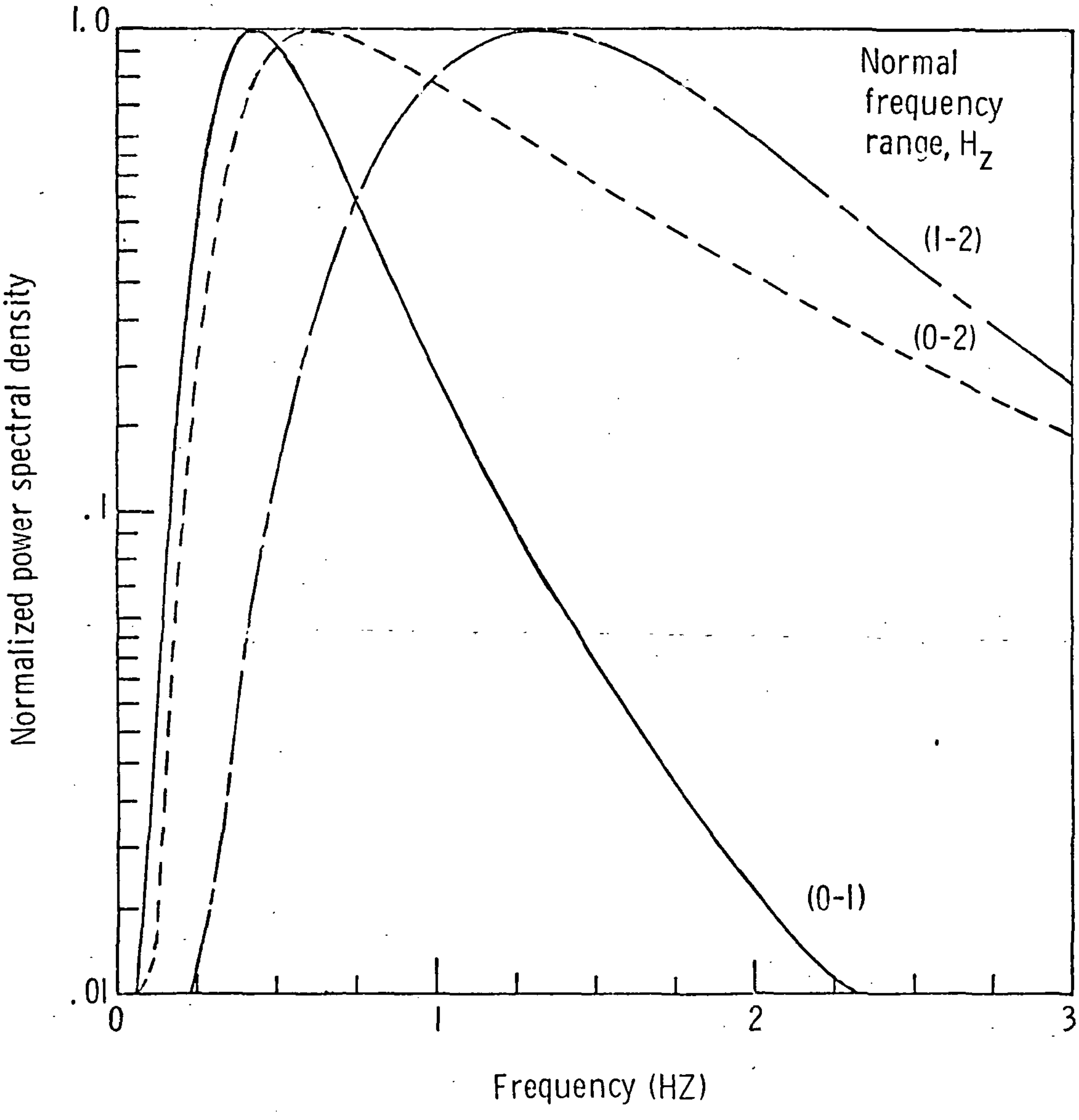
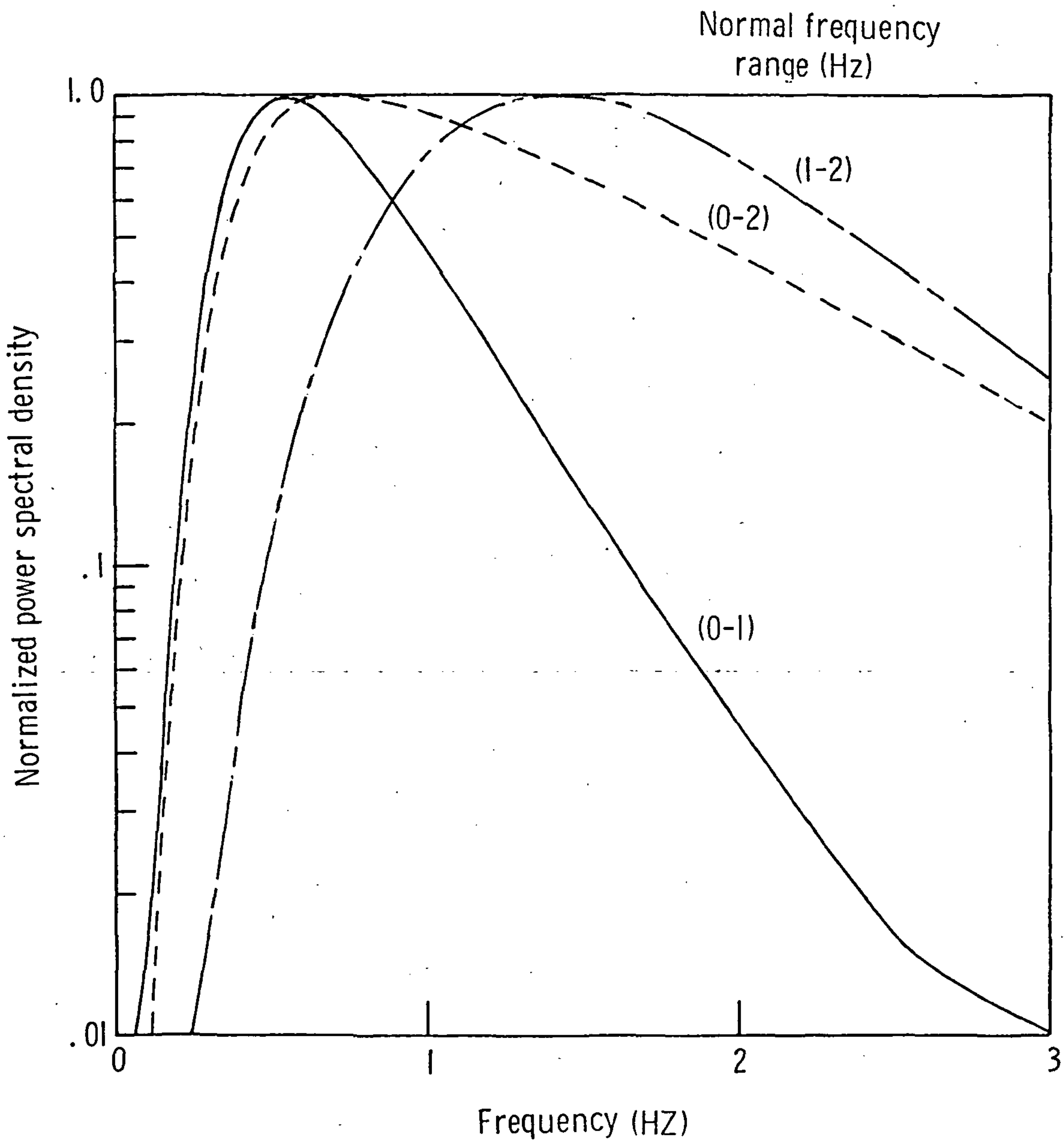


Figure 1 - Langley six-degree-of-freedom, vision motion simulator.



(a) Typical spectra.

Figure 2 - Nominal power spectra of motion components.



(b) Flat spectra

Figure 2 - Concluded.

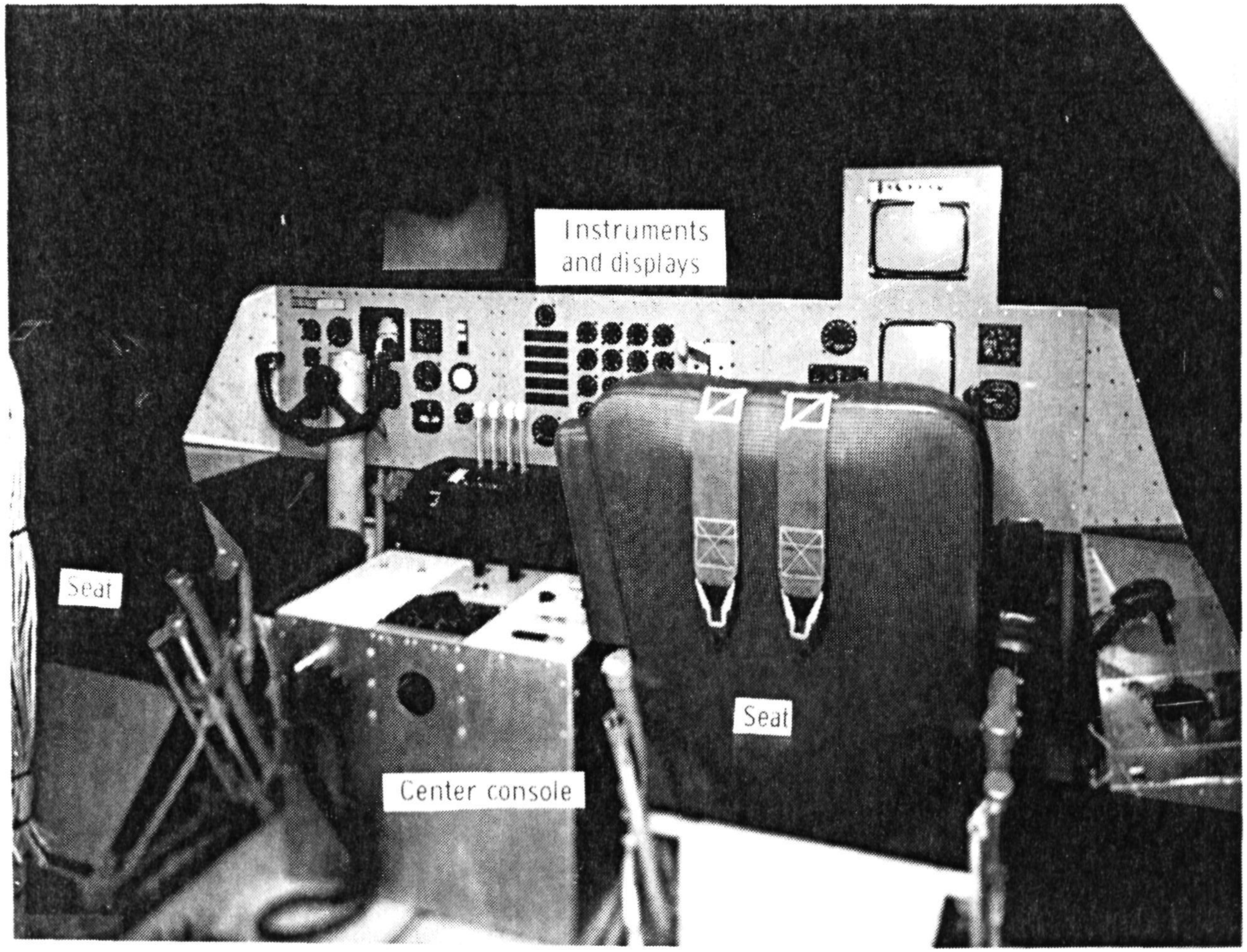
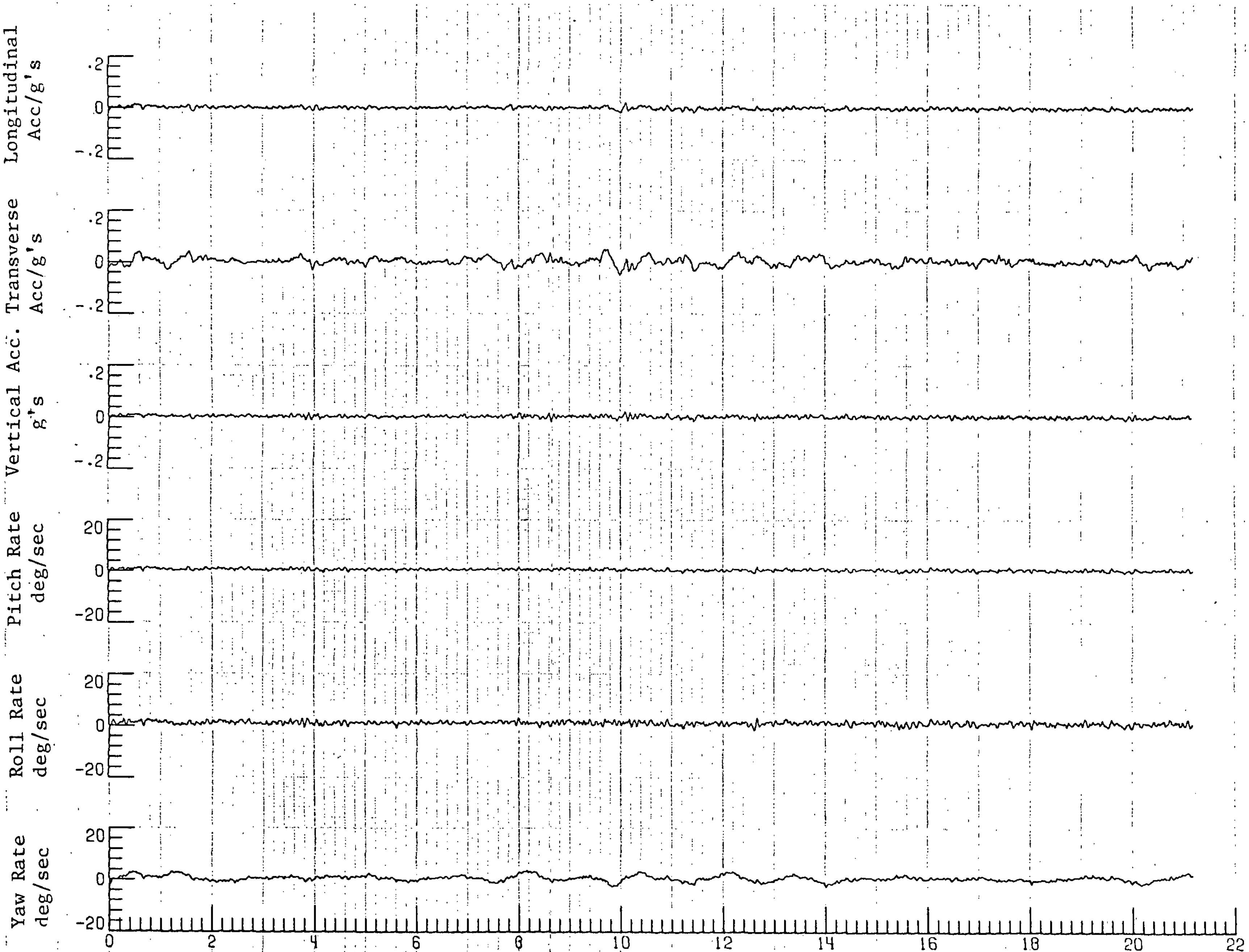
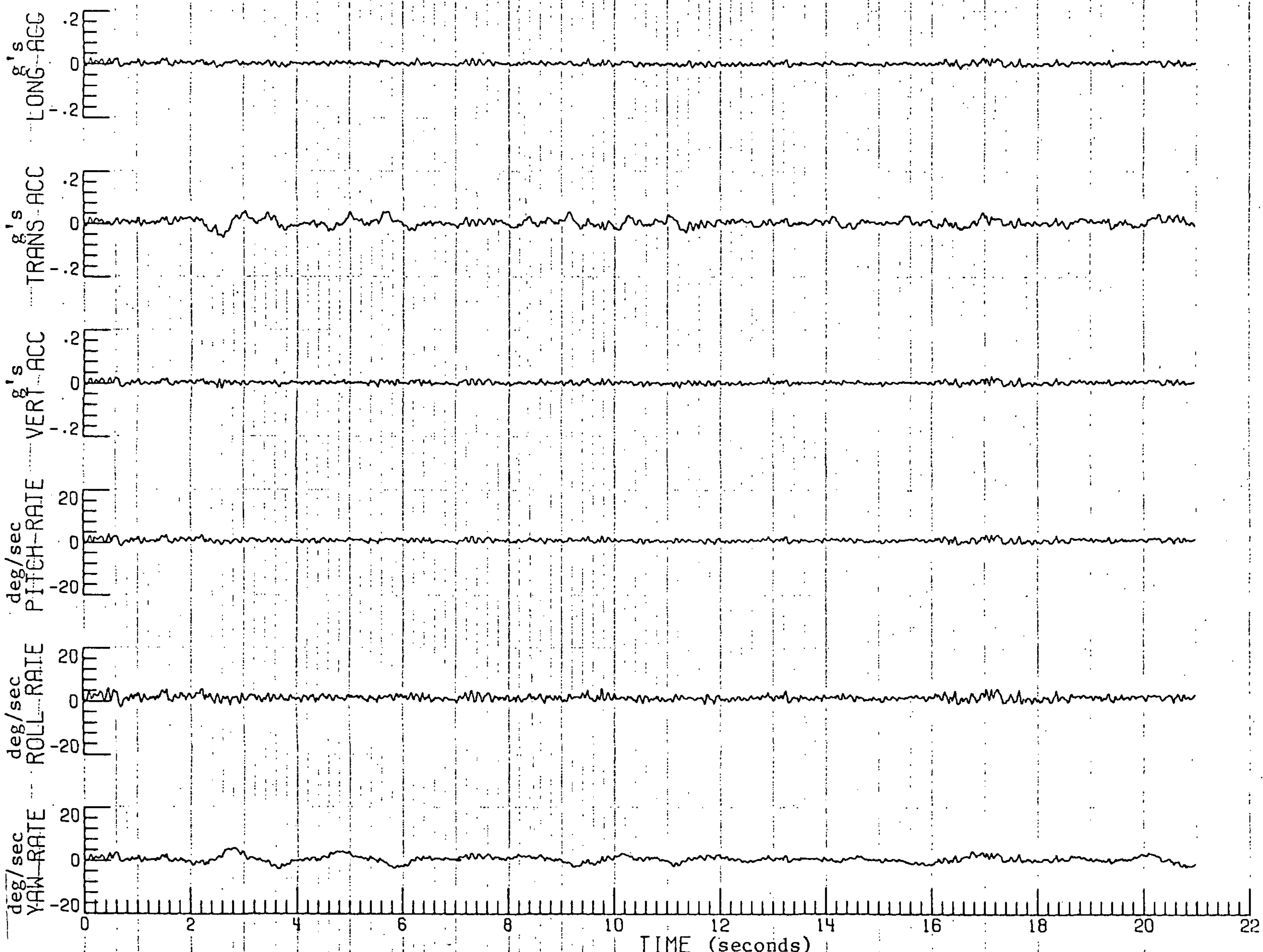


Figure 3 - Interior of the Langley six-degree-of-freedom vision motion simulator.



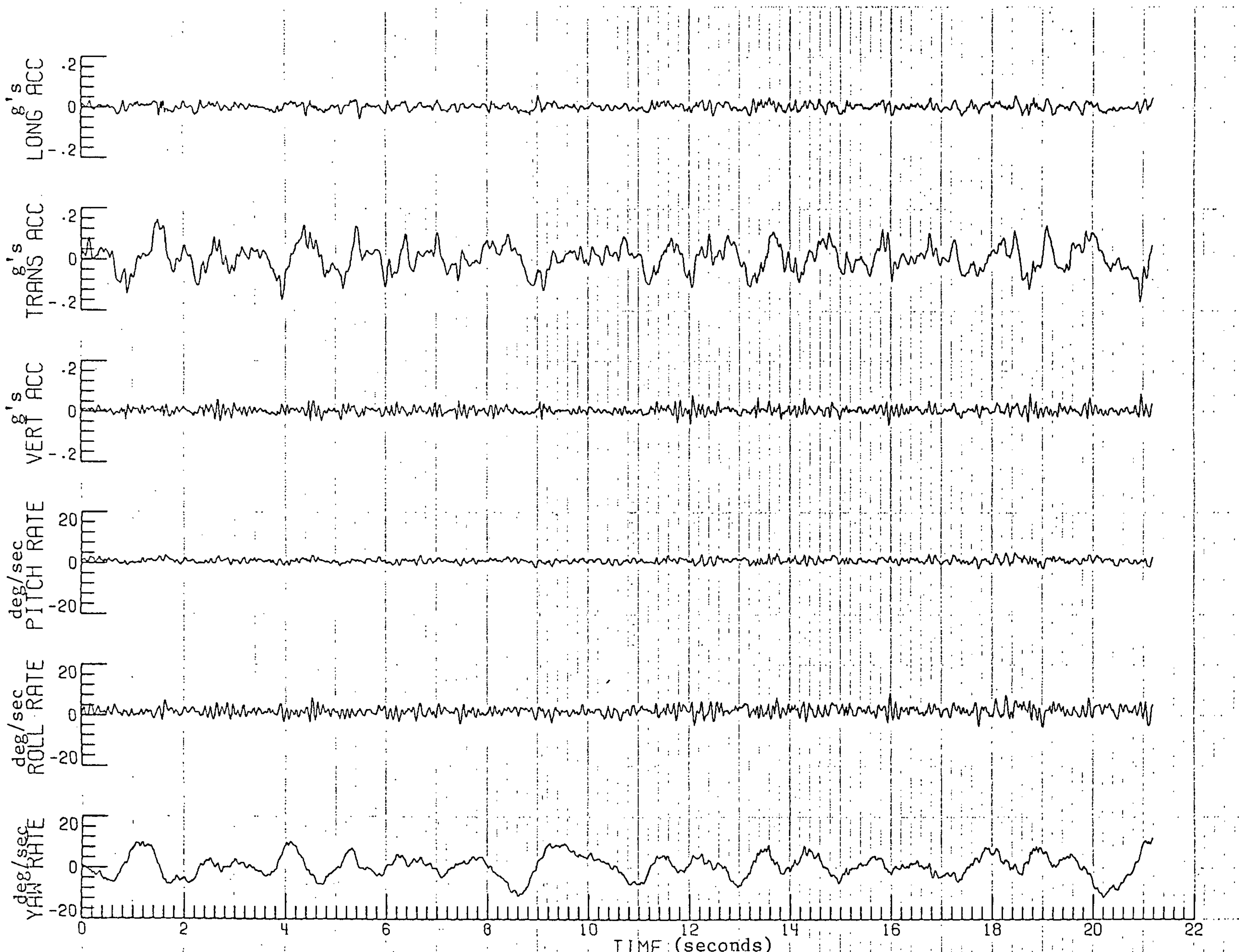
(a) Time histories (RMS yawing velocity 1.070 deg/sec)

Figure 4. MEASURED MOTION CHARACTERISTICS USING YAWING VELOCITIES WITH TYPICAL 0 - 1 HZ INPUTS



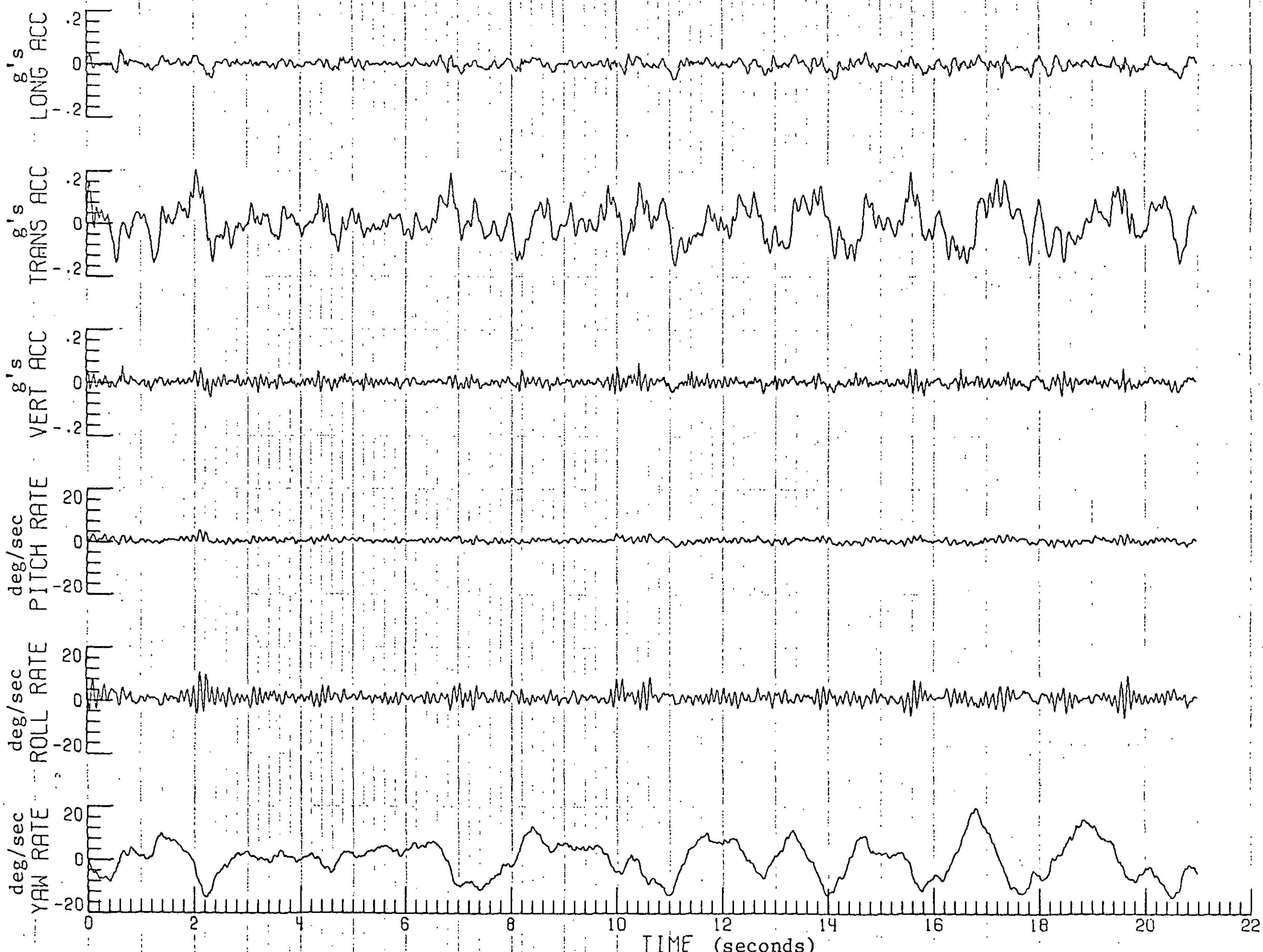
(a) Time histories (RMS yawing velocity 1.328 deg/sec)

Figure 4. Continued.



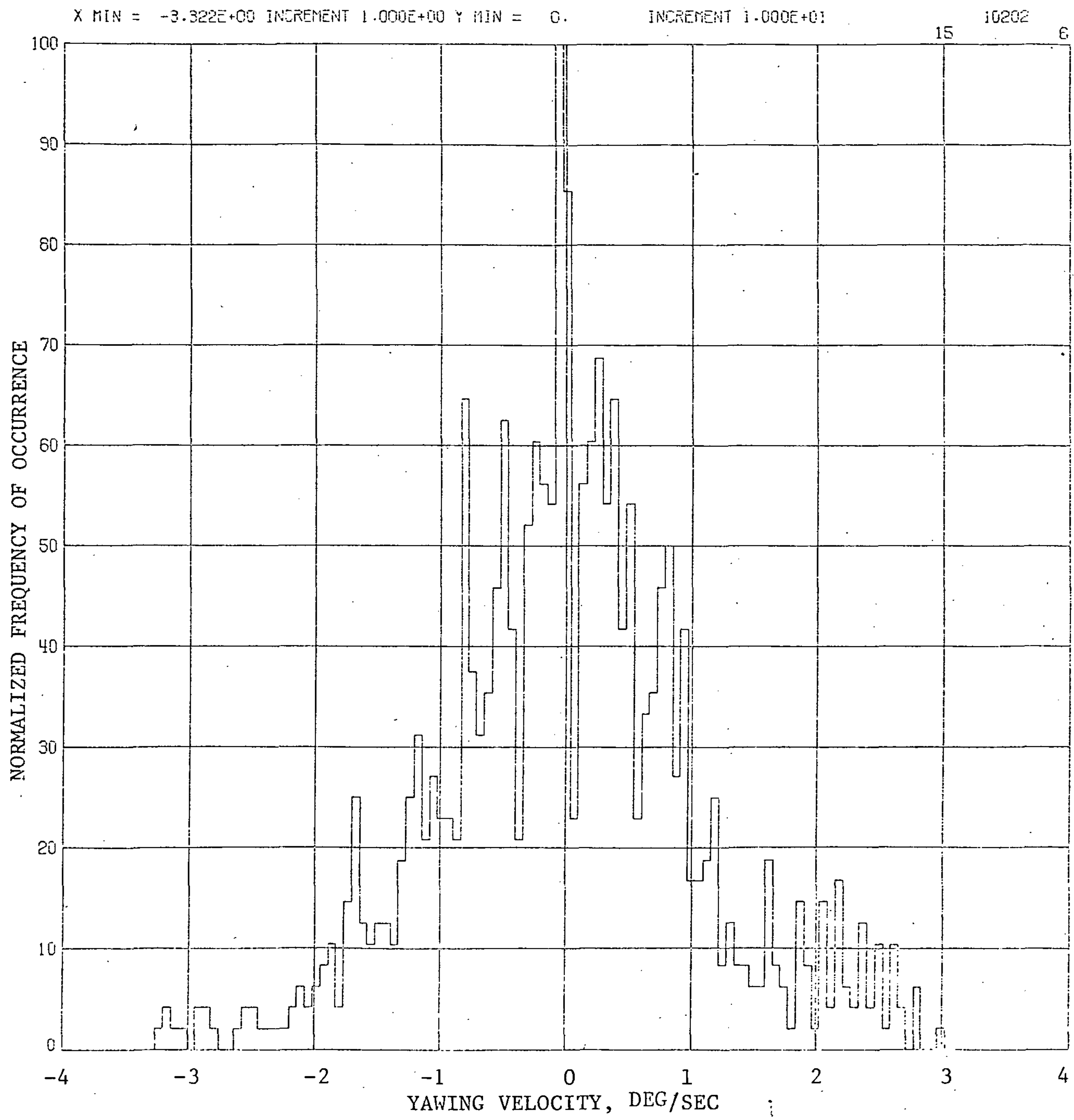
(a) Time histories (RMS yawing velocity 4.525 deg/sec)

Figure 4. Continued.



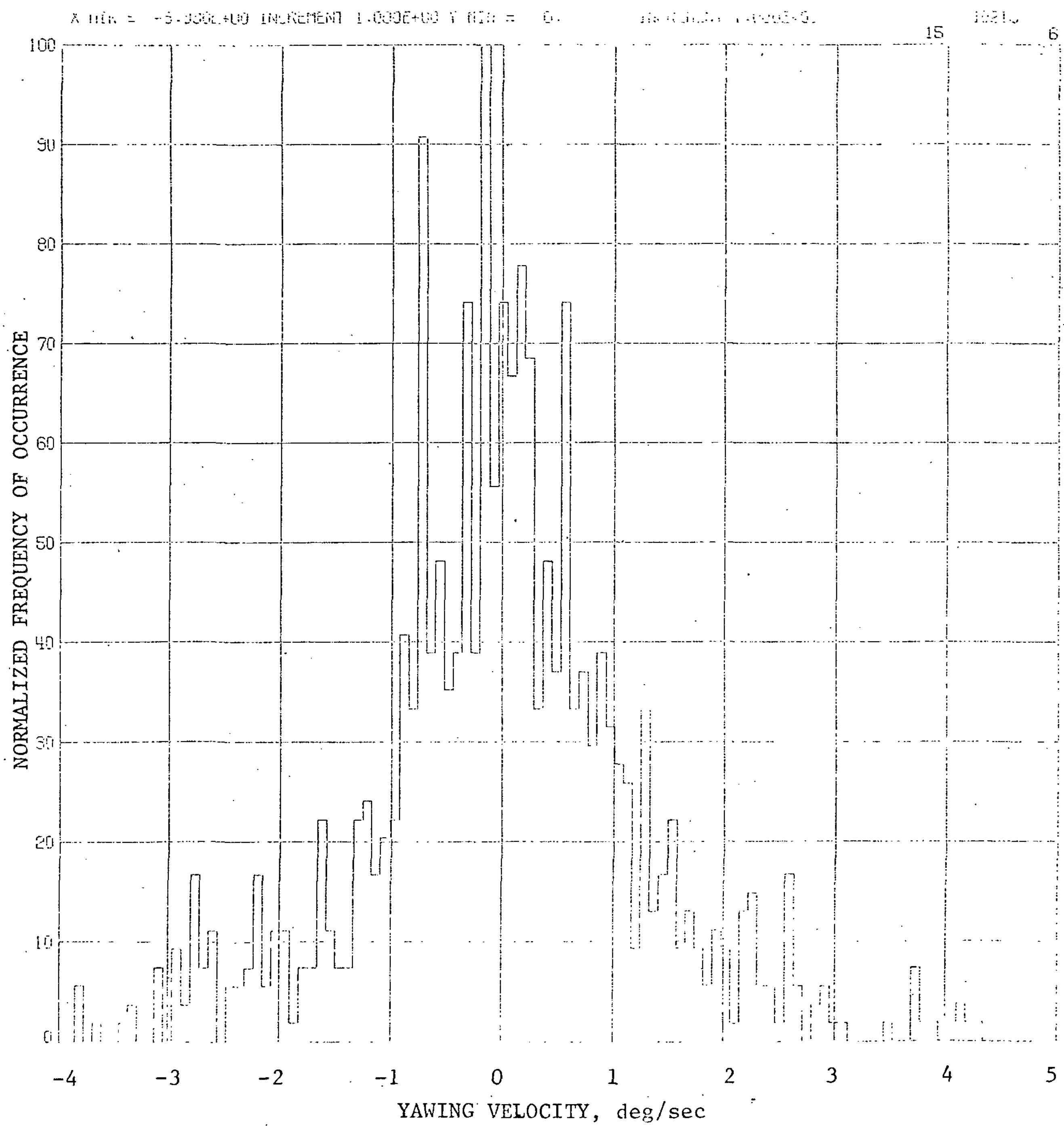
(a) Time histories (RMS yawing velocity 6.907 deg/sec)

Figure 4. Continued.



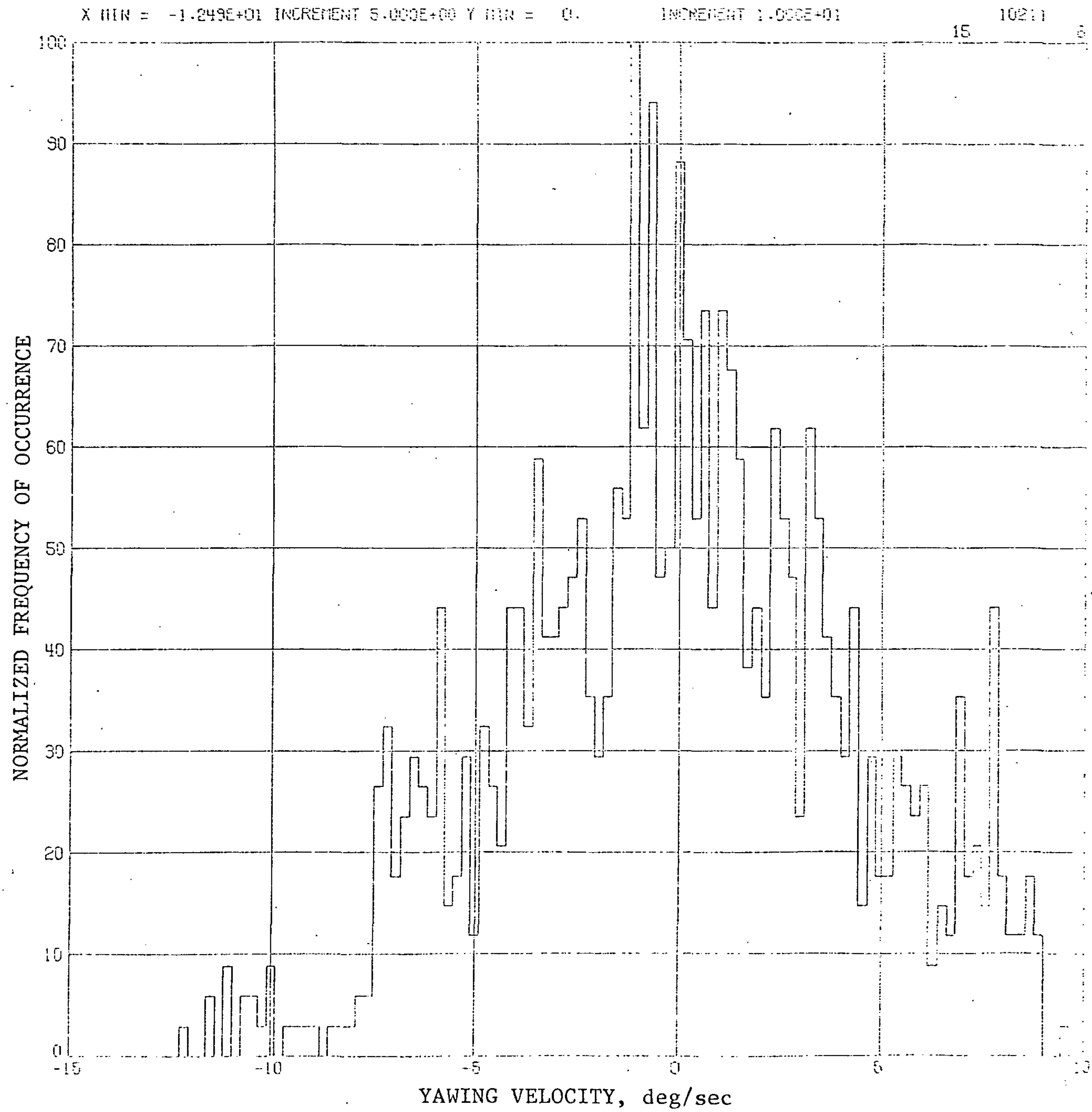
(b) Yawing velocity histogram (RMS yawing velocity 1.0703 deg/sec)

Figure 4. Continued.



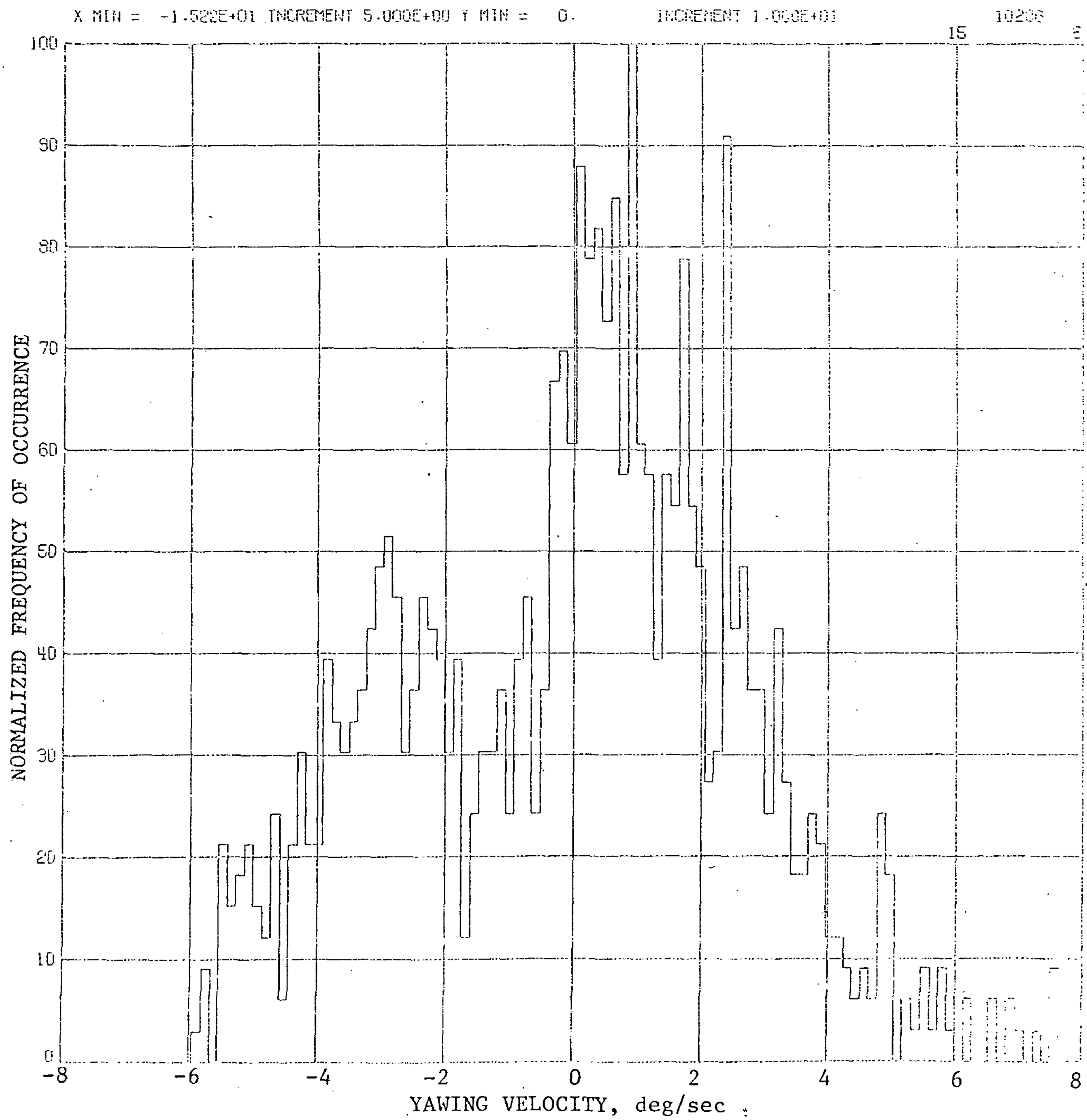
(b) Yawing velocity histogram (RMS yawing velocity 1.328 deg/sec)

Figure 4. Continued.



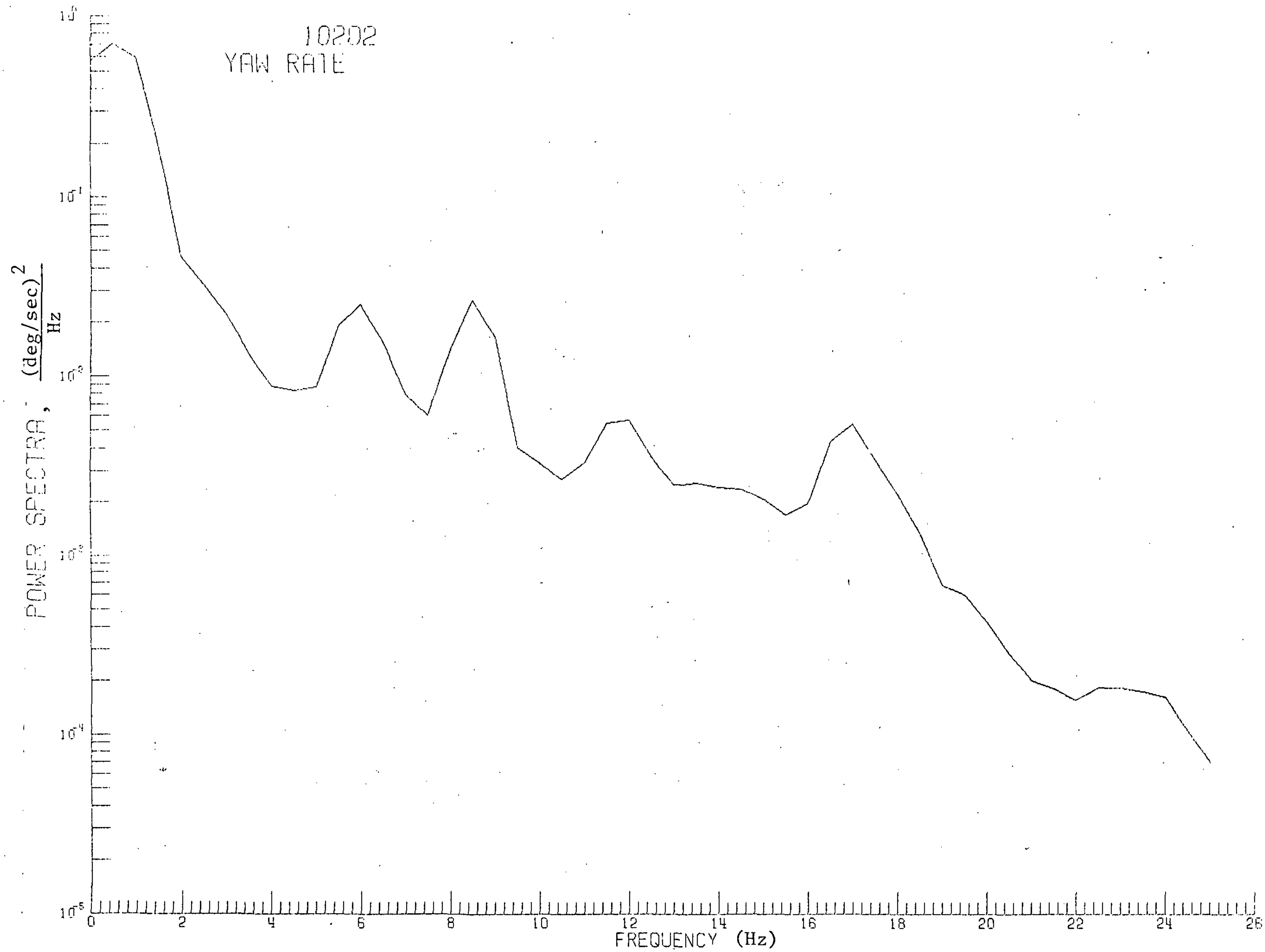
(b) Yawing velocity histogram (RMS yawing velocity 4.525 deg/sec)

Figure 4. Continued.



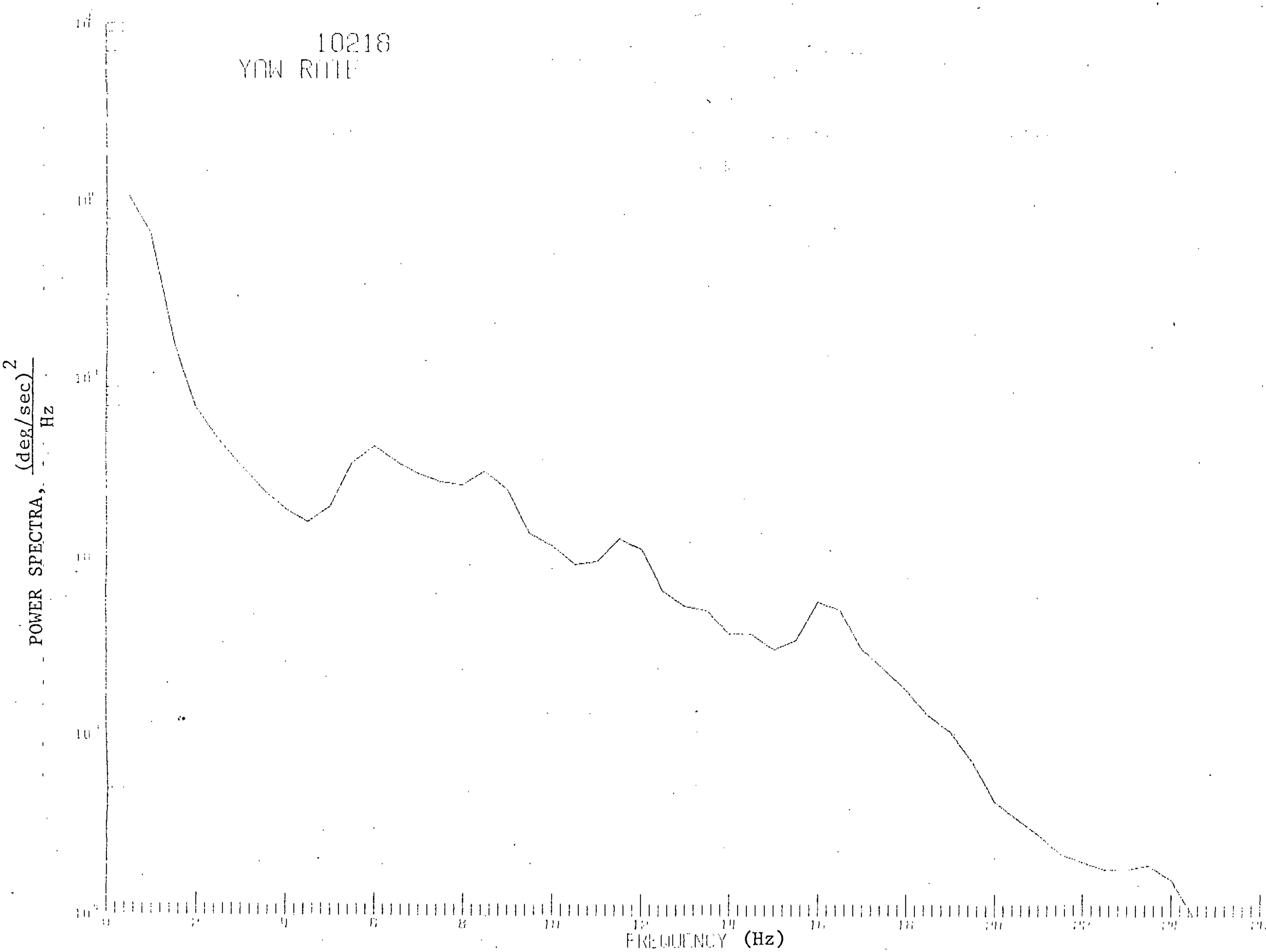
(b) Yawing velocity histogram (RMS yawing velocity 6.907 deg/sec)

Figure 4. Continued.



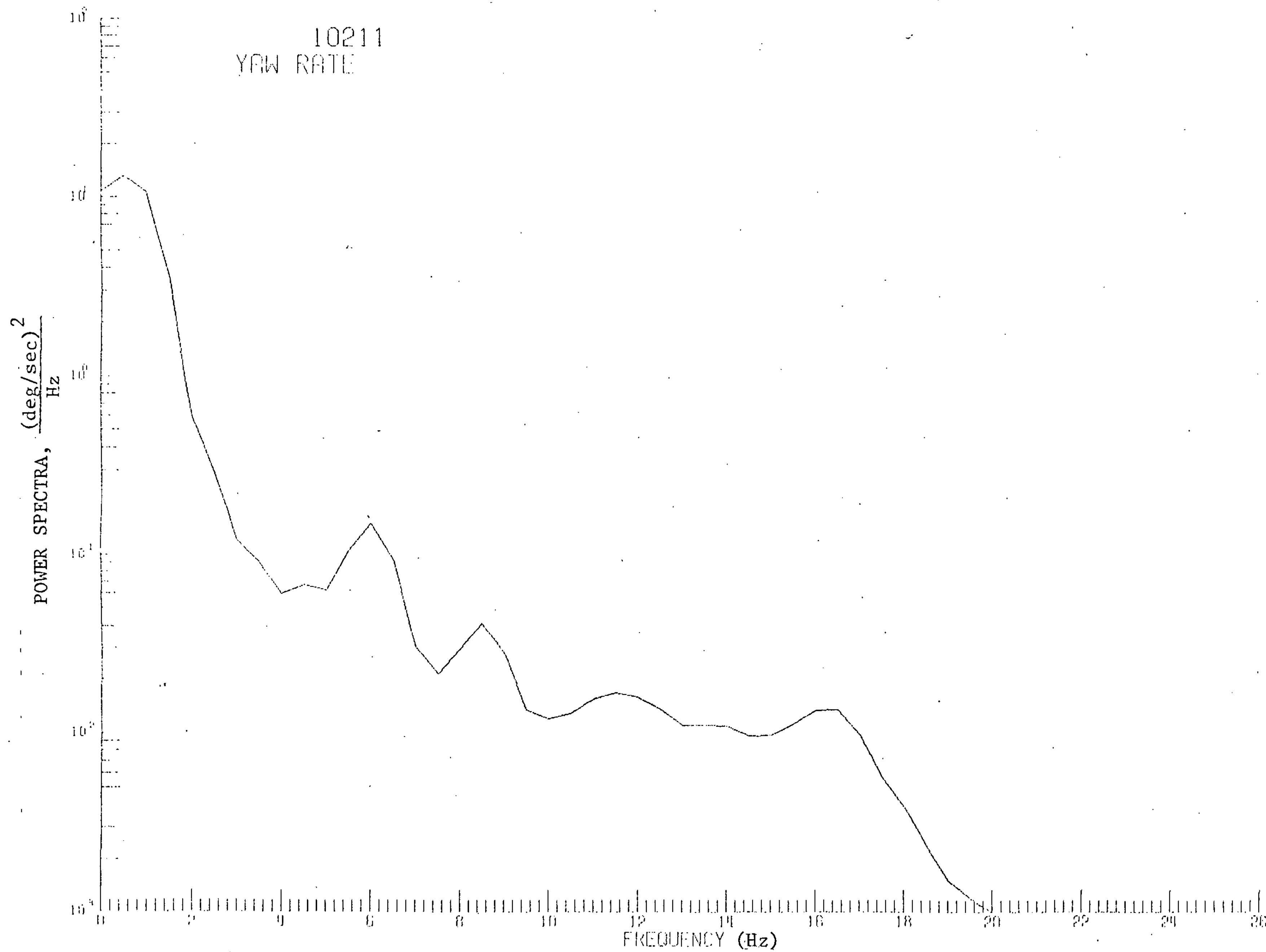
(c) Yawing velocity power spectrum (RMS yawing velocity 1.070 deg/sec)

Figure 4. Continued.



