MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Laser Interferometer Gravitational Wave Observatory (LIGO) Project

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Refer to: LIGO-T960147-00-D
Date: 5 September, 1996

Subject: **Lisa's summary of lock acquisition results**

I talked with Lisa about the attached memo, and she wanted to emphasize that this is a snapshot of unfinished work in progress. She intended to update us about where she was when she left for maternity leave. With that qualification, I feel it's important enough to distribute more widely. One of her principal findings, uncovered only in her last week before leave, is that there seems to be a catch-22 in we had assumed was the most straightforward locking sequence. For this reason we aren't where we'd like to be at this time in the preliminary design phase. Nonetheless, alternate strategies are proposed which Lisa just didn't get a chance to look at yet, so I don't recommend jumping to any dark conclusions. I'm fairly optimistic that on closer examination (probably when Lisa gets back, ~ end of October) one of these previously neglected ideas will prove satisfactory.

In the meantime, if you have any pertinent thoughts please communicate them to Lisa, Jordan and me (Lisa is checking email now and then).

mez:mez

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Summary of Lock Acquisition Results To Date on a Recycled Configuration

LIGO-T960147-00-D **Lisa Sievers 8/23/96**

1.0 Cardinal Rule That Drove Design Process

In order to reach the state where the entire ifo (i.e. power recycled Michelson with Fabry-Perot arms) is locked, you sequence through 4 different locked states (e.g. average Michelson arm length locked => sidebands resonant in power recycled Michelson => sidebands resonant in power recycled Michelson and carrier resonant in one Fabry-Perot=> entire ifo locked). During this sequencing, the length of the "next cavity" to be locked must be locked on a length that is also appropriate for the state where the entire ifo is locked, irrespective of what is happening with the field intensities of the light in the ifo (e.g. bright and dark port of beam splitter are allowed to reverse).

2.0 Initial Assumptions

The LIGO parameters stated during the LSC DRR were used in all of the locking sequence simulations. The configuration assumed is shown below:

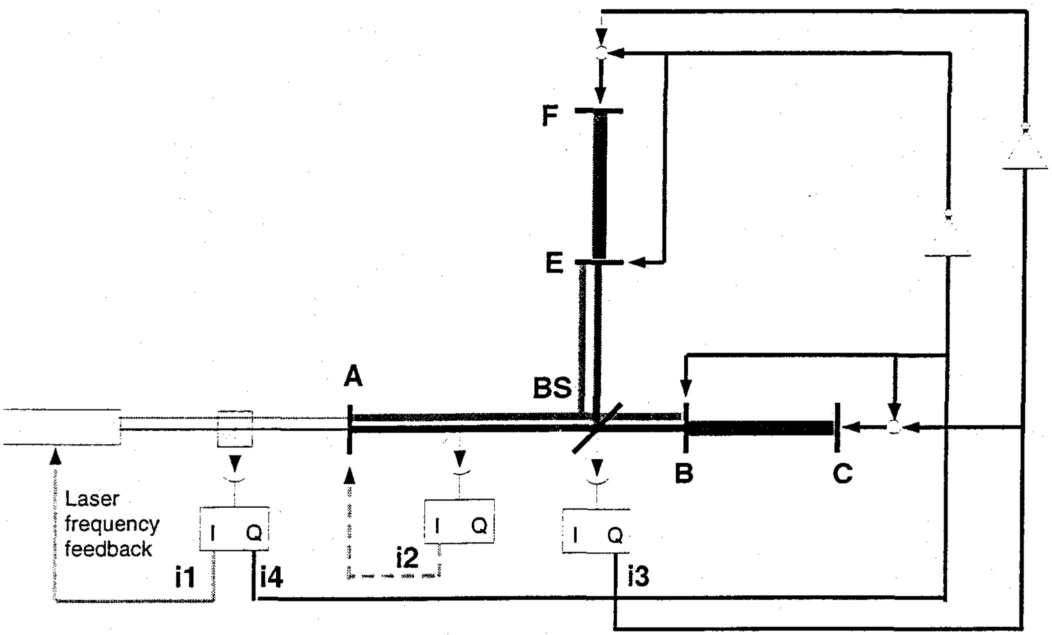


FIGURE 1. Configuration-1 used for Lock Acquisition Studies (baseline configuration)

The variables i1, i2, and i3 and i4 are the extracted signals from the interferometer. It is also assumed that L1 is the pathlength between mirrors B and C, L2 is the pathlength between mirrors E and F, l1 is the pathlength between mirrors A and B, and l2 is the pathlength between mirrors A and E.

3.0 Basis for Choosing A Preferred Locking Sequence

There are 24 possible sequences to explore given that we have 4 DOFs to control. This number does not take into account the fact that the signs on the servos can also change as you sequence through states. Because of this large parameter space, a certain amount of time was invested in thinking through what the best candidate for a successful sequence would be. This section provides a discussion on how this choice was made.

3.1 Insights About Locking Sidebands

When you lock only the i2 signal, you don't lock either of the sidebands in one of the Power Recycled Michelson (PRM) arms, instead you lock the l1+l2 degree of freedom. This is the breathing mode of the PRM which holds the l1 and l2 pathlengths so that they are always equal; as the two lengths vary together the field intensities in both arms are always equal but also vary together as the two arms breath. Not surprisingly a complementary observation was made when the i4 servo is locked alone; the average Michelson arm length is held on a constant value in this state.

This observation, leads one to believe that the only way to get a sideband resonating in a PRM arm is to lock both i2 and i4 together, consequently setting both arm lengths of the recycling cavity in the correct positions.

3.2 Locking Sequence Choice

Given the results of 3.1, I felt the most likely sequence was one where both sidebands are locked in the PRM first and then each of the long arm cavities is locked in sequence. This results in a preferred locking sequence of i4 =>i2 =>i1 =>i3. Locking the ifo in this way should set up all the lengths in the correct state, consequently this was the sequence that I spent most of my time working through.

Other locking sequences would involve locking either i2 or i4 (i.e. the PRM common mode or differential controllers) last. I thought this was a low probability choice since this would mean the ifo had to go through a state where the two long arm cavities were locked on the carrier but the arms of the PRM would be continually varying in length with neither carrier or sideband resonant even though i2 or i4 would also be locked. This may or may not have been a correct conclusion. I will address this issue in Section 4.3.1.

4.0 Results on Preferred Locking Sequence i4=>i2=>i1=>i3

4.1 List of Steps for Designing Servo

1. Calculate the 4x5 matrix of transfer functions for the case when the entire ifo is in its desired resonant state (i.e. carrier resonating in PRM and both Fabry-Perot arms, also sidebands resonating in PRM). These transfer functions are shown in Appendix 1.
2. Calculate the 4x5 matrix of transfer functions for the case when the sidebands are resonating in the PRM and the carrier is resonant in only one of the Fabry-Perot arms. These transfer functions are shown in Appendix 2.
3. Calculate the 4x5 matrix of transfer functions for the case when only the sidebands are resonating in the PRM and the carrier is not resonant in either arm cavity.
4. Design a 4x4 diagonal linear controller that is simultaneously stable for the above 3 states.

4.2 Results obtained from Design Process

I was able to first lock sidebands in the PRM with the i2 and i4 loops (i.e. l1+l2 and l1-l2 loops, respectively). In order to accomplish this the phase of the i2 and i4 loops required a 180^o phase shift relative to the case when the entire ifo was on resonance. Interestingly enough, the two loops seemed to lock simultaneously.

I was also able to lock the sidebands in the PRM and then the carrier in one of the Fabry-Perot arms with the i3 (i.e. L1-L2) servo as long as the i1 (i.e. L1+L2) servo was off. The phase of the i2 and i4 loops were also 180^o out of phase for this state relative to the state when the entire ifo is locked.

The problems arose in the design of the laser feedback servo which uses the i1 signal to control laser frequency. I found it impossible to design a high bandwidth servo for the i1 loop that was both stable for the state where the entire ifo is locked and also the state where the sidebands are locked in the PRM and the carrier is locked in only one of the Fabry-Perot arms. This appears to be a fundamental problem. The figure below shows the approximate contribution of l1+l2 and L1+L2 to both i1 and i2 for the state when the sidebands are resonant in the PRM and the carrier is locked in only one of the Fabry-Perot arms.

The i2 servo sees a much larger component of L1+L2 than l1+l2 while the laser loop (i1) servo sees a much larger component of l1+l2 than L1+L2 (see transfer functions in Appendices). The laser loop is high bandwidth and nulls the l1+l2 signal while the i2 loop (which actuates the l1+l2 degree of freedom) sees a signal essentially proportional to L1+L2. This is a very unstable situation and I was unable to come up with any way of getting around this problem other than changing the feedback configuration.

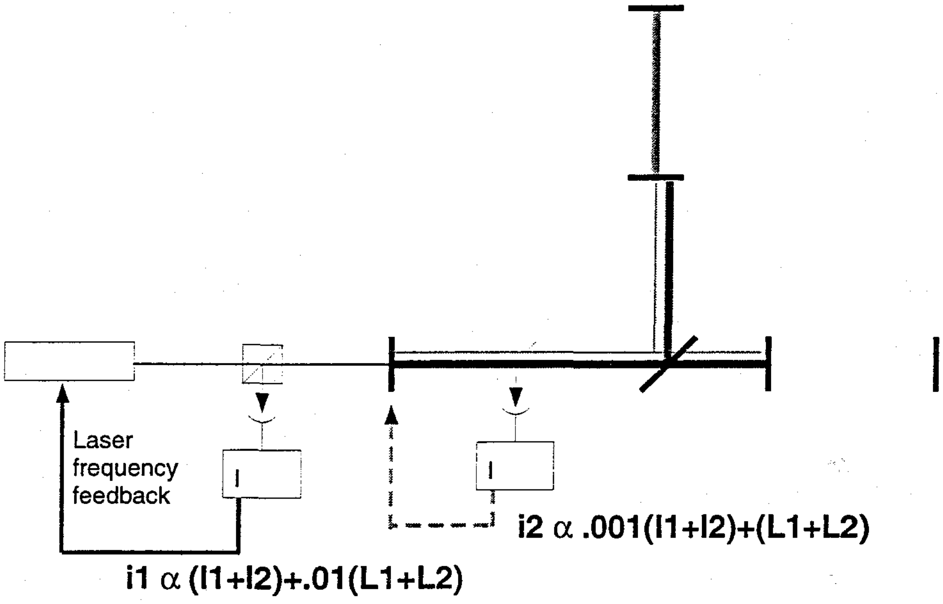


FIGURE 2. Diagram showing contribution of l1+l2 and L1+L2 displacements to the i1 and i2 signals when sidebands locked in PRM and carrier locked in only 1 Fabry-Perot.

4.3 Implications for LIGO Design

4.3.1 Assuming Baseline Configuration for LIGO

Given the results of section 4.2 I have given up on the possibility of using a sequence where the sidebands are locked first in the PRM. Though, inputs from others on how this sequence might be salvaged are very welcome).

If we assume the baseline LIGO configuration shown in Figure 1, it appears we have only one other option for the locking sequence: the case discussed in Section 3.2 where the ifo has to go through a state where the carrier is locked in both arm cavities and the l1+l2 or l1-l2 degree of freedom is also locked, resulting in the PRM not being locked at a fixed length. I initially threw out this sequence as a possibility since it wasn't intuitive (Jordan and Stan also agreed that this sequencing seemed unlikely). On a more positive note about the possibility of using this alternate sequence, Martin appears to have done something similar to this type of sequencing when he locked his tabletop experiment. Although his parameters were very different and his feedback configuration different, it appears he locked the recycling mirror and the 2 Fabry-Perot arms first and then the beam splitter last. Unless someone can come up with a fundamental reason why this alternate sequence can't work, I think it would be well worth our time to try and work through a design for this case even though it is not intuitive.

4.3.2 Assuming Alternate Configurations

If we change the baseline configuration so that the i1 signal is fed back to the recycling mirror and the i2 signal is fed to the laser loop, it appears that the fundamental problem experienced in the baseline configuration may be corrected. This train of thought is covered in Section 5.0.

After discussions with Jordan about the consequences of using the nonresonant sideband in the locking process, we concluded that there did not appear an obvious way in which using the extra sideband would help.

4.4 Implications for 40 M

Since the 40 M will be operating with different lengths, reflectivities, etc., it is possible that there will not be a problem in locking the ifo using the "preferred" strategy. This could be checked by using the 40 m parameters and running the transfer functions in Twiddle for the fully resonant recycled ifo and the transfer functions when one of the Fabry-Perot arms is not locked but the rest of the ifo is. This test should reveal whether there is a fundamental problem with stability of the laser loop and the recycling mirror loop for this particular locking sequence similar to that experienced with the LIGO parameters.

5.0 Investigation of Alternate Configuration

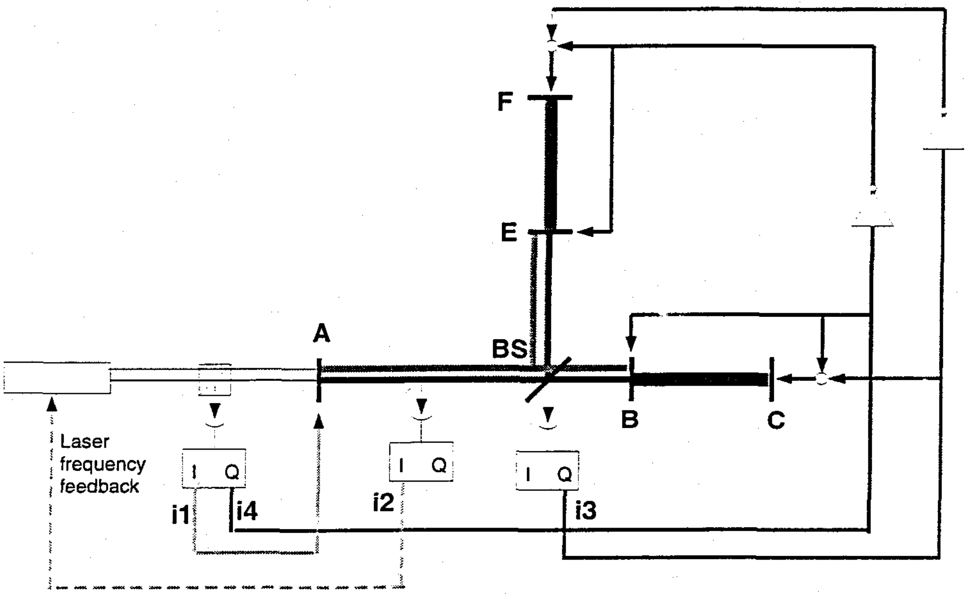


FIGURE 3. Configuration-2 used for Lock Acquisition Studies. The roles of i1 and i2 have been switched from the baseline configuration.

