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B Servo System Measurement and Modeling

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Reported by: S. Y. Zhang

Subject:

$\dot{B}$ Servo System measurement and modeling -- The frequency responses of the Siemens $\dot{B}$ servo system have been measured under three different loop parameter settings. A model of the multiphase rectifier under the operation conditions is found from the first test, and it seems can be used to predict the rest two tests.

I. System Description

The AGS main magnet power supply consists of two stations. The voltage output of each station is regulated through the so-called $\dot{B}$ servo loop, which consists of the Siemens power supply, i.e. the 12 phase rectifier system; the feedback coefficient system, i.e. the voltage dividers; and the feedback regulator, i.e. the phase delay network. The block diagram is shown in Fig.1. In the following, we shall briefly describe the system through the transfer functions of each element.

The most important element in the $\dot{B}$ loop is the multiphase rectifier. The sampling frequency is 720Hz, therefore the rectifier frequency response has severe uncertainties in both magnitude and phase for the high frequencies, i.e. between 360Hz to 720Hz. Moreover, even the DC and the low frequency dynamic gain of the rectifier varies heavily depending on the rectifier phase back angle. The chart of this relation in the Siemens rectifier system is shown in Fig.2. The rectifier phase back angle is determined by two things, i.e. the rectifier DC voltage output level and the generator AC voltage output. We note that at the Siemens the low frequency dynamic gain may vary from -20 to -150 in different operation conditions. At the time of the tests, this gain was approximately -60.

The phase delay network is a first order delay system with the adjustable bandwidth from 6.77Hz to 33.86Hz, it was at 6.77Hz, while the fixed DC gain was at 4.7. The followed buffer provides a gain adjustment from 0.21 to 2.67. Let the total DC gain in the phase delay network be denoted by g. We note that g can be adjusted from 0.99 to 12.55. The transfer function of the network can then be written as

$$G_d(s)\times g = \frac{42.55\times g}{s+42.55} \tag{1}$$

where $G_d(s)$ is a pure delay network with a unity DC gain.

The voltage divider system at the Siemens provides a feedback coefficient, denoted as β. It was 0.01.

If we denote the transfer function of the rectifier as $G_{RECT}(s)$, then the transfer function of the closed loop $\dot{B}$ system is

$$G_{\dot{B}1}(s) = \frac{G_{RECT}(s)\times G_d(s)\times g}{1 - 0.01\times G_{RECT}(s)\times G_d(s)\times g} \tag{2}$$

We note that the DC loop gain should be $0.01 \times 60 \times g = 0.6g$.

II. Measurement

In the measurement, the machine was operated alike to the SEB mode, while the beam was off. The spill servo signal cable at the Siemens control room was disconnected. Instead, sine waveform signals were injected to the $\dot{B}$ servo loop. The amplitude of the sine waveform signals was set at about 400mv peak to peak, and also adjusted at the higher frequency range in order to ensure that the associated Siemens voltage output signal component kept distinguished from the subharmonic ripples and the background noise. The waveforms from the so-called magnet voltage, i.e. the sum of the two station voltage outputs, were observed by HP3561A Spectrum Analyzer. The resolution, sampling period, and the frequency span of the Analyzer were set at 1Hz, 1sec., and 400Hz, respectively, for the low frequency measurement; and at 2Hz, 0.5sec., and 800Hz, respectively, for the high frequency measurement. The T_0 trigger signal was compared with the input sine waveforms, the output was then used to trigger the Spectrum Analyzer. Therefore, we were able to select the sampling period in the middle of the flatop, and the input and output waveform phases could also be read, and compared. All data were 5-time averaged. Every step in the averaging had been observed in order to ensure that the data taken were meaningful.

Between the input signal and the $\dot{B}$ loop, there was a spill signal filter, its transfer function was

$$F_1(s) = \frac{-2338}{s+6865} \tag{3}$$

i.e. the corner frequency is about 1KHz.

In choosing the input signals, we had tried to keep them away from the subharmonic ripple frequencies in order to avoid bad readings. Also, although the readings at the high frequency range, i.e. higher than 360Hz, are with considerable uncertainties, we still took the data for the reference.

The first measurement was performed under the condition of g=5.3, and therefore the loop gain was 3.18, with the spill signal filter $F_1(s)$. The data for the input and output signals are listed in the Table 1, for both amplitude and phase. The transfer function data, calculated from the input and output data, are also listed.

We note that in the $\dot{B}$ loop, the feedback coefficient is β=0.01, therefore, if the rectifier is an ideal amplifier with a large enough gain, the closed loop $\dot{B}$ servo system should provide a DC gain 100, i.e. 40db. In the measurement, all input signal amplitude readings were 20db higher than the signals injected, and all output signals were taken from the -60db voltage dividers. Also, since the output signal was from the sum of the two stations, it was 6.02db higher than that from one station. Finally, the filter (3) provided a -9.3db DC gain reduction. Therefore, to nomalize the magnitude transfer function data, we should add

$$60db + 20db + 9.3db - 6.02db = 83.28db$$

to the transfer function magnitude readings.

After the first measurement, we replaced two boards in the $\dot{B}$ loop. The new boards provided a higher loop gain and a different spill signal filter. We performed the measurement again. This is the experiment 2. Later, by adjusting the loop gain to be the lower, the measurement was repeated one more time. This is the experiment 3.

In the experiment 2, the loop gain was increased by about 14 times, i.e. at 44.52. In the experiment 3, the loop gain was increased by 6 times, lower than that in the experiment 2, at about 19.08. In both experiments 2 and 3, the spill servo filter was modified to be

$$F_2(s) = \frac{-1182}{s+5708} \tag{4}$$

The data for the two measurements and the transfer function calculations are listed in the Tables 2, and 3, respectively. In these two tests, since the filter provided a -13.68db DC reduction, to nomalize the magnitude transfer function data, we should add 87.66db to the readings.

III. Modeling

According to the data obtained in the measurement 1, we have tried to give the rectifier a model. Under the operation condition of the Siemens rectifier, the model could be as

$$\begin{aligned} G_{RECT}(s) &= -60\times(\frac{4500}{s+4500})^2\times\frac{13500}{s+13500} \\ &= -\frac{1.64E13}{s^3+22500s^2+1.418E8s+2.734E11} \end{aligned} \tag{5}$$

The Bode Plot of this model is shown in Fig.3a and 3b.

Thus, including the spill signal filter $F_1(s)$, we have the simulated system model in the measurement 1 to be

$$\begin{aligned} G_1(s) &= G_{\dot{B}1}(s)\times F_1(s)\times 2.94 \\ &= \frac{2.539E19}{s^5+29408s^4+2.975E8s^3+1.259E11s^2+1.967E15s+3.338E17} \end{aligned} \tag{6}$$

where $G_{\dot{B}1}(s)$ is calculated by using (2), and the coefficient 2.94 is the reciprocal of the servo signal filter DC reduction coefficient, and is used to normalize the low frequency gain.