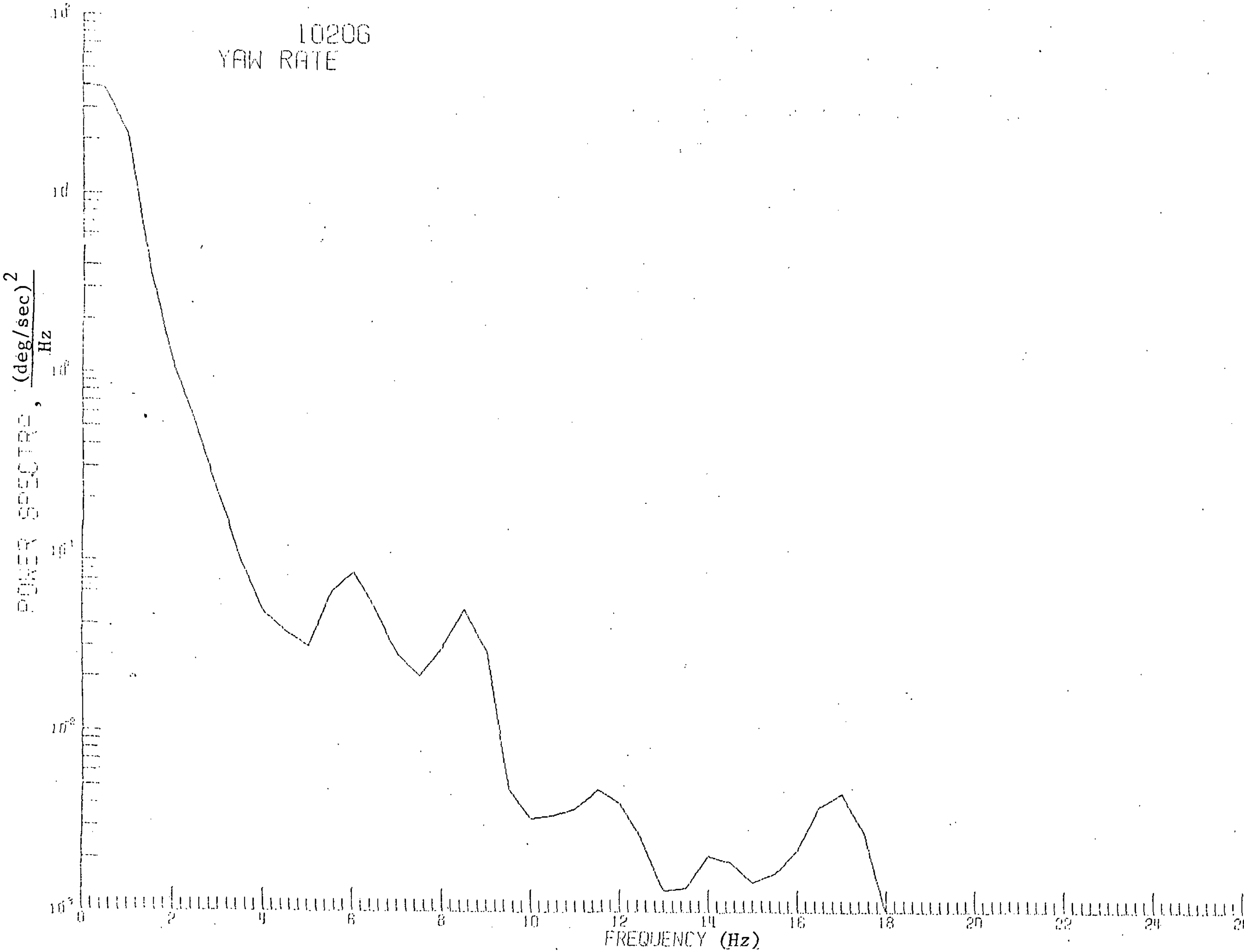
(c) Yawing velocity power spectrum (RMS yawing velocity 1.328 deg/sec)

Figure 4. Continued.



(c) Yawing velocity power spectrum (RMS yawing velocity 4.525 deg/sec)

Figure 4. Continued.



(c) Yawing velocity power spectrum (RMS yawing velocity 6.907 deg/sec)

Figure 4. Continued.

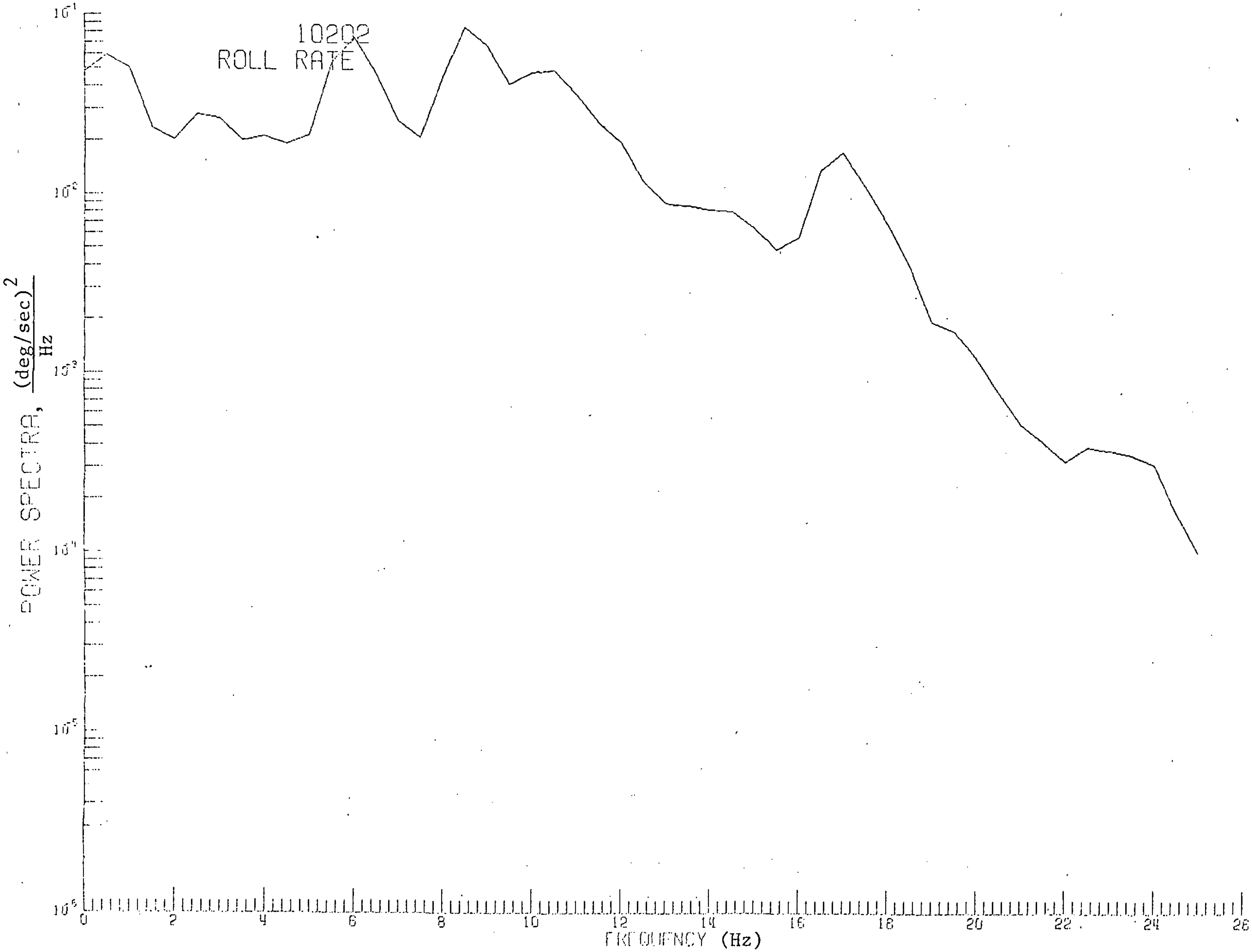


Figure 4. Continued.- (d) Rolling velocity power spectrum (RMS rolling velocity 0.824 deg/sec)

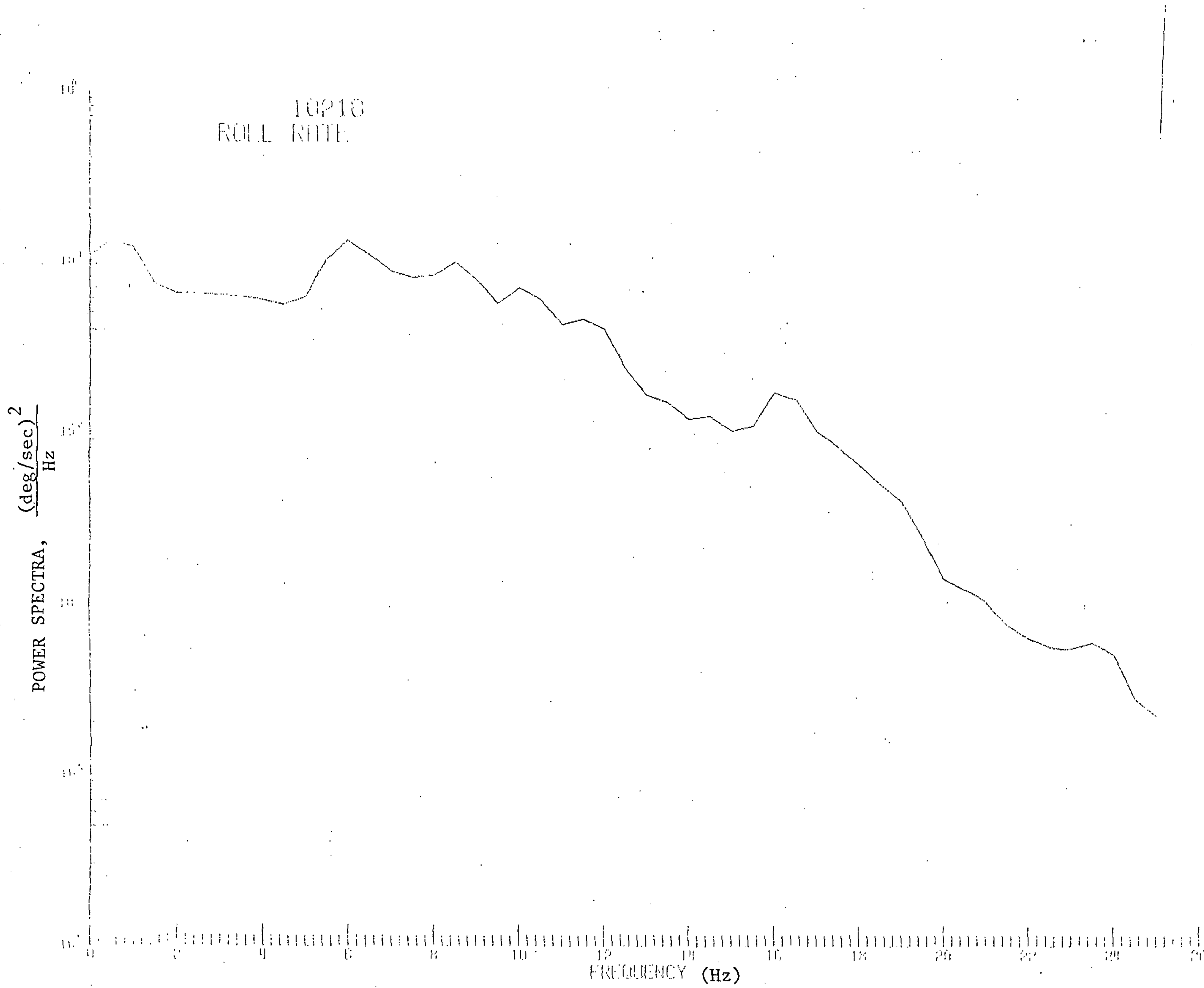


Figure 4. Continued - (d) Rolling velocity power spectrum (RMS rolling velocity 1.101 deg/sec)

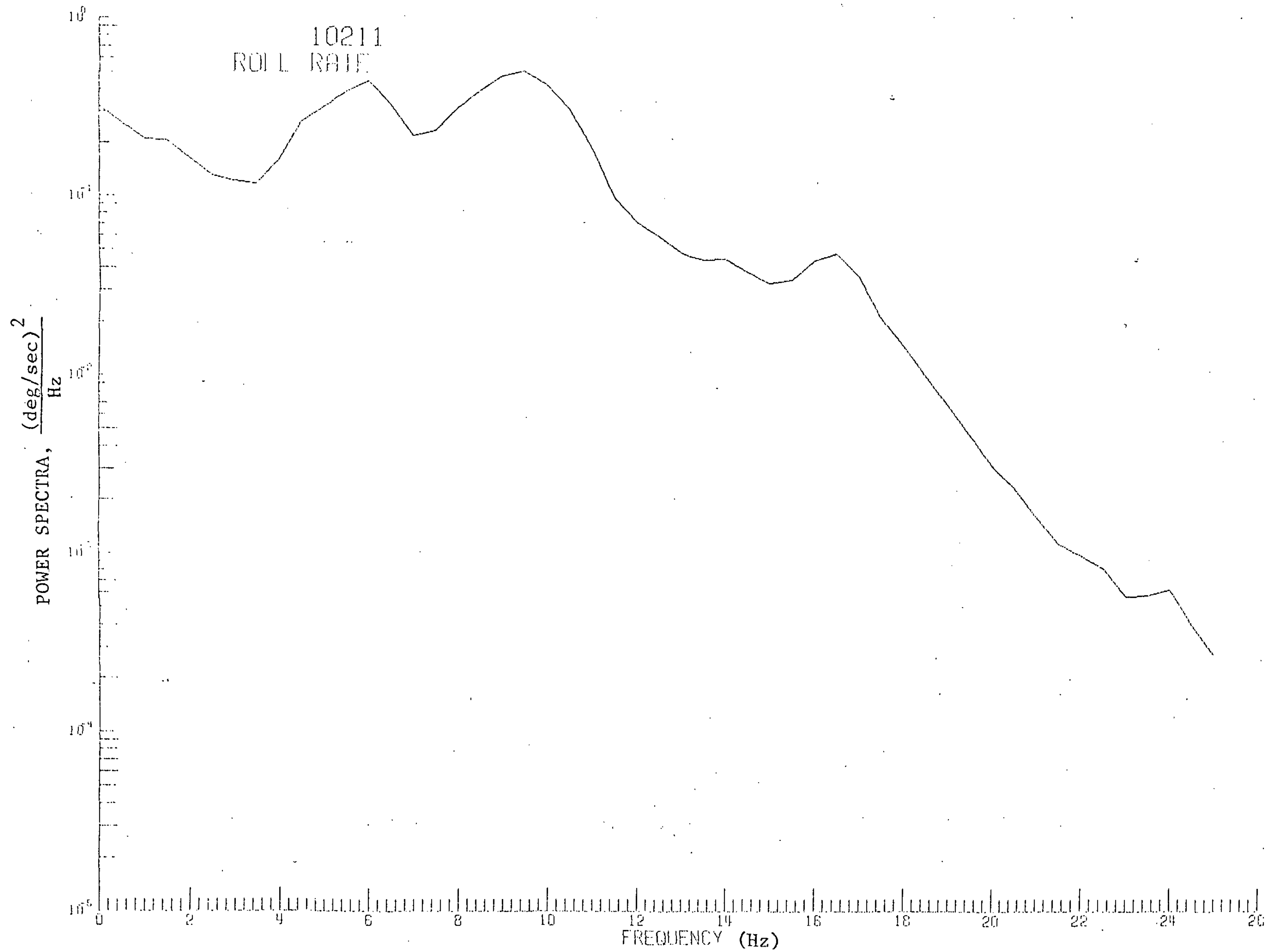


Figure 4. Continued - (d) Rolling velocity power spectrum (RMS rolling velocity 2.237 deg/sec)

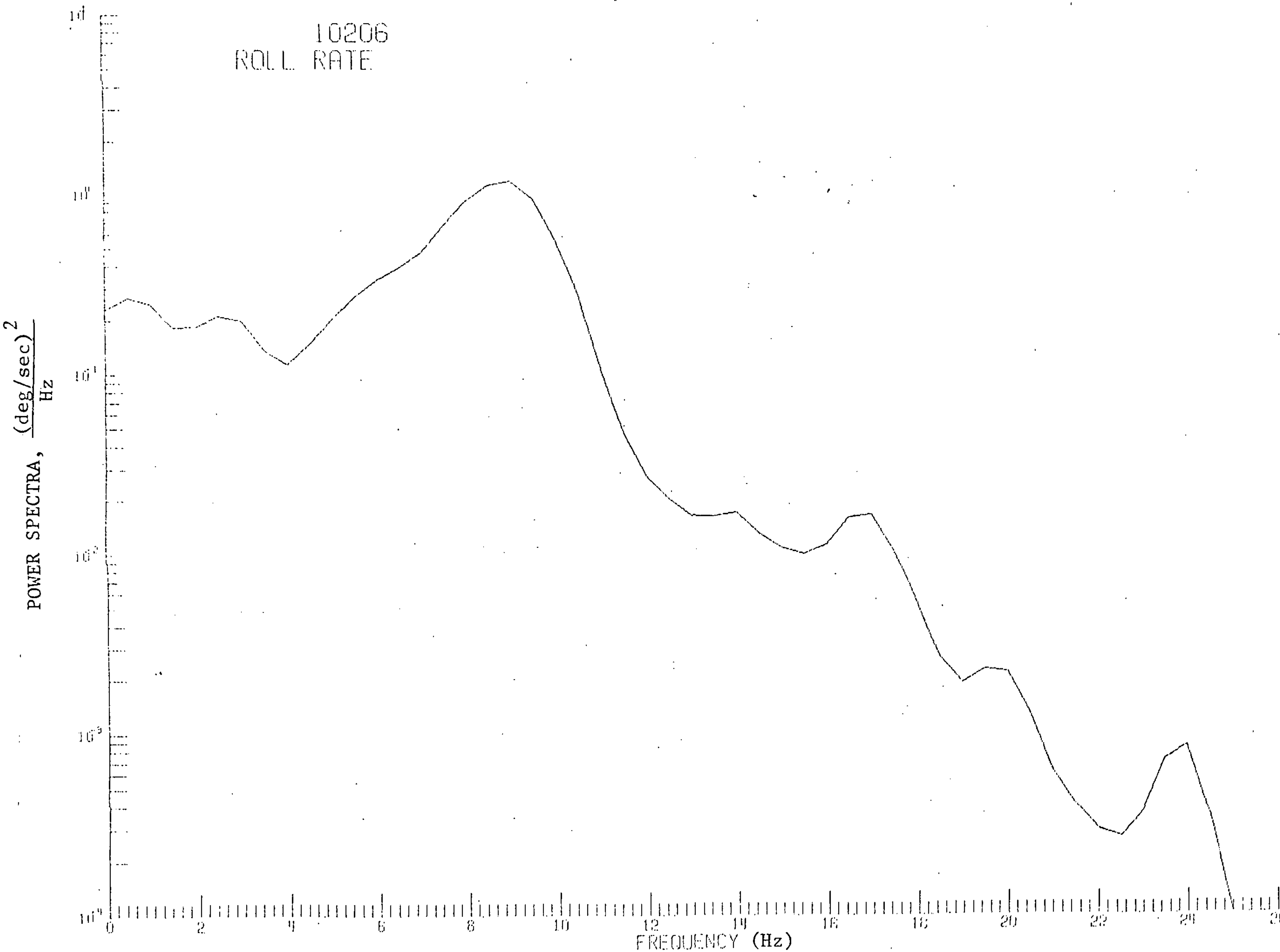
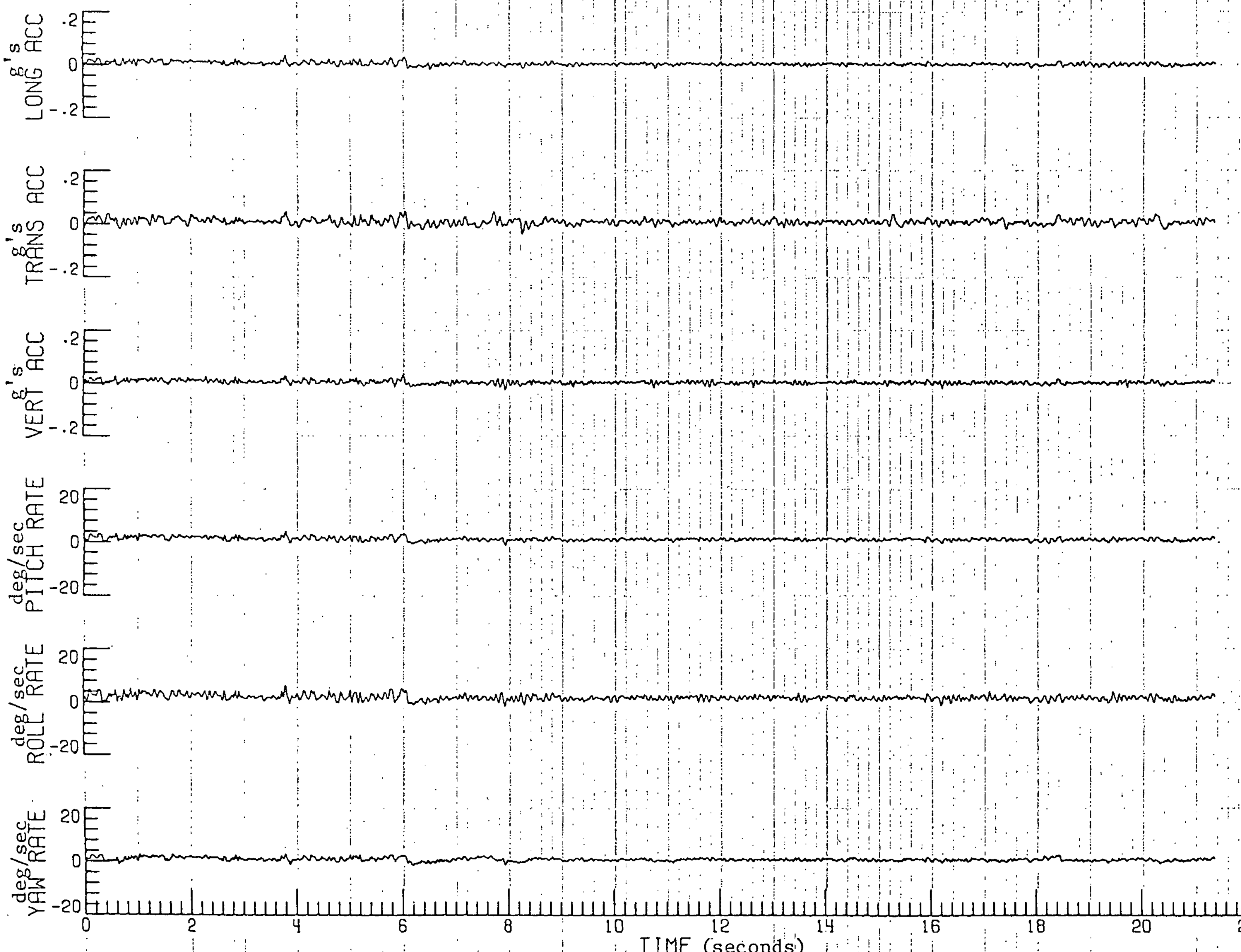
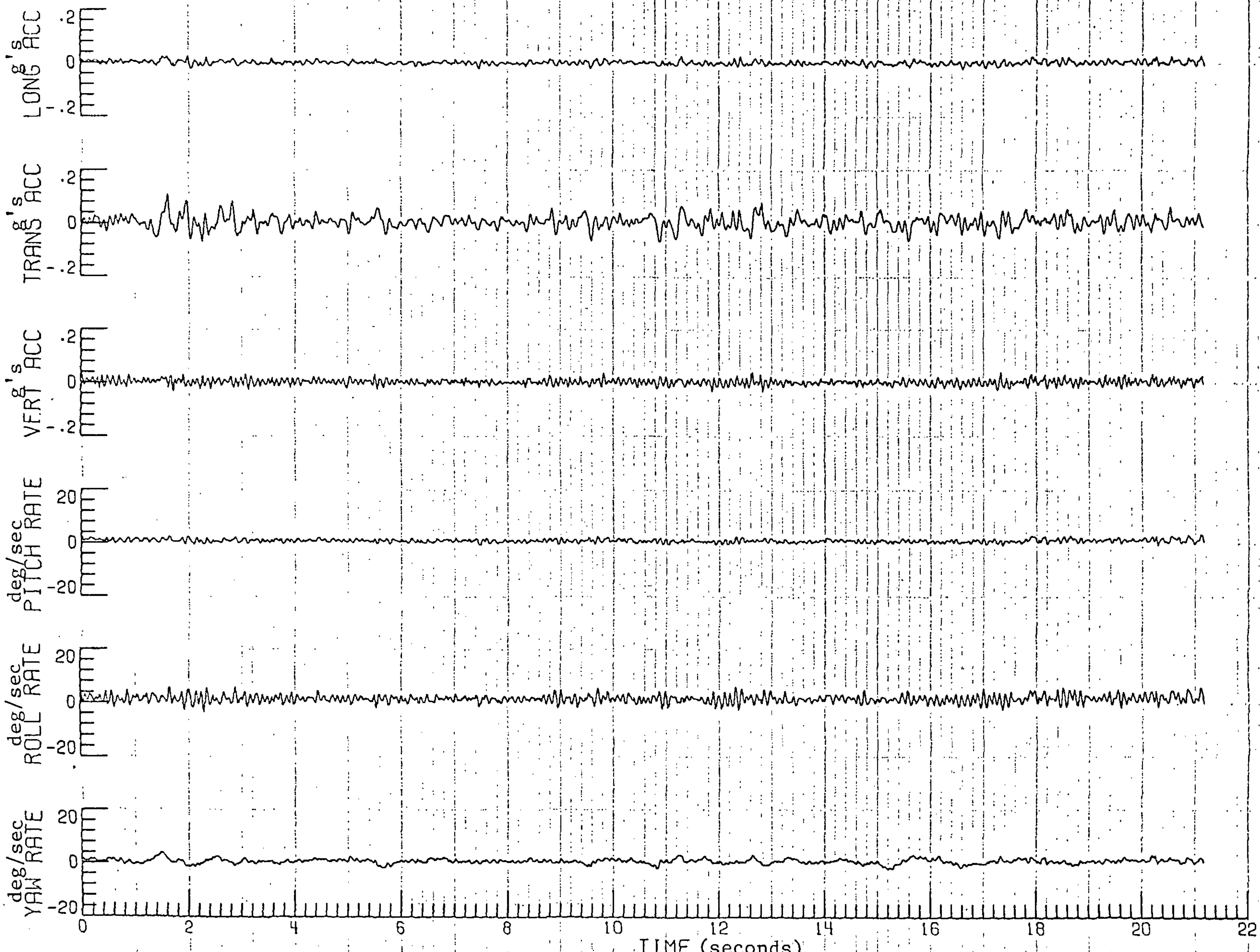


Figure 4. Concluded - (d) Rolling velocity power spectrum (RMS rolling velocity 2.791 deg/sec)



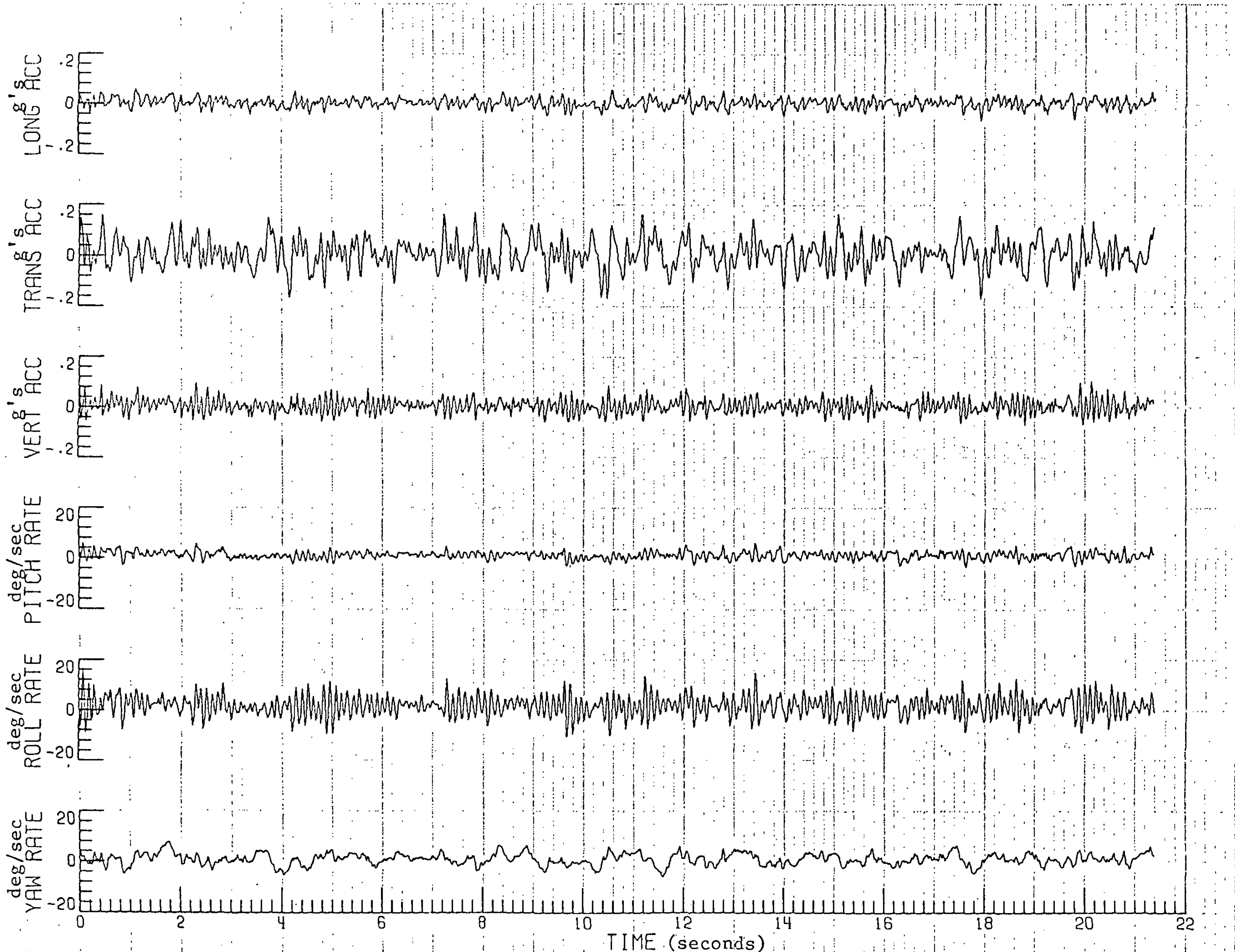
(a) Time histories (RMS yawing velocity 0.757 deg/sec)

Figure 5. MEASURED MOTION CHARACTERISTICS USING YAWING VELOCITIES WITH TYPICAL 0 - 2 HZ INPUTS



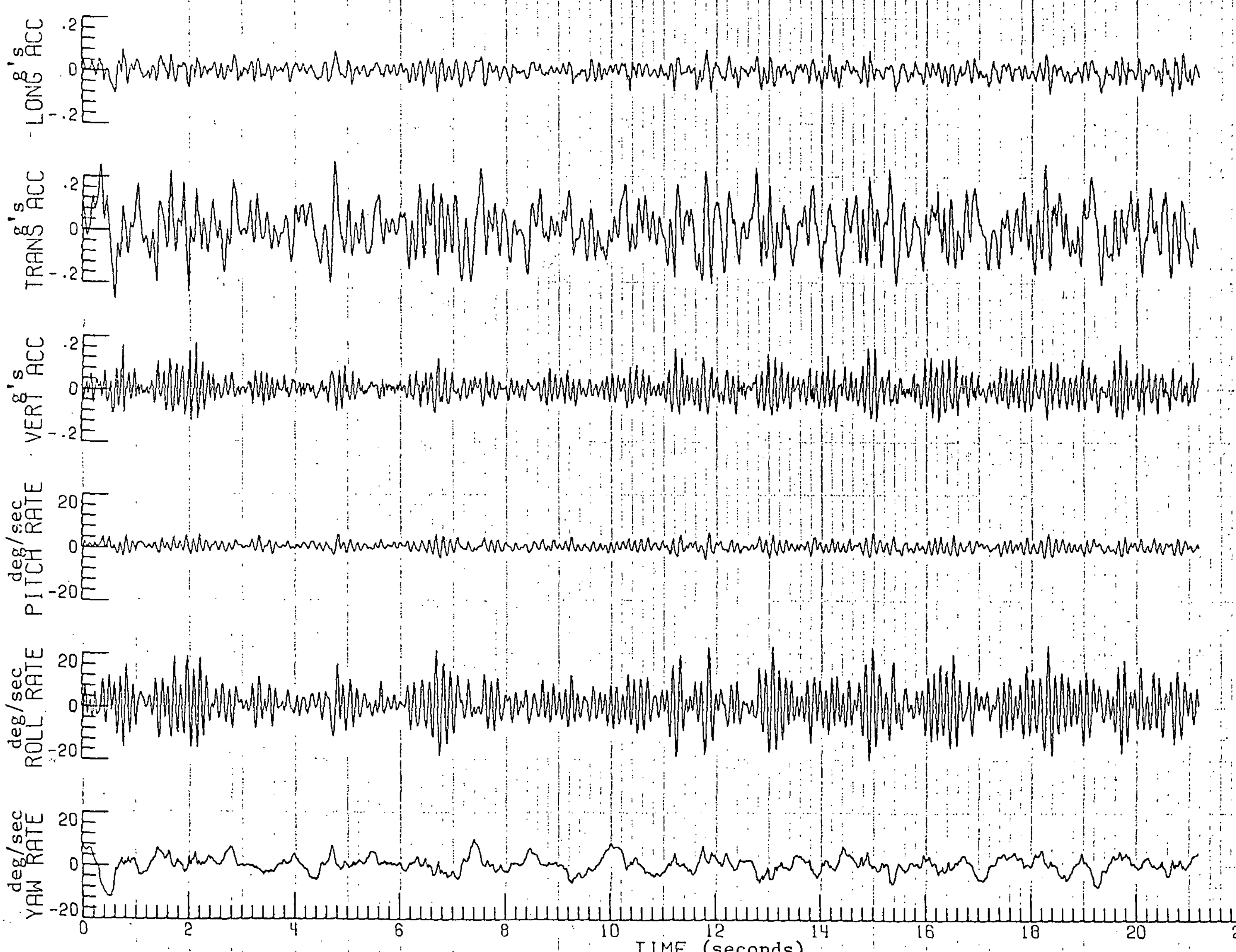
(a) Time histories (RMS yawing velocity 1.080 deg/sec)

Figure 5. Continued.



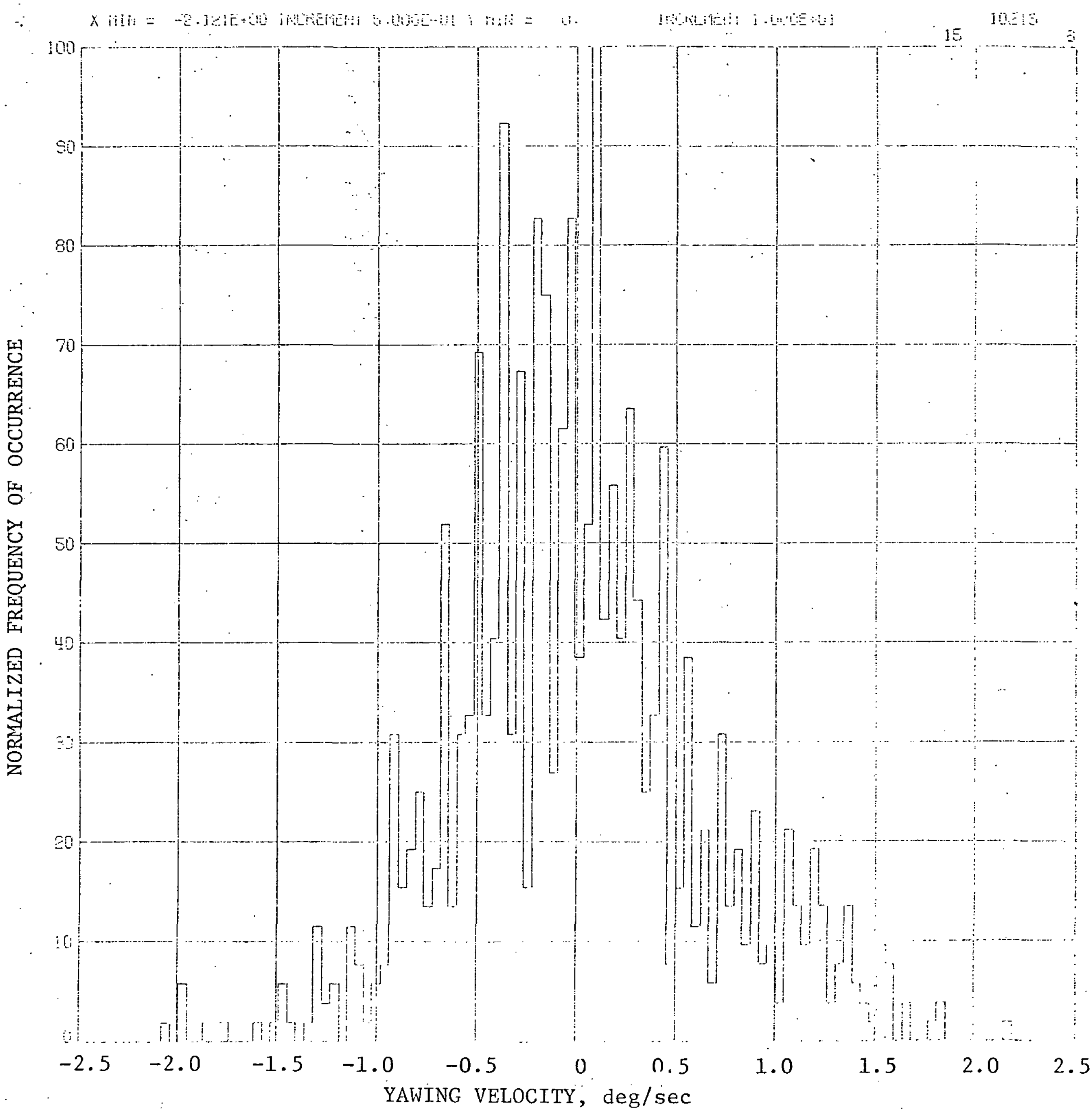
(a) Time histories (RMS yawing velocity 2.263 deg/sec)

Figure 5. Continued.



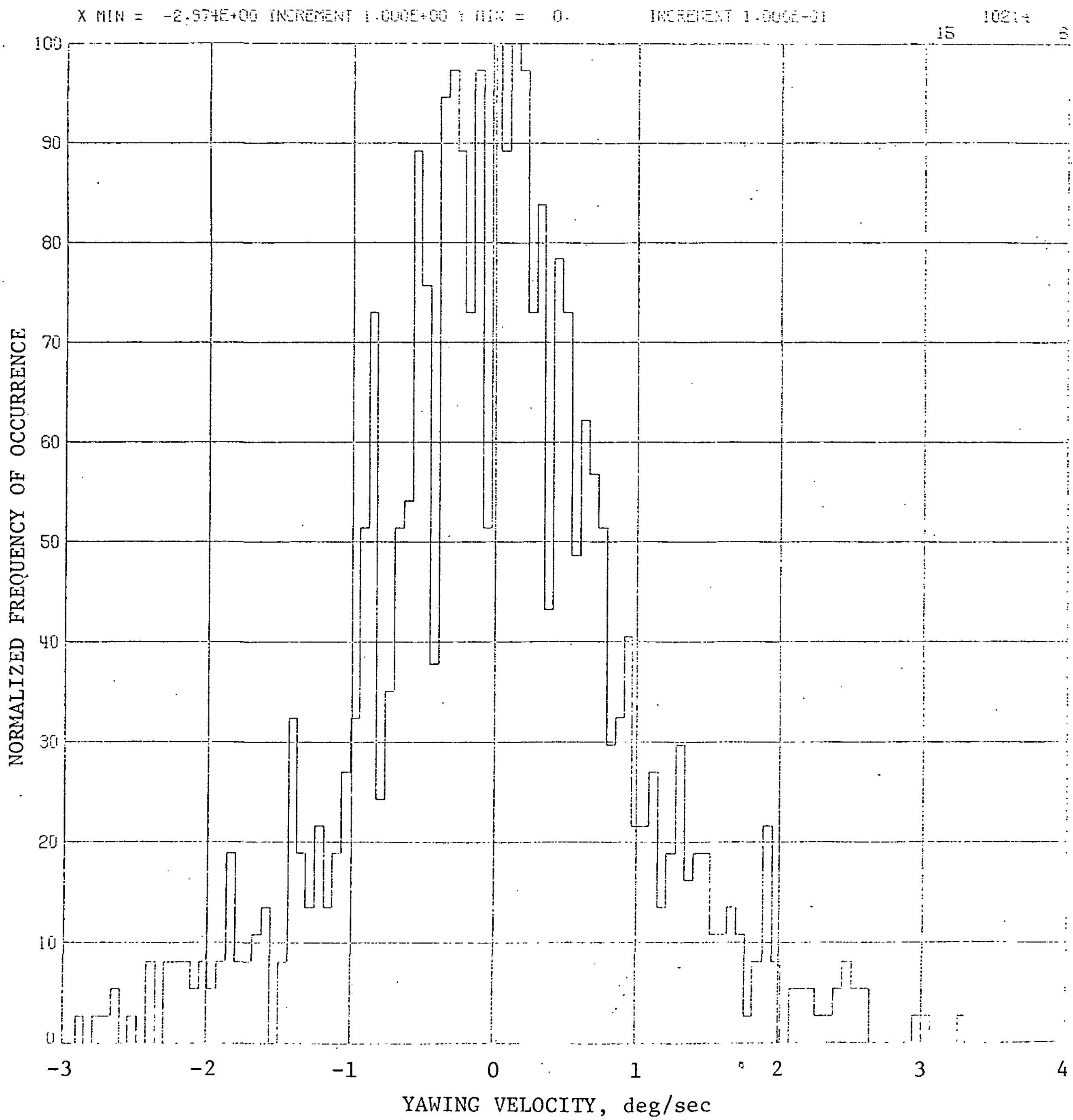
(a) Time histories (RMS yawing velocity 3.046 deg/sec)

Figure 5. Continued.



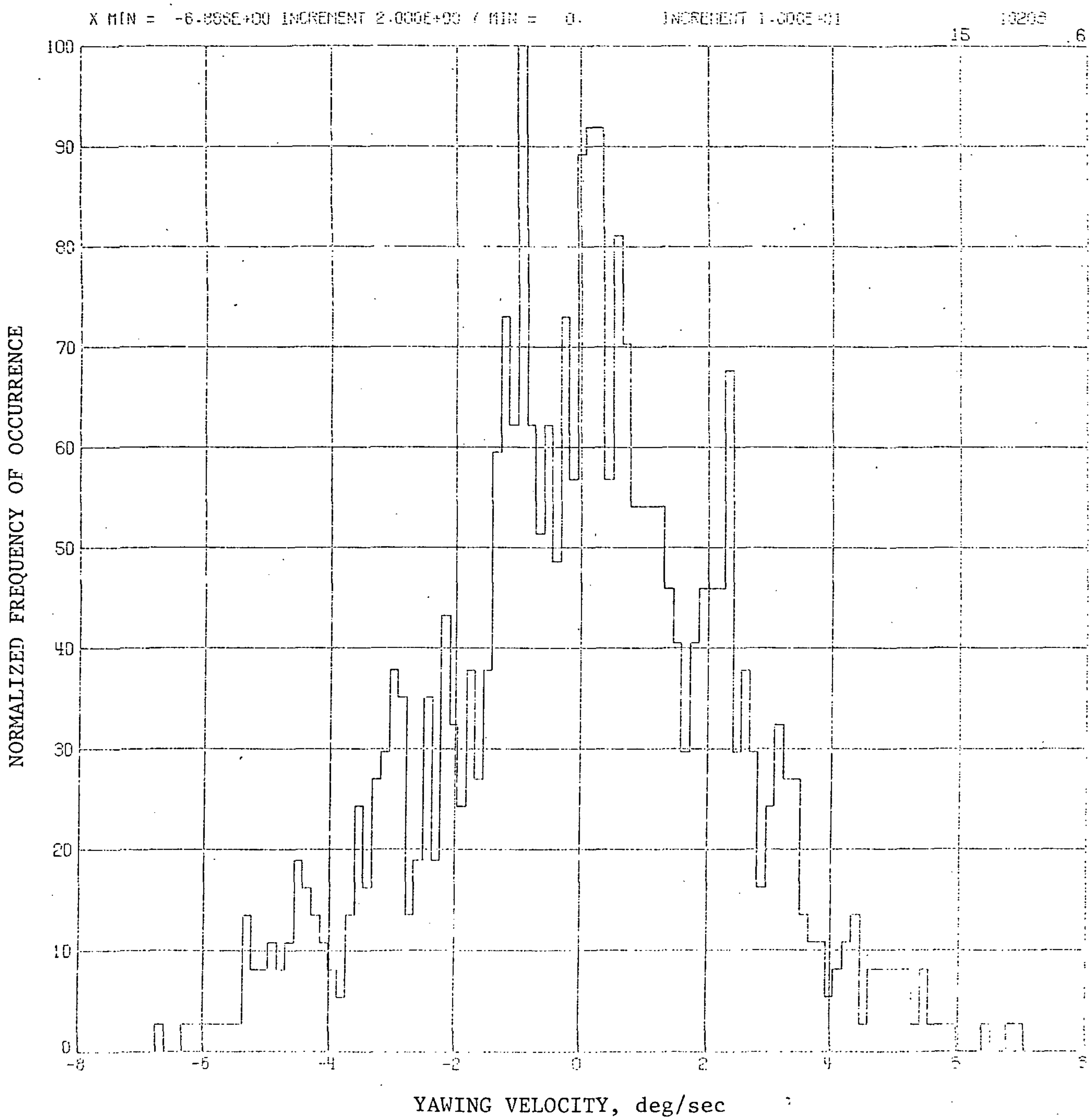
(b) Yawing velocity histogram (RMS yawing velocity 0.757 deg/sec)

Figure 5. Continued.



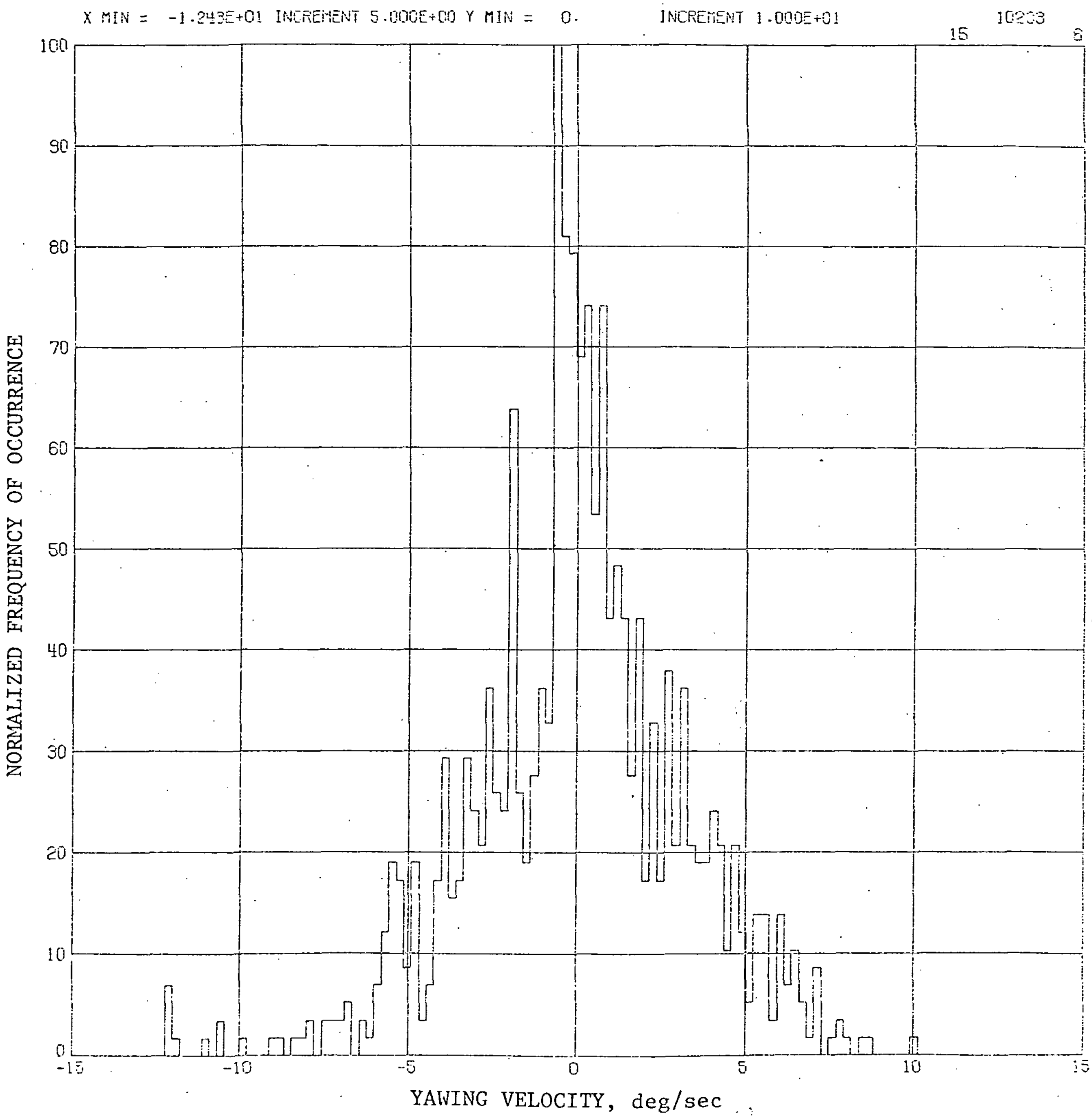
(b) Yawing velocity histogram (RMS yawing velocity 1.080 deg/sec)

Figure 5. Continued.



(b) Yawing velocity histogram (RMS yawing velocity 2.263 deg/sec)

Figure 5. Continued.



(b) Yawing velocity histogram (RMS yawing velocity 3.046 deg/sec)

Figure 5. Continued.