The change in the baseline configuration is that the laser feedback path is now being driven by the i2 signal and the feedback to the recycling mirror is now being driven by i1. I went through the same design process as explained in section 4 and came up with the following results:

1. I was able to first lock sidebands in the PRM with the i1 and i4 loops (i.e. l1+l2 and l1-l2 loops, respectively). In order to accomplish this the phase of the i1 and i4 loops required a 180° phase shift relative to the case when the entire ifo was on resonance. The two loops seemed to lock simultaneously.
2. I was also able to lock the sidebands in the PRM and then the carrier in 1 Fabry-Perot with either the i3 (L1-L2) loop or the i2 (L1+L2) loop in a stable way. The phase of the i2 and i4 loops were also 180° out of phase with the case when the entire ifo is locked.
3. In steps 1 and 2, I showed you can sequence from i4 => i1 => i2. The final stage is to switch the phase of the i4 and i1 servos as the second Fabry-Perot arm comes into resonance so it locks using i3. Fundamentally this looks like a very robust process since the fringe width of the second Fabry-Perot is very very broad. I implemented a switch where I triggered the phase change on the i1 and i4 loops when the transmitted light in both arm cavities is above a certain level. Unfortunately, I was never able to simulate the second arm locking as planned after the triggering event. I did not have the time to troubleshoot for possible errors in the switching code or experiment with different triggers. I don't see any fundamental problems in doing the switching but I won't count on this fact until I see it actually work in simulation.

The bottom-line for this configuration is that I think this sequence should work but still need time to verify this.

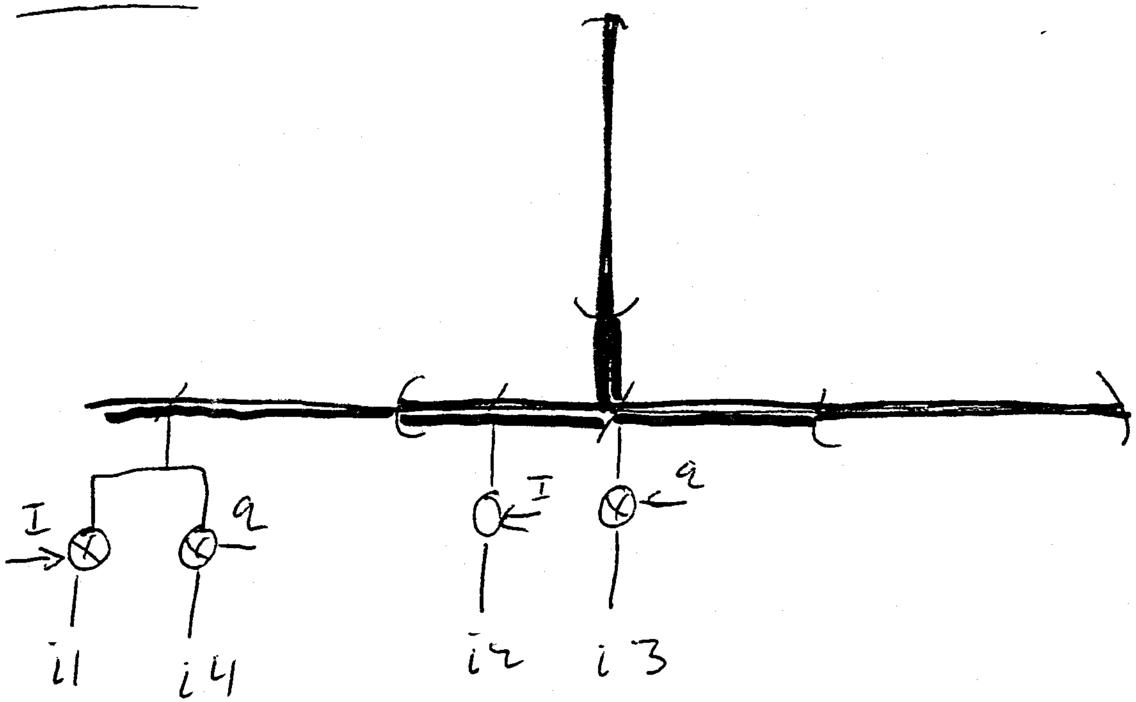
6.0 Synopsis of Results to Date

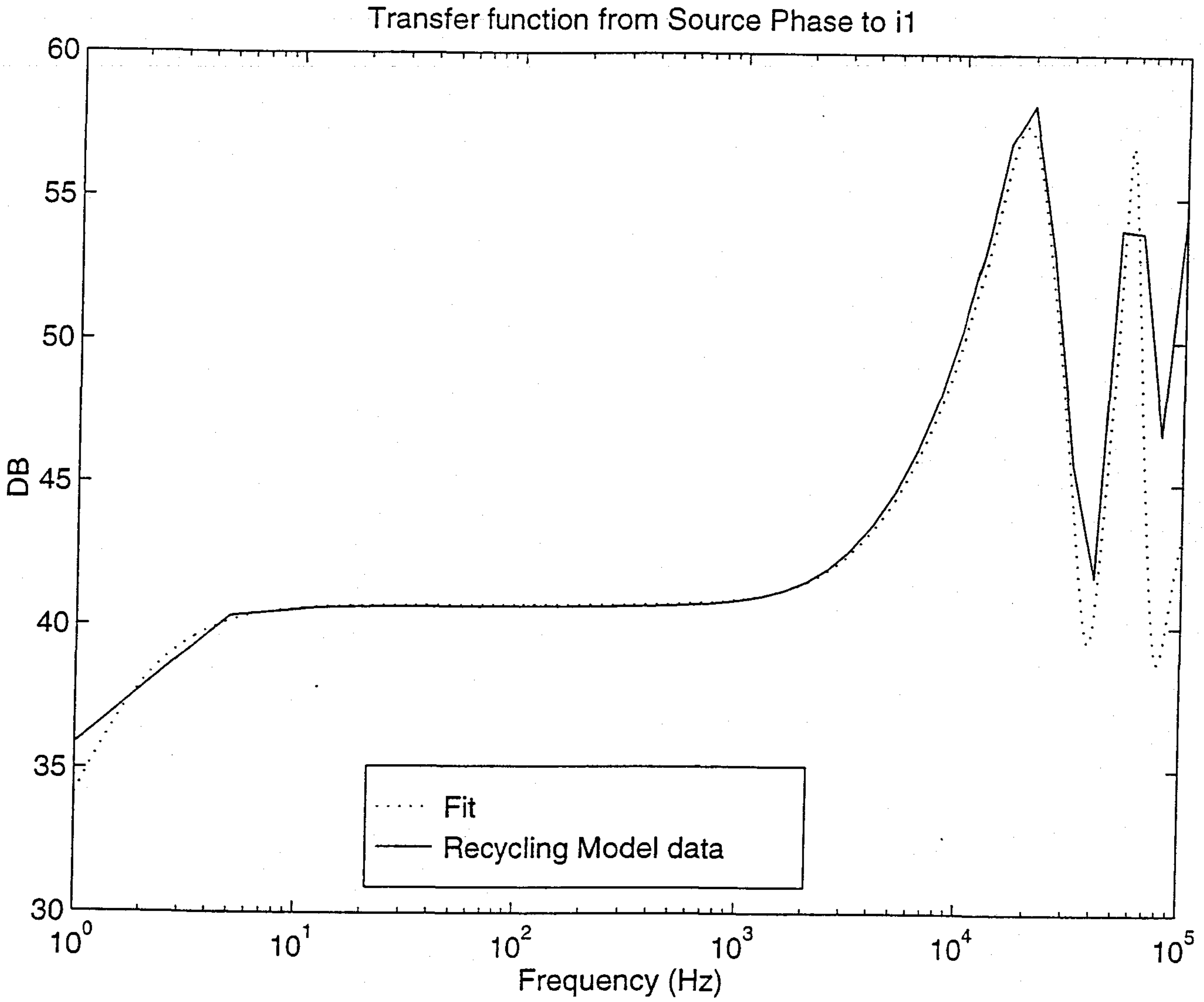
Assuming the baseline configuration for LIGO and the LIGO parameters, I investigated whether a LIGO interferometer could be locked using the set of locking sequences that included the state where the sidebands were resonant in the PRM and the carrier was resonant in only one of the Fabry-Perot cavities. I concluded that there was a fundamental problem in locking the interferometer in this way.

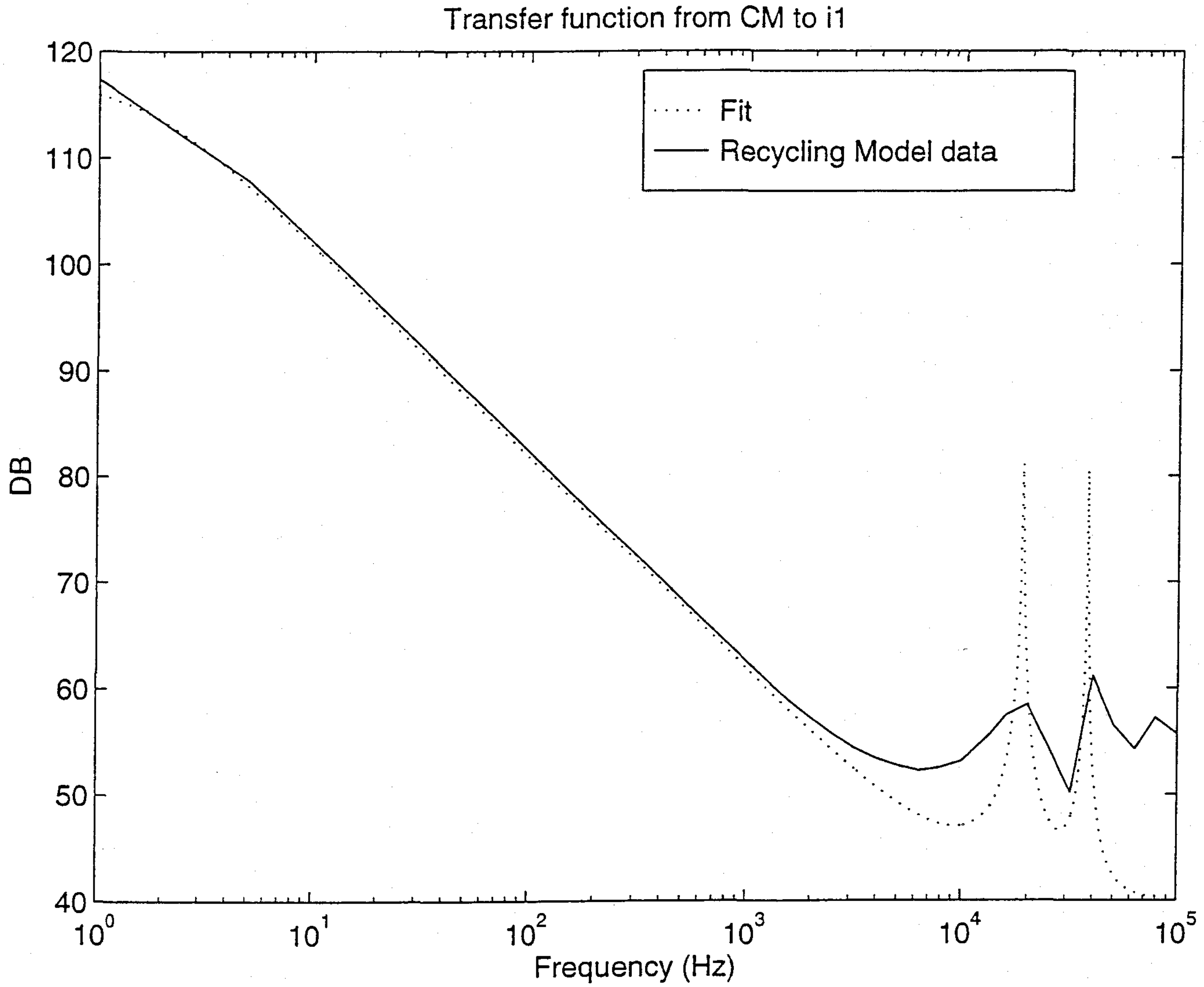
There is one other set of locking sequences to investigate in order to determine whether the baseline configuration can be easily locked or not. This is the set of sequences that include the state where the carrier resonates in both the arm cavities and either the common mode or differential mode of the PRM is locked. This set of sequences was not investigated initially since it intuitively seemed like it shouldn't work. Martin locked his tabletop ifo using a sequence that roughly corresponds to this type of sequencing so there is an off-chance that this might be the correct way to go. It should be noted though that the correlation between Martin's tabletop ifo and the LIGO ifo is very loose.