In Fig.4a and 4b, we show the Bode Plot of the simulated system (6) by continuous curves. Meanwhile, the nomalized transfer function data in Table 1 are also plotted, which are denoted by '*' and 'o', for the magnitude and phase, respectively. It is observed that in the low frequency range, the curves match the experiment data closely, while at the frequency range higher than 360Hz, they are separated, as expected.

That the model (5) is useful or not, however, depends on whether applying this model to the operations in the experiments 2 and 3 can match the data there, or not. If the data would match, then the model can be used to predict what is going to happen if we adjust the loop gain, i.e. it can be used in the design. The model seems to be useful.

The $\dot{B}$ loop transfer functions under the conditions in the experiments 2 and 3, are

$$G_{\dot{B}2}(s) = \frac{G_{RECT}(s)\times G_d(s)\times 5.3\times 14}{1-0.01\times G_{RECT}(s)\times G_d(s)\times 5.3\times 14} \tag{7}$$

and

$$G_{\dot{B}3}(s) = \frac{G_{RECT}(s)\times G_d(s)\times 5.3\times 6}{1-0.01\times G_{RECT}(s)\times G_d(s)\times 5.3\times 6} \tag{8}$$

Thus, the simulated transfer functions become

$$G_2(s) = \frac{2.956E20}{s^5+28251s^4+2.714E8s^3+1.094E12s^2+2.124E15s+3.022E18} \tag{9}$$

and

$$G_3(s) = \frac{1.267E20}{s^5+28251s^4+2.714E8s^3+1.094E12s^2+1.828E15s+1.333E18} \tag{10}$$

The curves from these transfer function models are shown in Fig.5a and 5b, and Fig.6a and 6b, respectively. The measurement data are also plotted. The matches are good.

IV. Discussion

We have the following comments.

1. A precise model for the multiphase rectifier would be very complicated. The result presented in Section III shows that under some conditions, a simplified linear model can be obtained and used to simulate the system. Indeed, the model obtained from the experiment 1 can be used to predict the system behaviour in the next two experiments at different loop gains. This sort of models may provide convenience in simulation and design.

2. It is interesting to notice that in the Bode Plot of the experiment 1, at 300Hz, the magnitude curve has a slope of about -40db/decade, and the phase shift is approaching -180 degrees. The loop gain increase at a factor of 14 in the experiment 2 extends the closed-loop bandwidth to be higher than 300Hz. The system is still stable, however, the damping ratio is less than one, at about 0.4, as shown in both simulated Bode Plot and the measurement data in Fig.5. Under this operation condition, although the phase margin was about -45 degrees, we had observed a considerable ripple increase. In the experiment 3, the bandwidth is only increased to 157Hz, the problem did not occur.

3. It seems that under the current feedback configuration, i.e. two rectifier station feedbacks are independent with each other, and the system is merely the 12 phase rectifier system, the closed-loop bandwidth should not exceed 200Hz. In addition, if a 6.77Hz phase delay network is employed, as what we have now, the loop gain should not exceed 28.

4. We note that the low frequency gain of the multiphase rectifier is a very important factor in the loop. The gain variation will affect the B loop gain directly. Therefore, this gain should be watched closely. The Siemens voltage set up, the generator excitation reference set up, and the tap position of the transformer should all be considered in using the rectifier model. We may say that the model (5) can be referred only under the following conditions, i.e. at the flatop, the each Siemens station voltage output is approximately 550v; the generator excitation flatop reference is -7.3v, and the tap position of the main magnet power supply transformer is at 2.

5. It was conjectured before that a 12 phase rectifier system might have some corner frequencies between 240Hz and 480Hz. The model obtained here shows, however, this is not true. The model (5) only has a double corner frequency at 720Hz, and another one at around 2150Hz. These corner frequencies yield considerable phase shift from 240Hz to 480Hz, but the caused magnitude droop is not much.

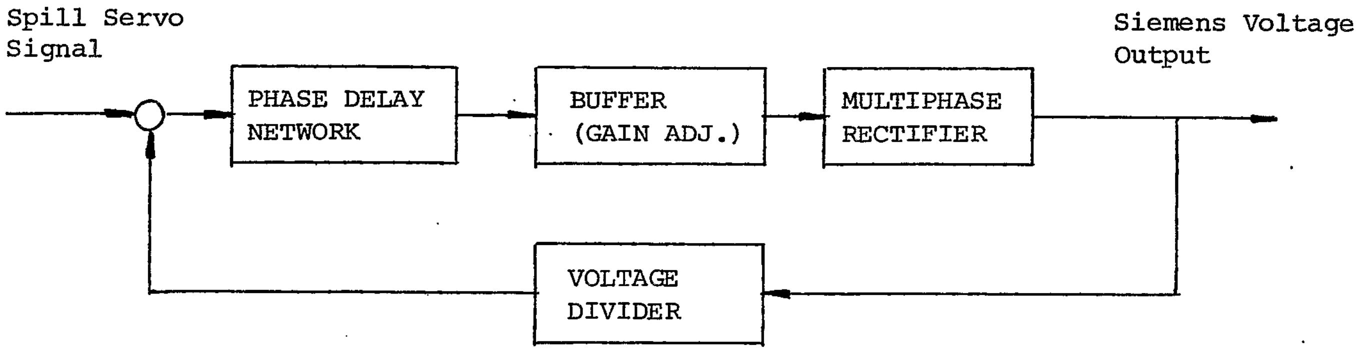
Spill Servo
Signal
PHASE DELAY
NETWORK
BUFFER
(GAIN ADJ.)
MULTIPHASE
RECTIFIER
Siemens Voltage
Output
VOLTAGE
DIVIDER