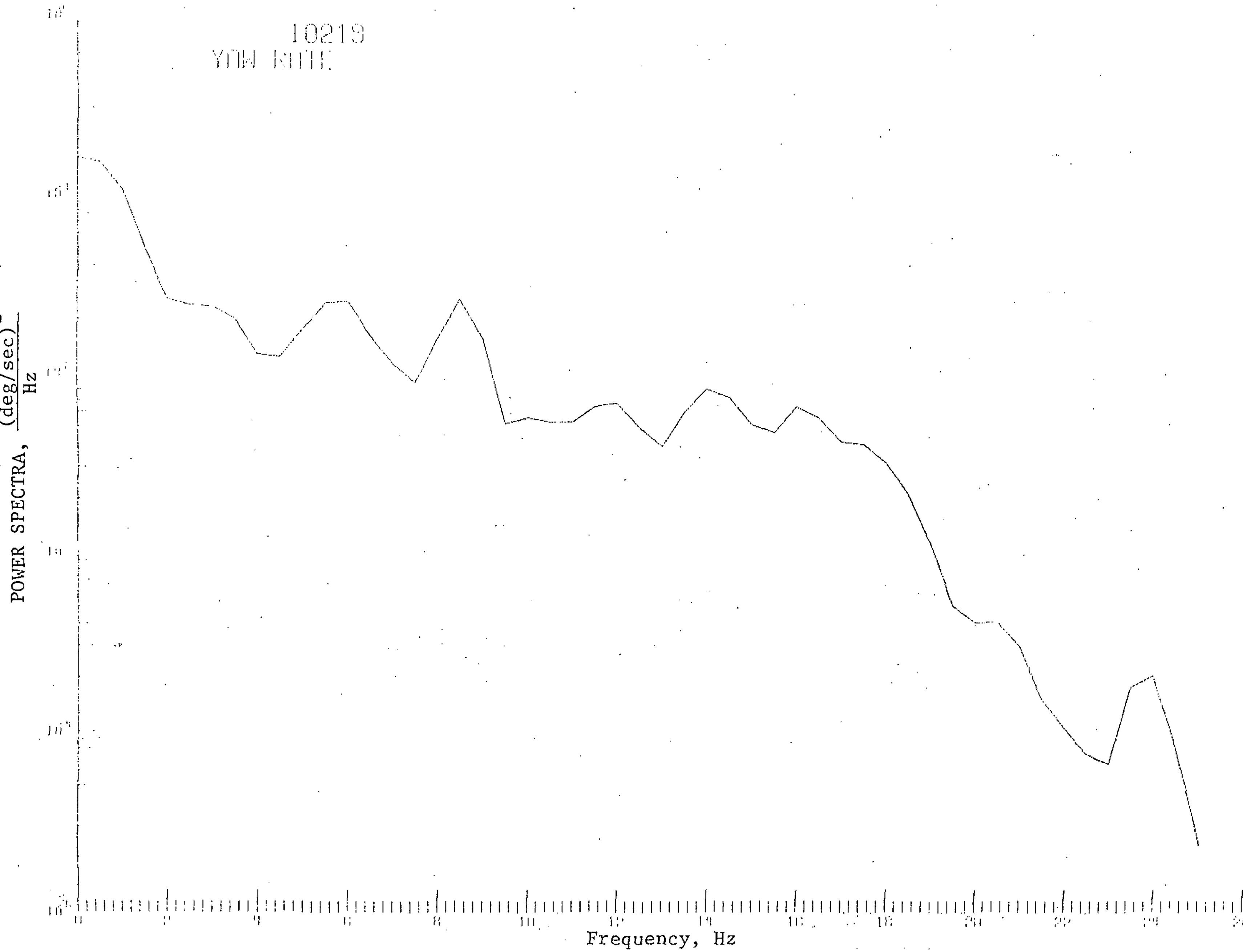


Figure 5. Continued - (c) Yawing velocity power spectrum (RMS yawing velocity 0.757 deg/sec)

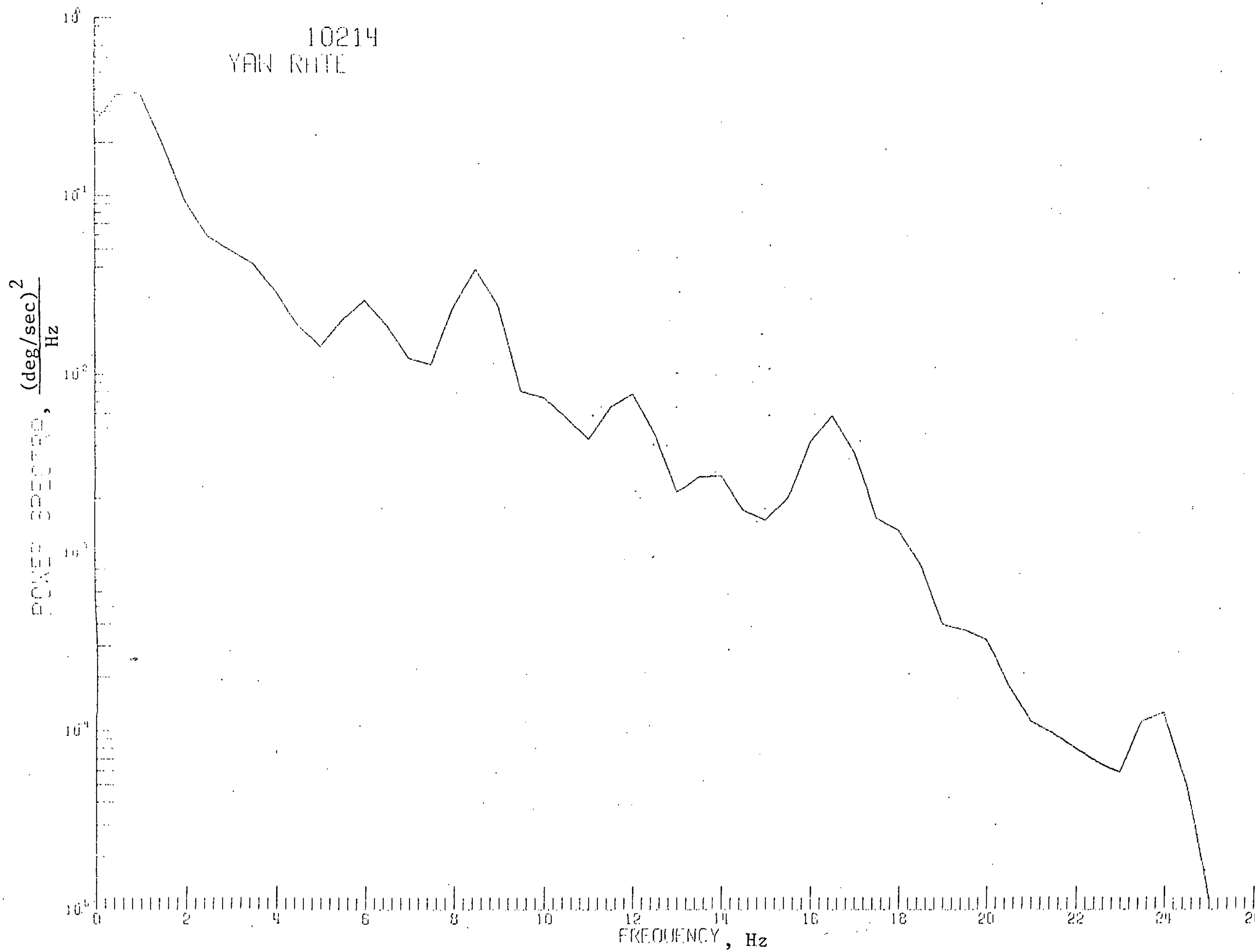


Figure 5. Continued - (c) Yawing velocity power spectrum (RMS yawing velocity 1.080 deg/sec)

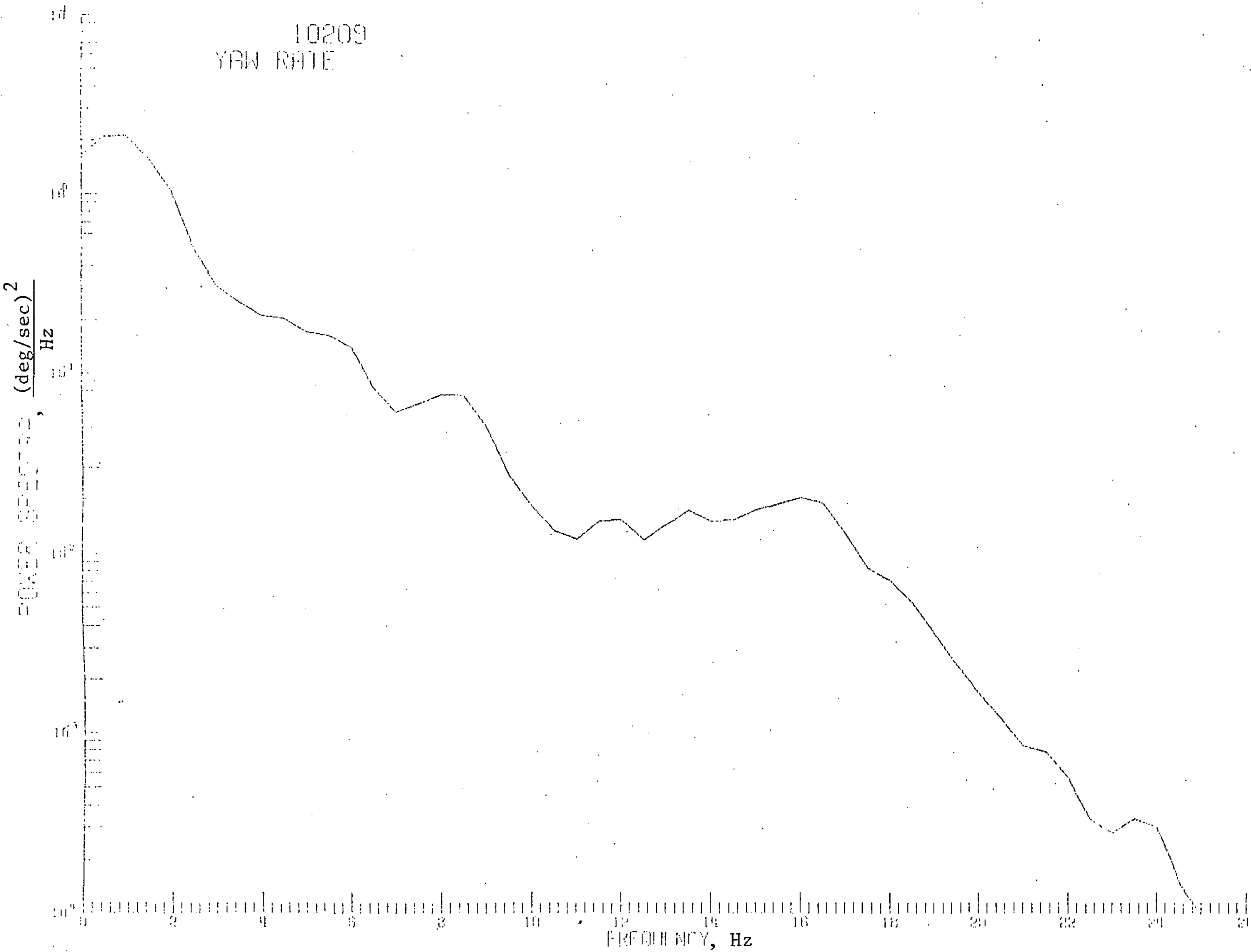


Figure 5. Continued - (c) Yawing velocity power spectrum (RMS yawing velocity 2.263 deg/sec)

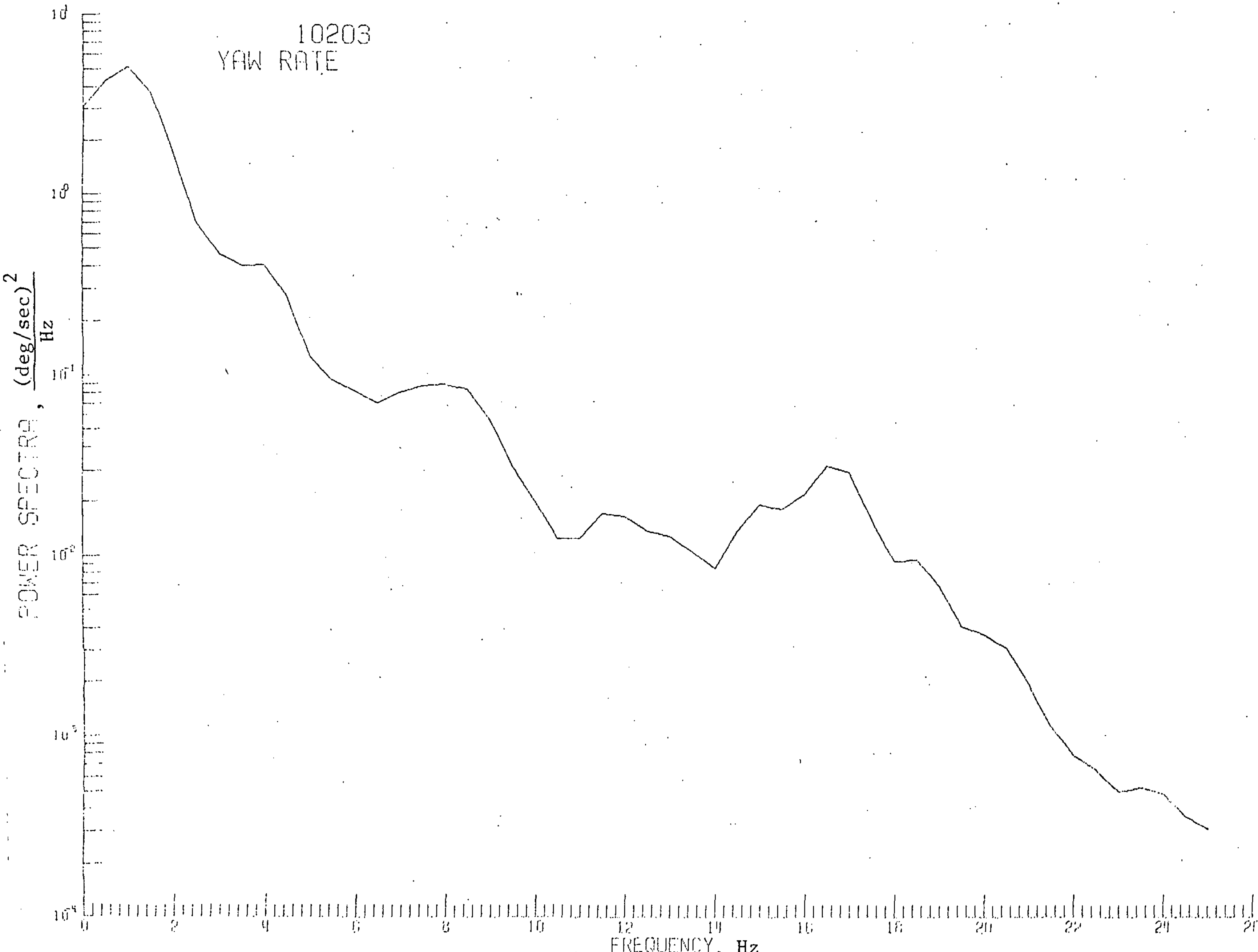


Figure 5. Continued - (c) Yawing velocity power spectrum (RMS yawing velocity 3.046 deg/sec)

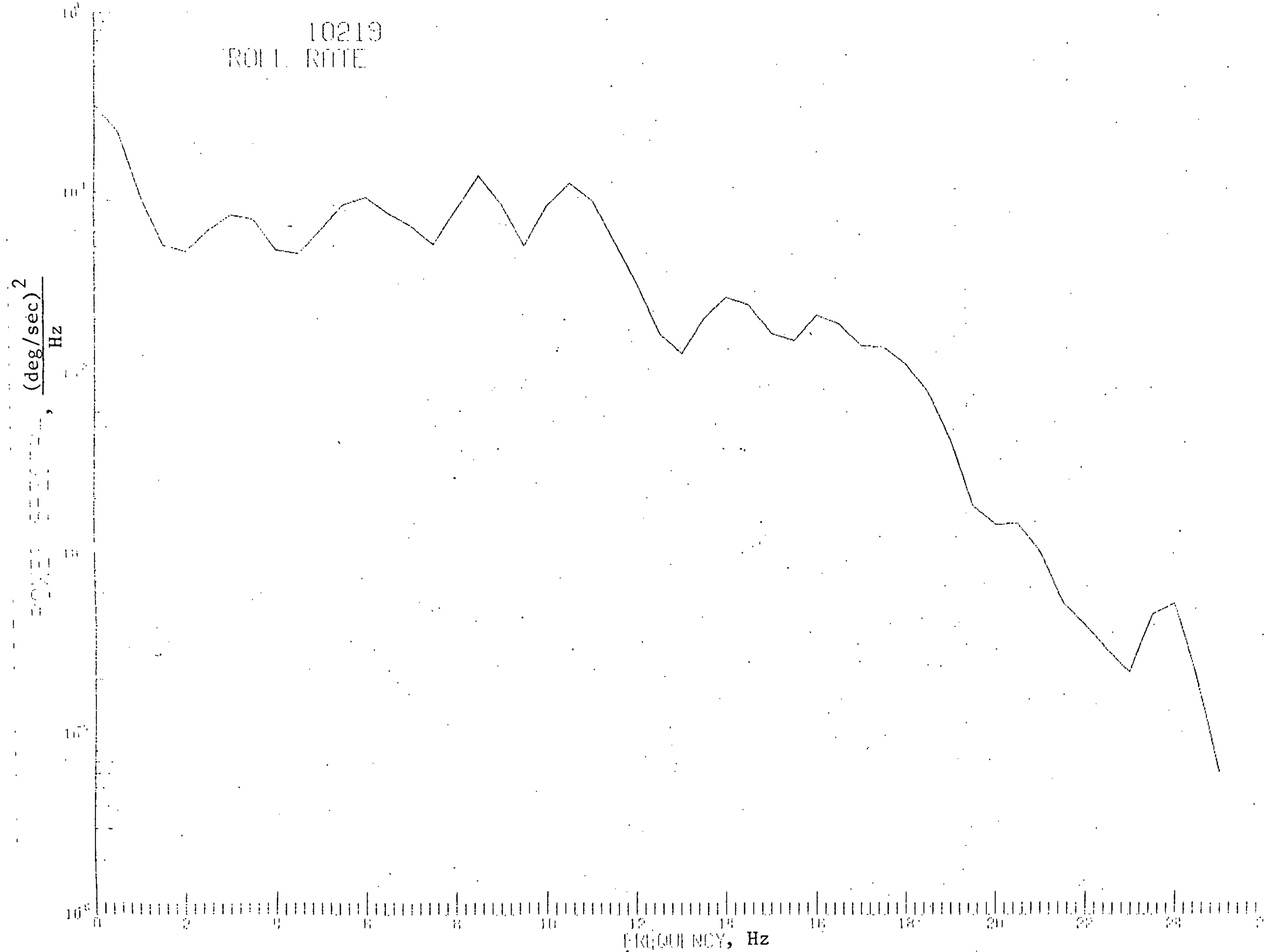


Figure 5. Continued - (d) Rolling velocity power spectrum (RMS rolling velocity 1.354 deg/sec)

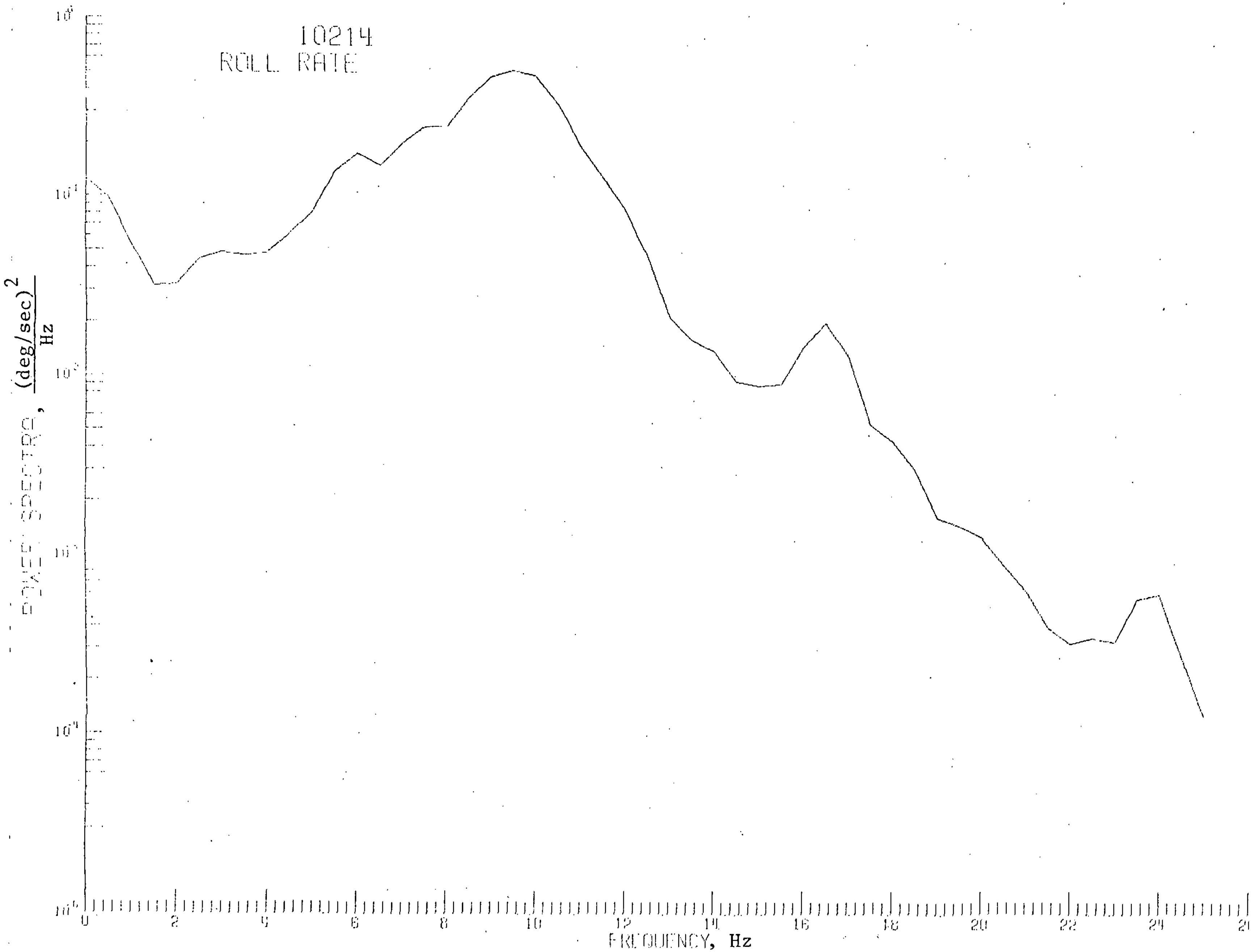


Figure 5. Continued - (d) Rolling velocity power spectrum (RMS rolling velocity 2.011 deg/sec)

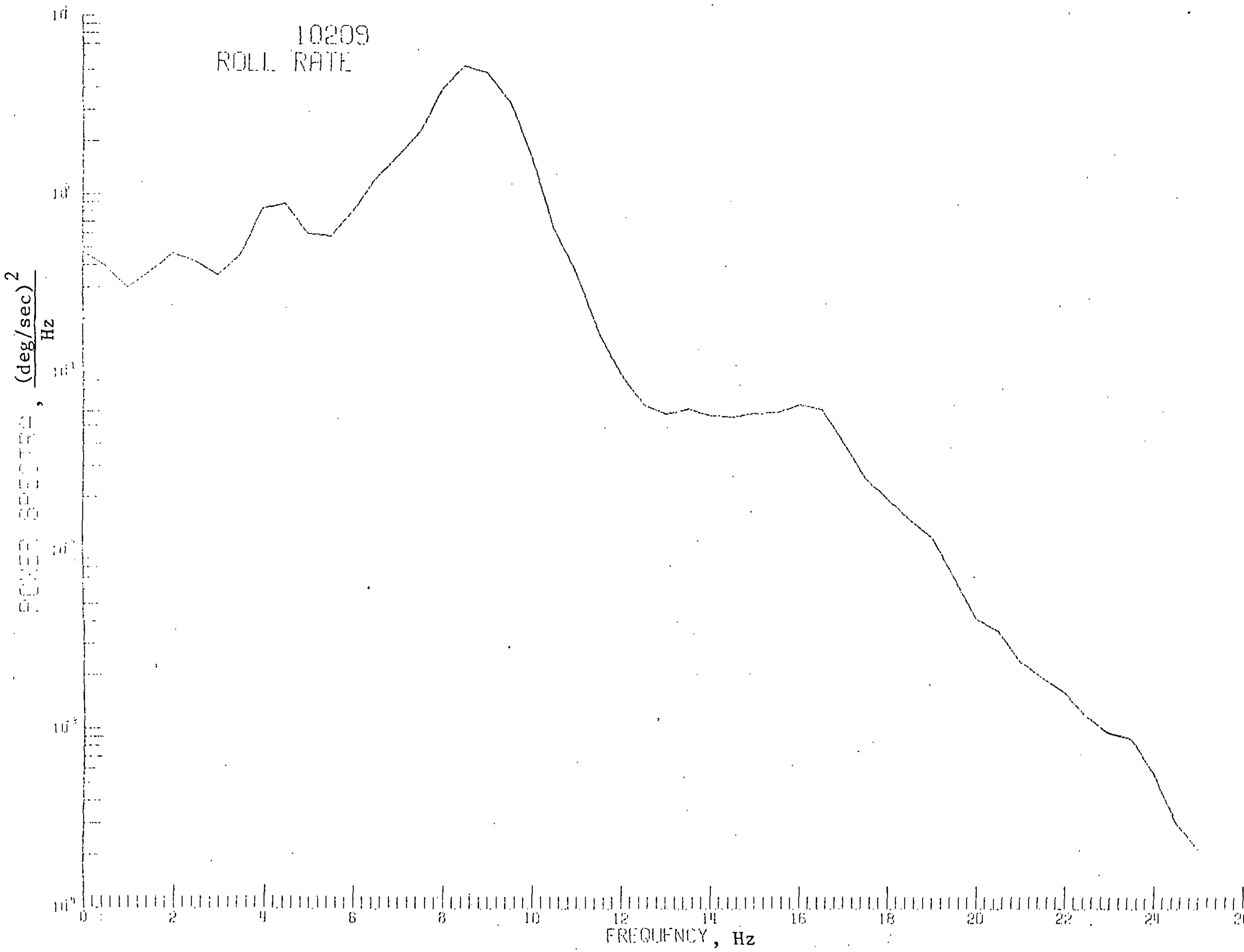


Figure 5. Continued - (d) Rolling velocity power spectrum (RMS rolling velocity 4.790 deg/sec)

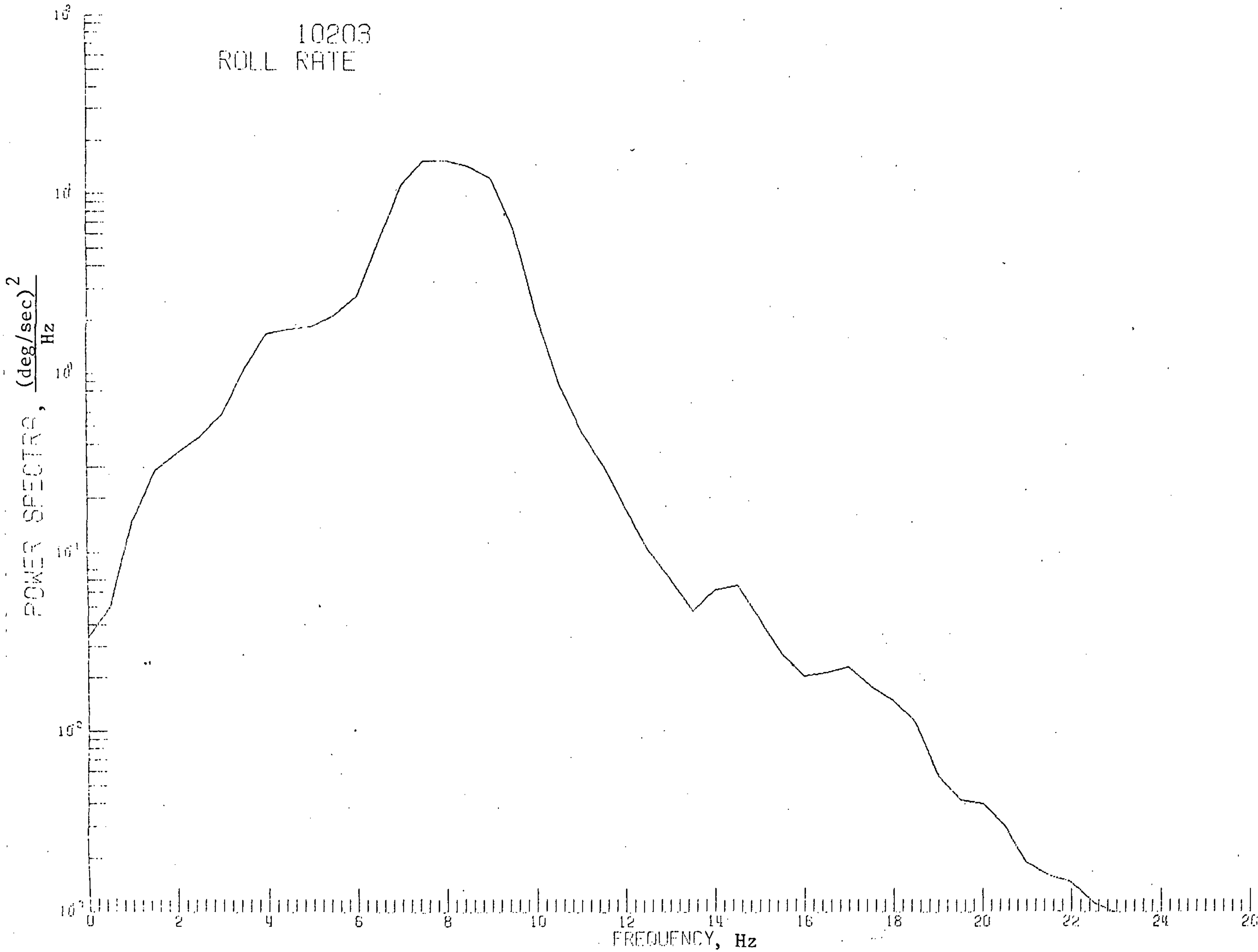
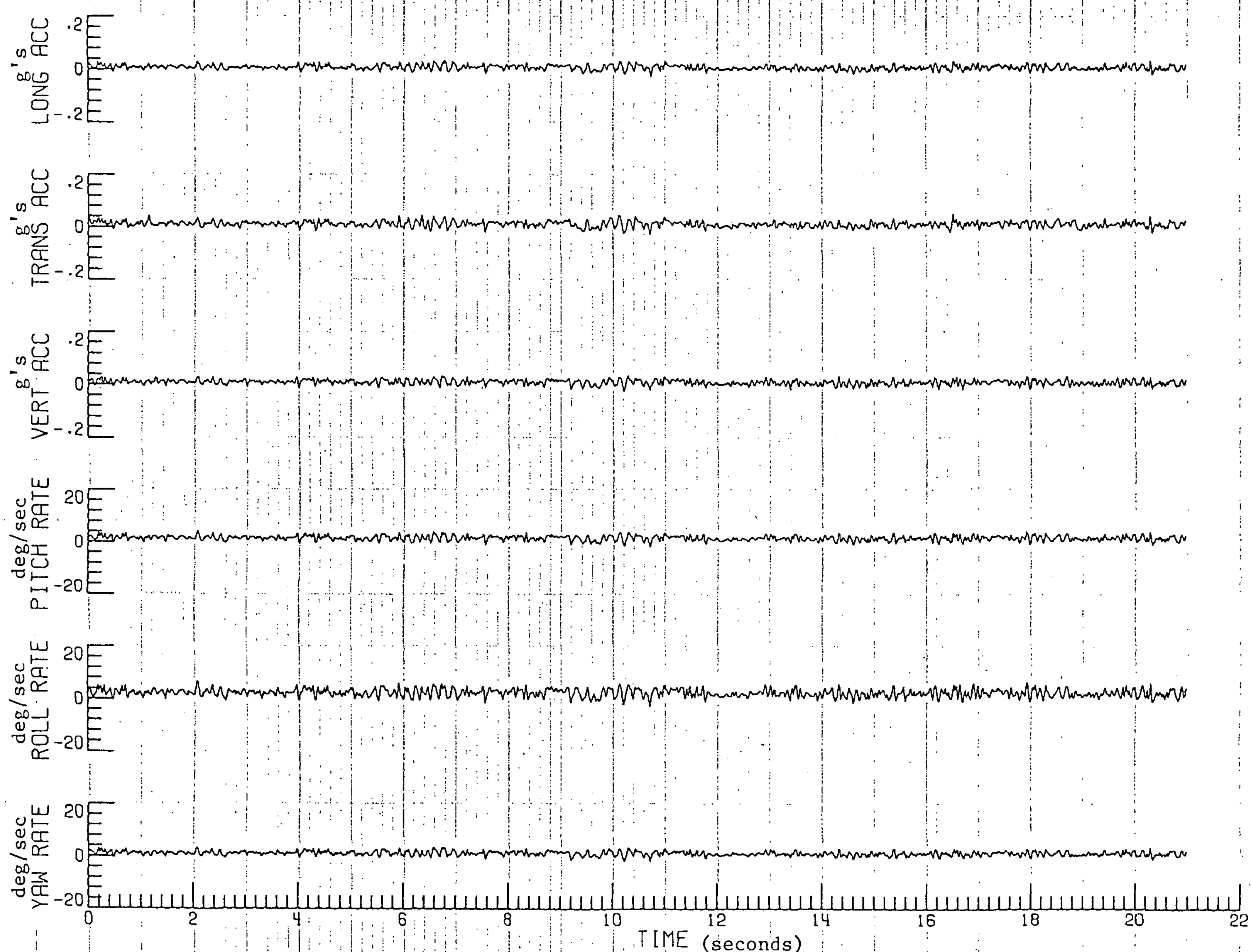
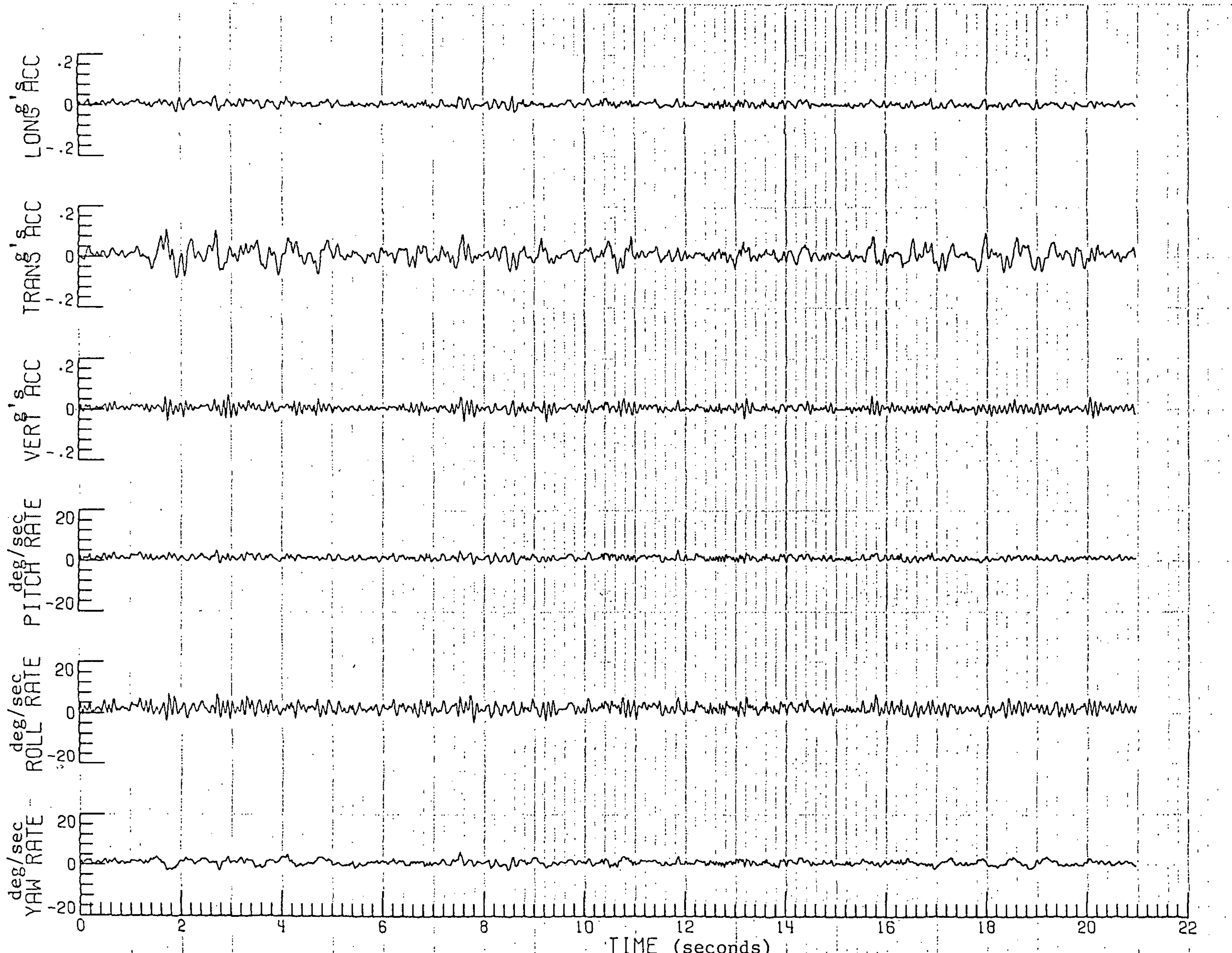


Figure 5. Concluded - (d) Rolling velocity power spectrum (RMS rolling velocity 8.085 deg/sec)



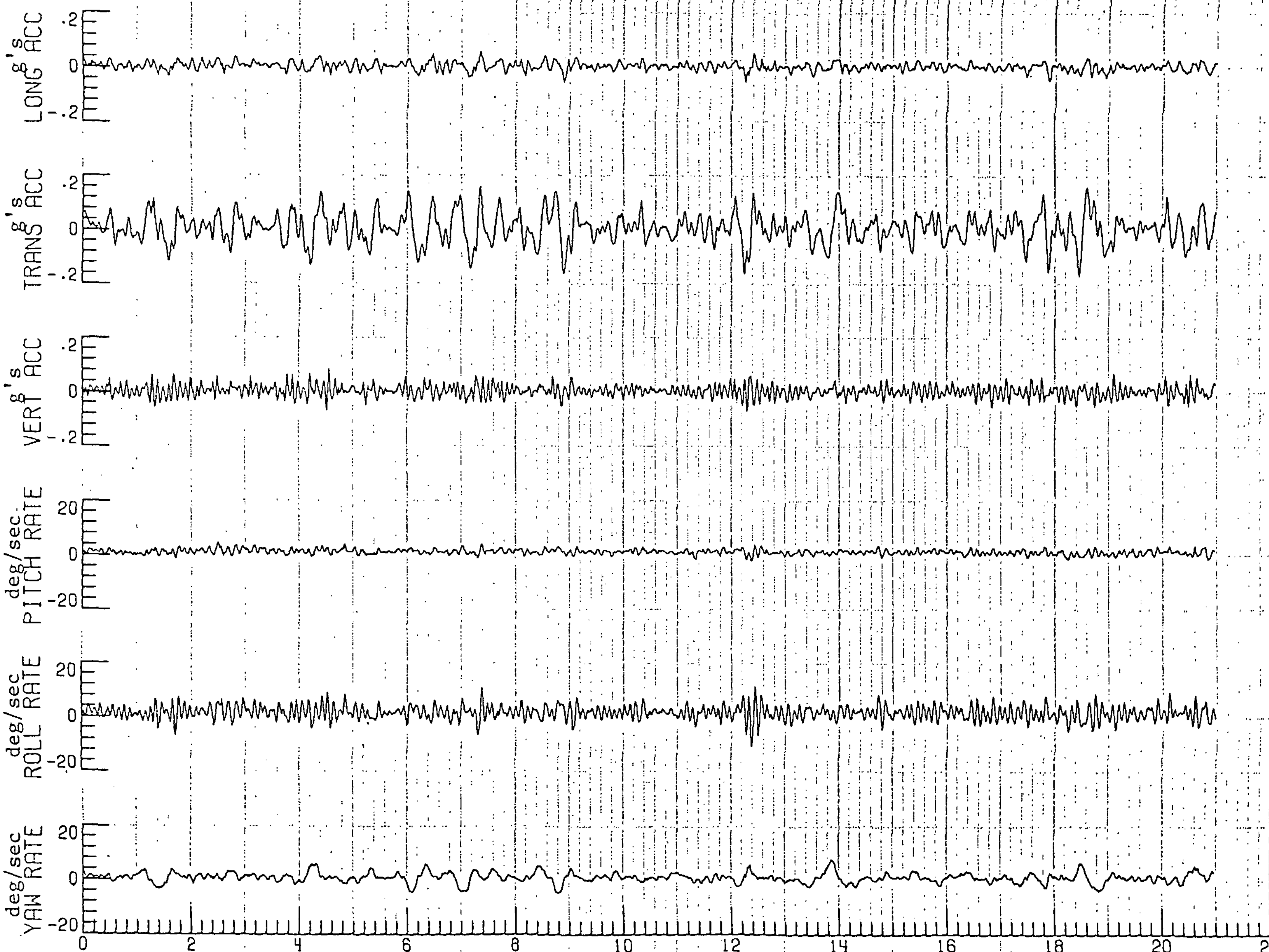
(a) Time histories (RMS yawing velocity 0.813 deg/sec)

Figure 6. MEASURED MOTION CHARACTERISTICS USING YAWING VELOCITIES WITH TYPICAL - 2 HZ INPUTS



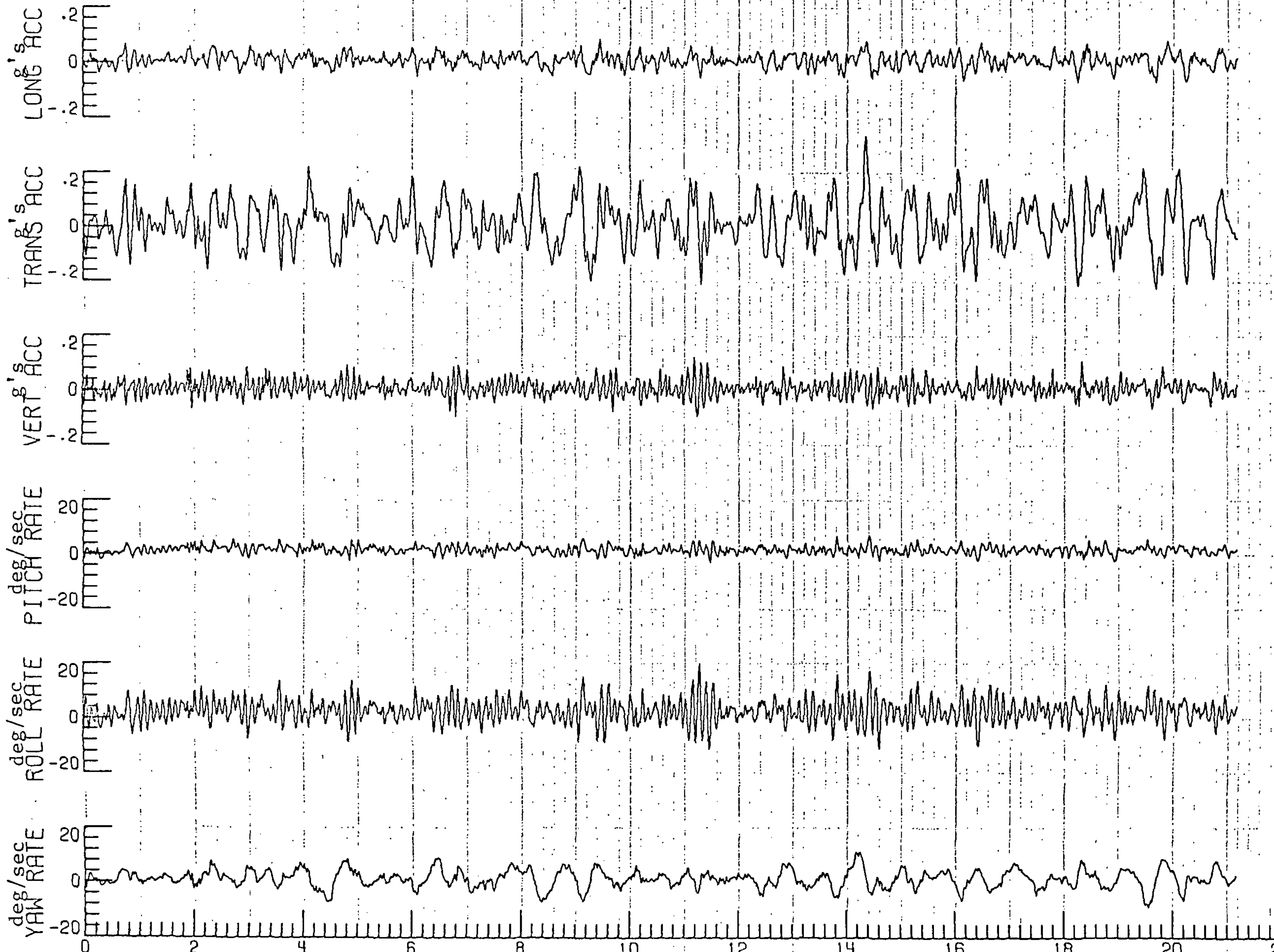
(a) Time histories (RMS yawing velocity 1.064 deg/sec)

Figure 6. Continued.



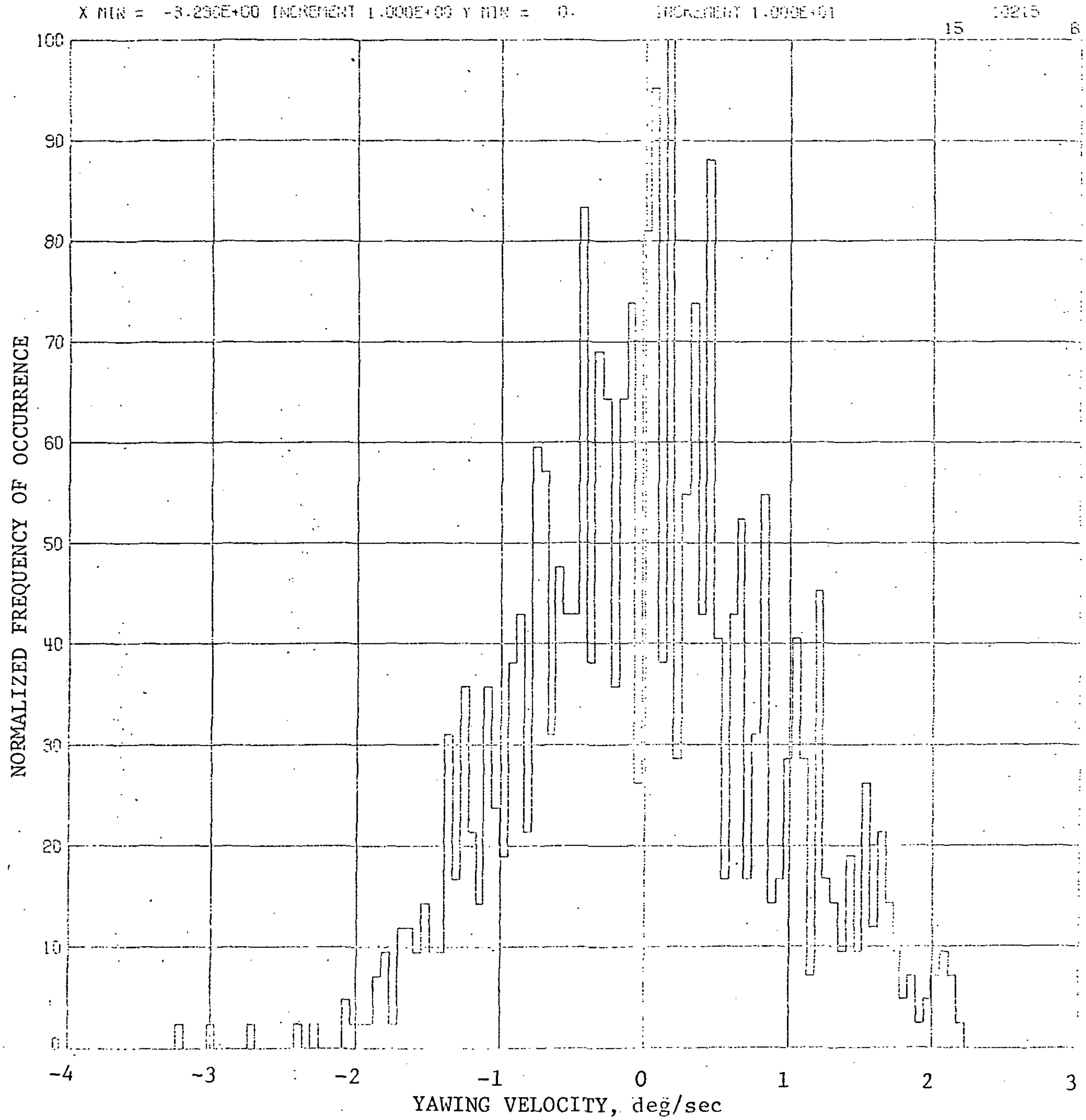
(a) Time histories (RMS yawing velocity 1.948 deg/sec)

Figure 6. Continued.



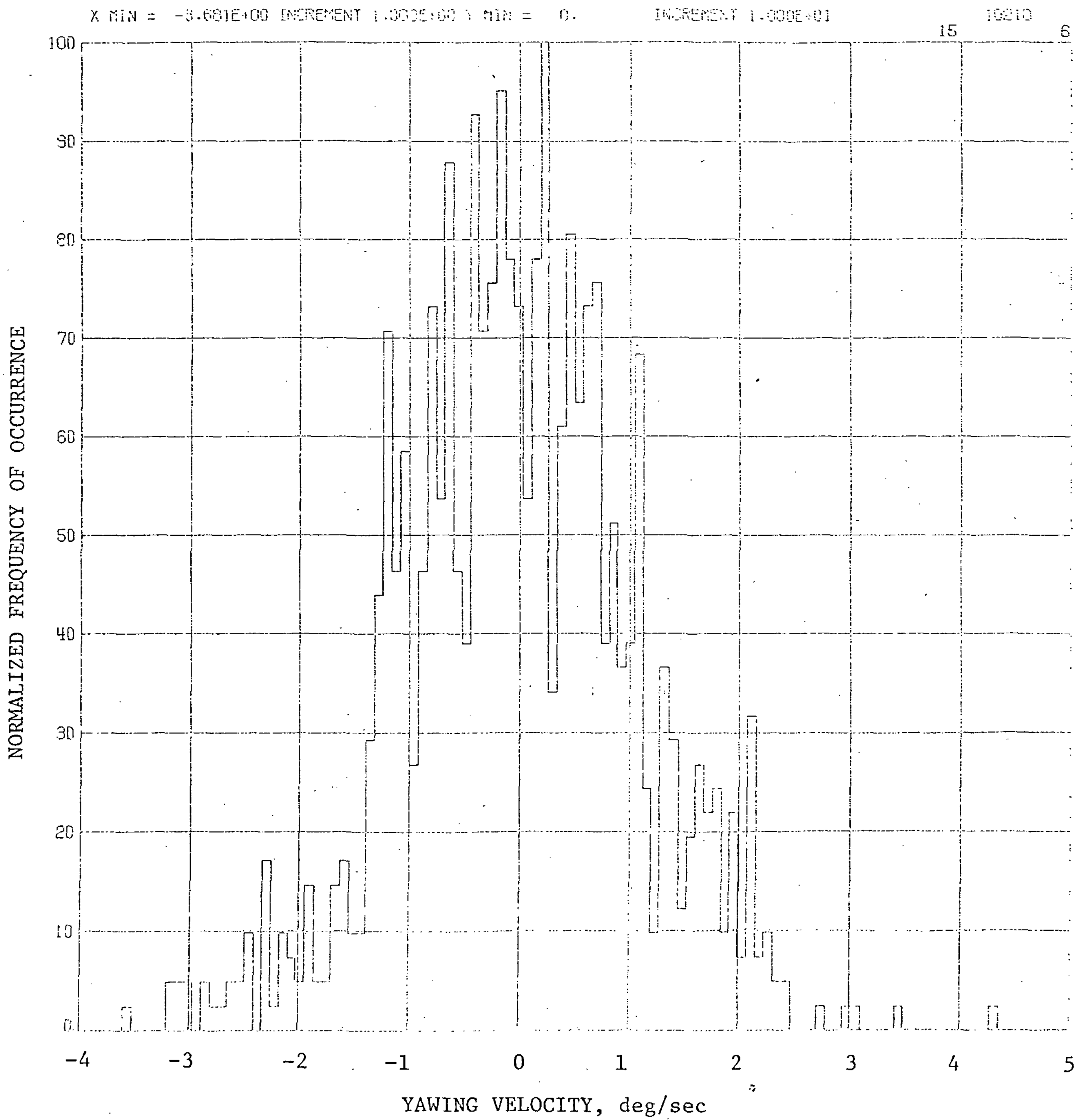
(a) Time histories (RMS yawing velocity 3.097 deg/sec)

Figure 6. Continued.



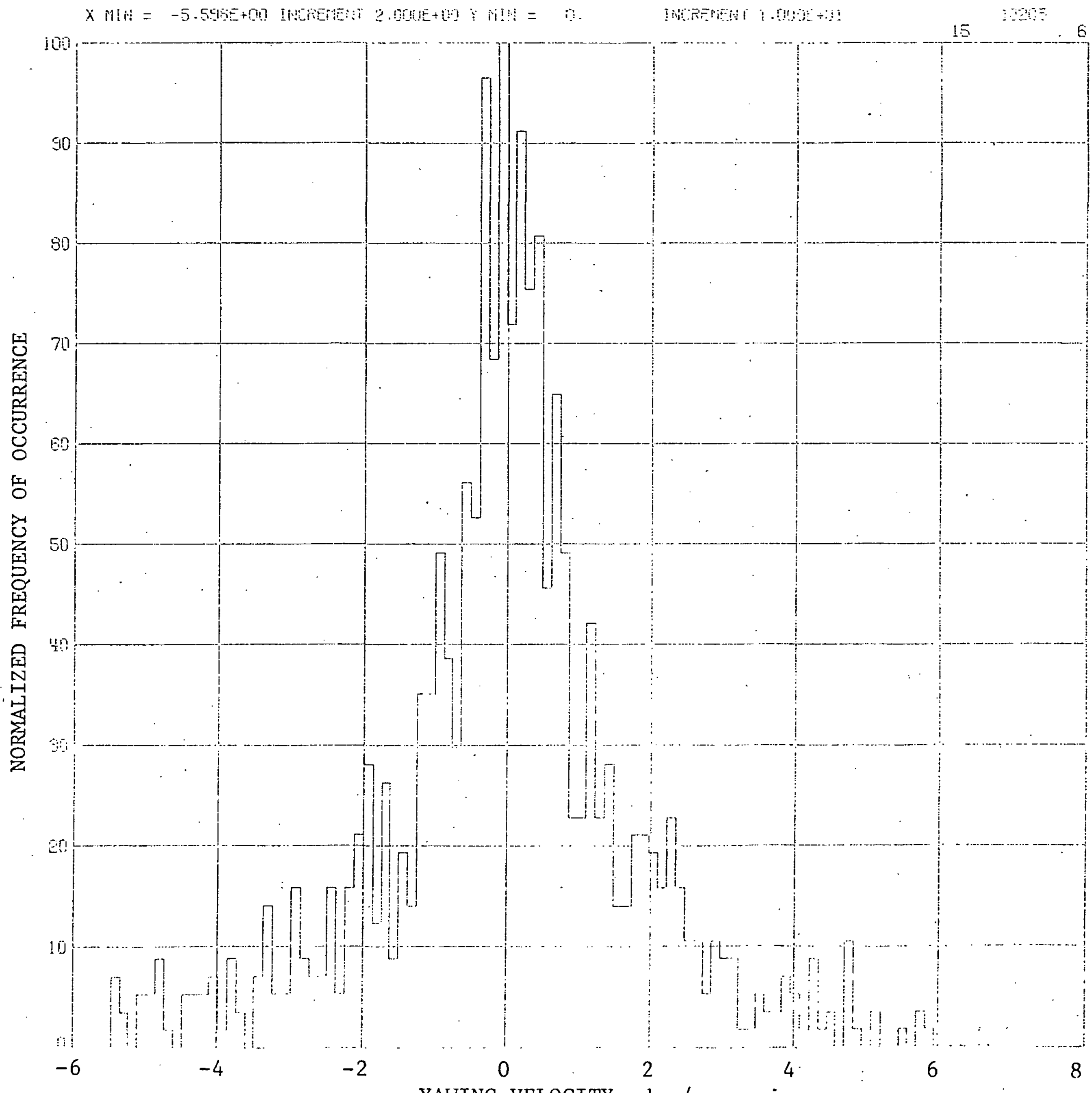
(b) Yawing velocity histograms (RMS yawing velocity 0.813 deg/sec)

Figure 6. Continued.