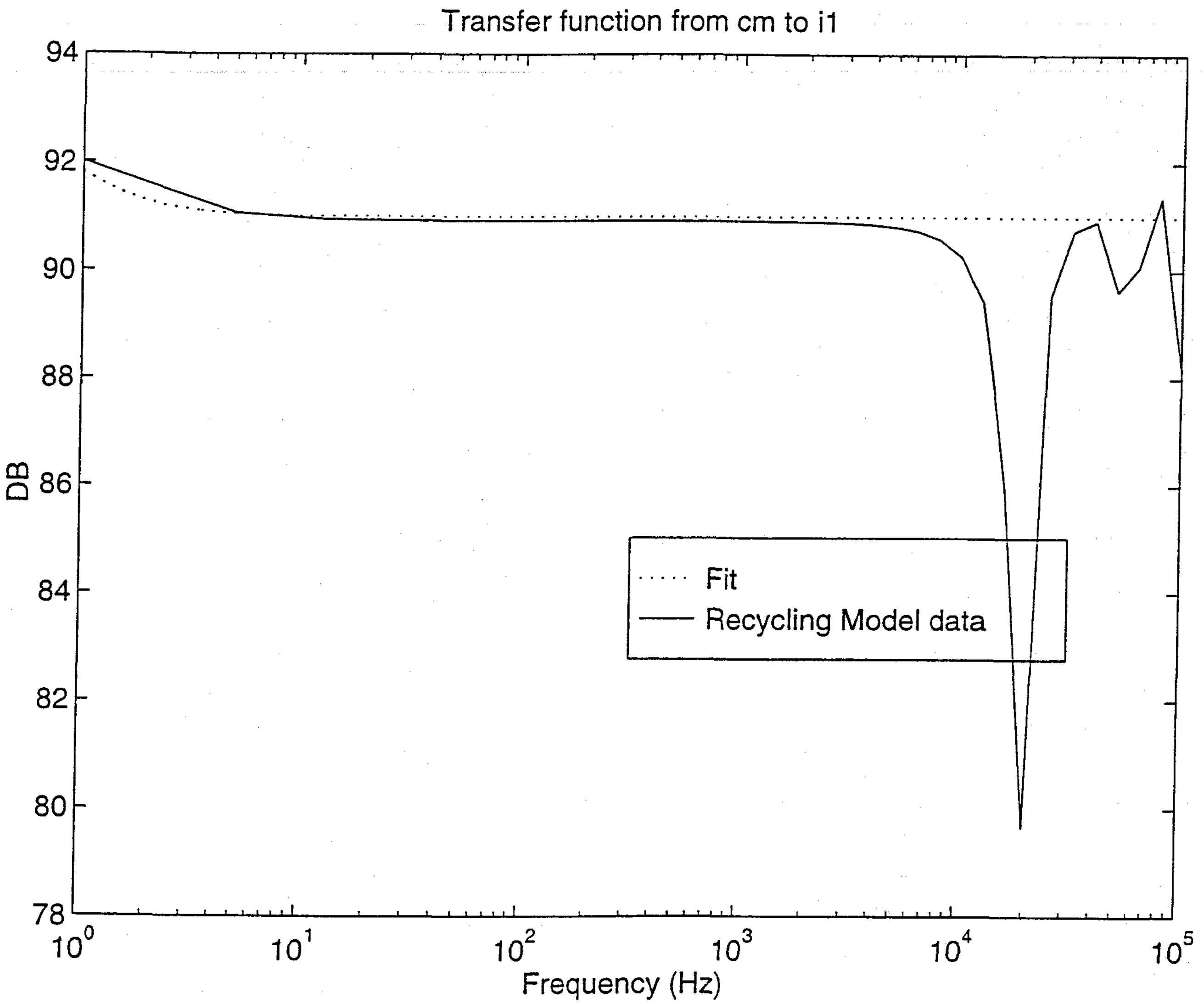
In the course of this work, I also investigated a configuration that differed from the LIGO configuration somewhat; I changed the roles of the laser feedback loop and the recycling mirror feedback loop. This configuration looks very promising, although I haven't been able to demonstrate the servo system's ability to sequence through the set of 4 states in order to lock the complete interferometer, yet.

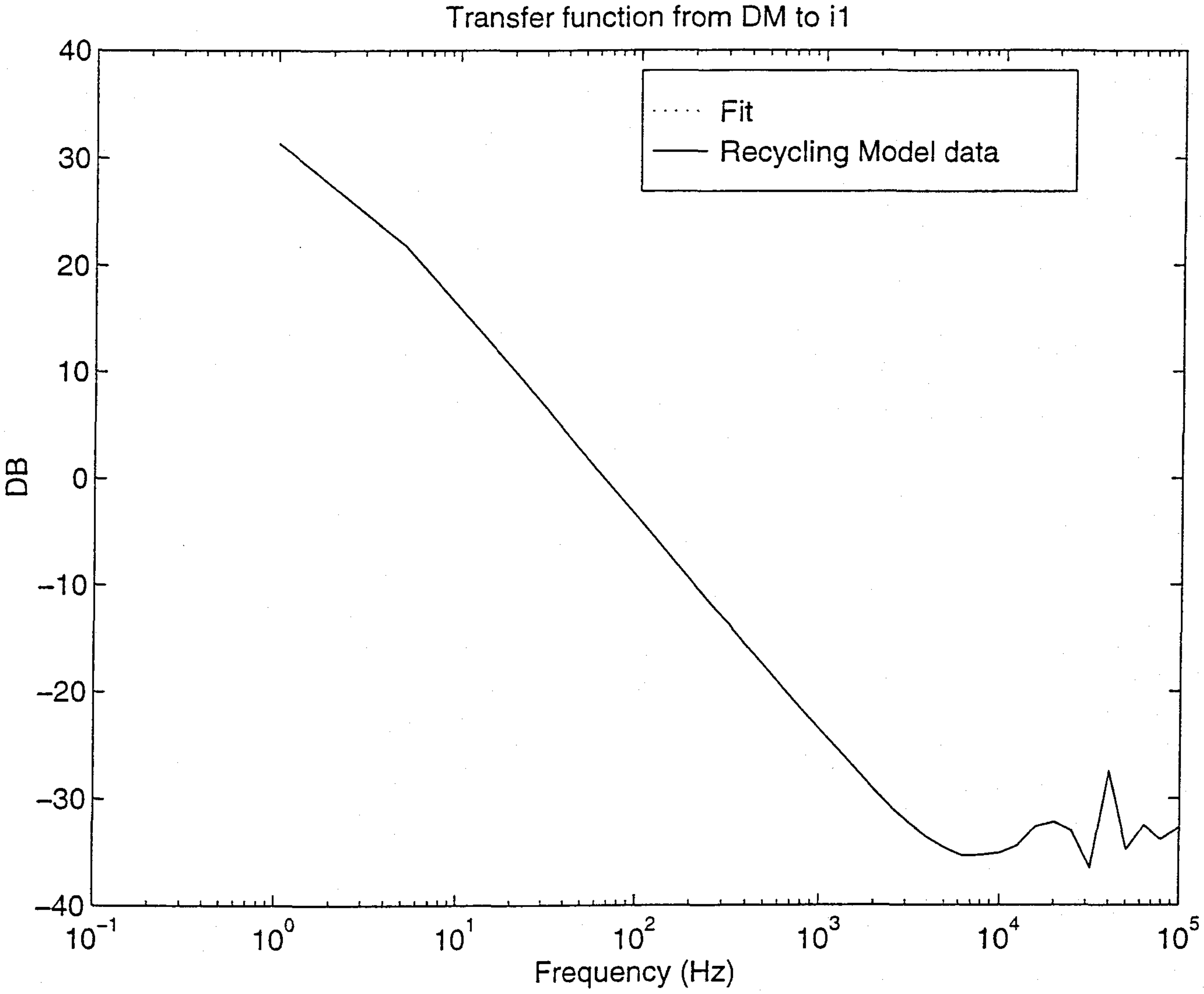
Appendix I Recycled Ifo Transfer Functions

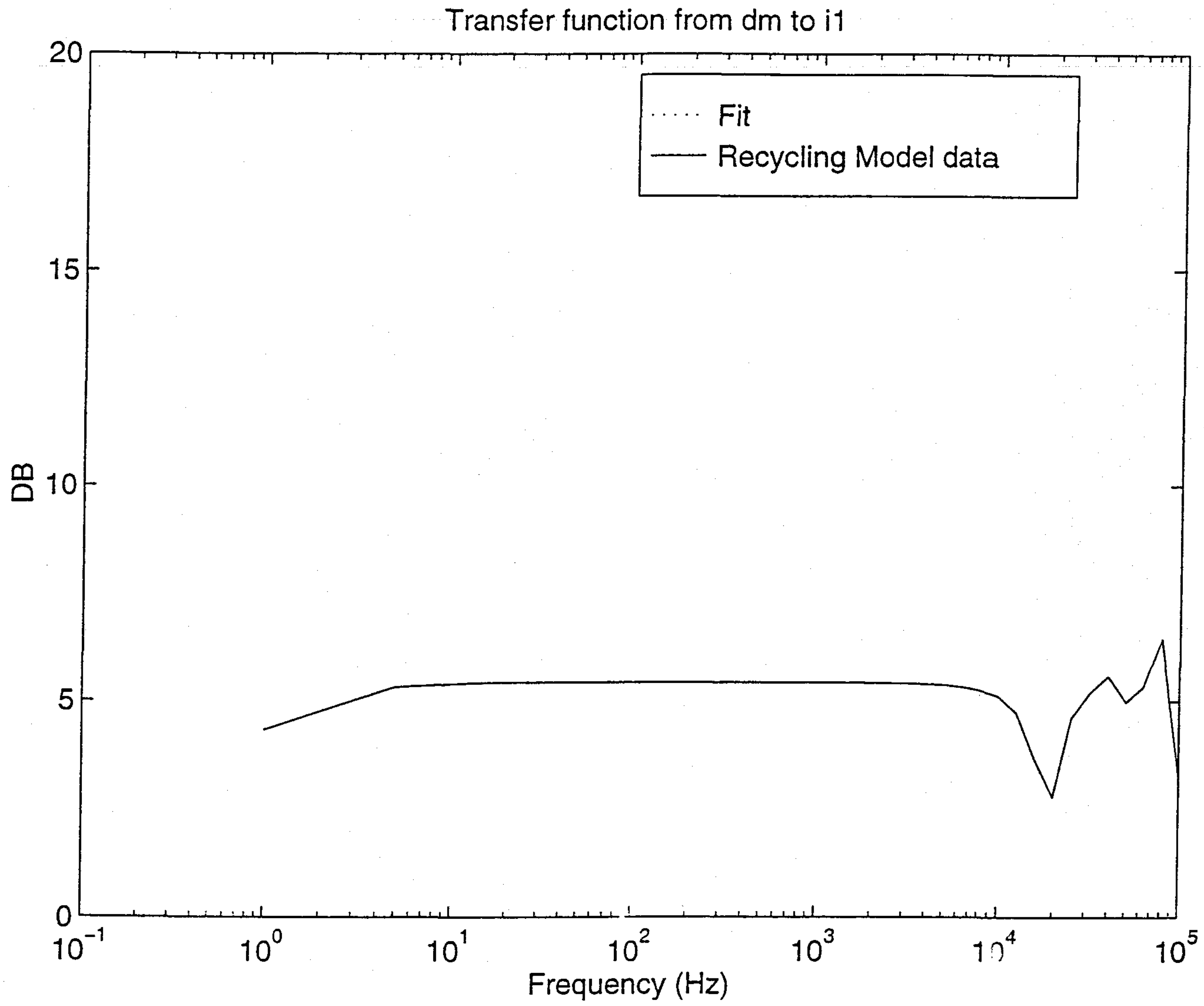


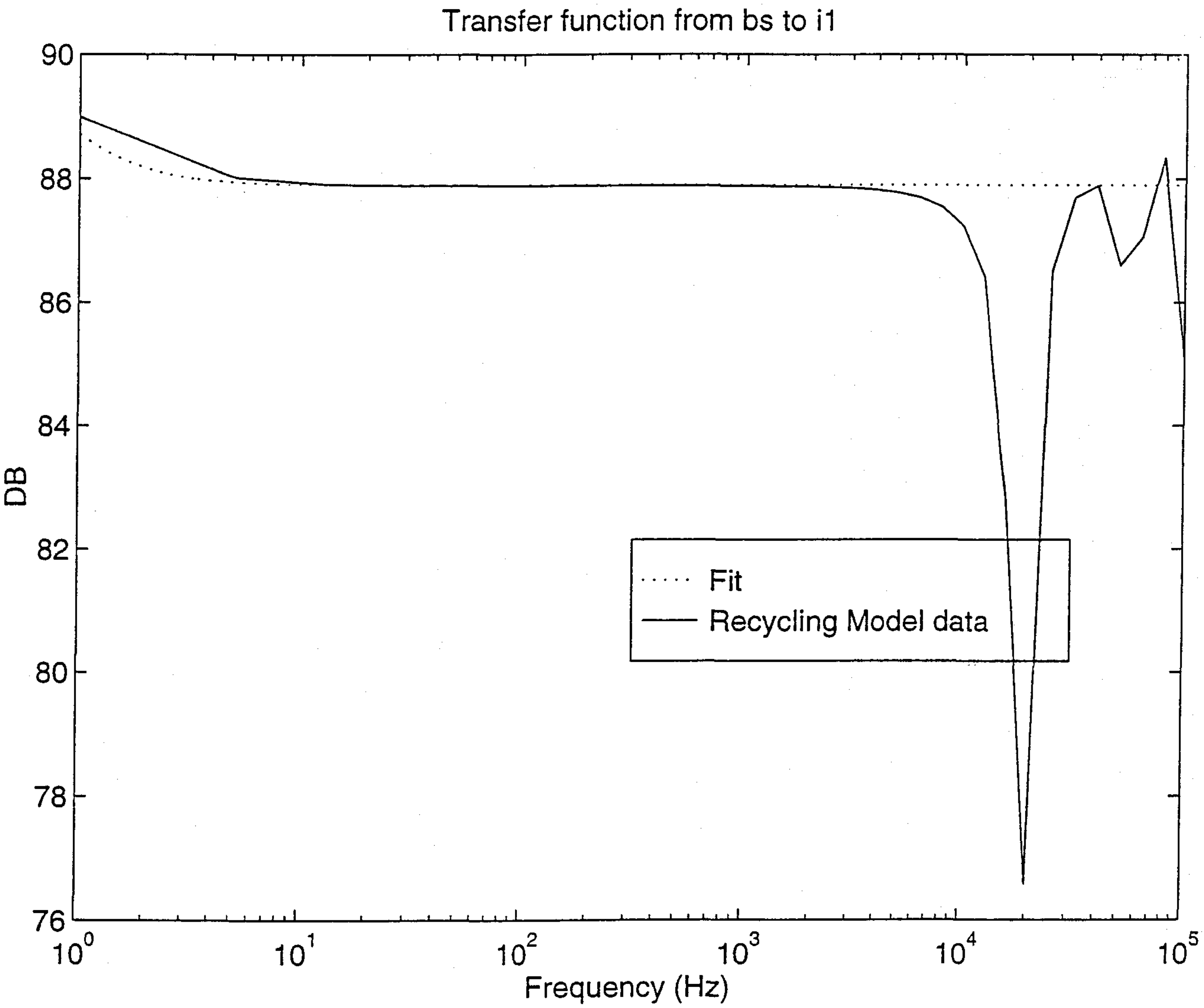

Transfer function from Source Phase to i1
60
55
50
45
40
35
30
DB
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)
Fit
Recycling Model data