Fig.1

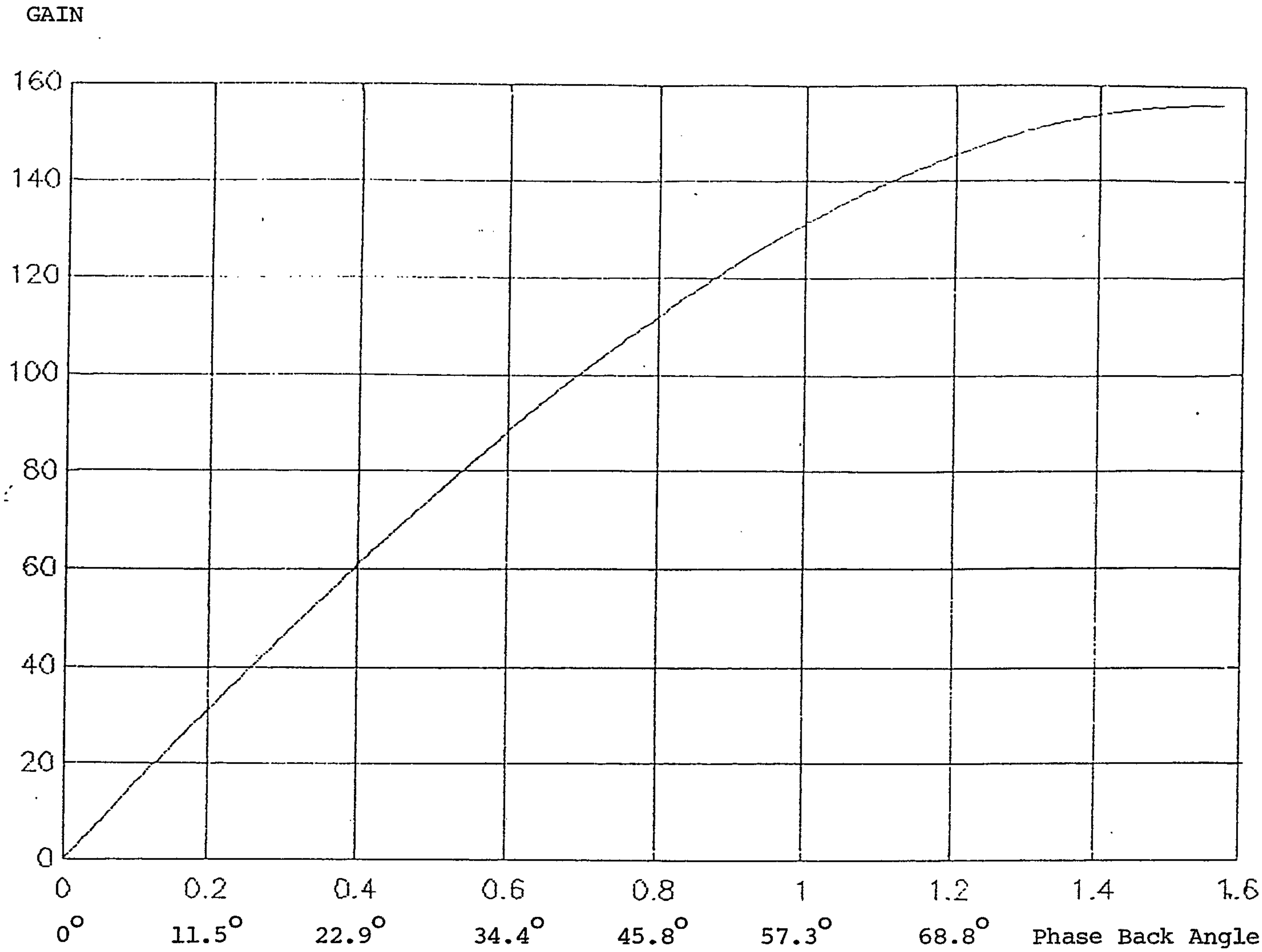
GAIN
160
140
120
100
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0°
11.5°
22.9°
34.4°
45.8°
57.3°
68.8°
Phase Back Angle

Fig.2

B DOT MEASUREMENT 1

FREQ (Hz)	INPUT AMPL (db)	INPUT PHASE (Deg.)	OUTPUT AMPL (db)	OUTPUT PHASE (Deg.)	BODE AMPL (db)	BODE PHASE (Deg.)
5	3.45	-107.7	-42.36	-118.5	-45.81	-10.8
8	3.45	77.1	-42.62	60.9	-46.07	-16.2
10	3.45	77.2	-42.89	57.7	-46.34	-19.5
15	3.45	-107.1	-43.2	-138.3	-46.65	-31.2
20	3.45	74.7	-44.09	38.5	-47.54	-36.2
29	3.45	-98.3	-45.39	-145	-48.84	-46.7
39	3.44	-97.9	-46.59	-154.7	-50.03	-56.8
47	3.44	-108.4	-46.59	-163.5	-50.03	-55.1
56	3.44	75.7	-46.76	-4.3	-50.2	-80
65	3.44	-104.6	-47.45	170	-50.89	-85.4
75	3.44	-101.7	-51.25	163.4	-54.69	-94.9
79	3.44	-102.6	-52.29	163.1	-55.73	-94.3
86	3.44	71.6	-52.22	-24.2	-55.66	-95.8
97	3.44	-116.7	-53.83	142.8	-57.27	-100.5
106	3.44	68.1	-53.65	-34	-57.09	-102.1
116	3.43	-33.5	-54.41	-133.2	-57.85	-99.7
128	3.44	57.1	-55.37	-52.7	-58.81	-109.8
138	3.45	116.7	-55.97	7.9	-59.42	-108.8
148	3.45	79	-56.71	-40.8	-60.16	-119.8
156	3.42	75.5	-57.57	-33.4	-60.99	-108.9
168	3.45	99	-57.84	-22.8	-61.29	-121.8
175	3.45	-62.1	-58.4	179.7	-61.85	-118.2
186	3.45	159.7	-58.68	20.3	-62.13	-139.4
196	3.45	101.3	-59.77	-25.6	-63.22	-126.9
210	3.45	117.9	-60.33	-9.9	-63.78	-127.8
220	5.48	100.1	-59.01	-38.4	-64.49	-138.5
231	5.47	-85.9	-59.13	147.2	-64.6	-126.9
260	5.46	175.3	-61.14	28.5	-66.6	-146.8
274	8.48	88	-58.24	-77.7	-66.72	-165.7
286	8.48	94	-58.93	-82.1	-67.41	-176.1
295	8.48	-96.8	-61.08	114.8	-69.56	-148.4
309	10.26	-42.1	-59.87	165.2	-70.13	-152.7
318	10.22	68.3	-59.4	-78	-69.62	-146.3
329	12.1	-90.2	-58.78	108	-70.88	-161.8
338	12.03	114.5	-57.72	-34.6	-69.75	-149.1
346	12.11	117.8	-57.83	-83.4	-69.94	-201.2
370	12.11	159.9	-58.87	-15.5	-70.98	-175.4
395	12.09	2.8	-61.82	139.3	-73.91	-223.5
410	12.1	-90.5	-62.86	94.5	-74.96	-175
432	14.64	99.6	-59.54	-85.2	-74.18	-184.8
458	14.63	-67.4	-60.27	109	-74.9	-183.6
494	14.64	-112.3	-63.75	50	-78.39	-197.7
510	14.64	-70.1	-63.28	99.4	-77.92	-190.5
550	17.13	-90.5	-66.71	72.8	-83.84	-196.7
584	17.12	67	-68.02	-135	-85.14	-202
624	17.13	105.3	-71.81	-136.9	-88.94	-242.2
680	26.44	104.7	-66.64	-49.3	-93.08	-154
690	26.42	-49.7	-67.44	154.4	-93.86	-155.9

