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HUMAN COMFORT RESPONSE TO RANDOM MOTIONS WITH A DOMINANT ROLLING MOTION

Ralph W. Stone, Jr.

July 1975

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16. Abstract

Subjective ride comfort response ratings have been measured on the Langley Visual Motion Simulator with rolling velocity inputs with various power spectra shapes and magnitudes. The results show only little influence of spectra shape on comfort response. The effects of magnitude on comfort response indicate the applicability of psychophysical precepts for comfort modeling.

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HUMAN COMFORT RESPONSE TO RANDOM MOTIONS WITH A DOMINANT ROLLING MOTION

By Ralph W. Stone, Jr.

SUMMARY

The effects of random rolling velocities on passenger ride comfort response were examined on the 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 data obtained. There existed during this study motions in all other degrees of freedom, as well as the intended rolling motion, because of the characteristics of the simulator. These unwanted motions may introduce some interactive effects 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 a NASA program (ref. (2)). 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 degree of freedom motion of aircraft (refs. (3), (4), (5), (6), and (7), for example). The interactions of the various degrees of freedom of motion as they affect human comfort responses is not known. The nature of these interactions is important to the understanding of the total comfort response. In addition, data available for subjective comfort responses to single degree of freedom motions exist primarily for sinusoidal oscillations at specific frequencies (ref. (8)).

The influence of single degree of freedom motions having random oscillations typical of those of aircraft in turbulence also is not known. Typical airplane response to turbulence have power spectra shape that decreases rapidly beyond 1 to 2 Hertz. However, some response motions of the airplane

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(particularly the angular motion) have a somewhat flatter power spectra shape. It is not known if these different spectral shapes will have a significant influence on the ride comfort. Consequently, a program to measure human comfort response ratings 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 is in progress at the NASA Langley Research Center. References (9), (10), and (11) present the data obtained for the studies of the subjective ride comfort response to random vertical, transverse, and longitudinal accelerations, respectively. The present paper presents the subjective ride comfort response ratings obtained when using oscillations in the rolling degree of freedom on the Visual Motion Simulator at Langley (fig. 1).

SYMBOLS

R_s	ride quality rating
σ_{R_s}	standard deviation of ride quality rating
g	acceleration due to gravity
Hz	frequency, cps

TESTS AND TEST CONDITIONS

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, longitudinal acceleration 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 decreases rapidly beyond 1 to 2 Hertz. However, some responses, particularly for 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 variation 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.

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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 similar to those of the "typical" spectra. However, the "flat" spectra 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.

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. The desired motions are developed by extending the legs in a prescribed manner. In order to obtain the desired motions without exceeding the mechanical limitations of the simulator, various control and limiting systems were incorporated. The simulator, as a dynamic device, has its own natural frequencies and damping, and thus exerts an effect on the resulting motion. 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 had the rolling 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 mentioned previously were supposed to be alike for each input spectra shape; however, because of the dynamic response characteristics of the simulator, it provided different RMS values of the rolling velocities for the different spectra shapes.

Each "flight" was flown four to 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

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of the four or five "flights" used. The standard deviation of the rolling velocities from the average values for the various segments in terms of percent of the average values is 12.88 percent. The maximum deviation was 24.02 percent. The actual output of the simulator for a test segment representing most nearly the average output for a given input segment and, therefore, the motions essentially experienced by the subjects are presented in figures 4 to 9. Those include time histories for all six degrees of freedom, histograms of the rolling velocity and power spectral densities of the rolling velocities for the 24 segments of "flight" as follows:

Figure	Spectra shape	Frequency range
4	Typical	0-1 Hz
5	"	0-2 Hz
6	"	1-2 Hz
7	Flat	0-1 Hz
8	"	0-2 Hz
9	"	1-2 Hz

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

The reference axis used was relative to the seated passengers and is shown in figure 10. The rolling velocities used for this paper were along the rolling 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 alined with each axis, and three rate gyros also alined with each axis.

As noted previously, 24 segments of flight were used in examining the rolling 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 20second 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. (4) and (7), 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
2-1/2 = Somewhat comfortable
3 = Acceptable
3-1/2 = 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 deviation 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 rolling velocity.

As noted previously, the data presented herein are for rolling motion inputs and the existence of the other motion components in tables II and III are the result of 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 are in the subjective ride comfort responses presented in this paper. The RMS rolling velocity varied from 1.6 to 9.73 times larger than the RMS pitching or yawing velocities that occurred. These can be compared because they are similar types of stimulation to the rolling velocity. Because the linear RMS accelerations are a different form of stimulation than the angular velocities, no comparison as to their relative significance to the RMS rolling velocity can be directly made. It should be noted that the values of linear acceleration range from about 0.0074 to 0.056 g, and have an average value of 0.021 g. These values generally exceed the values normally established as thresholds of preception for linear

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acceleration (see, for example, refs. (12) and (13)). Subjects exposed to these motions may, therefore, have been cognizant of the existence of linear acceleration during the study. Whether these accelerations were sufficient to alter the subjective ride comfort ratings will not be clear until the interactive effects of multiple degrees of freedom are understood.

The subjective ride comfort responses presented on table II have an average standard deviation for all 24 segments of 0.715. This compares favorably with other experience as, for example, the average standard deviation for the results of reference (7) is 0.758 units of response rating. The value of 0.715 for this rolling velocity study compares favorably with those for other motion components presented in references (9), (10), and (11).

As expected, there is a progressive increase in response ratings with increasing rolling velocity. The variation (table II) is not, however, a linear function of rolling velocity. The subjective ride comfort responses are, therefore, plotted against the $\log_{10}$ of the RMS rolling velocities for typical power spectra in figure 11 and for flat power spectra in figure 12. Thus plotted, the data show a nearly linear variation of the response, with the $\log_{10}$ of the rolling velocity stimulus. This observation implies that the comfort response to RMS rolling velocities conforms to the laws of psychophysical responses, wherein the response varies with the $\log_{10}$ of the stimulus (ref. (14)).

CONCLUDING REMARKS

A study has been made on the Langley Visual Motion Simulator to examine the influence of random rolling velocities on human subjective ride comfort responses. The effects of two general shapes of power spectral density of the rolling 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 rolling velocities, because of the characteristics of the simulator there occurred in the study some amounts of motion in all other degrees of freedom. Analysis of these data must maintain cognizance of this fact. The response data appear to vary linearly with the $\log_{10}$ of the rolling RMS velocities indicating congruity with psychophysical law.

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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 ROLLING 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							
0.0096	0.0122	0.0095	0.9544	1.7686	0.8327	2.100	0.843
.0105	.0165	.0113	.9235	2.4855	.8071	3.000	.624
.0146	.0284	.0186	.9187	6.0854	.7137	3.300	.810
.0178	.0373	.0202	1.0220	7.1084	.8202	4.500	.756
(b) Typical 0-2 Hz inputs							
0.0113	0.0135	0.02113	1.1089	1.7775	0.9465	1.750	0.540
.0137	.0200	.0152	1.0240	2.2539	.8625	2.500	.667
.0212	.0358	.0247	1.1803	4.0481	.9271	3.375	.876
.0309	.0552	.0368	1.4186	6.1042	.9348	4.150	.852
(c) Typical 1-2 Hz inputs							
0.0103	0.0123	0.0099	0.9783	1.5786	0.8387	1.375	0.518
.0132	.0207	.01710	1.0798	2.4882	.9154	2.650	.784
.0196	.0352	.0238	1.1486	3.7420	.9008	3.500	.850
.0259	.0510	.0323	1.0013	5.2493	.6297	3.850	.852

TABLE II.- MEAN RMS VALUES OF MEASURED MOTION COMPONENTS WITH ROLLING VELOCITY INPUTS AND MEAN RIDE COMFORT RESPONSES (CONTINUED)

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							
0.0082	0.0116	0.0083	0.7954	1.5315	0.6819	2.100	0.568
.0087	.0165	.0107	.6250	2.2713	.5312	2.700	.715
.0153	.0323	.0187	.7960	5.8136	.5896	3.850	.709
.0195	.0441	.0227	.9787	7.1358	.7334	4.900	.316
(e) Flat 0-2 Hz inputs							
0.0077	0.0102	0.0078	0.7309	1.2312	0.6139	1.350	0.580
.0115	.0186	.0139	.7644	1.9809	.5896	2.750	.589
.0184	.0323	.0212	.7866	3.1771	.4379	3.438	1.050
.0276	.0522	.0321	1.1885	5.2468	.6938	4.200	.715
(f) Flat 1-2 Hz inputs							
0.0074	0.0097	0.0077	0.6708	1.1677	0.5522	1.800	0.823
.0112	.0202	.0161	.8064	2.2195	.6012	2.400	.699
.0183	.0357	.0245	.9629	3.5383	.6451	3.450	.550
.0273	.0557	.0334	1.0650	5.2196	.6557	3.900	.876

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

Longitudinal -Vertical	Longitudinal -Pitch	Transverse -Roll	Transverse -Yaw	Vertical -Pitch	Roll -Yaw
(a) Typical 0-1 Hz inputs					
0.9404	0.9458	0.7880	0.8425	0.9465	0.9050
.8102	.8361	.4731	.6627	.8049	.7000
.4407	.2868	.1119	.2141	.2880	.2287
.6259	.6164	.2363	.3543	.5130	.3909
(b) Typical 0-2 Hz inputs					
0.8380	0.9172	0.7209	0.8202	0.9196	0.9327
.4596	.6088	.2021	.4755	.5936	.6686
.3298	.3992	- .0286	.2602	.4031	.4573
.2312	.1910	- .1066	.0929	.1543	.2078
(c) Typical 1-2 Hz inputs					
0.8354	0.9221	0.7581	0.8540	0.9120	0.9565
.4394	.7204	.2410	.5440	.6921	.6984
.4479	.4886	.0929	.3550	.4544	.4343
.4135	.1747	.0314	.1572	.2055	.0745

TABLE III.- CROSS-CORRELATION COEFFICIENTS OF MOTION COMPONENTS WITH ROLLING VELOCITY INPUTS (CONTINUED)

Longitudinal -Vertical	Longitudinal -Pitch	Transverse -Roll	Transverse -Yaw	Vertical -Pitch	Roll -Yaw
(d) Flat 0-1 Hz inputs					
0.8069	0.8893	0.5961	0.7053	0.8606	0.8071
.4380	.5177	.1471	.2572	.5103	.4260
.4976	.3240	.2132	.3147	.3352	.2210
.5498	.3599	.2478	.3877	.3287	.1611
(e) Flat 0-2 Hz inputs					
0.6864	0.8662	0.5650	0.7364	0.8447	0.8444
.3114	.6119	.1215	.4350	.5719	.5079
.1624	.1234	- .0617	.1367	.2145	- .0289
(f) Flat 1-2 Hz inputs					
0.6541	0.8545	0.5404	0.7453	0.8243	0.8108
.1528	.5343	.0288	.3871	.5457	.4030
.2243	.2955	- .0787	.1803	.4168	.1092
.1412	- .0022	- .0888	.1837	.1505	- .2936

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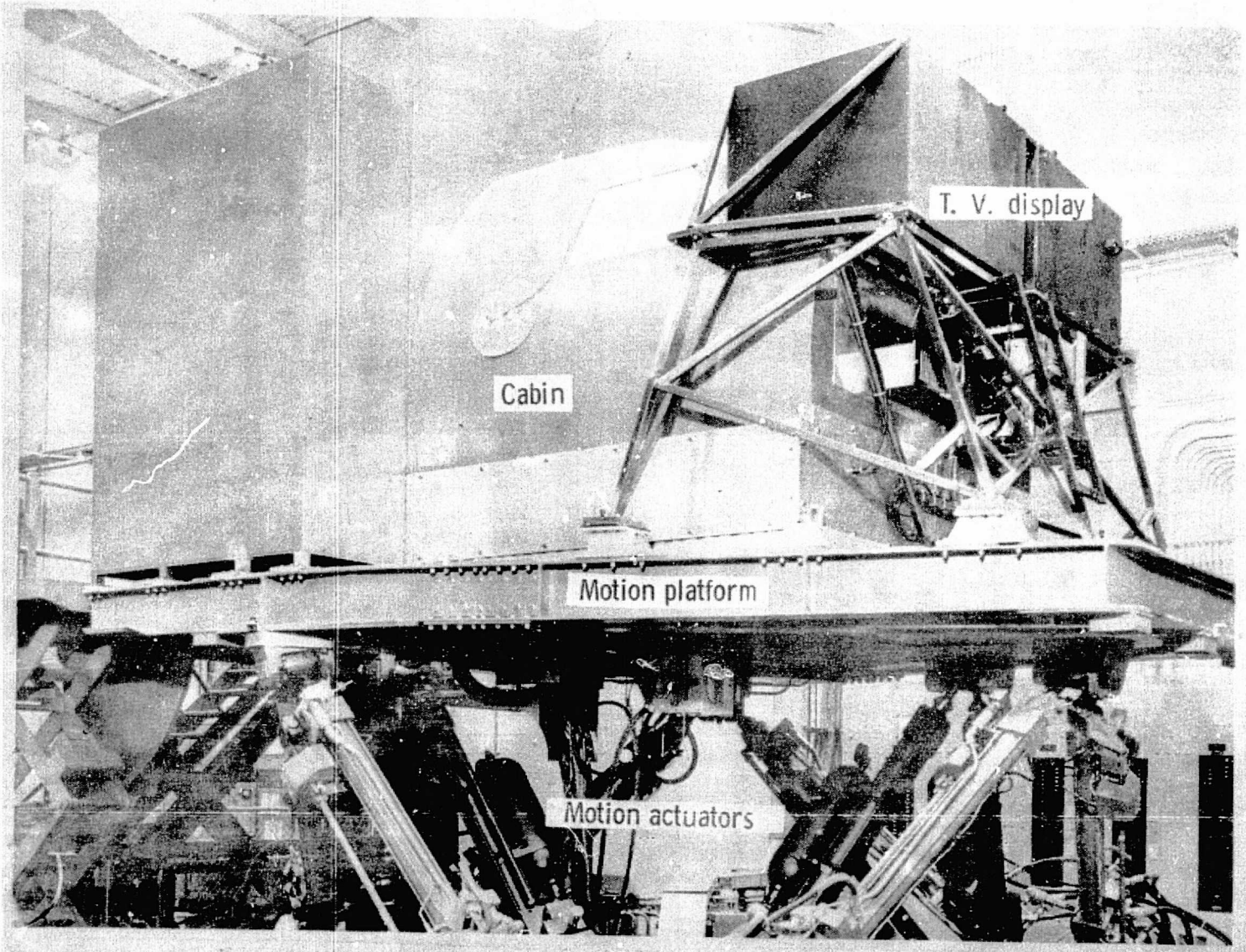
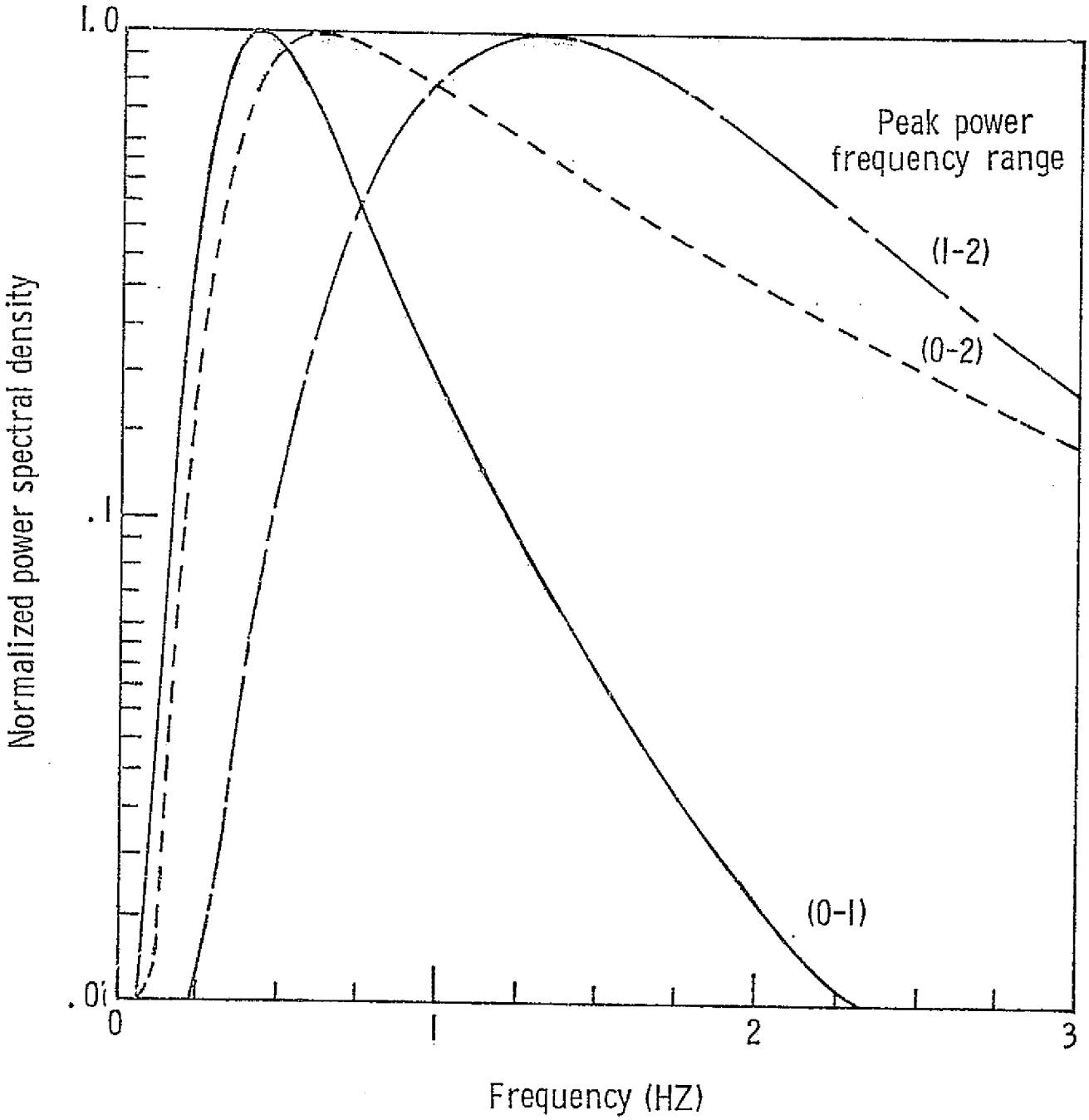
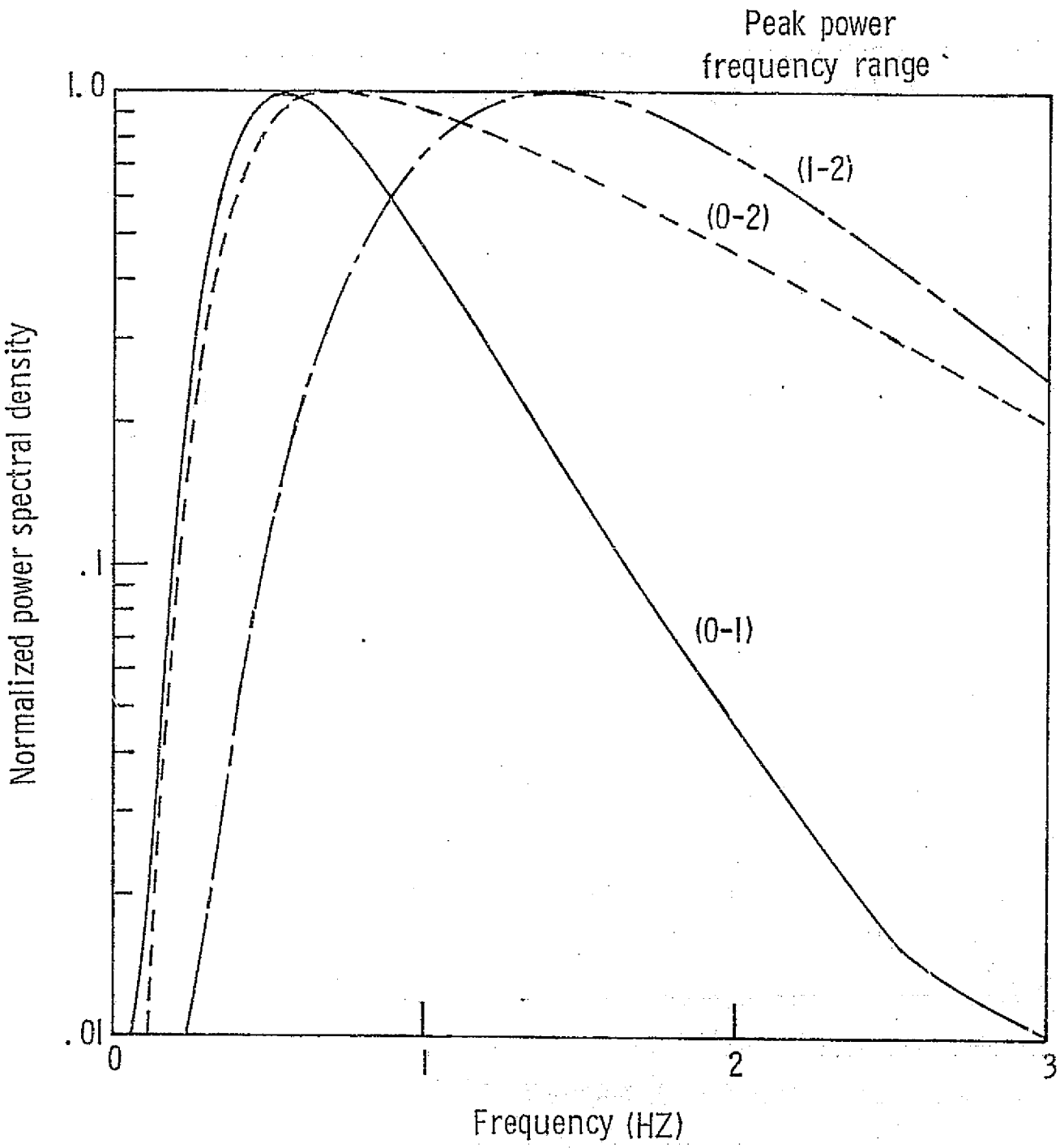


Figure 1.- Langley six-degree-of-freedom visual-motion simulator.



(a) Typical spectra.

Figure 2.- Nominal power spectra of motion components.



(b) Flat spectra

Figure 2.- Concluded.

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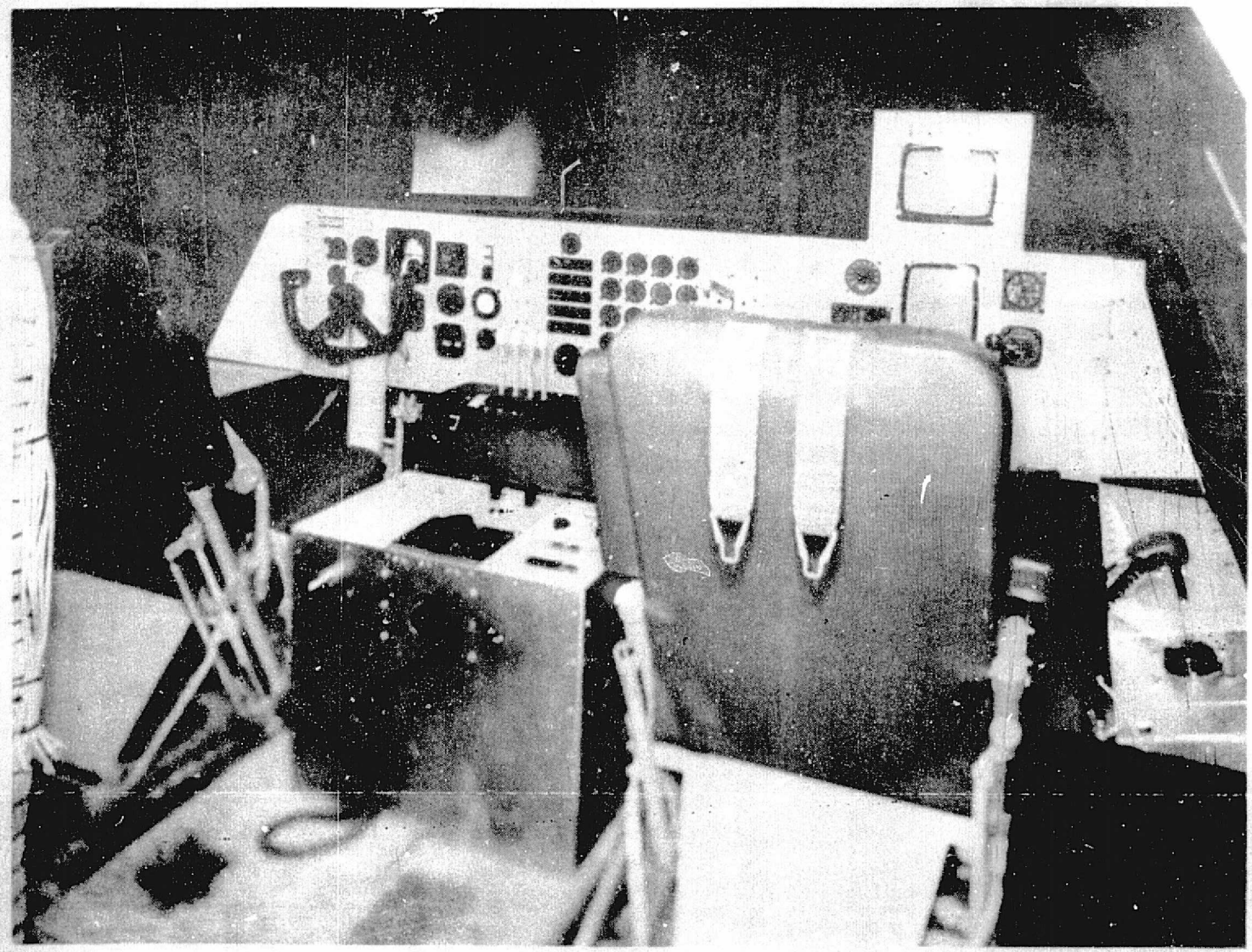
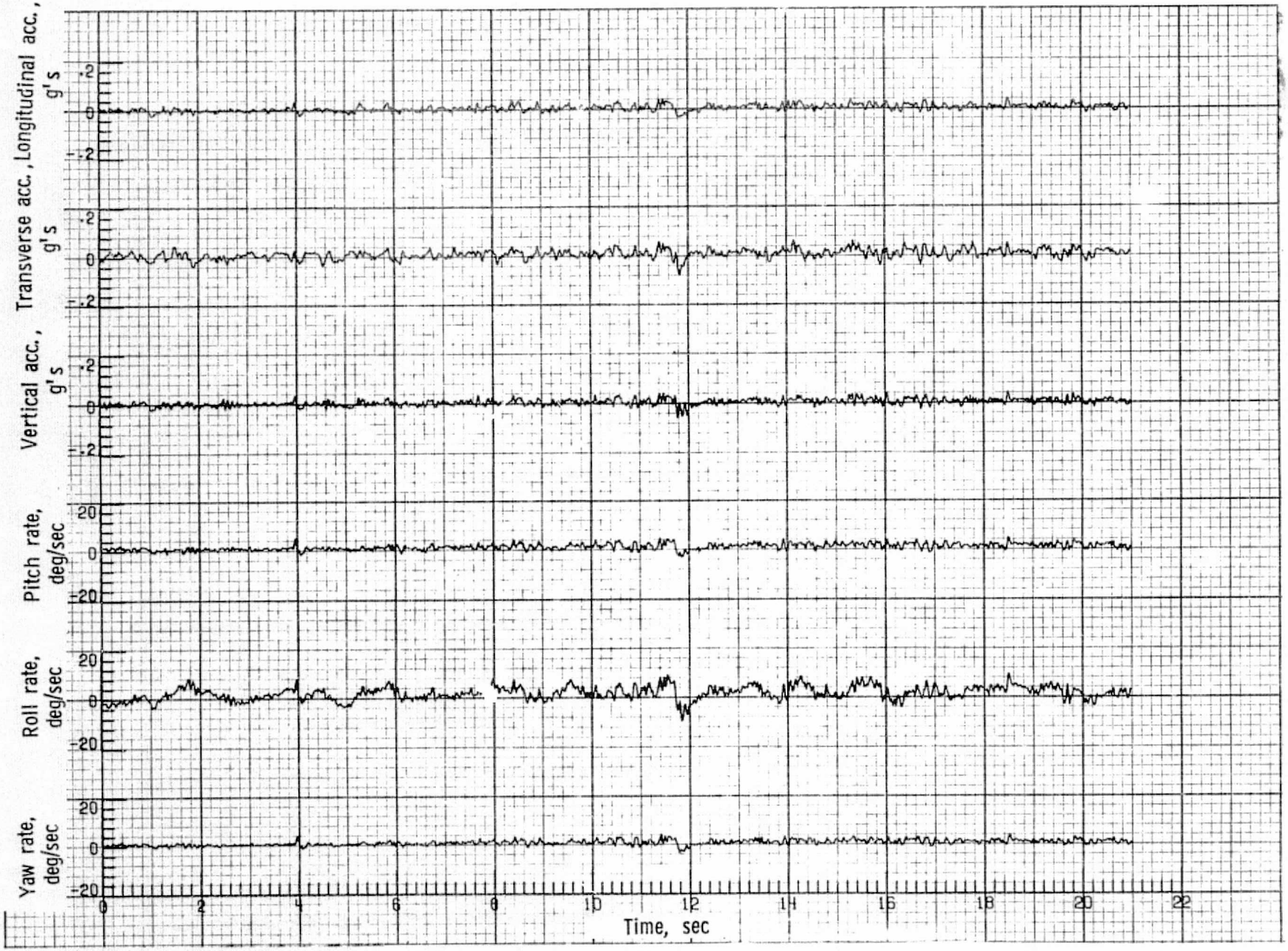


Figure 3.- Interior of Langley Six-Degree-of-Freedom, Visual Motion Simulator.

(a) Time histories (RMS rolling velocity 1.769 deg/sec).

Figure 4.- Measured motion characteristics using rolling velocity with typical 0-1 Hz inputs.



(a) Time histories (RMS rolling velocity 2.486 deg/sec).

Figure 4.- Continued.