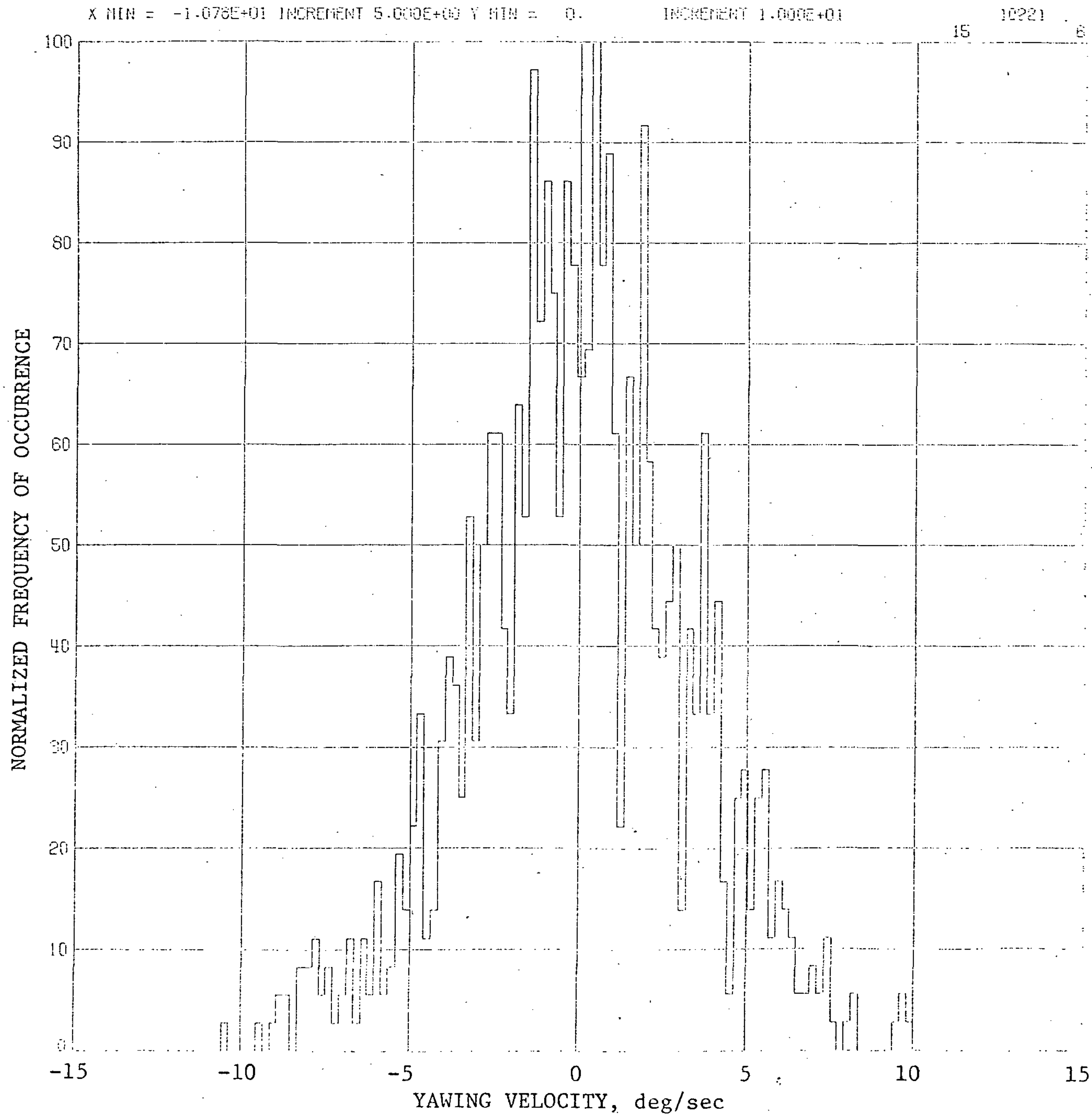
(b) Yawing velocity histograms(RMS yawing velocity 1.064 deg/sec)

Figure 6. Continued.



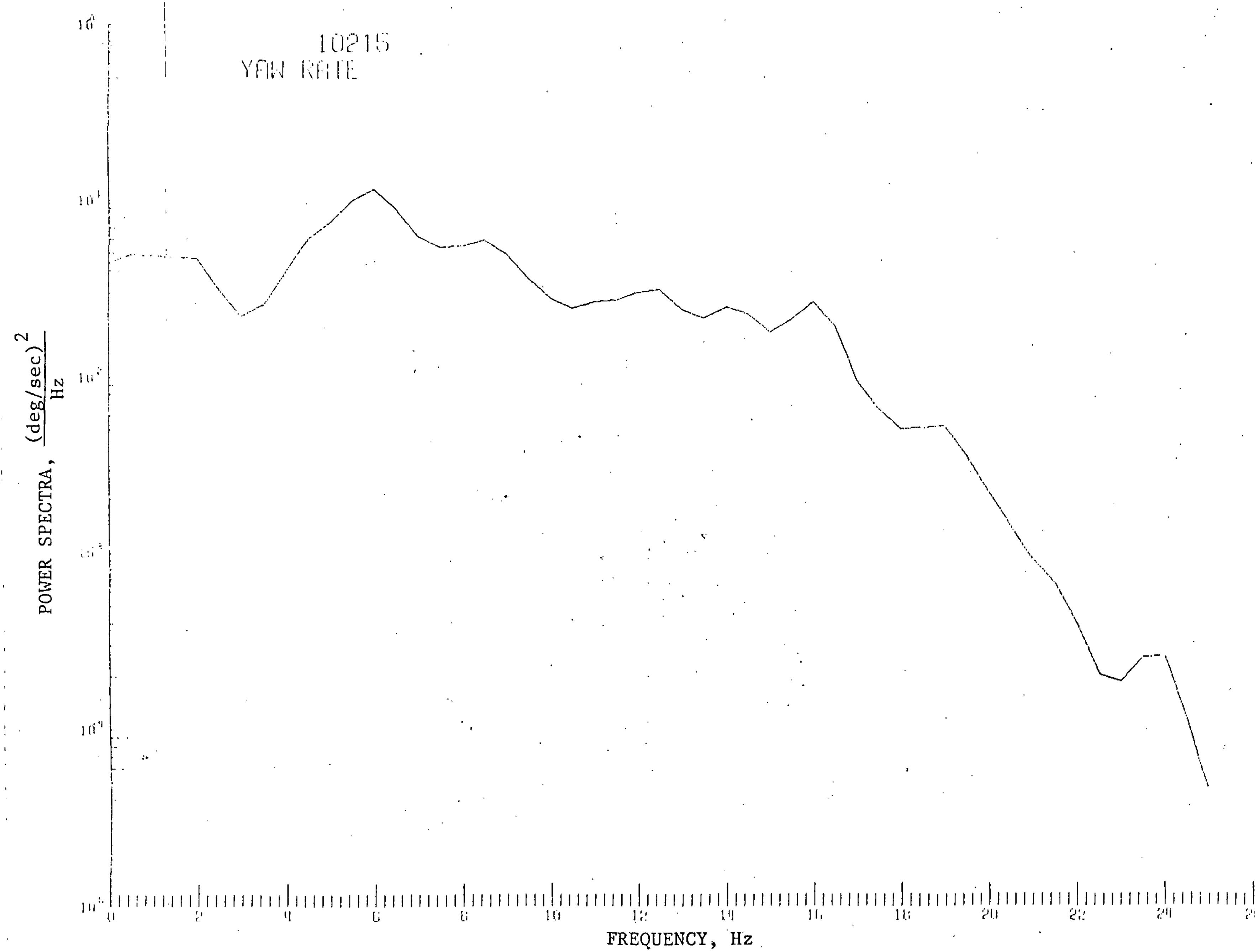
(b) Yawing velocity histograms (RMS yawing velocity 1.948 deg/sec)

Figure 6. Continued.



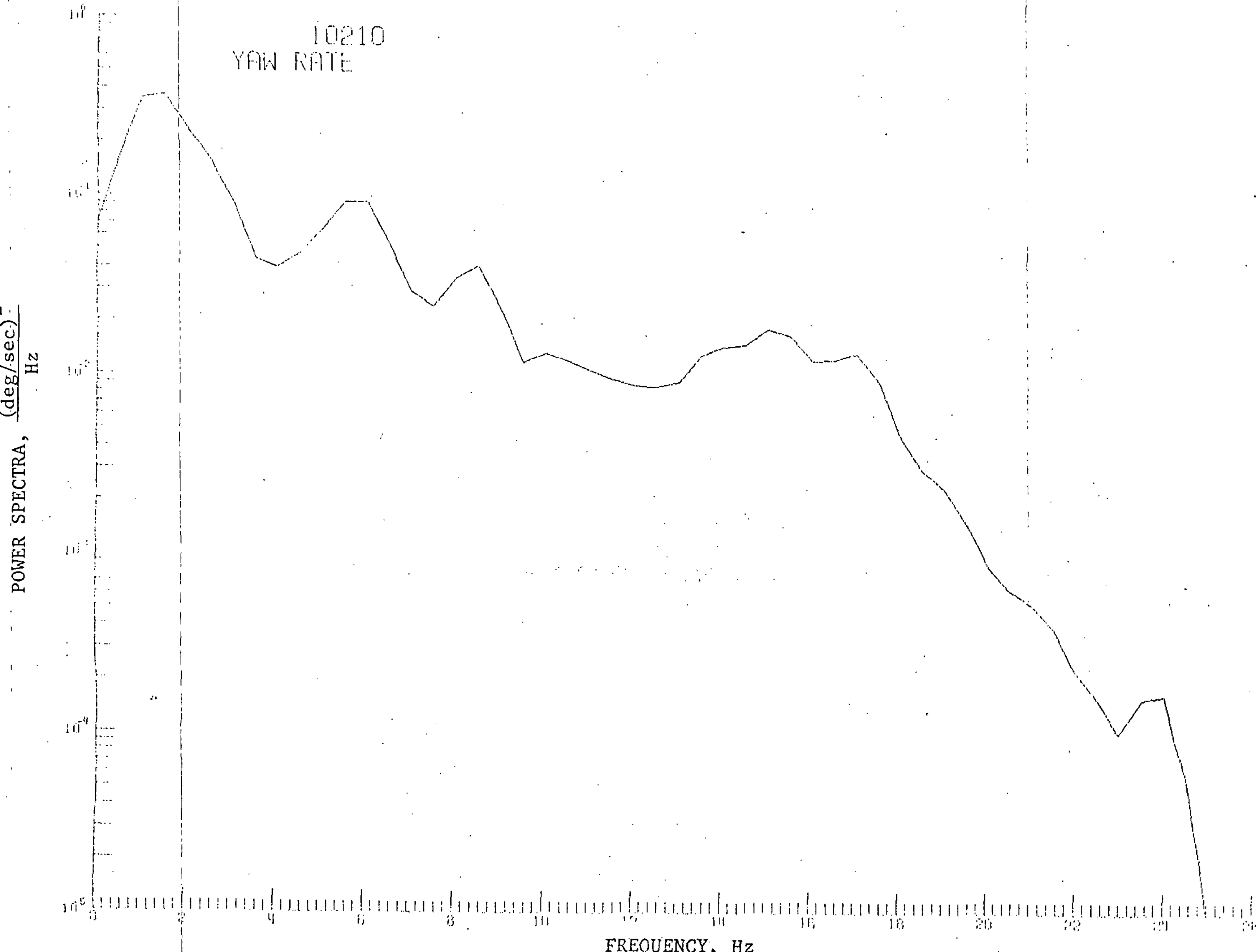
(b) Yawing velocity histograms (RMS yawing velocity 3.097 deg/sec)

Figure 6. Continued.



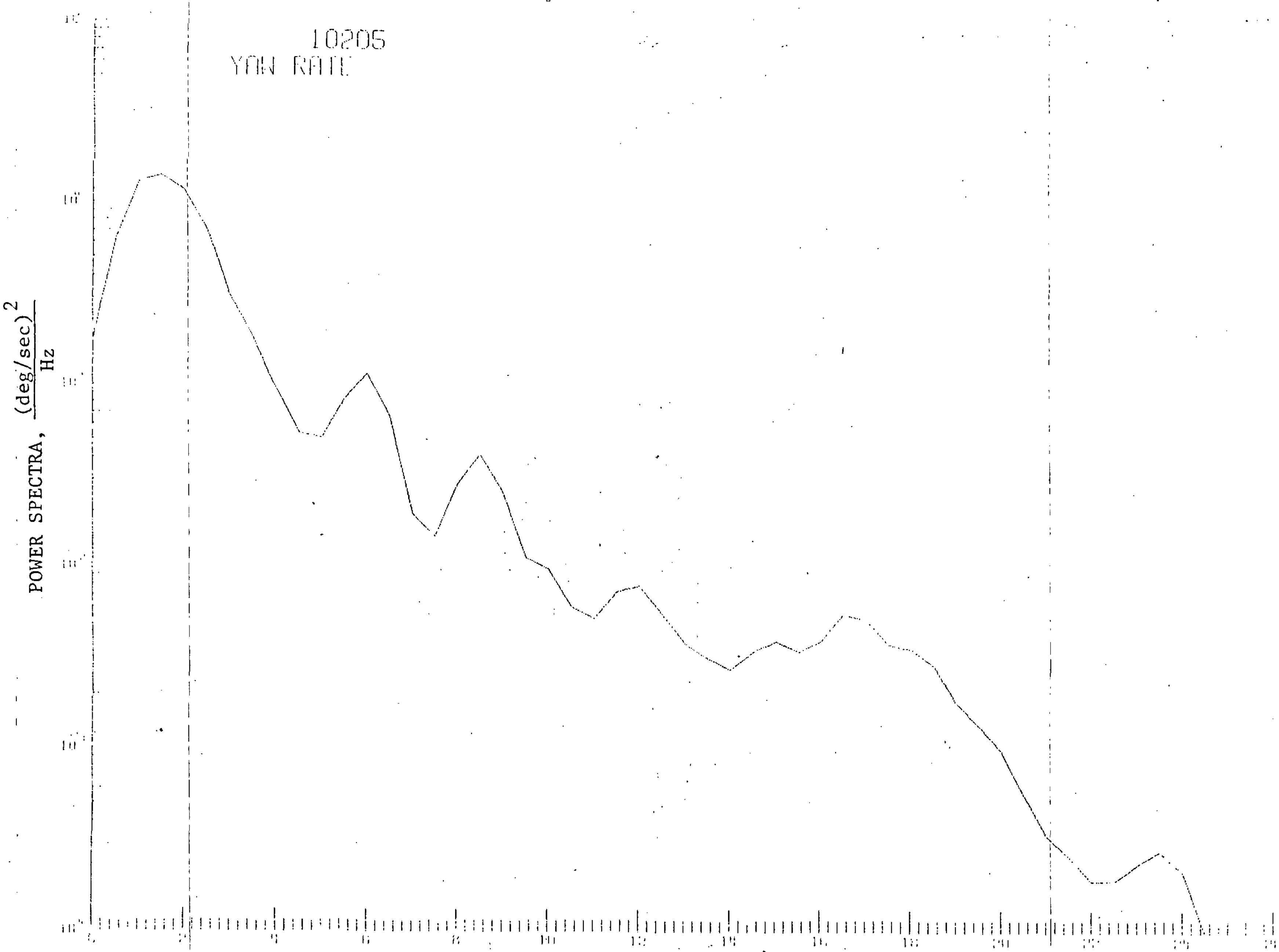
(c) Yawing velocity power spectrum (RMS yawing velocity 0.813 deg/sec)

Figure 6. Continued.



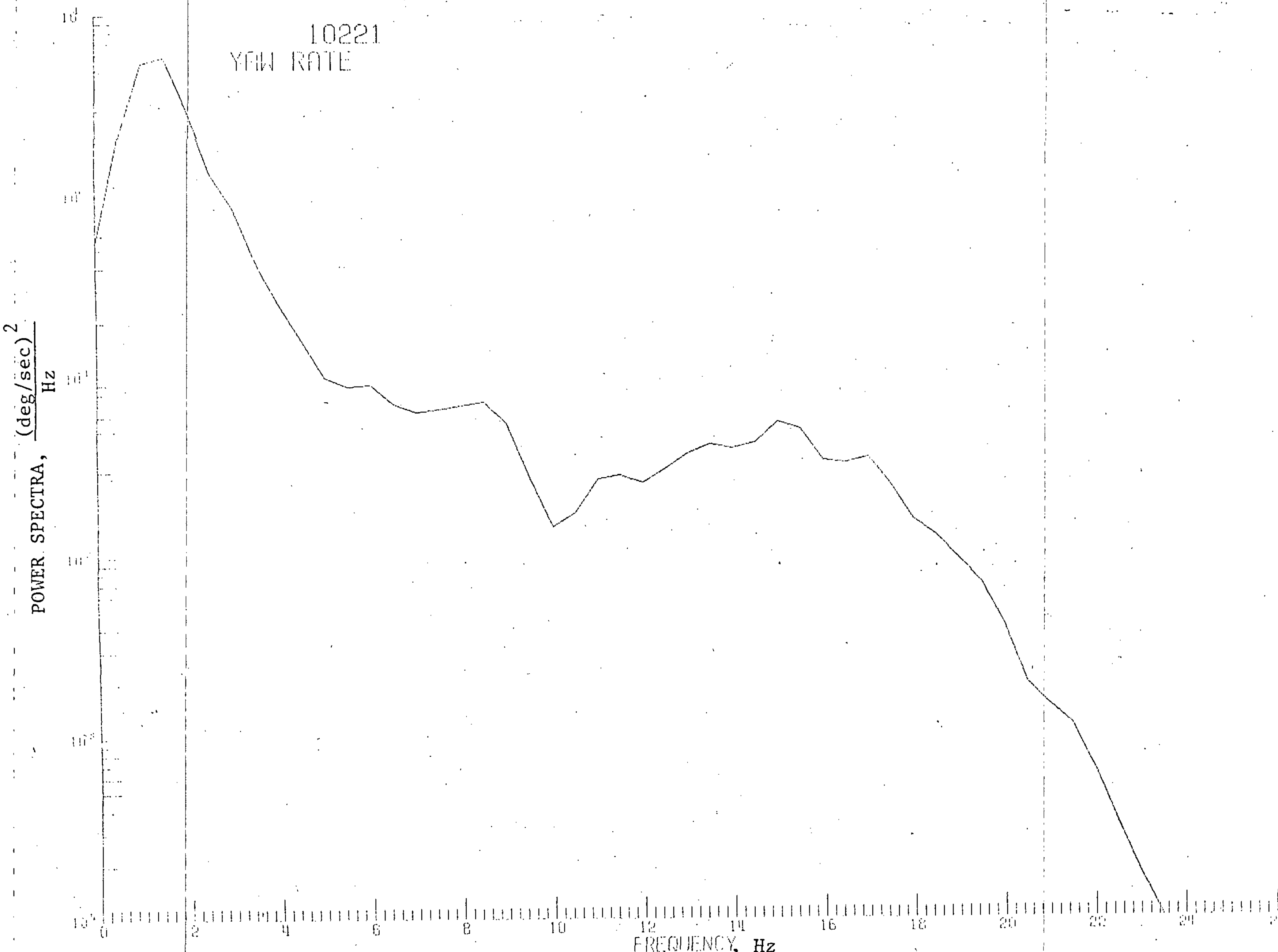
(c) Yawing velocity power spectrum (RMS yawing velocity 1.064 deg/sec)

Figure 6. Continued.



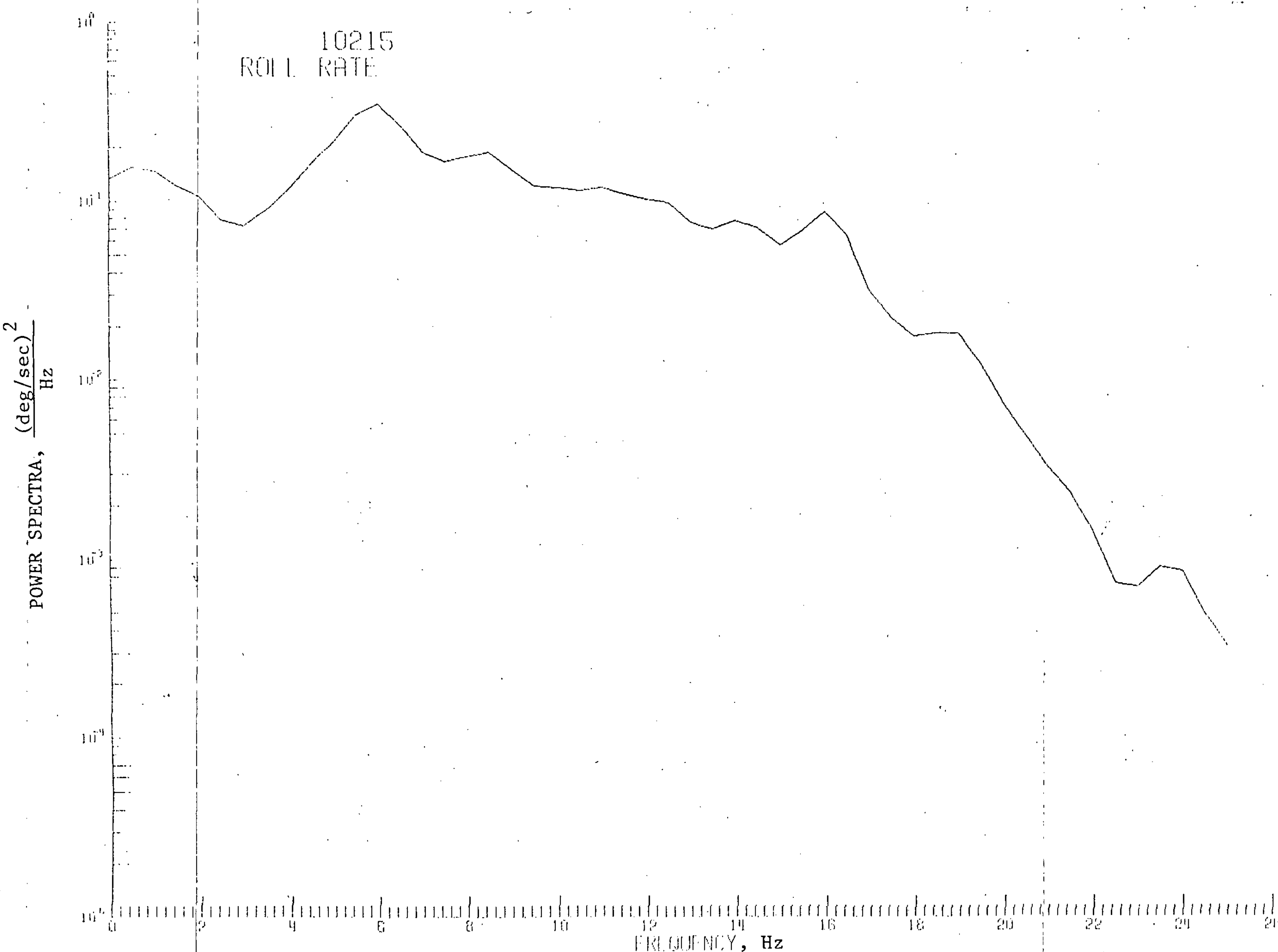
(c) Yawing velocity power spectrum (RMS yawing velocity 1.948 deg/sec)

Figure 6. Continued.



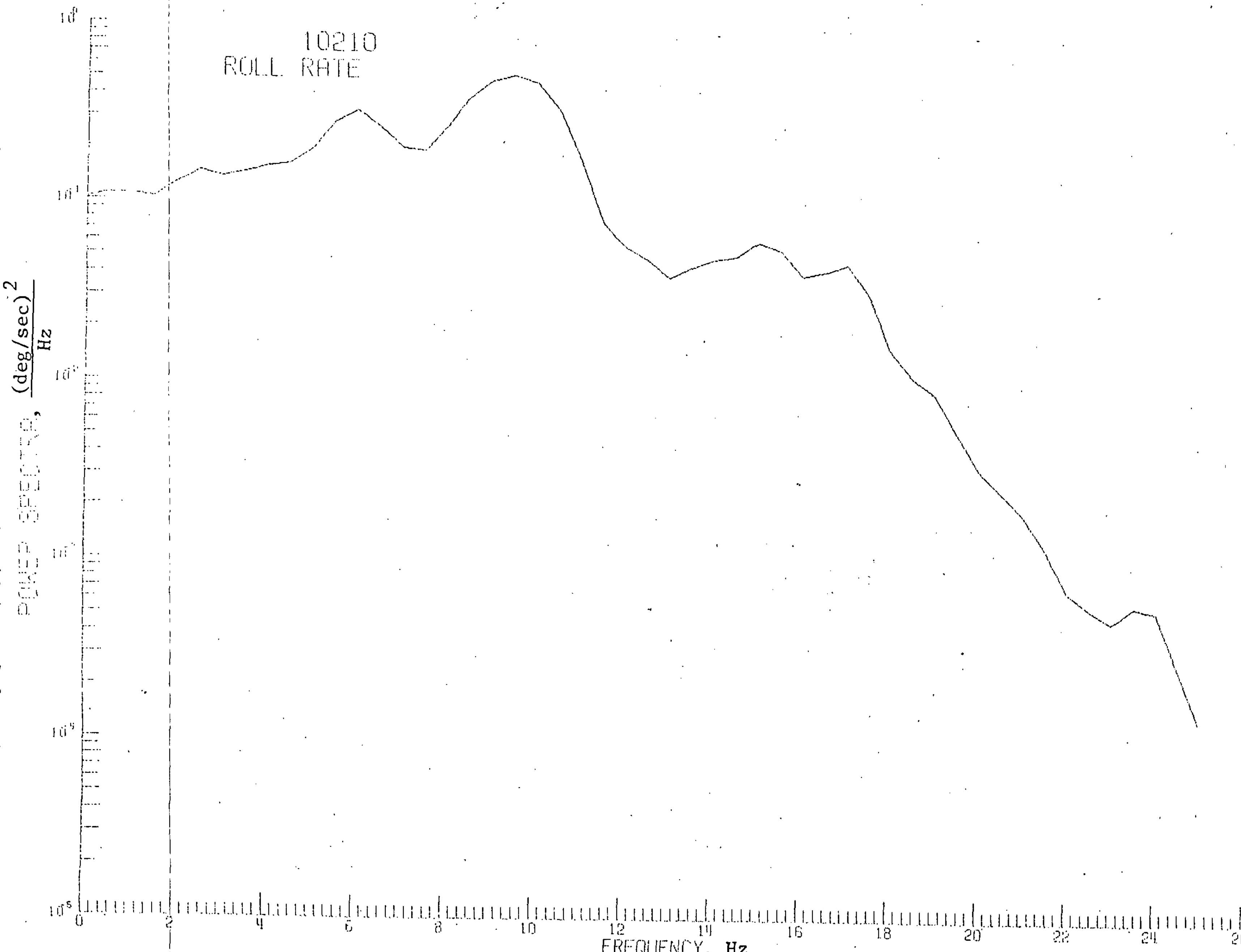
(c) Yawing velocity power spectrum (RMS yawing velocity 3.097 deg/sec)

Figure 6. Continued.



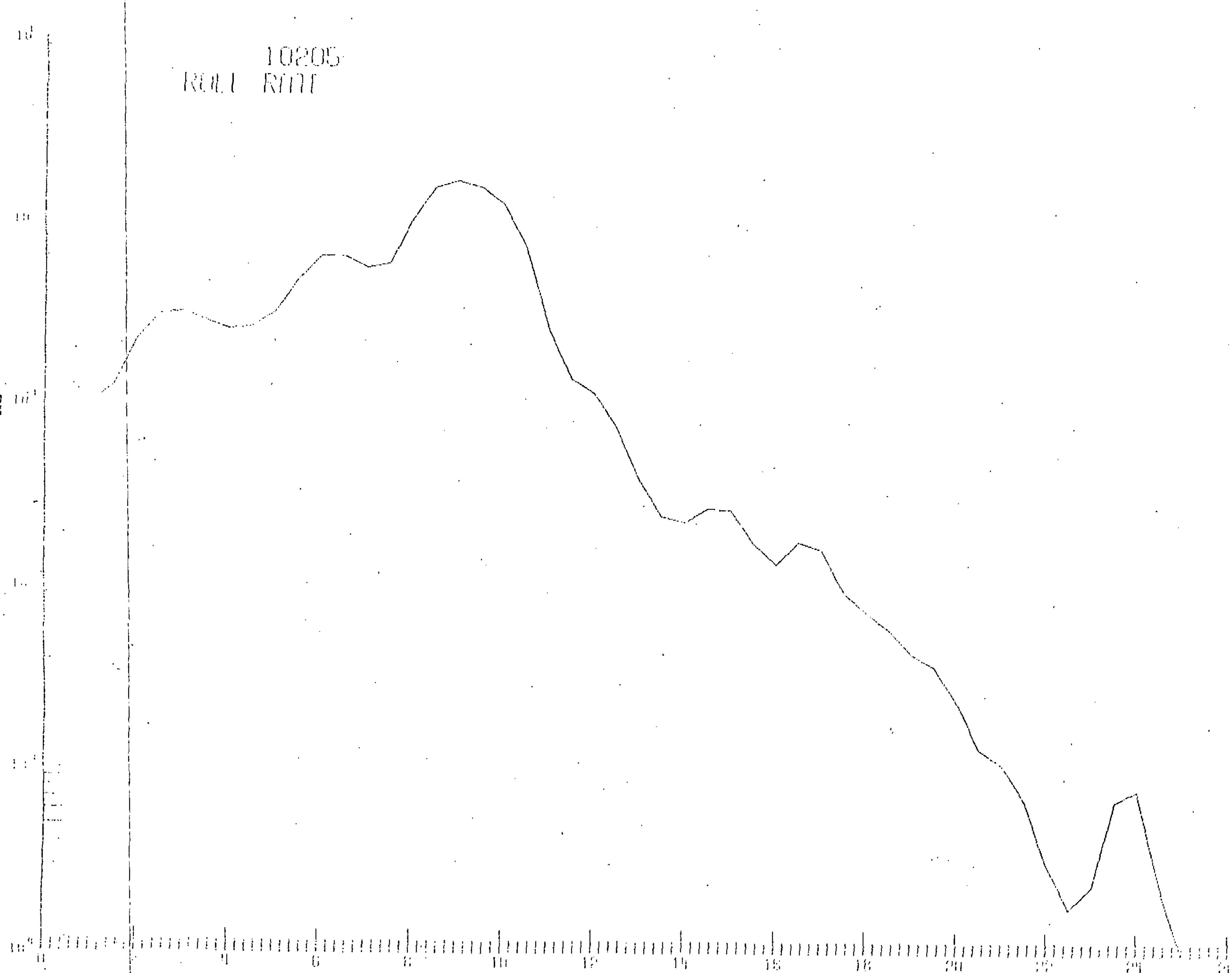
(d) Rolling velocity power spectrum (RMS rolling velocity 1.467 deg/sec)

Figure 6. Continued.



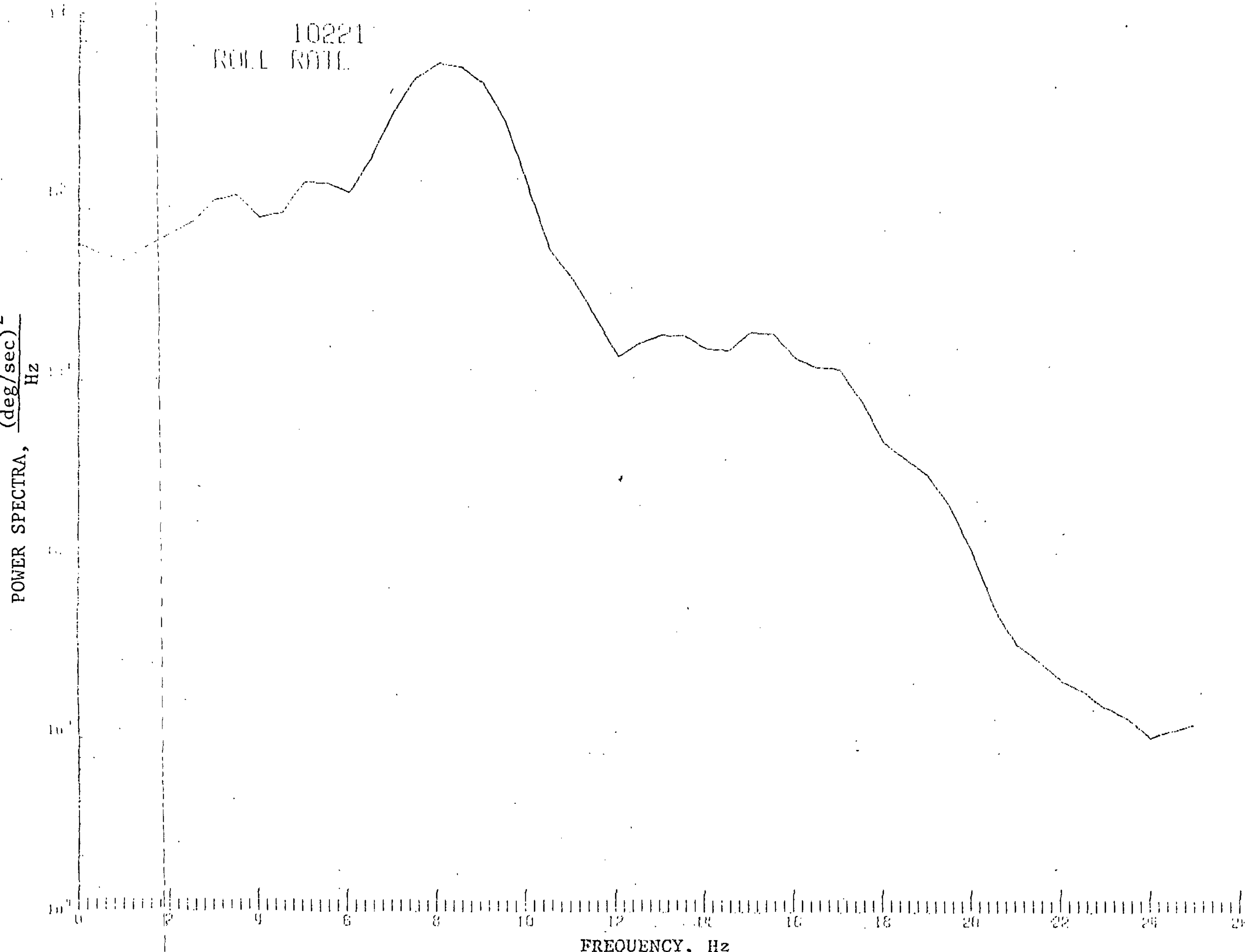
(d) Rolling velocity power spectrum (RMS rolling velocity 1.959 deg/sec)

Figure 6. Continued.



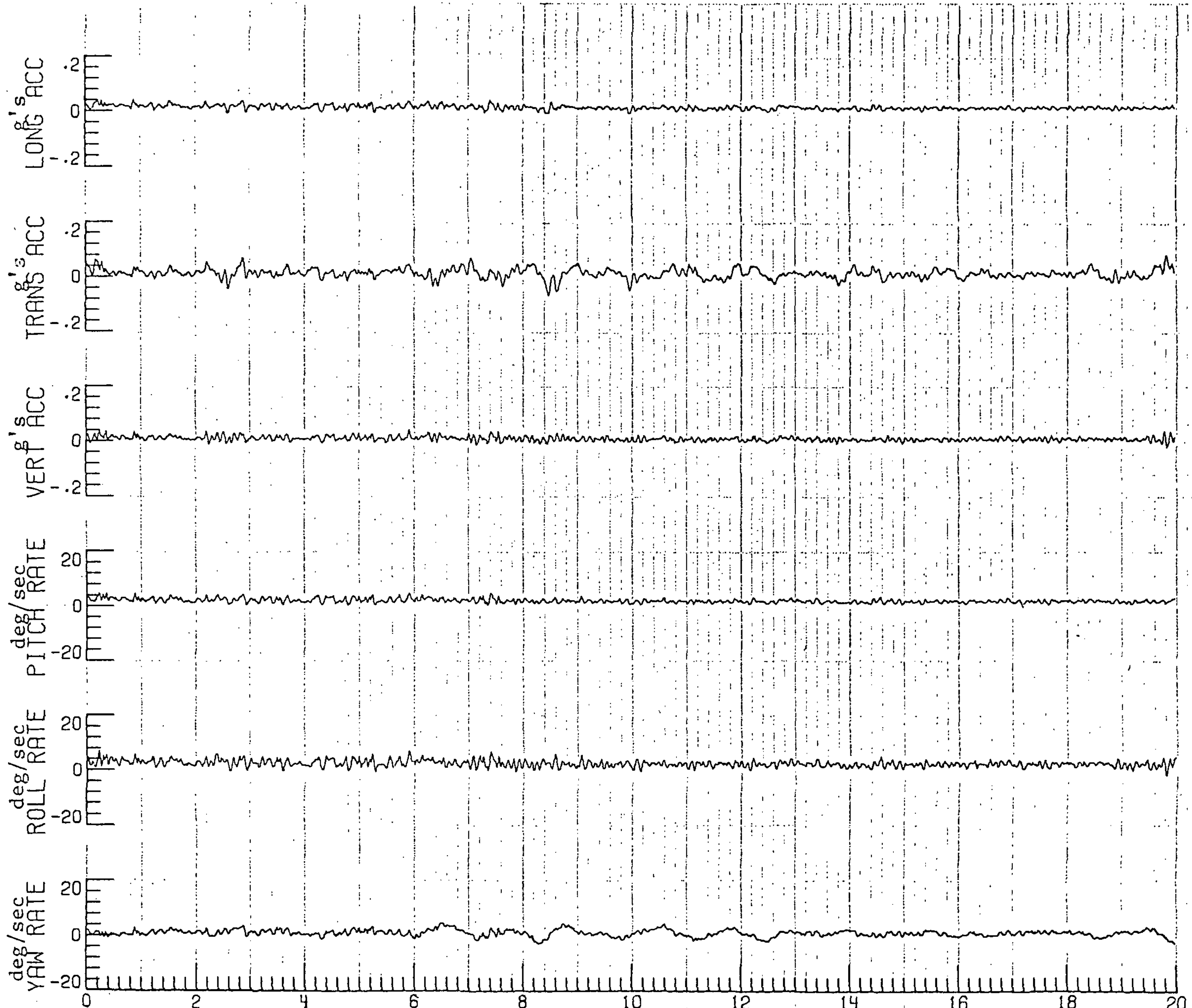
(d) Rolling velocity power spectrum (RMS rolling velocity 3.223 deg/sec)

Figure 6. Continued.



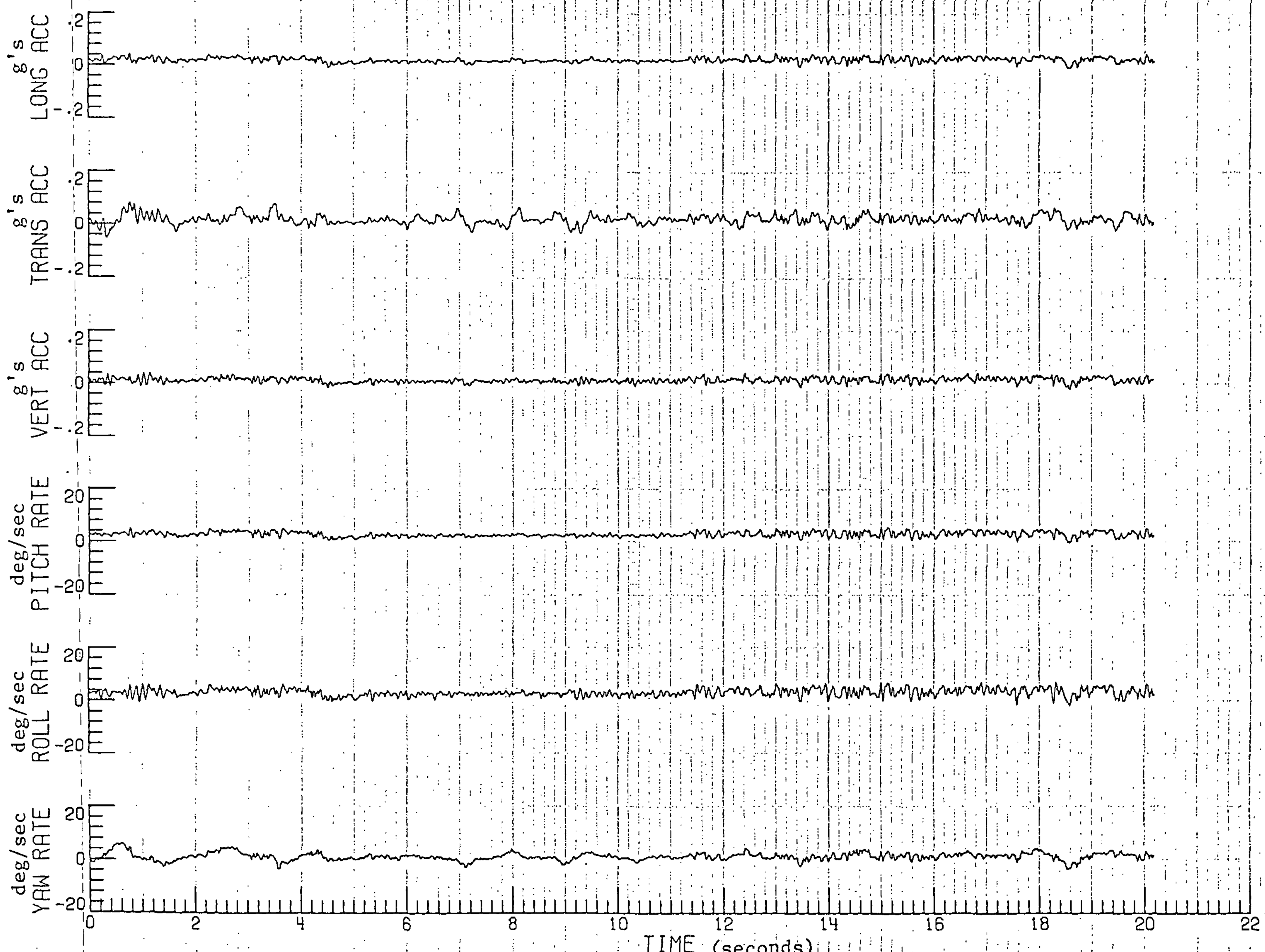
(d) Rolling velocity power spectrum (RMS rolling velocity 4.764 deg/sec)

Figure 6. Concluded.



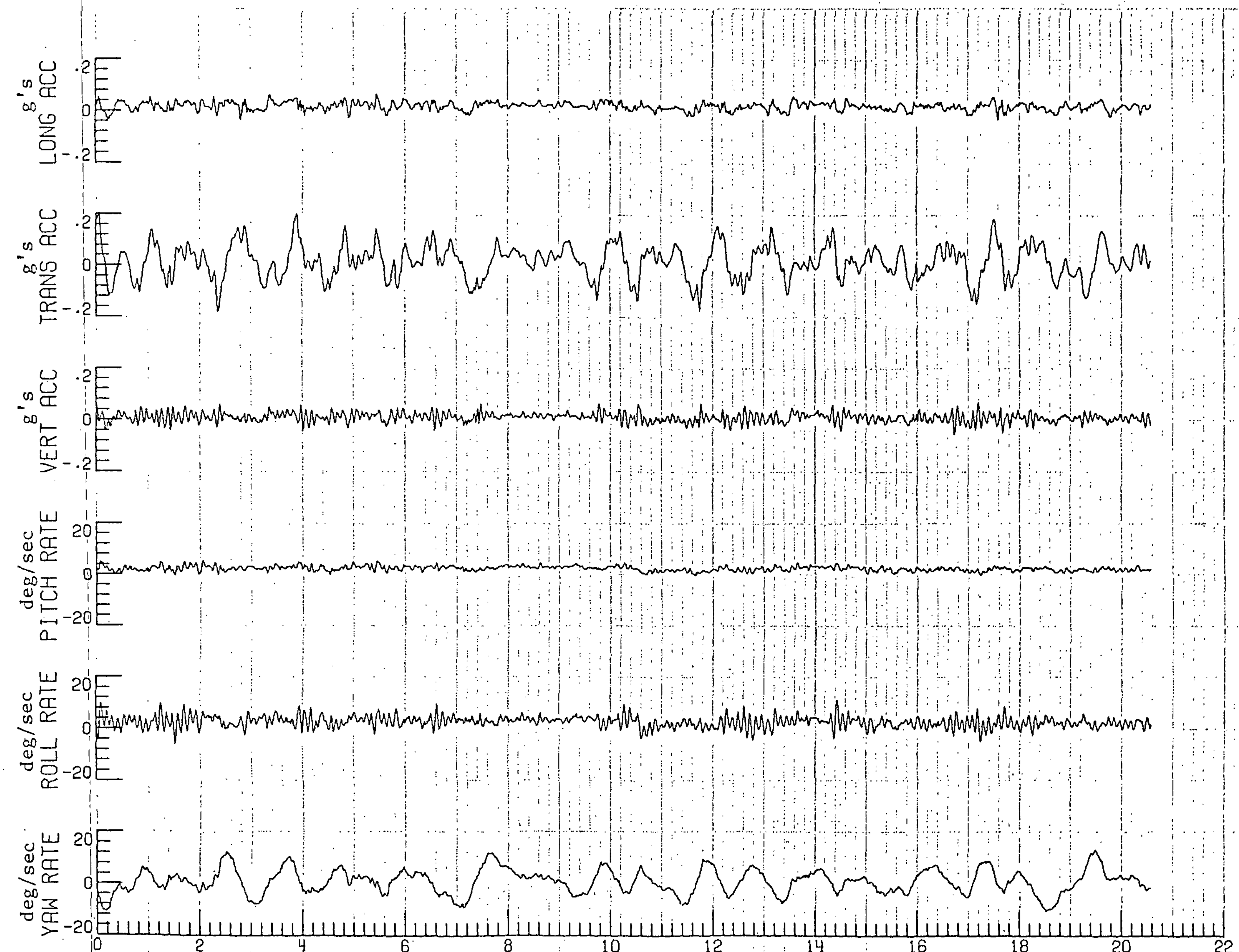
(a) Time histories (RMS yawing velocity 1.134 deg/sec)

Figure 7. MEASURED MOTION CHARACTERISTICS USING YAWING VELOCITIES WITH FLAT 0 - 1 HZ INPUTS



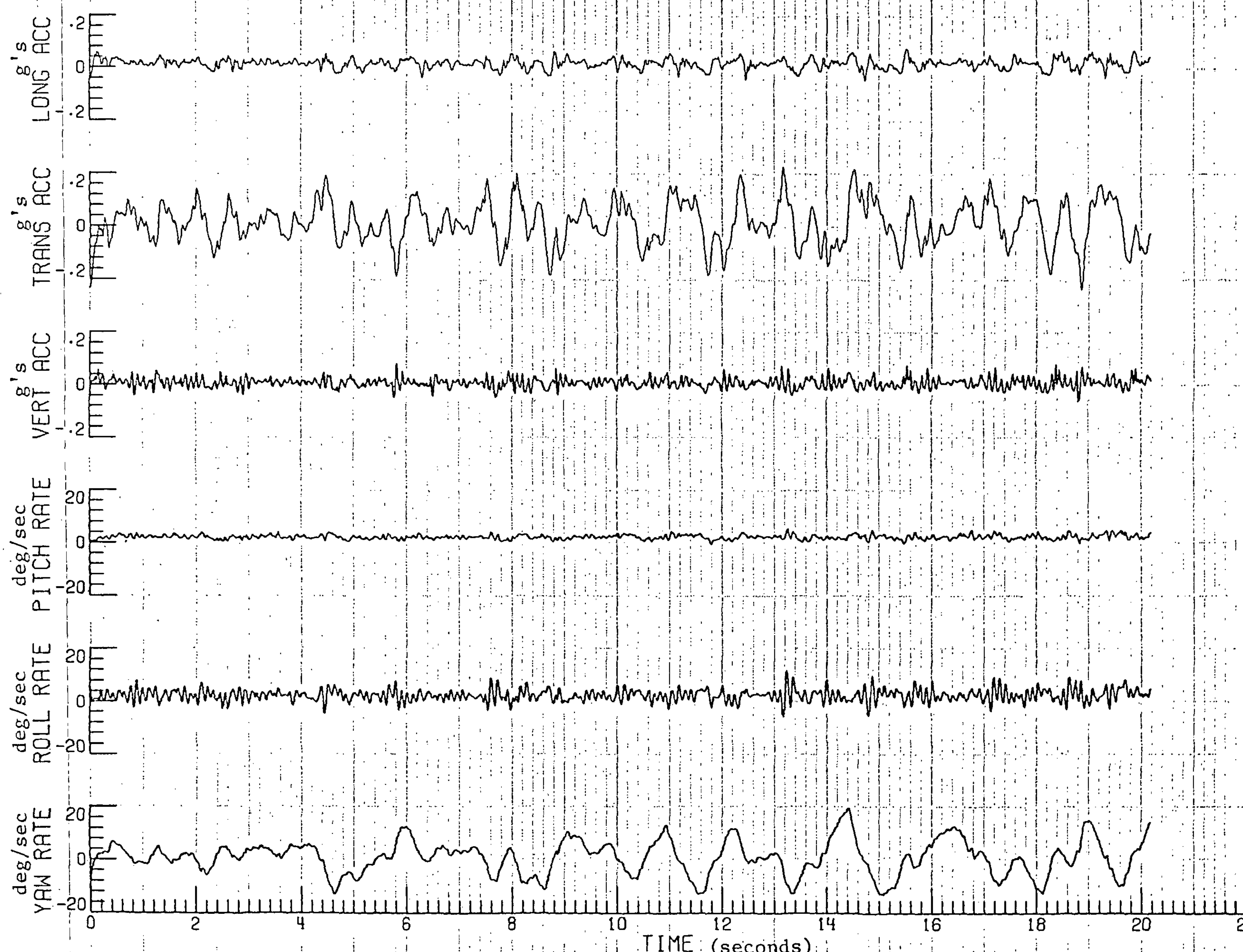
(a) Time histories (RMS yawing velocity 1.247 deg/sec)

Figure 7. Continued.