To normalize: +83.28db

Table 1

B DOT MEASUREMENT 2

FREQ (Hz)	INPUT AMPL (db)	INPUT PHASE (Deg.)	OUTPUT AMPL (db)	OUTPUT PHASE (Deg.)	BODE AMPL (db)	BODE PHASE (Deg.)
10	6.44	75.3	-41.25	72.4	-47.69	-2.9
15	6.44	-98.3	-41.2	-103.1	-47.64	-4.8
20	6.44	70.1	-41.27	62.6	-47.71	-7.5
29	6.44	-93.3	-41.16	-103.4	-47.6	-10.1
39	6.44	-102.3	-41.13	-111.6	-47.57	-9.3
47	6.44	-103.8	-41.3	-116	-47.74	-12.2
56	6.43	88.4	-40.81	72.2	-47.24	-16.2
65	6.43	88.4	-40.73	-116.5	-47.16	-204.9
75	6.43	-98.7	-40.44	-127.1	-46.87	-28.4
86	6.43	81.5	-40.96	56.3	-47.39	-25.2
97	6.43	-103.4	-41.06	-132	-47.49	-28.6
106	6.43	76.4	-40.95	42.3	-47.38	-34.1
138	6.43	70.8	-42.68	25.2	-49.11	-45.6
168	6.43	137.2	-40.39	78.2	-46.82	-59
196	6.36	84.2	-39.8	29.1	-46.16	-55.1
231	6.44	-65.9	-39.43	-128.8	-45.87	-62.9
274	6.42	56.7	-36.18	-29.9	-42.6	-86.6
286	6.4	122.7	-34.04	-35.4	-40.44	-158.1
295	6.45	-93.3	-38.84	136.4	-45.29	-130.3
309	6.44	-91.6	-42.21	144.5	-48.65	-123.9
318	6.44	31	-39.6	-84	-46.04	-115
346	6.41	74.4	-37.4	-78.2	-43.81	-152.6
458	6.44	-94.3	-54.1	-11.2	-60.54	-276.9
510	16.02	-97.4	-62.39	-38.6	-78.41	-301.2
584	16.02	110	-57	5.6	-73.02	-104.4
624	16.05	64.5	-53.86	-55.9	-69.88	-120.4
680	16.04	86.1	-54.44	-43.6	-70.48	-129.7

To normalize: +87.66db

Table 2

B DOT MEASUREMENT 3

FREQ (Hz)	INPUT AMPL (db)	INPUT PHASE (Deg.)	OUTPUT AMPL (db)	OUTPUT PHASE (Deg.)	BODE AMPL (db)	BODE PHASE (Deg.)
20	16.03	91.2	-32.04	80	-48.07	-11.2
47	16.04	-84.8	-32.33	-105.1	-48.37	-20.3
97	16.03	-88.2	-32.9	-142.7	-48.93	-54.5
168	16.03	47.3	-34.78	-40.1	-50.81	-87.4
231	16.02	-92.3	-36.37	145.9	-52.39	-121.8
286	16.03	38.8	-38.51	-130.8	-54.54	-169.6
318	16.04	65.4	-41.69	-85.2	-57.73	-150.6
346	15.98	97	-42.49	-71	-58.47	-168
394	16.05	-79.8	-47.41	80	-63.46	-200.2
410	16.05	-108.4	-51.08	61	-67.13	-190.6
458	16.05	-6.3	-51.76	133	-67.81	-220.7
510	16.05	-97.3	-59.38	30.3	-75.43	-232.4
550	15.99	-83.6	-65.72	87.4	-81.71	-189
584	16.05	81	-66.39	-90.6	-82.44	-171.6
624	29.8	85	-49.73	-56.1	-79.53	-141.1
680	29.8	129.7	-49.85	-24.6	-79.65	-154.3

To normalize: +87.66db

Table 3

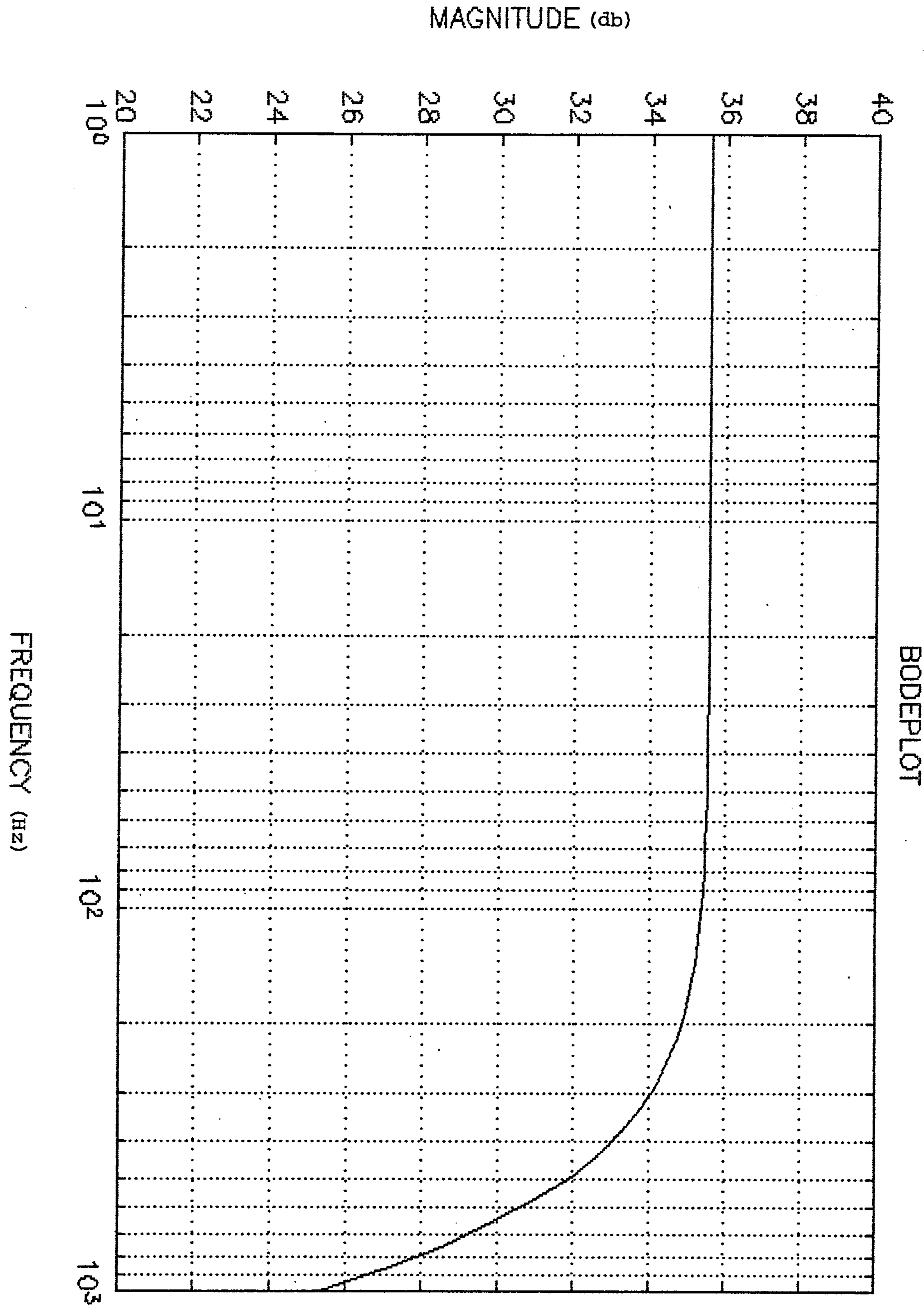
MAGNITUDE (db)
20
22
24
26
28
30
32
34
36
38
40
BODEPLOT
FREQUENCY (Hz)
10^0
10^1
10^2
10^3