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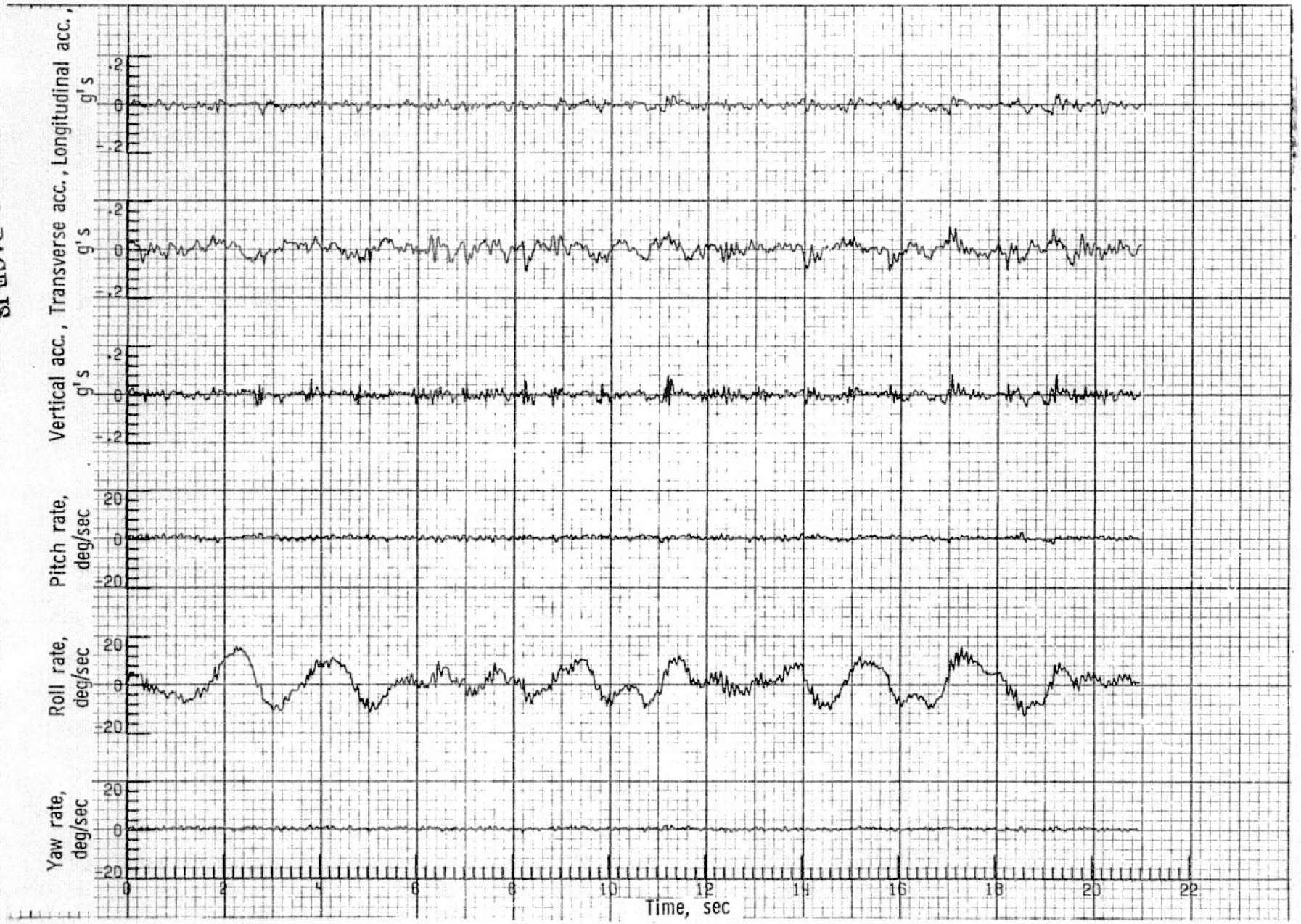
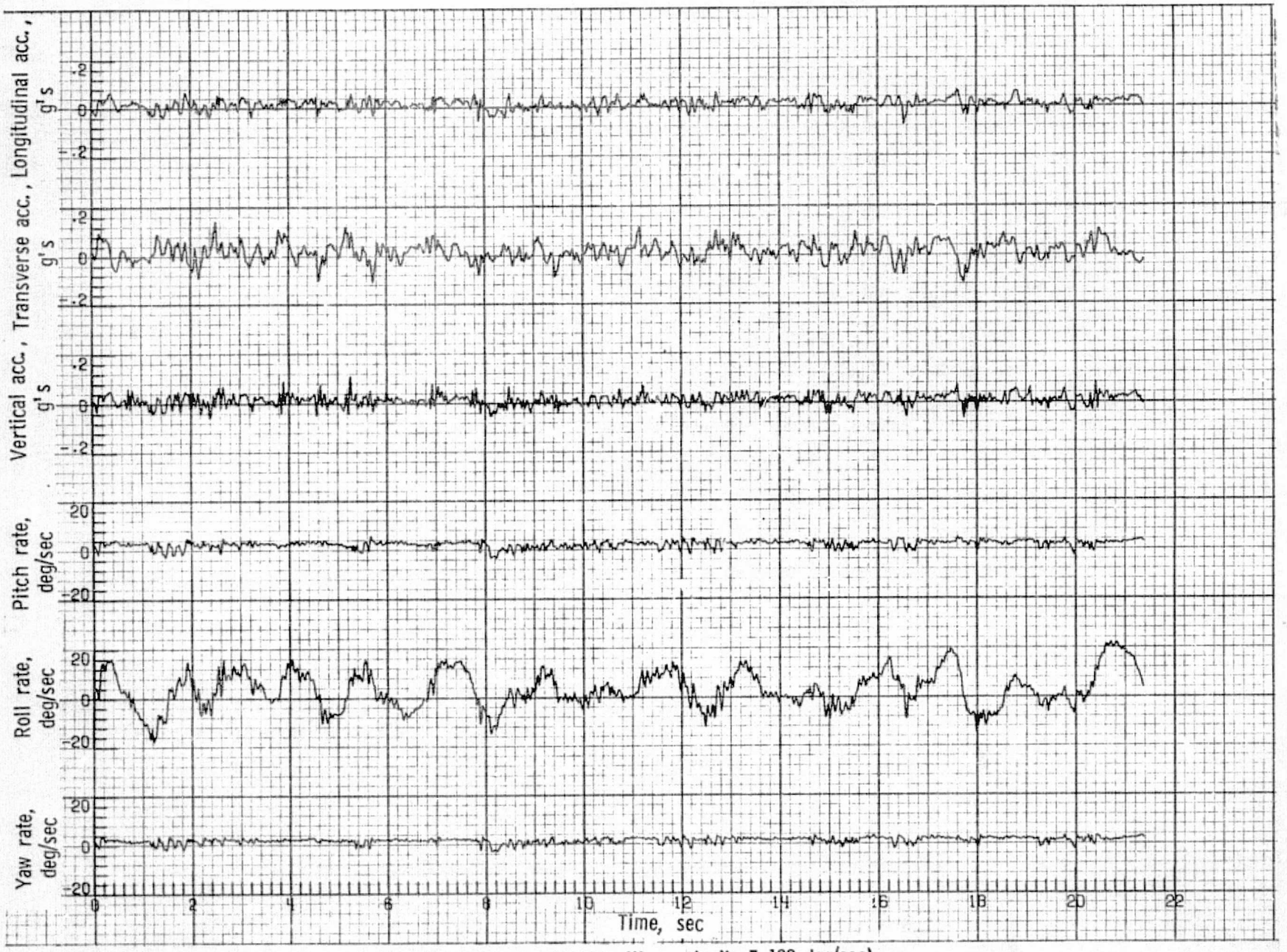


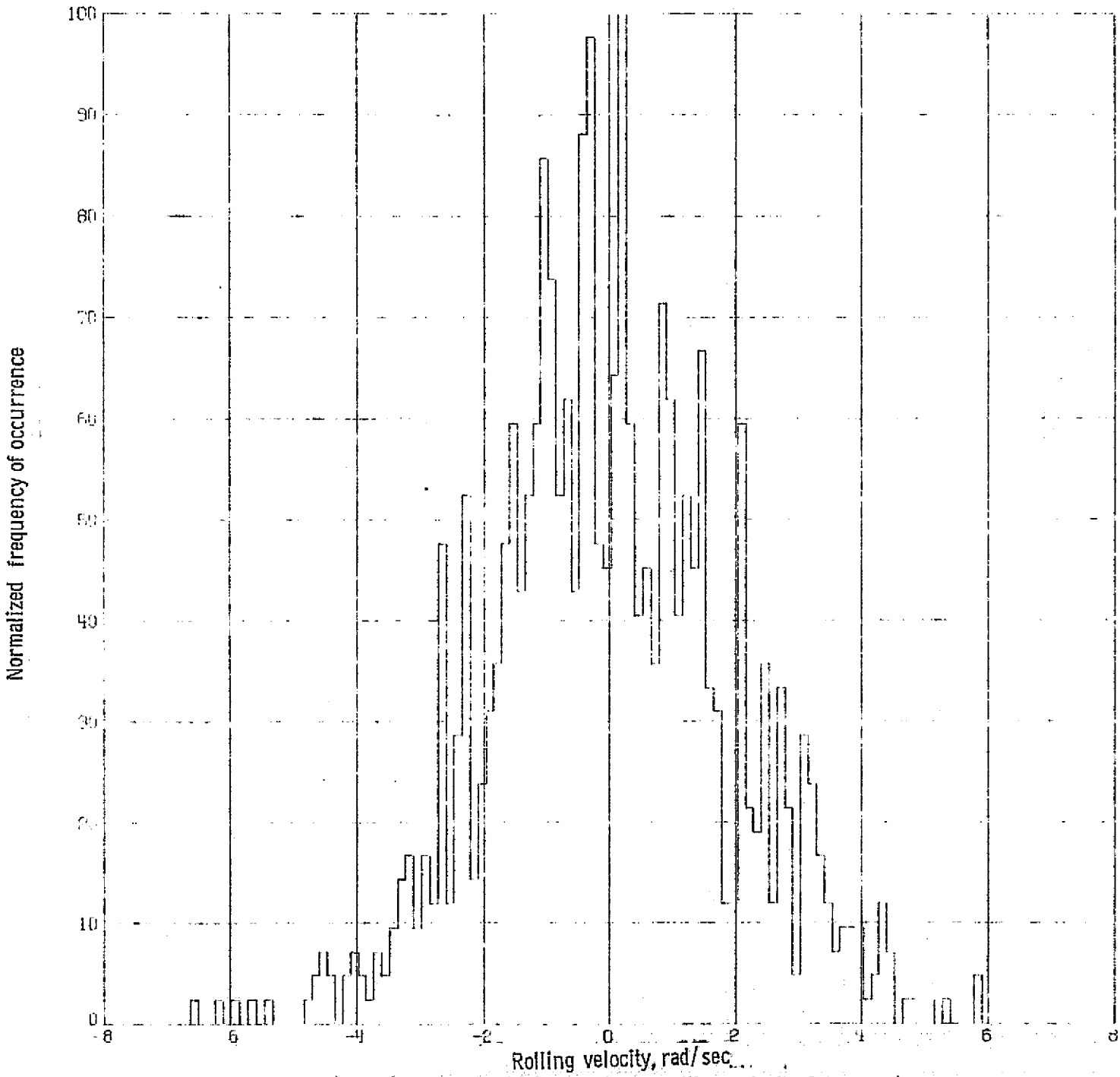
(a) Time histories (RMS rolling velocity 6.085 deg/sec).

Figure 4. - Continued.



(a) Time histories (RMS rolling velocity 7.108 deg/sec).

Figure 4.- Continued.



(b) Rolling velocity histogram (RMS rolling velocity 1.769 deg/sec).

Figure 4.- Continued.

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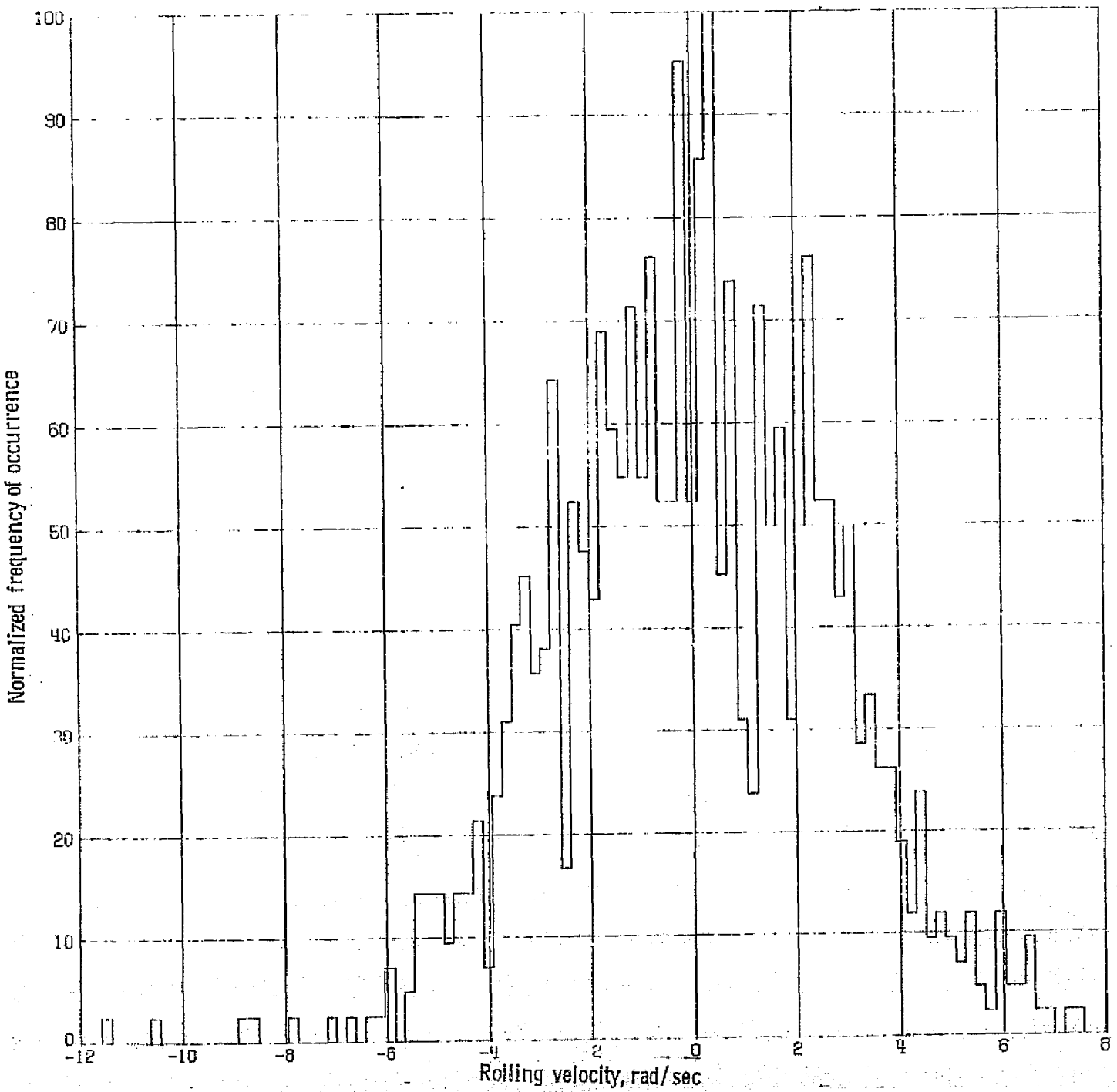
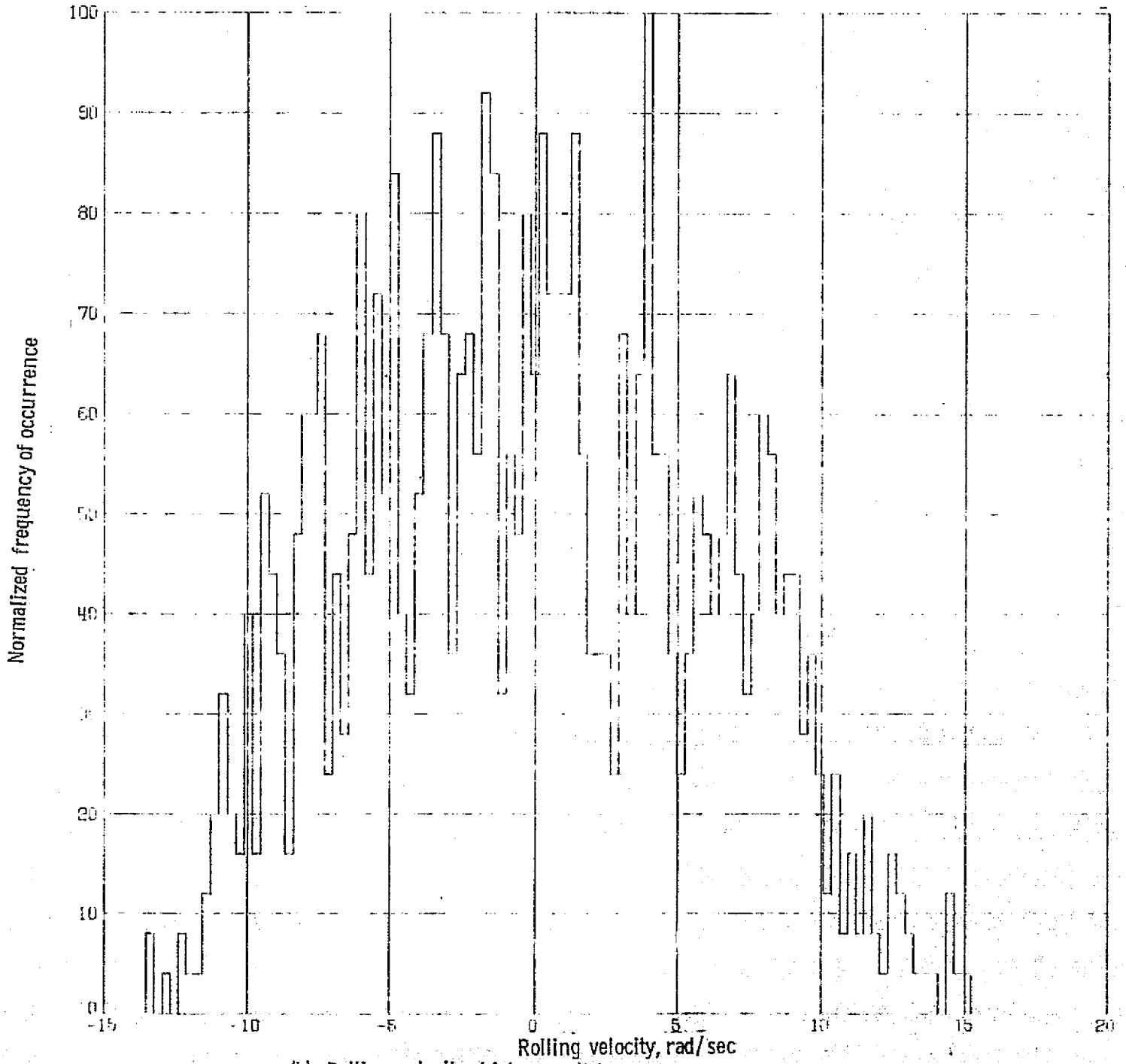


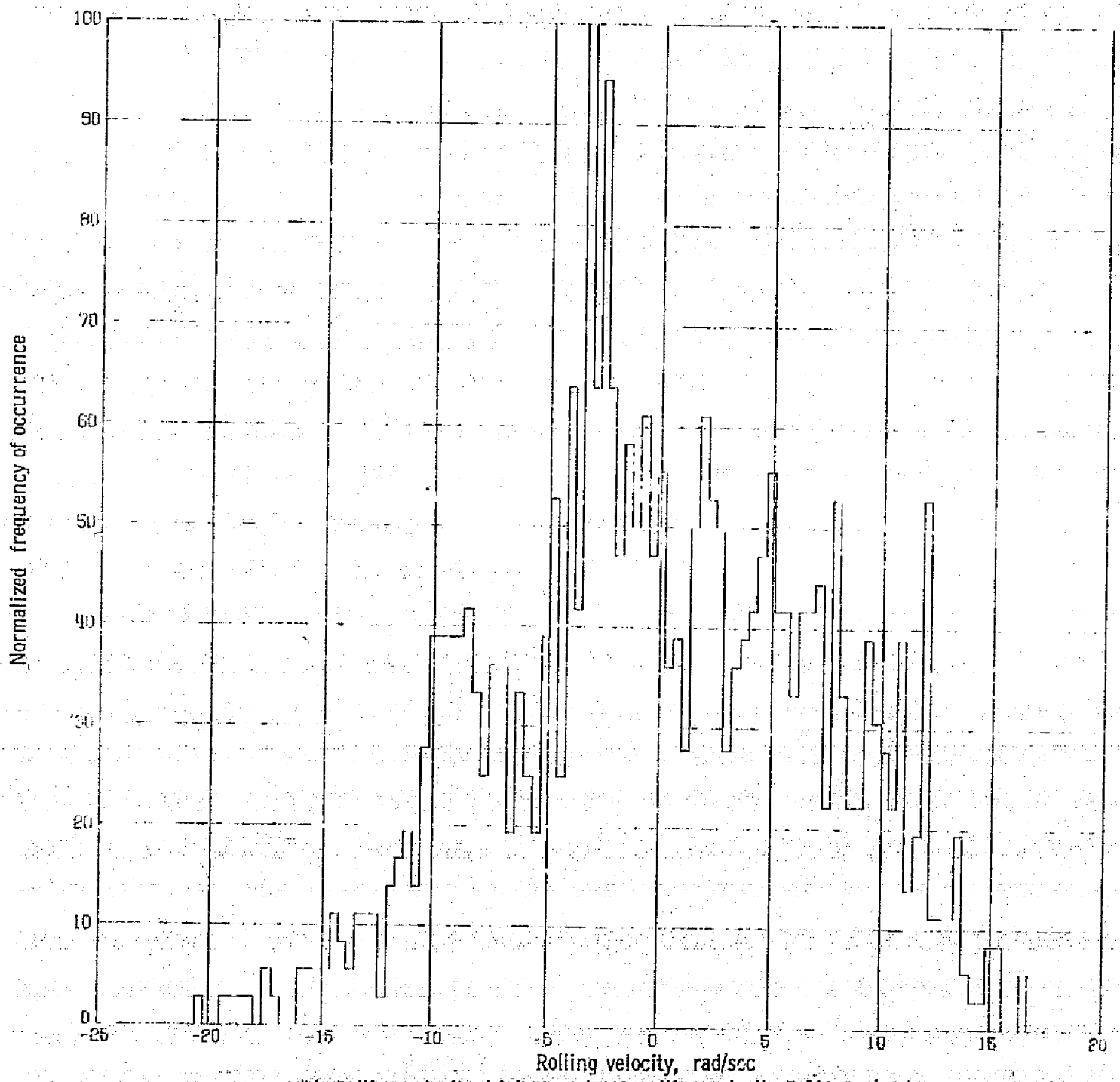
(b) Rolling velocity histogram (RMS rolling velocity 2.486 deg/sec).

Figure 4.- Continued.



(b) Rolling velocity histogram (RMS rolling velocity 6.085 deg/sec).

Figure 4.- Continued.



(b) Rolling velocity histogram (RMS rolling velocity 7.108 deg/sec).

Figure 4.- Continued.

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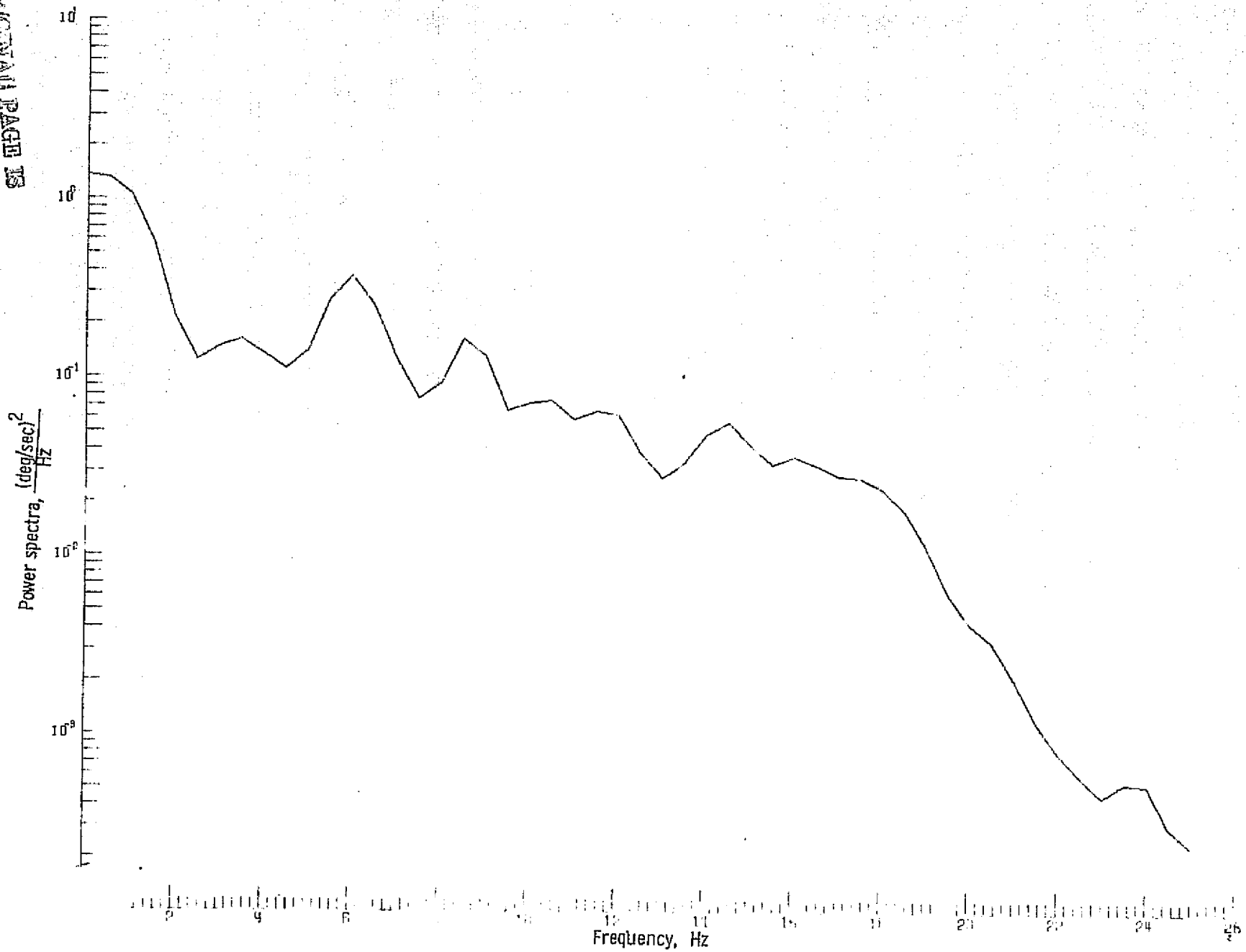
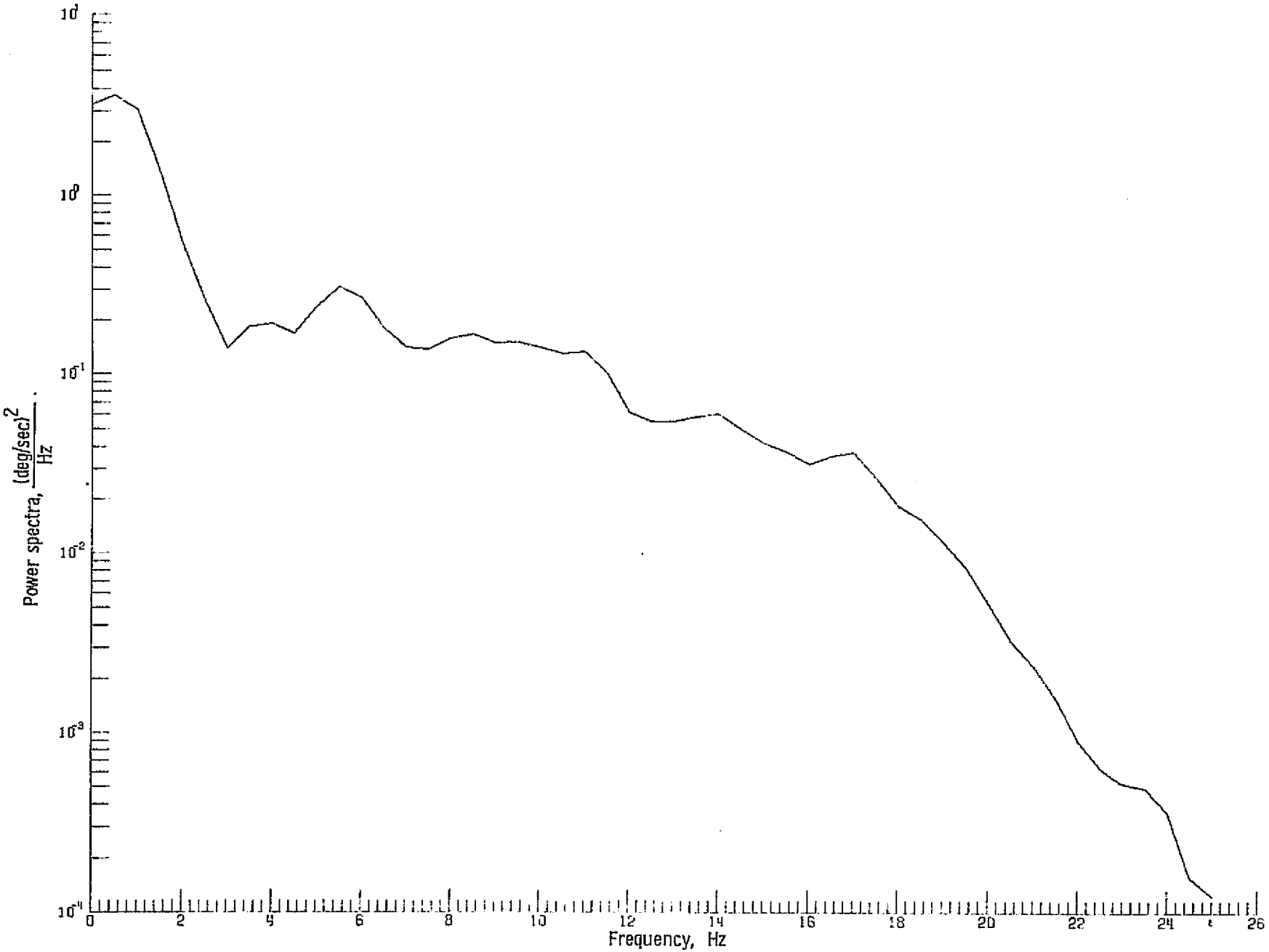


(c) Rolling velocity power spectrum (RMS rolling velocity 1.769 deg/sec).

Figure 4. - Continued.



(c) Rolling velocity power spectrum (RMS rolling velocity 2.486 deg/sec).

Figure 4.- Continued.

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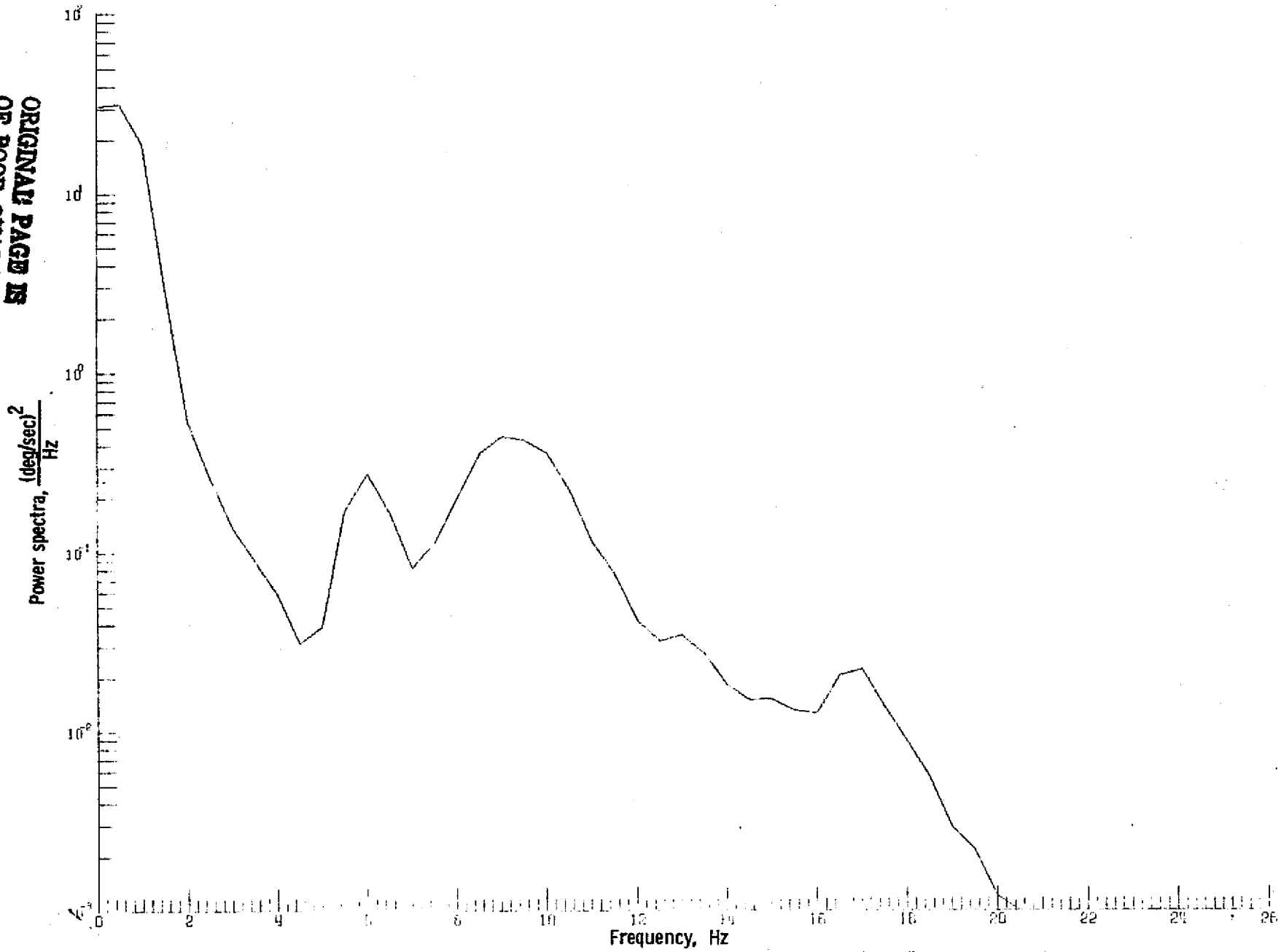
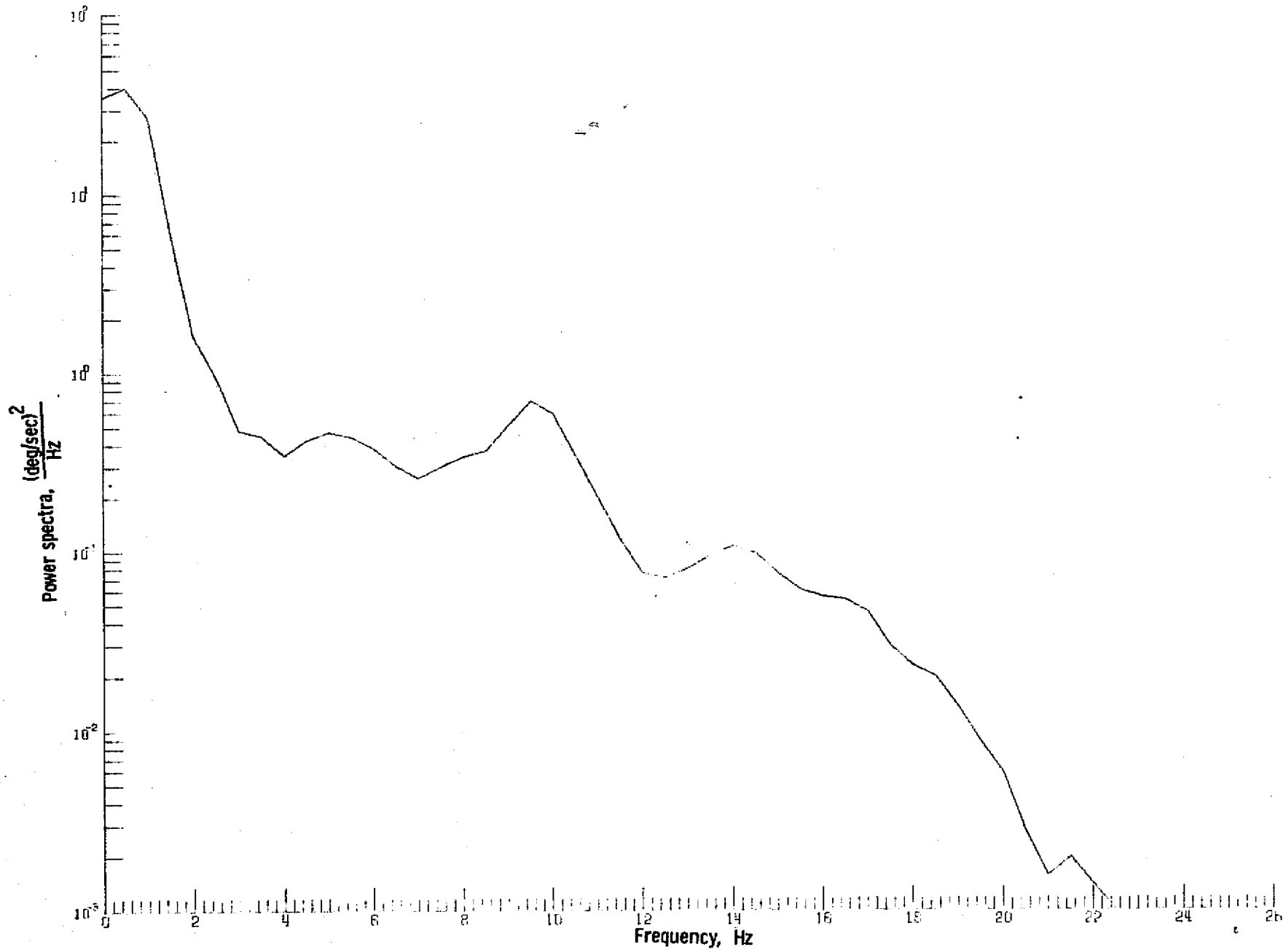


(c) Rolling velocity power spectrum (RMS rolling velocity 6.085 deg/sec).