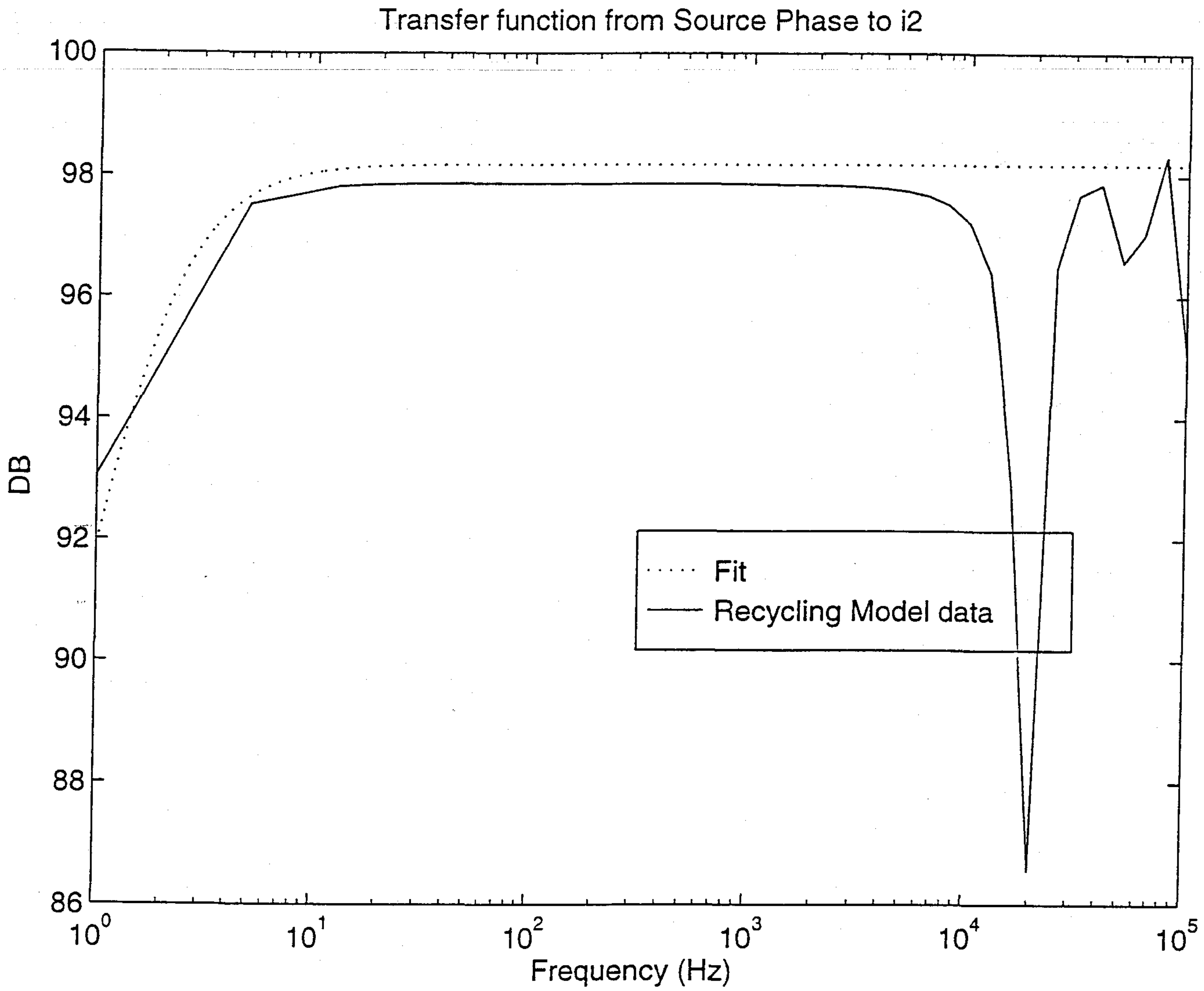

Transfer function from CM to i1
Fit
Recycling Model data
DB
120
110
100
90
80
70
60
50
40
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

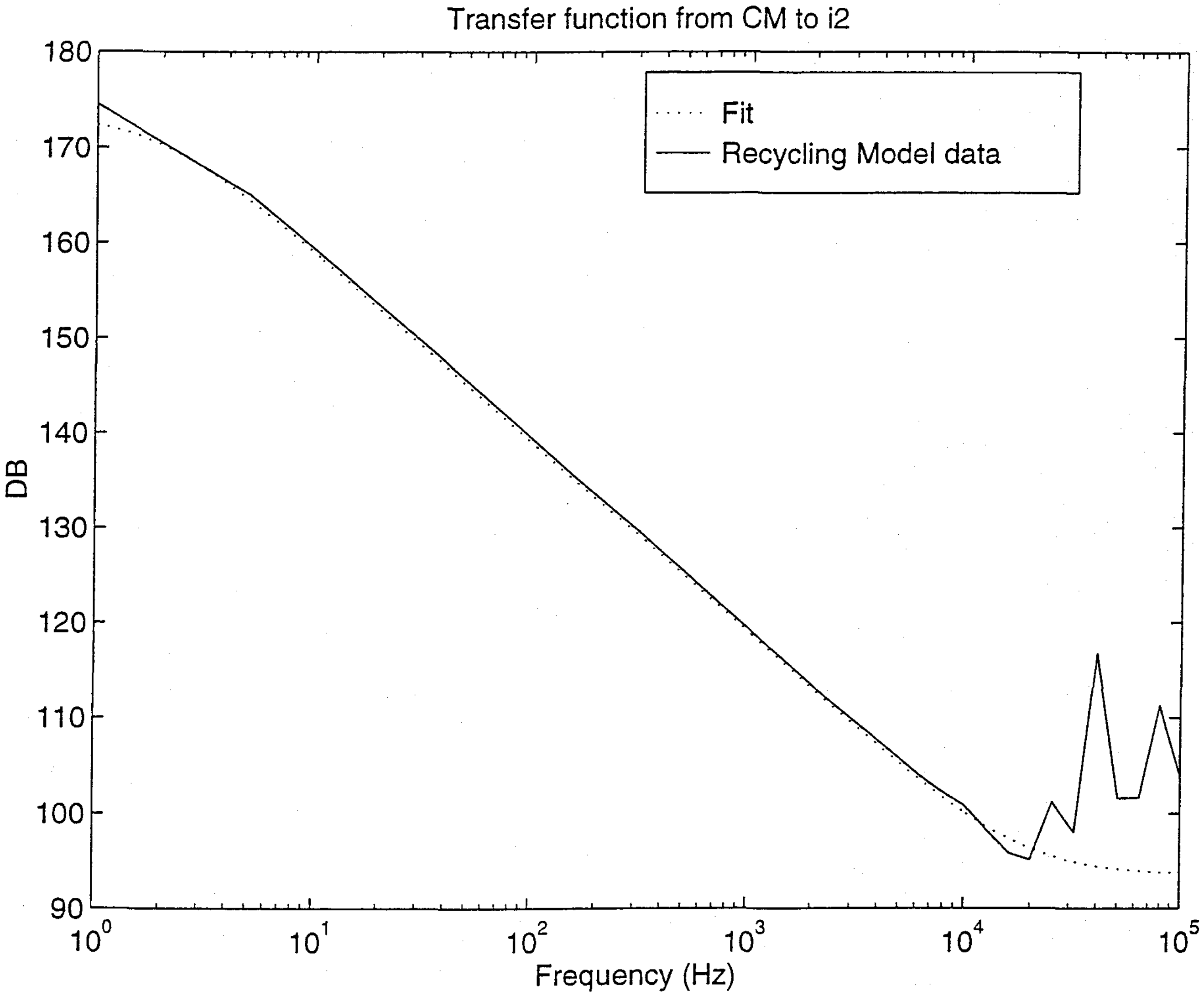

Transfer function from cm to i1
94
92
90
88
86
84
82
80
78
DB
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)
Fit
Recycling Model data

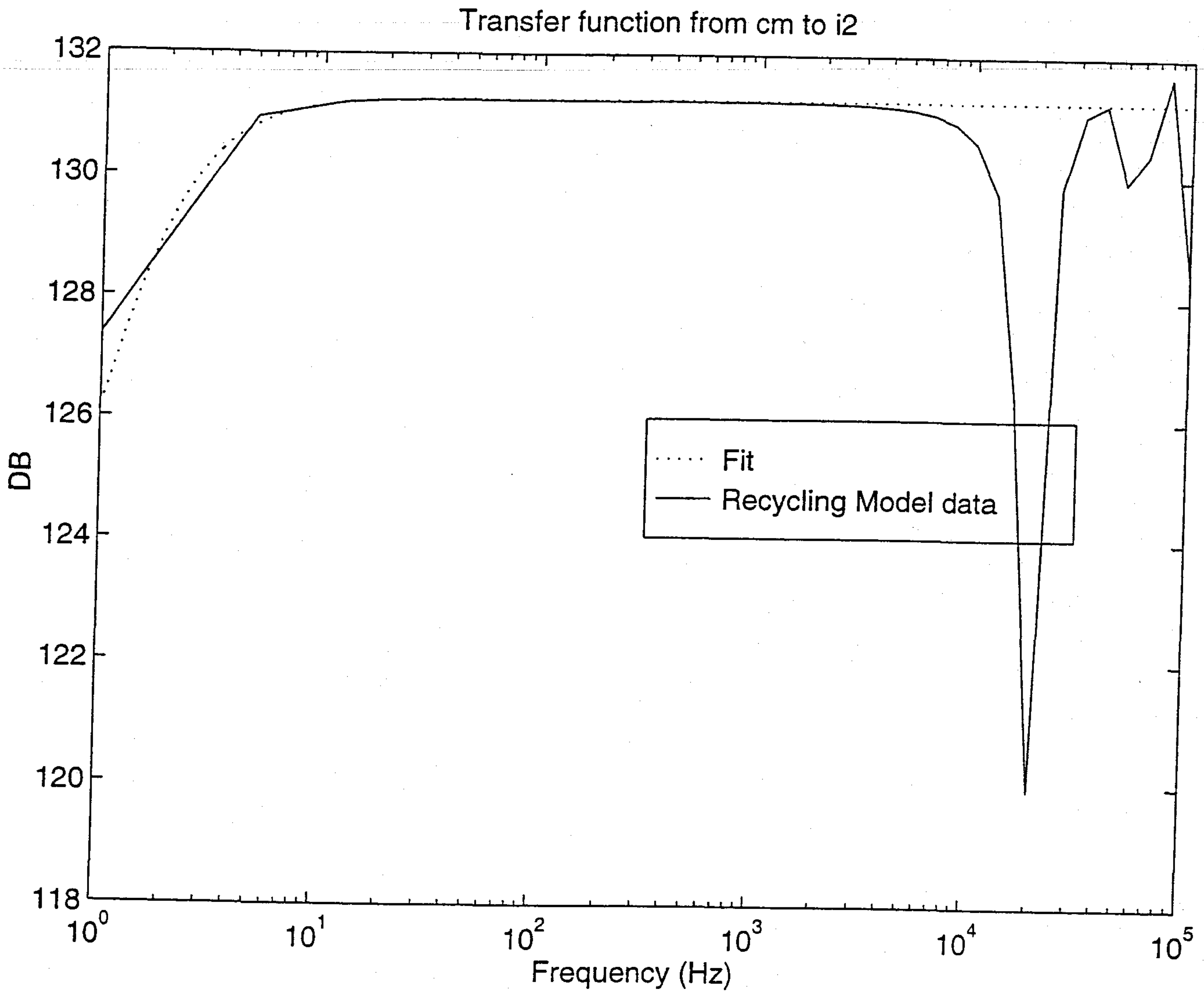

Transfer function from DM to i1
Fit
Recycling Model data
DB
40
30
20
10
0
−10
−20
−30
−40
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Frequency (Hz)

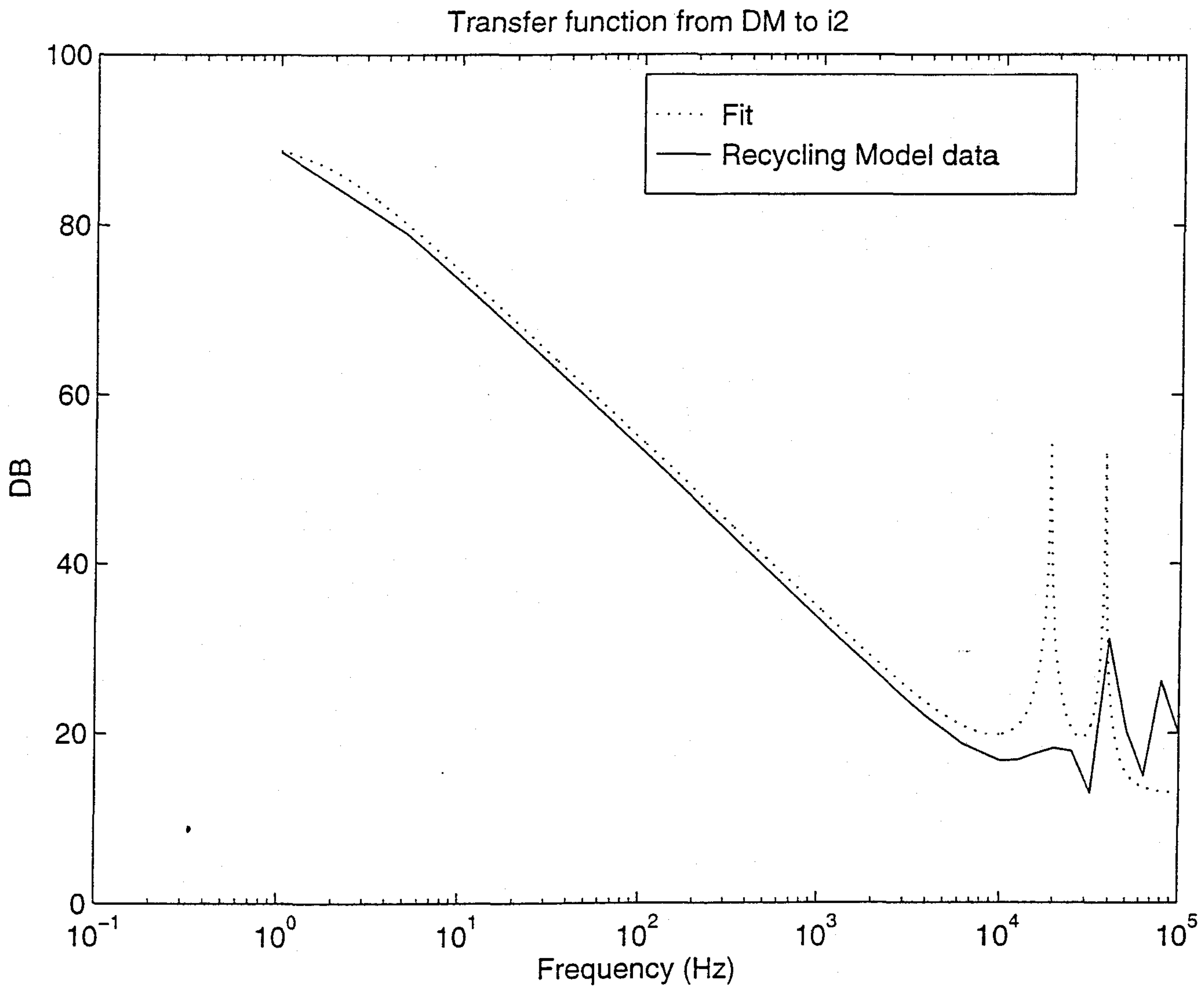

Transfer function from dm to i1
Fit
Recycling Model data
DB
20
15
10
5
0
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