Fig. 3a

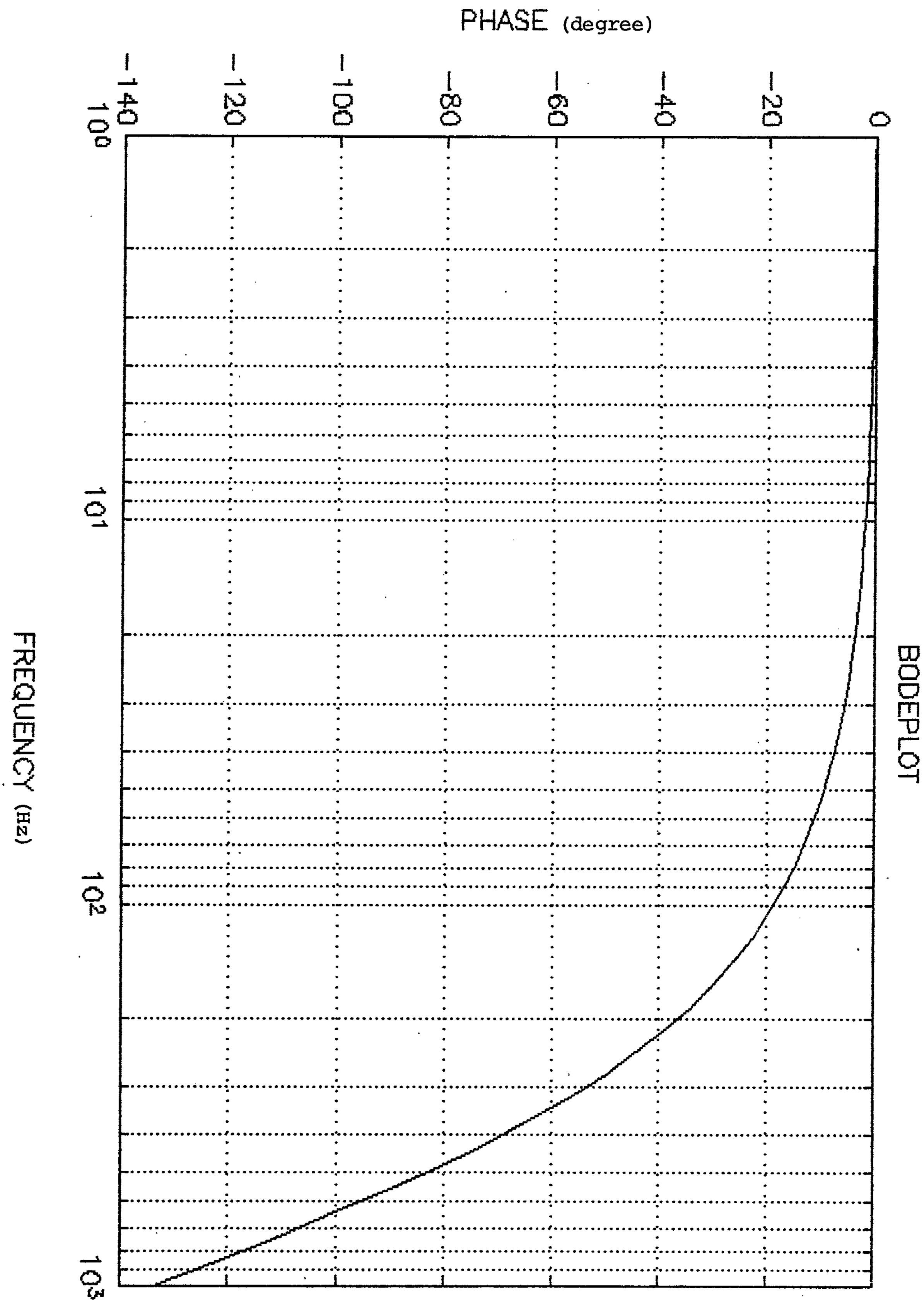
PHASE (degree)
BODEPLOT
FREQUENCY (Hz)
0
-20
-40
-60
-80
-100
-120
-140
10^0
10^1
10^2
10^3

Fig. 3b

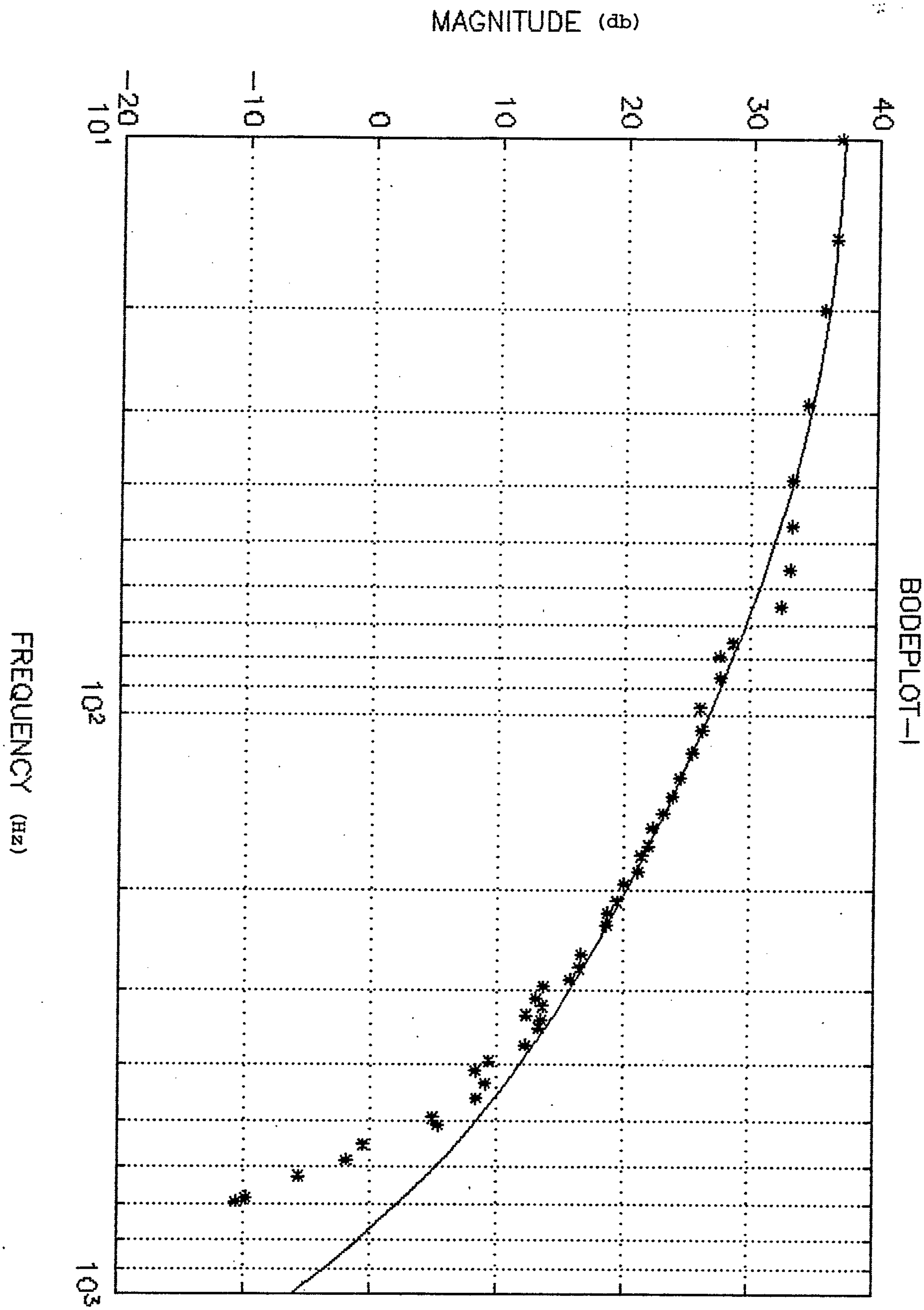
BODEPLOT—I
MAGNITUDE (db)
40
30
20
10
0
−10
−20
10¹
10²
10³
FREQUENCY (Hz)