Figure 4. - Continued.



(c) Rolling velocity power spectrum (RMS rolling velocity 7.108 deg/sec).

Figure 4. - Concluded.

(a) Time histories (RMS rolling velocity 1.778 deg/sec).

Figure 5.- Measured motion characteristics using rolling motion velocity with typical 0-2 Hz inputs.

(a) Time histories (RMS rolling velocity 2.254 deg/sec).

Figure 5. - Continued.

(a) Time histories (RMS rolling velocity 1.778 deg/sec).

Figure 5.- Measured motion characteristics using rolling motion velocity with typical 0-2 Hz inputs.

(a) Time histories (RMS rolling velocity 2.254 deg/sec).

Figure 5. - Continued.

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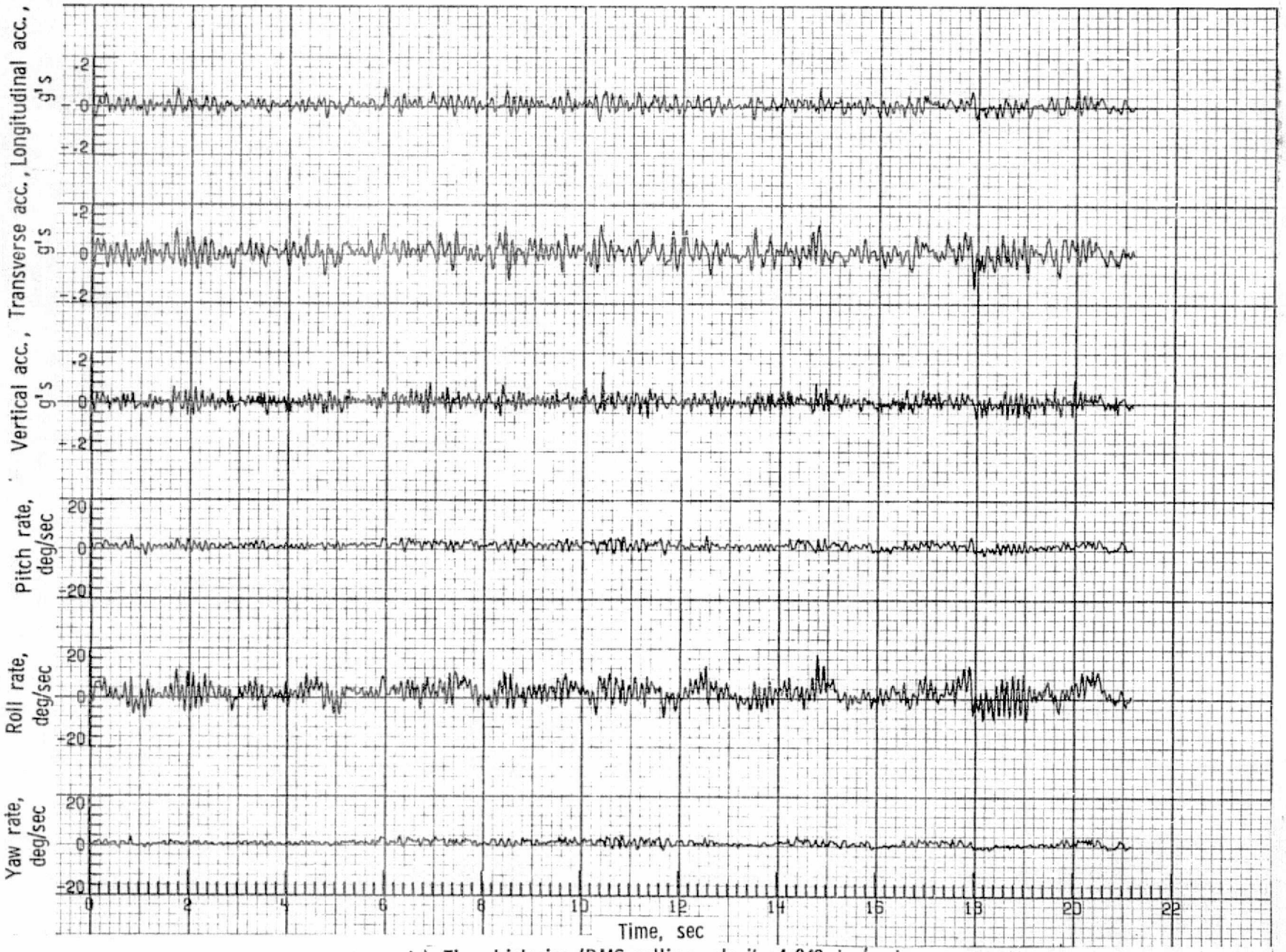

(a) Time histories (RMS rolling velocity 4.048 deg/sec).

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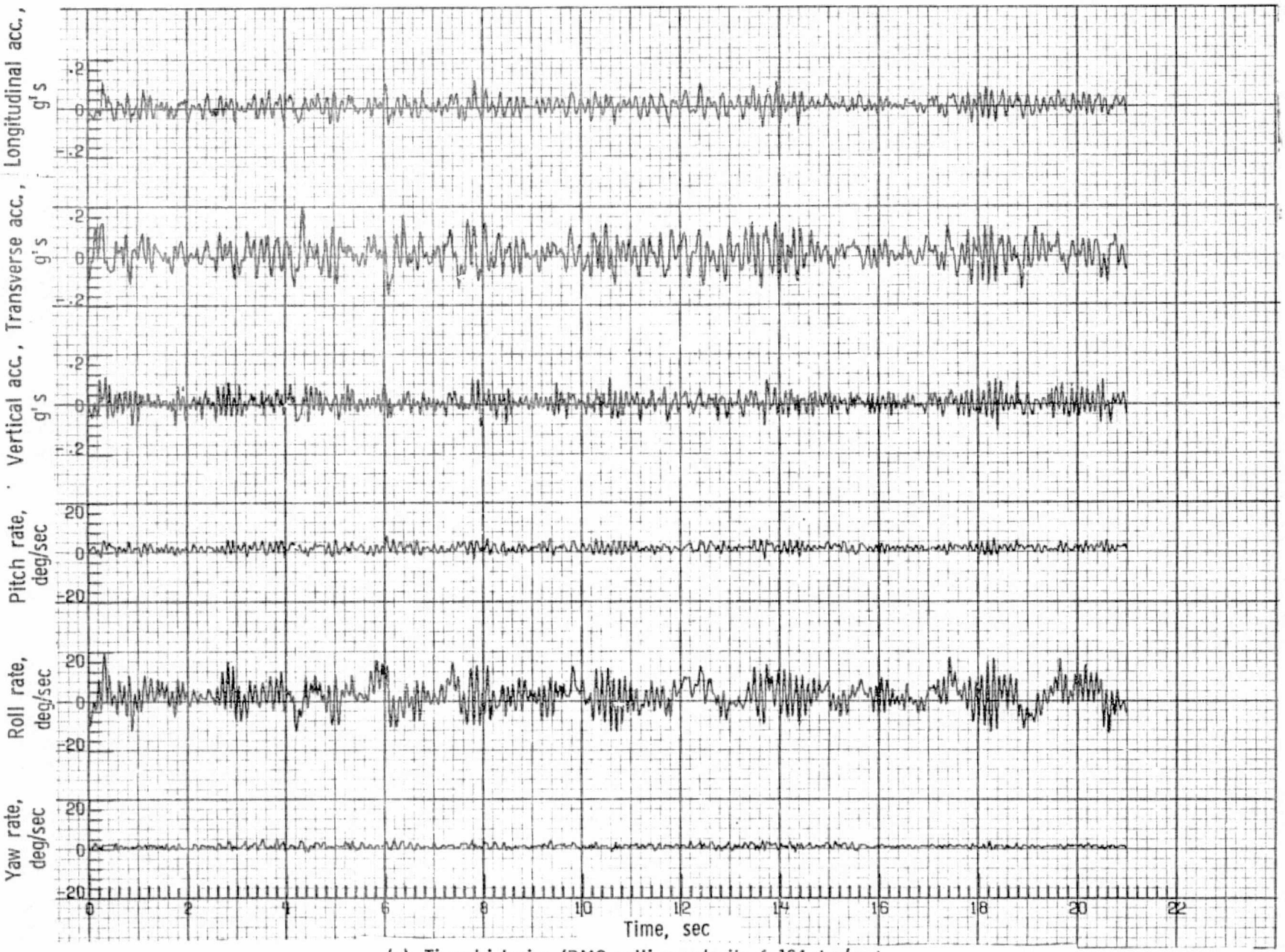
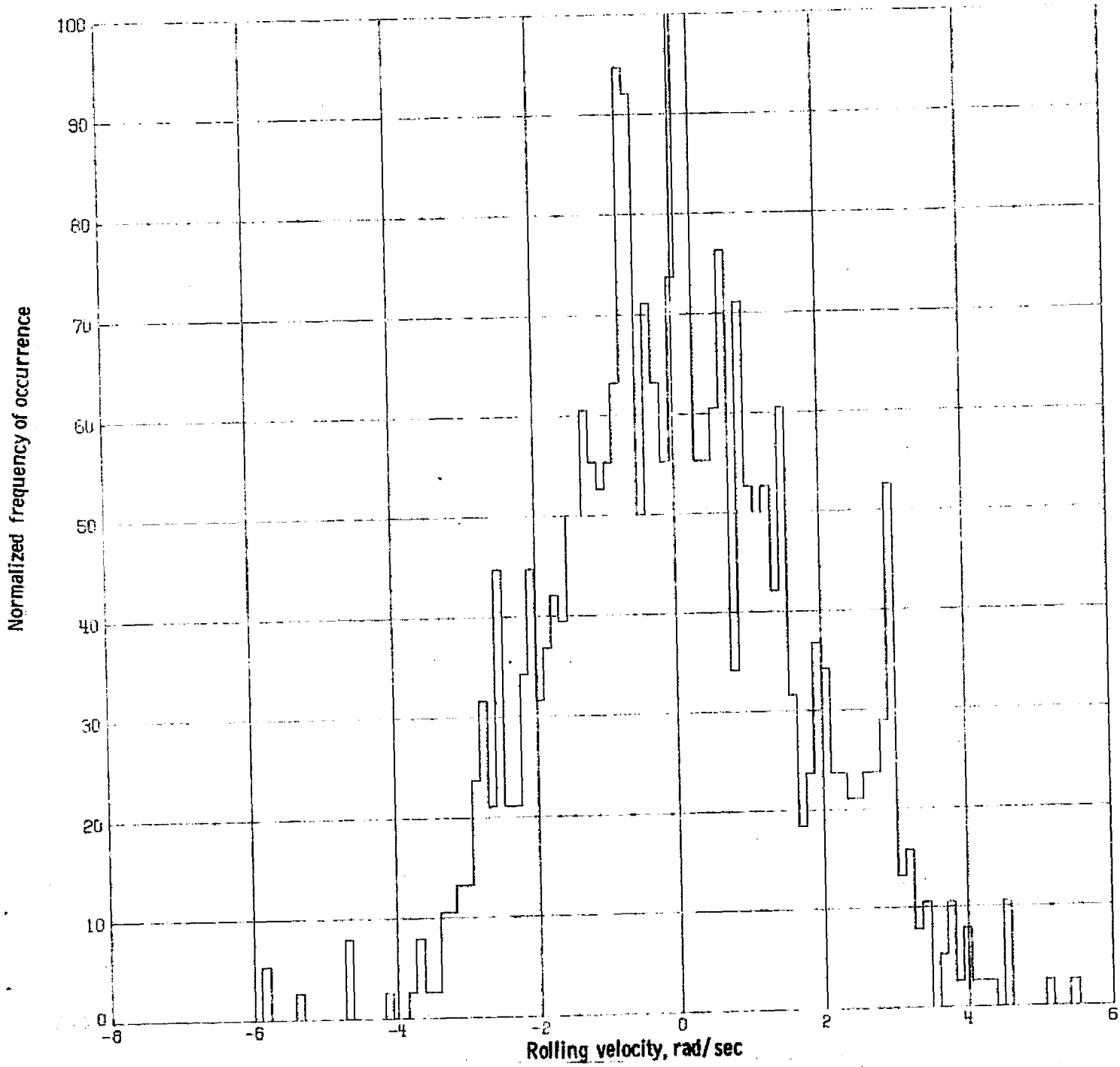


(a) Time histories (RMS rolling velocity 6.104 deg/sec).

Figure 5. - Continued.



(b) Rolling velocity histogram (RMS rolling velocity 1.778 deg/sec).

Figure 5.- Continued.

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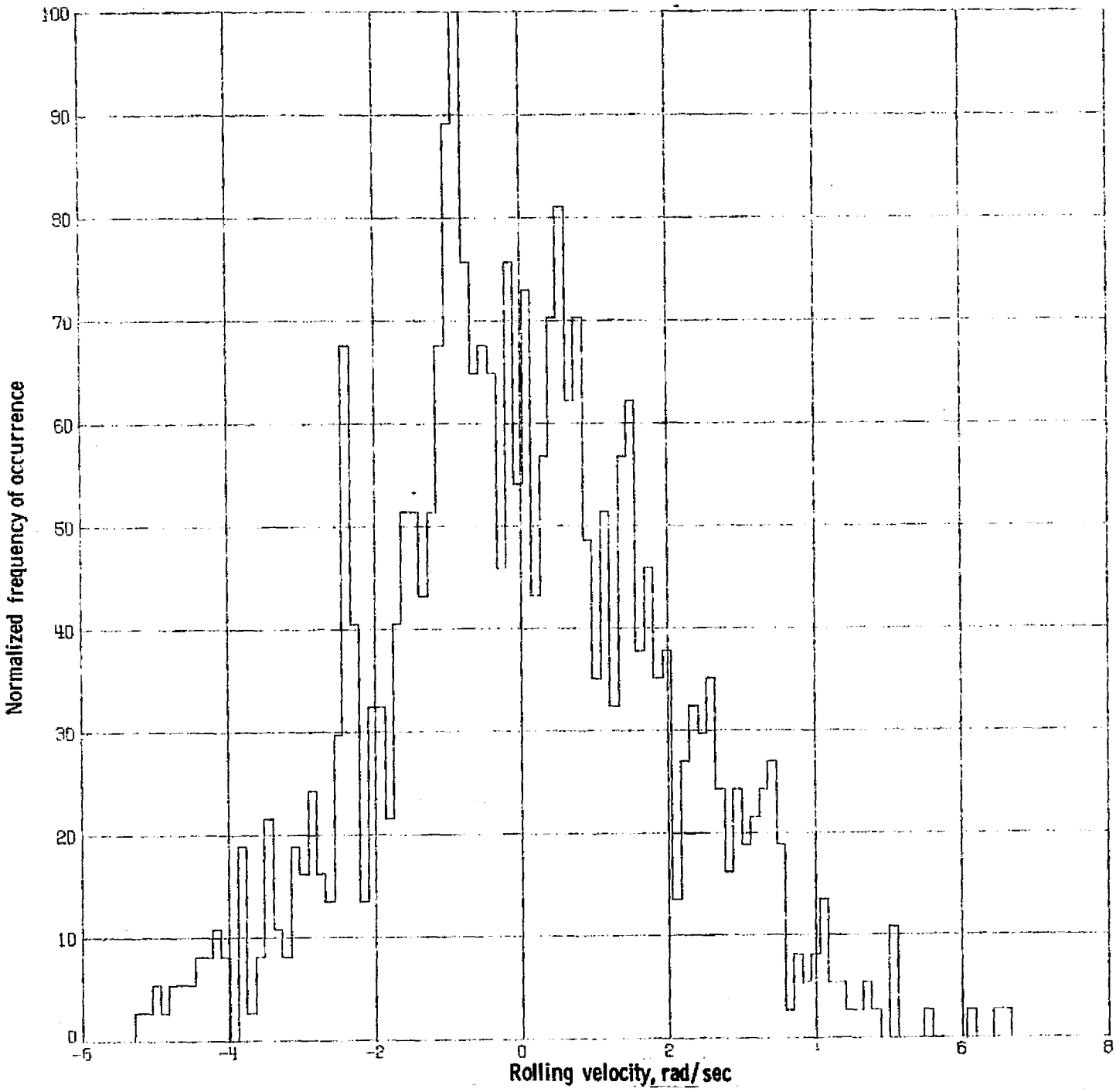
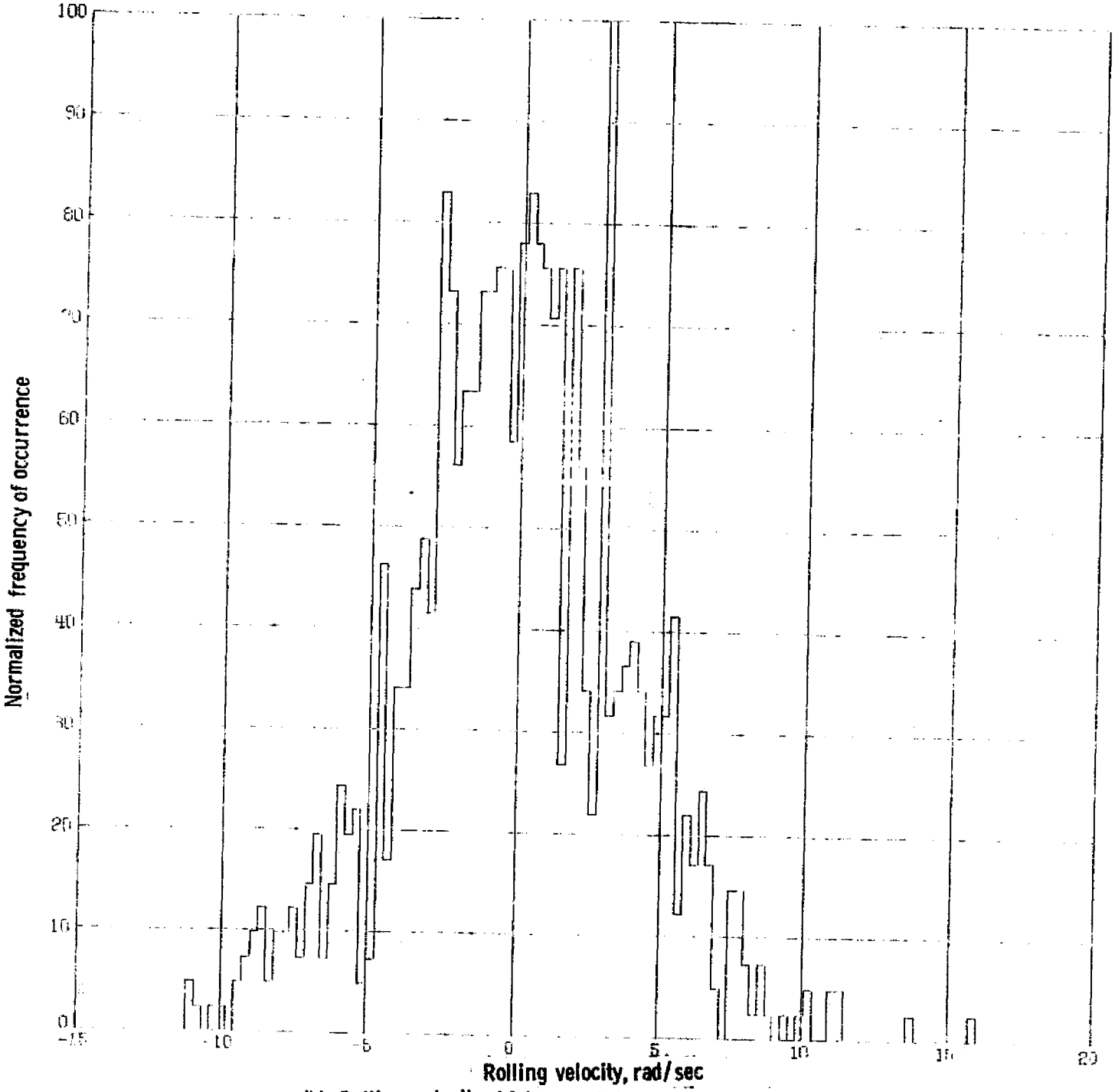


(b) Rolling velocity histogram (RMS rolling velocity 2.254 deg/sec).

Figure 5.- Continued.



(b) Rolling velocity histogram (RMS rolling velocity 4.048 deg/sec).

Figure 5. - Continued.

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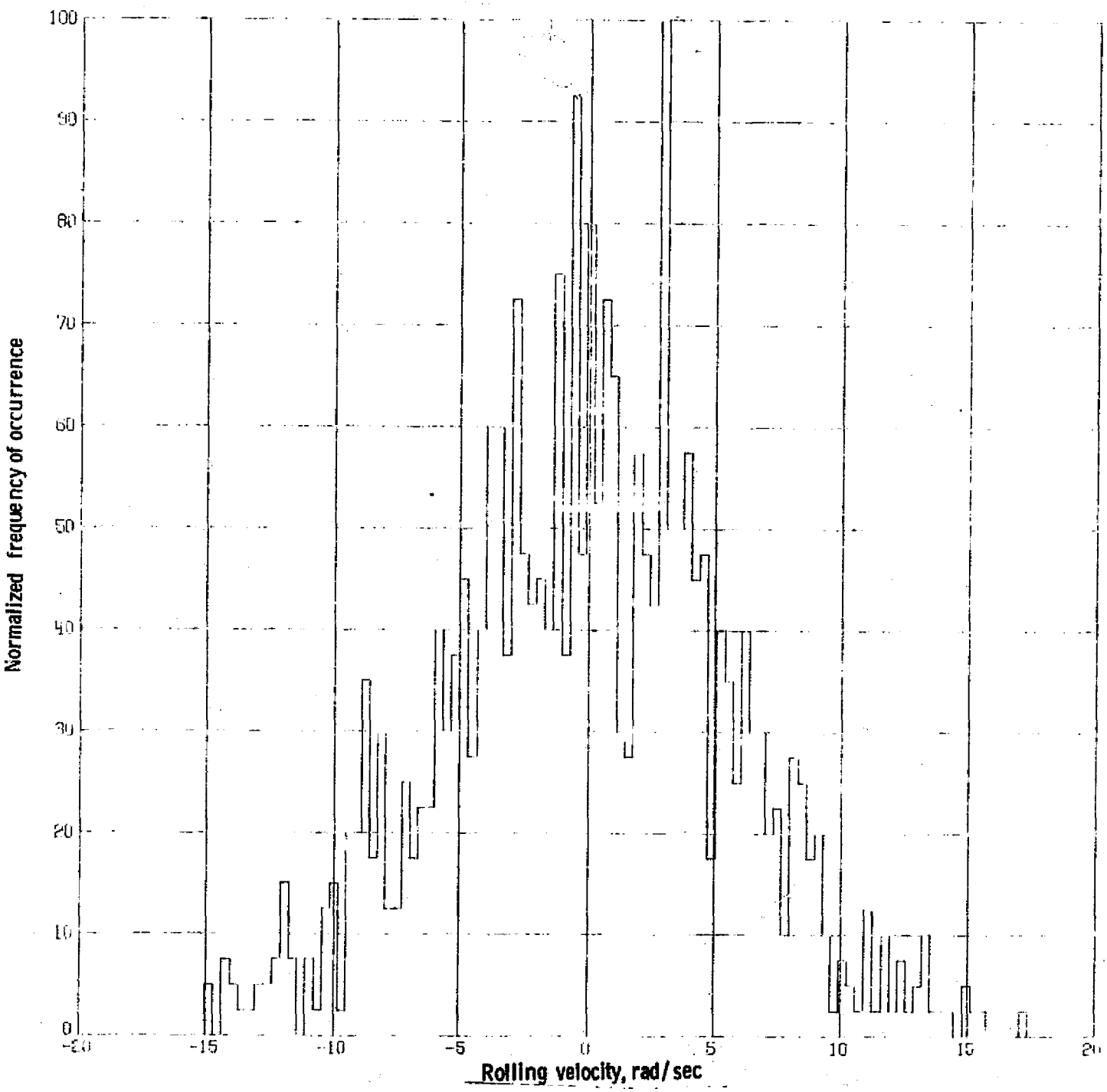

(b) Rolling velocity histogram (RMS rolling velocity 6.104 deg/sec).

Figure 5. - Continued.

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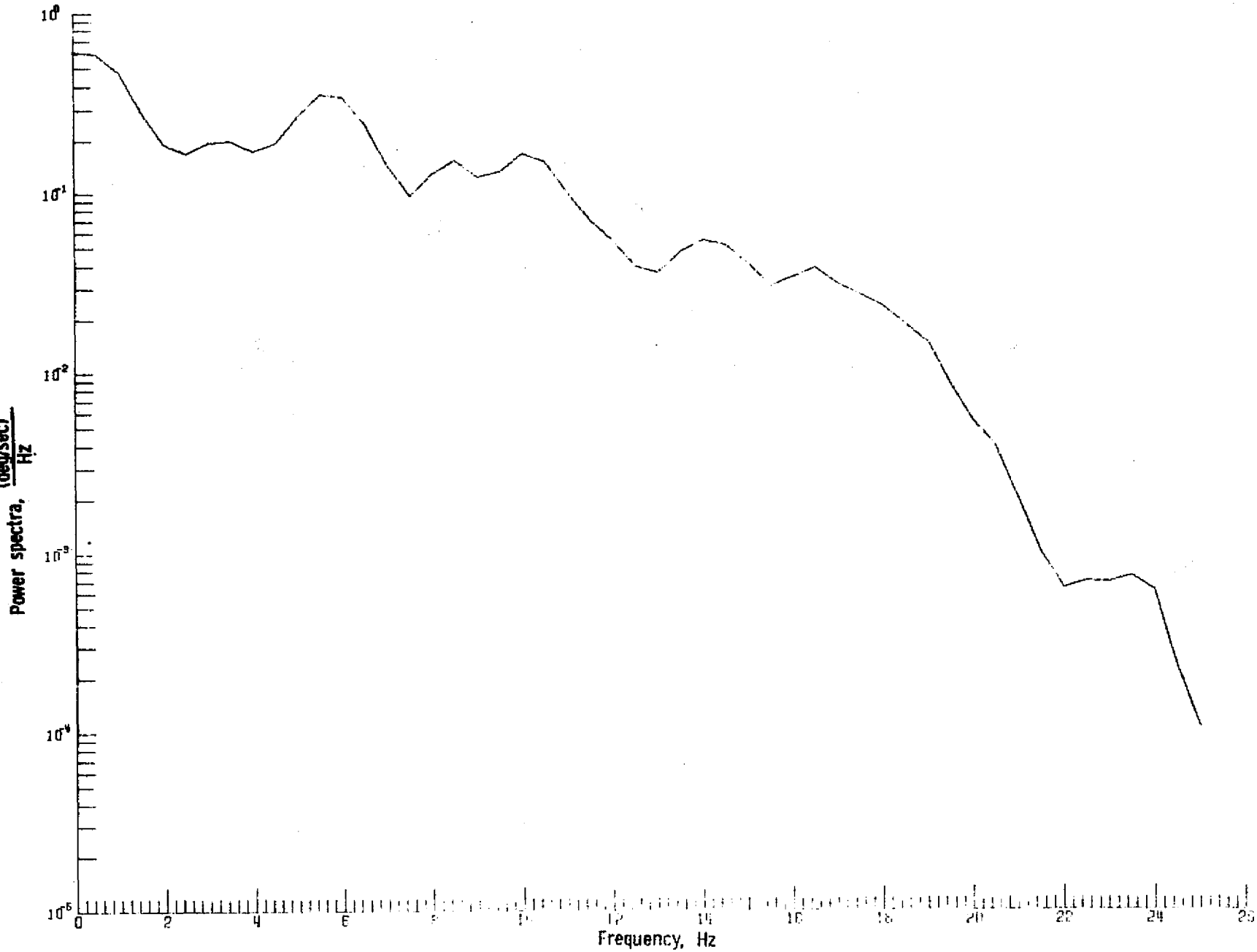
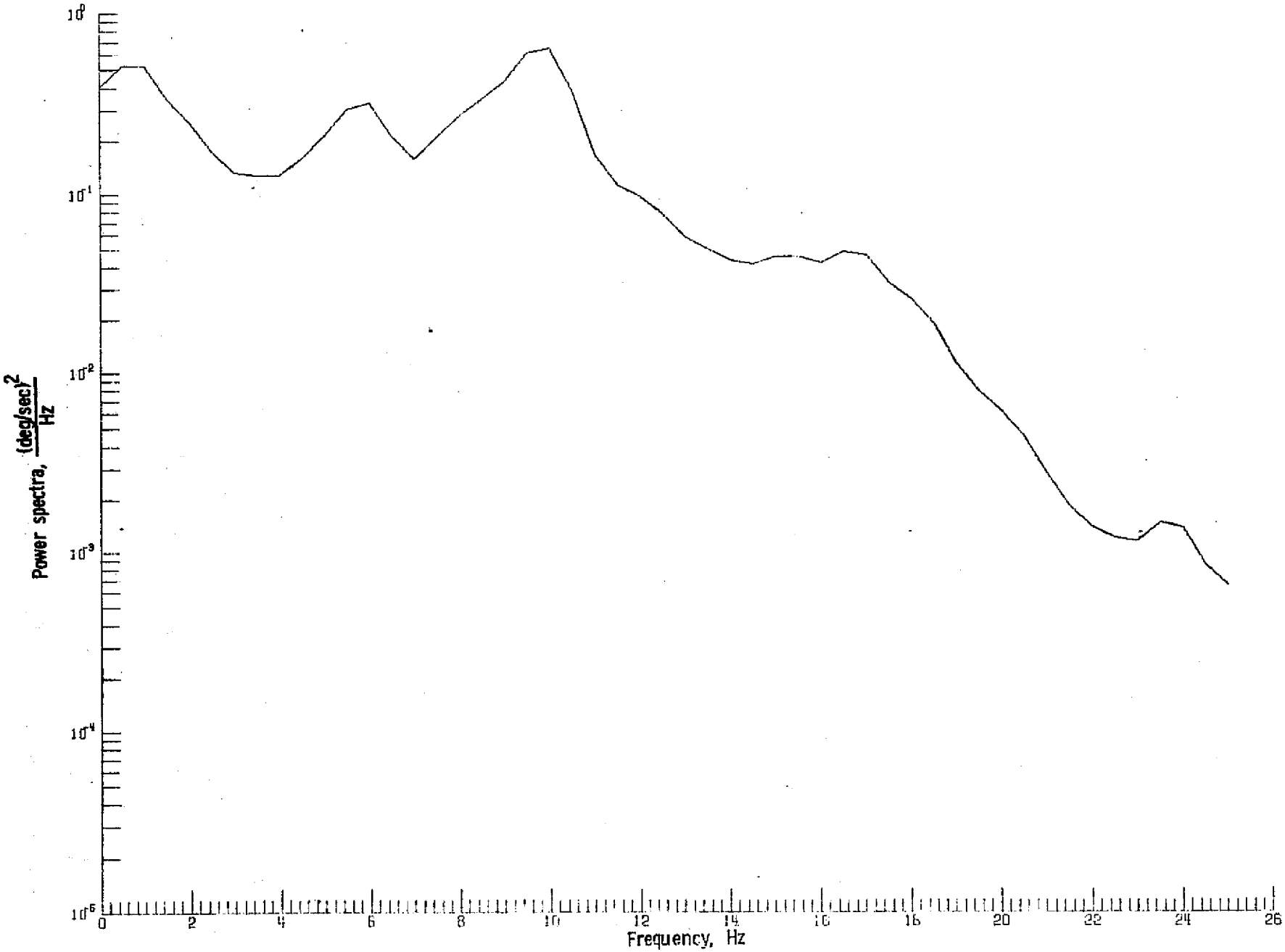


(c) Rolling velocity power spectrum (RMS rolling velocity 1.778 deg/sec).

Figure 5.- Continued.



(c) Rolling velocity power spectrum (RMS rolling velocity 2.254 deg/sec).

Figure 5.- Continued.