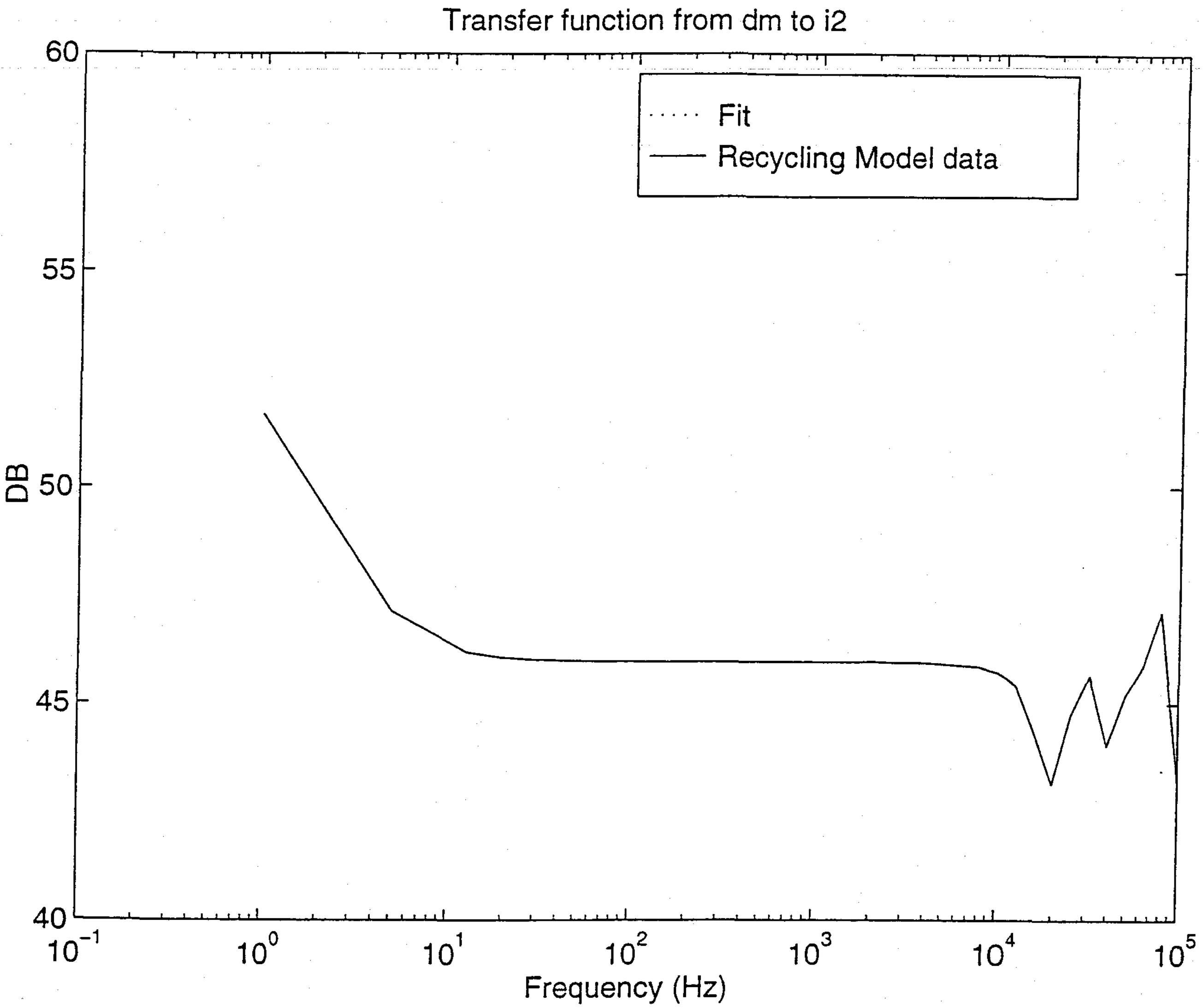

Transfer function from bs to i1
90
88
86
84
82
80
78
76
DB
Fit
Recycling Model data
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

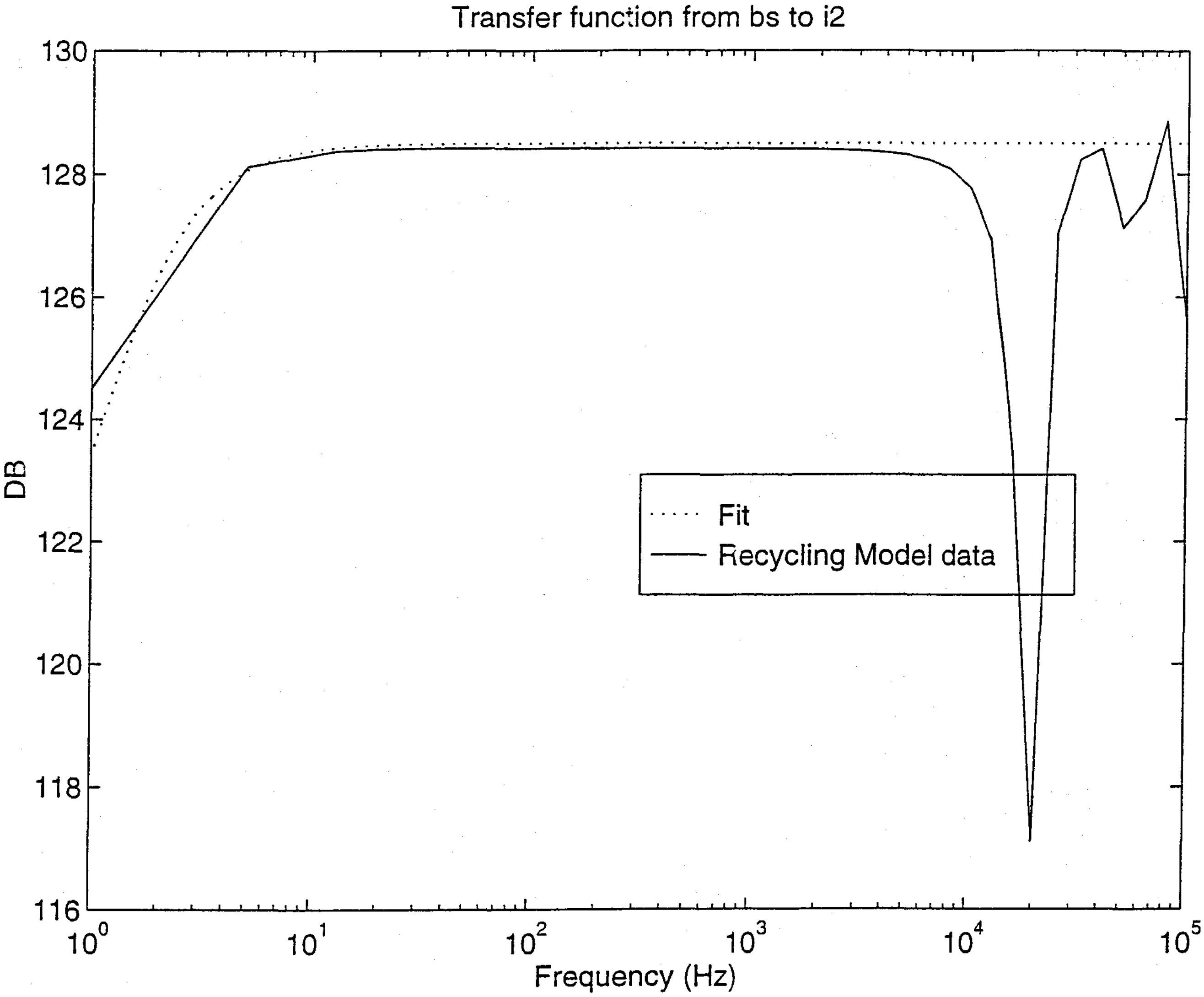

Transfer function from Source Phase to i2
100
98
96
94
92
90
88
86
DB
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)
Fit
Recycling Model data


Transfer function from CM to i2
180
170
160
150
140
130
120
110
100
90
DB
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)
Fit
Recycling Model data

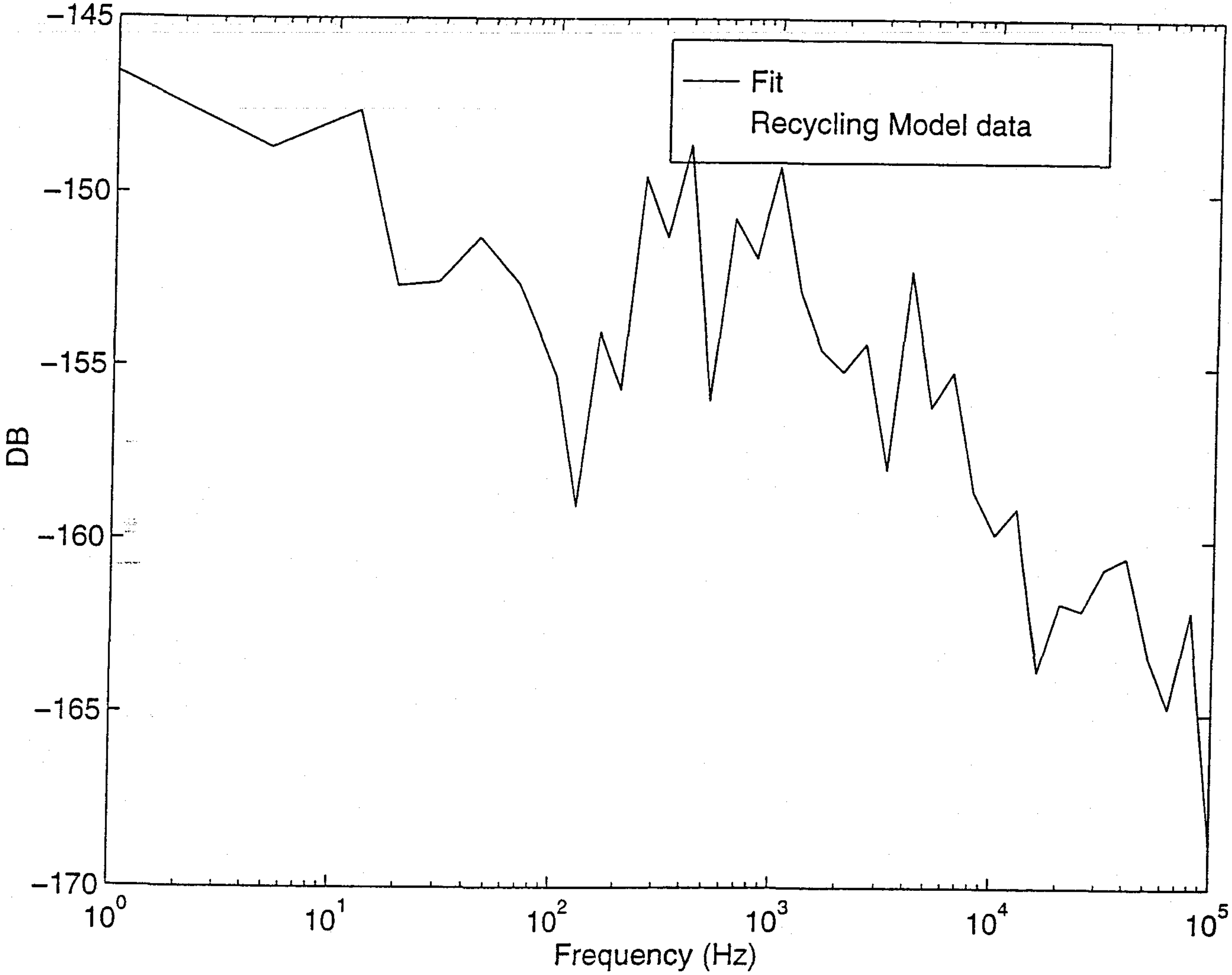

Transfer function from cm to i2
132
130
128
126
124
122
120
118
DB
Fit
Recycling Model data
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