Fig.4a

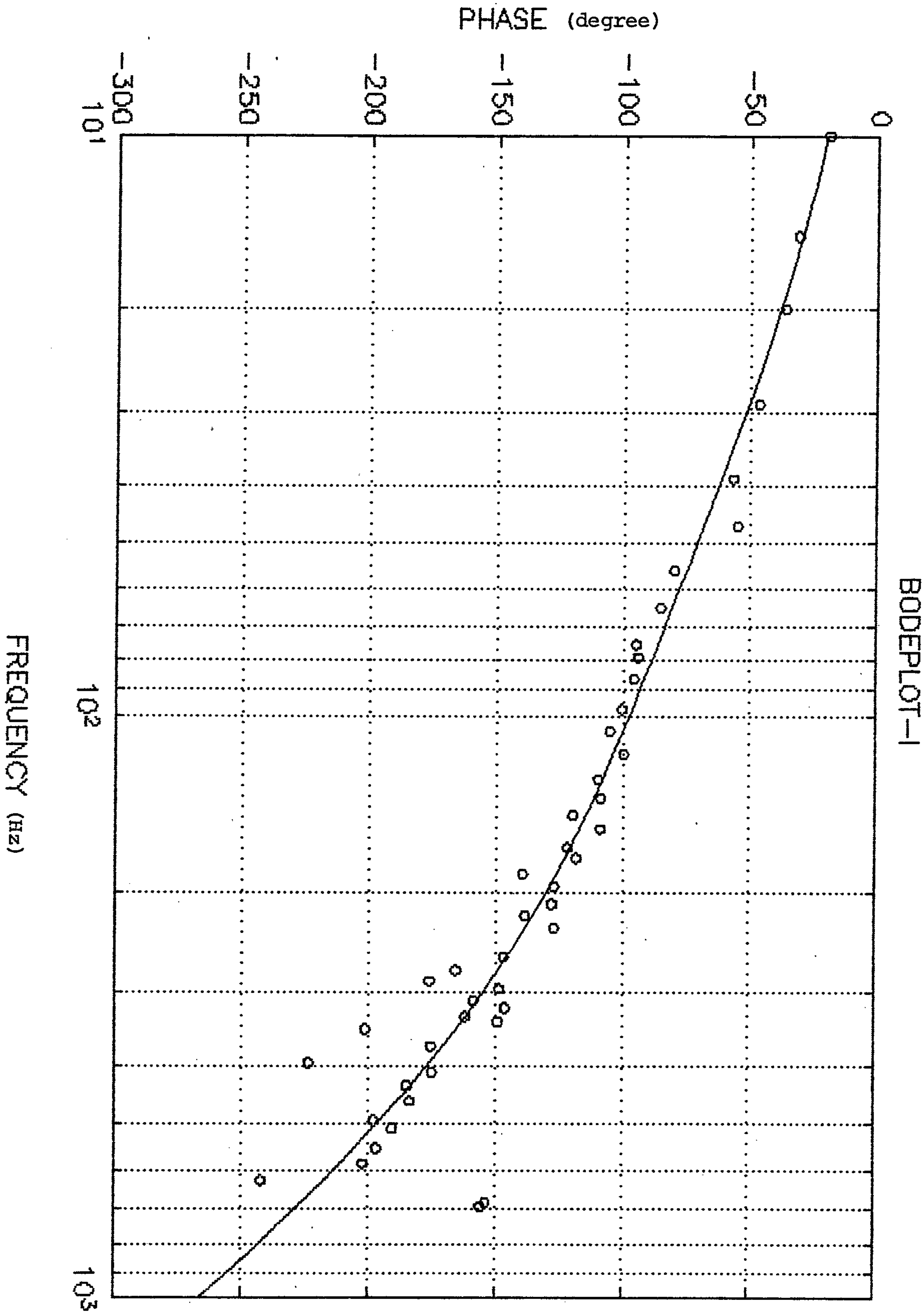
BODEPLOT—I
PHASE (degree)
0
−50
−100
−150
−200
−250
−300
FREQUENCY (Hz)
10^1
10^2
10^3

Fig. 4b

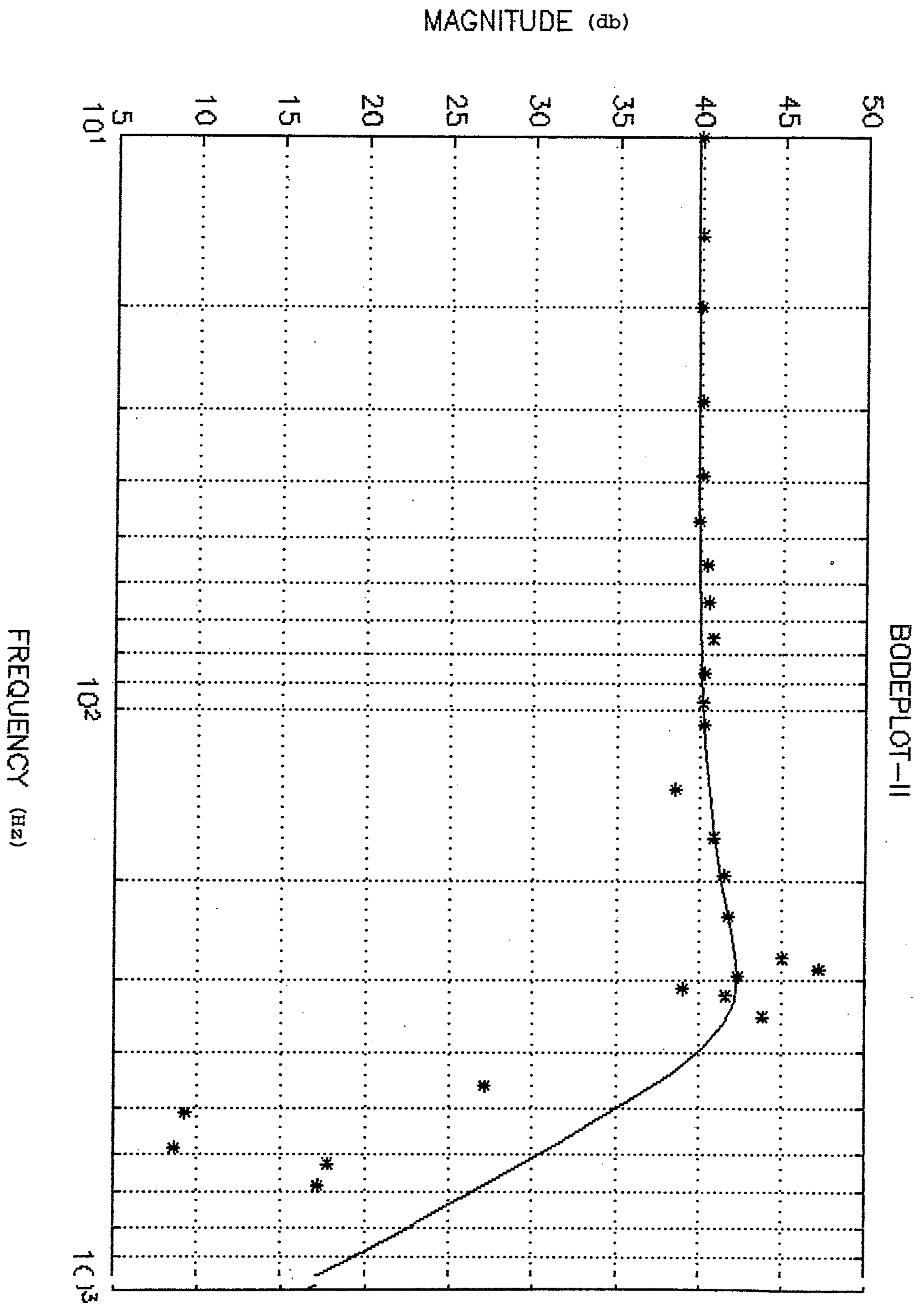
BODEPLOT–II
MAGNITUDE (db)
5
10
15
20
25
30
35
40
45
50
FREQUENCY (Hz)
10^1
10^2
10^3