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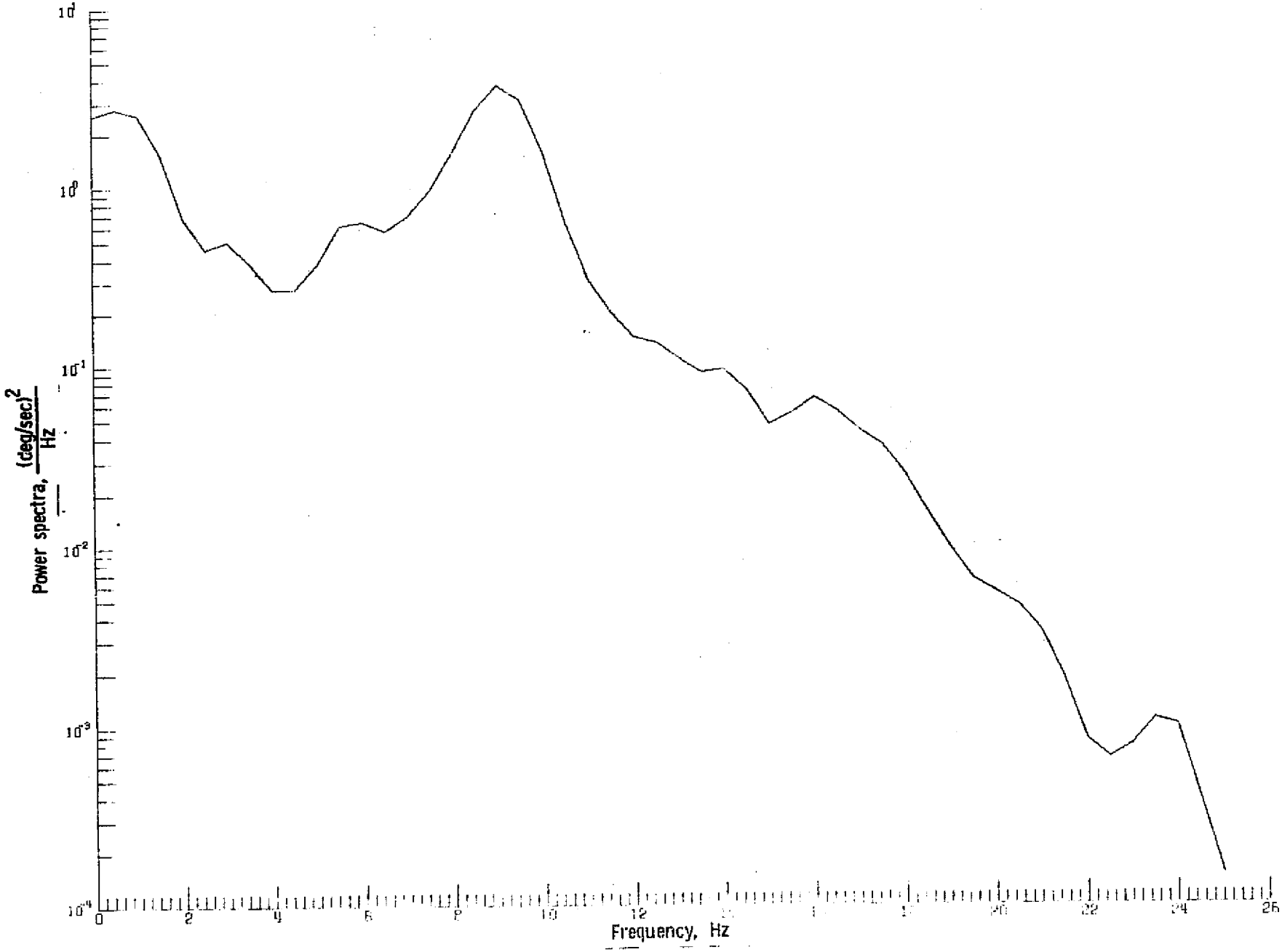
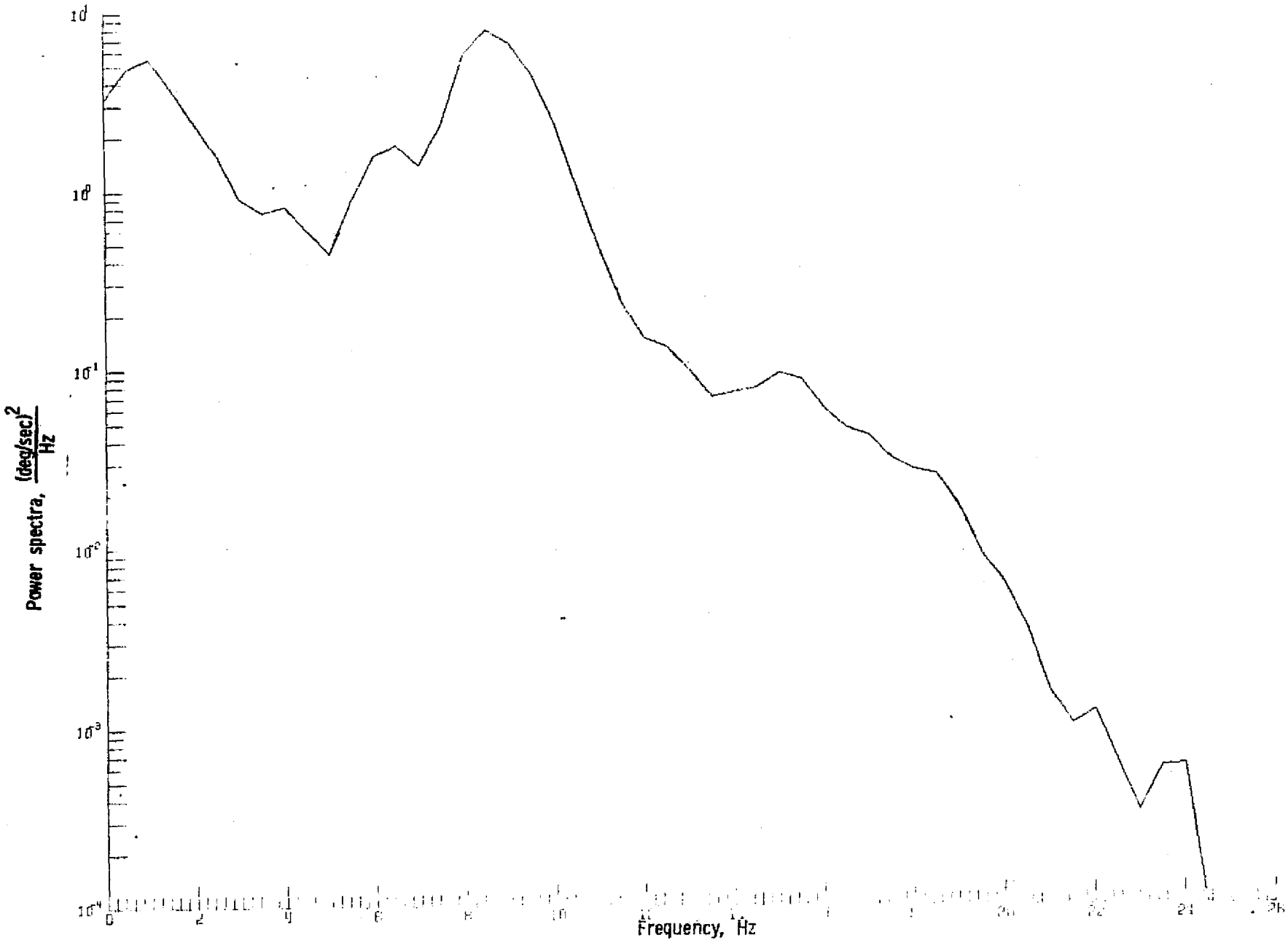


(c) Rolling velocity power spectrum (RMS rolling velocity 4.048 deg/sec).

Figure 5. - Continued.



(c) Rolling velocity power spectrum (RMS rolling velocity 6.104 deg/sec).

Figure 5. – Concluded.

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(a) Time histories (RMS rolling velocity 1.579 deg/sec).

Figure 6.- Measured motion characteristics using rolling velocity with typical 1-2 Hz inputs.

(a) Time histories (RMS rolling velocity 2.488 deg/sec).

Figure 6. - Continued.

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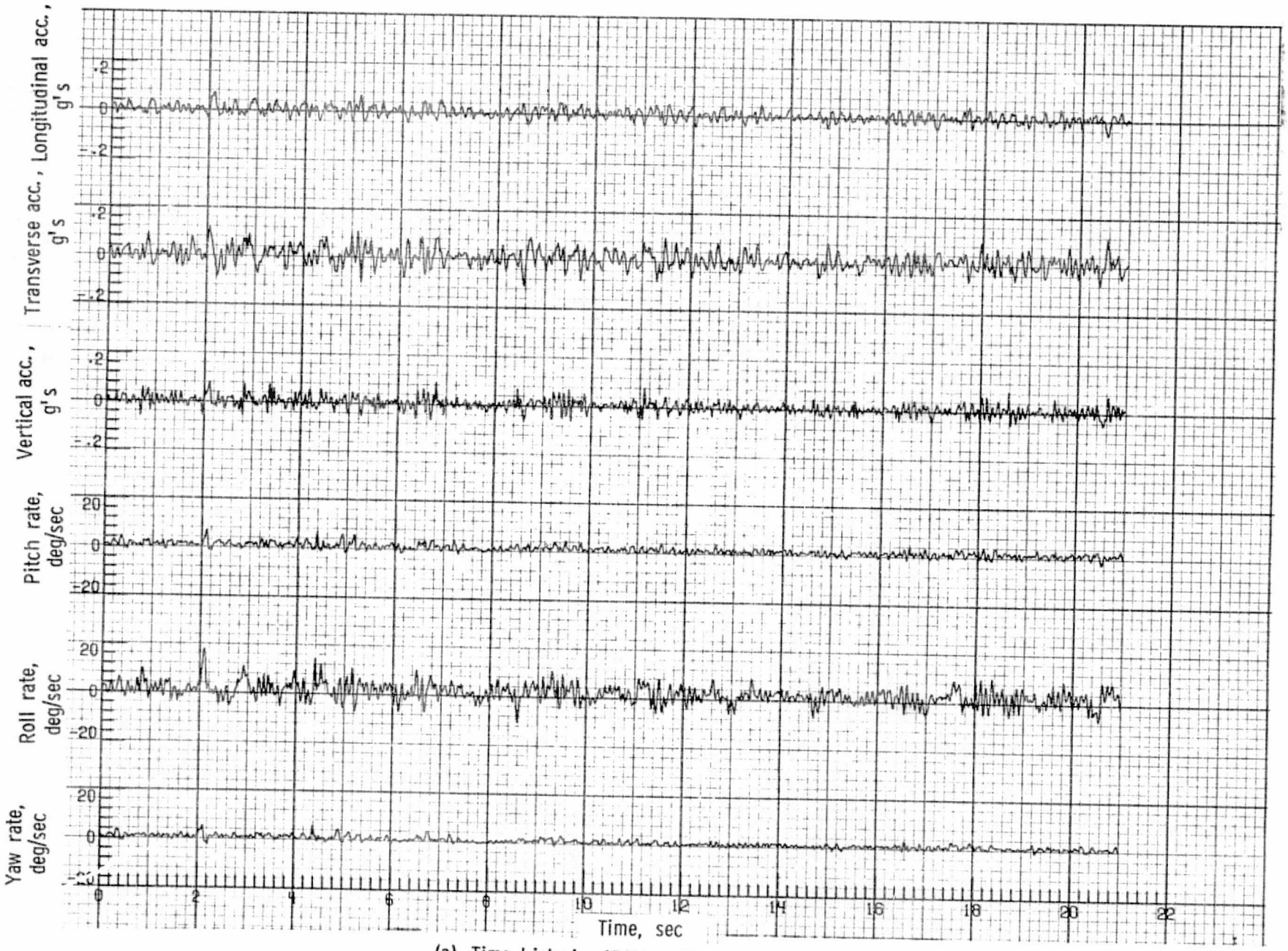
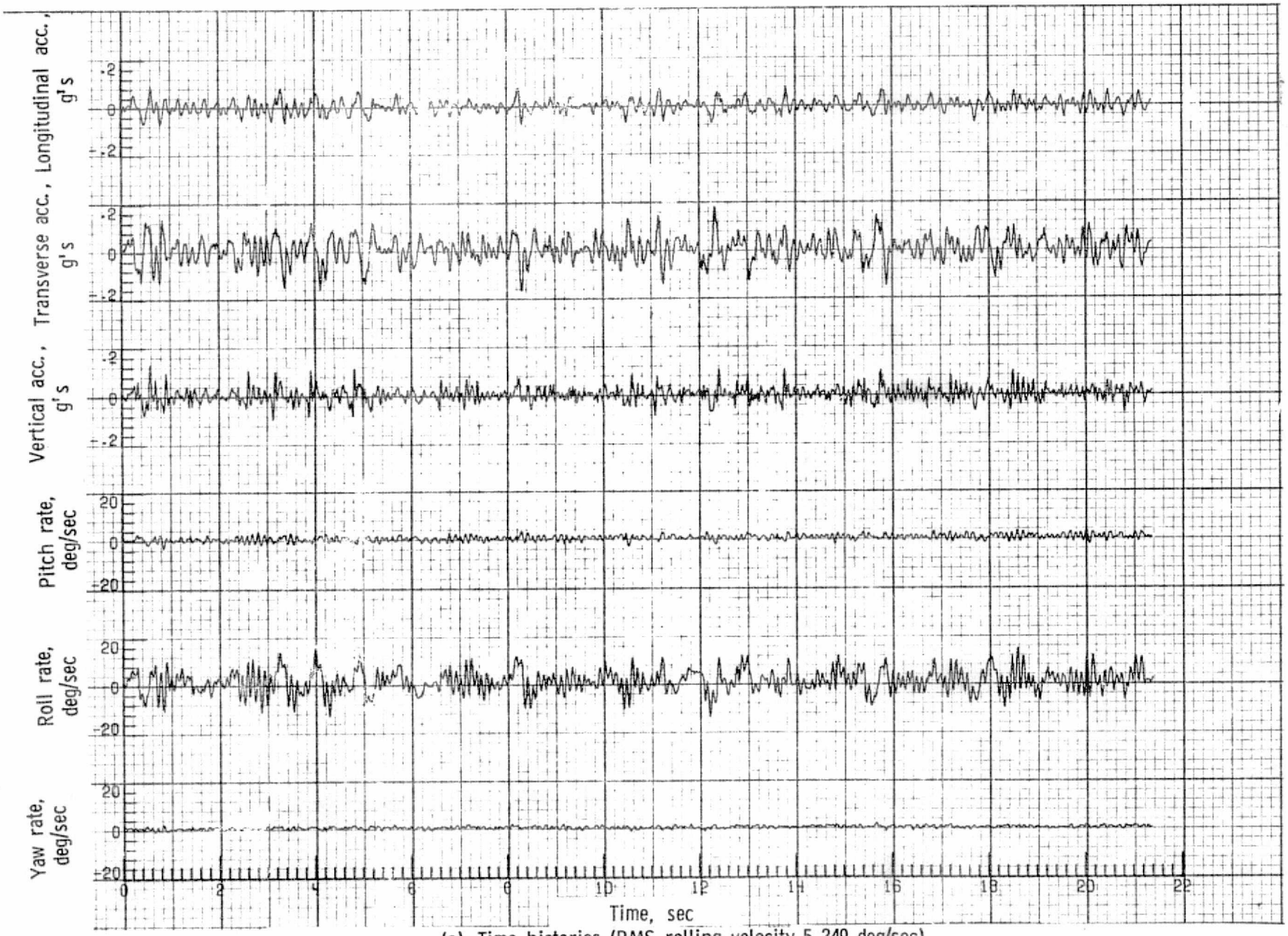


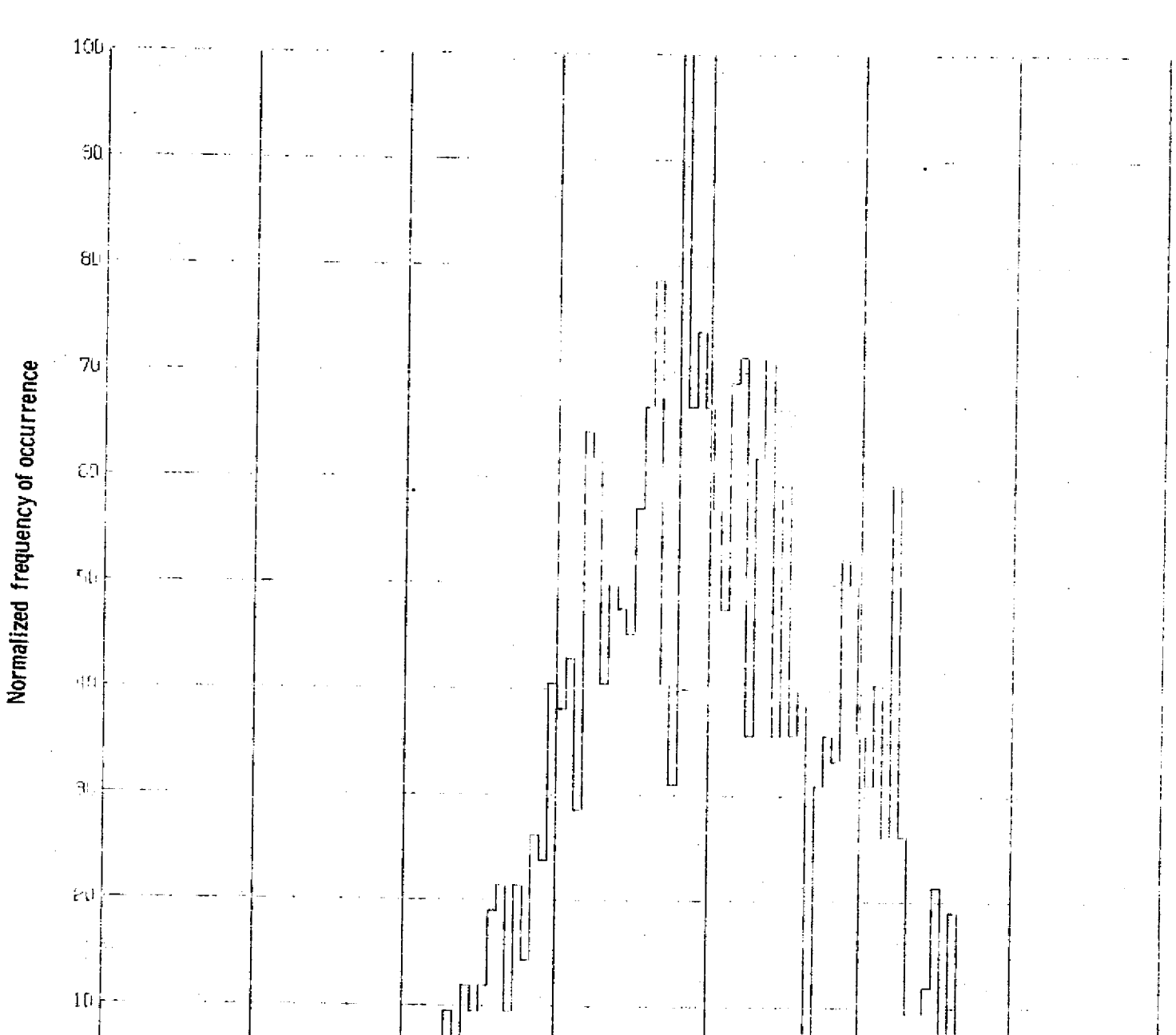
(a) Time histories (RMS rolling velocity 3.742 deg/sec).

Figure 6. - Continued.



(a) Time histories (RMS rolling velocity 5.249 deg/sec).

Figure 6.- Continued.



(b) Rolling velocity histogram (RMS rolling velocity 1.579 deg/sec).

Figure 6. - Continued.

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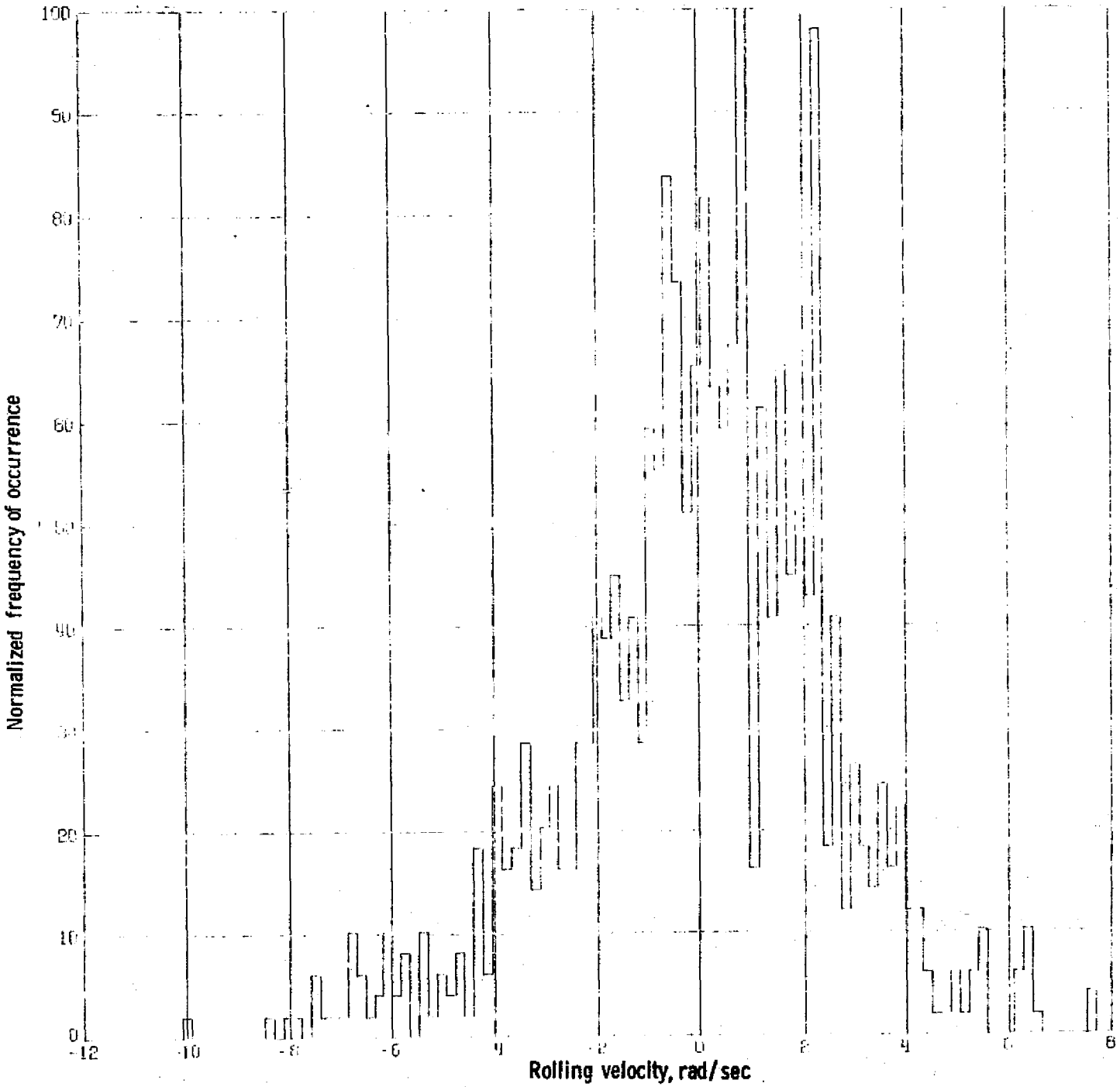
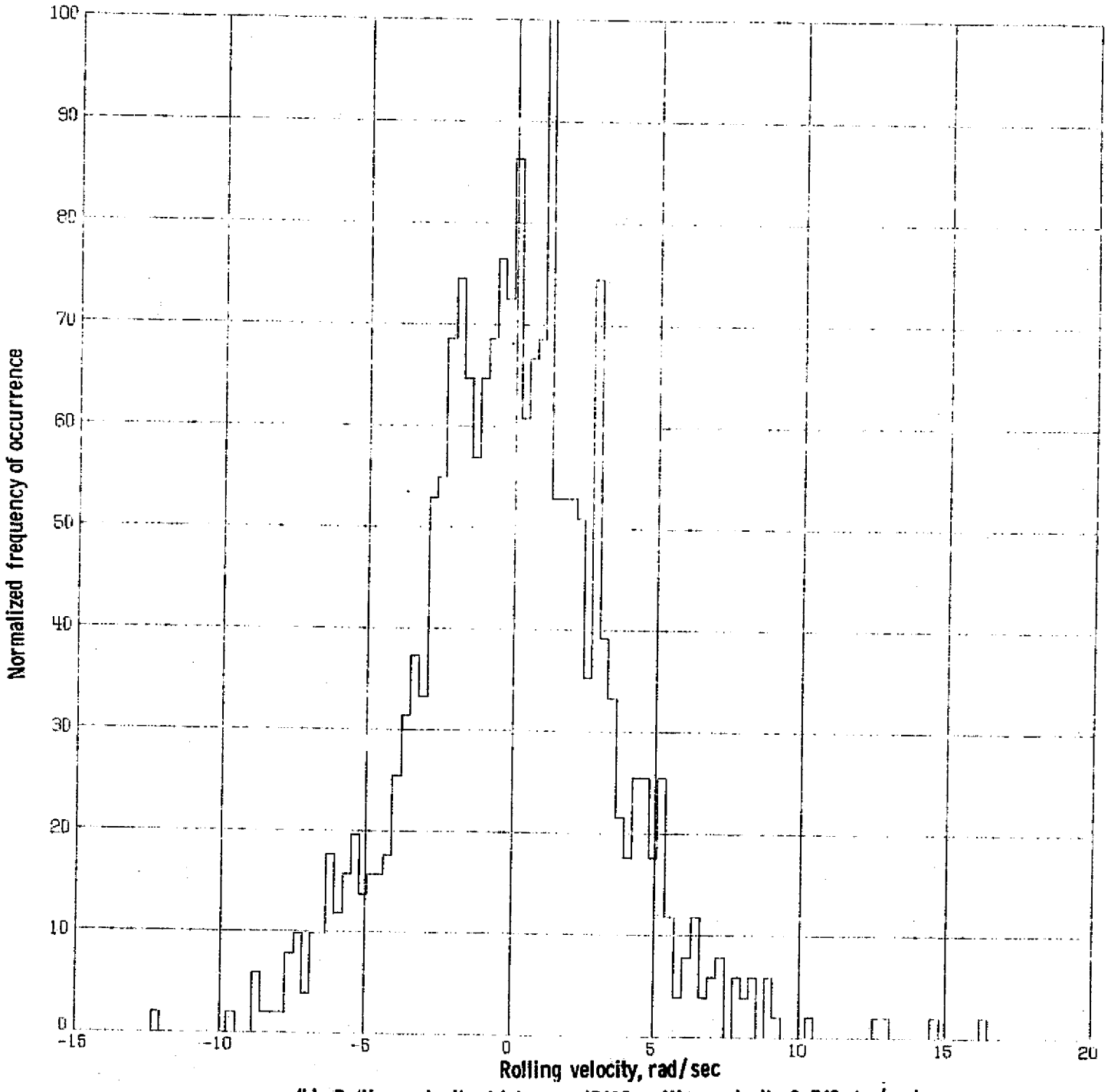


(b) Rolling velocity histogram (RMS rolling velocity 2.488 deg/sec).

Figure 6. - Continued.



(b) Rolling velocity histogram (RMS rolling velocity 3.742 deg/sec).

Figure 6.- Continued.

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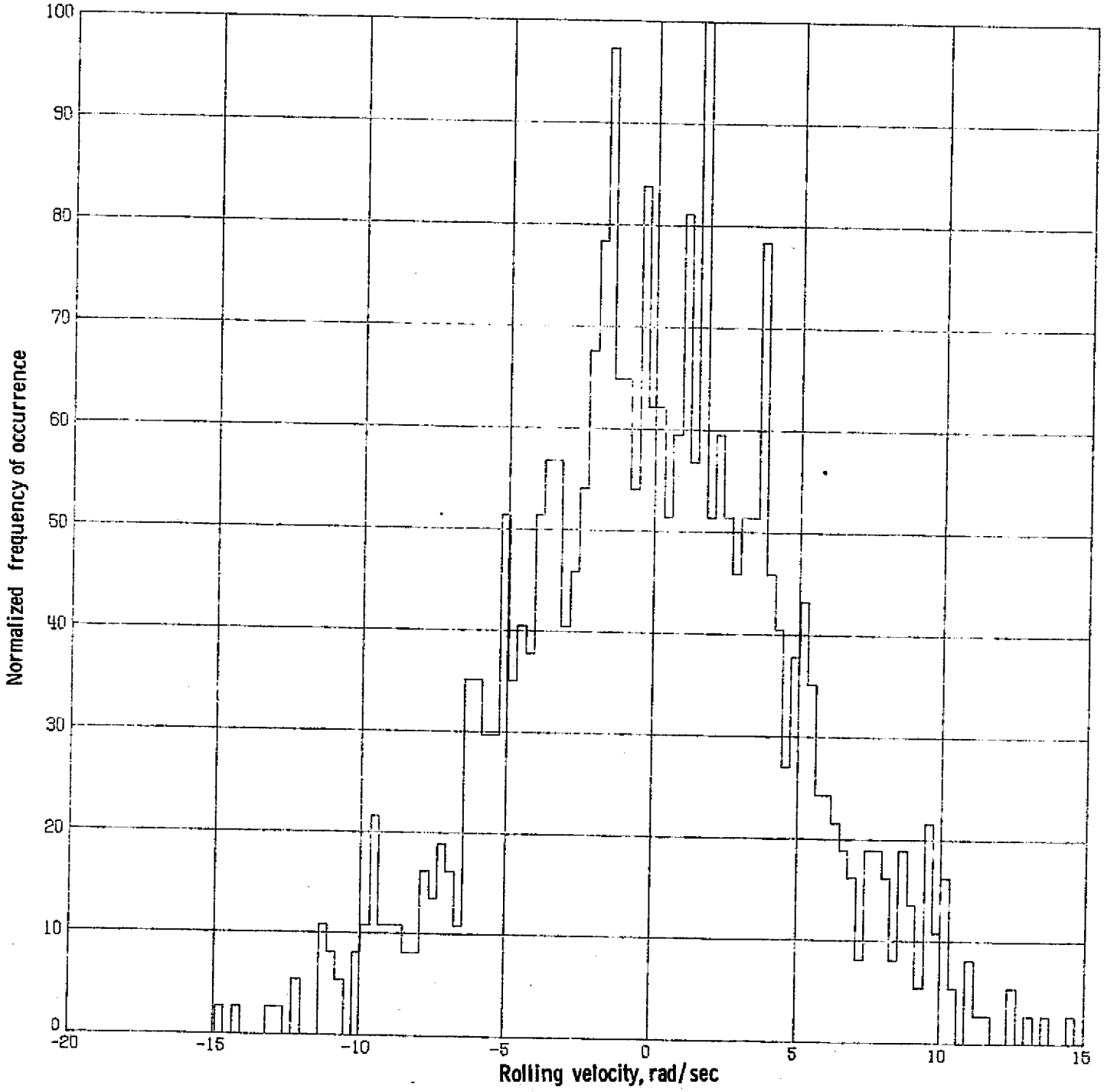

(b) Rolling velocity histogram (RMS rolling velocity 5.249 deg/sec).

Figure 6. - Continued.

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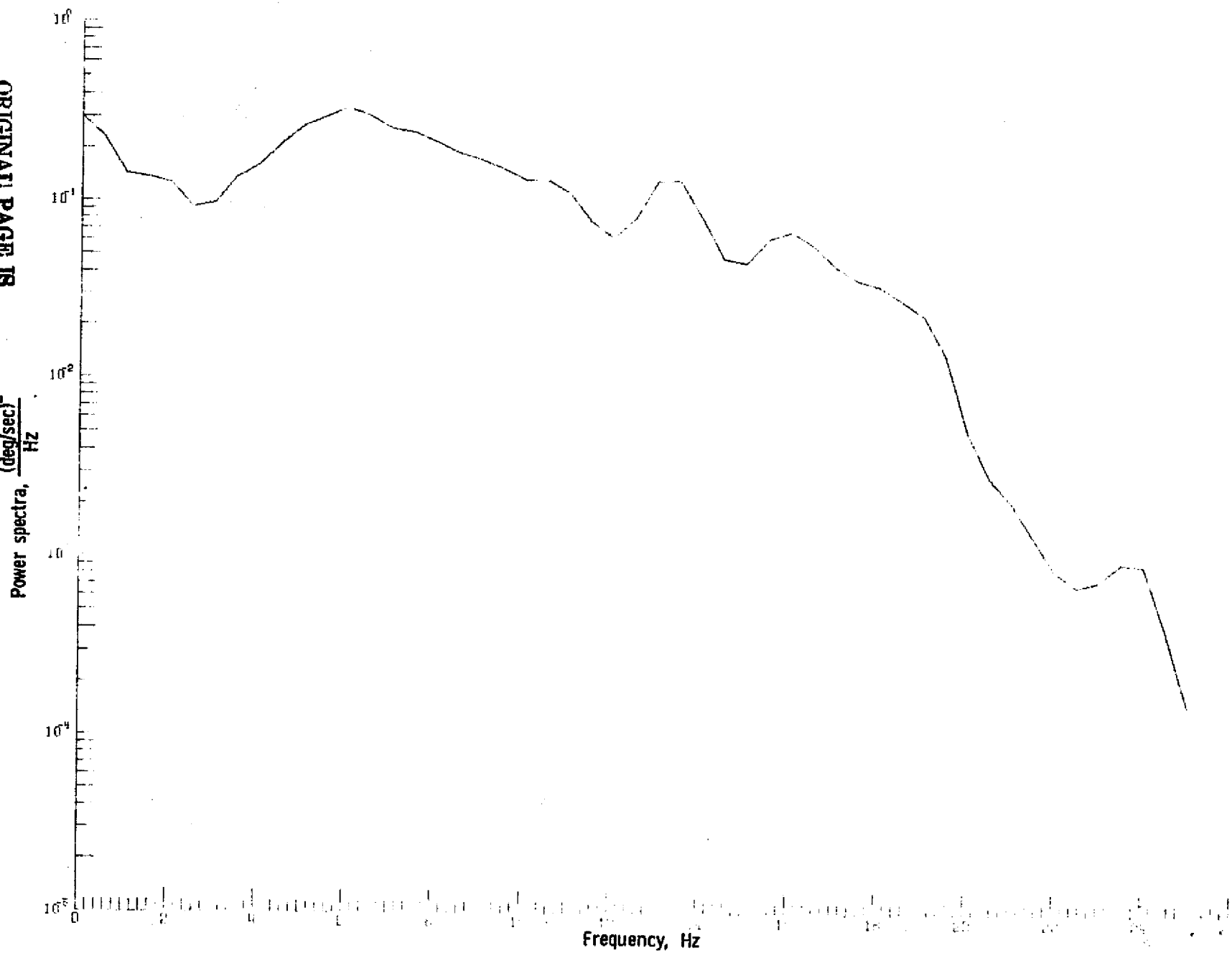

(c) Rolling velocity power spectrum (RMS rolling velocity 1.579 deg/sec).