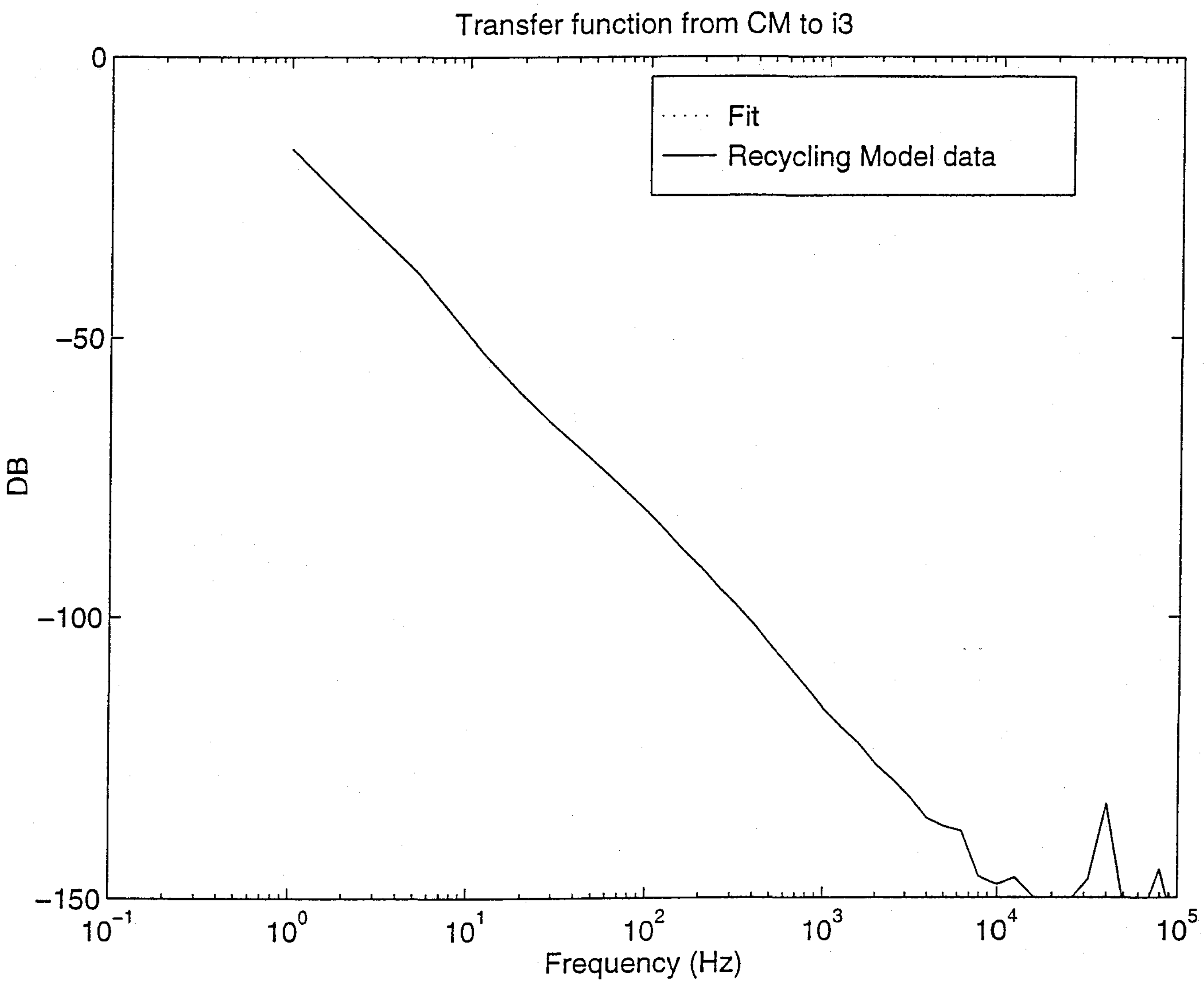

Transfer function from DM to i2
Fit
Recycling Model data
DB
Frequency (Hz)
0
20
40
60
80
100
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

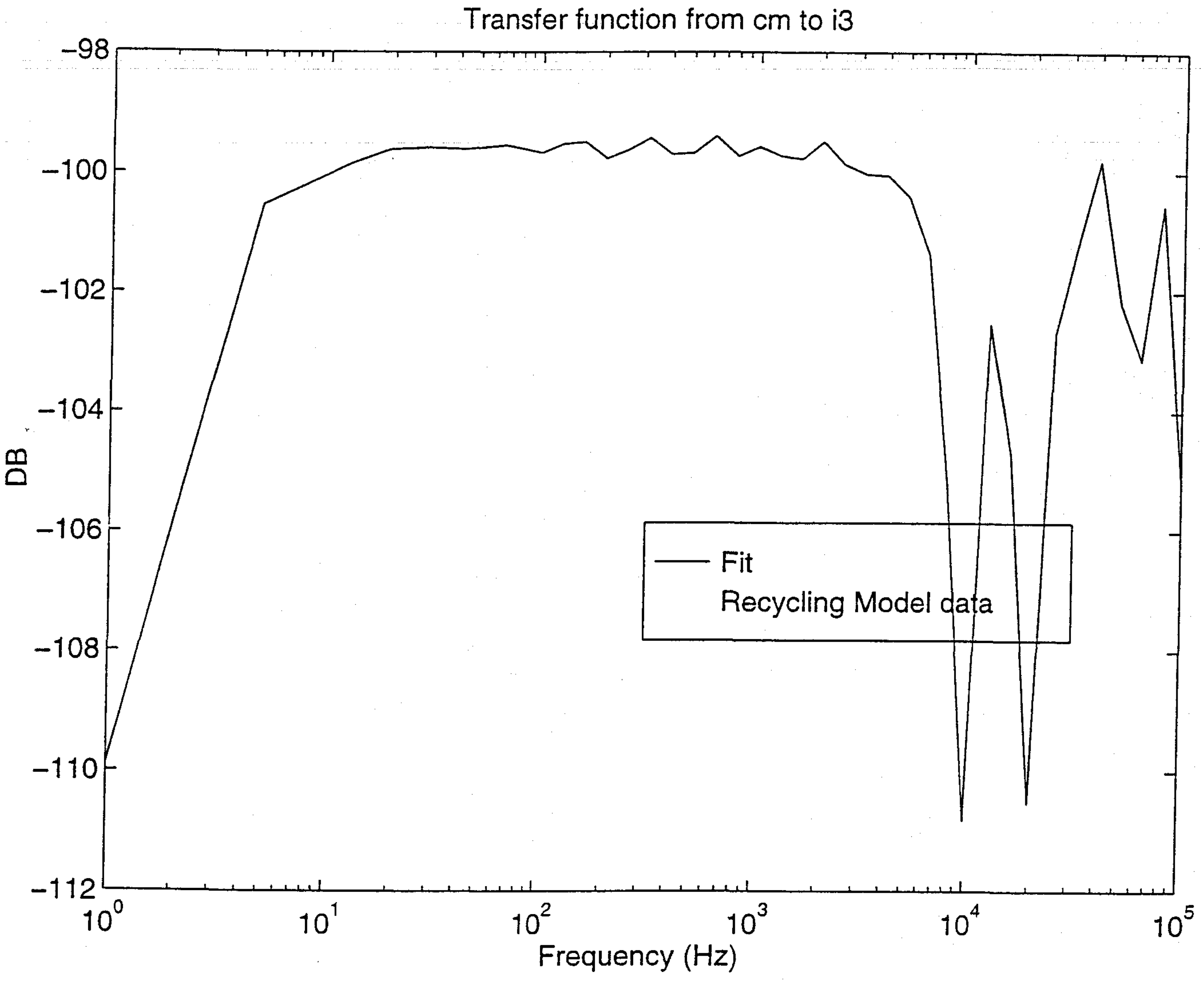

Transfer function from dm to i2
Fit
Recycling Model data
DB
60
55
50
45
40
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Frequency (Hz)


Transfer function from bs to i2
130
128
126
124
122
120
118
116
DB
Fit
Recycling Model data
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

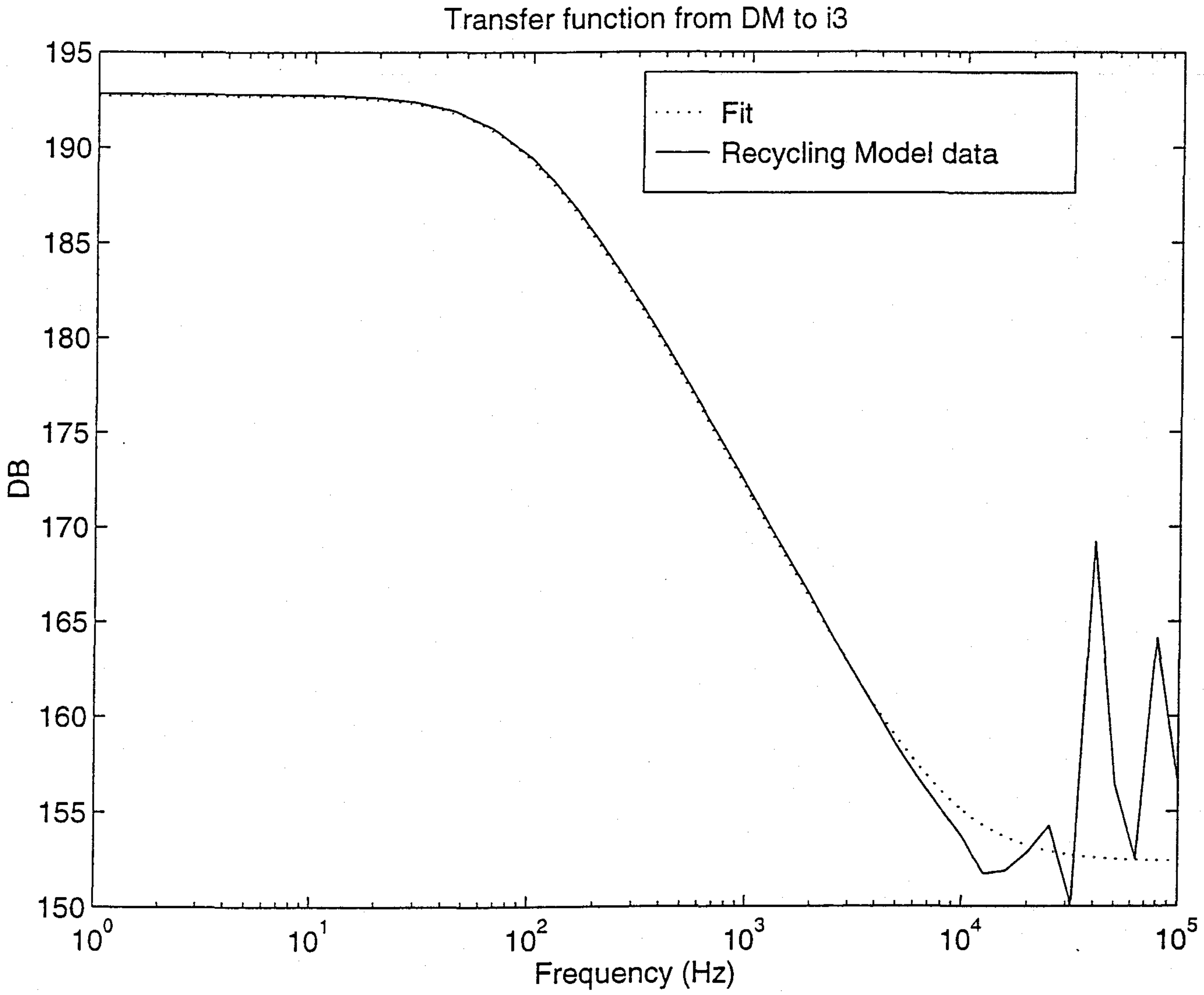
Transfer function from Source Phase to i3