Fig.5a

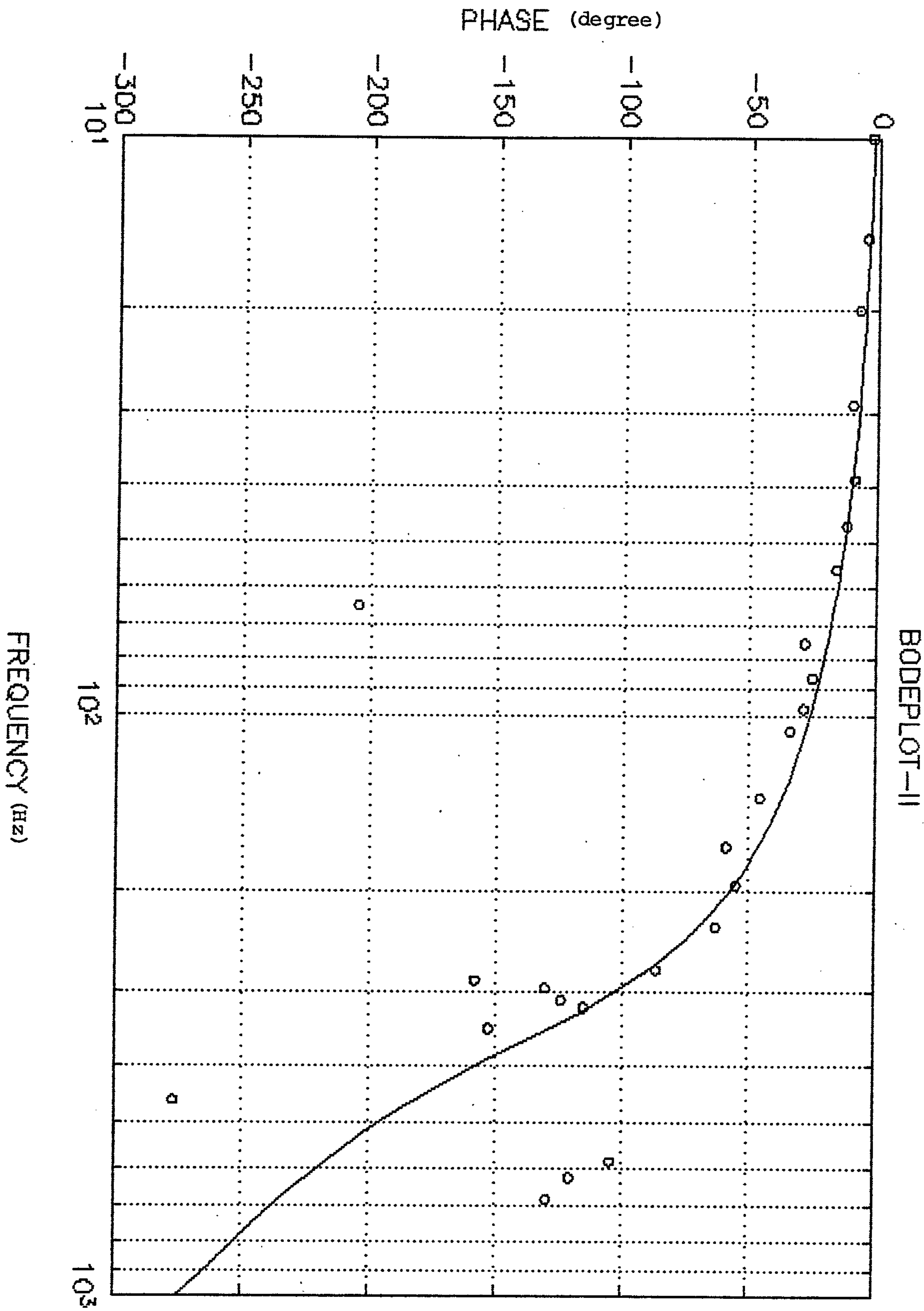
PHASE (degree)
0
−50
−100
−150
−200
−250
−300
10¹
10²
10³
FREQUENCY (Hz)
BODEPLOT−II