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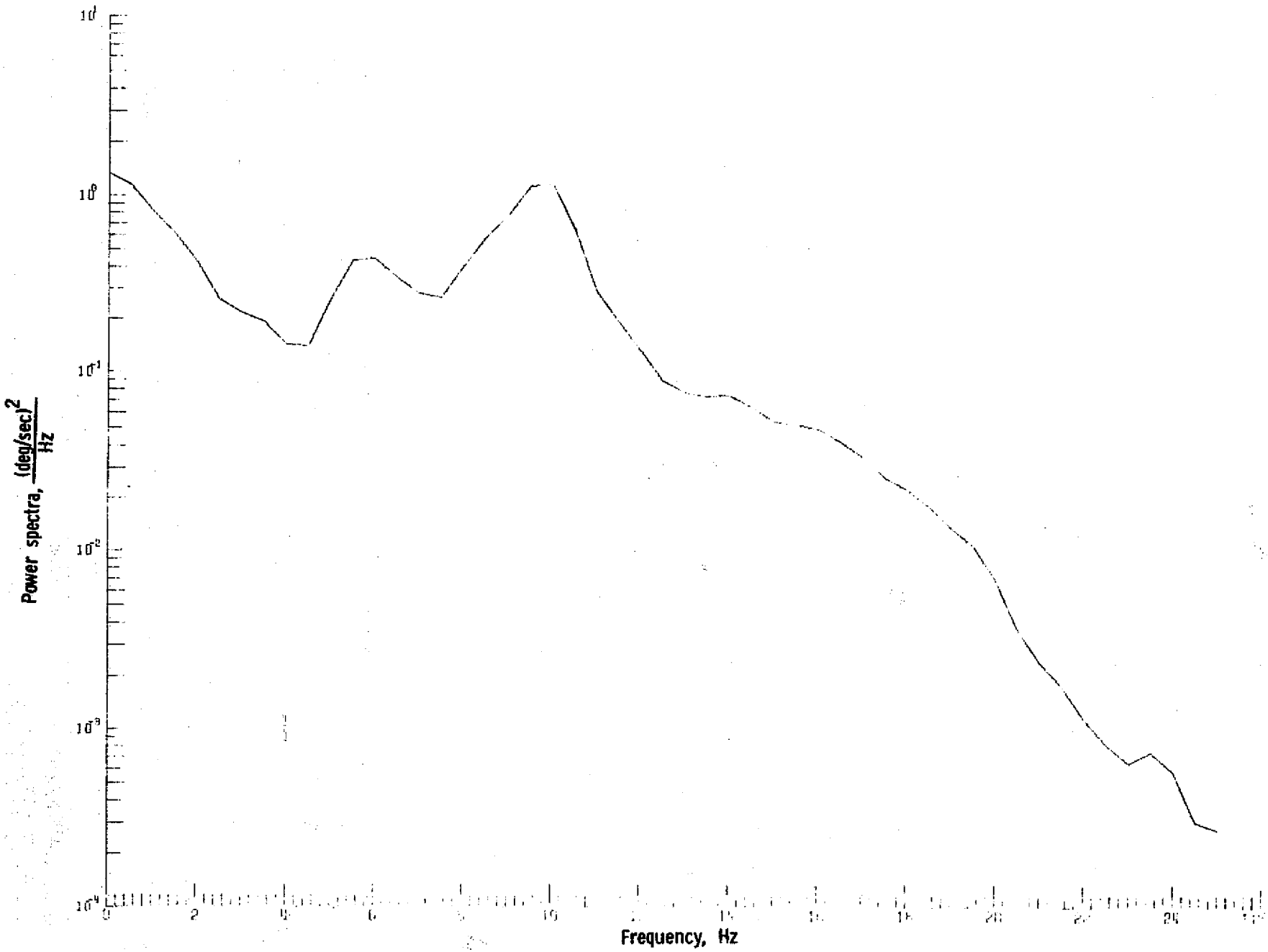

(c) Rolling velocity power spectrum (RMS rolling velocity 2.488 deg/sec).

Figure 6. - Continued.

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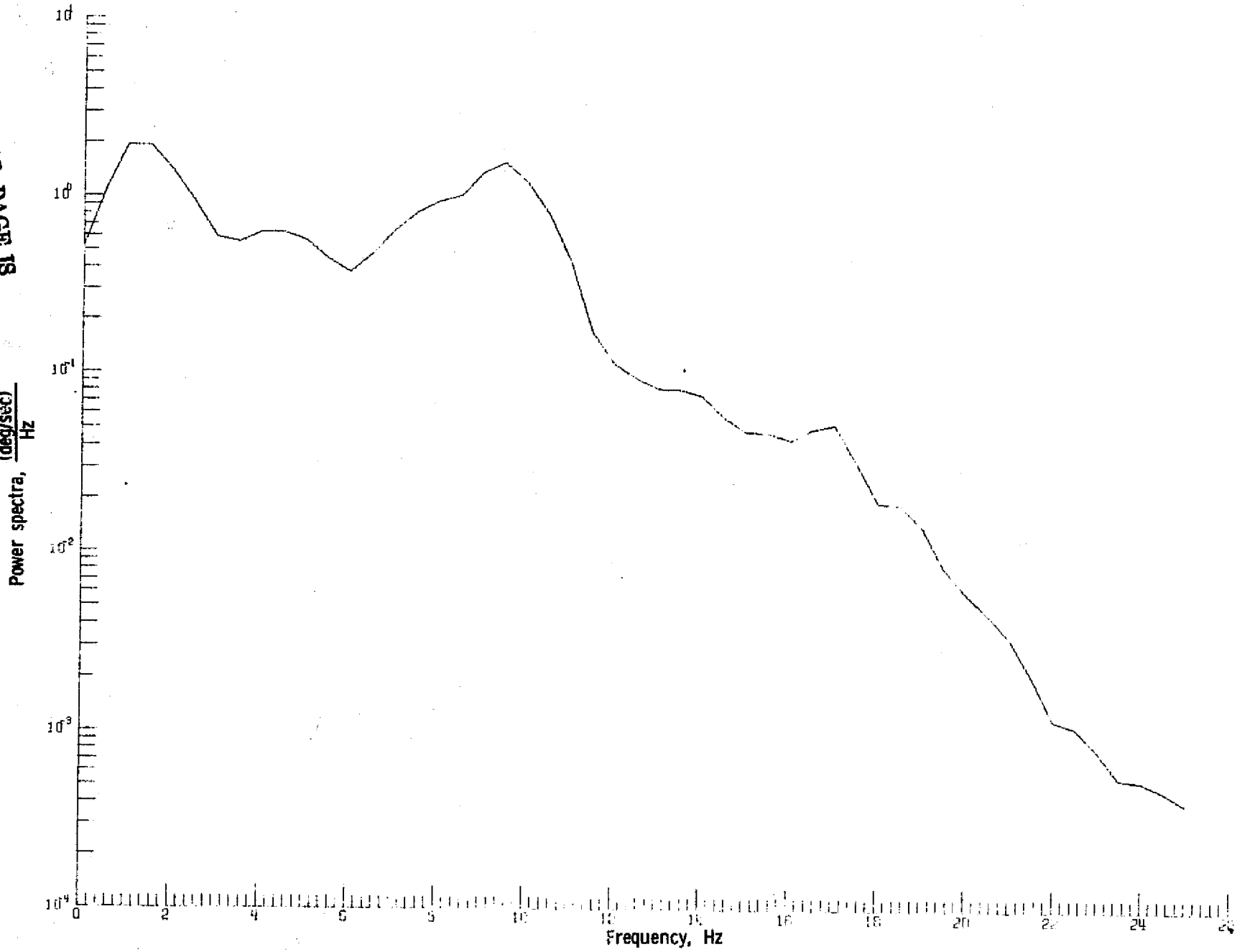

(c) Rolling velocity power spectrum (RMS rolling velocity 3.742 deg/sec).

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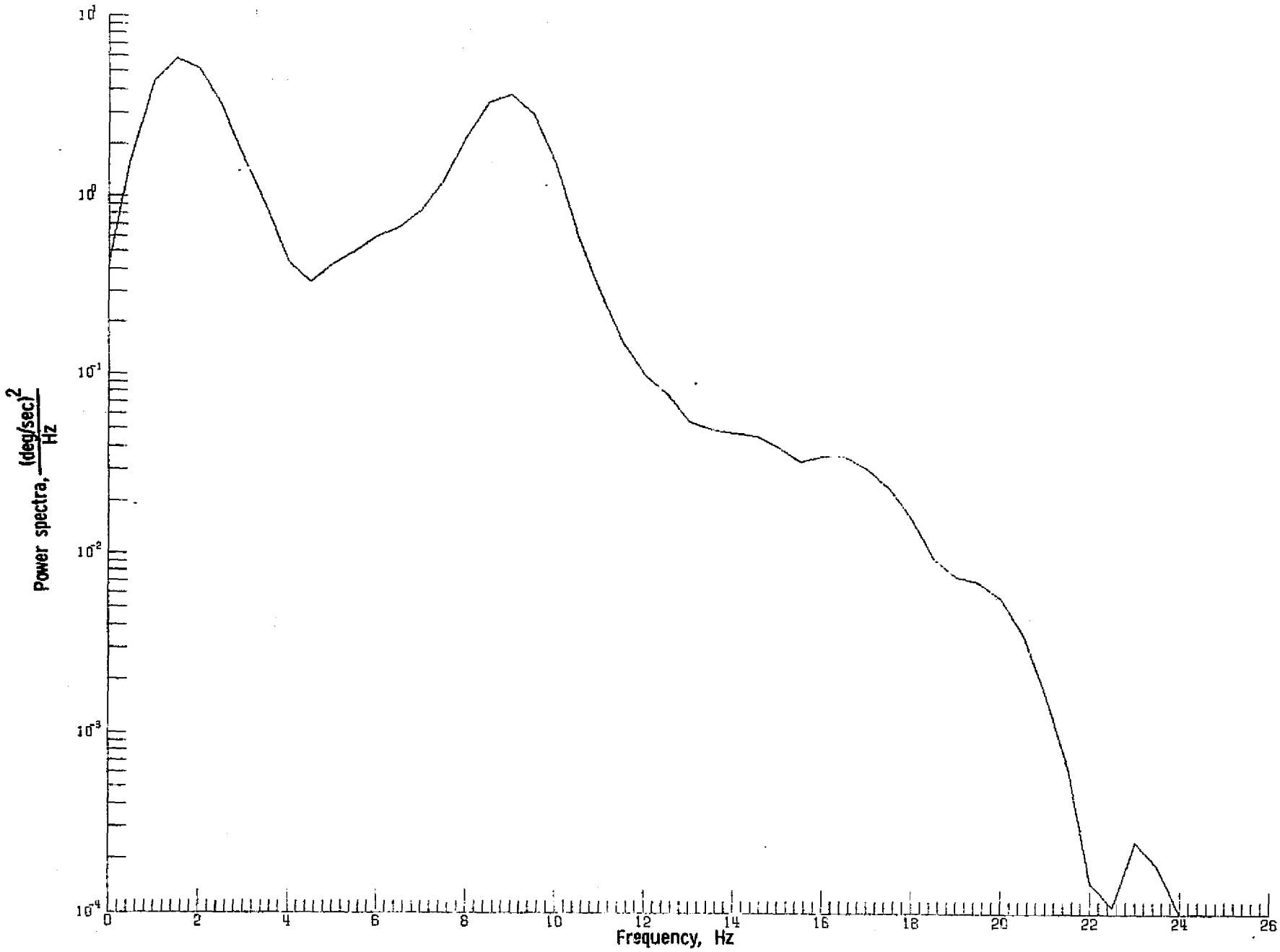

(c) Rolling velocity power spectrum (RMS rolling velocity 5.249 deg/sec).

Figure 6. - Concluded.

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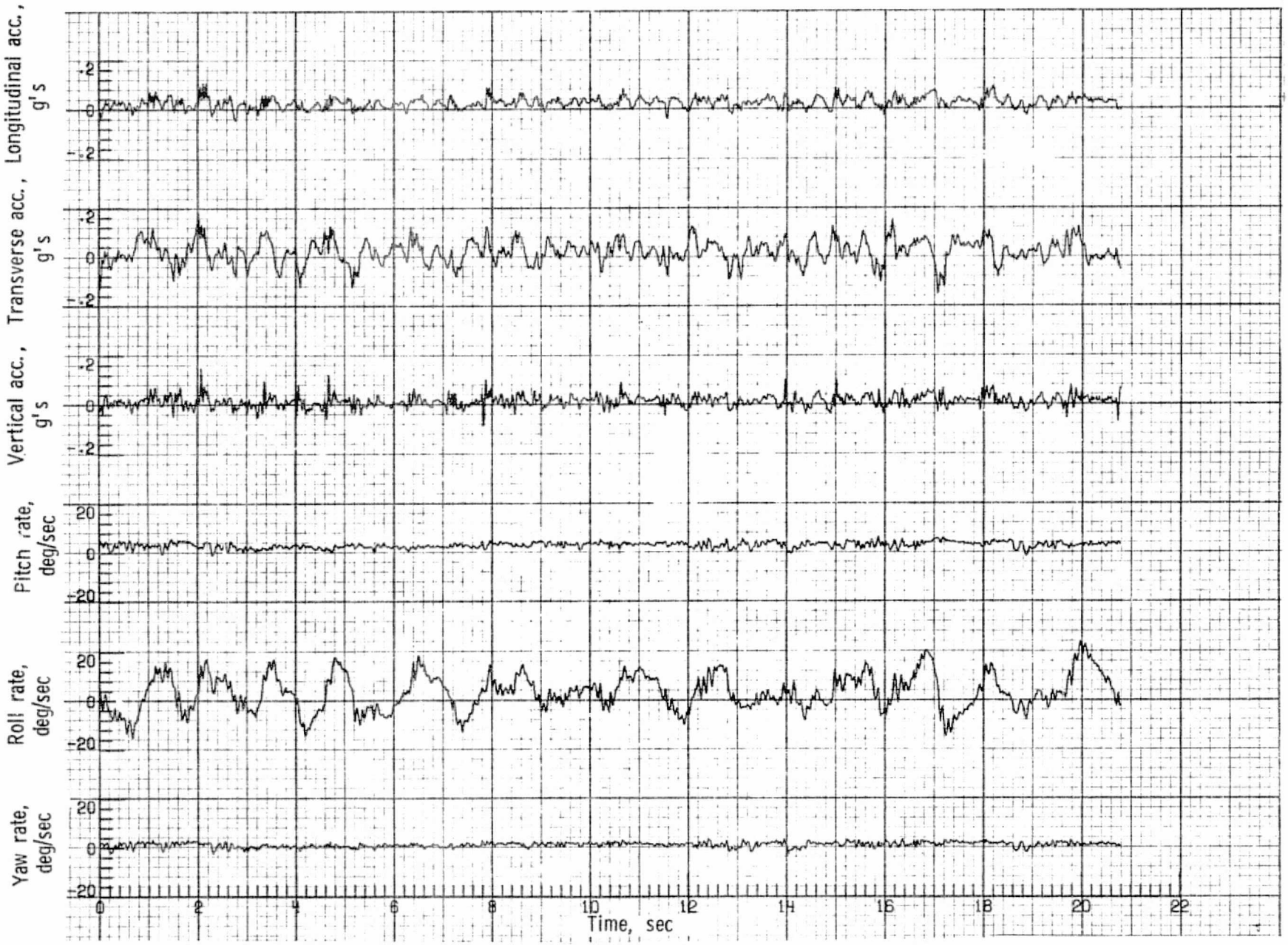
(a) Time histories (RMS rolling velocity 1.532 deg/sec).

Figure 7.- Measured motion characteristics using vertical velocity with flat 0-1 Hz inputs.

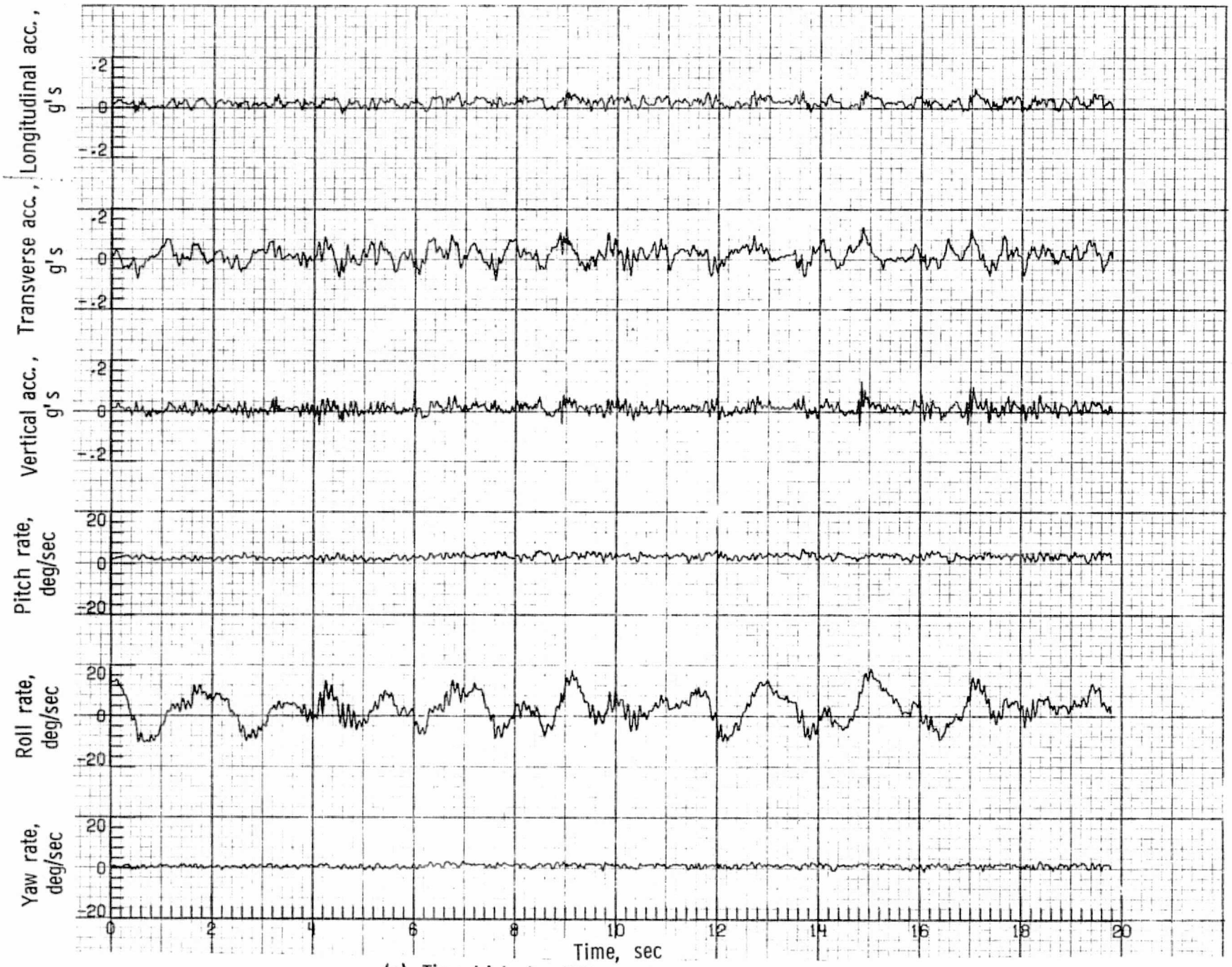
(a) Time histories (RMS rolling velocity 2.271 deg/sec).

Figure 7.- Continued.



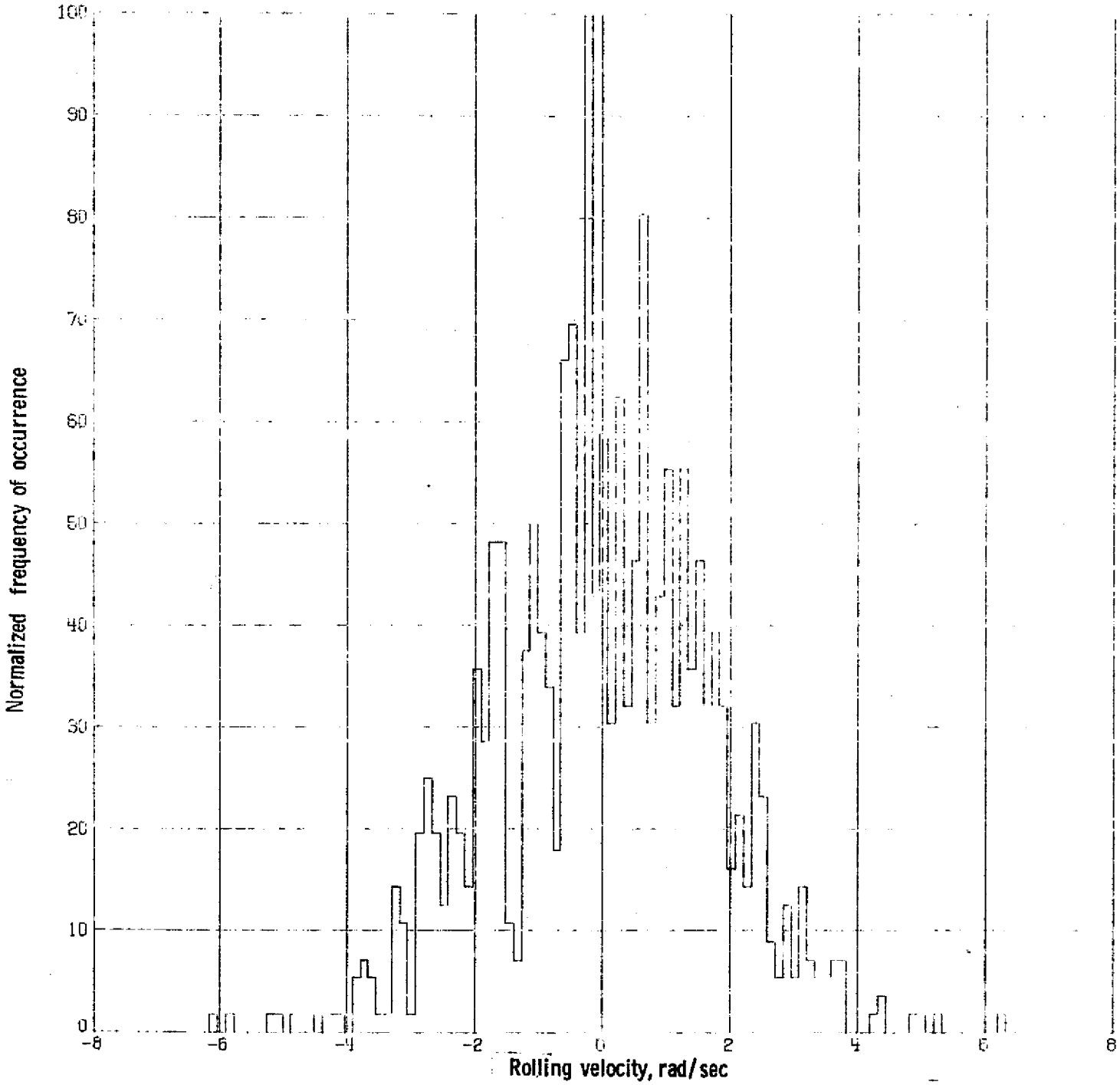
(a) Time histories (RMS rolling velocity 7.136 deg/sec).

Figure 7.- Continued.



(a) Time histories (RMS rolling velocity 5.814 deg/sec).

Figure 7.- Continued.



(b) Rolling velocity histogram (RMS rolling velocity 1.532 deg/sec).

Figure 7. - Continued.

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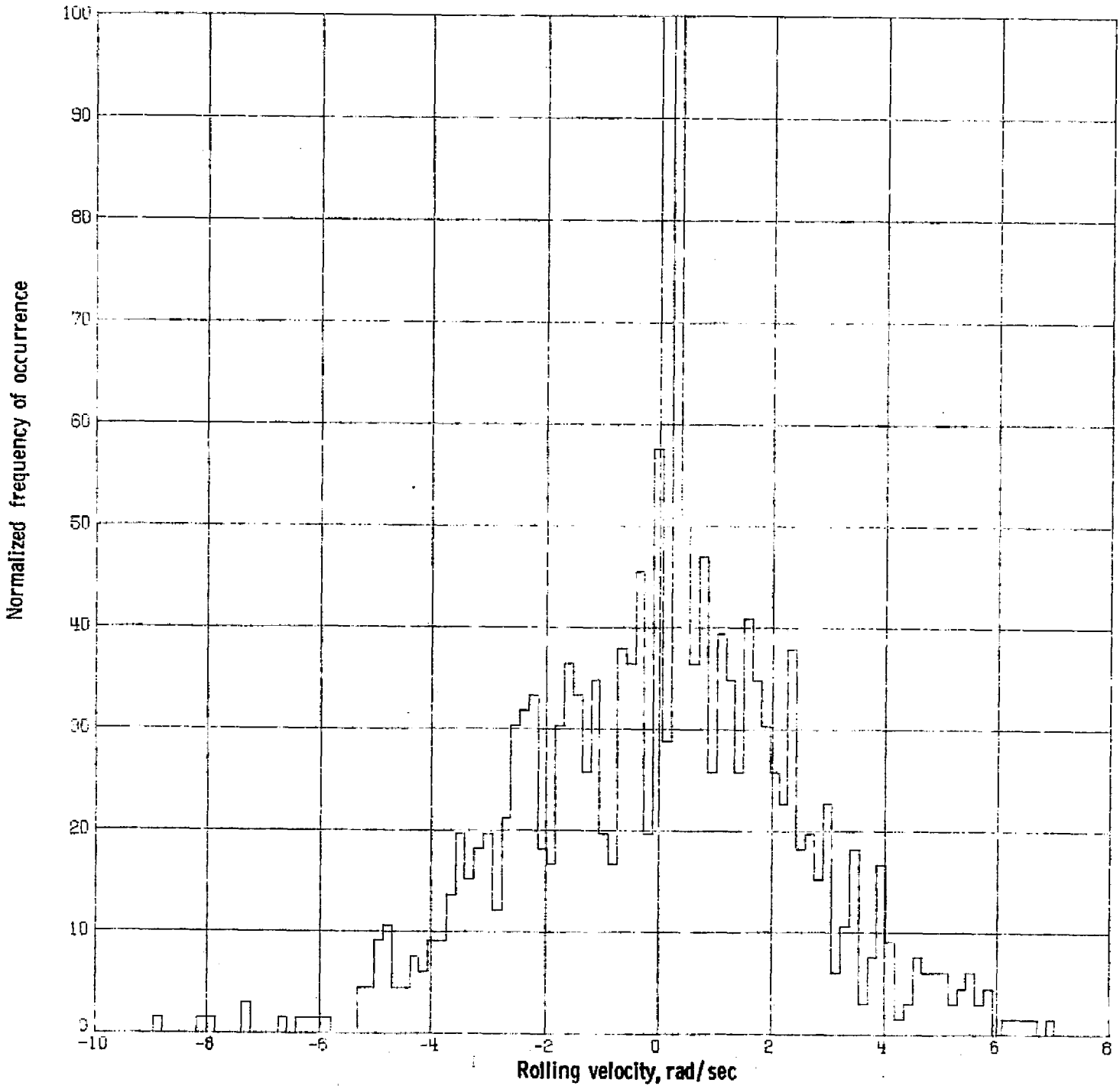
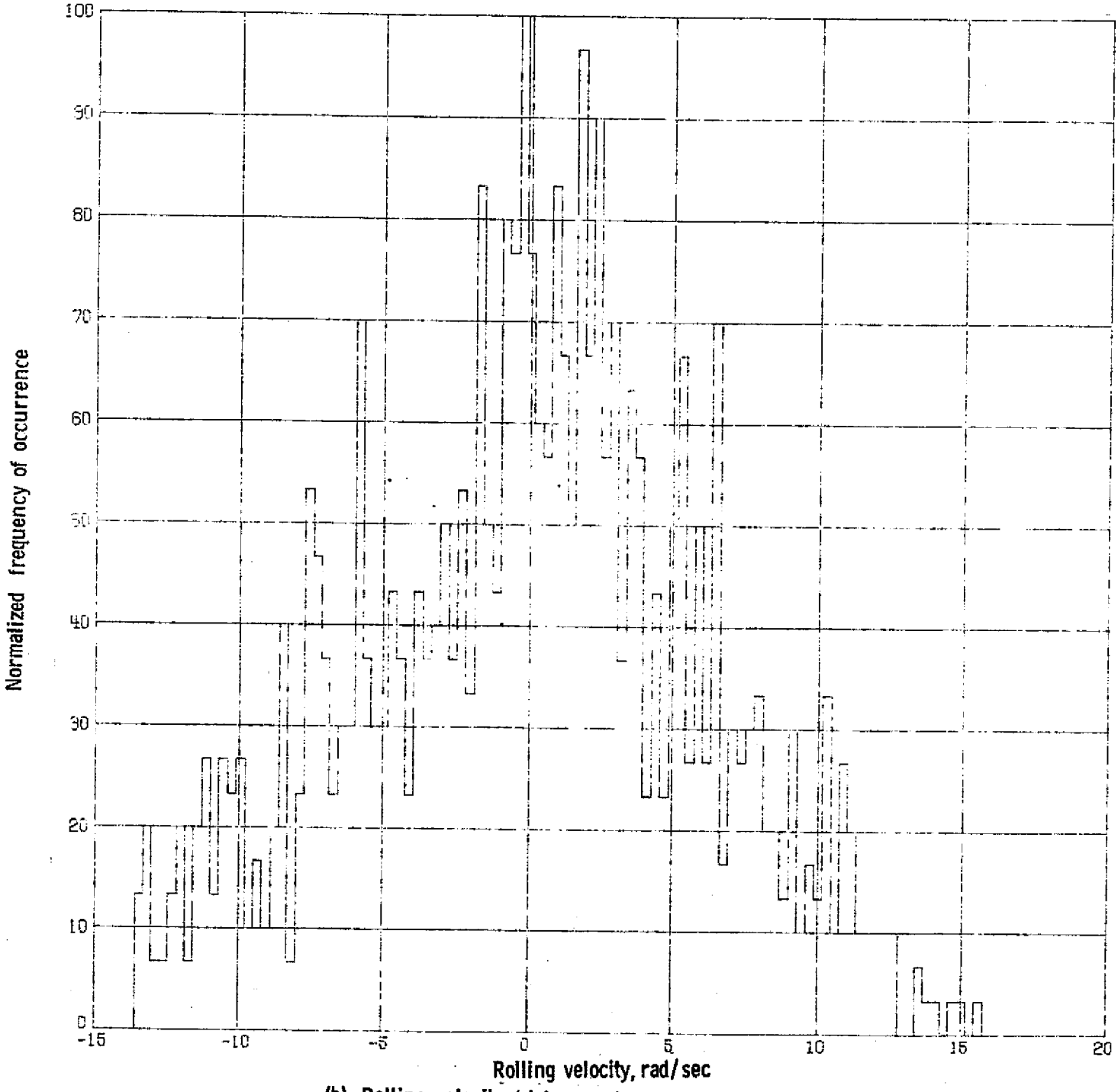


(b) Rolling velocity histogram (RMS rolling velocity 2.271 deg/sec).

Figure 7. - Continued.



(b) Rolling velocity histogram (RMS rolling velocity 5.814 deg/sec).

Figure 7. - Continued.

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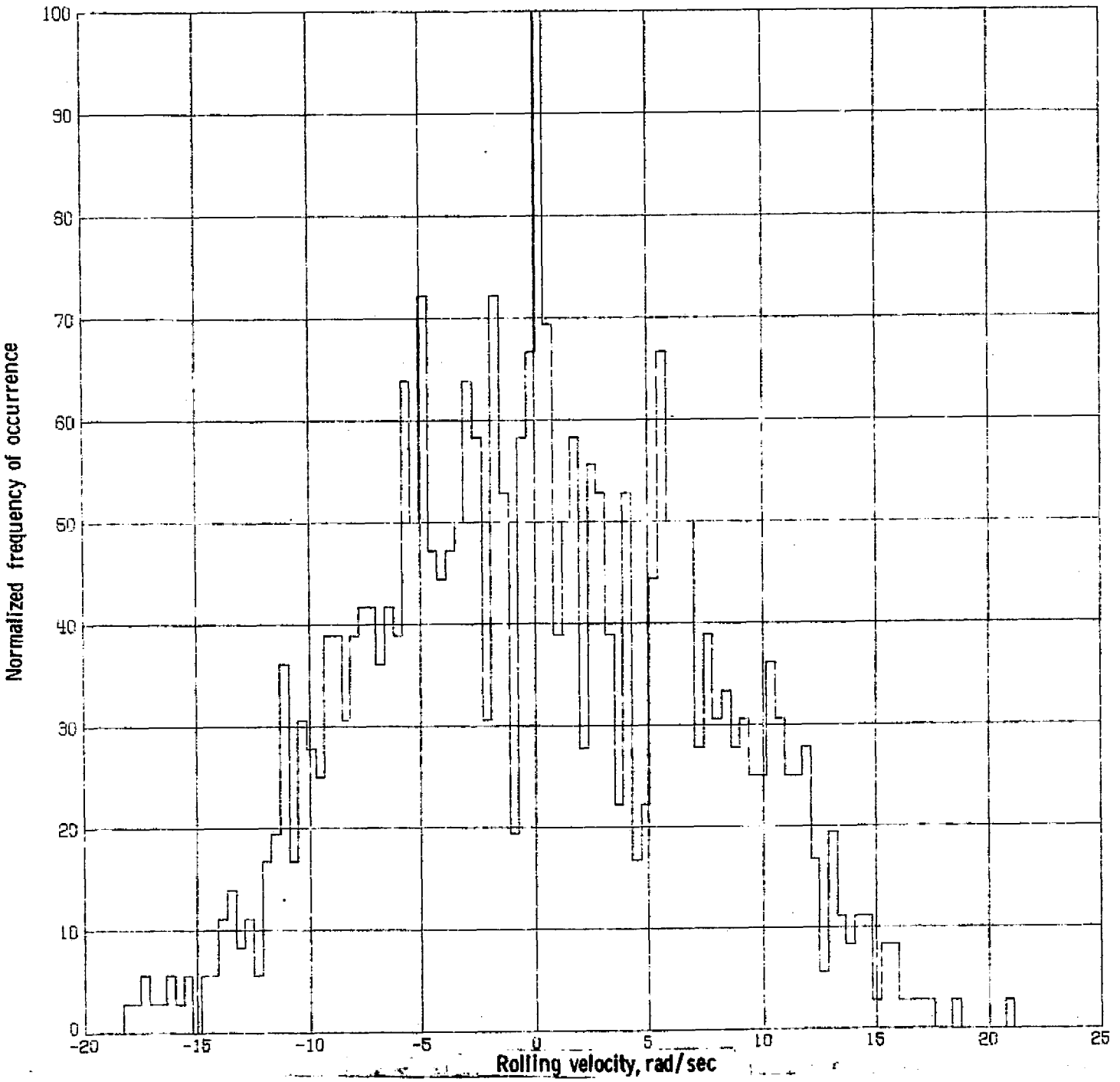

(b) Rolling velocity histogram (RMS rolling velocity 7.136 deg/sec).

Figure 7. - Continued.