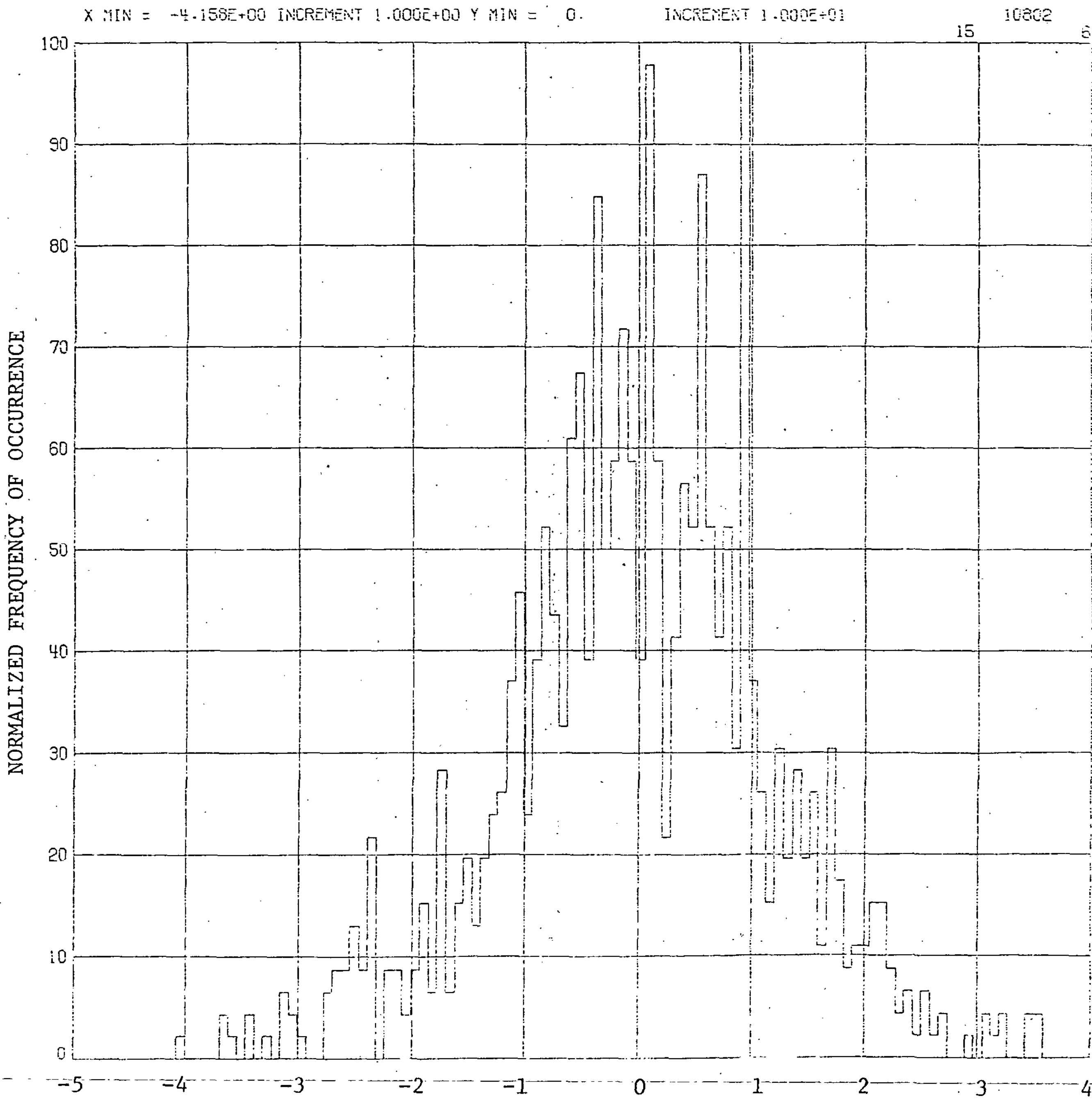
(a) Time histories (RMS yawing velocity 4.758 deg/sec)

Figure 7. Continued.



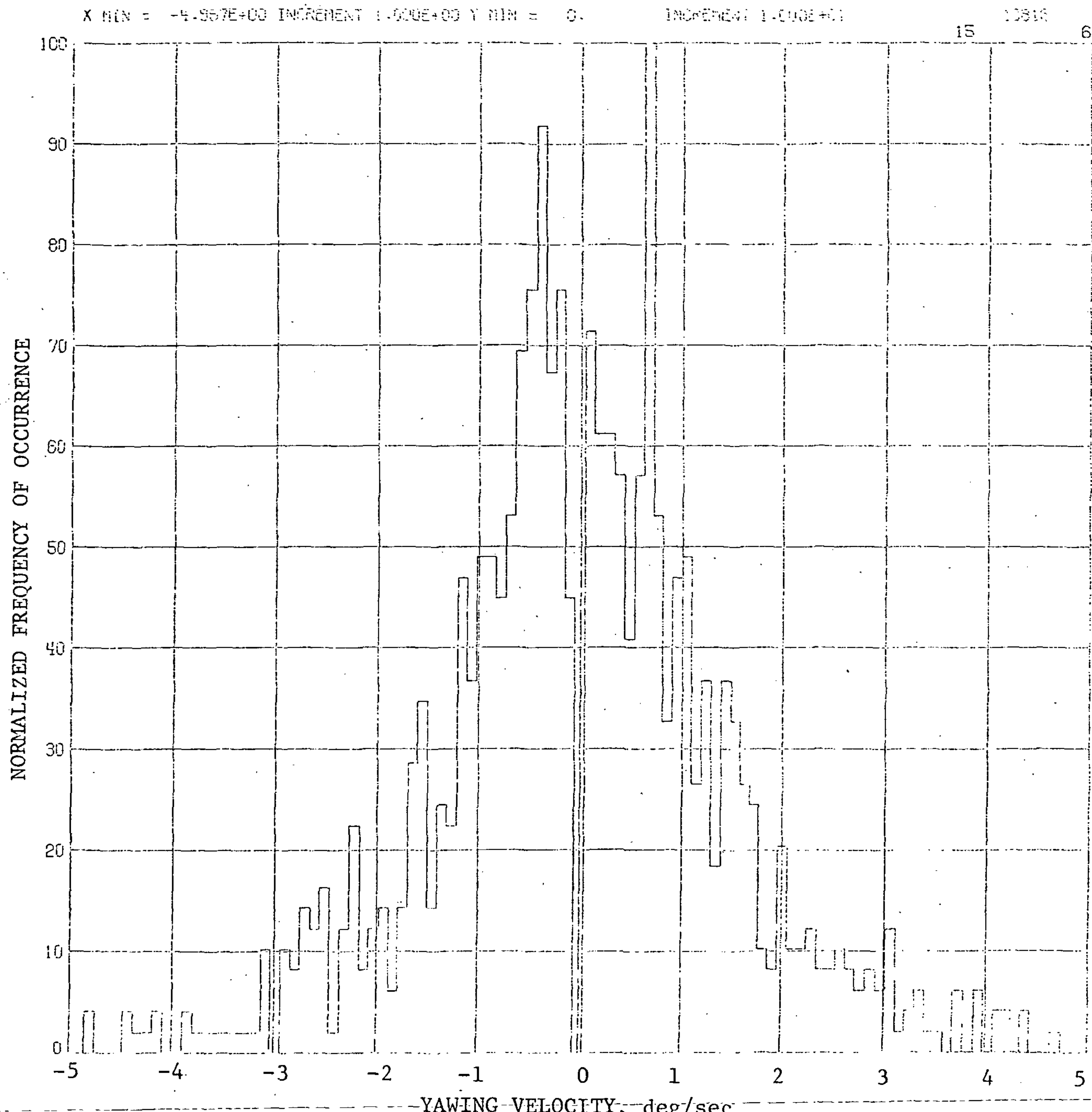
(a) Time histories (RMS yawing velocity 6.374 deg/sec)

Figure 7. Continued.



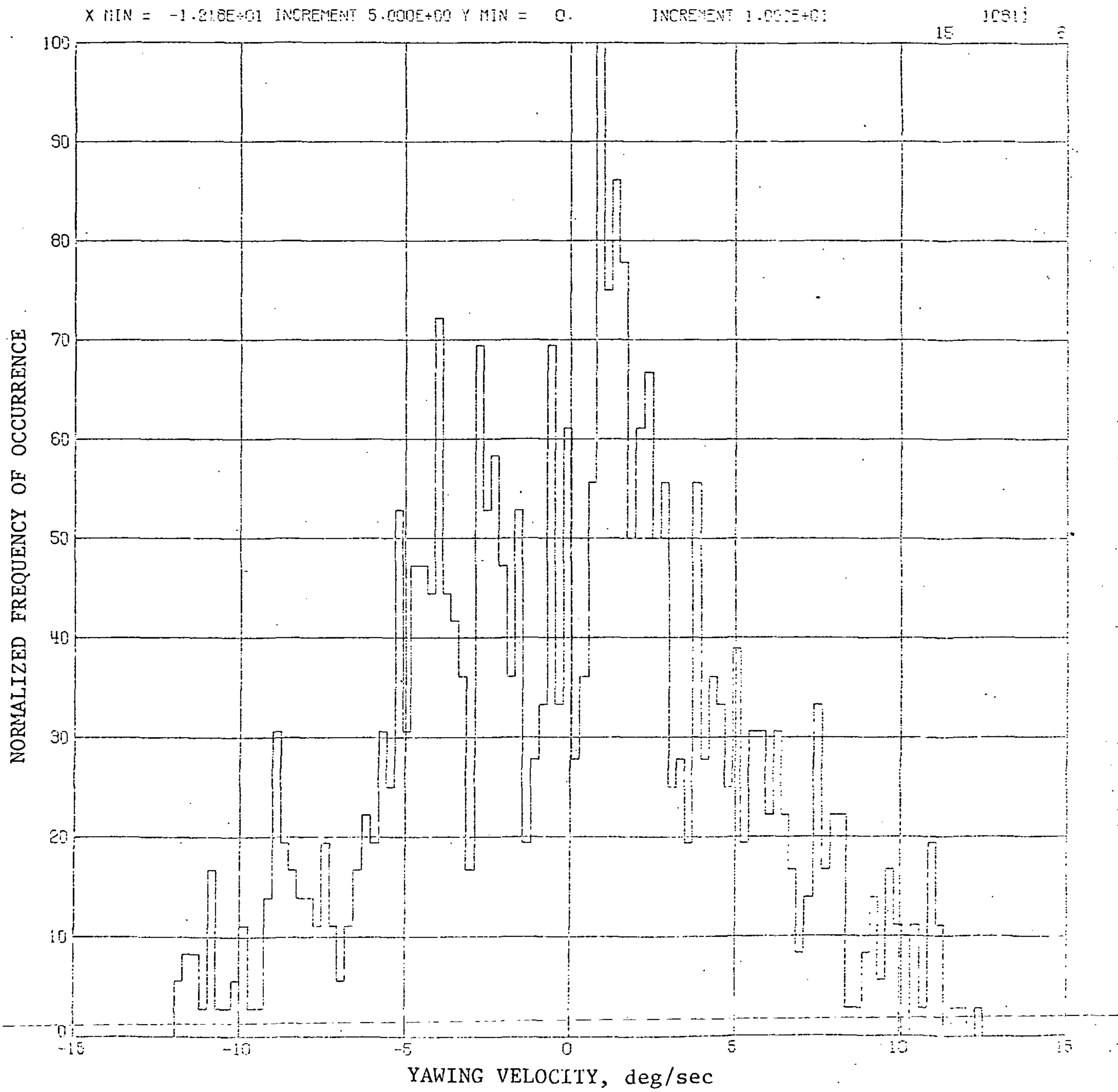
(b) Yawing velocity histograms (RMS yawing velocity 1.134 deg/sec)

Figure 7. Continued.



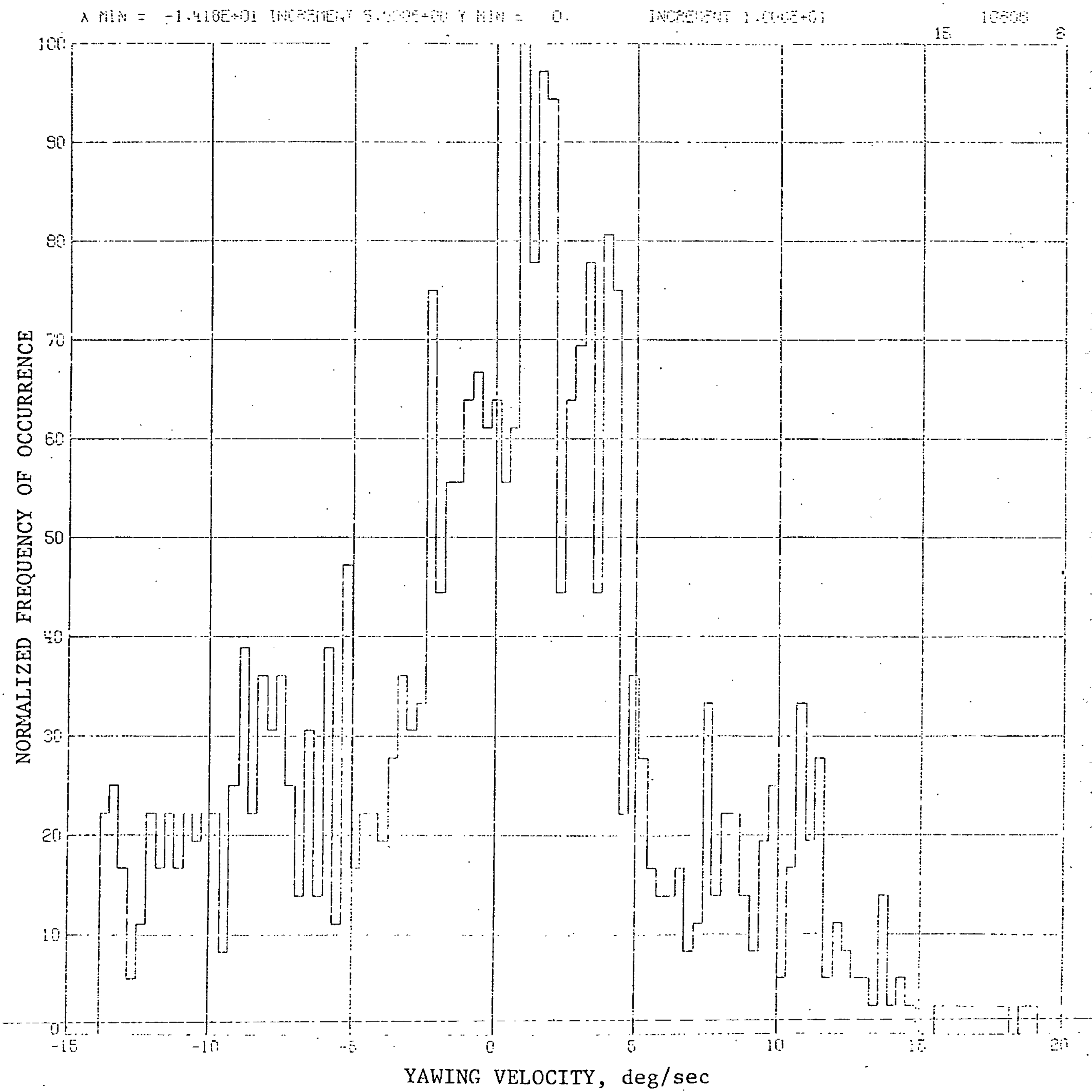
(b) Yawing velocity histograms (RMS yawing velocity 1.247 deg/sec)

Figure 7. Continued.



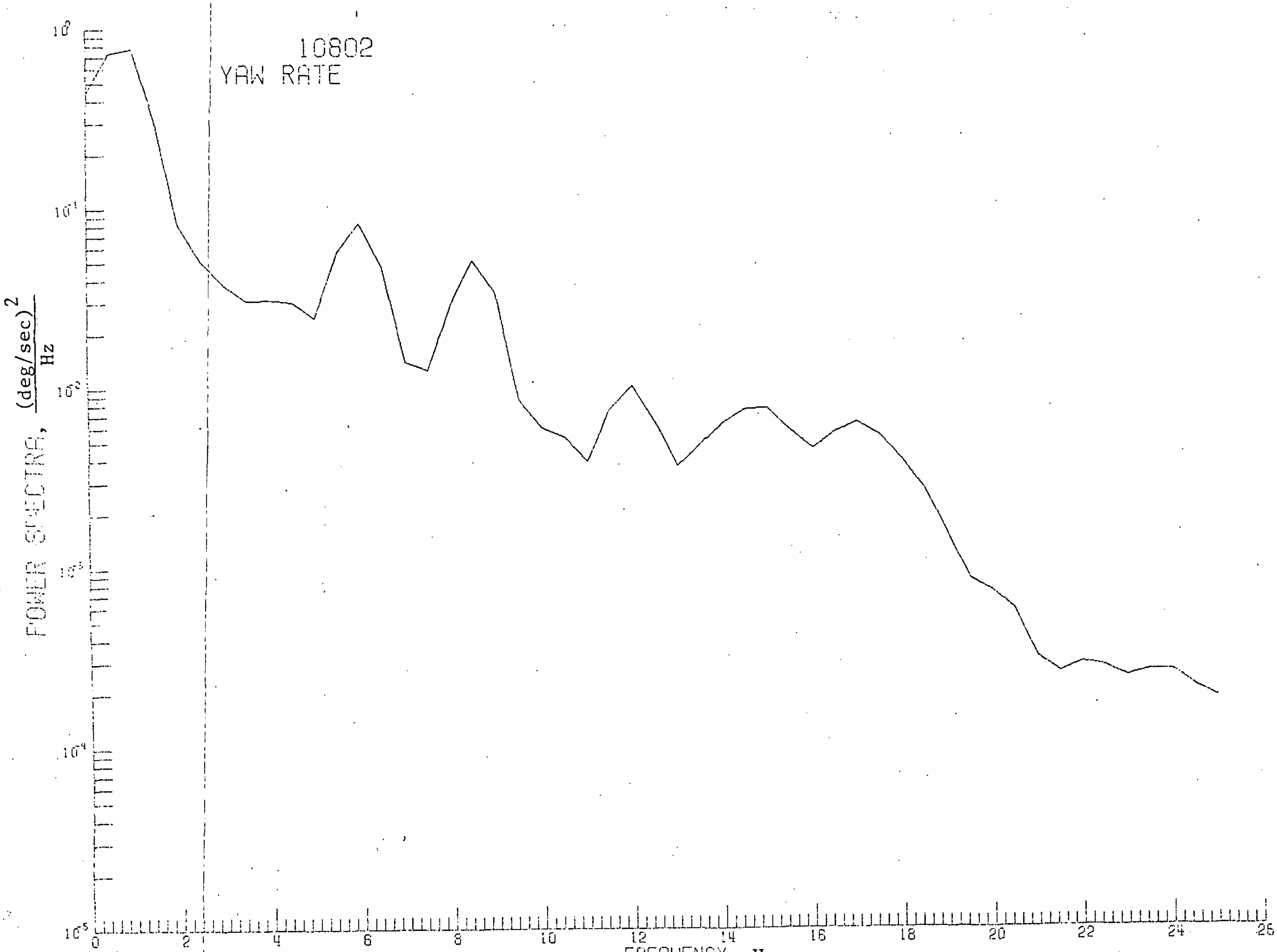
(b) Yawing velocity histograms (RMS yawing velocity 4.758 deg/sec)

Figure 7. Continued.



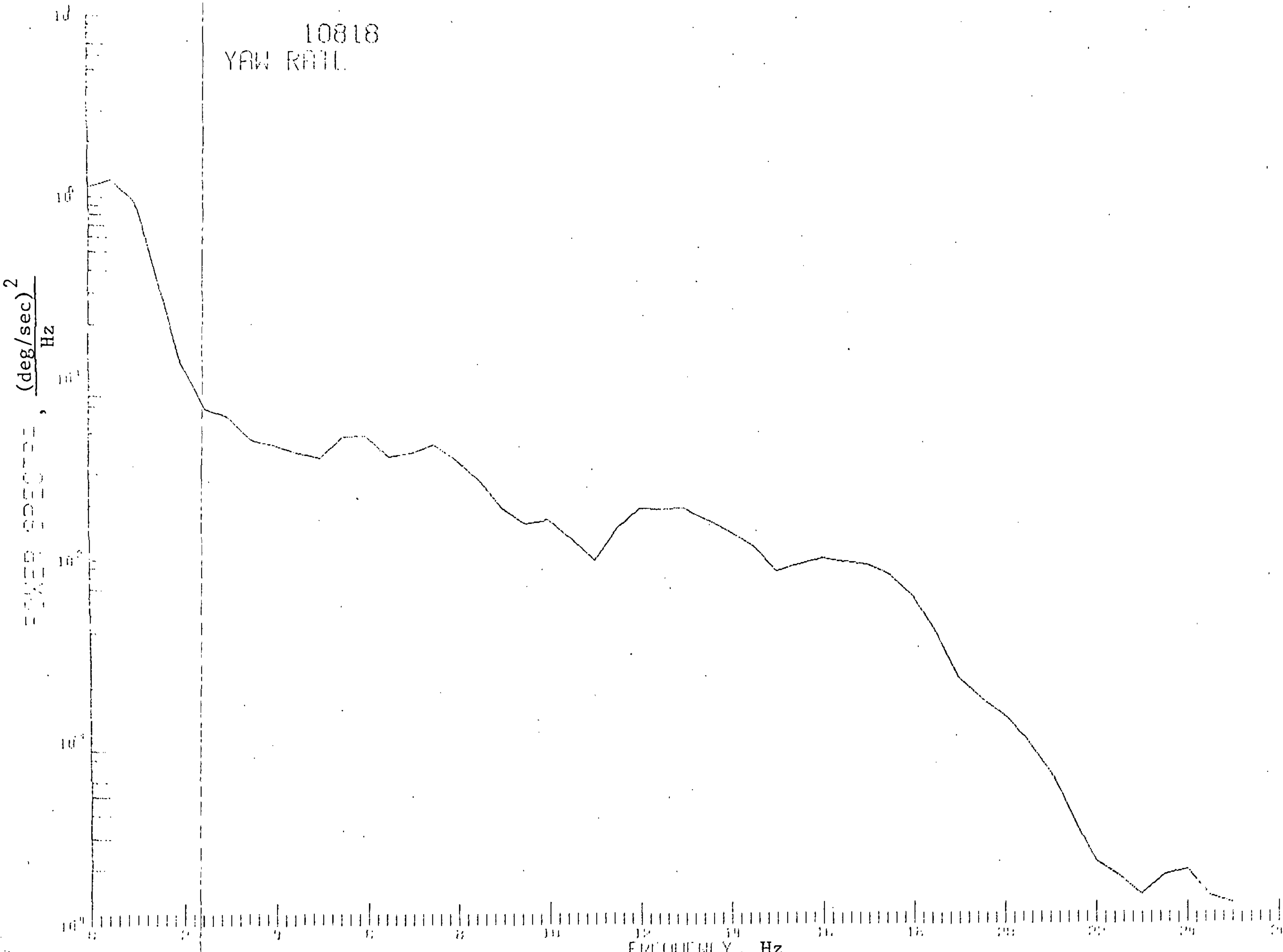
(b) Yawing velocity histograms (RMS yawing velocity 6.374 deg/sec)

Figure 7. Continued.



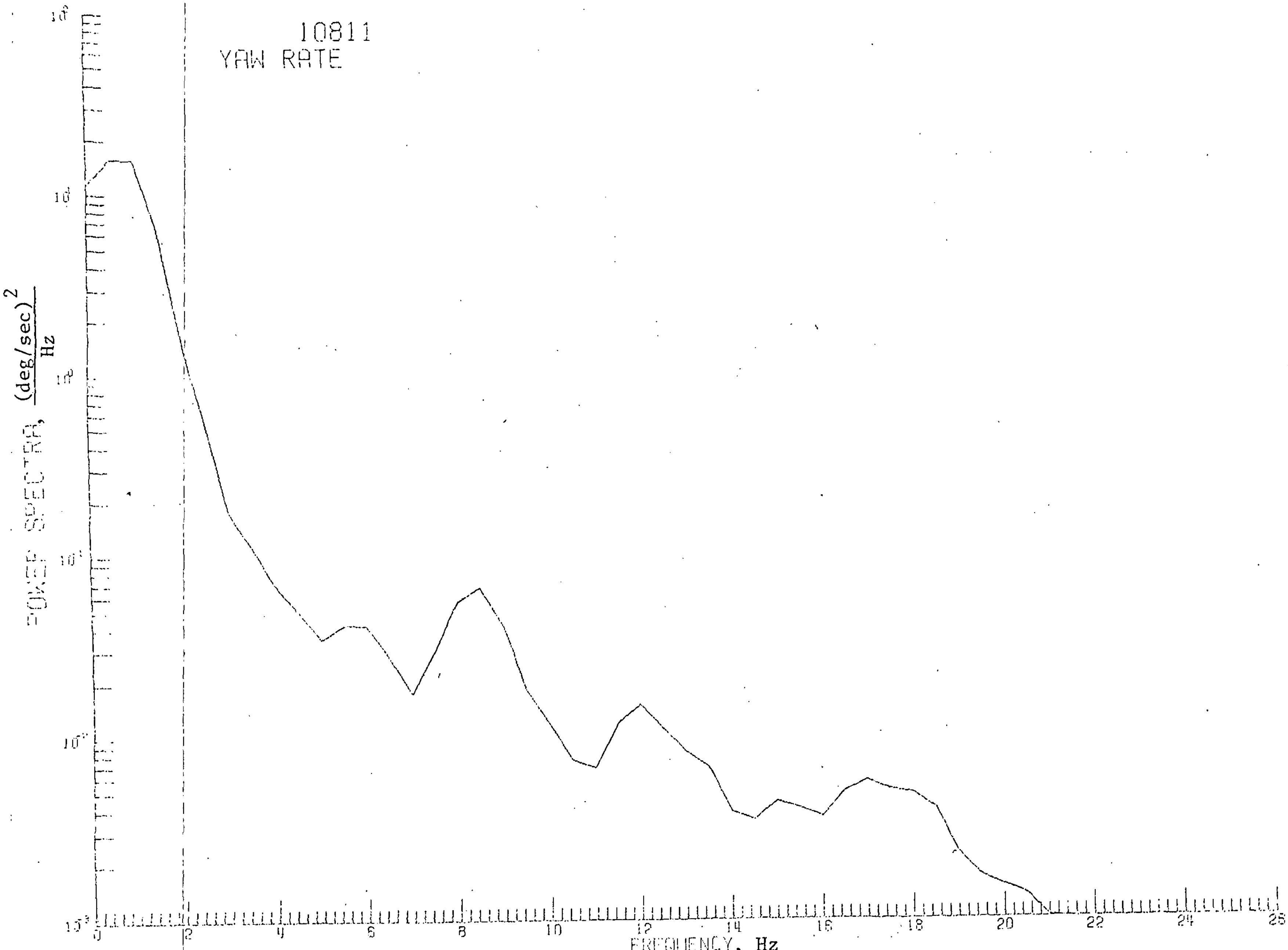
(c) Yawing velocity power spectrum (RMS yawing velocity 1.134 deg/sec)

Figure 7. Continued.



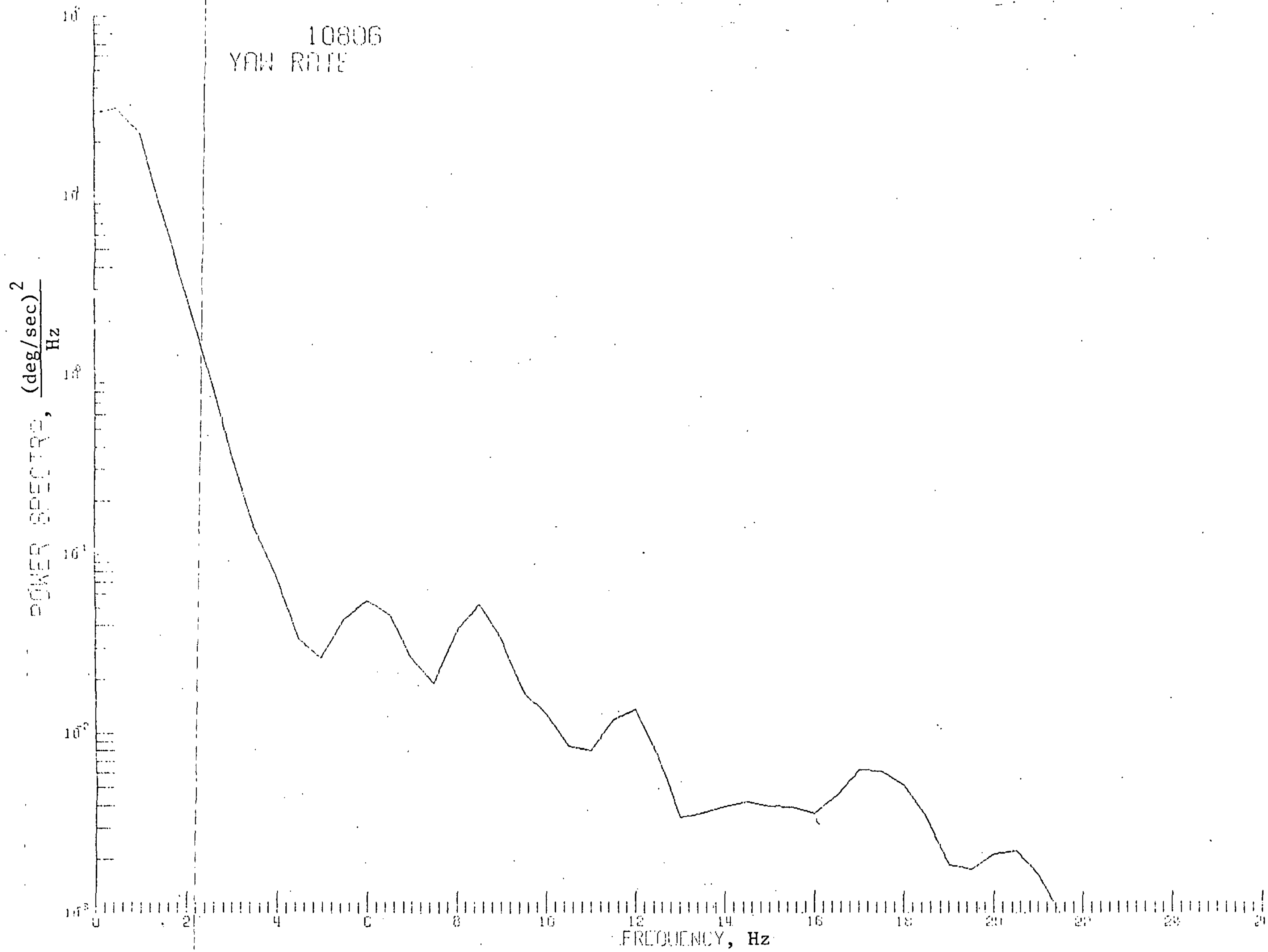
(c) Yawing velocity power spectrum (RMS yawing velocity 1.247 deg/sec)

Figure 7. Continued.



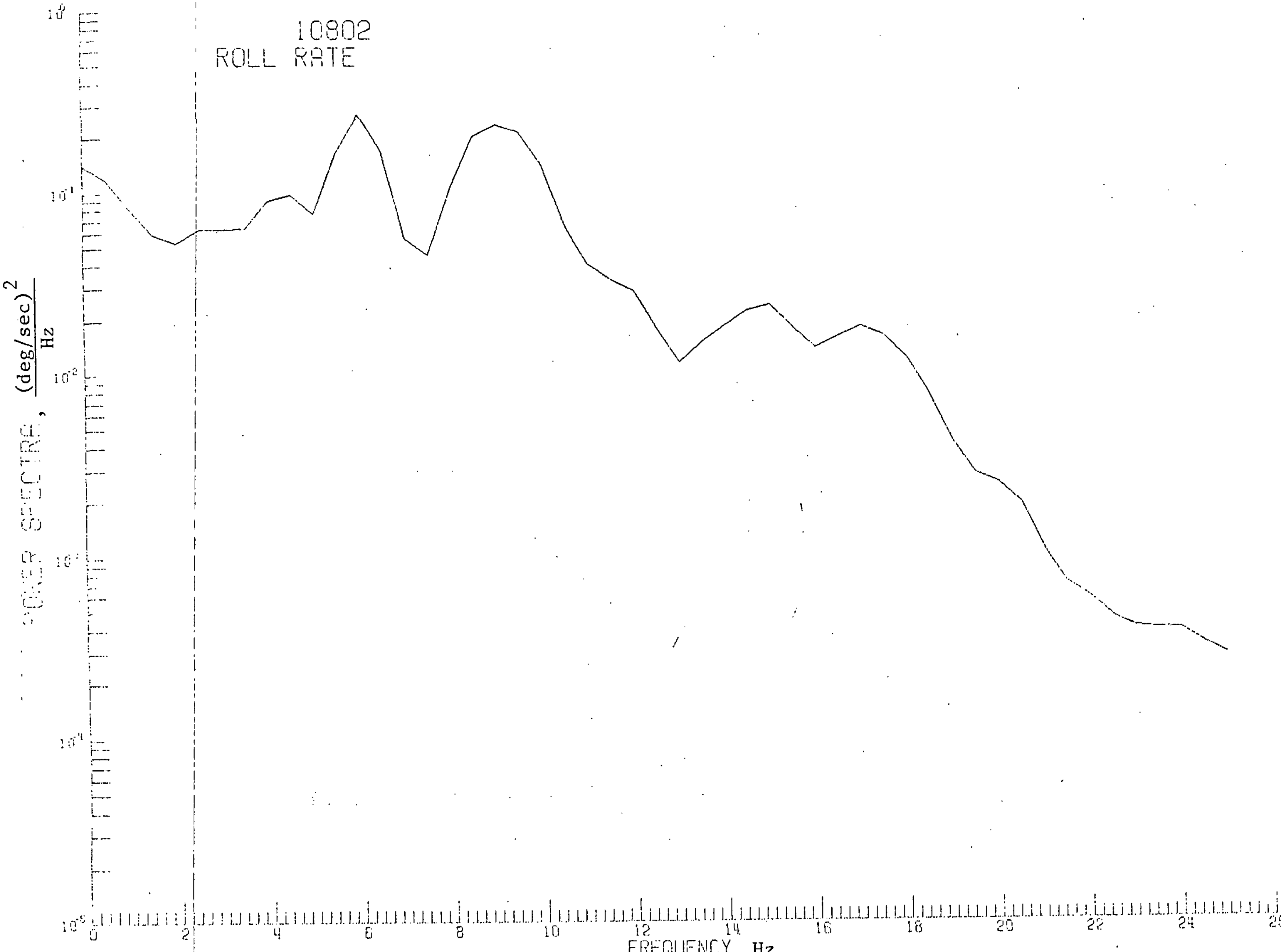
(c) Yawing velocity power spectrum (RMS yawing velocity 4.758 deg/sec)

Figure 7. Continued.



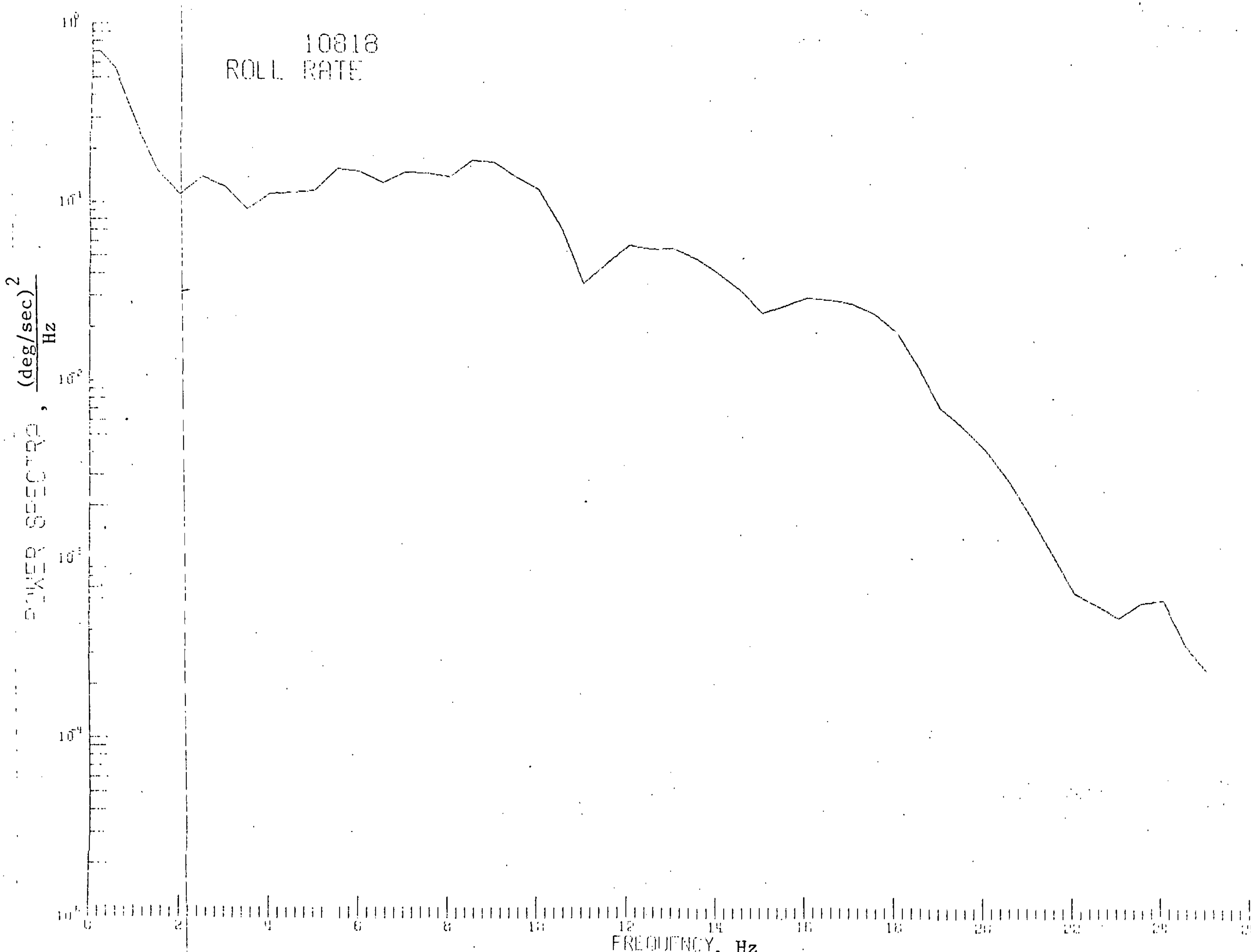
(c) Yawing velocity power spectrum (RMS yawing velocity 6.374 deg/sec)

Figure 7. Continued.



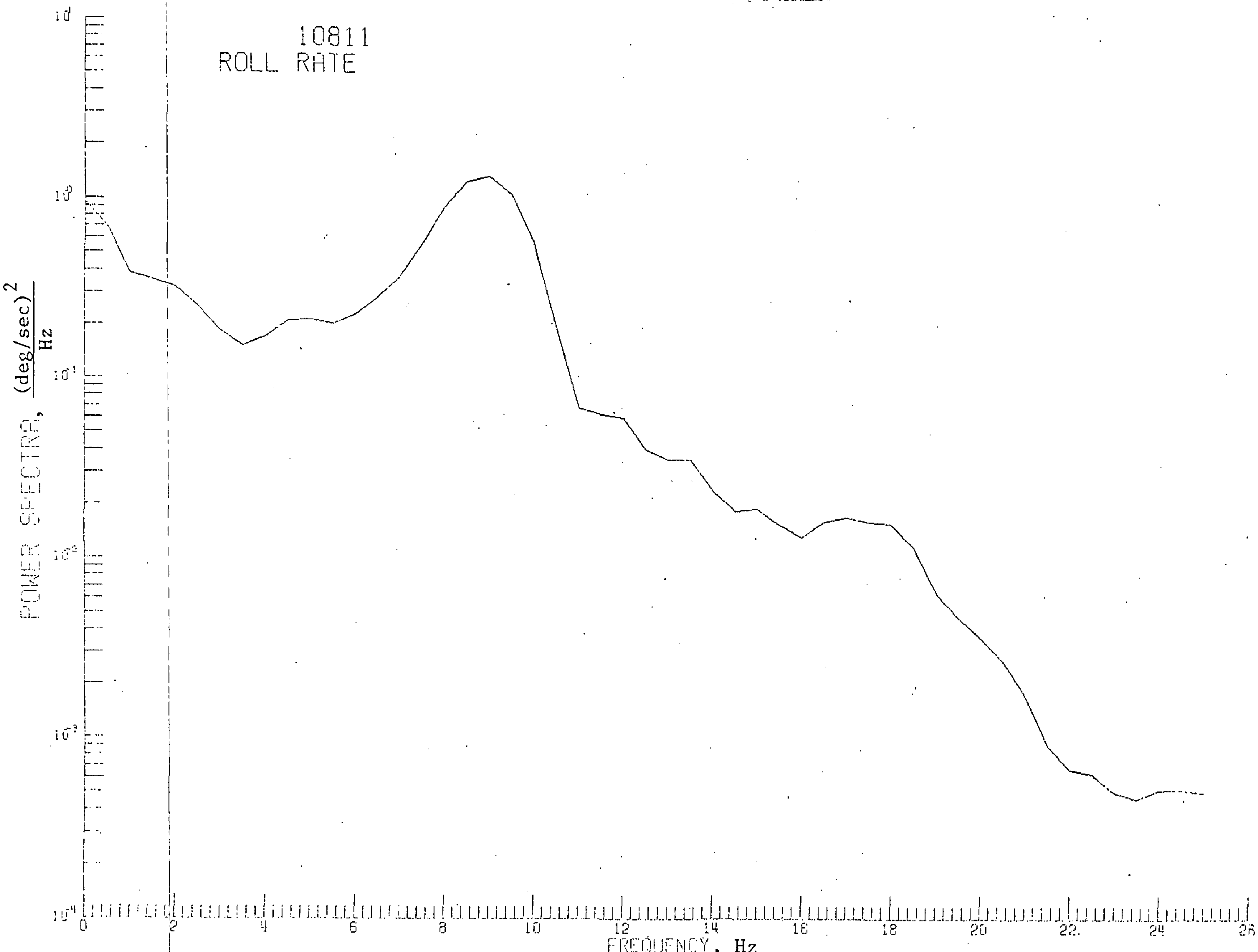
(d) Rolling velocity power spectrum (RMS rolling velocity 0.986 deg/sec)

Figure 7. Continued.



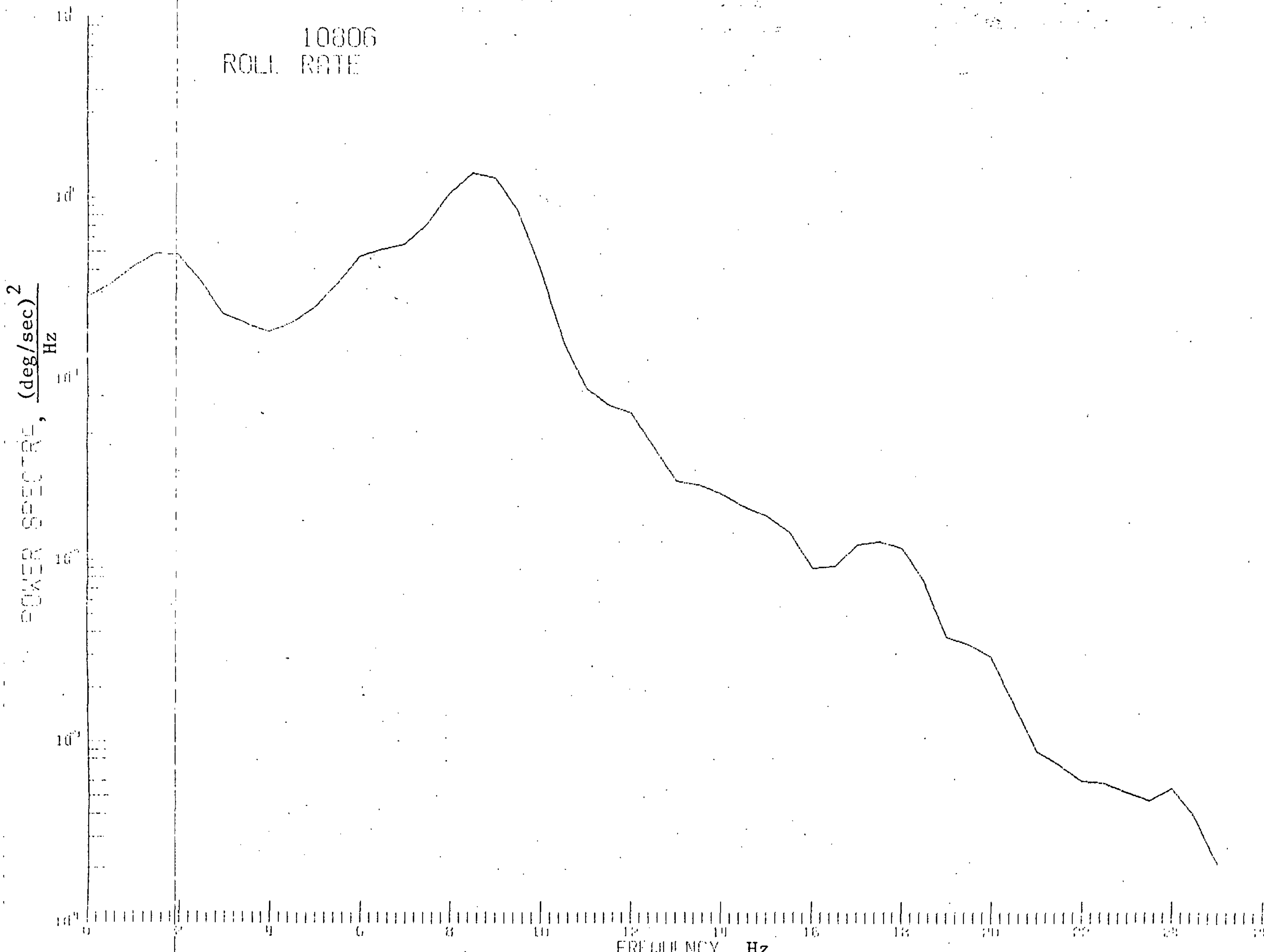
(d) Rolling velocity power spectrum (RMS rolling velocity 1.206 deg/sec)

Figure 7. Continued.



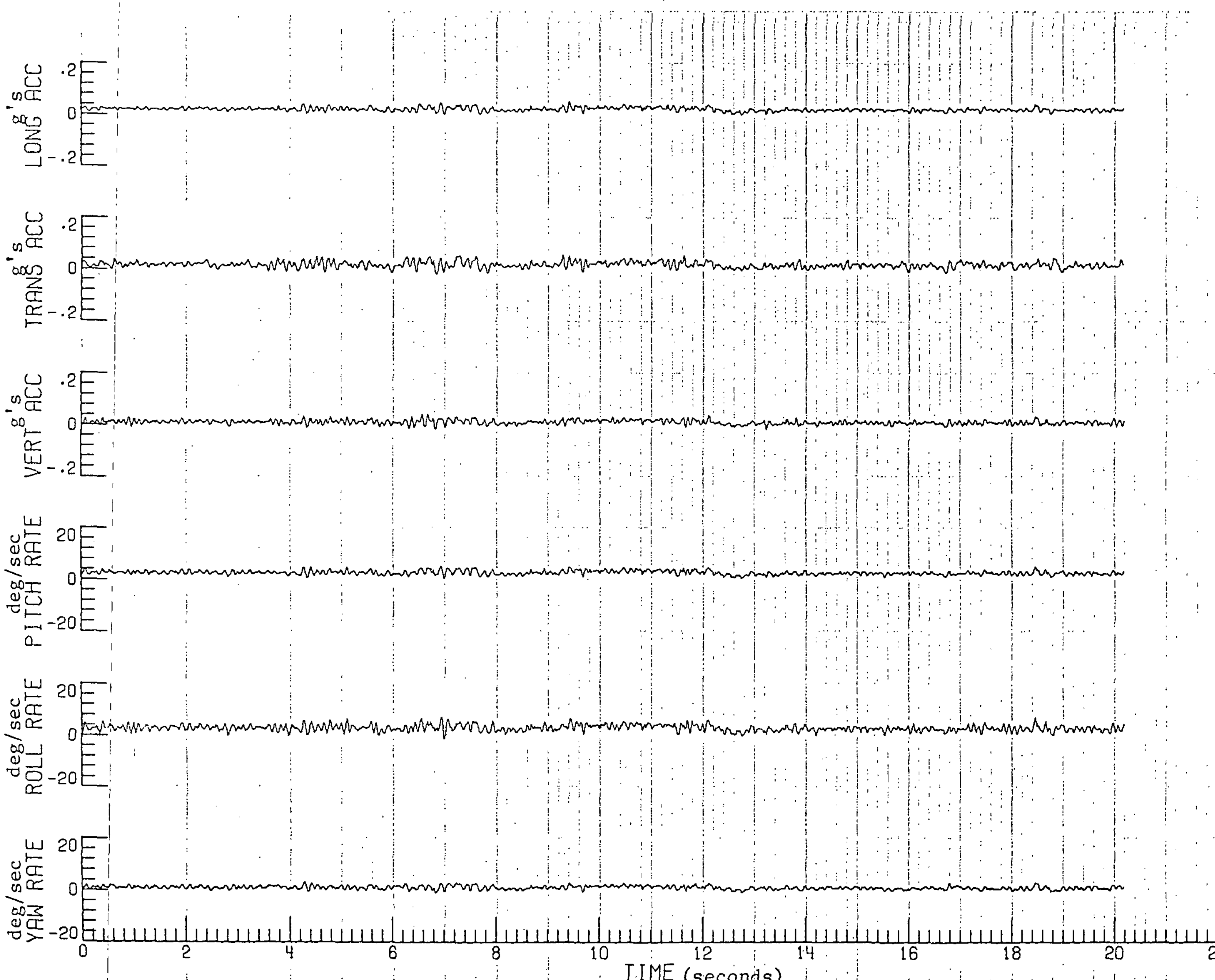
(d) Rolling velocity power spectrum (RMS rolling velocity 2.120 deg/sec)

Figure 7. Continued.



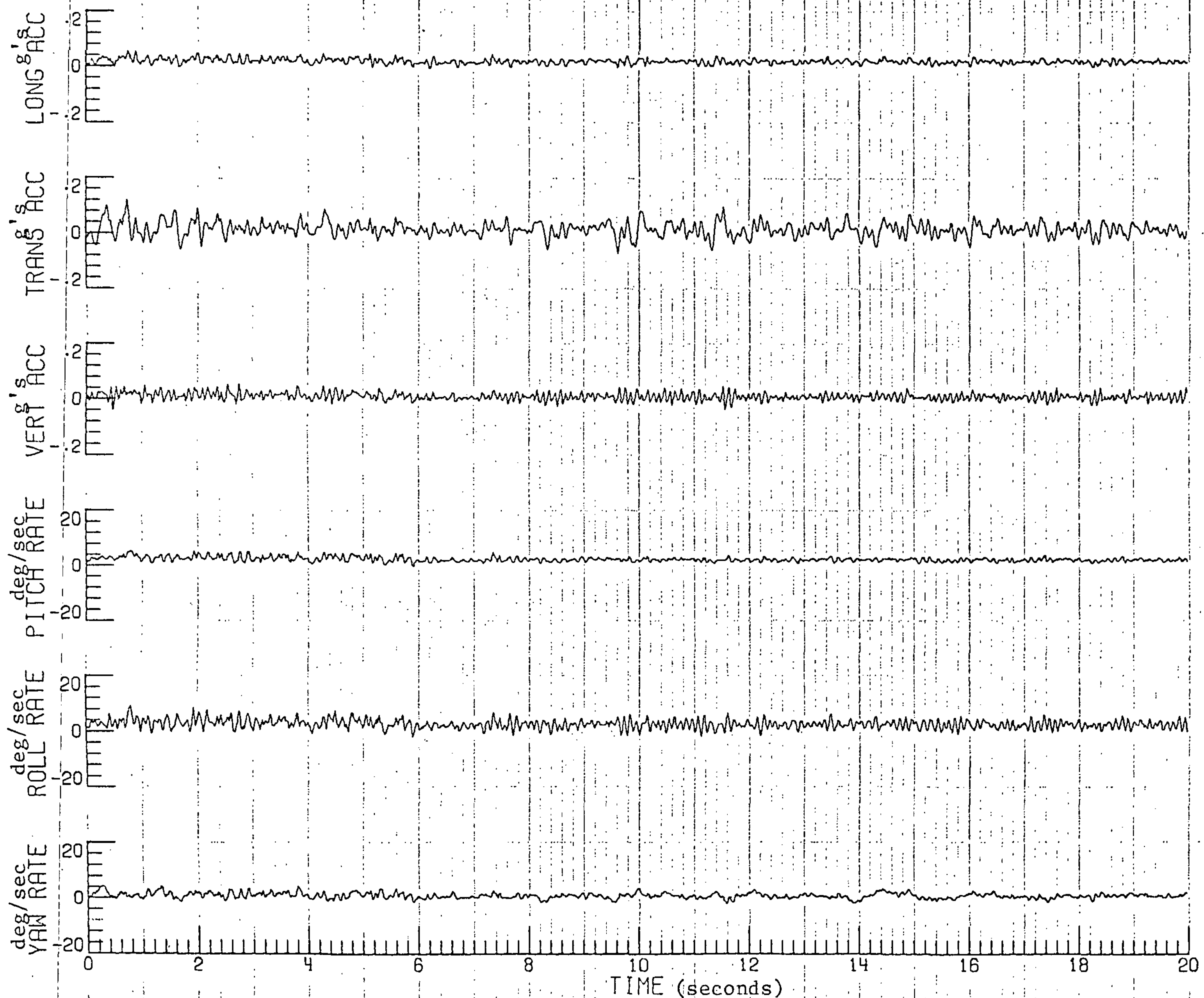
(d) Rolling velocity power spectrum (RMS rolling velocity 2.213 deg/sec)

Figure 7. Concluded.