Fig. 5b

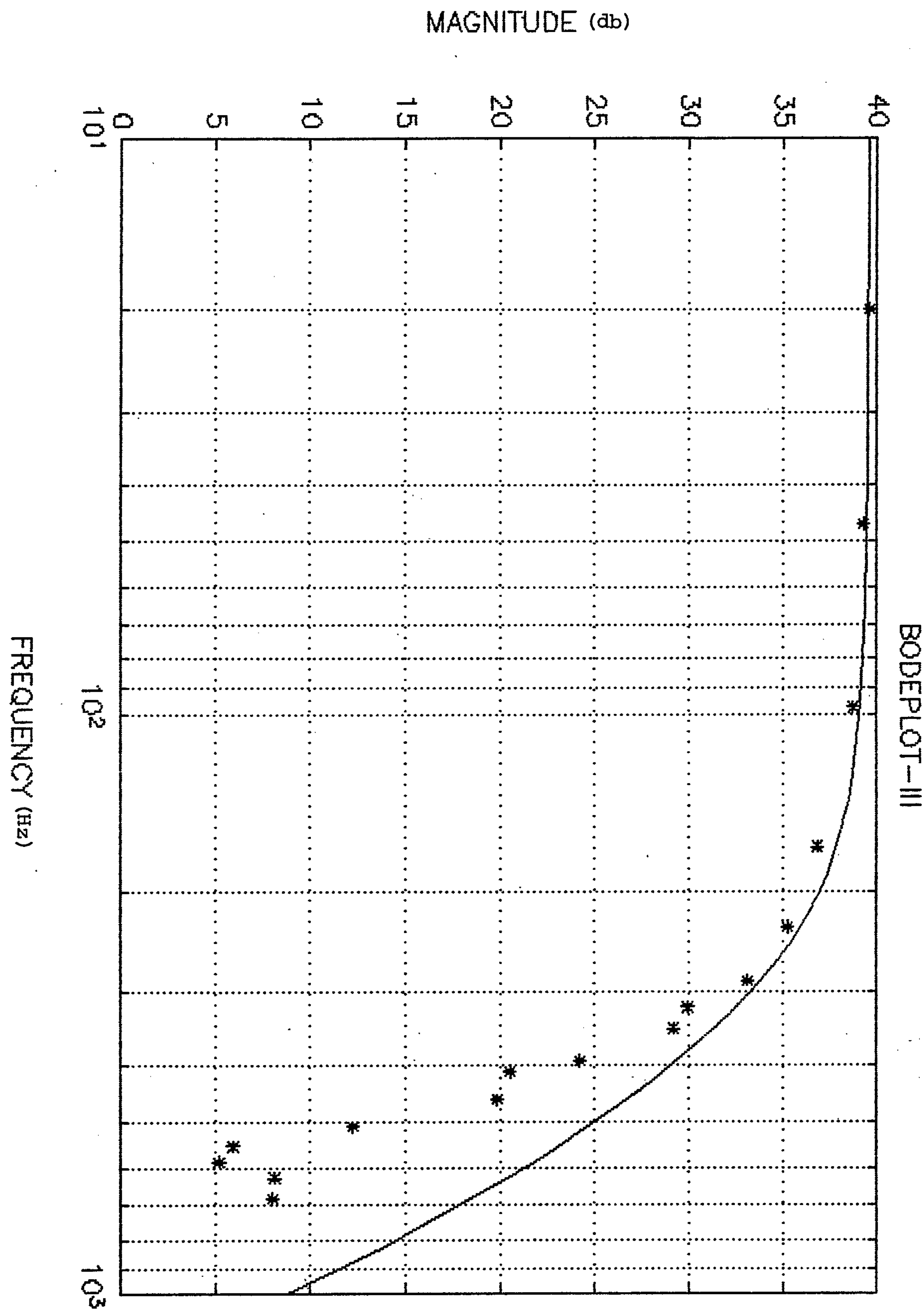
BODEPLOT–III
MAGNITUDE (db)
FREQUENCY (Hz)
0
5
10
15
20
25
30
35
40
10^1
10^2
10^3

Fig. 6a

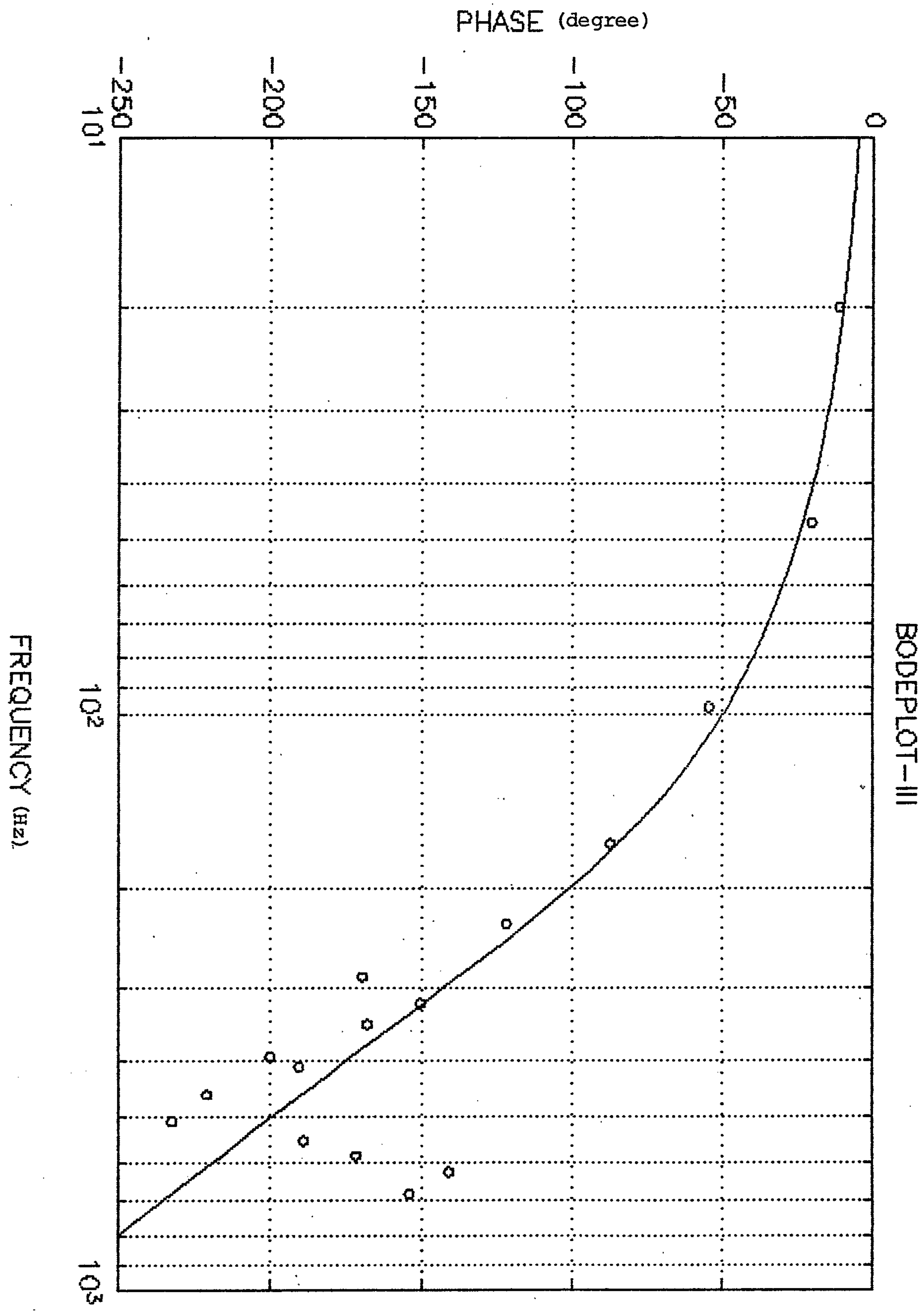
BODEPLOT–III
PHASE (degree)
0
-50
-100
-150
-200
-250
FREQUENCY (Hz)
10¹
10²
10³

Fig. 6b