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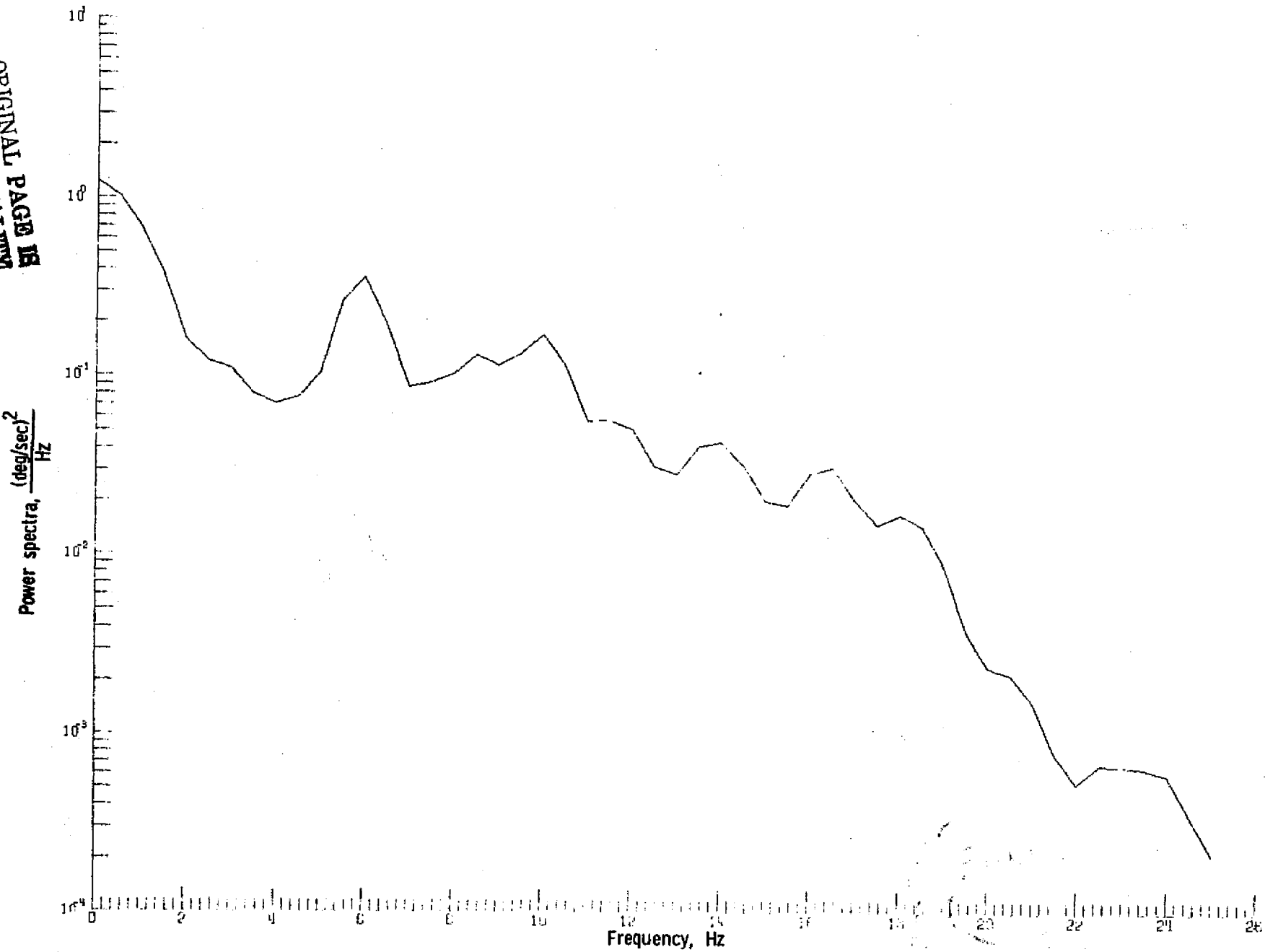
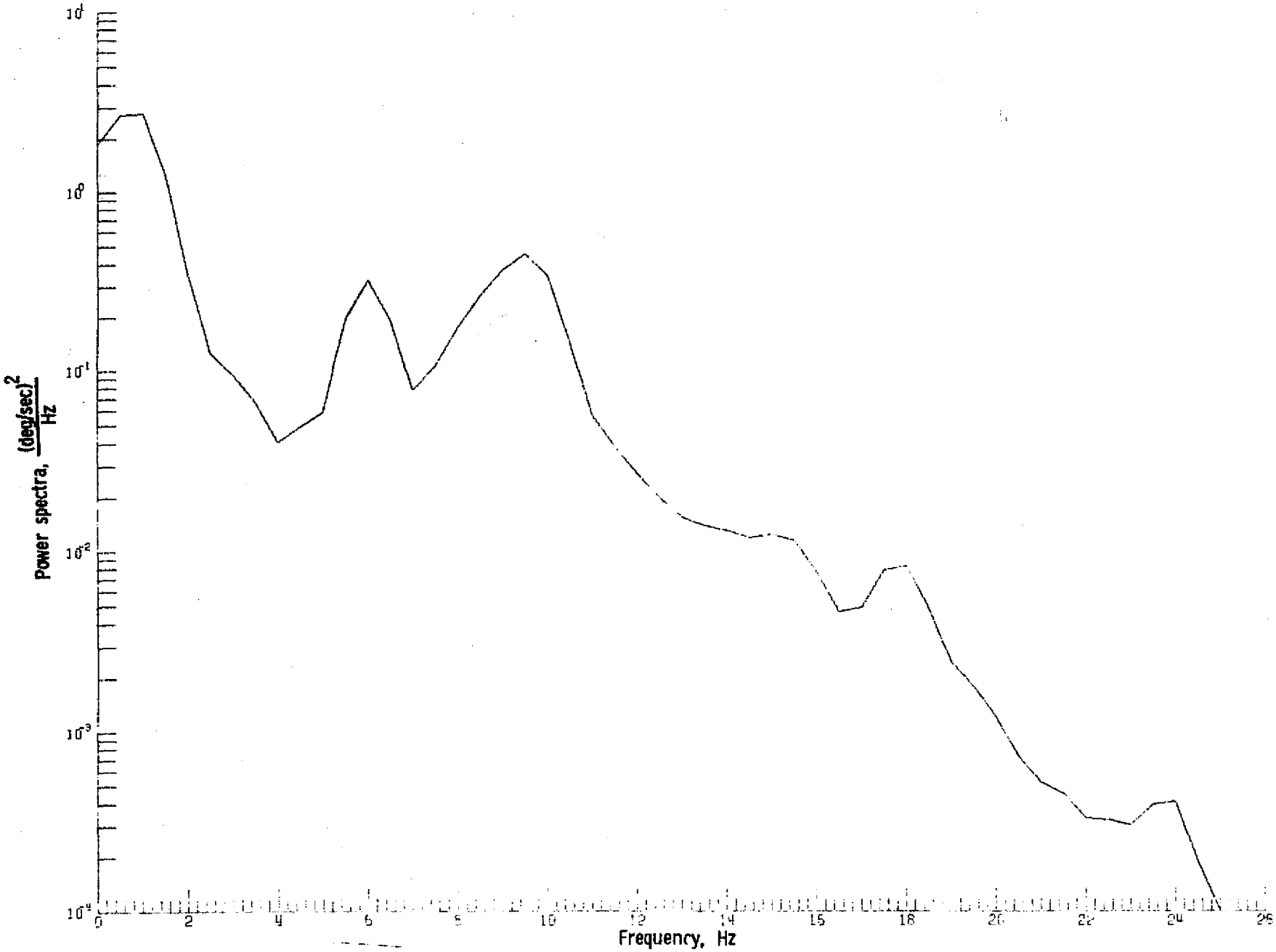


(c) Rolling velocity power spectrum (RMS rolling velocity 1.532 deg/sec).

Figure 7. - Continued.



(c) Rolling velocity power spectrum (RMS rolling velocity 2.271 deg/sec).

Figure 7.- Continued.

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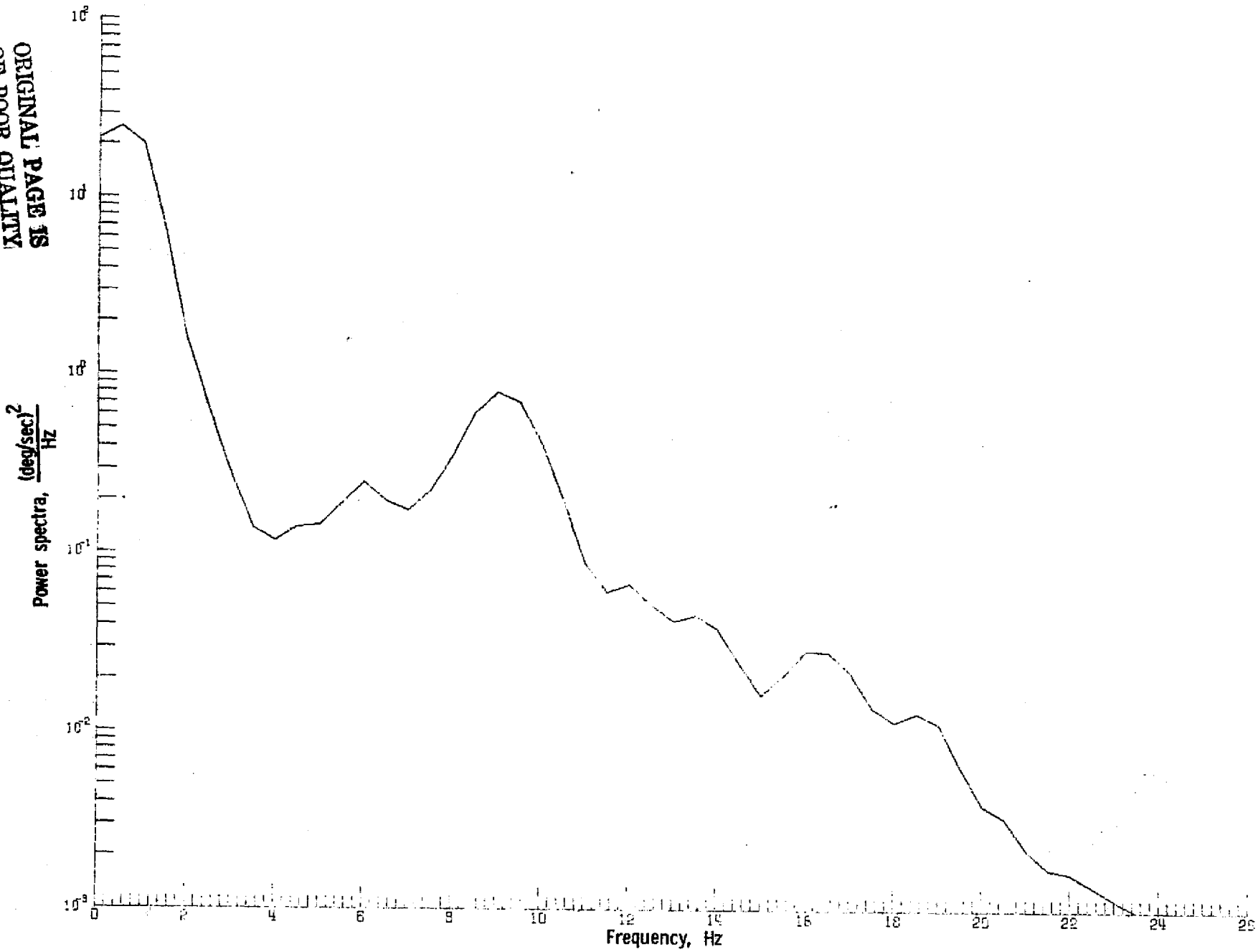

(c) Rolling velocity power spectrum (RMS rolling velocity 5.814 deg/sec).

Figure 7.- Continued.

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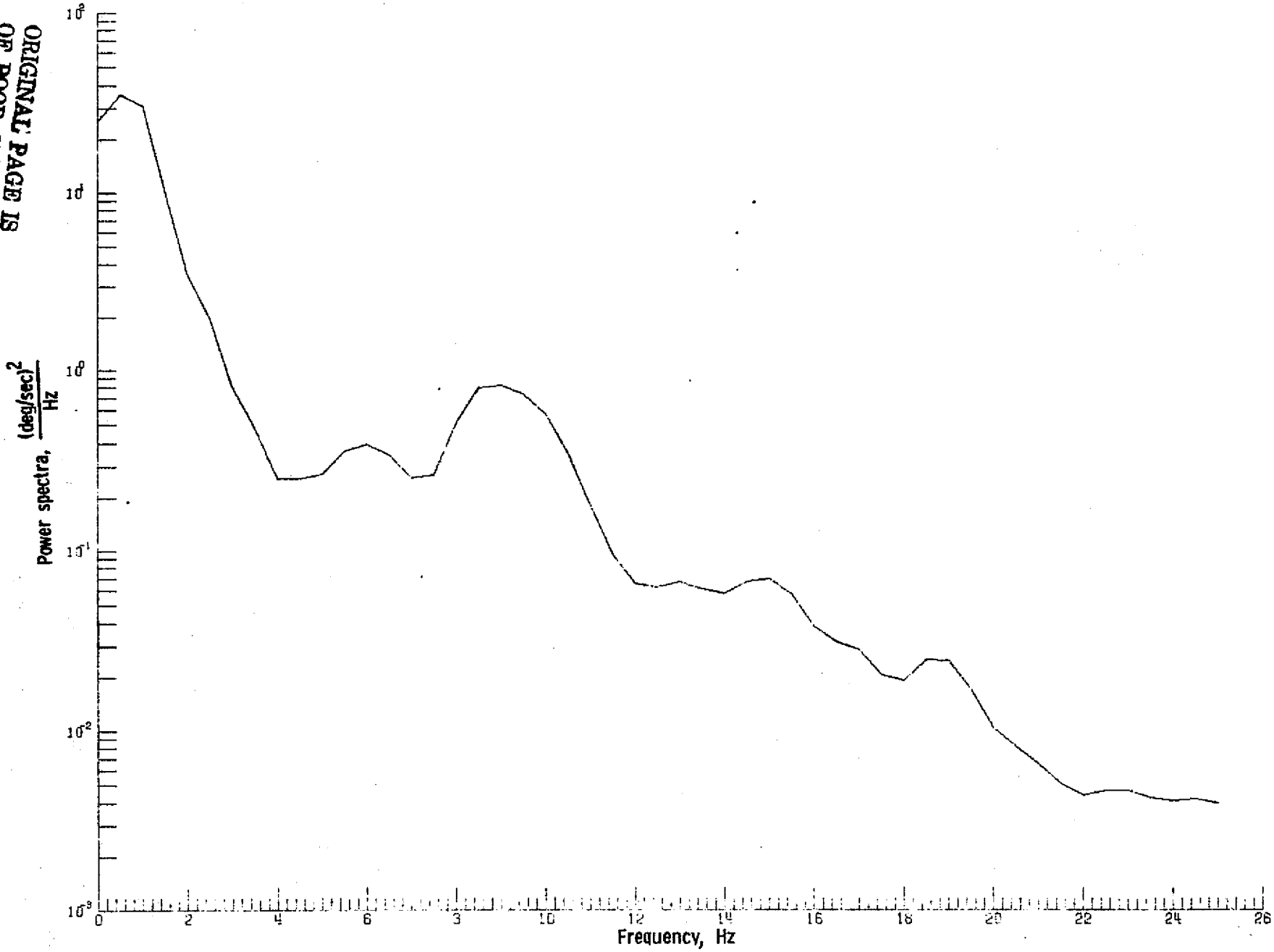

(c) Rolling velocity power spectrum (RMS rolling velocity 7.136 deg/sec).

Figure 7. - Concluded.

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(a) Time histories (RMS rolling velocity 1.231 deg/sec).

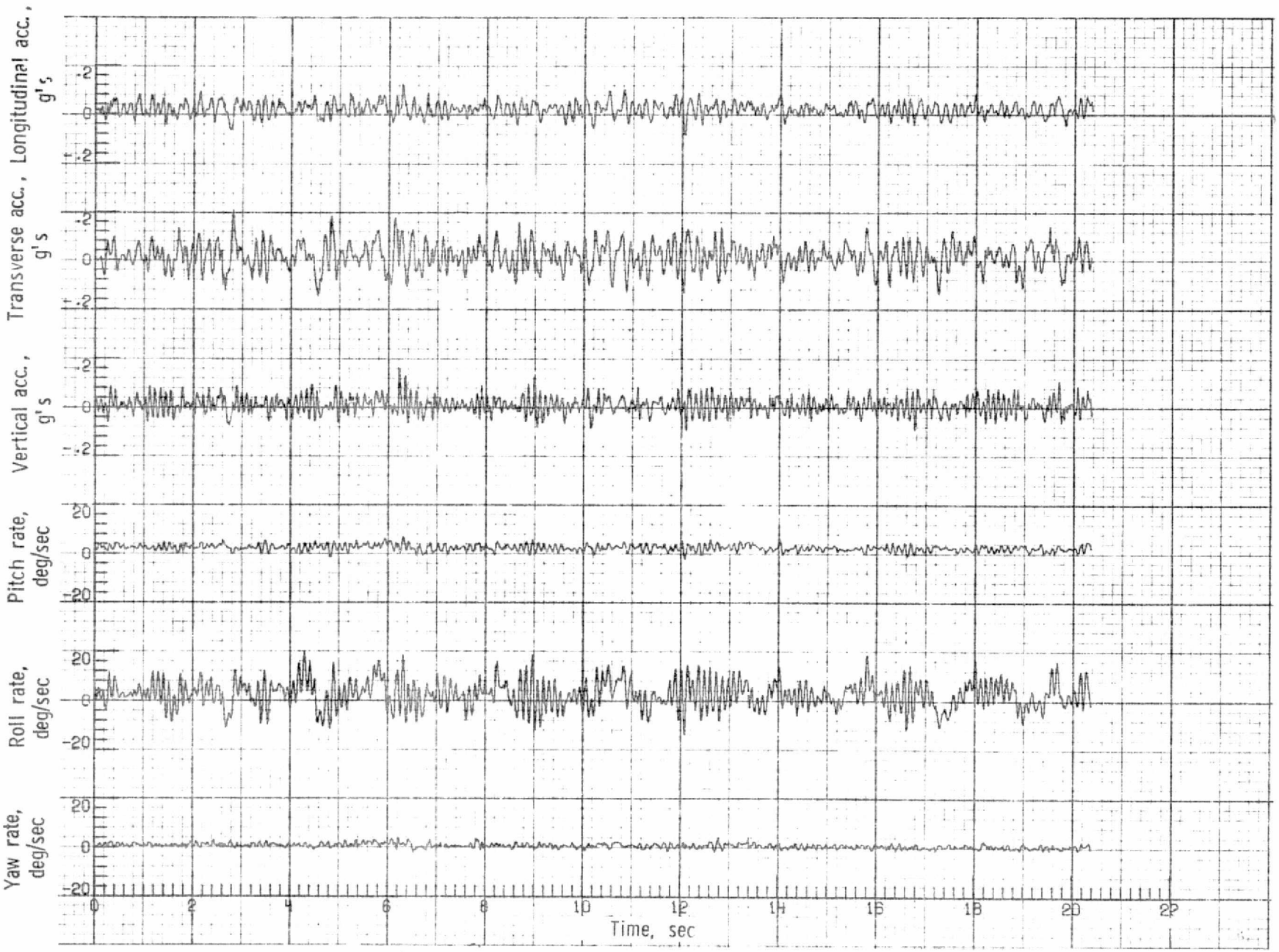
Figure 8. - Continued.

(a) Time histories (RMS rolling velocity 1.981 deg/sec).

Figure 8.- Measured motion characteristics using rolling velocity with flat 0-2 Hz inputs.

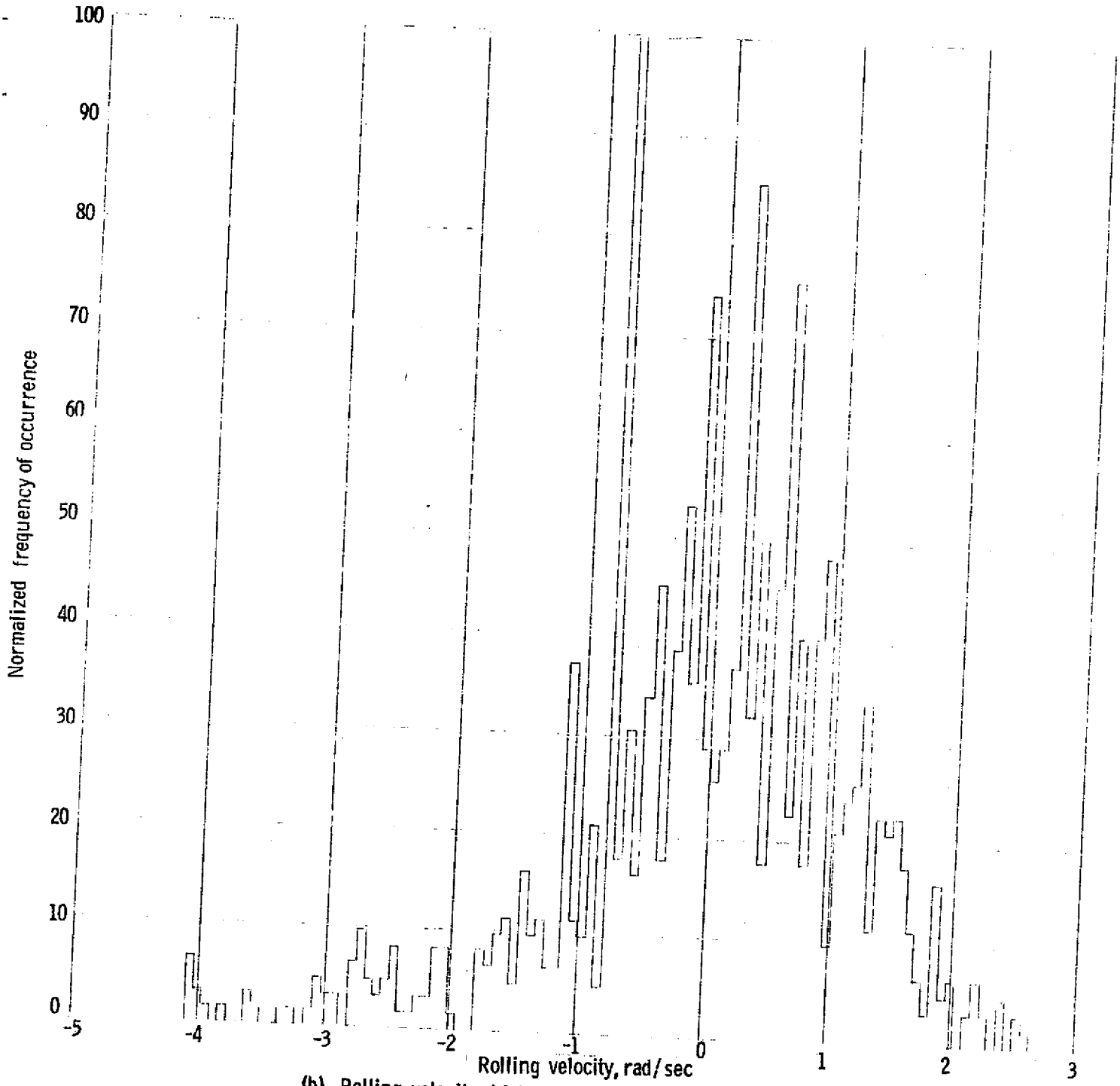
(a) Time histories (RMS rolling velocity 3.177 deg/sec).

Figure 8.- Continued.



(a) Time histories (RMS rolling velocity 5.247 deg/sec).

Figure 8. - Continued.



(b) Rolling velocity histogram (RMS rolling velocity 1.231 deg/sec).

Figure 8.- Continued.

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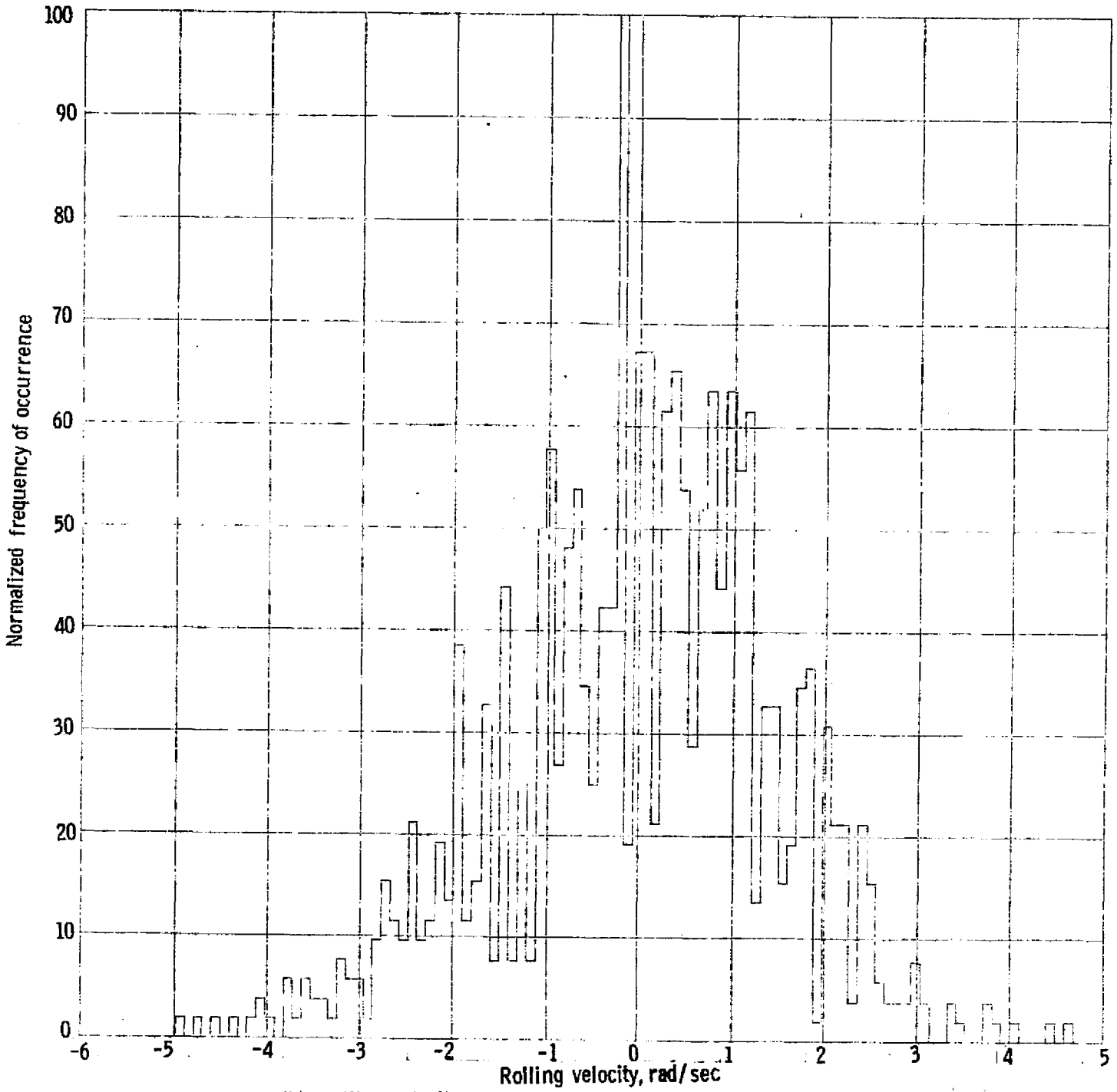
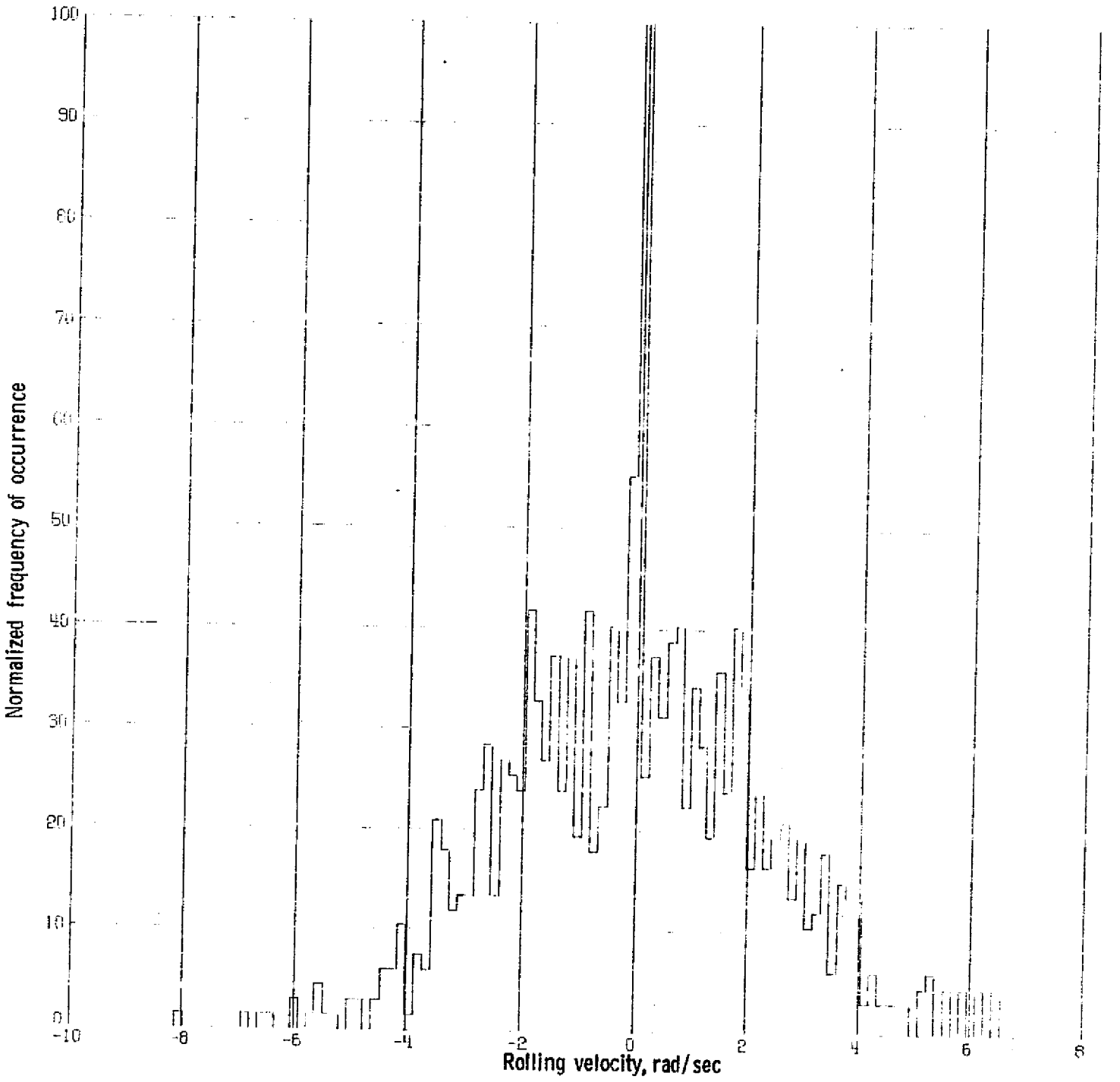


(b) Rolling velocity histogram (RMS rolling velocity 1.981 deg/sec).

Figure 8. - Continued.



(b) Rolling velocity histogram (RMS rolling velocity 3.177 deg/sec).

Figure 8. - Continued.

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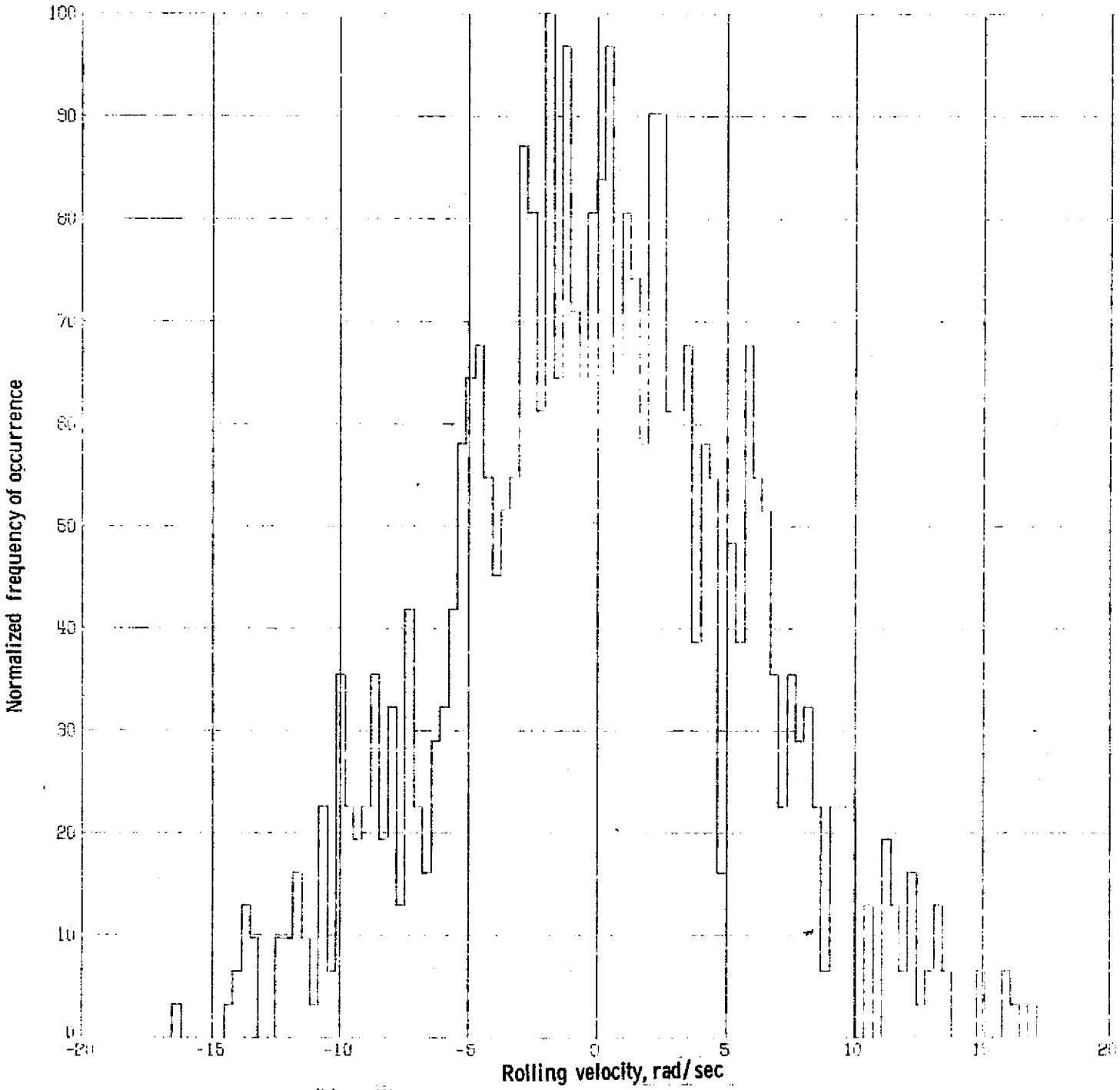

(b) Rolling velocity histogram (RMS rolling velocity 5.247 deg/sec).