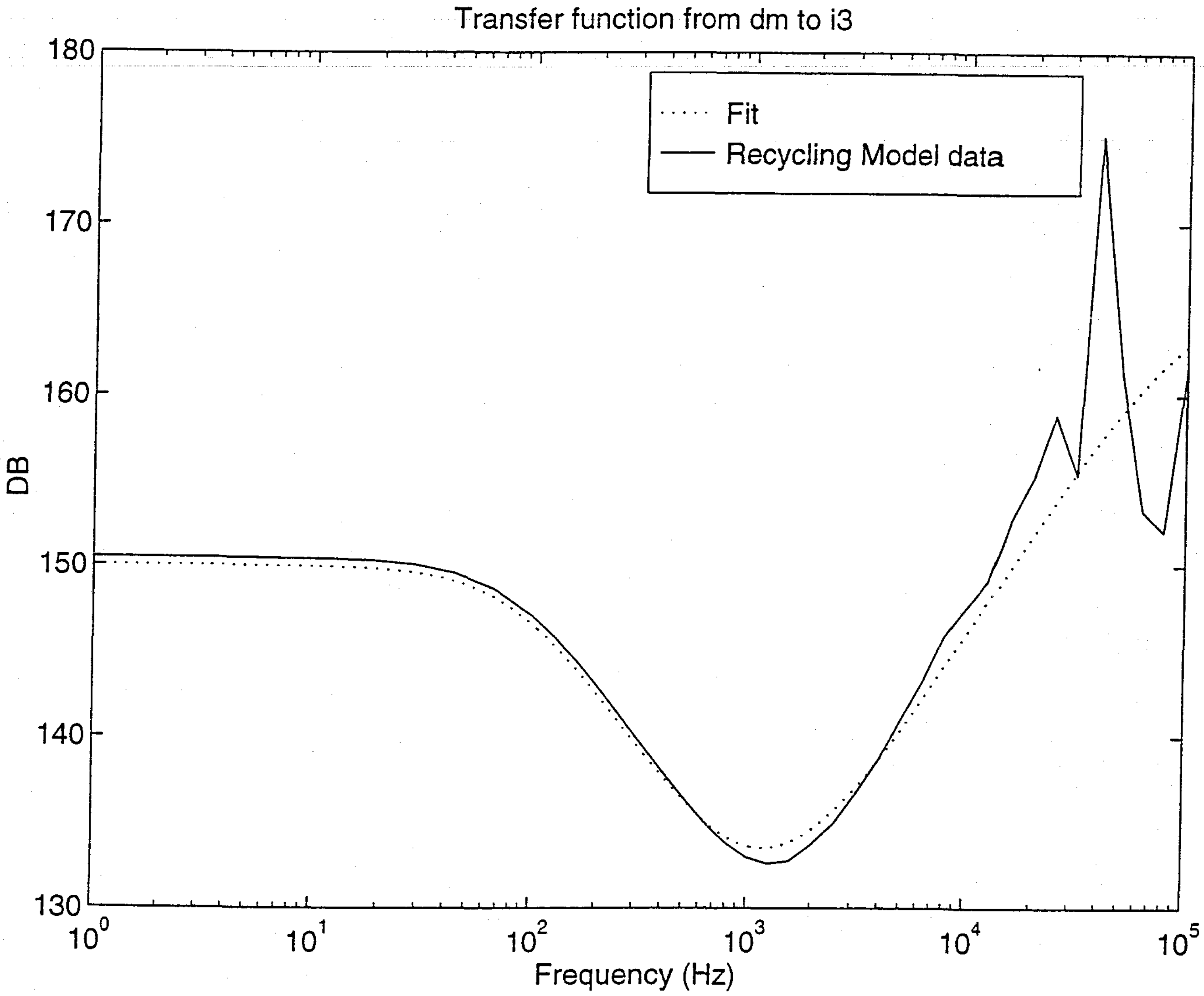


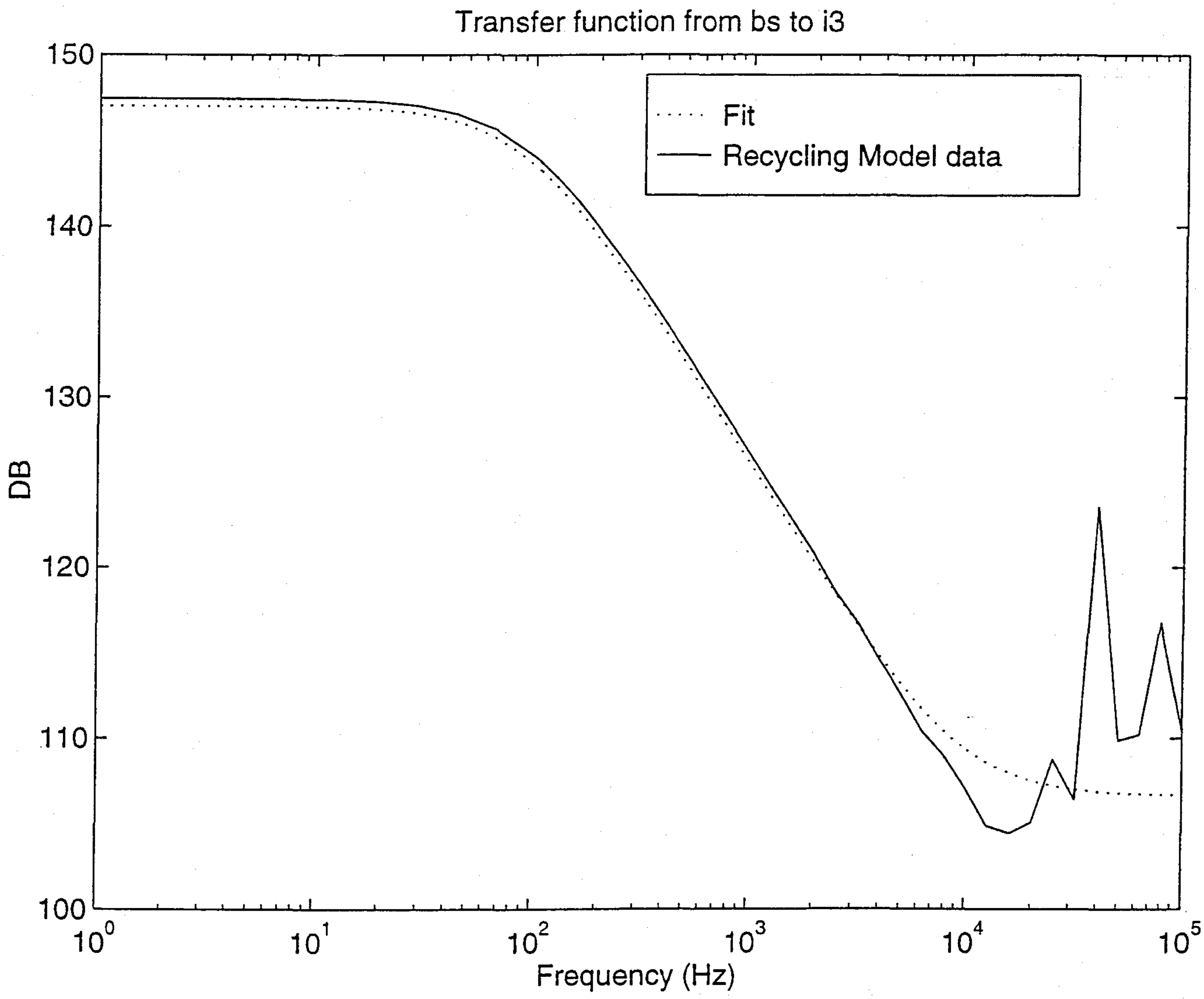

Transfer function from CM to i3
0
−50
−100
−150
DB
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Frequency (Hz)
Fit
Recycling Model data

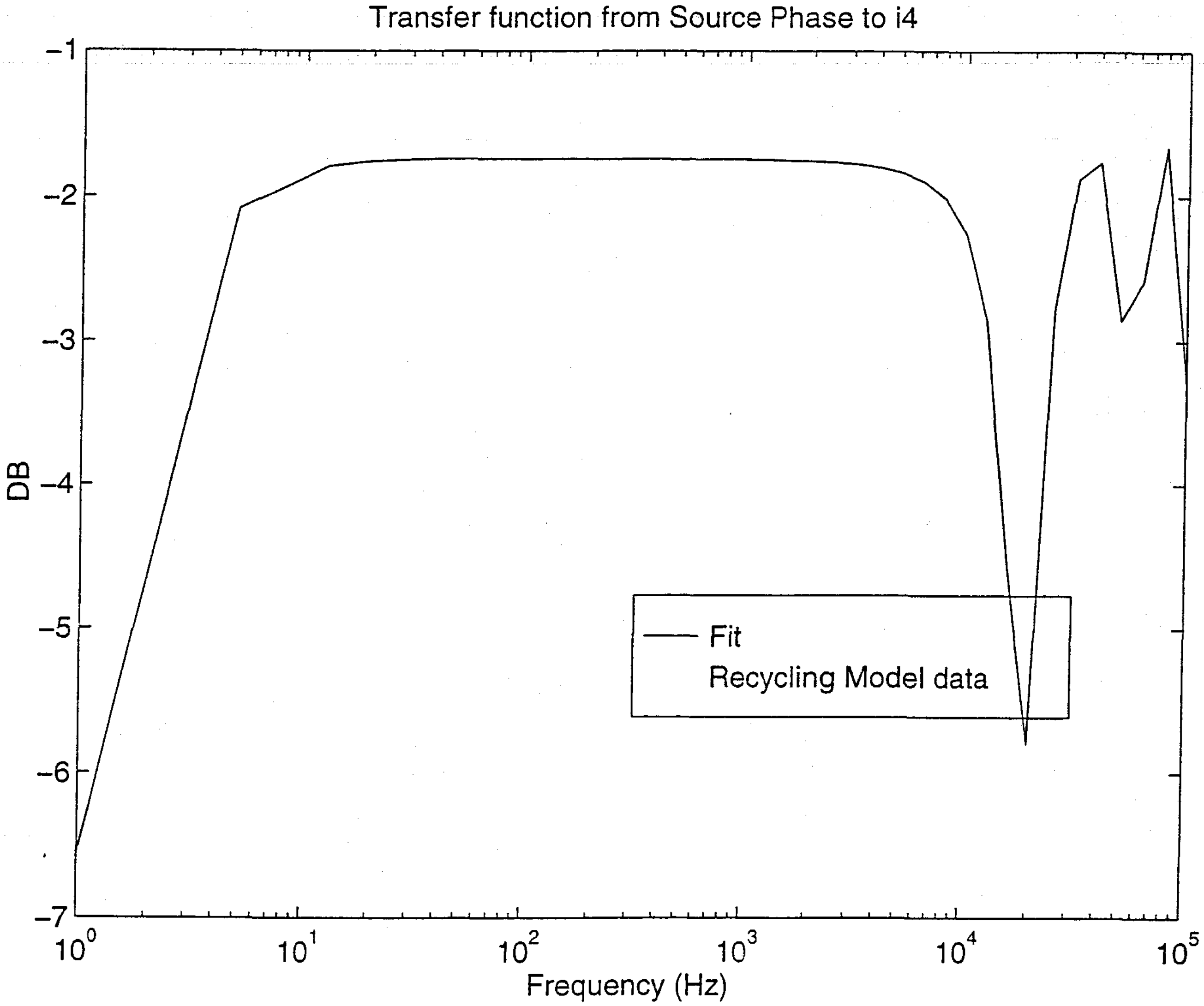


Transfer function from cm to i3

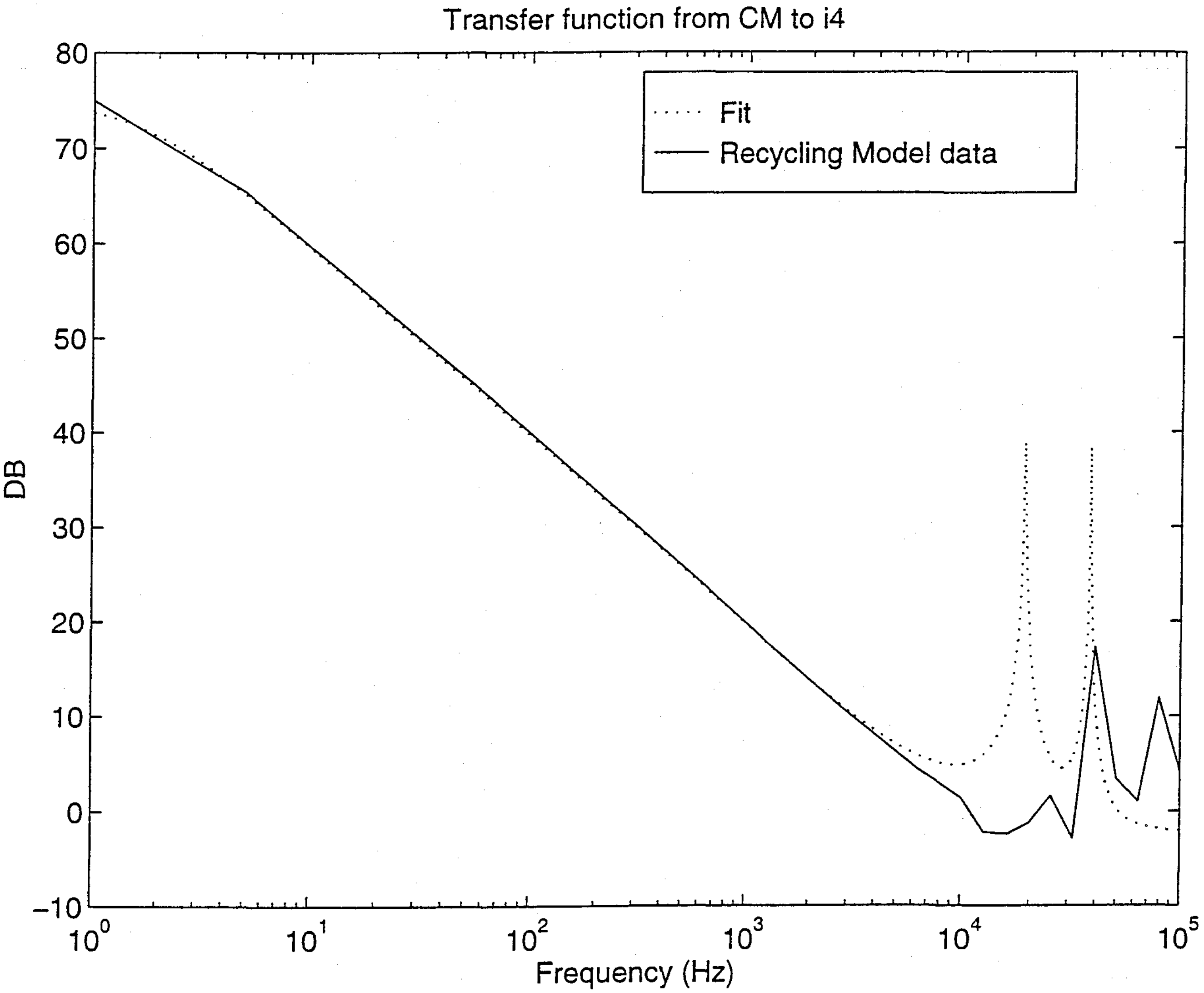

Transfer function from DM to i3
195
190
185
180
175
170
165
160
155
150
DB
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)
Fit
Recycling Model data


Transfer function from dm to i3
Fit
Recycling Model data
DB
180
170
160
150
140
130
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