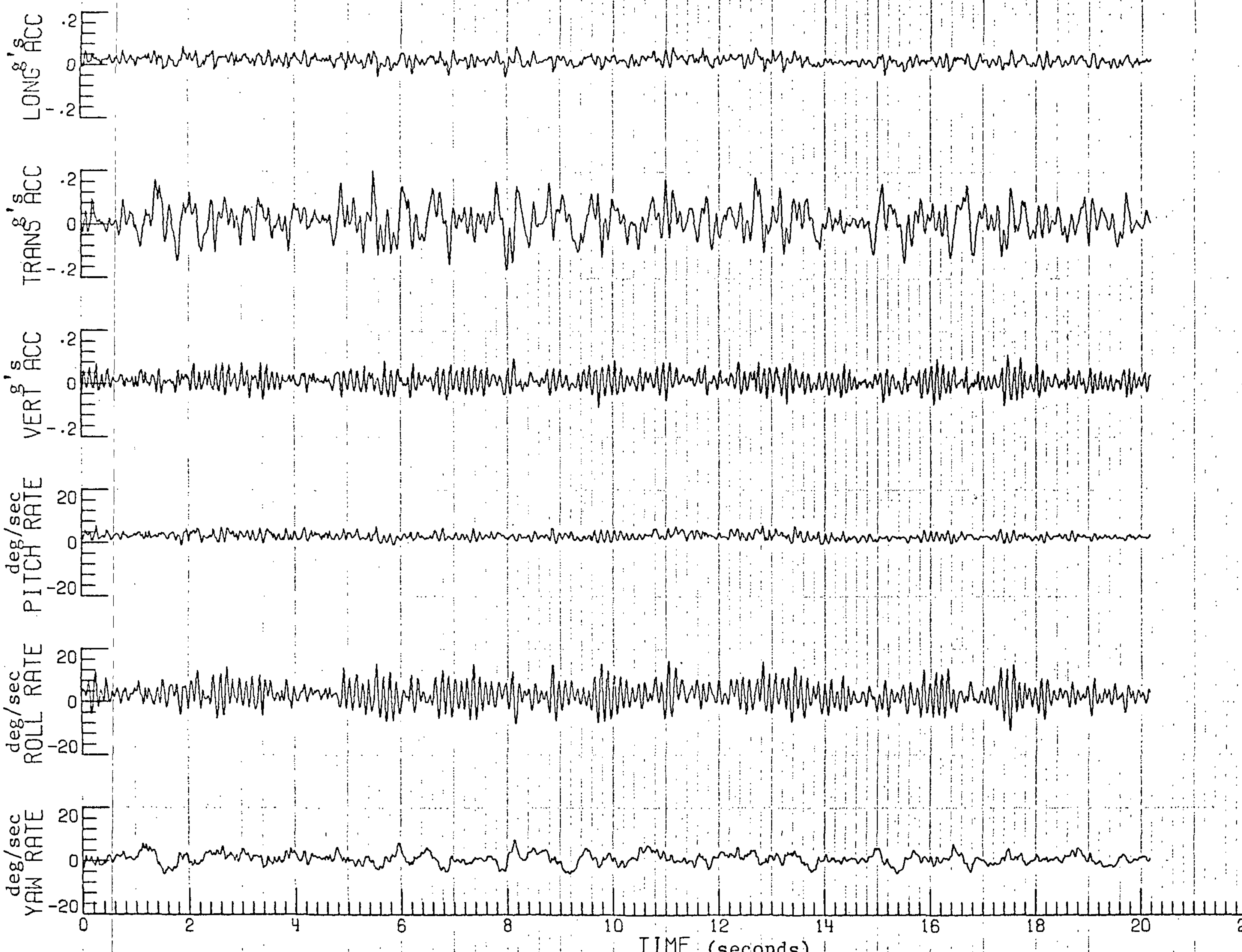
(a) Time histories (RMS yawing velocity 0.607 deg/sec)

Figure 8. MEASURED MOTION CHARACTERISTICS USING YAWING VELOCITIES WITH FLAT 0 - 2 HZ INPUTS



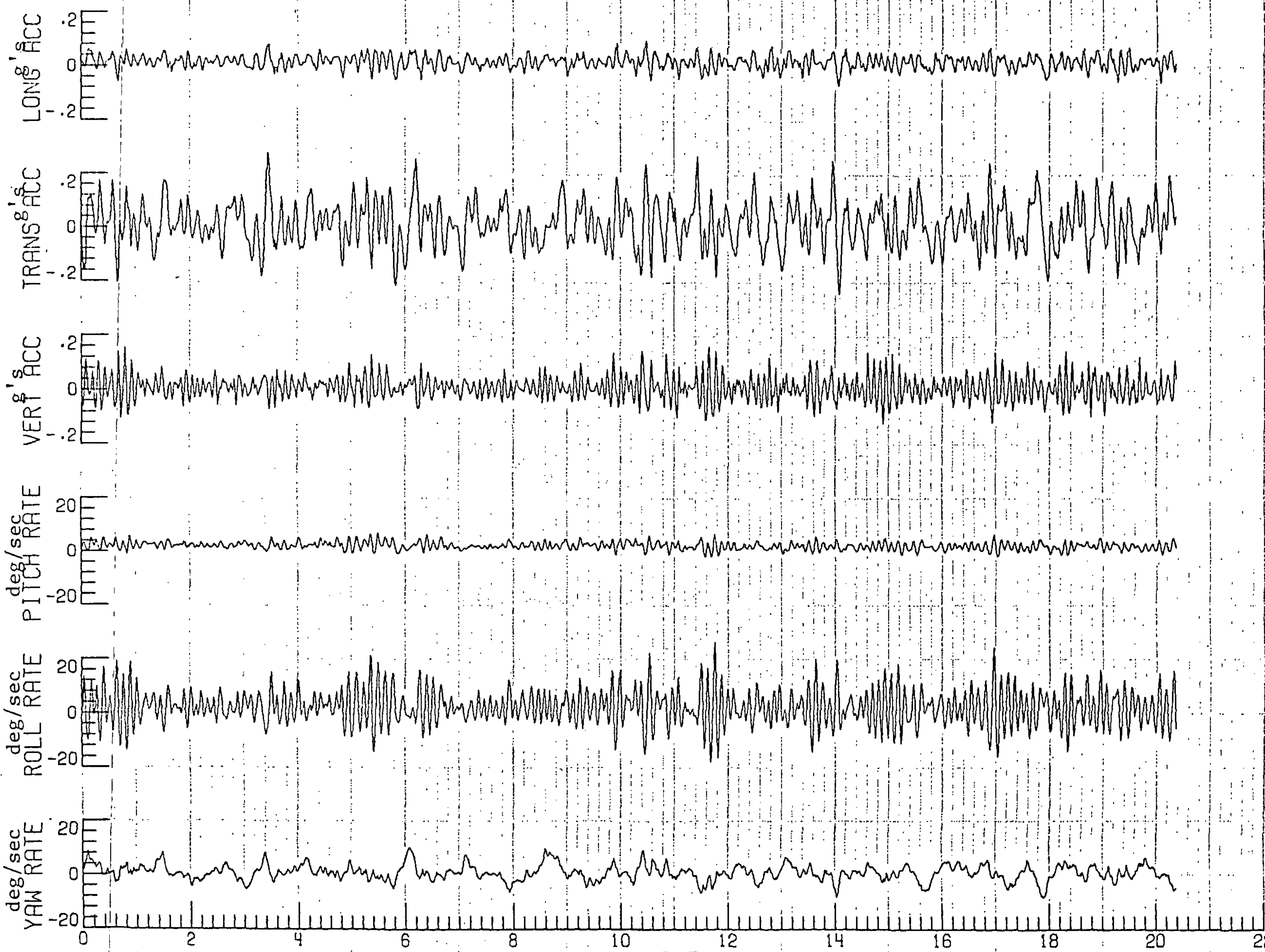
(a) Time histories (RMS yawing velocity 0.918 deg/sec)

Figure 8. Continued.



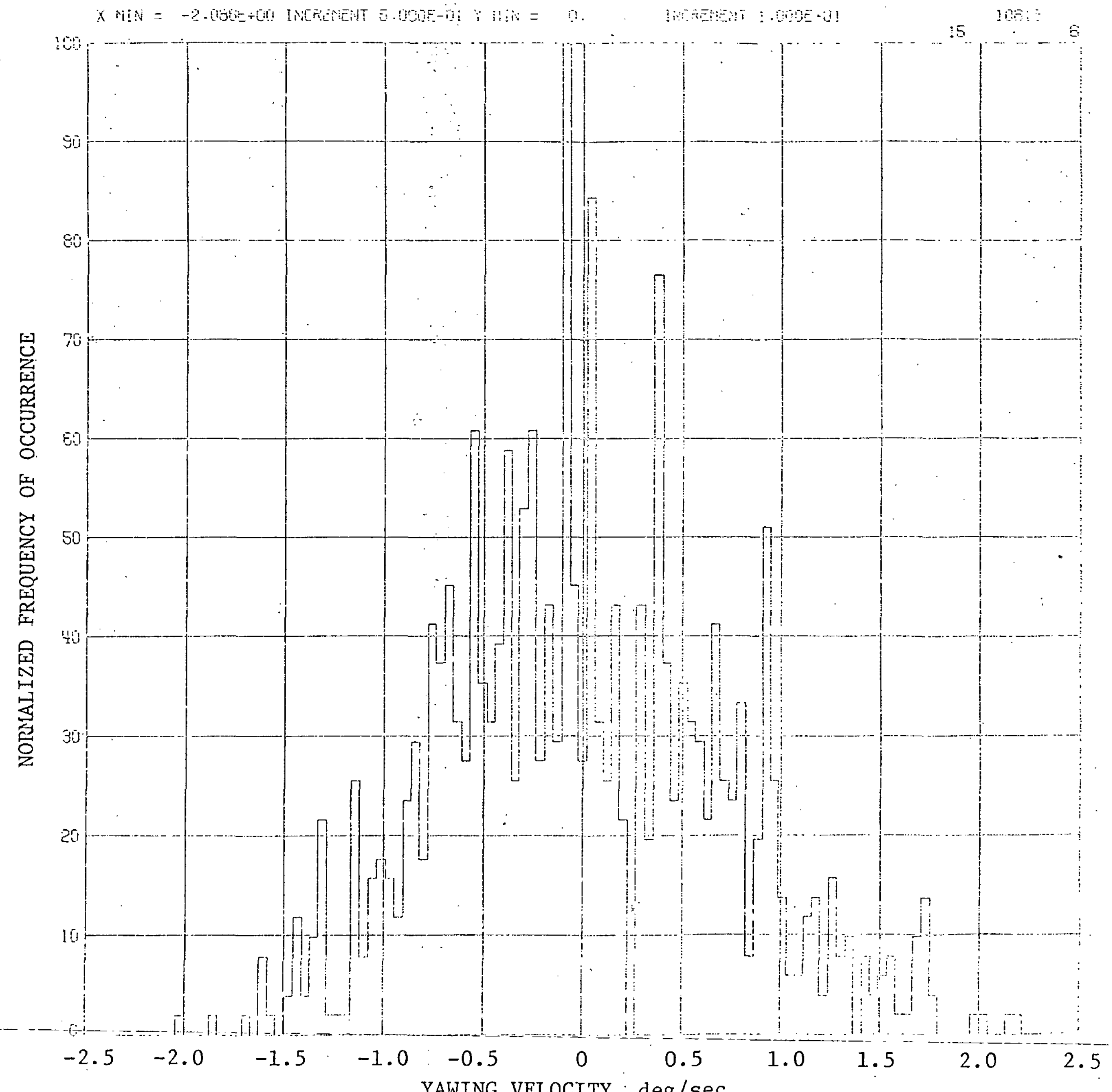
(a) Time histories (RMS yawing velocity 2.058 deg/sec)

Figure 8. Continued.



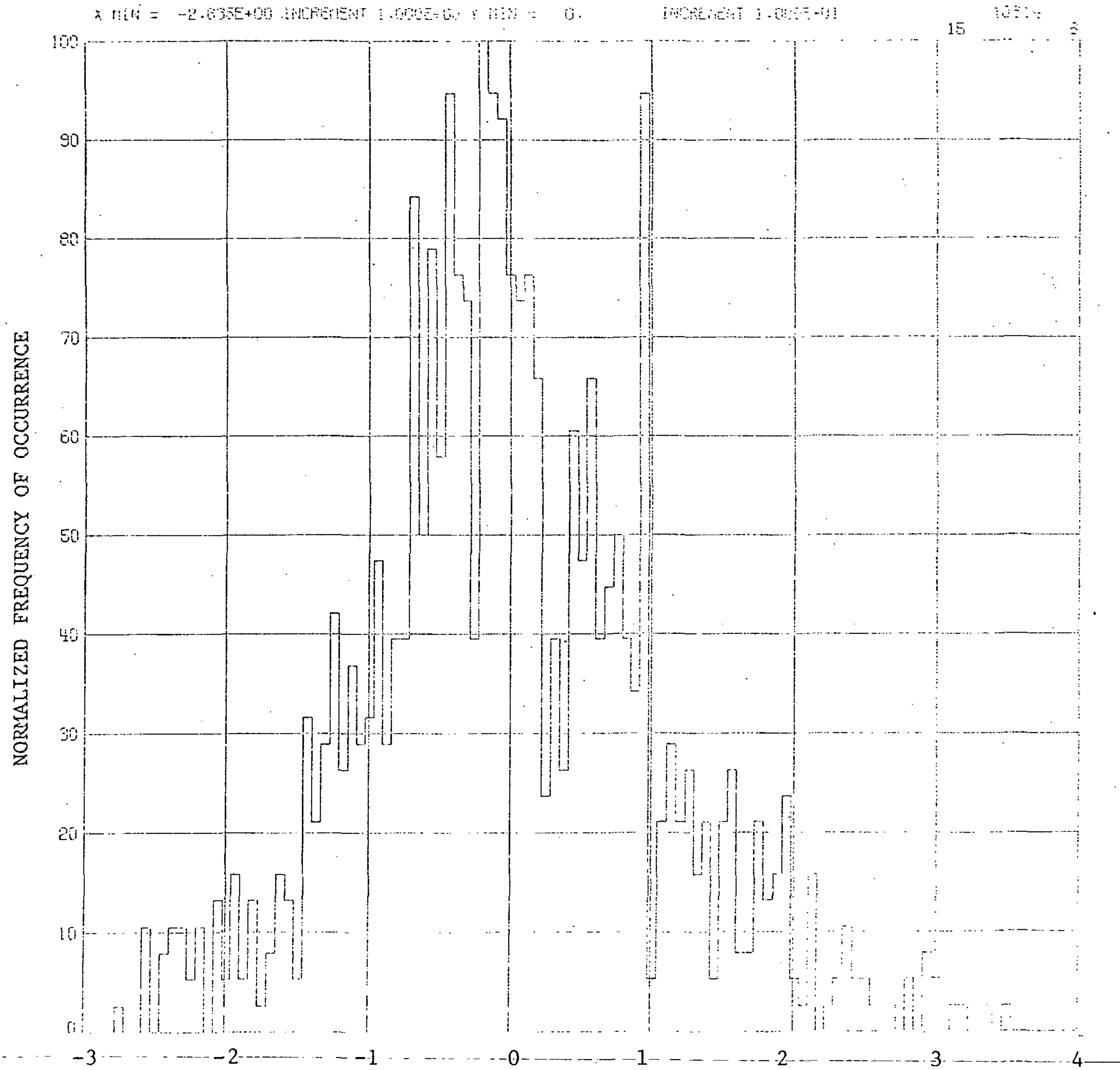
(a) Time histories (RMS yawing velocity 2.997 deg/sec)

Figure 8. Continued.



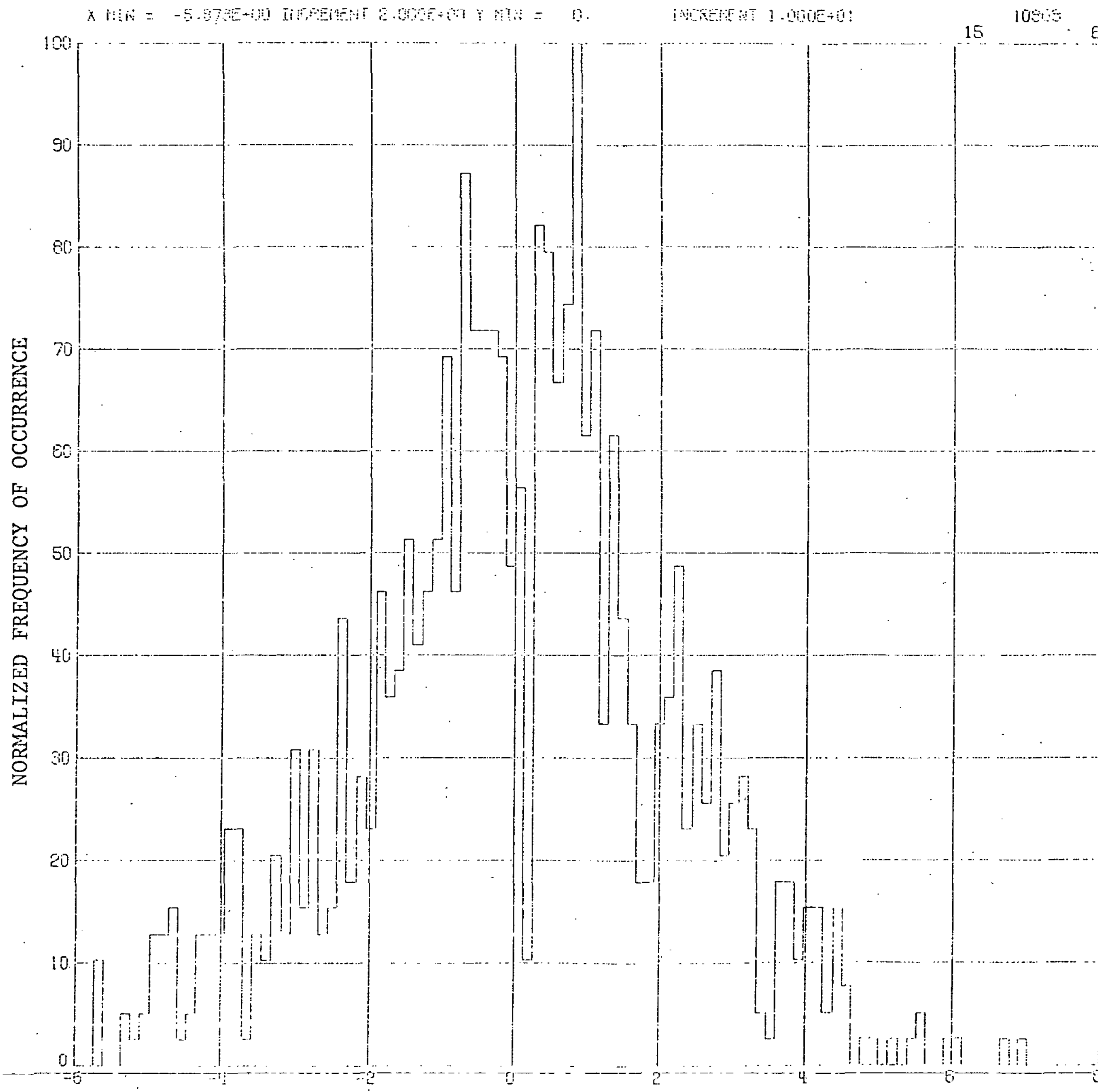
(b) Yawing velocity histograms (RMS yawing velocity 0.607 deg/sec)

Figure 8. Continued.



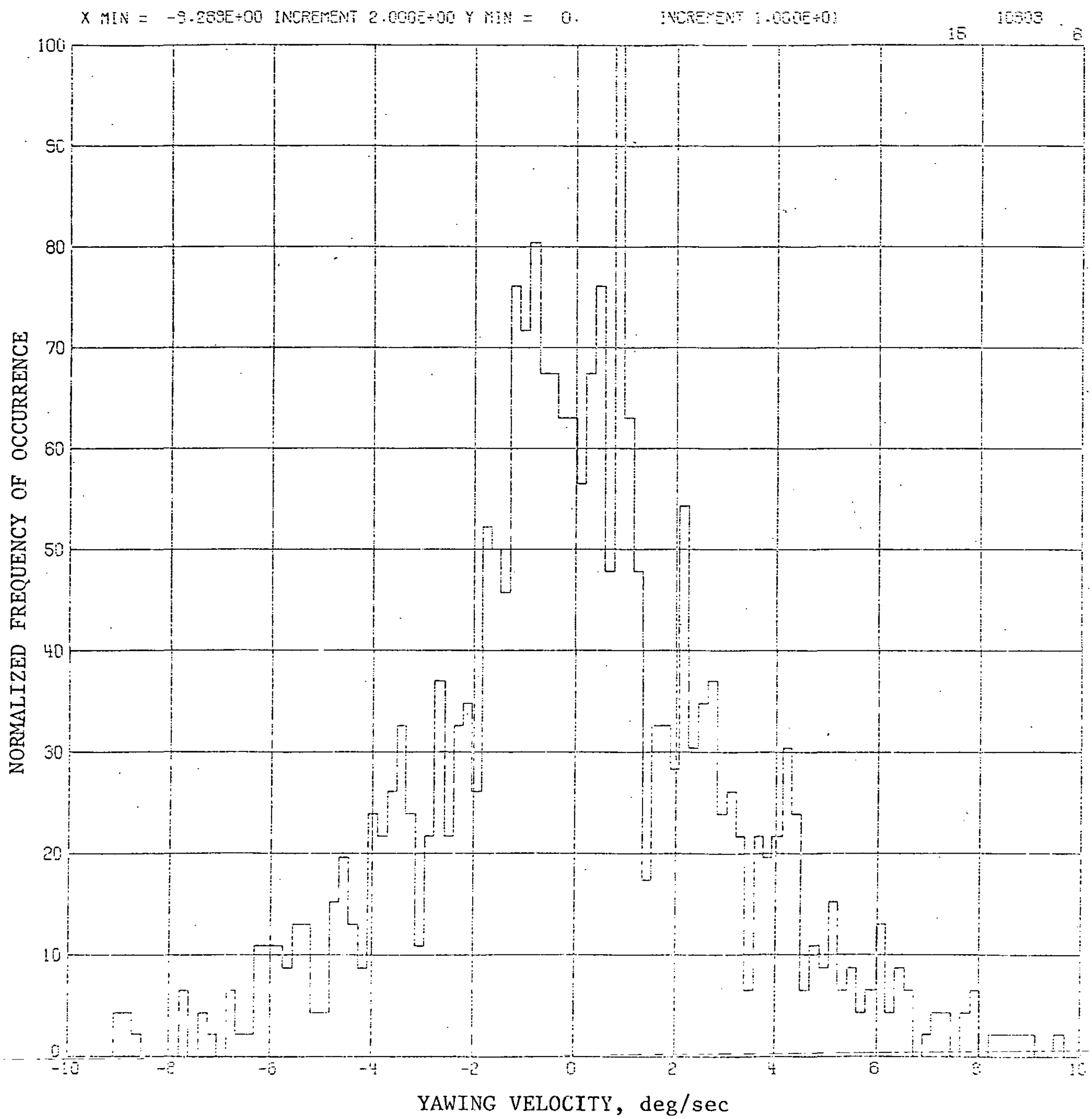
(b) Yawing velocity histograms (RMS yawing velocity 0.918 deg/sec)

Figure 8. Continued.



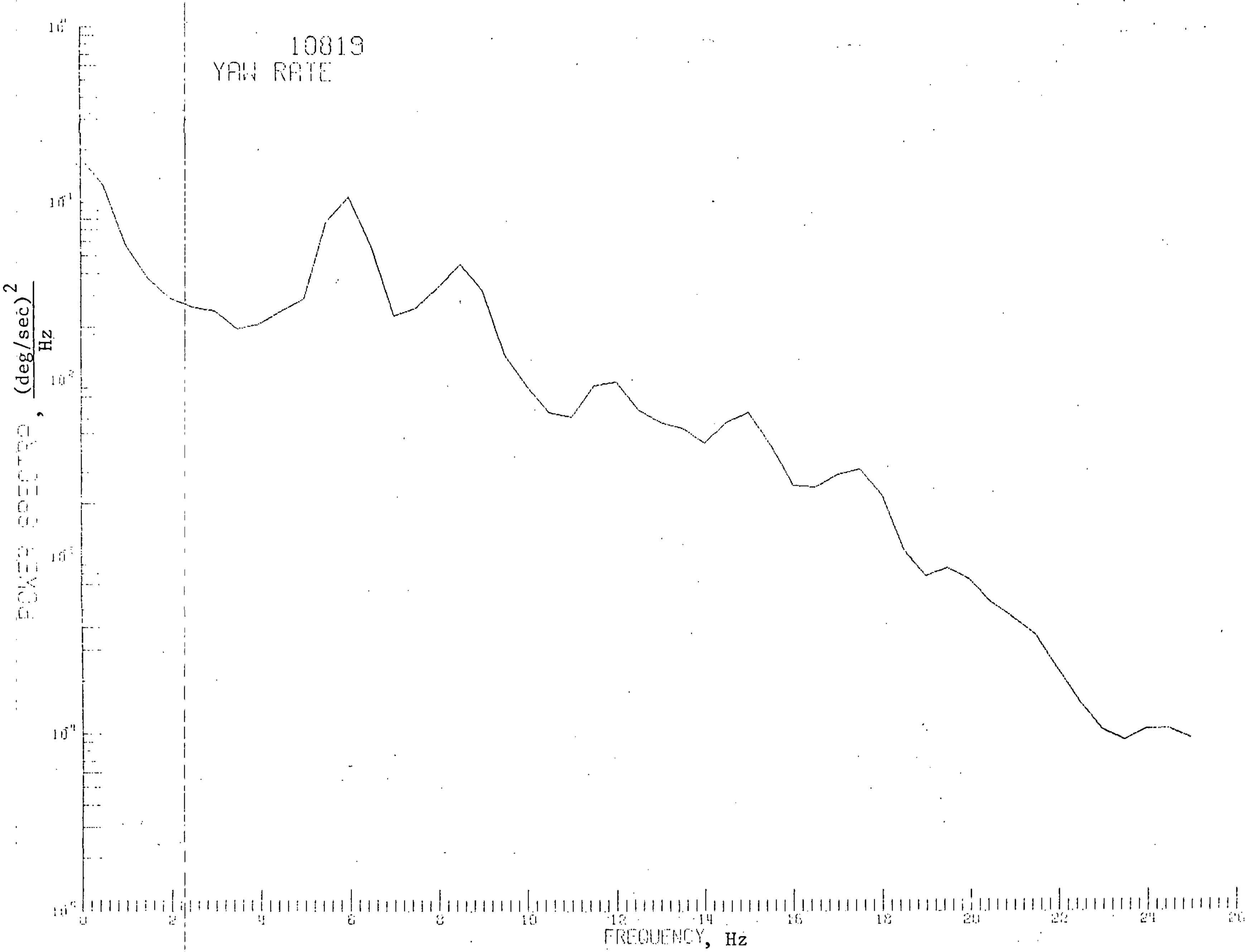
(b) Yawing velocity histograms (RMS yawing velocity 2.058 deg/sec)

Figure 8. Continued.



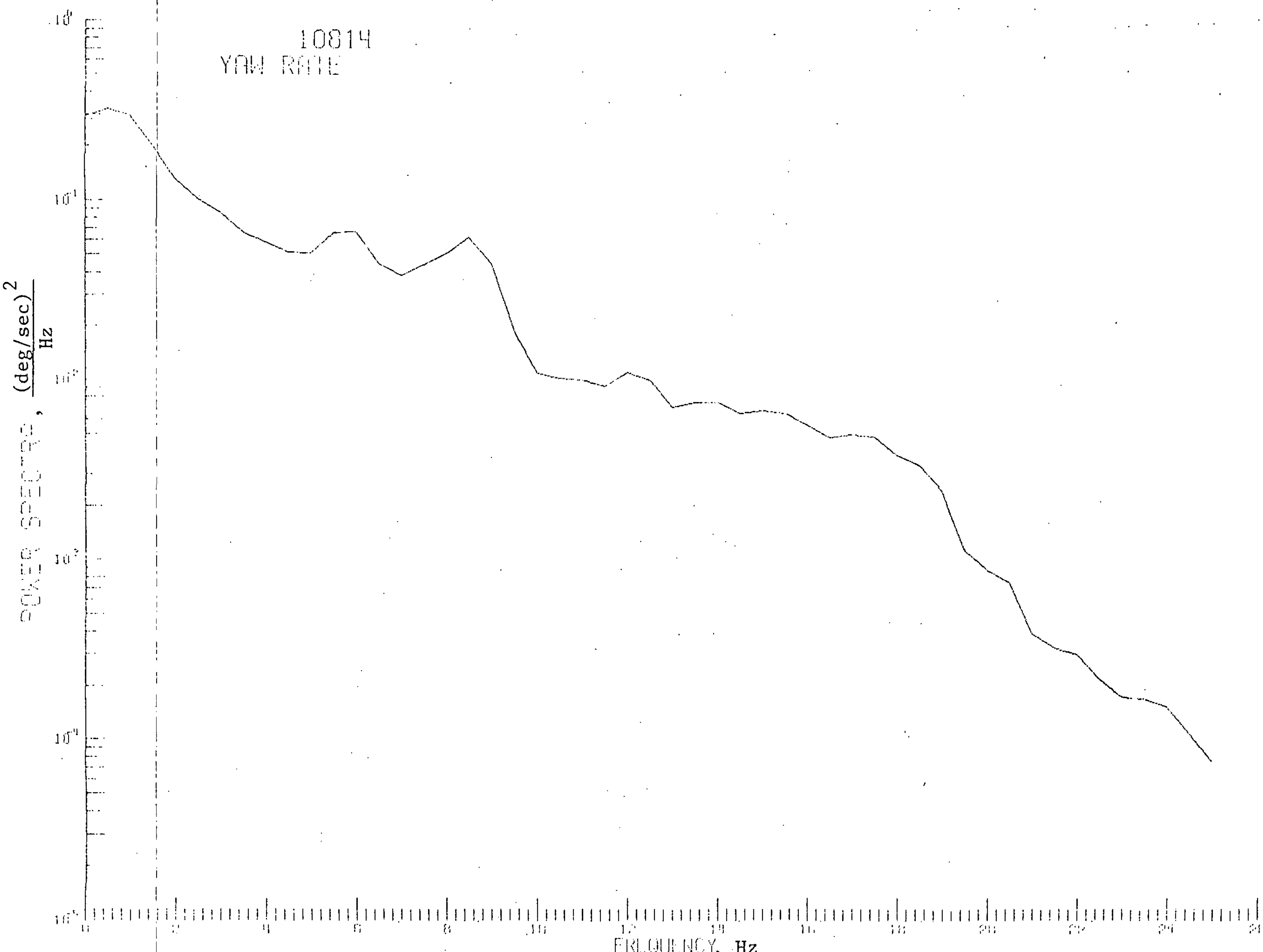
(b) Yawing velocity histograms (RMS yawing velocity 2.997 deg/sec)

Figure 8. Continued.



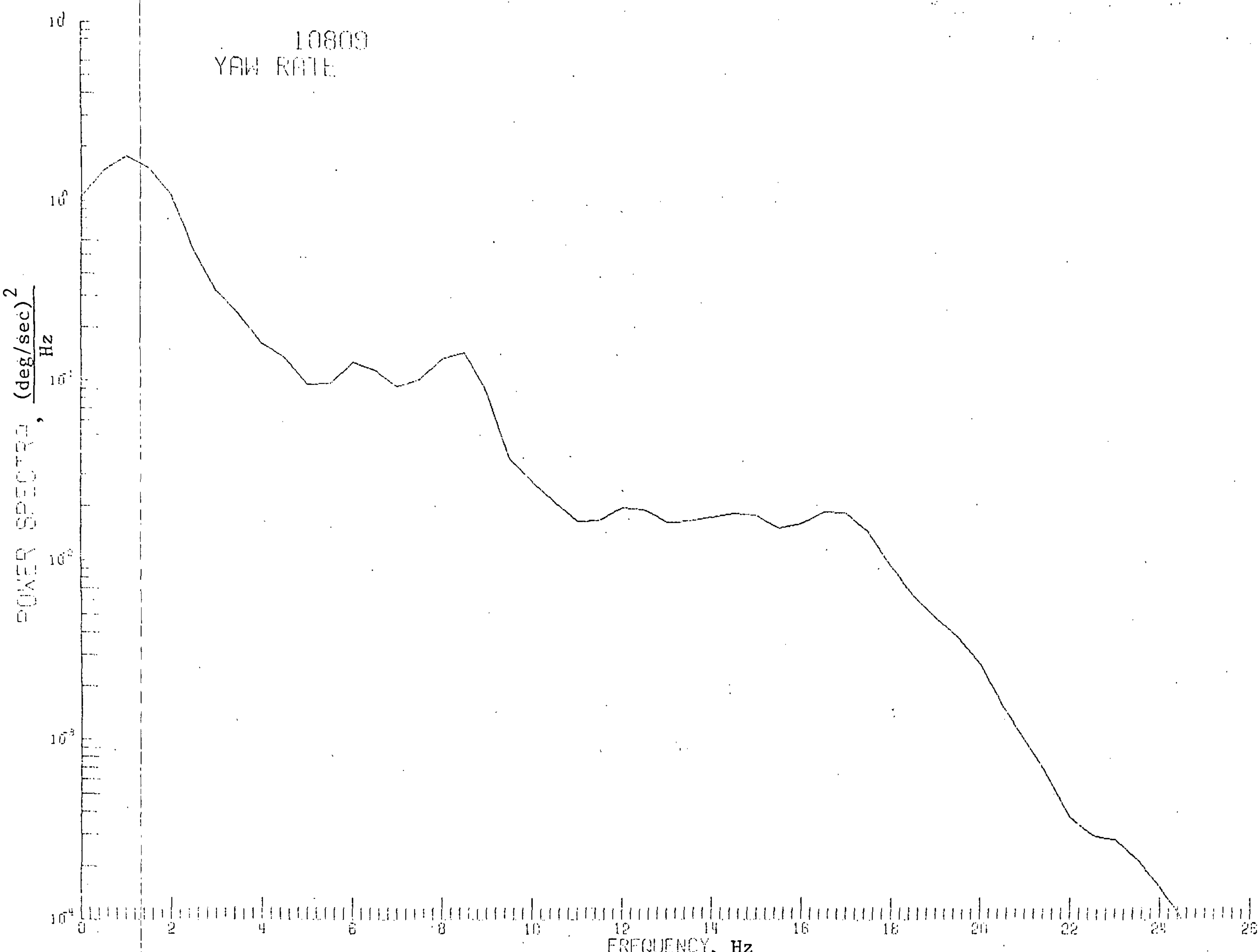
(c) Yawing velocity power spectrum (RMS yawing velocity 0.607 deg/sec)

Figure 8. Continued.



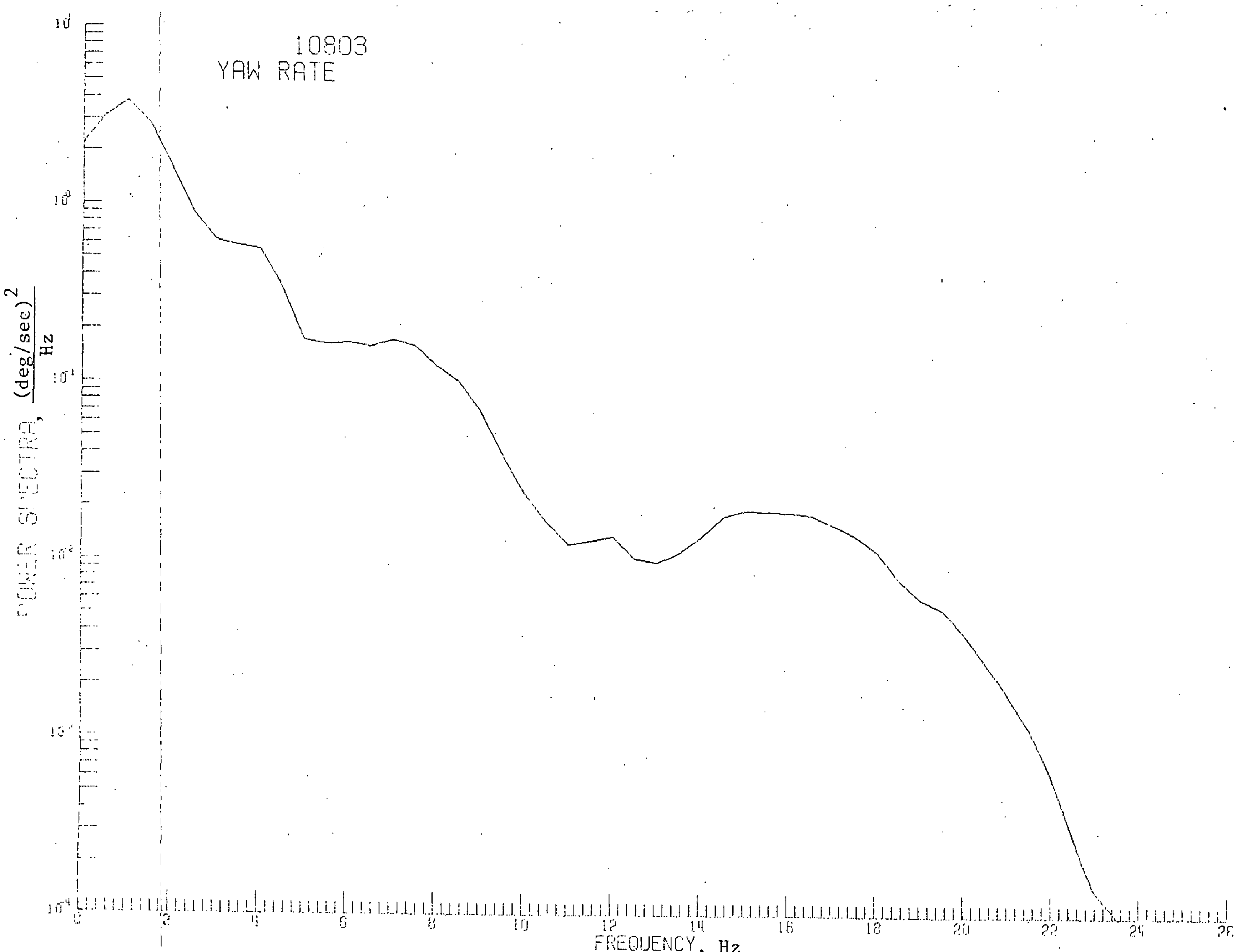
(c) Yawing velocity power spectrum (RMS yawing velocity 0.918 deg/sec)

Figure 8. Continued.



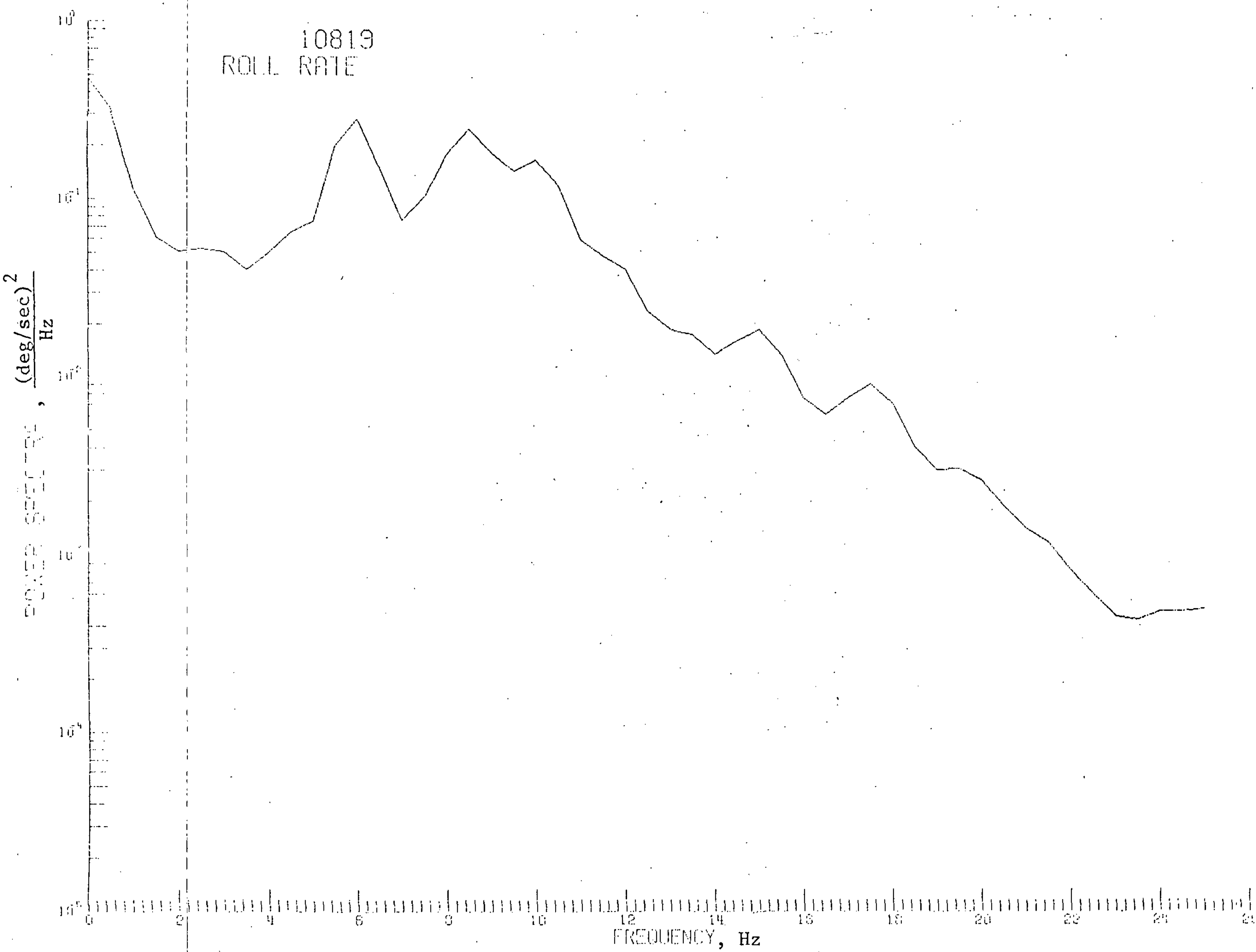
(c) Yawing velocity power spectrum (RMS yawing velocity 2.058 deg/sec)

Figure 8. Continued.



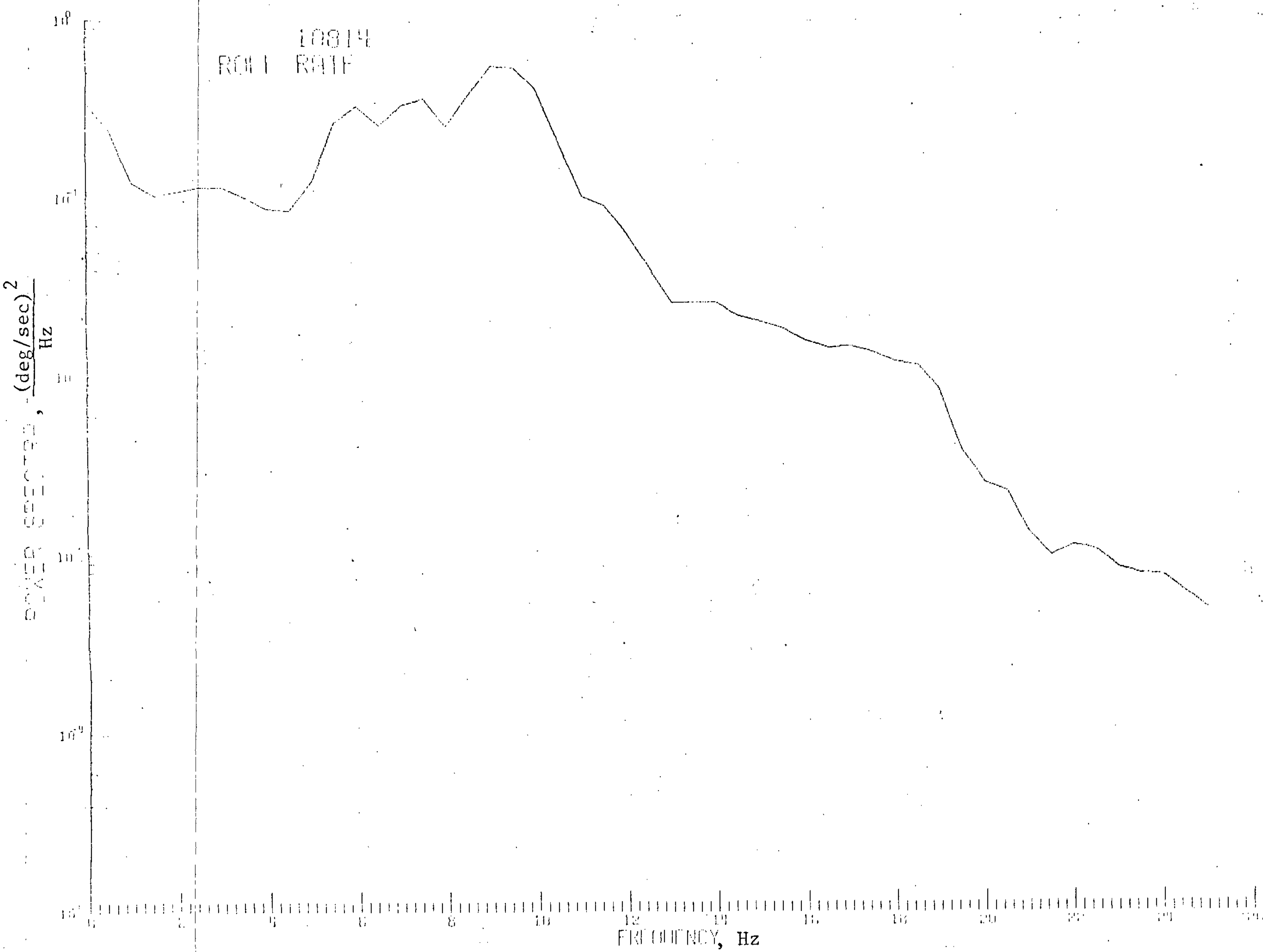
(c) Yawing velocity power spectrum (RMS yawing velocity 2.997 deg/sec)

Figure 8. Continued.



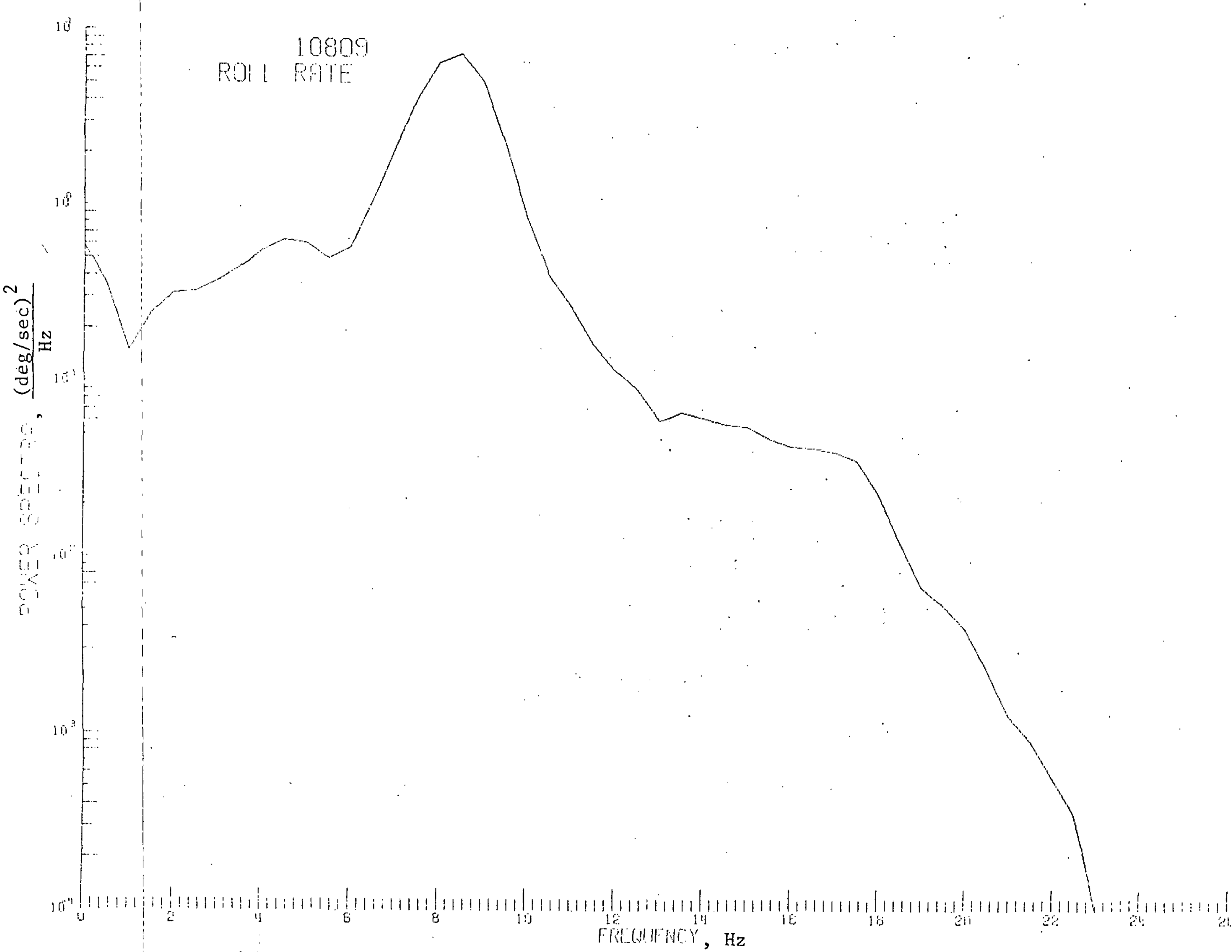
(d) Rolling velocity power spectrum (RMS rolling velocity 1.112 deg/sec)

Figure 8. Continued.



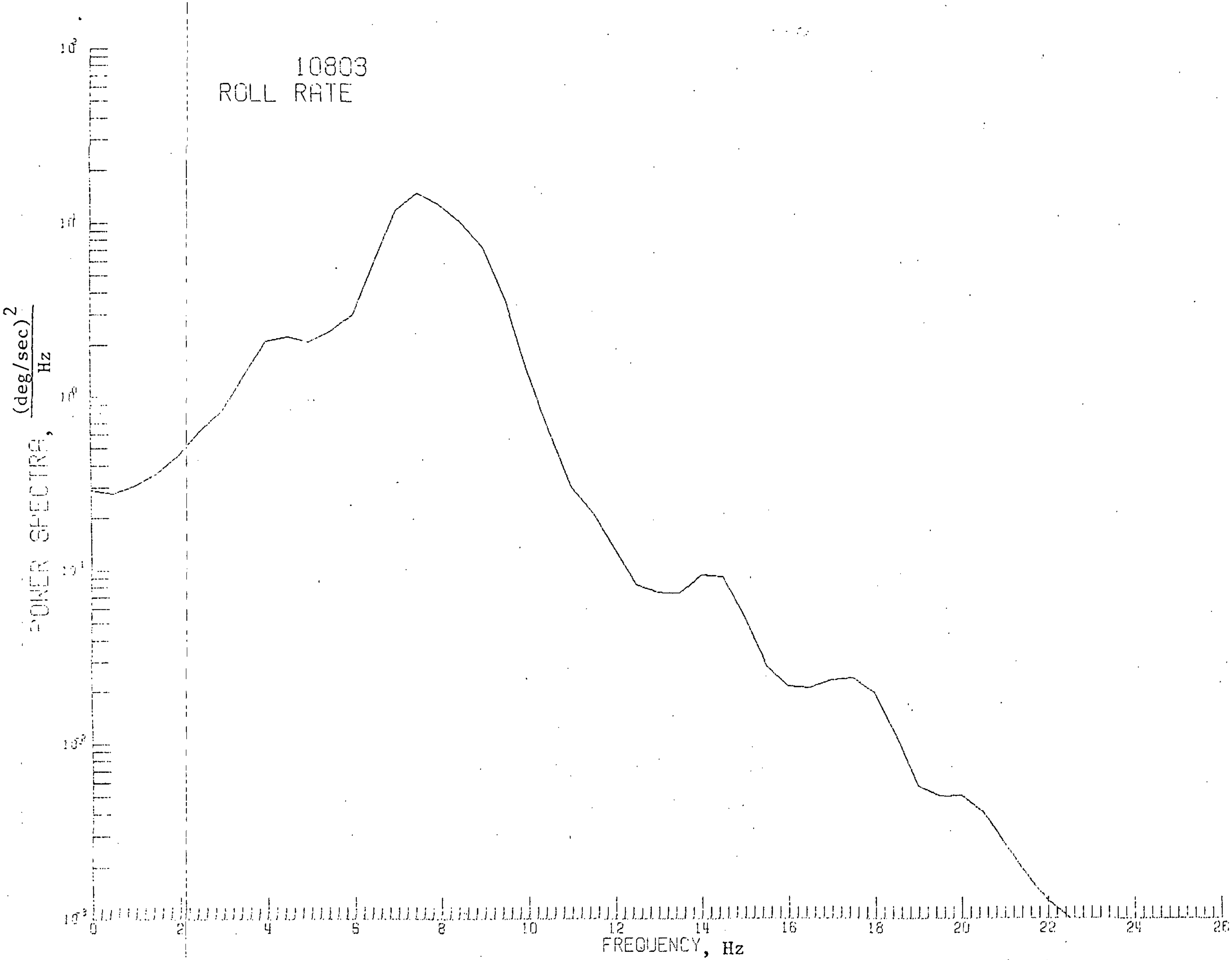
(d) Rolling velocity power spectrum (RMS rolling velocity 1.491 deg/sec)

Figure 8. Continued.