Figure 8. - Continued.

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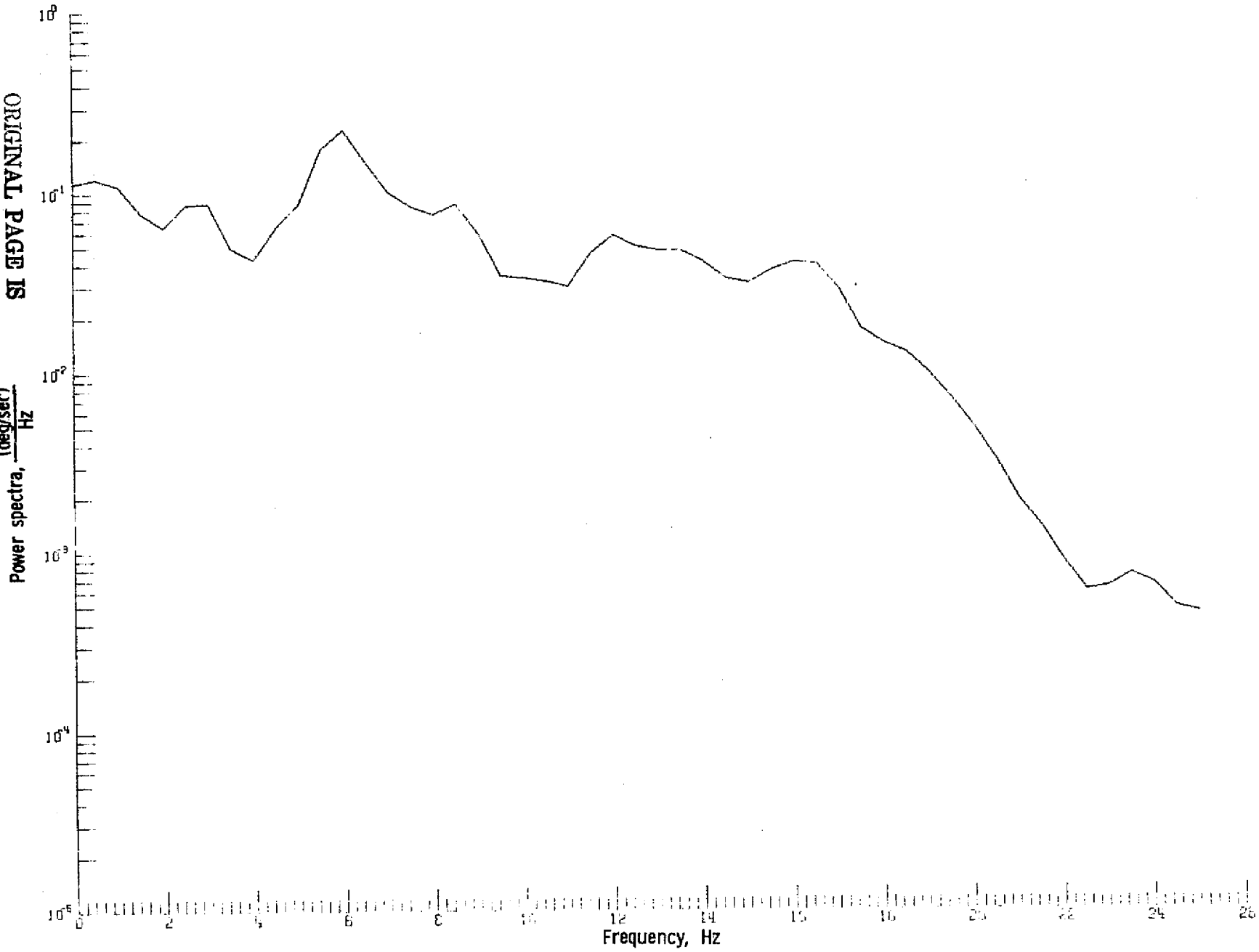
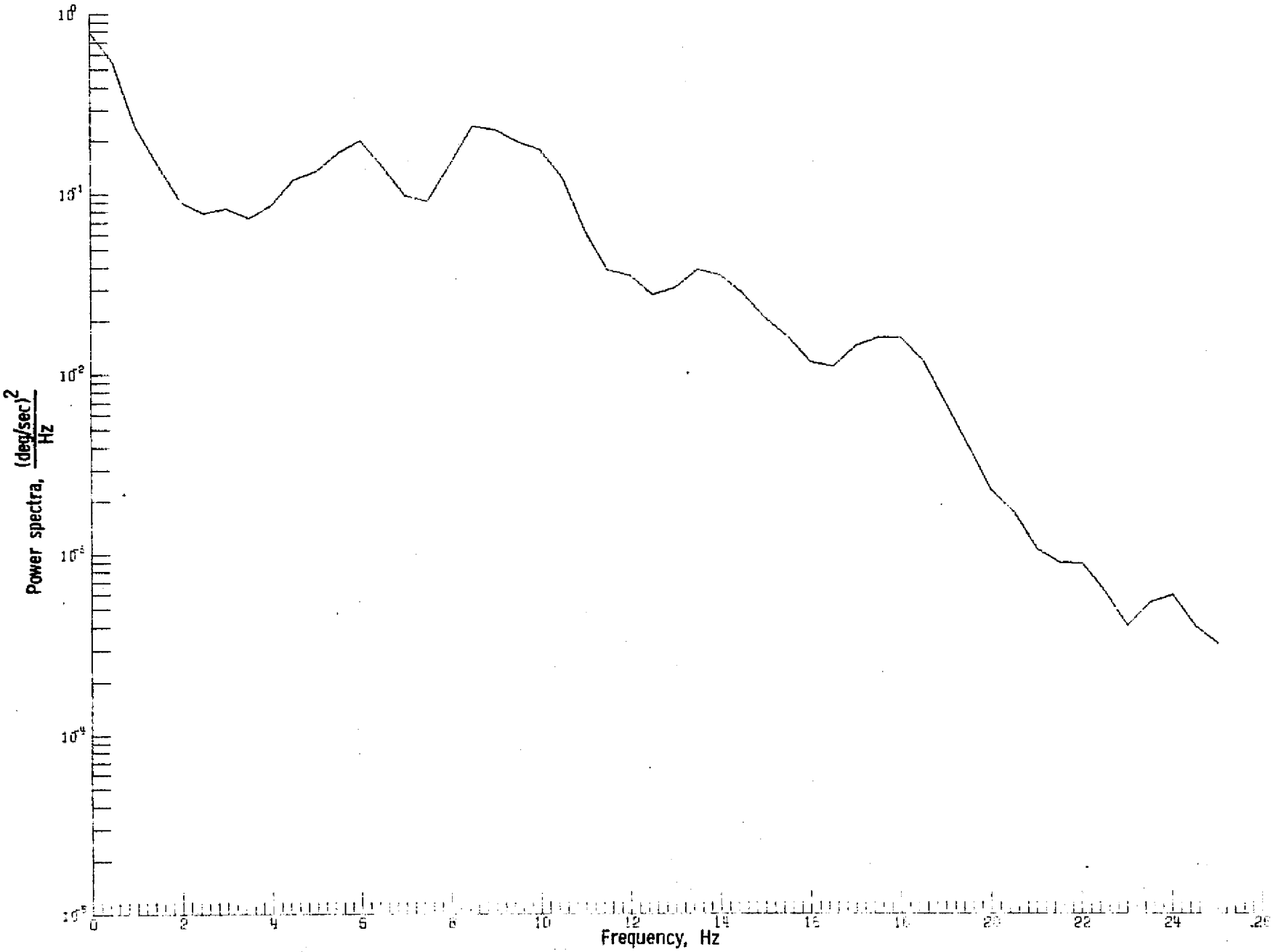


(c) Rolling velocity power spectrum (RMS rolling velocity 1.231 deg/sec).

Figure 8. - Continued.



(c) Rolling velocity power spectrum (RMS rolling velocity 1.981 deg/sec).

Figure 8.- Continued.

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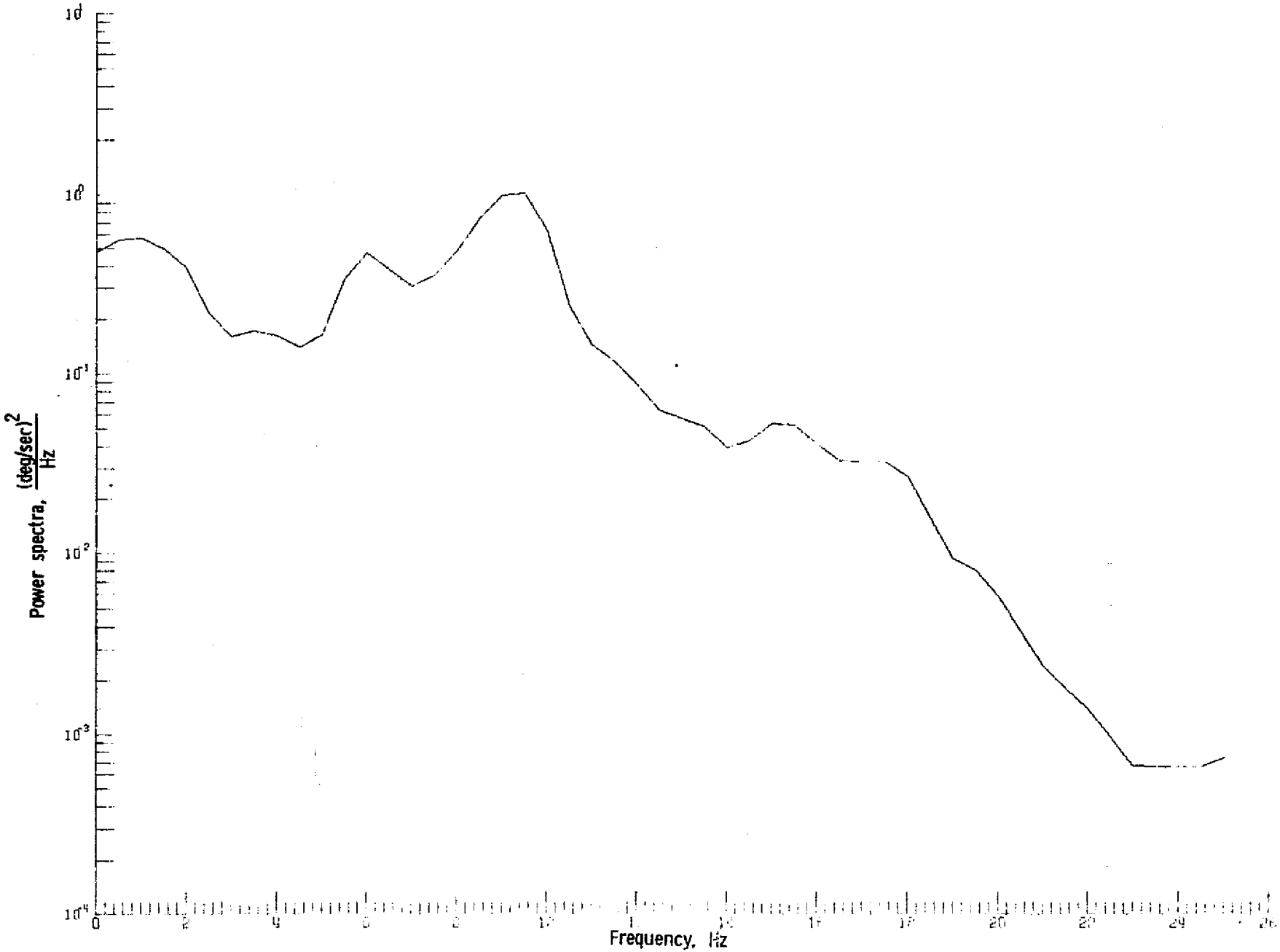
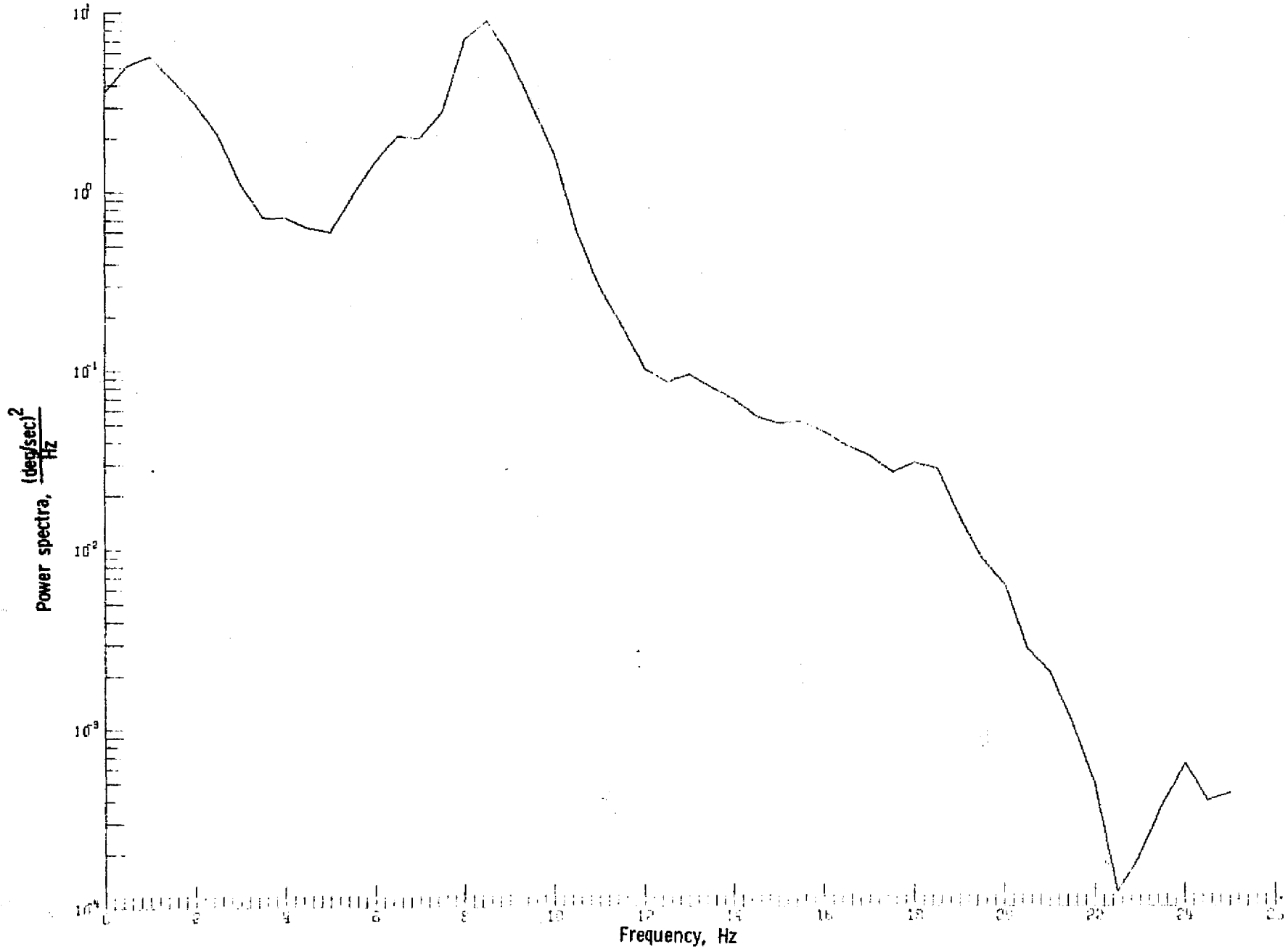


(c) Rolling velocity power spectrum (RMS rolling velocity 3.177 deg/sec).

Figure 8.- Continued.



(c) Rolling velocity power spectrum (RMS rolling velocity 5.247 deg/sec).

Figure 8. - Concluded.

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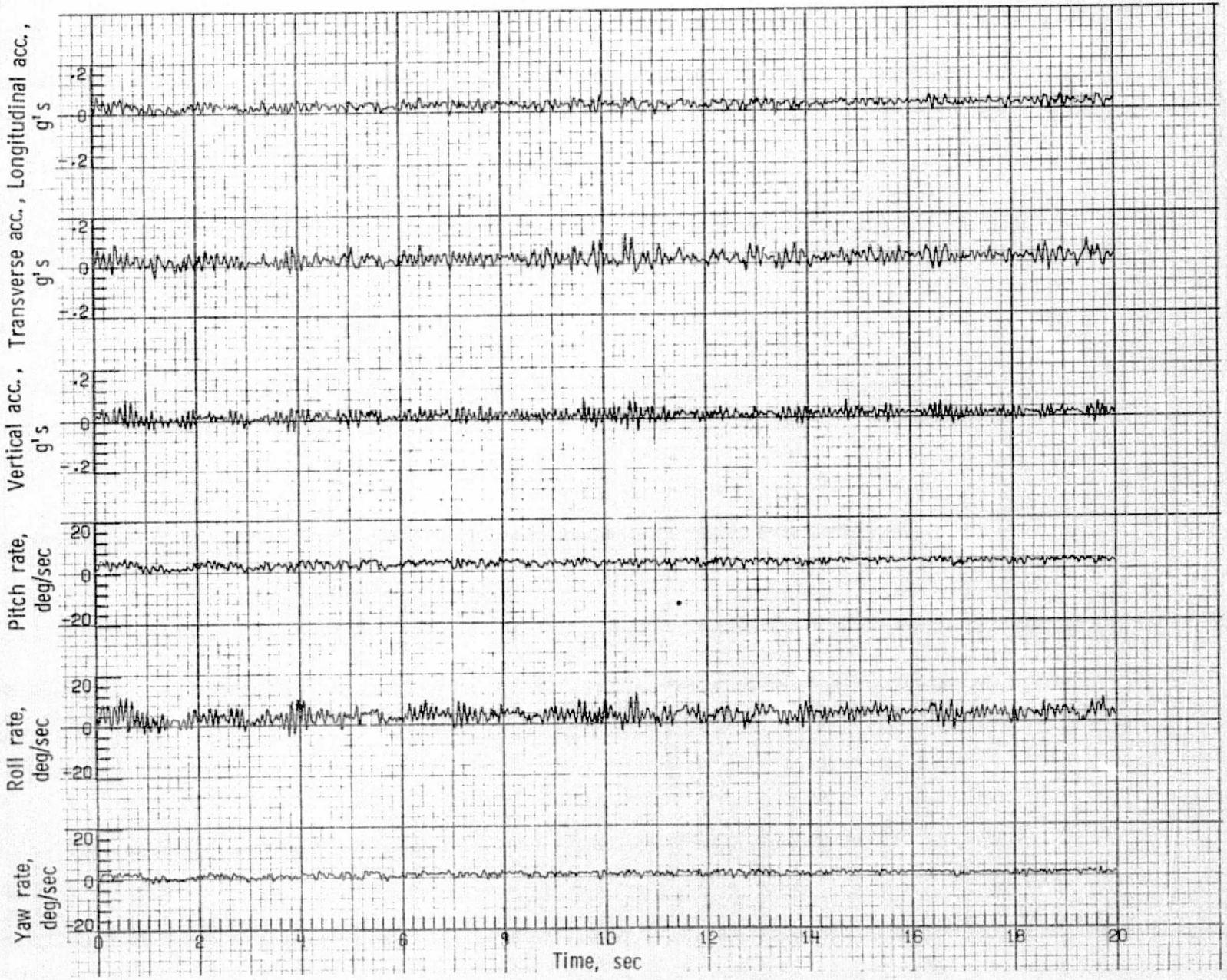
(a) Time histories (RMS rolling velocity 1.168 deg/sec).

Figure 9.- Measured motion characteristics using rolling velocity with flat 1-2 Hz inputs.



(a) Time histories (RMS rolling velocity 2.220 deg/sec).

Figure 9.- Continued.

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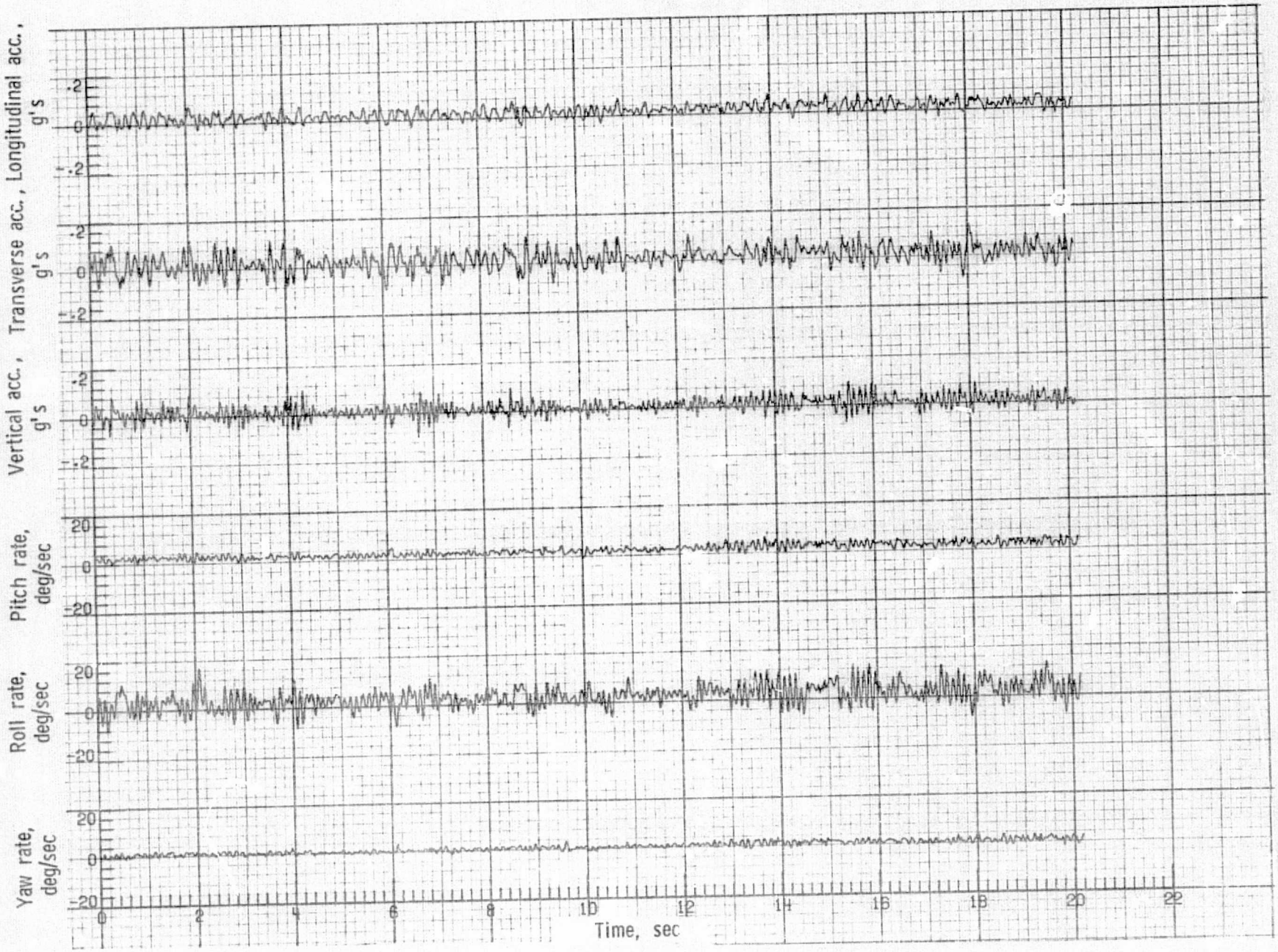
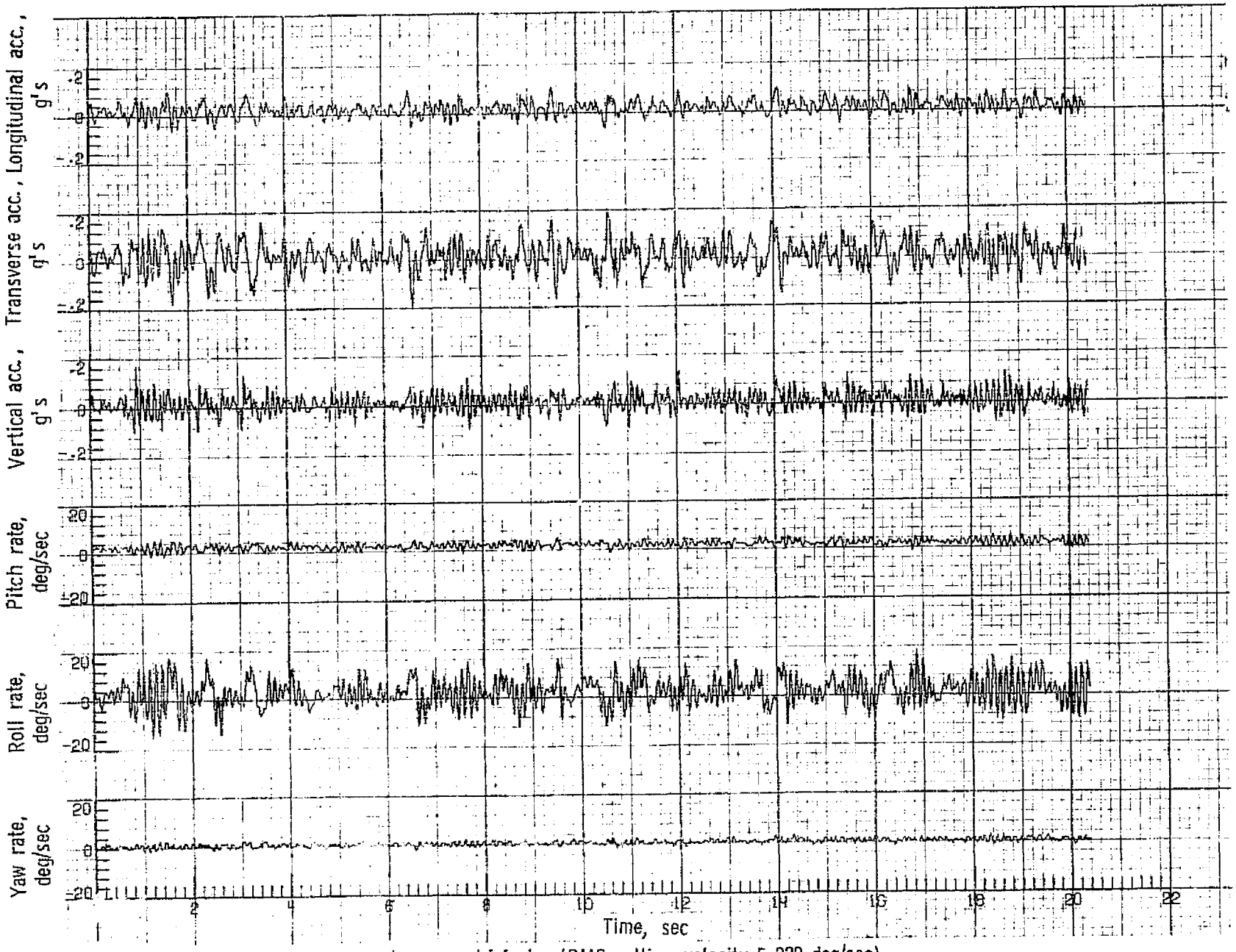


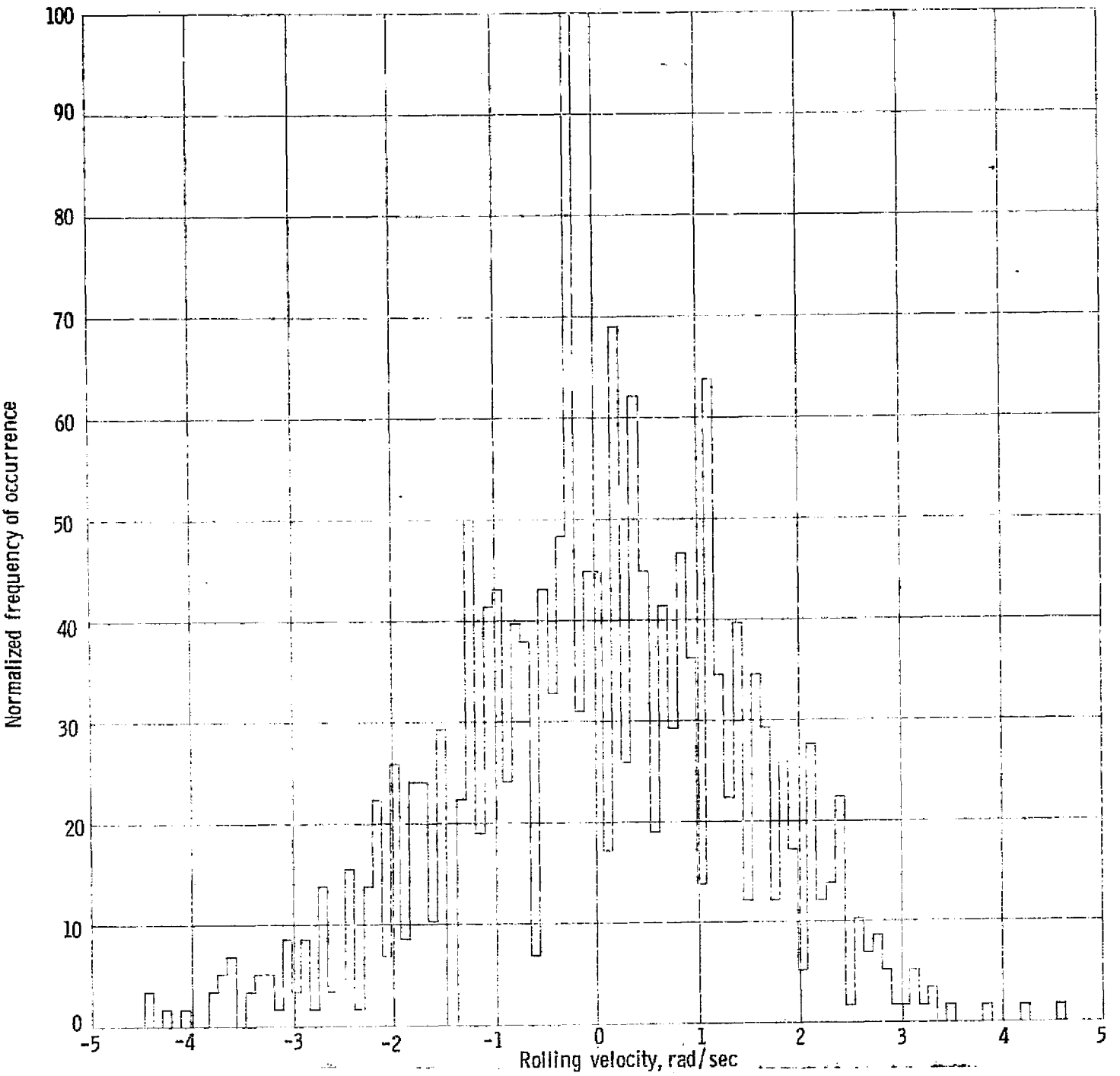
(a) Time histories (RMS rolling velocity 3.538 deg/sec).

Figure 9.- Continued.



ime histories (RMS rolling velocity 5.220 deg/sec).

Figure 9. - Continued.



(b) Rolling velocity histogram (RMS rolling velocity 1.168 deg/sec).

Figure 9. - Continued.

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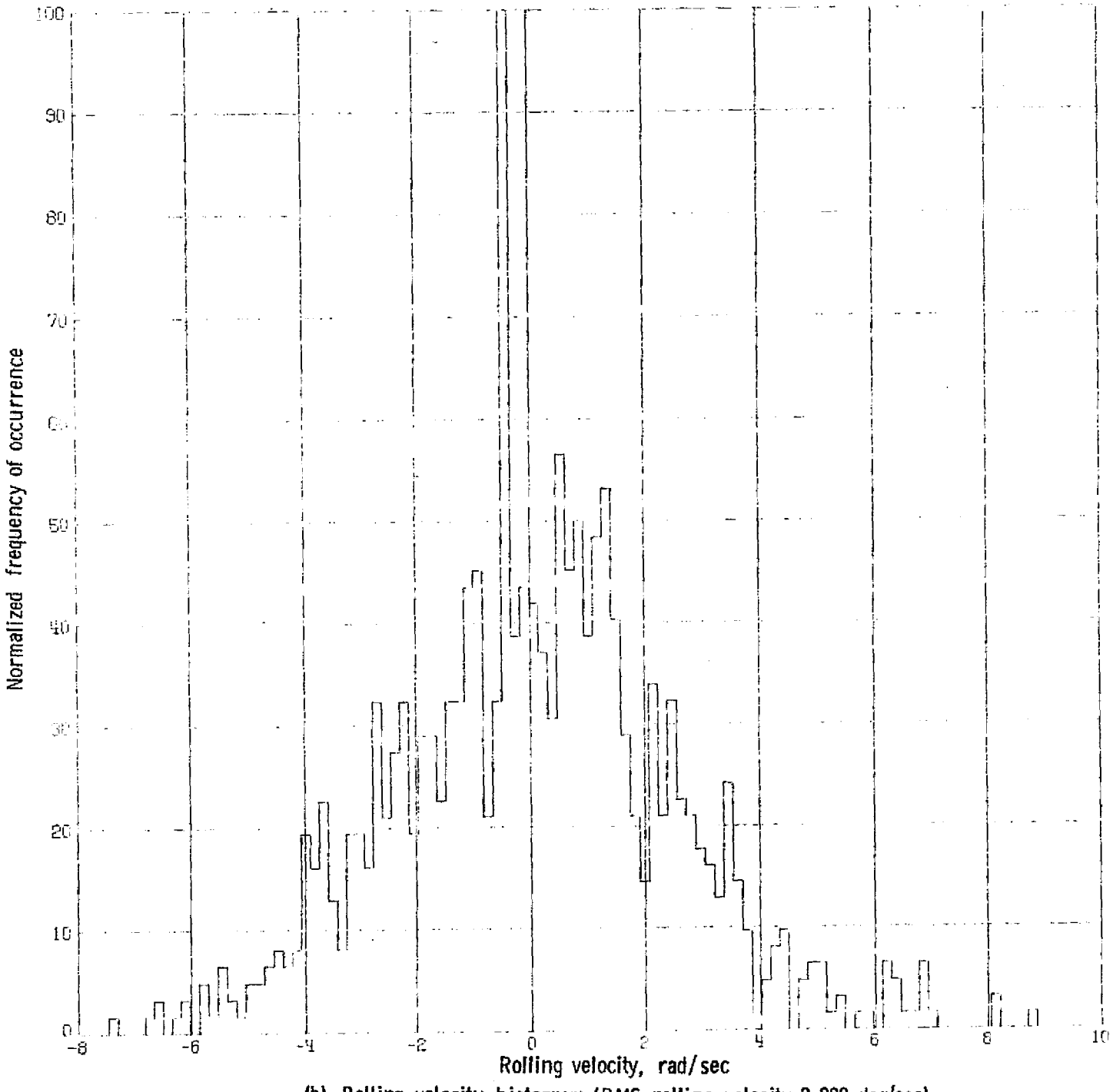
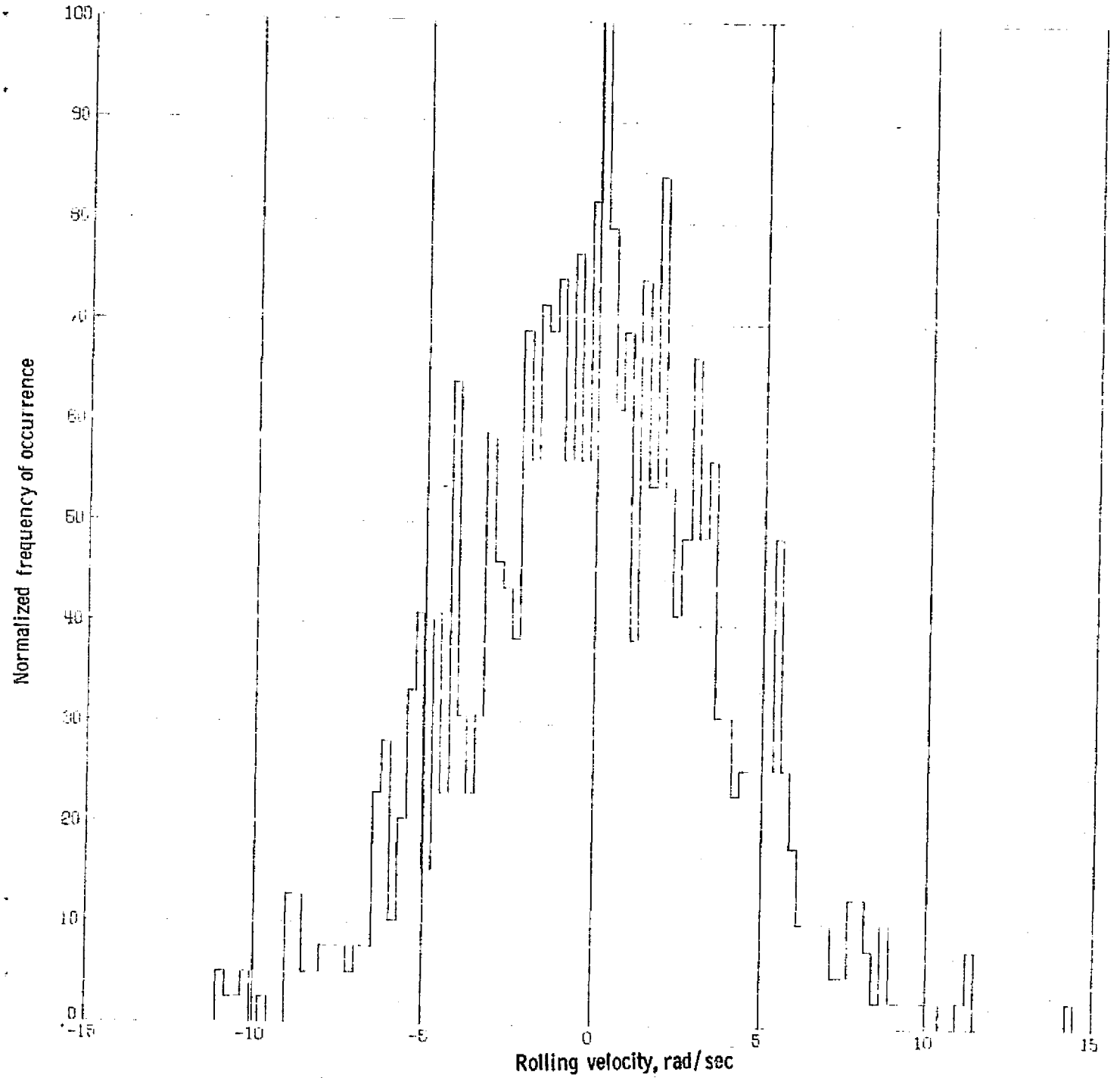


(b) Rolling velocity histogram (RMS rolling velocity 2.220 deg/sec).

Figure 9.- Continued.



(b) Rolling velocity histogram (RMS rolling velocity 3.538 deg/sec).

Figure 9. - Continued.

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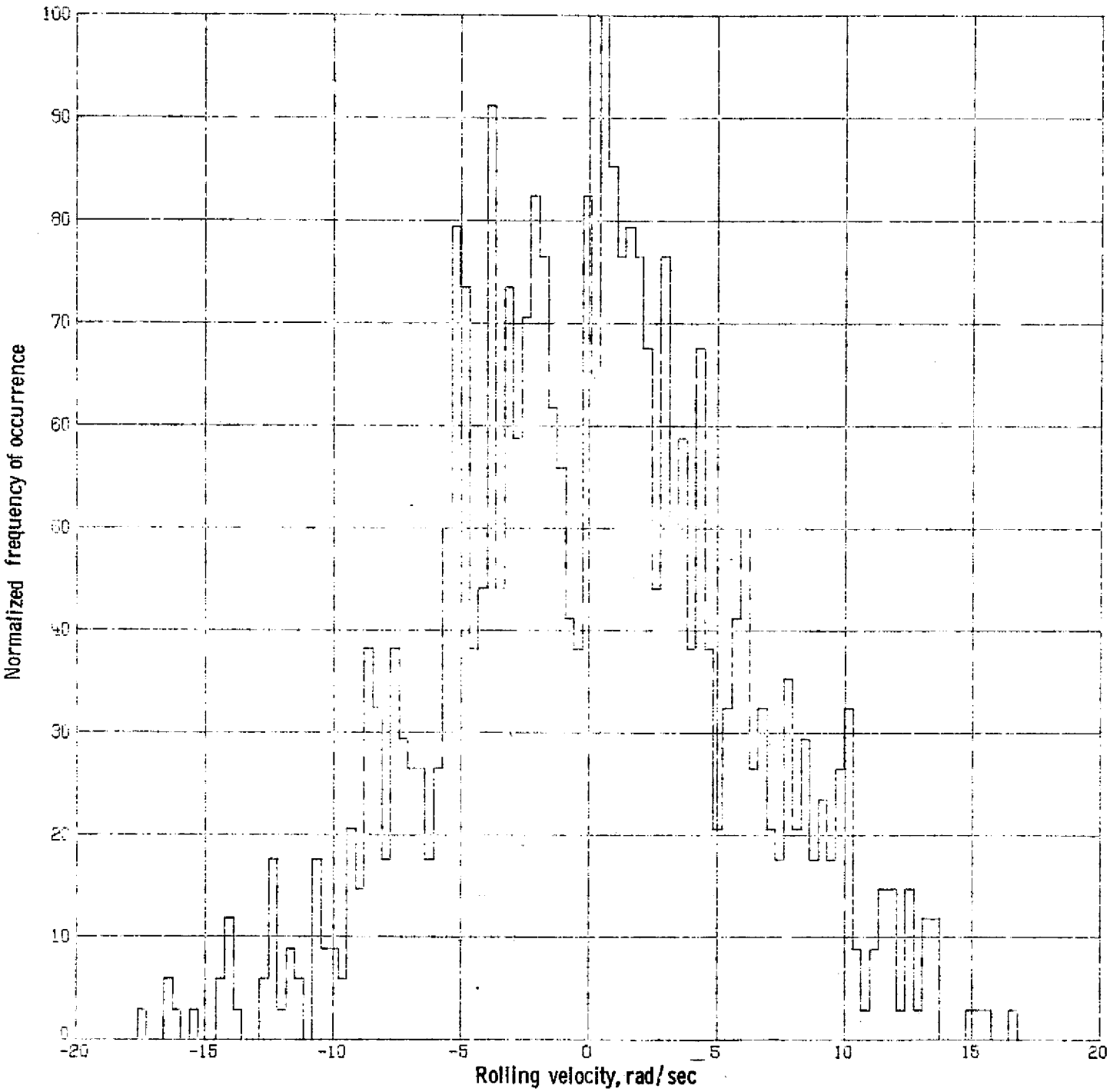

(b) Rolling velocity histogram (RMS rolling velocity 5.220 deg/sec).

Figure 9.- Continued.

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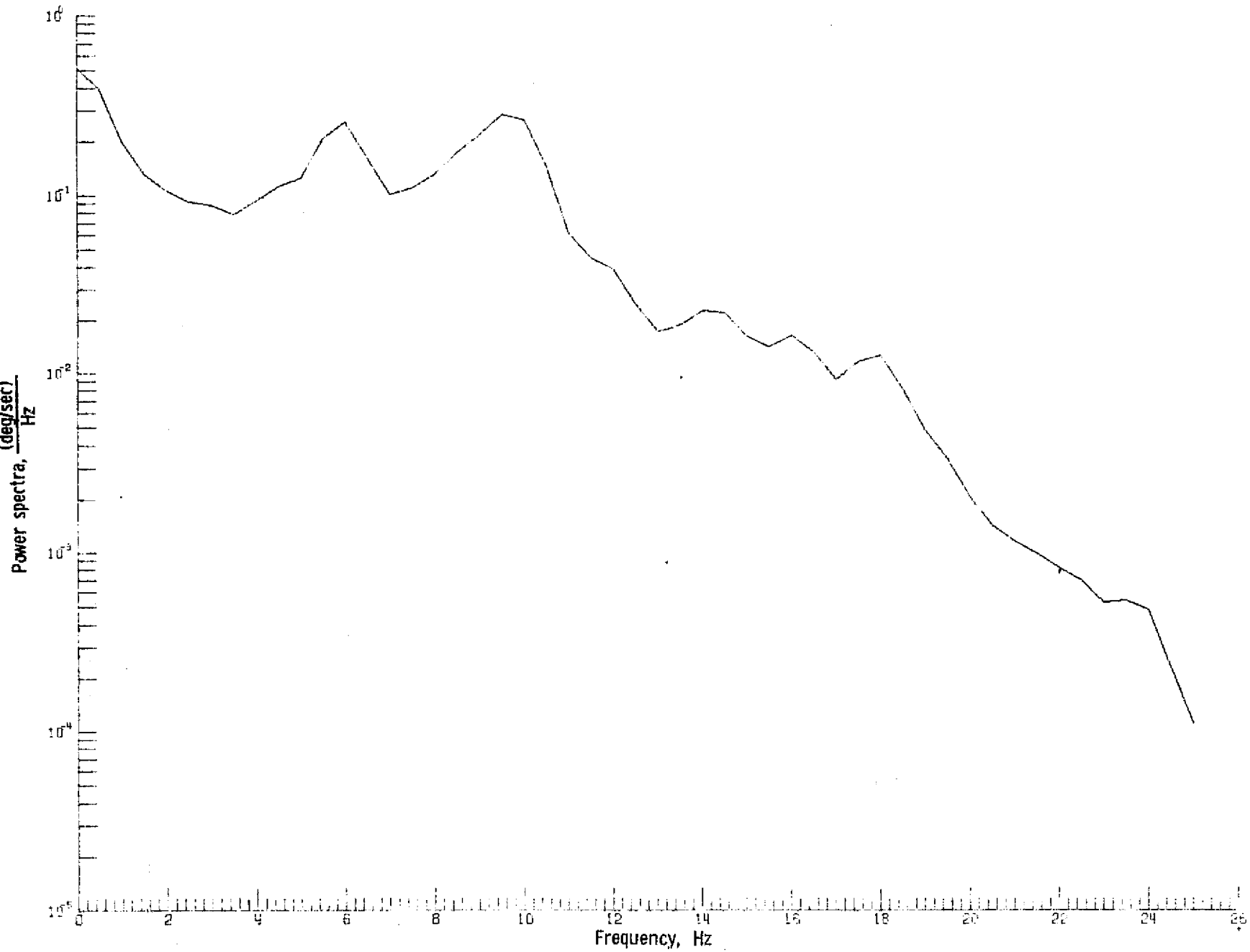
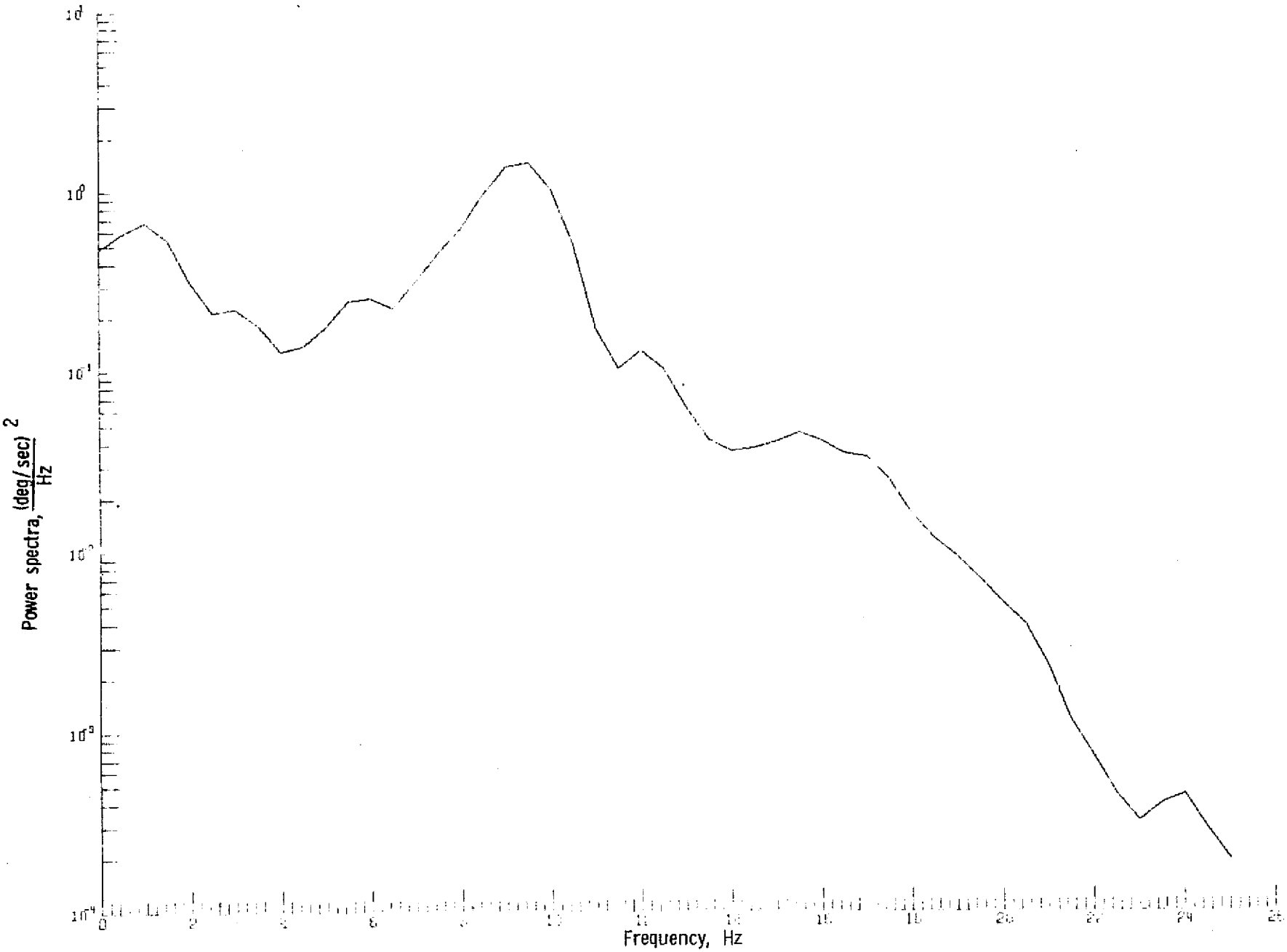


(c) Rolling velocity power spectrum (RMS rolling velocity 1.168 deg/sec).

Figure 9.- Continued.



(c) Rolling velocity power spectrum (RMS rolling velocity 2.220 deg/sec).

Figure 9.- Continued.

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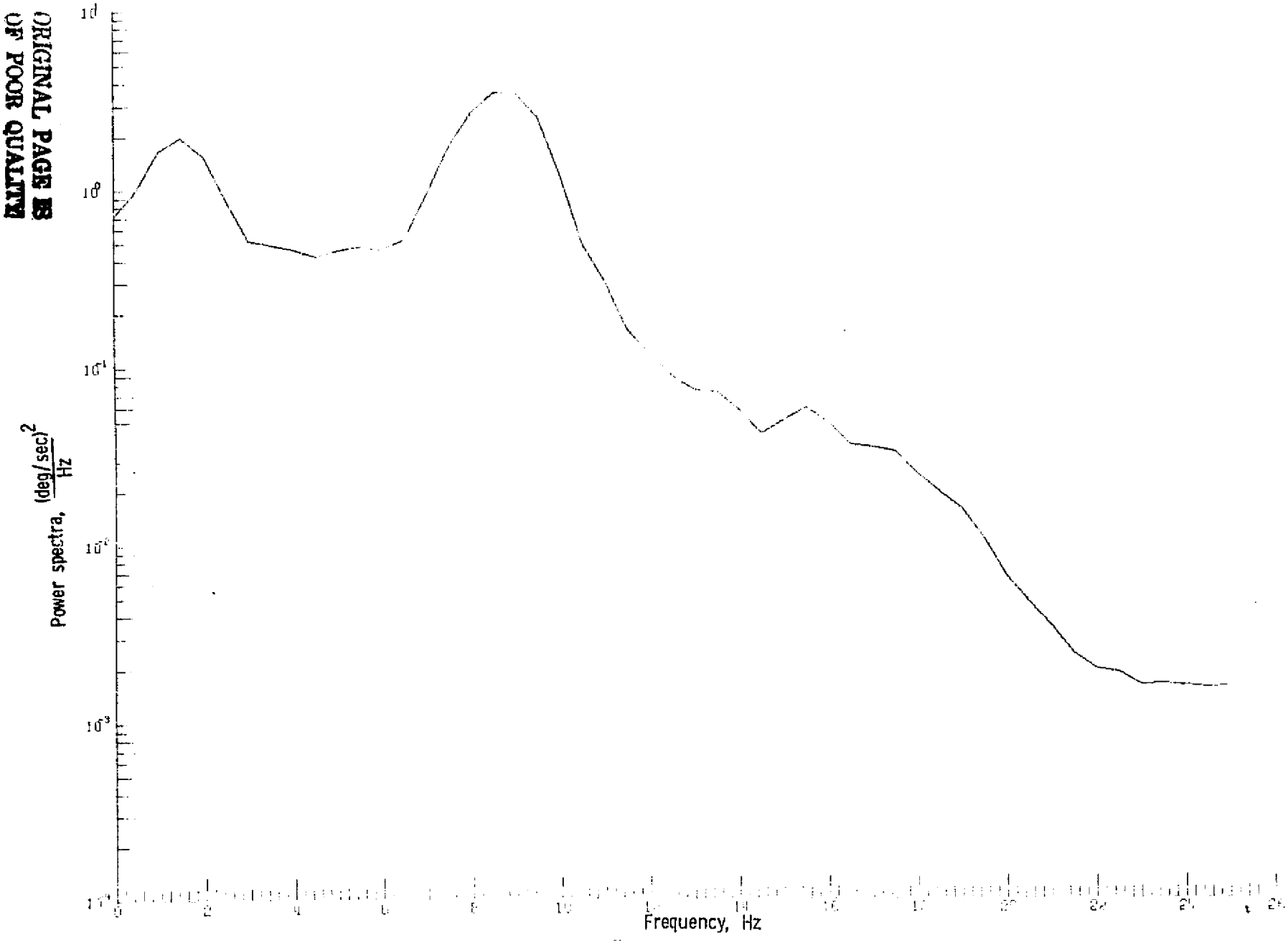
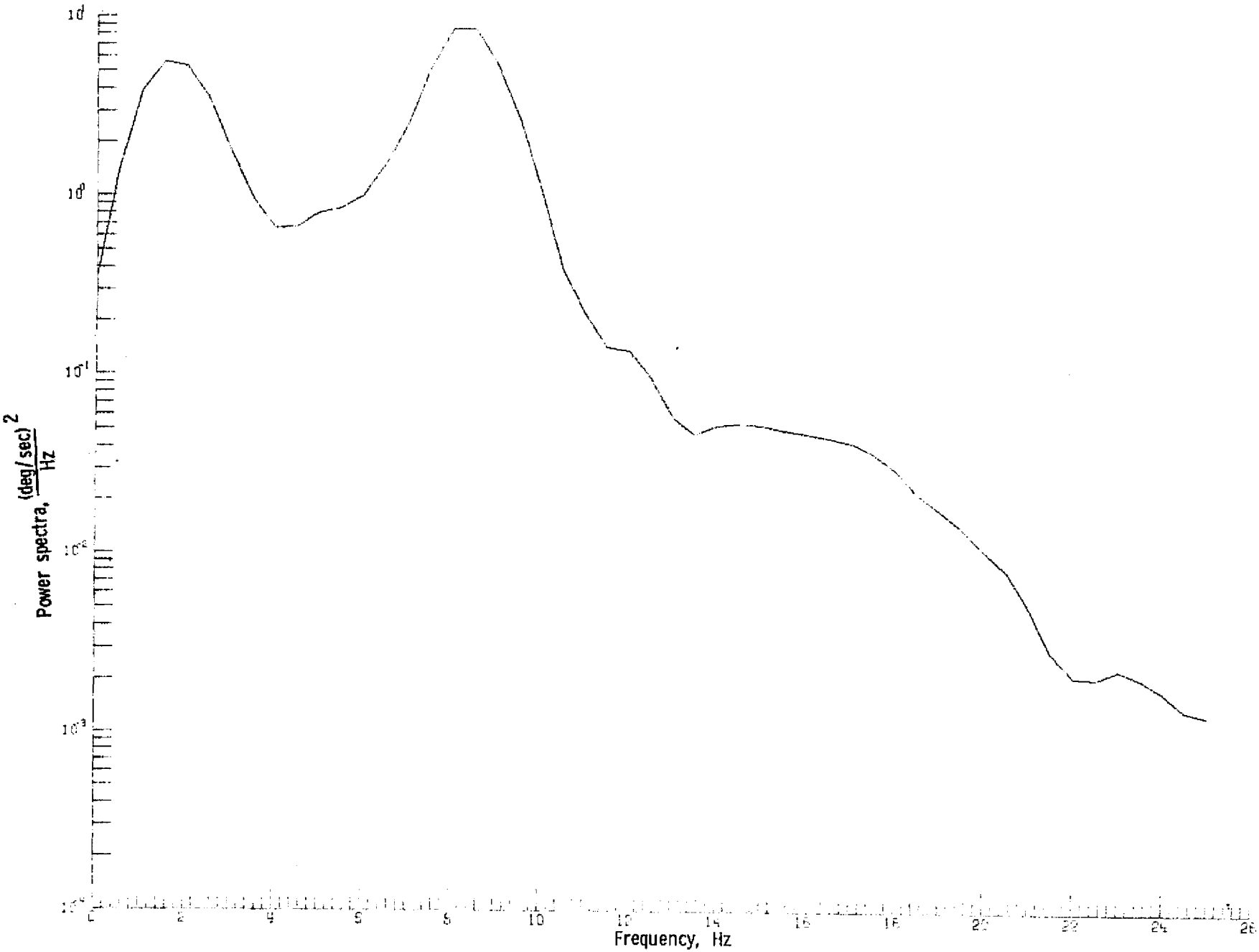


(c) Rolling velocity power spectrum (RMS rolling velocity 3.538 deg/sec).

Figure 9. - Continued.



(c) Rolling velocity power spectrum (RMS rolling velocity 5.220 deg/sec).

Figure 9.- Concluded.

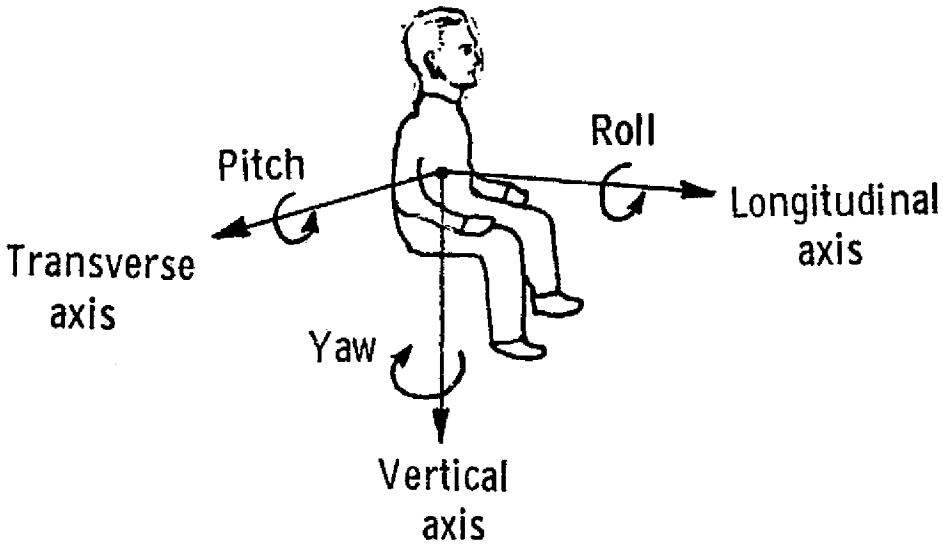


Figure 10.- Reference axes.

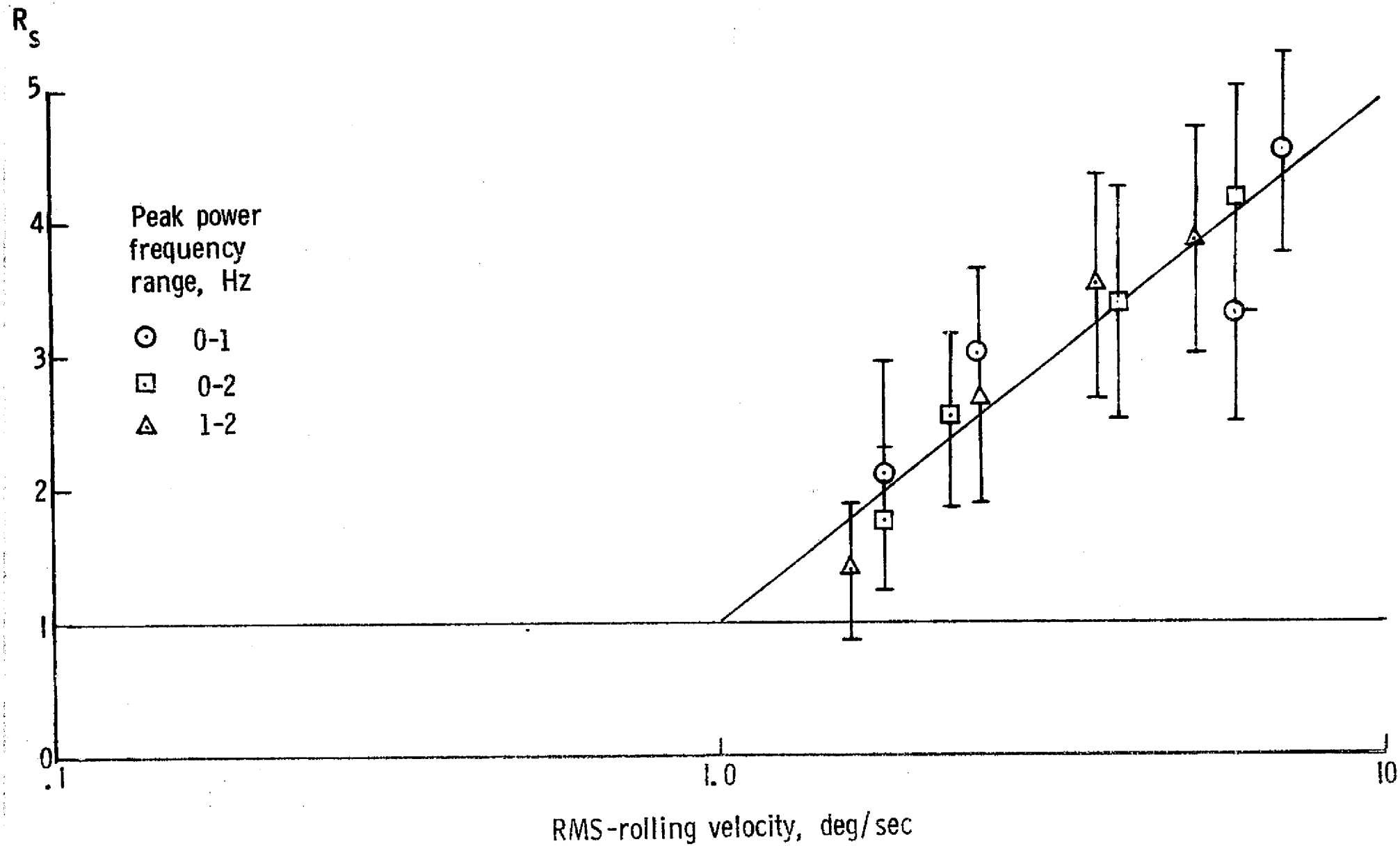


Figure 11.- Variations of ride comfort response with RMS-rolling velocities having typical power spectra.

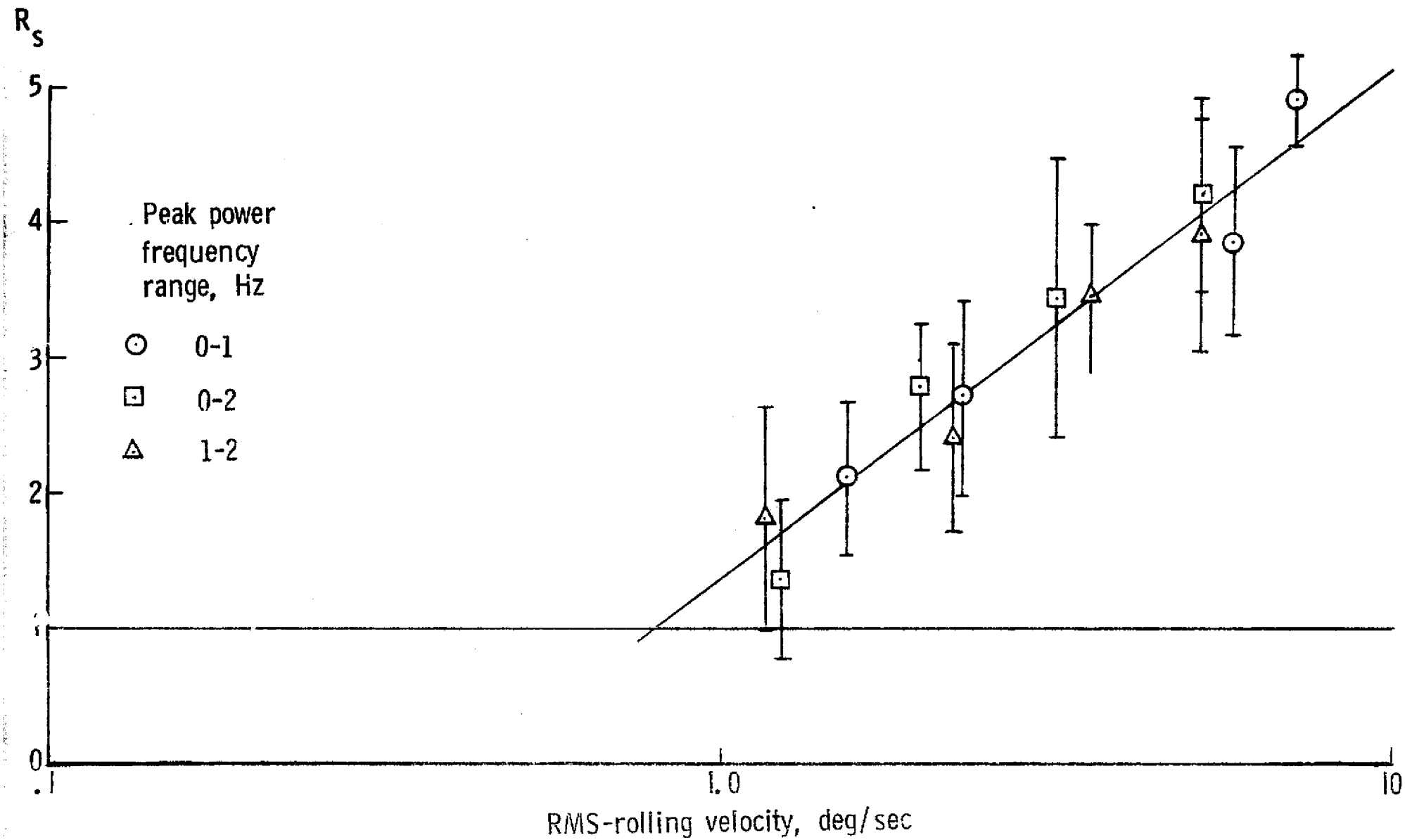


Figure 12.- Variations of ride comfort response with RMS-rolling velocities having flat power spectra.