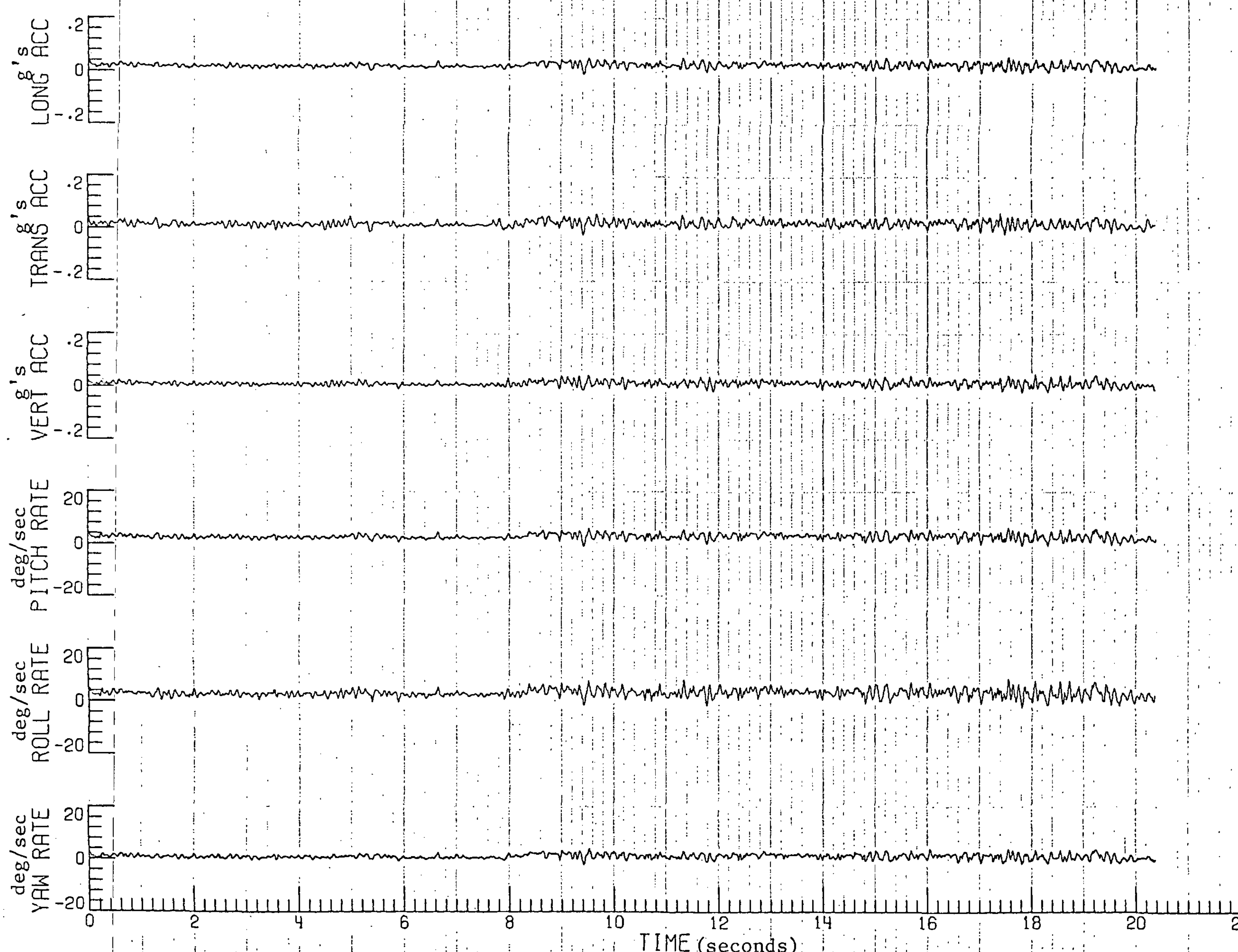
(d) Rolling velocity power spectrum (RMS rolling velocity 3.677 deg/sec)

Figure 8. Continued.



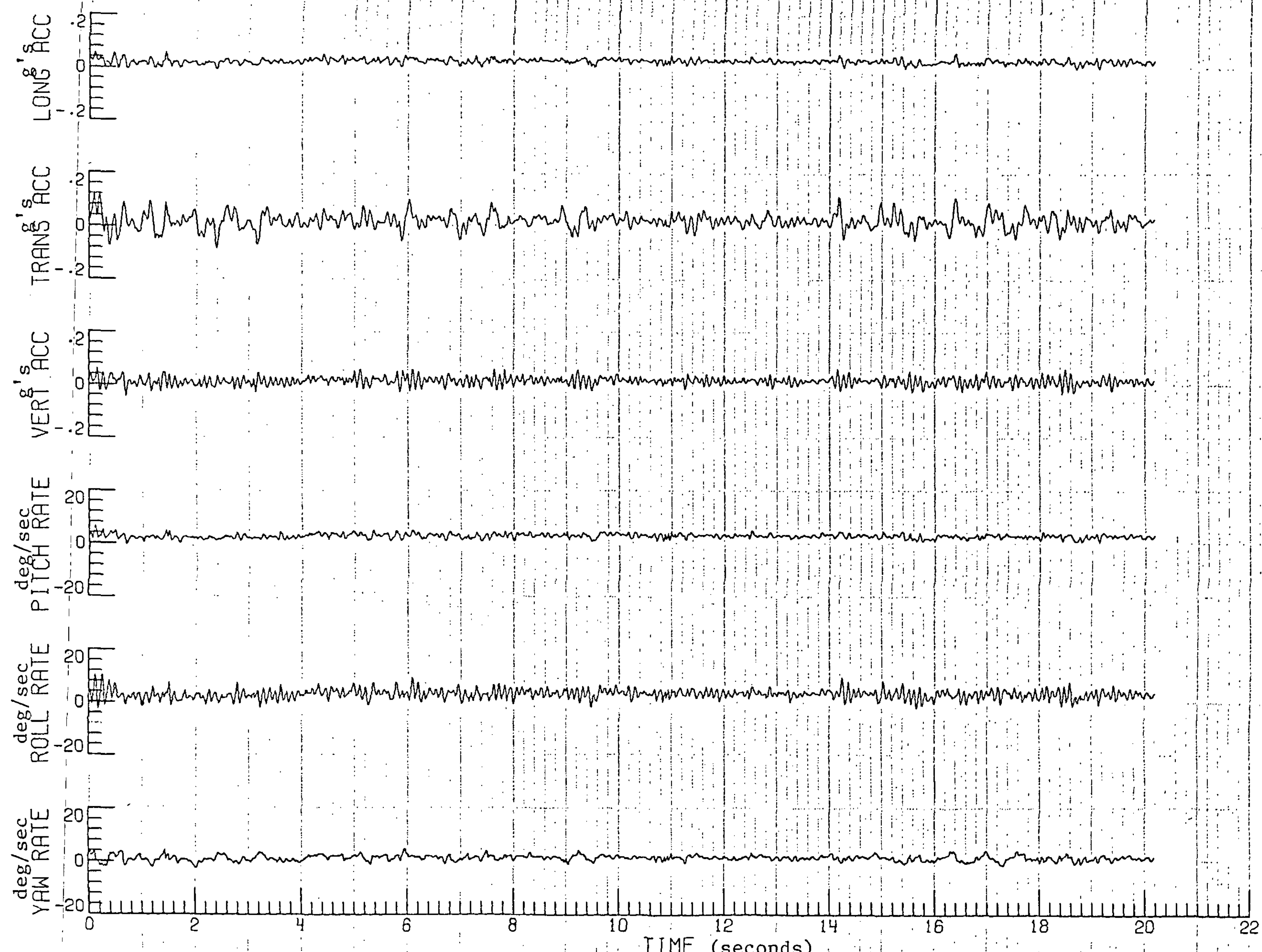
(d) Rolling velocity power spectrum (RMS rolling velocity 6.060 deg/sec)

Figure 8. Concluded.



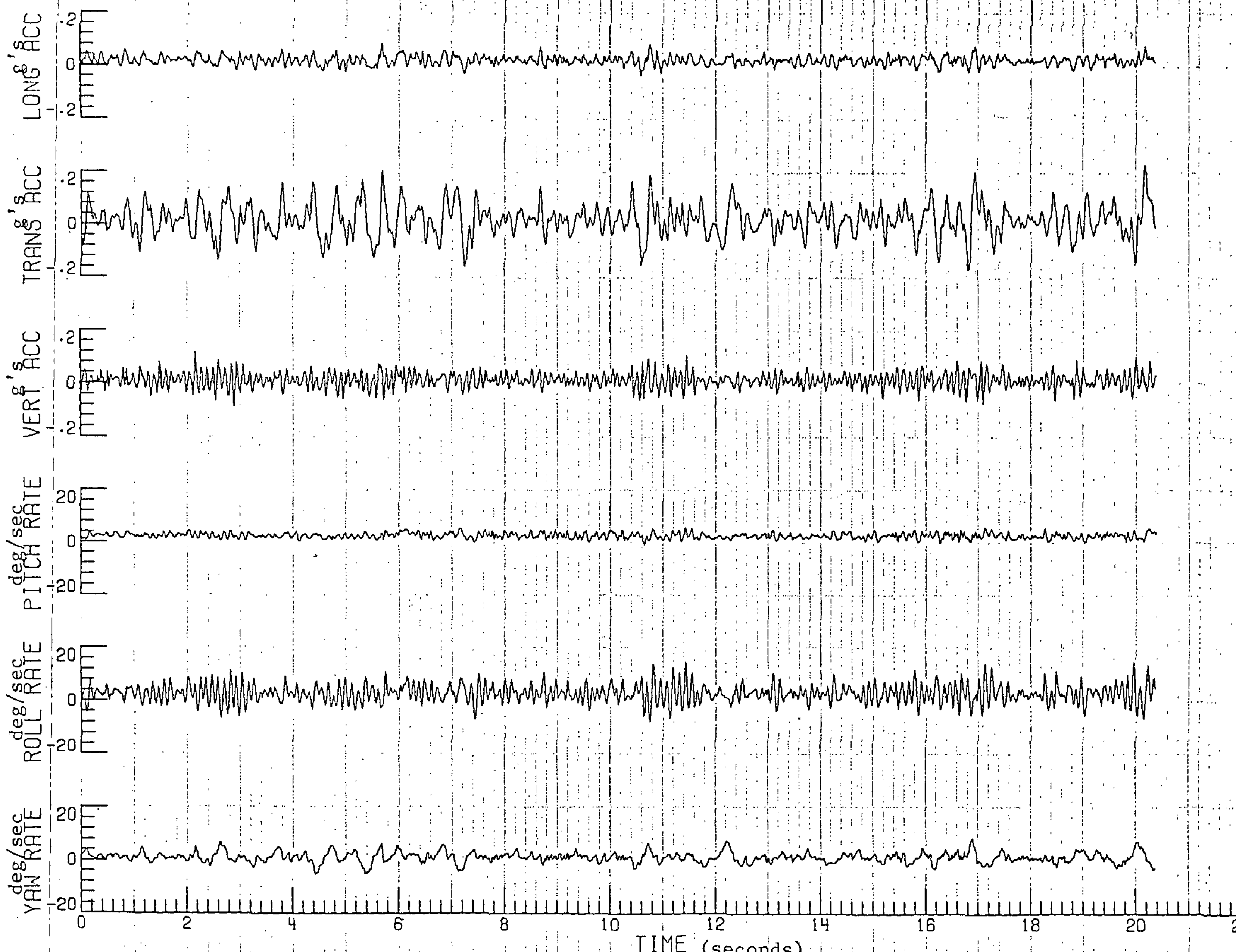
(a) Time histories (RMS yawing velocity 0.662 deg/sec)

Figure 9. MEASURED MOTION CHARACTERISTICS USING YAWING VELOCITY WITH FLAT 1 - 2 HZ INPUTS



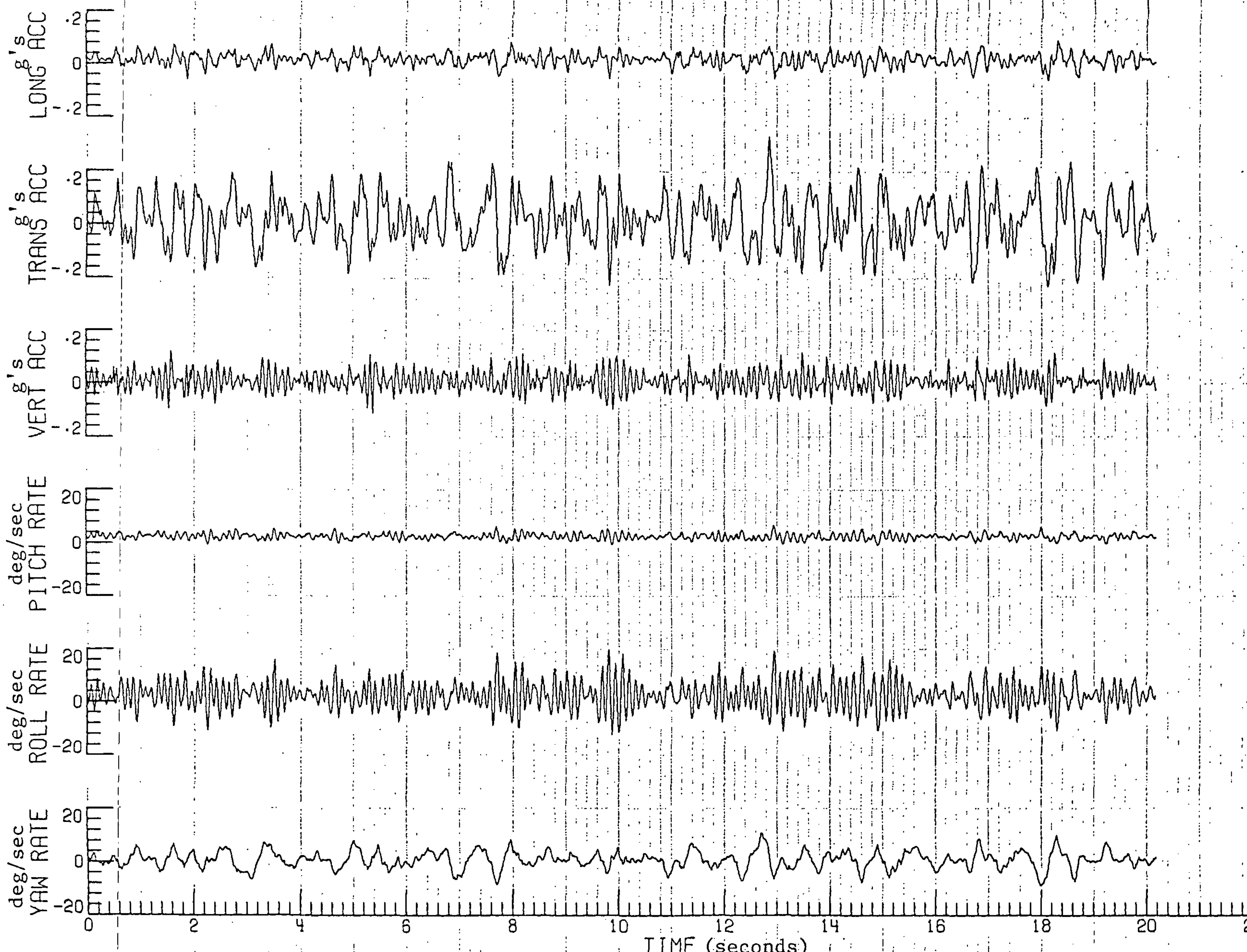
(a) Time histories (RMS yawing velocity 0.976 deg/sec)

Figure 9. Continued.



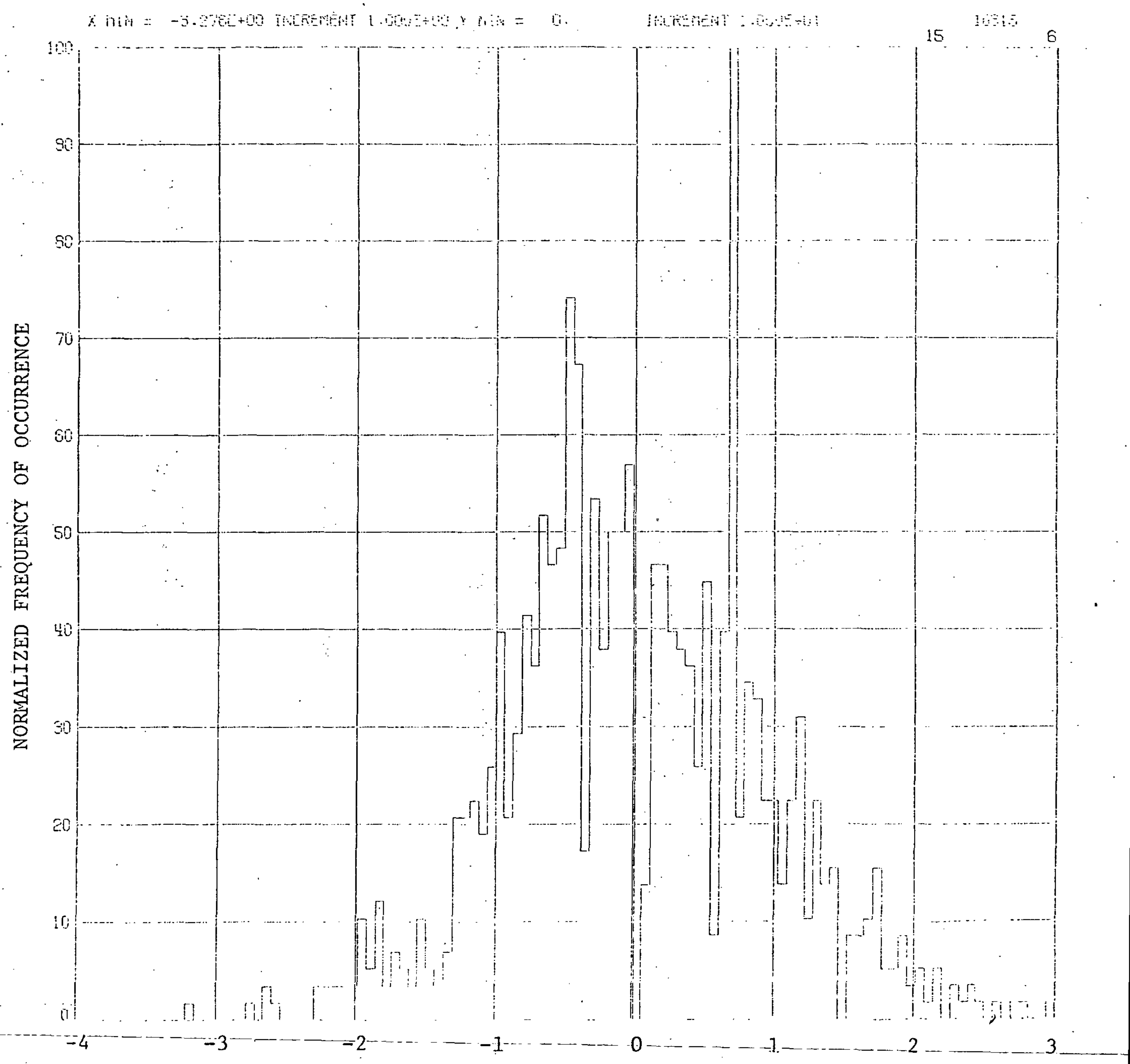
(a) Time histories (RMS yawing velocity 1.861 deg/sec)

Figure 9. Continued .



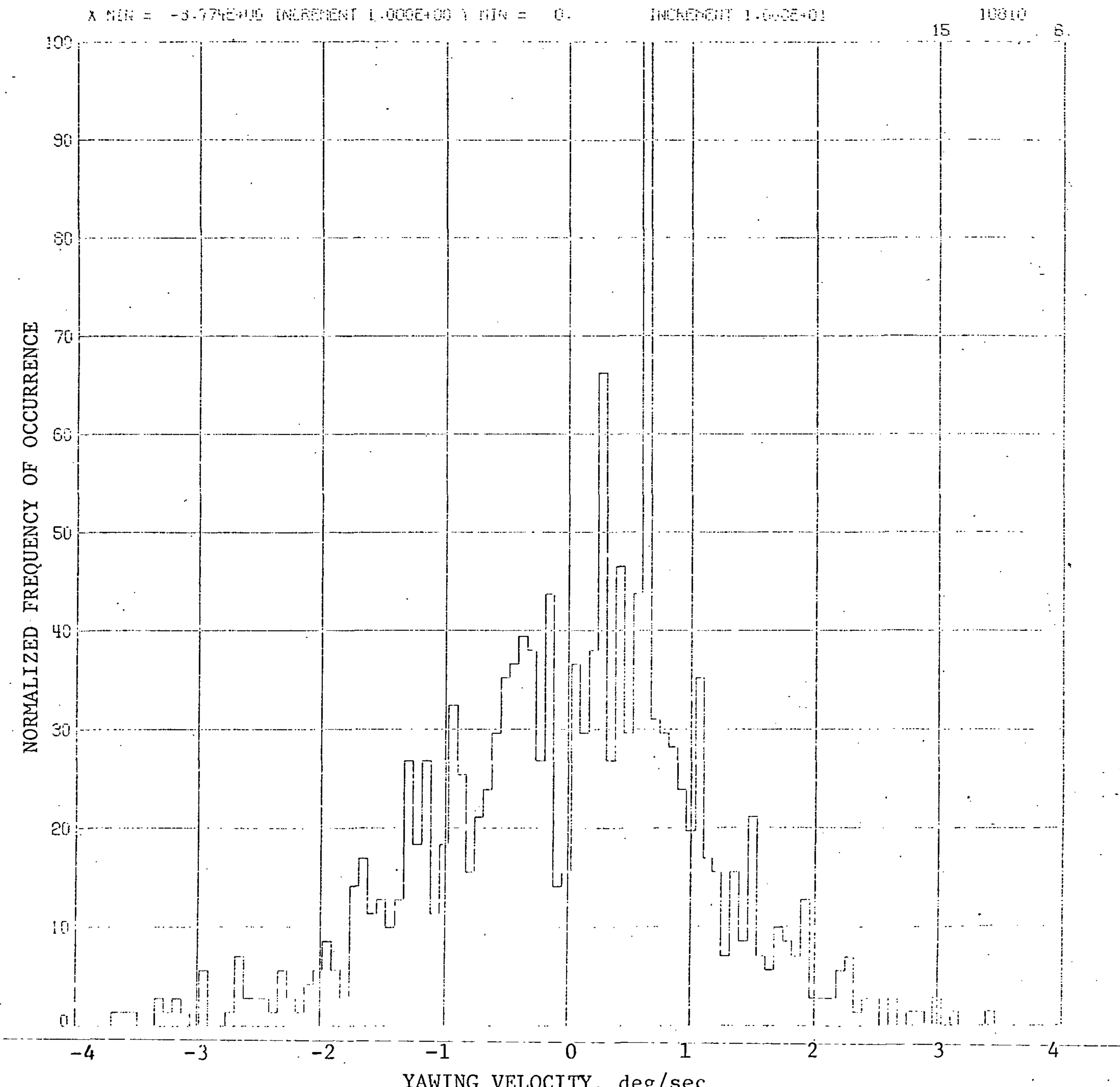
(a) Time histories (RMS yawing velocity 3.096 deg/sec)

Figure 9. Continued.



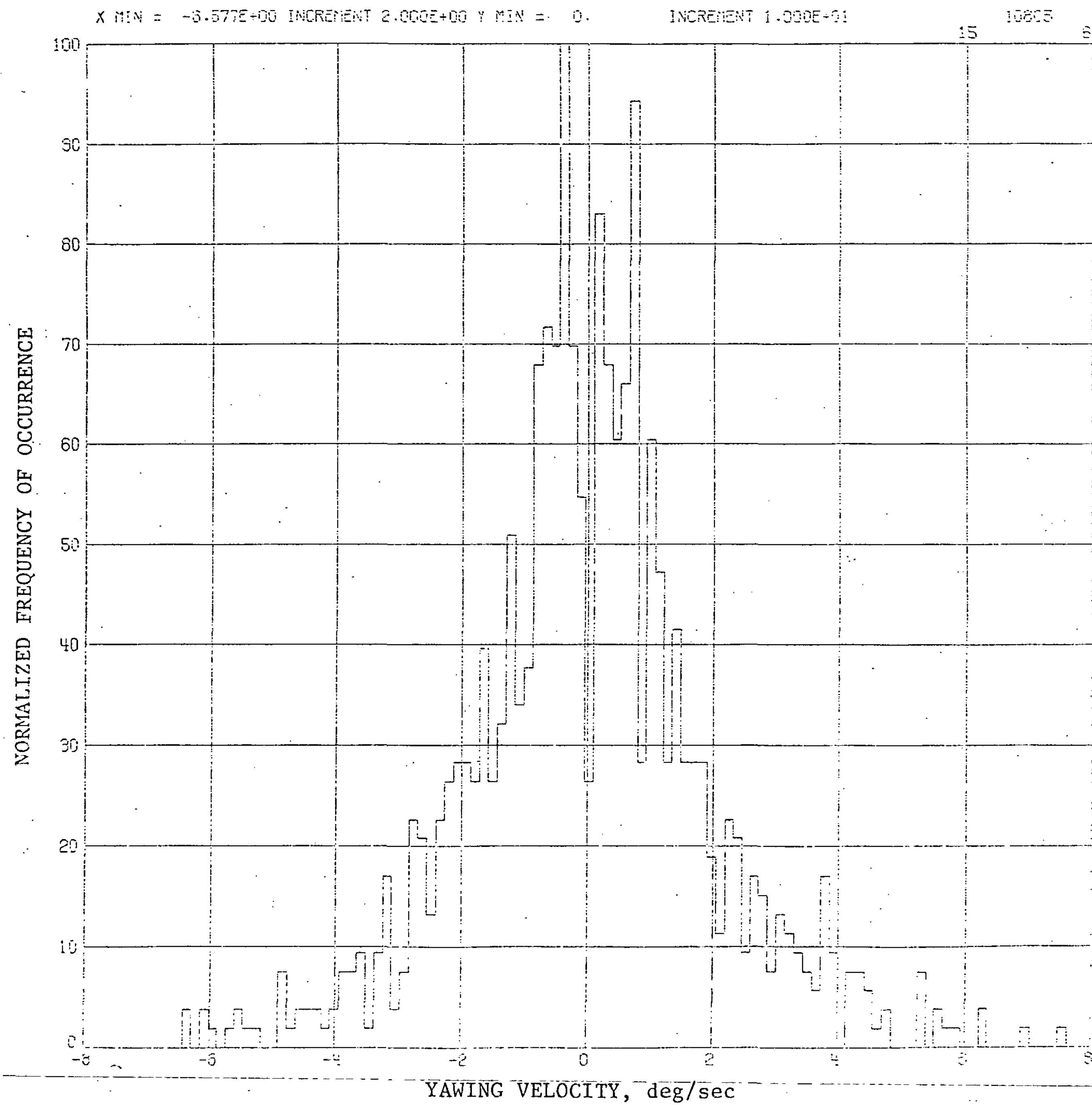
(b) Yawing velocity histograms (RMS yawing velocity 0.662 deg/sec)

Figure 9. Continued.



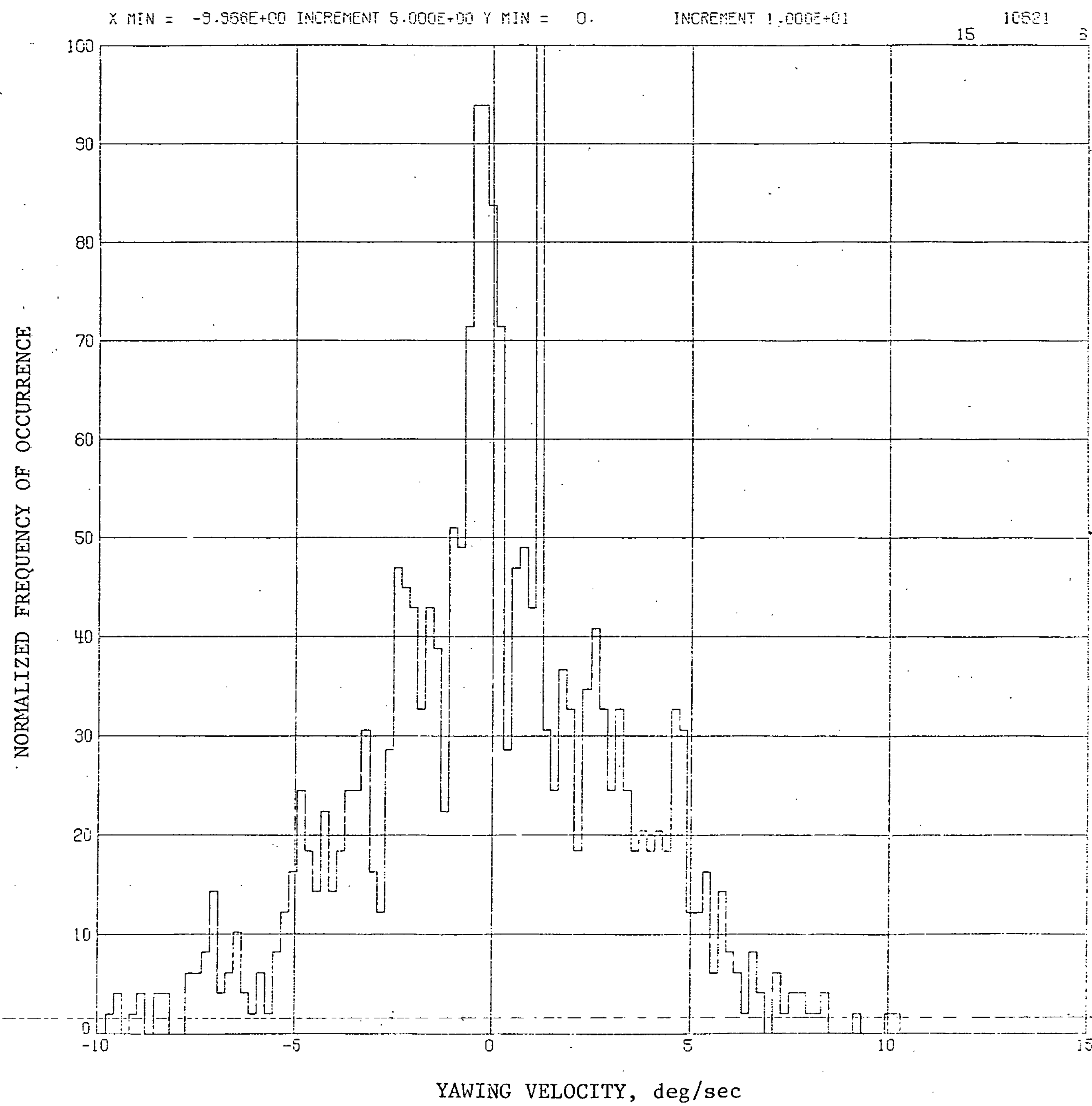
(b) Yawing velocity histograms (RMS yawing velocity 0.976 deg/sec)

Figure 9. Continued.



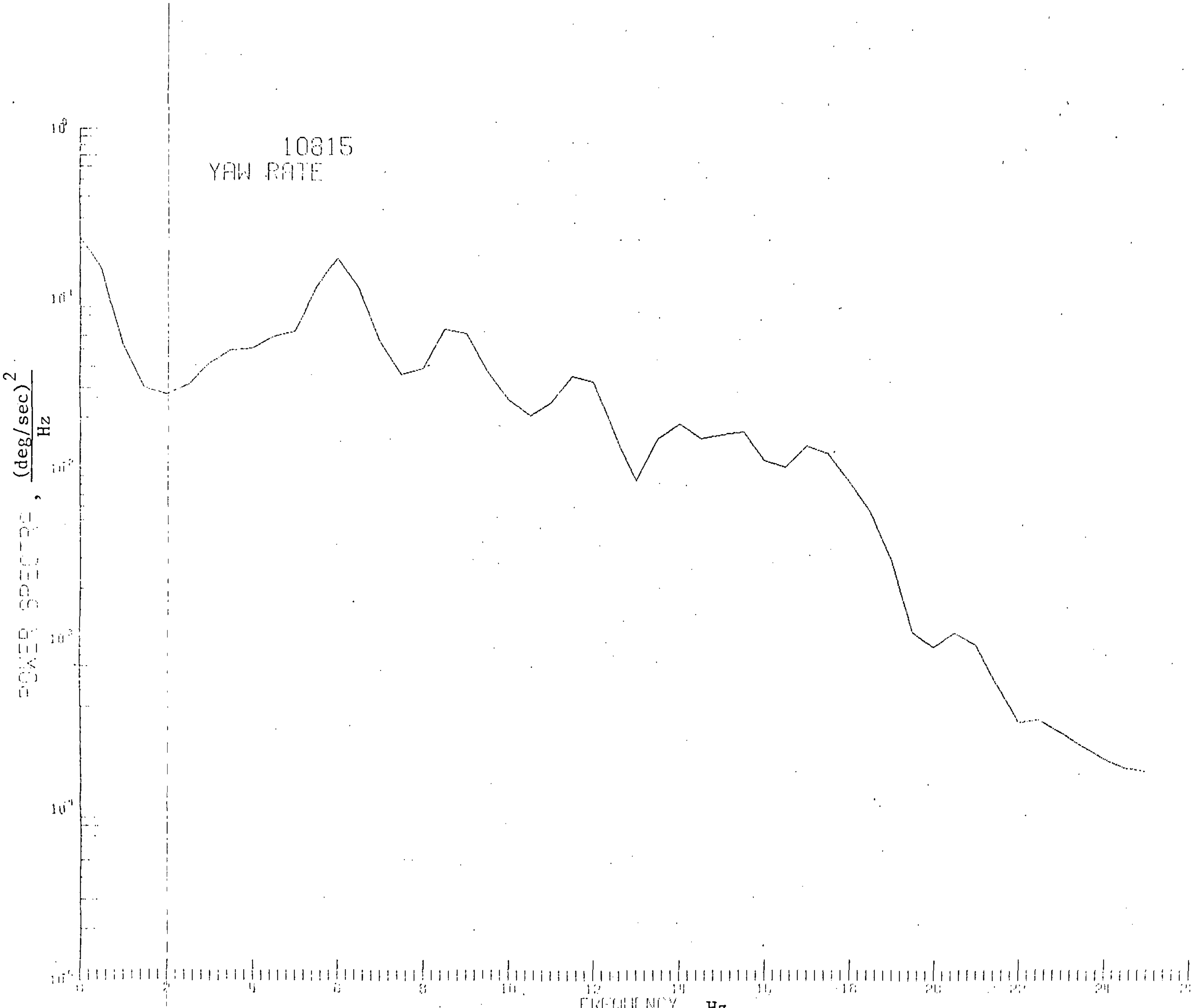
(b) Yawing velocity histograms (RMS yawing velocity 1.861 deg/sec)

Figure 9. Continued.



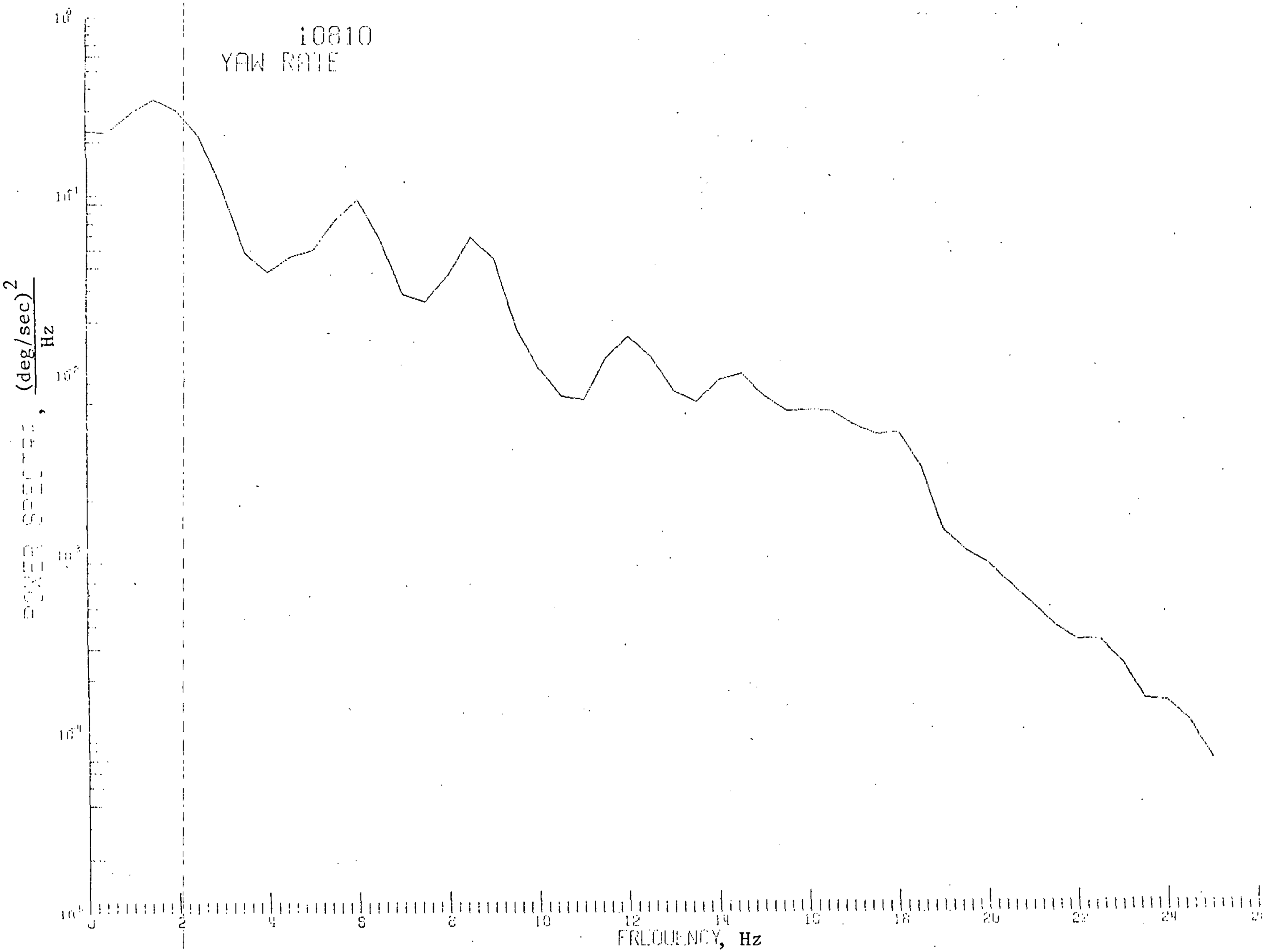
(b) Yawing velocity histograms (RMS yawing velocity 3.096 deg/sec)

Figure 9. Continued.



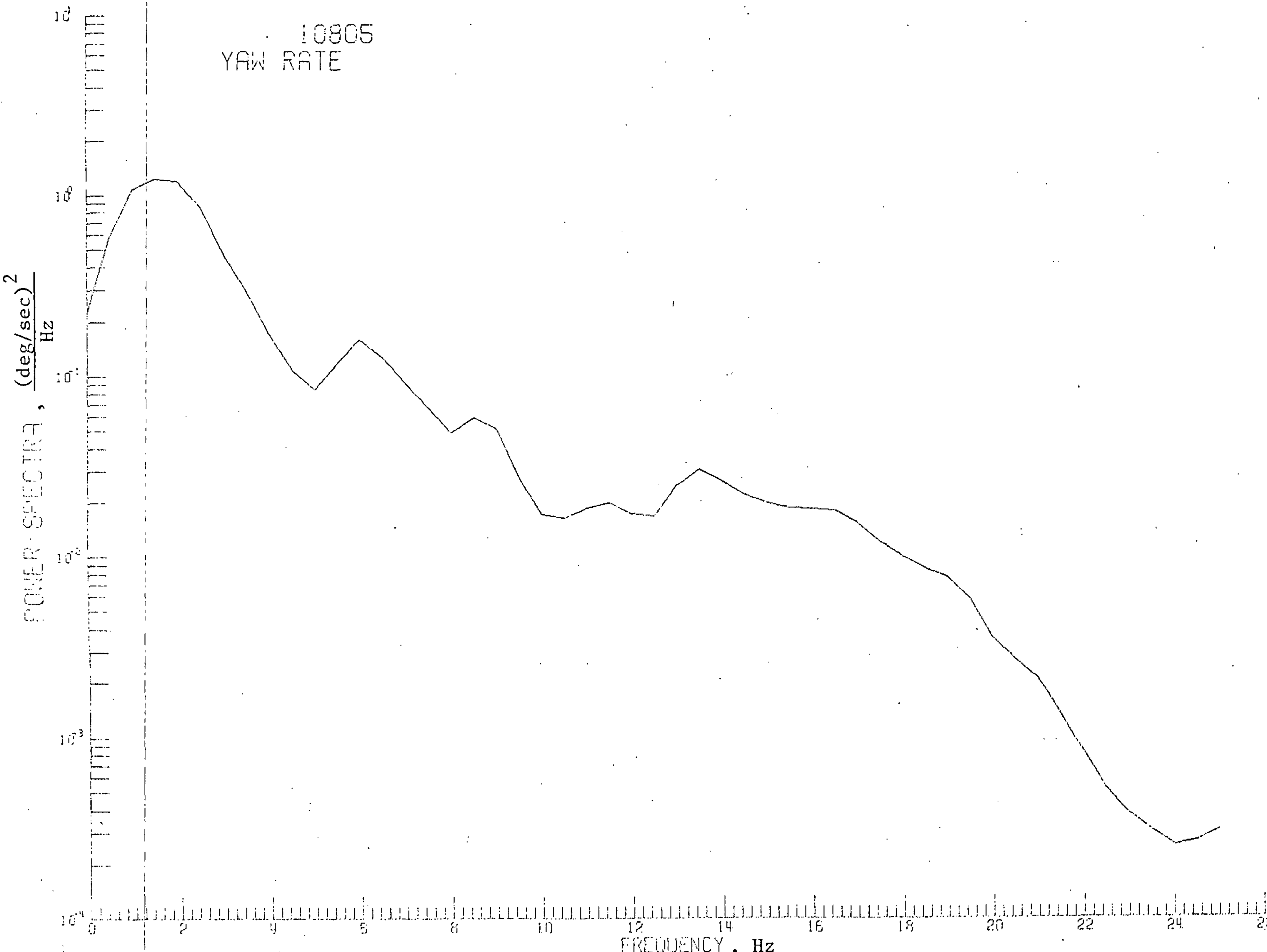
(c) Yawing velocity power spectrum (RMS yawing velocity 0.662 deg/sec)

Figure 9. Continued.



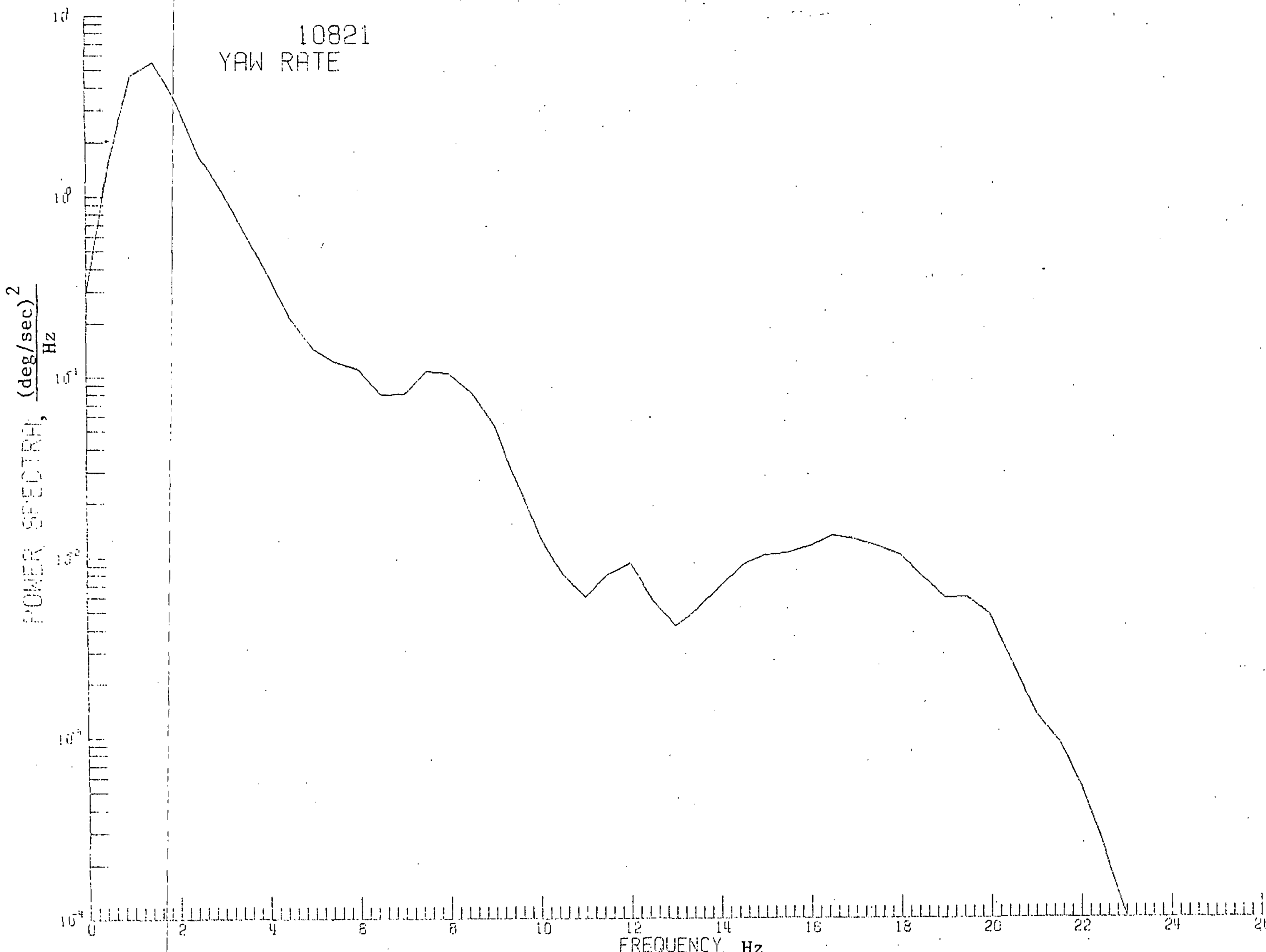
(c) Yawing velocity power spectrum (RMS yawing velocity 0.976 deg/sec)

Figure 9. Continued.



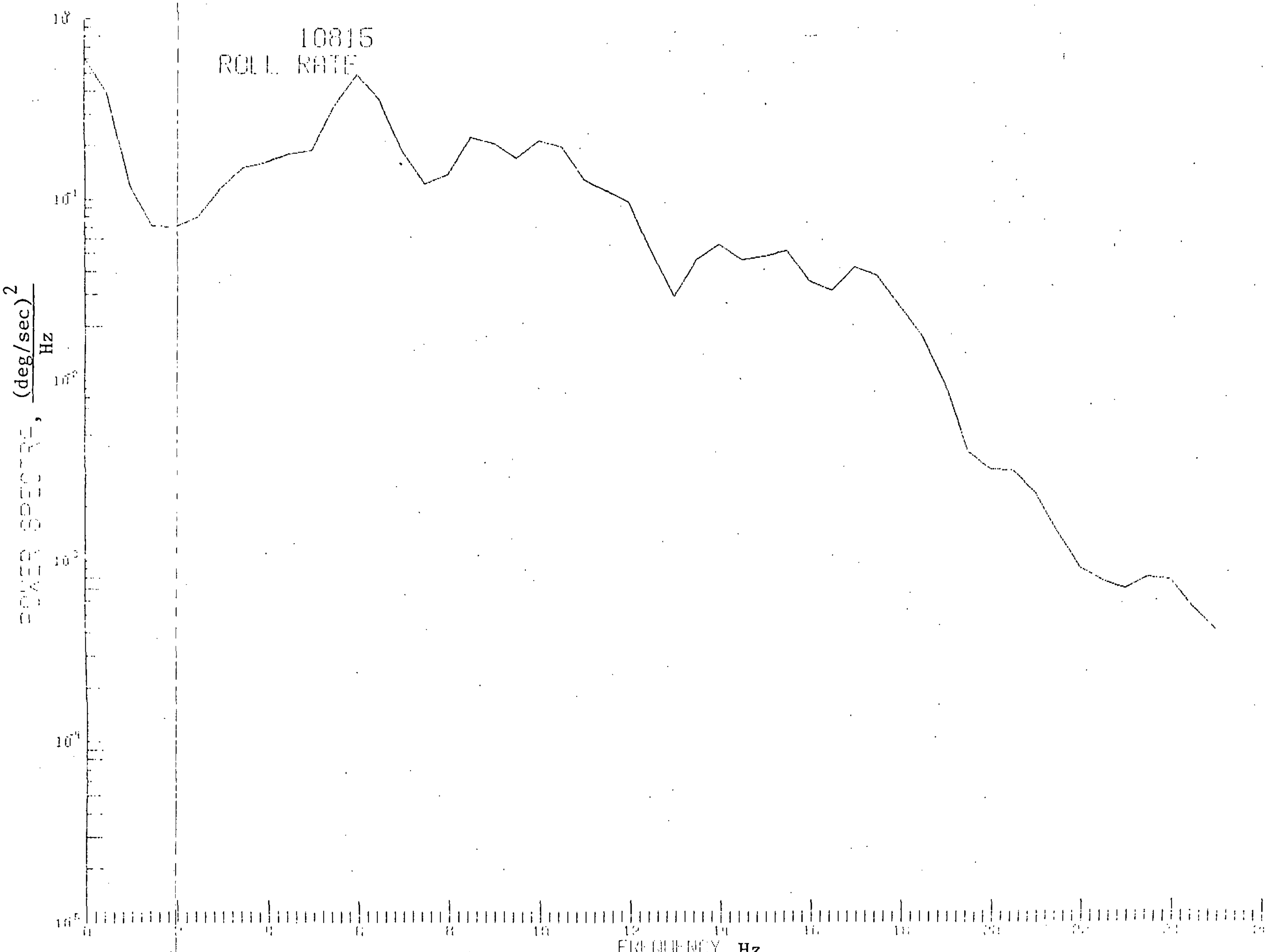
(c) Yawing velocity power spectrum (RMS yawing velocity 1.861 deg/sec)

Figure 9. Continued.



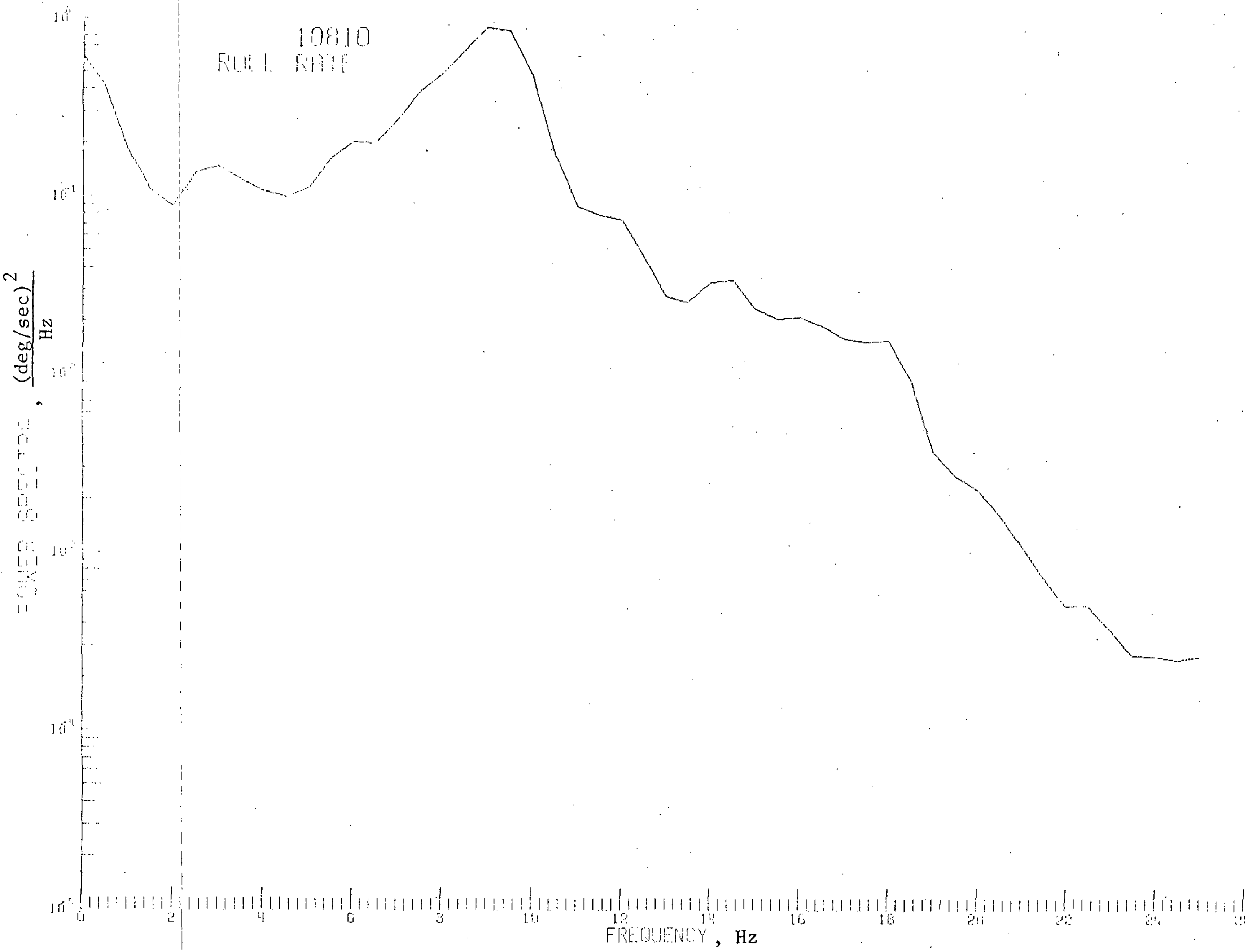
(c) Yawing velocity power spectrum (RMS yawing velocity 3.096 deg/sec)

Figure 9. Continued.



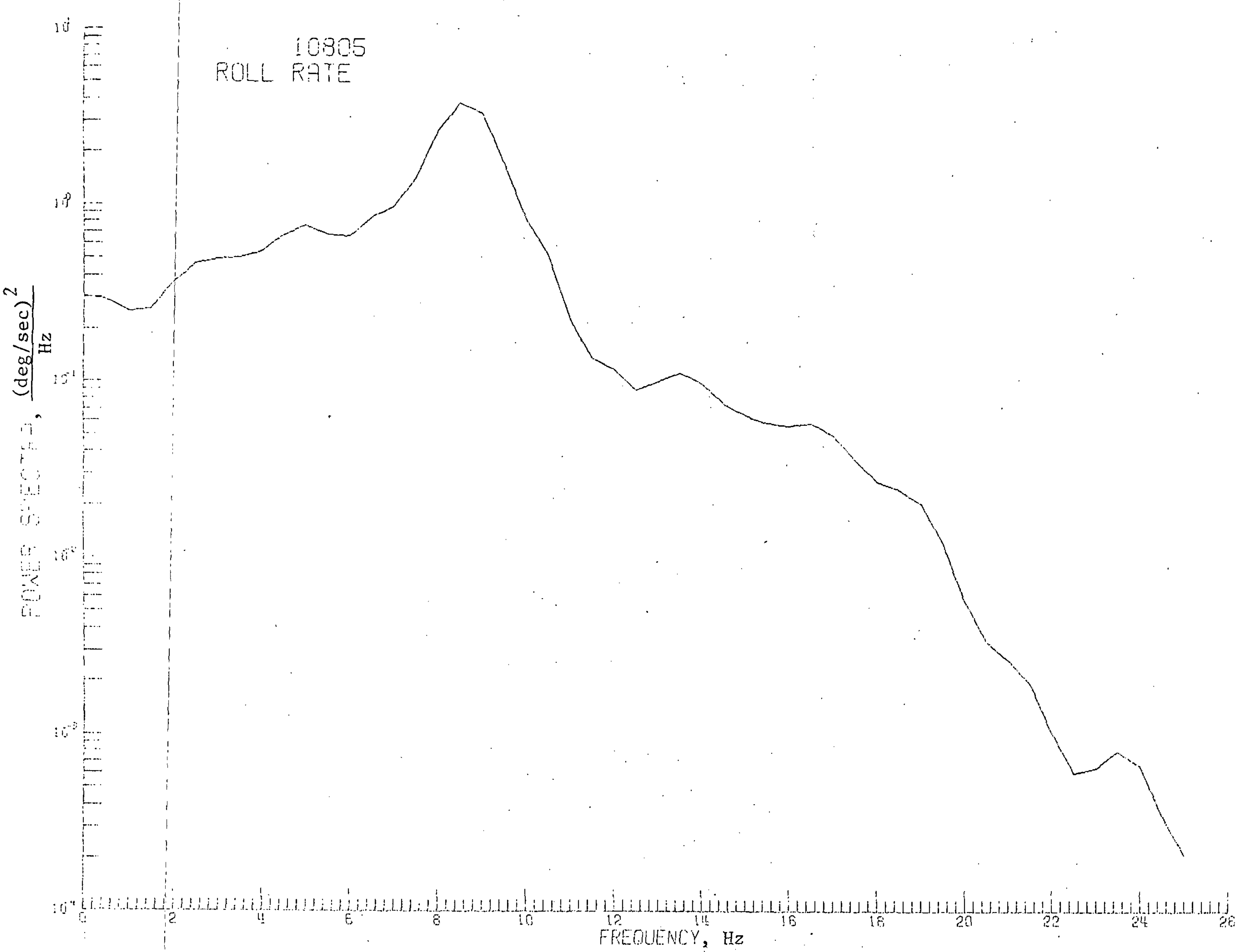
(d) Rolling velocity power spectrum (RMS rolling velocity 1.211 deg/sec)

Figure 9. Continued.



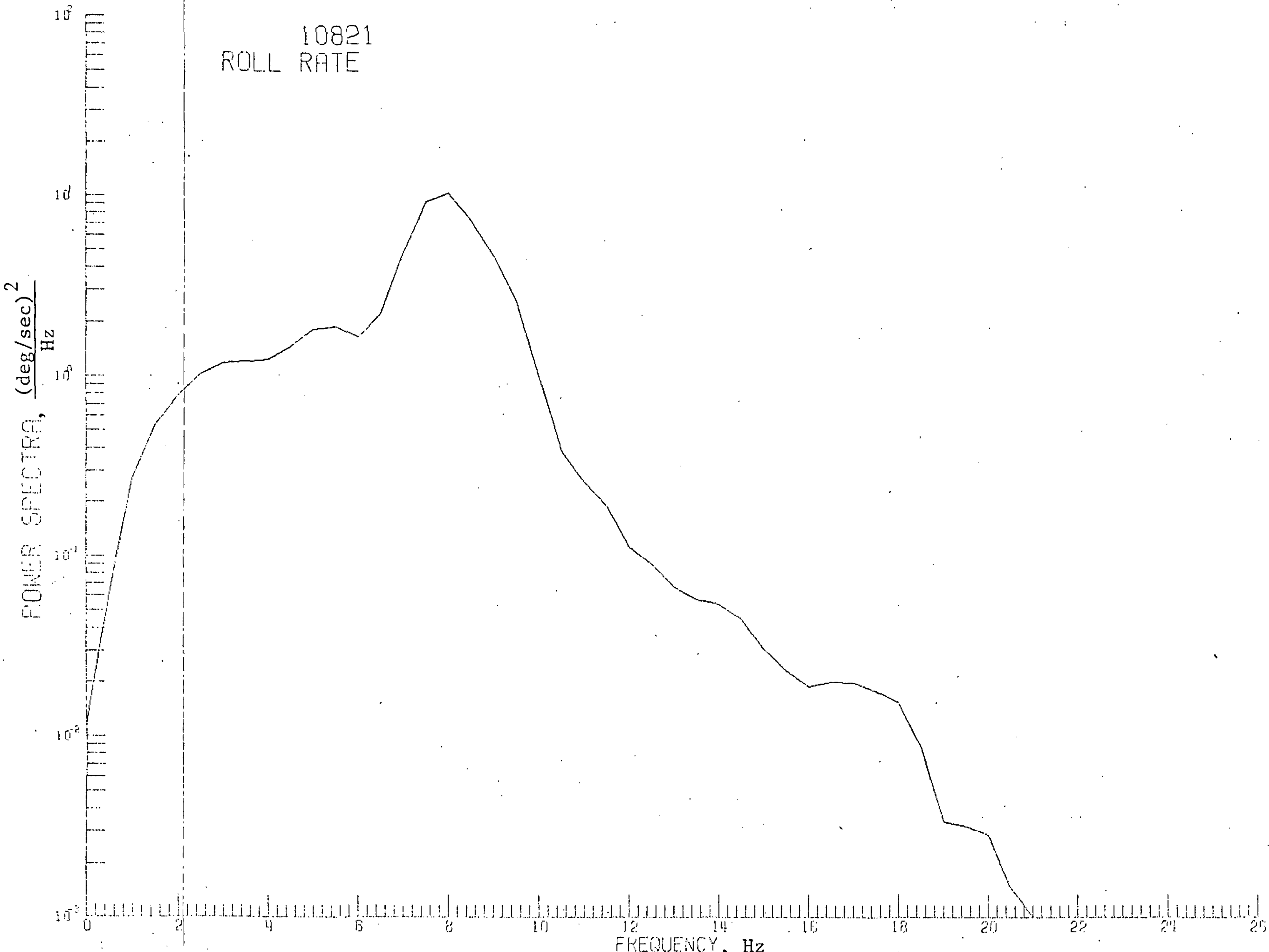
(d) Rolling velocity power spectrum (RMS rolling velocity 1.666 deg/sec)

Figure 9. Continued.



(d) Rolling velocity power spectrum (RMS rolling velocity 3.181 deg/sec)

Figure 9. Continued.



(d) Rolling velocity power spectrum (RMS rolling velocity 4.822 deg/sec)

Figure 9. Concluded.

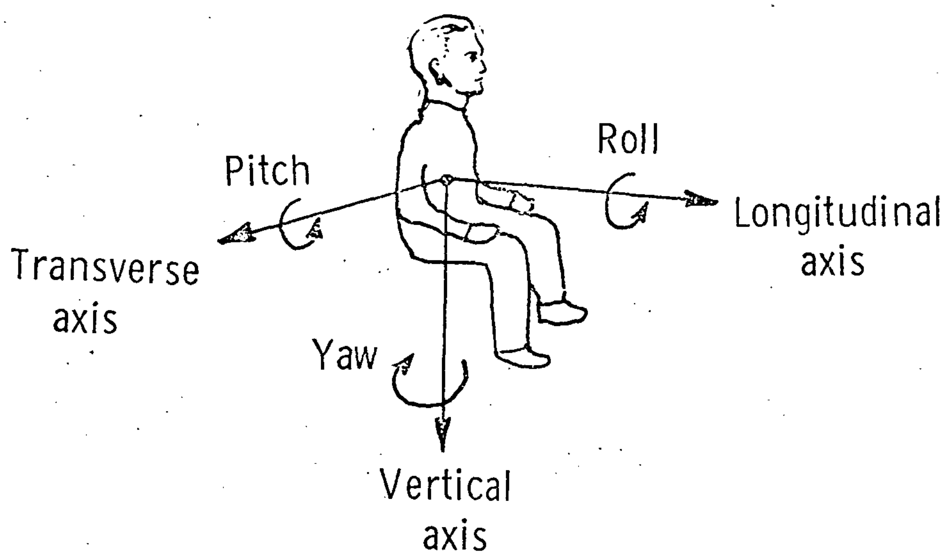


Figure 10- Reference axes.

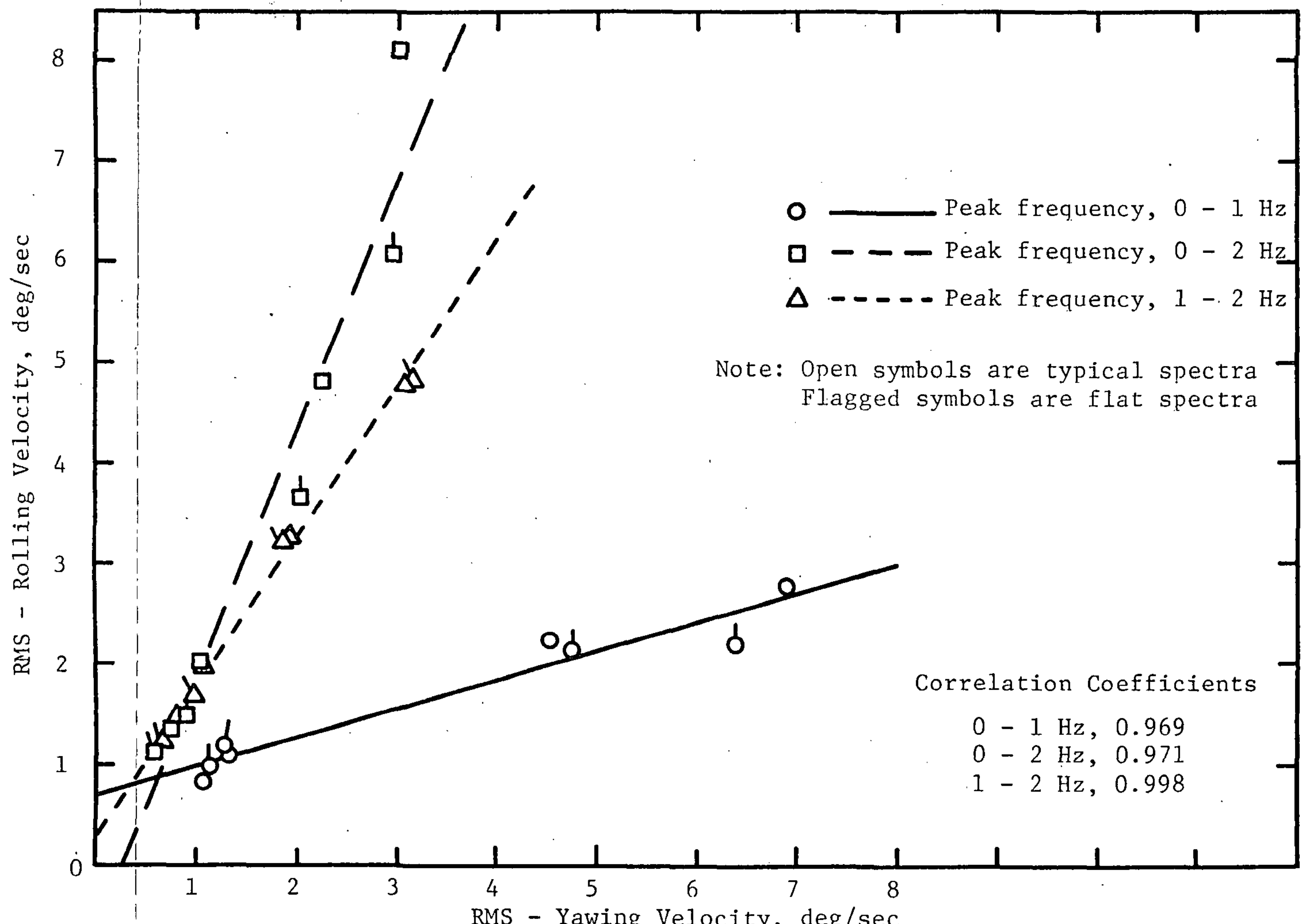
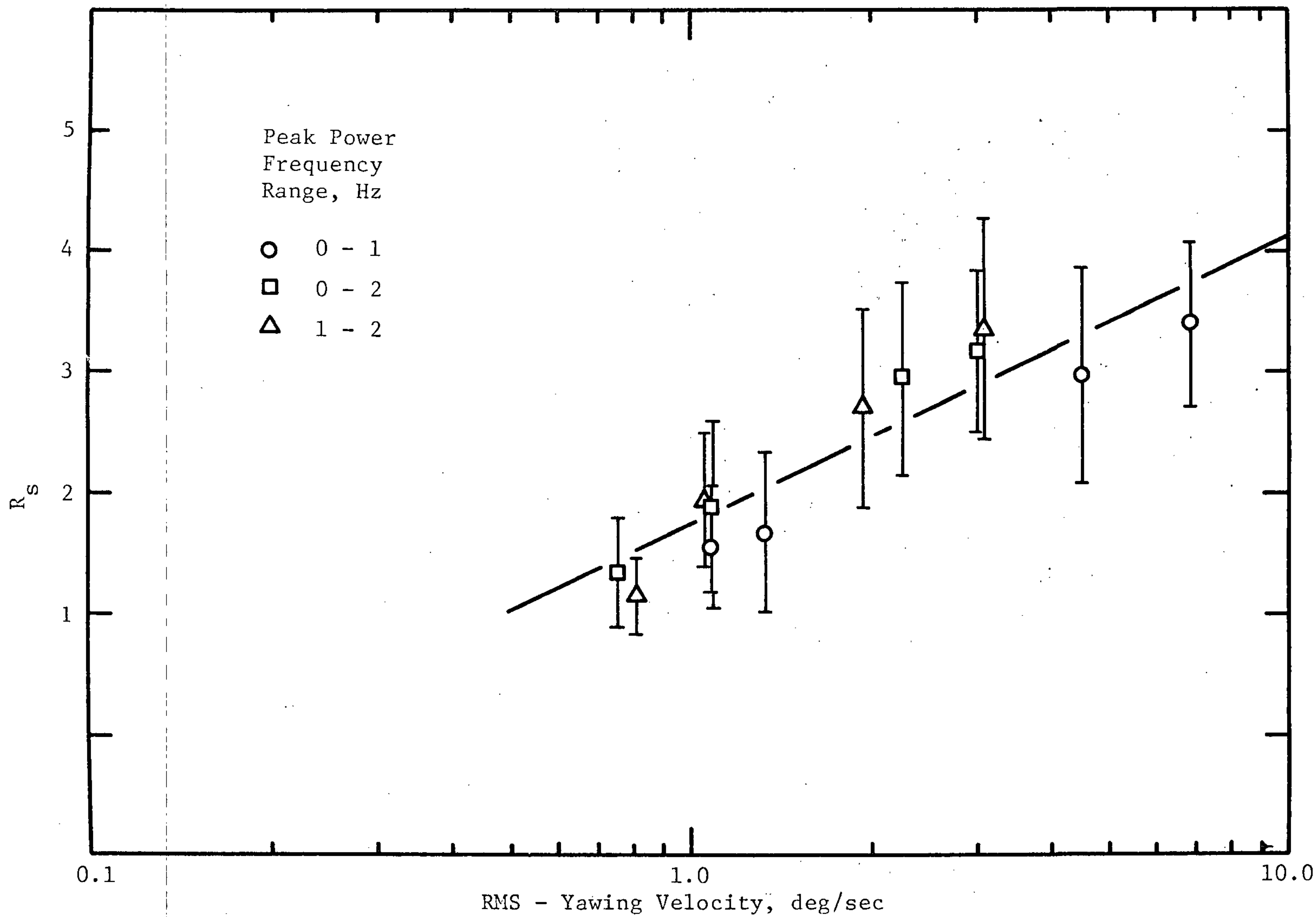
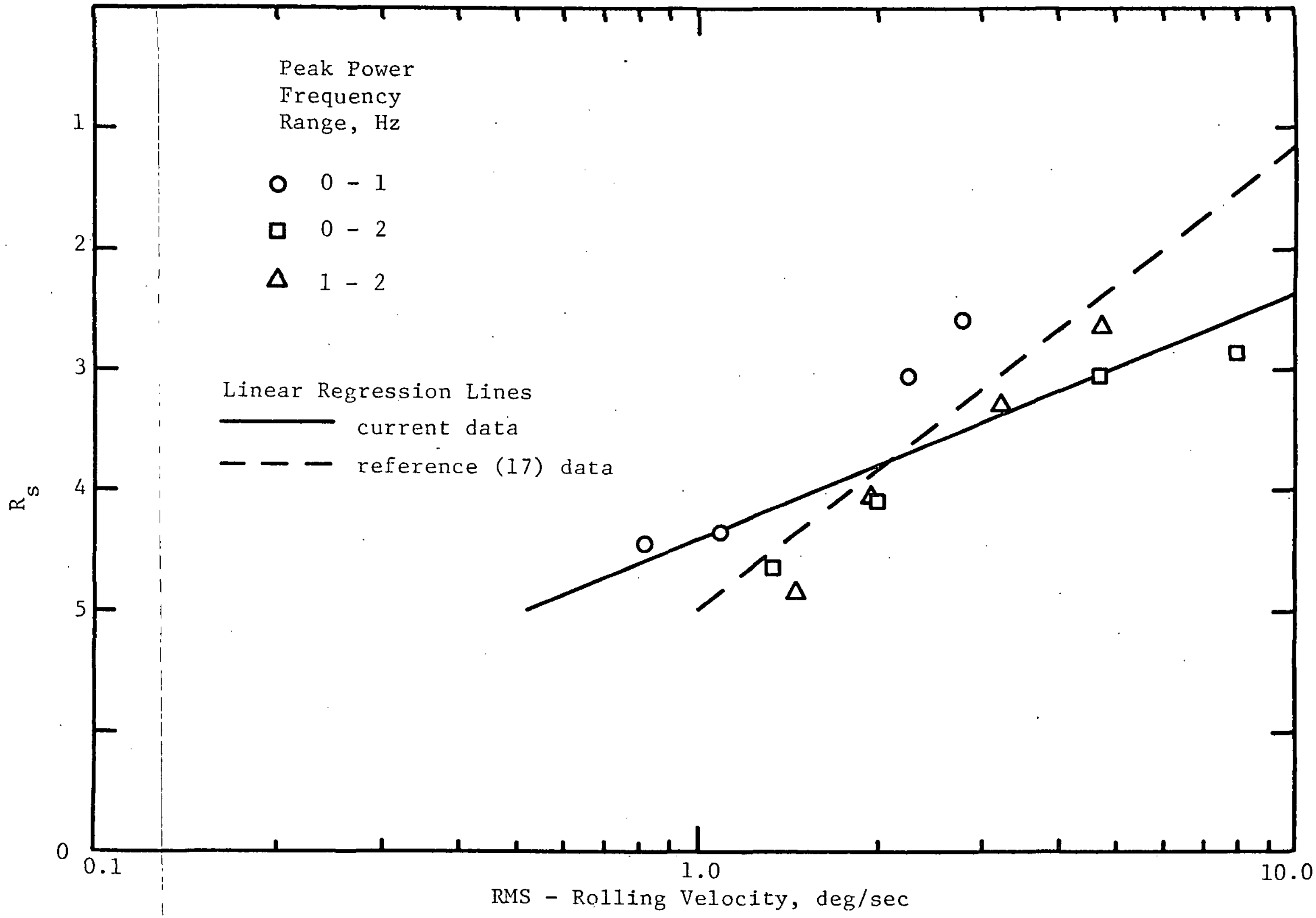


Figure 11. CORRELATION BETWEEN RMS ROLLING VELOCITY AND RMS YAWING VELOCITY



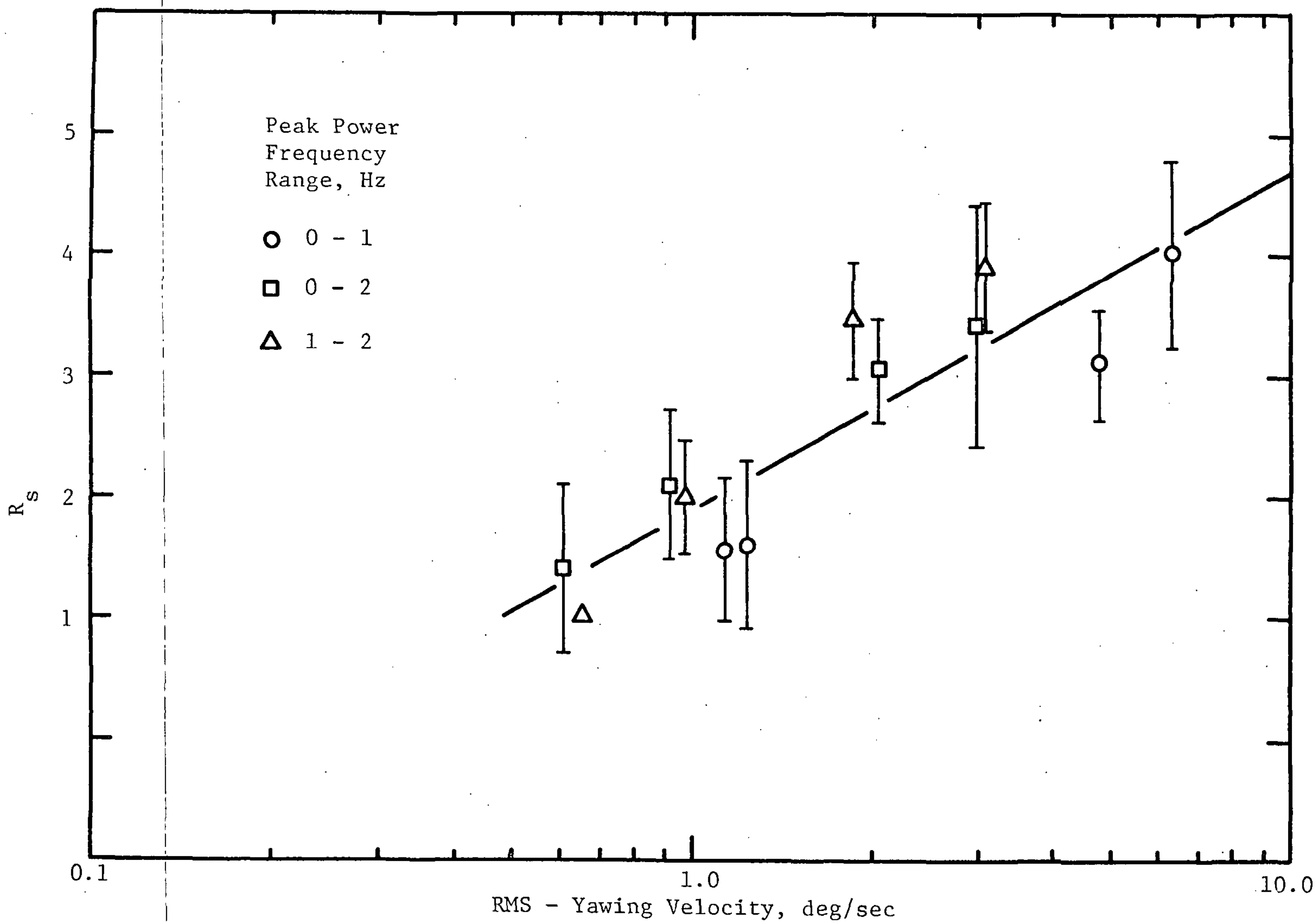
(a) R_s vs. RMS - Yawing velocity with typical power spectra

Figure 12. VARIATIONS OF RIDE COMFORT RESPONSE WITH ANGULAR VELOCITIES



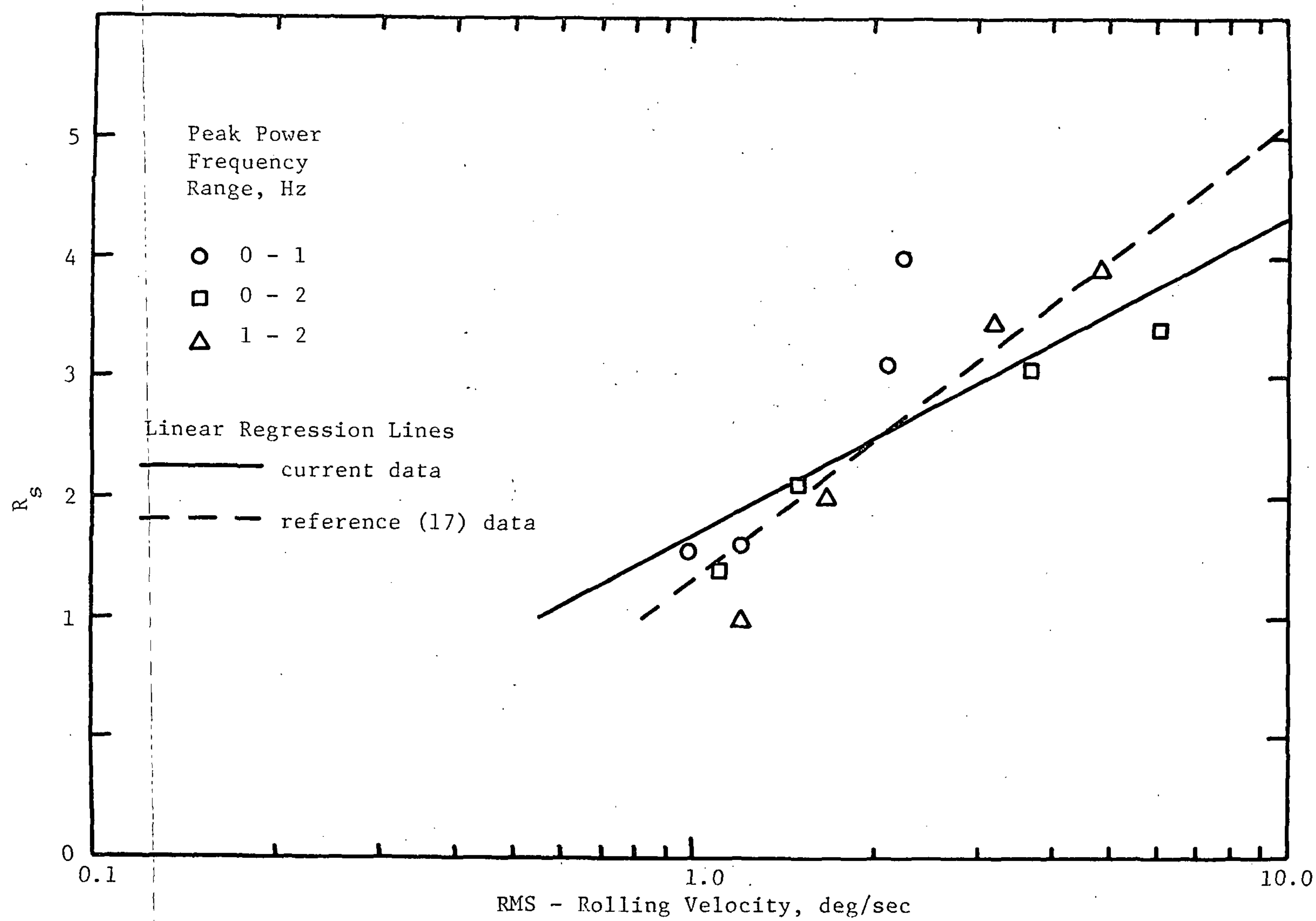
(b) R_s vs. RMS - Rolling velocity with typical power spectra

Figure 12. Concluded.



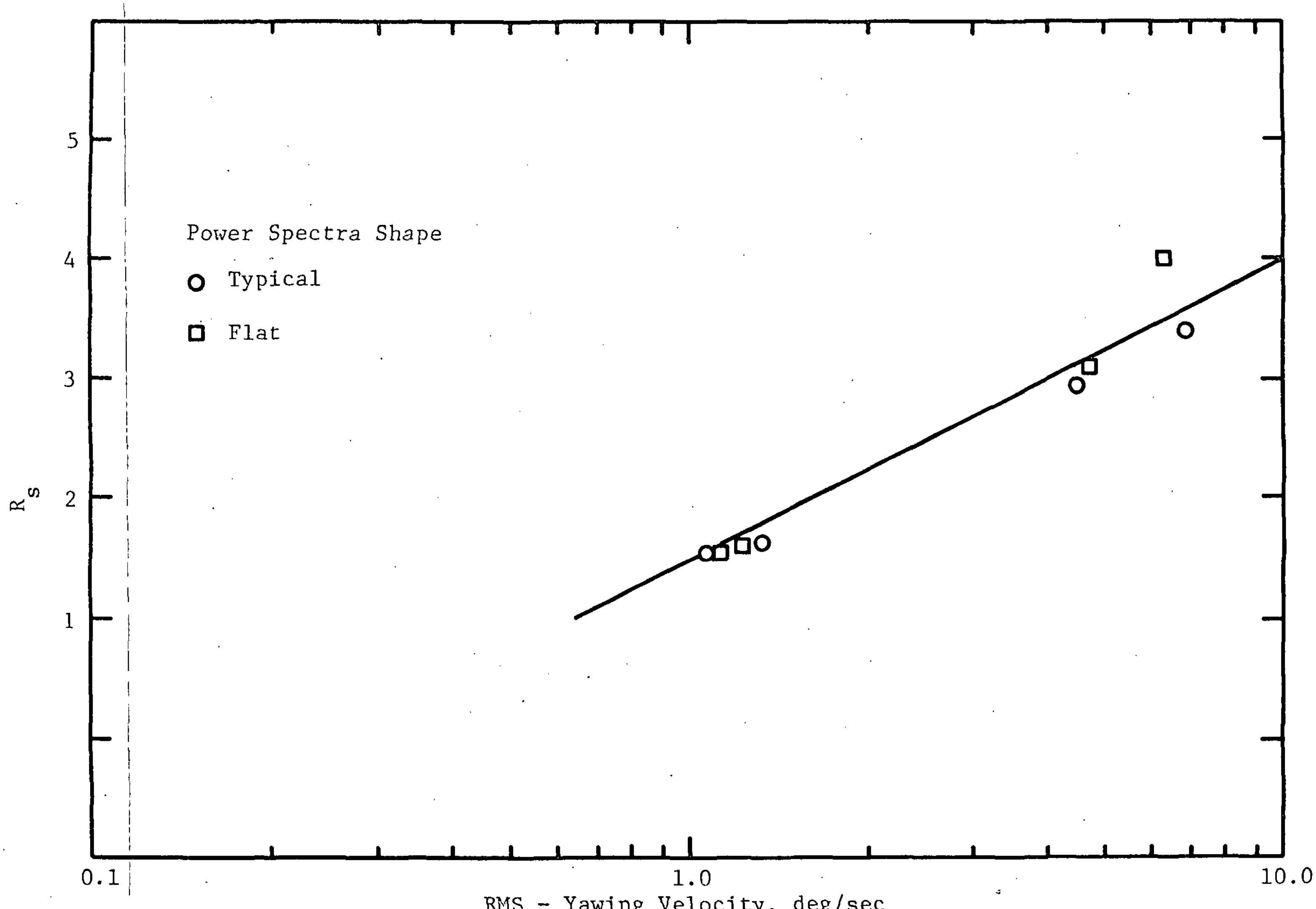
(a) R_s vs. RMS - Yawing velocity having flat power spectra

Figure 13. VARIATIONS OF RIDE COMFORT RESPONSE WITH ANGULAR VELOCITIES



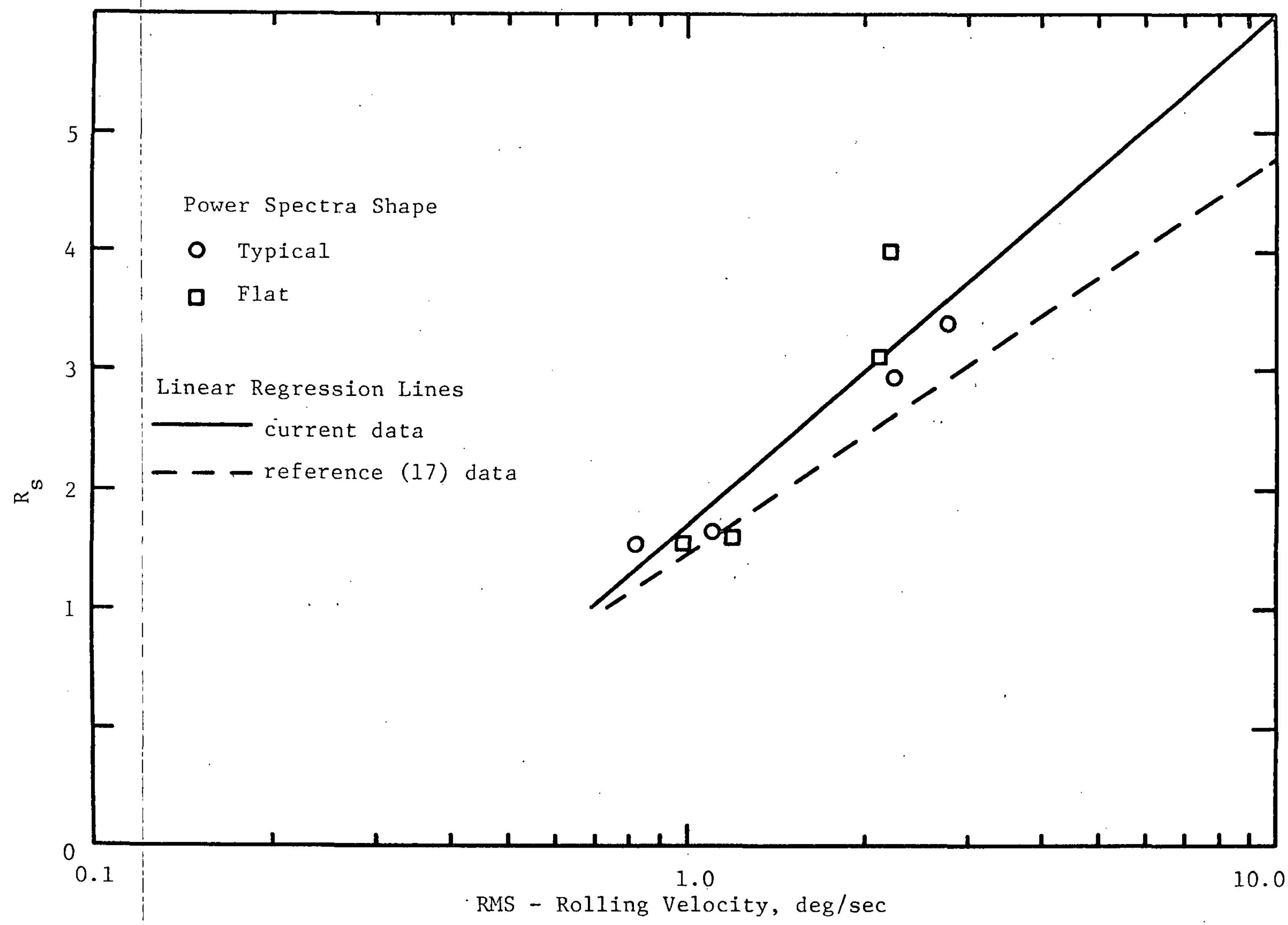
(b) R_s vs. RMS - Rolling velocity having flat power spectra

Figure 13. Concluded.



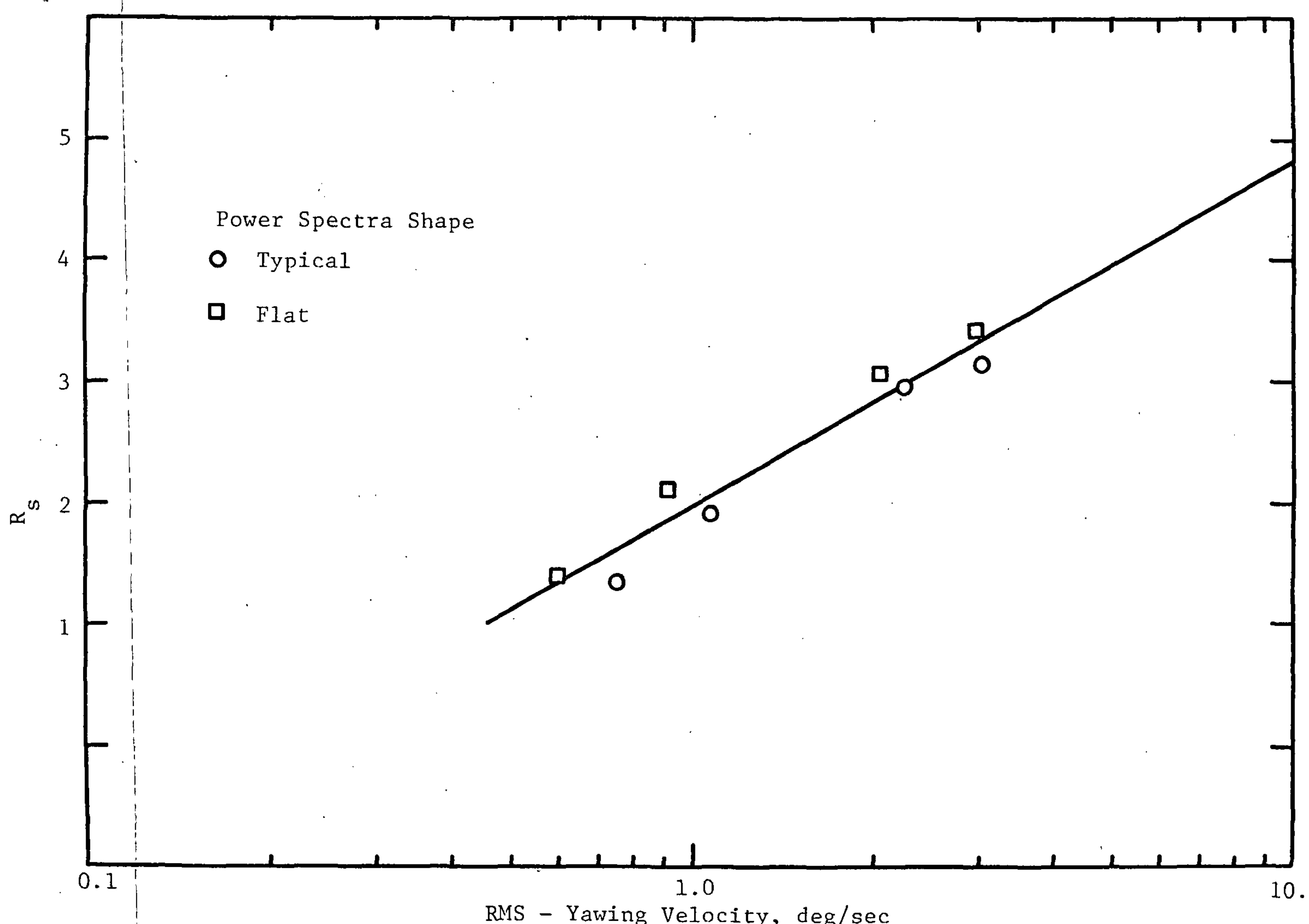
(a) R_s vs. RMS - Yawing velocity having peak power frequency ranges of 0 - 1 Hz

Figure 14. VARIATIONS OF RIDE COMFORT RESPONSE WITH ANGULAR VELOCITIES



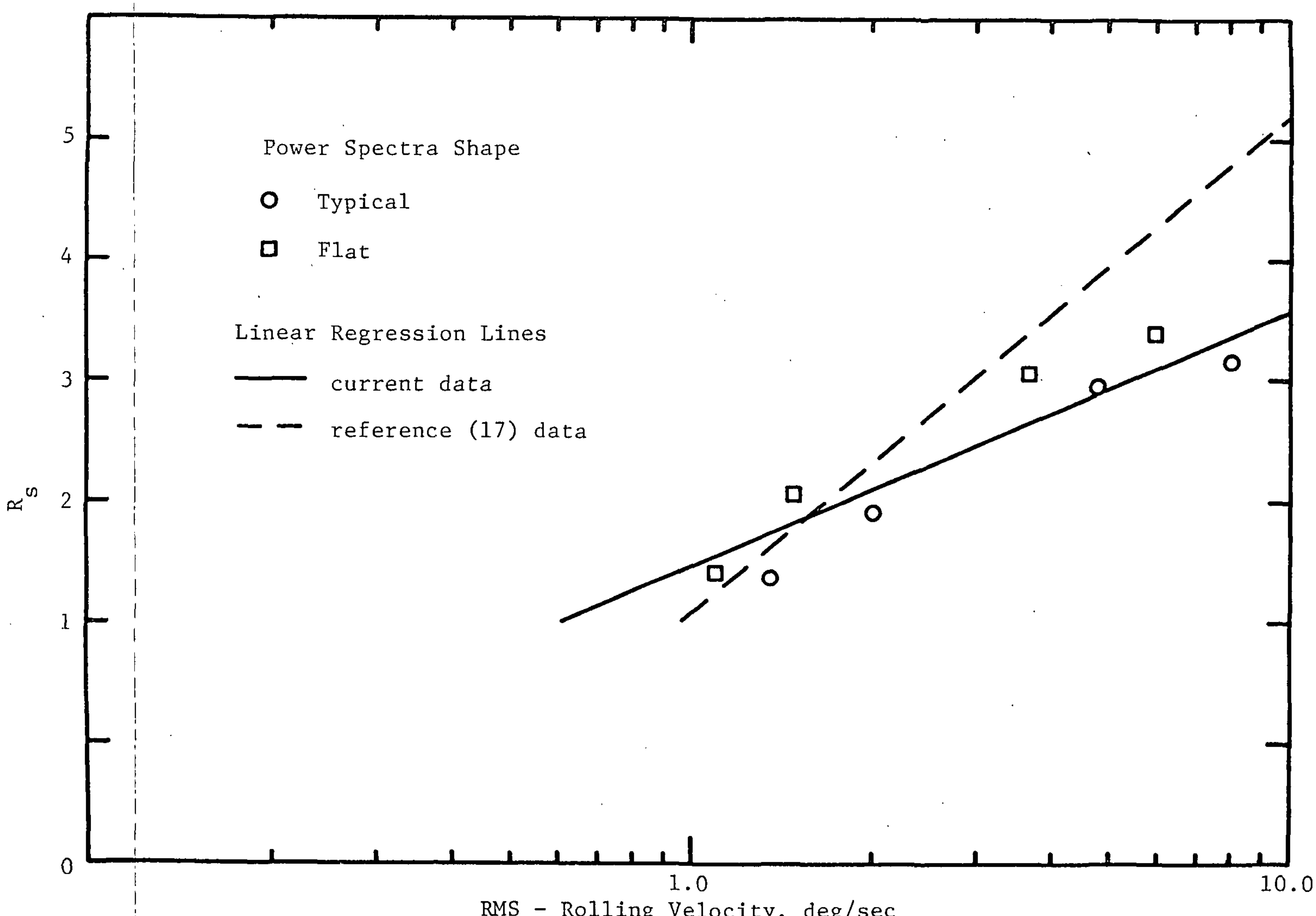
(b) R_s vs. RMS - Rolling velocity having peak power frequency ranges of 0 - 1 Hz

Figure 14. Concluded.



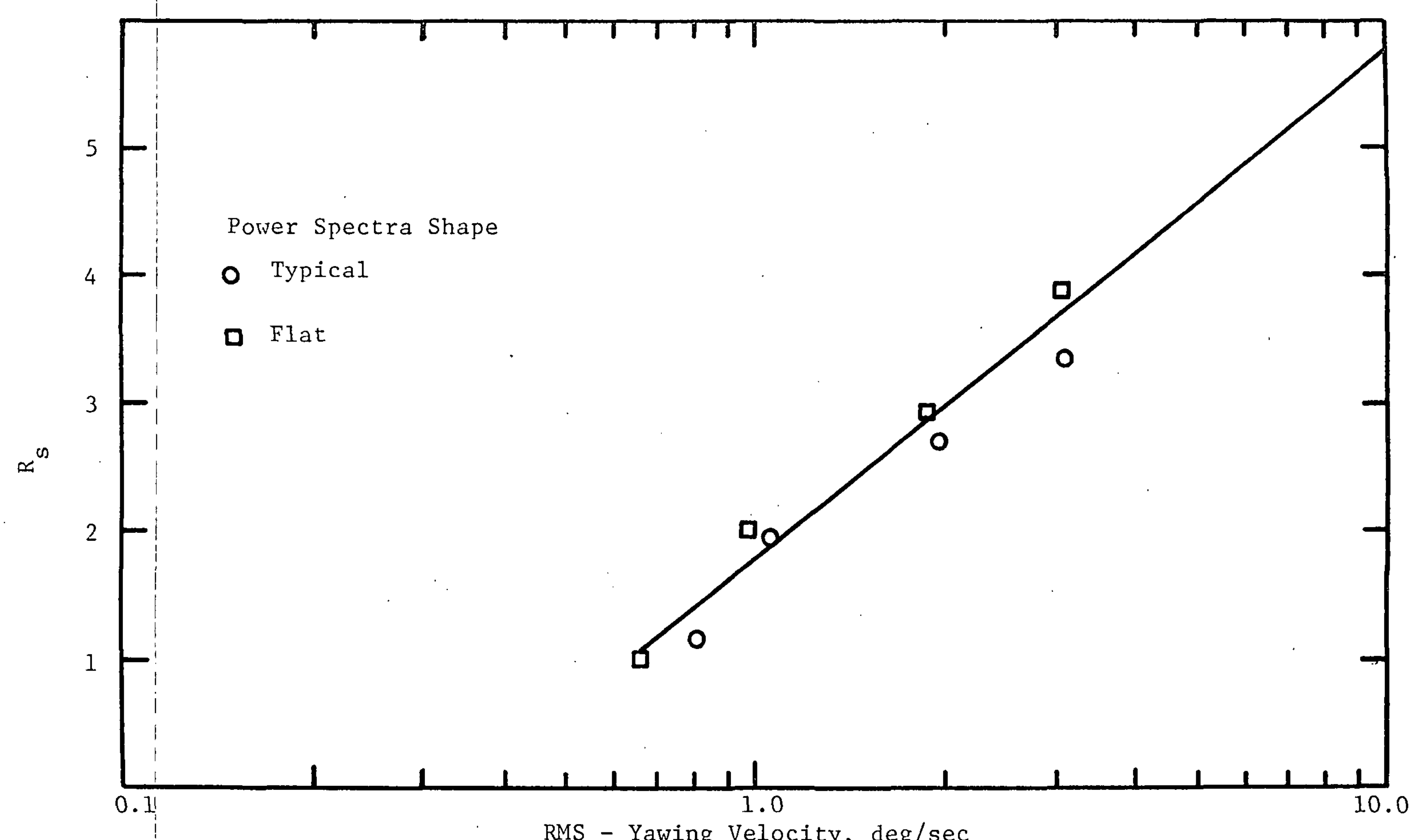
(a) R_s vs. RMS - Yawing velocity having peak power frequency ranges of 0 - 2 Hz

Figure 15. VARIATIONS OF RIDE COMFORT RESPONSE WITH ANGULAR VELOCITIES



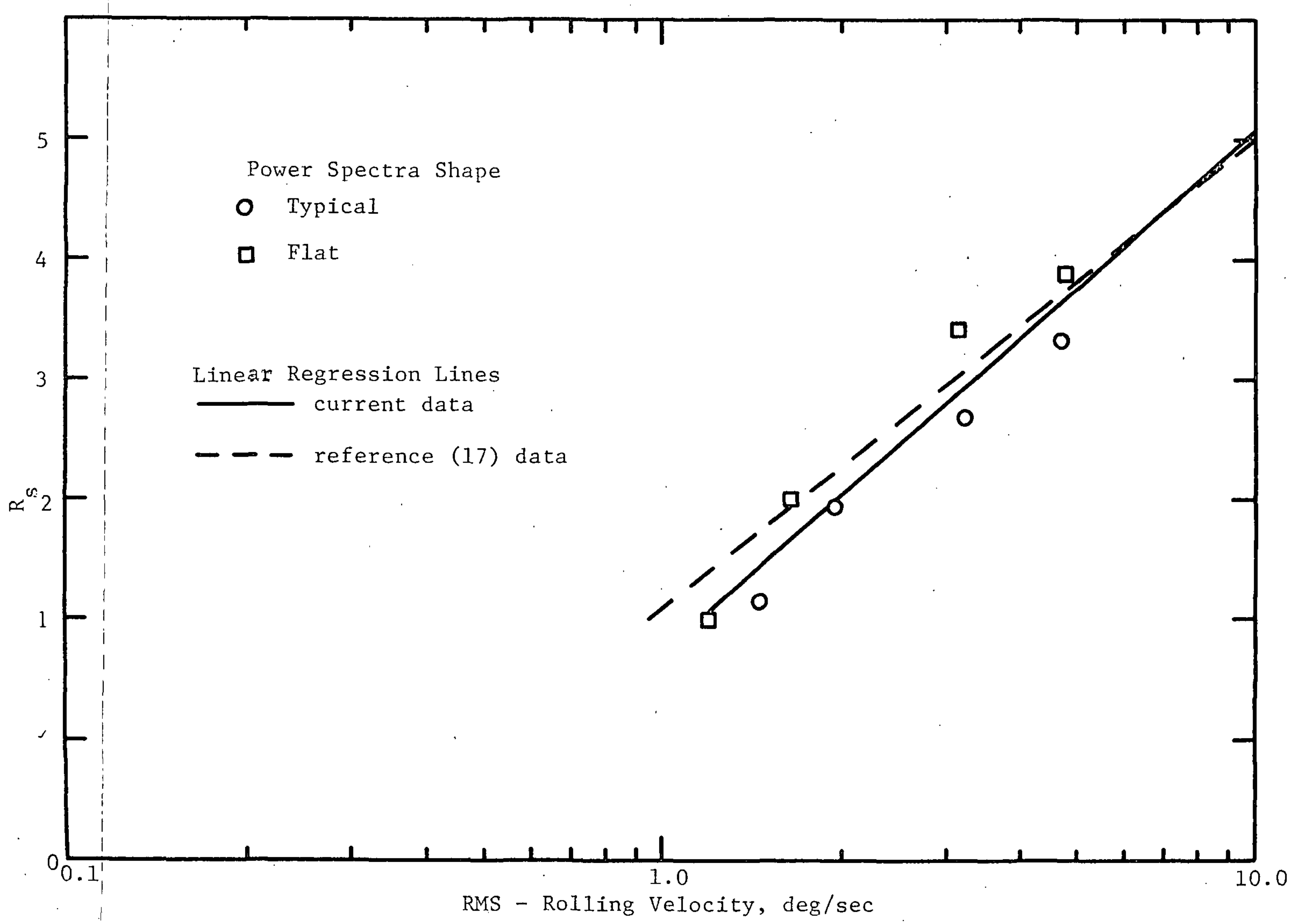
(b) R_s vs. RMS - Rolling velocity having peak power frequency ranges of 0 - 2 Hz

Figure 15. Concluded.



(a) R_s vs. RMS - Yawing velocity having peak power frequency ranges of 1 - 2 Hz

Figure 16. VARIATIONS OF RIDE COMFORT RESPONSE WITH ANGULAR VELOCITIES



(b) R_s vs. RMS - Rolling velocity having peak power frequency ranges of 1 - 2 Hz

Figure 16. Concluded.

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