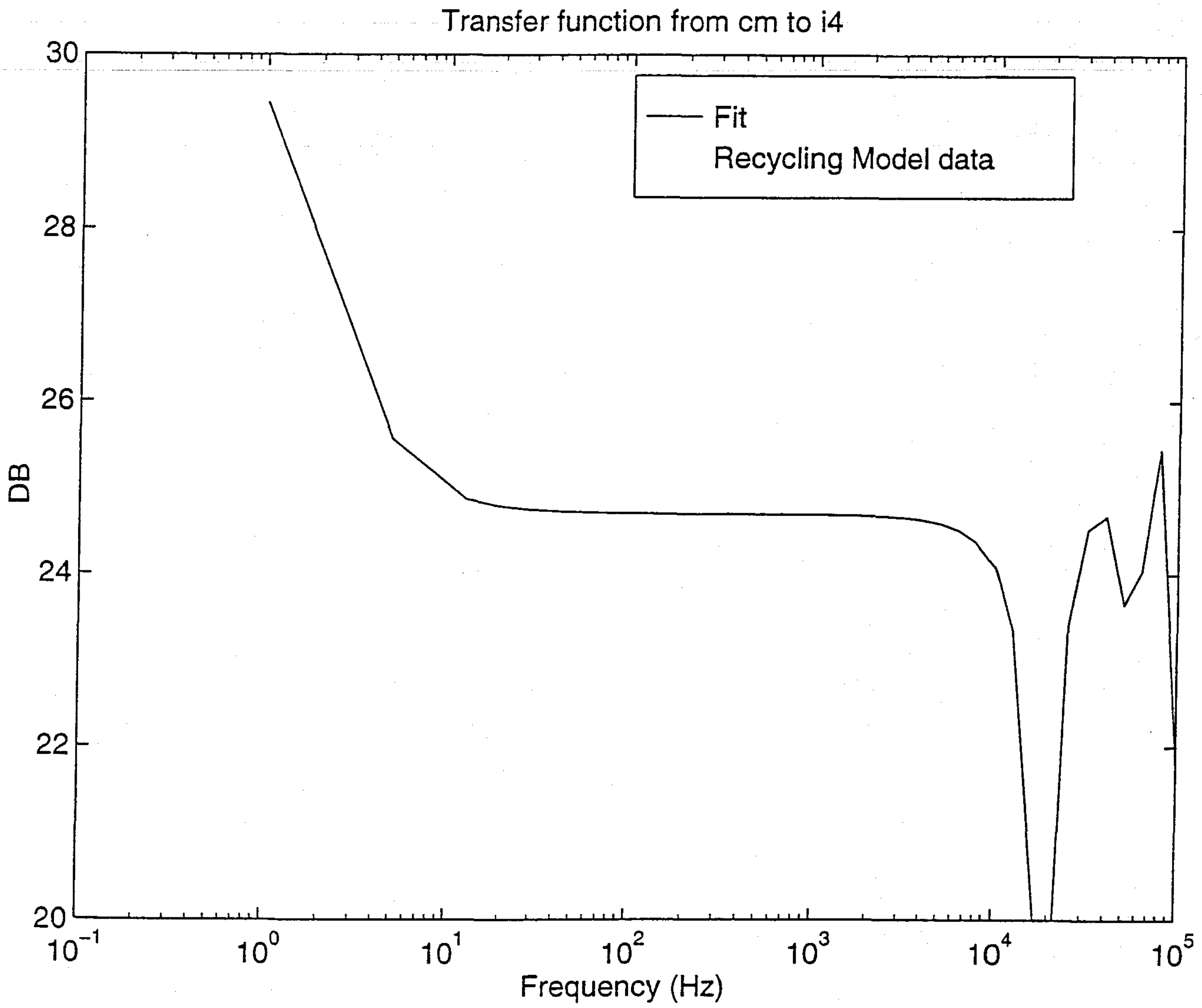

Transfer function from bs to i3
150
140
130
120
110
100
DB
Fit
Recycling Model data
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

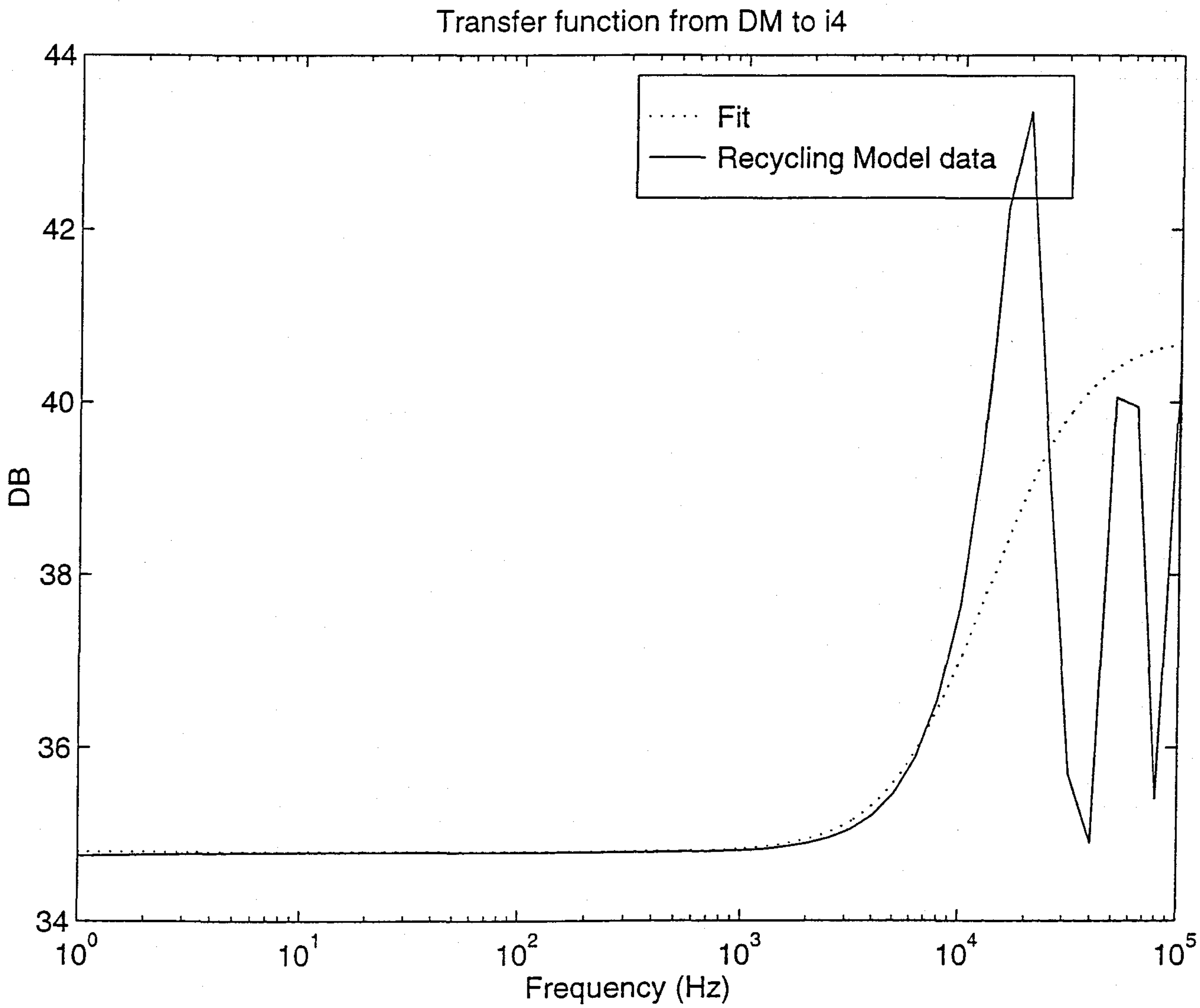


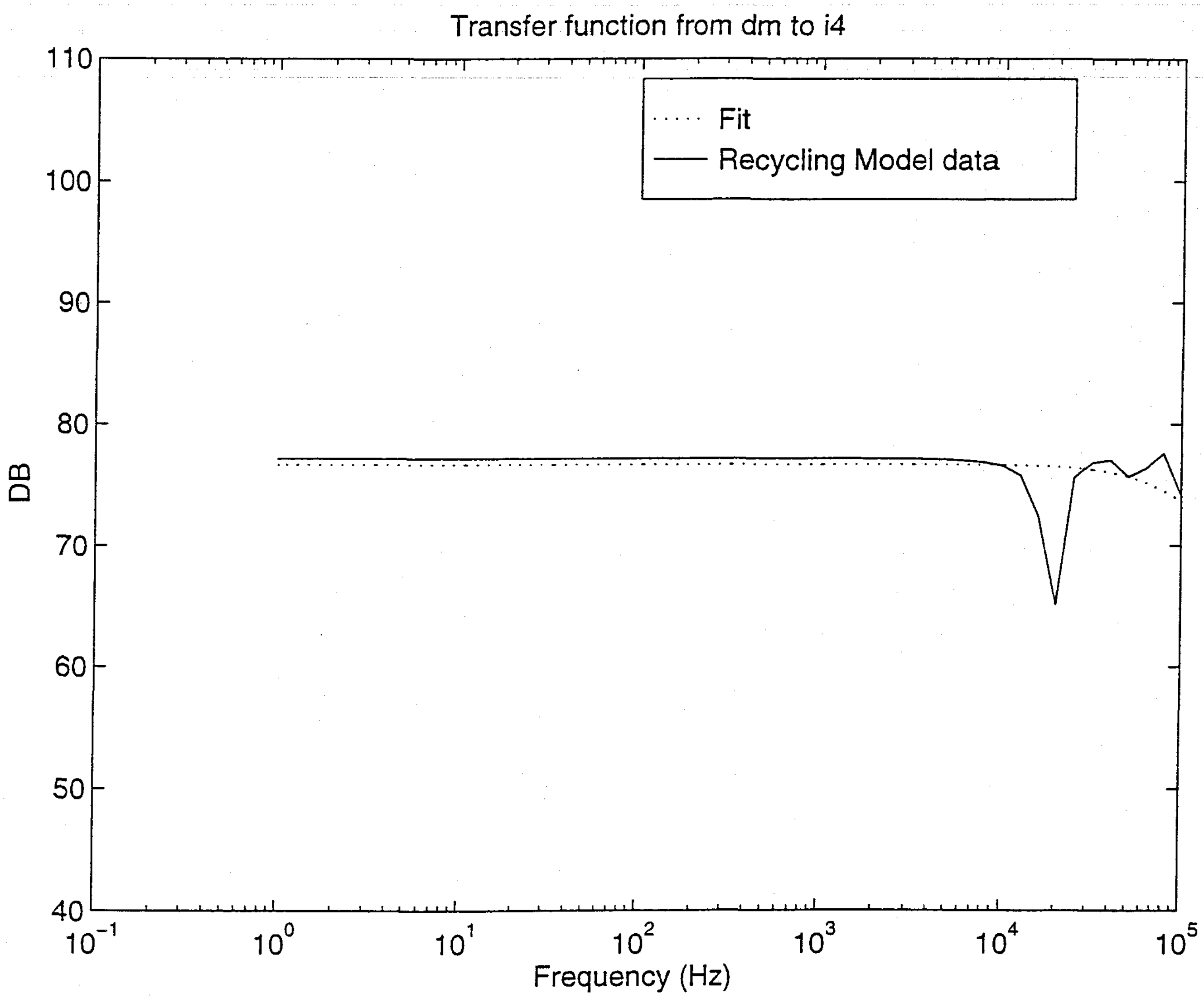
Transfer function from Source Phase to i4
DB
−1
−2
−3
−4
−5
−6
−7
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)
Fit
Recycling Model data



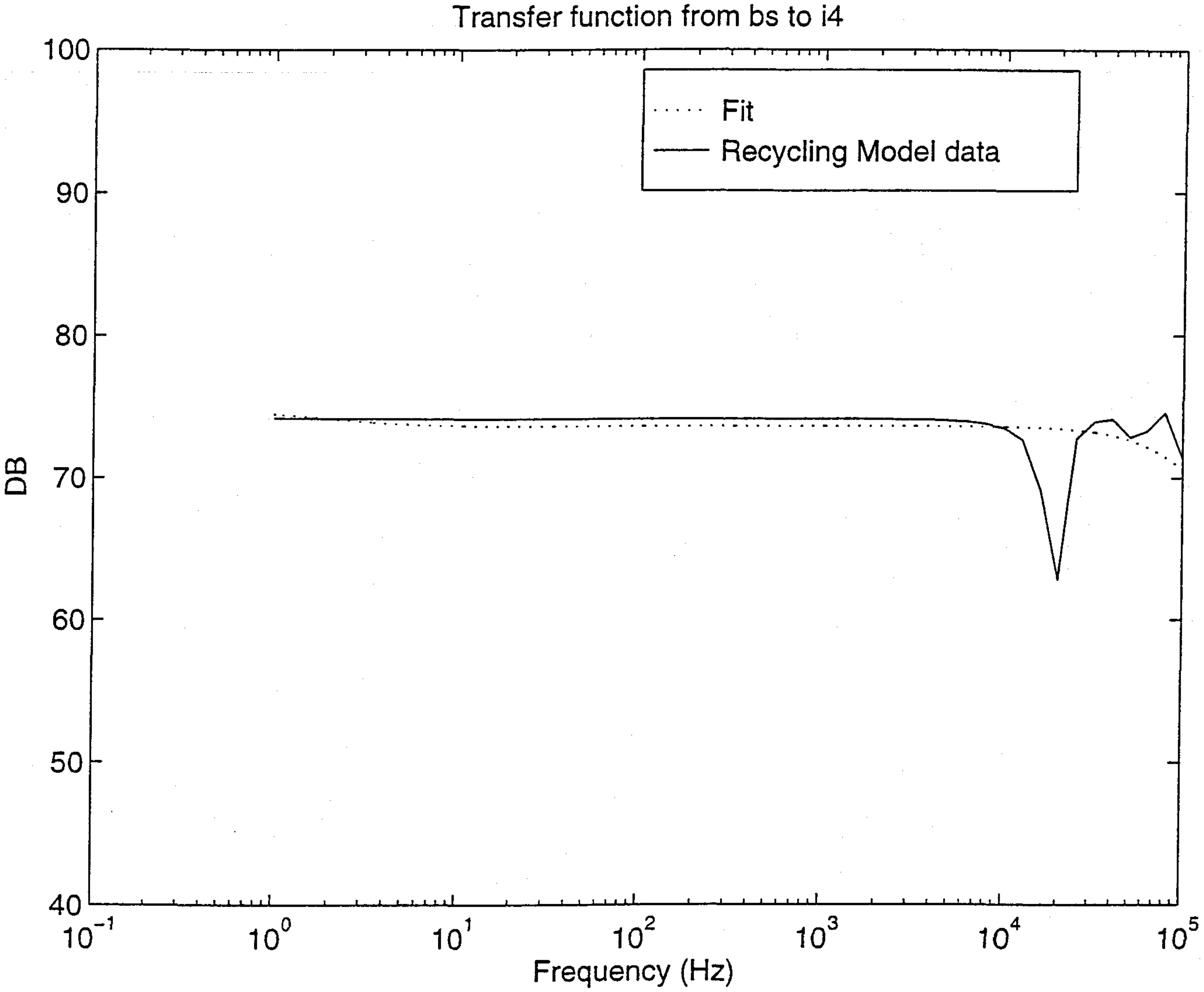
Transfer function from CM to i4
Fit
Recycling Model data
DB
80
70
60
50
40
30
20
10
0
−10
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)


Transfer function from cm to i4
Fit
Recycling Model data
30
28
26
24
22
20
DB
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Frequency (Hz)

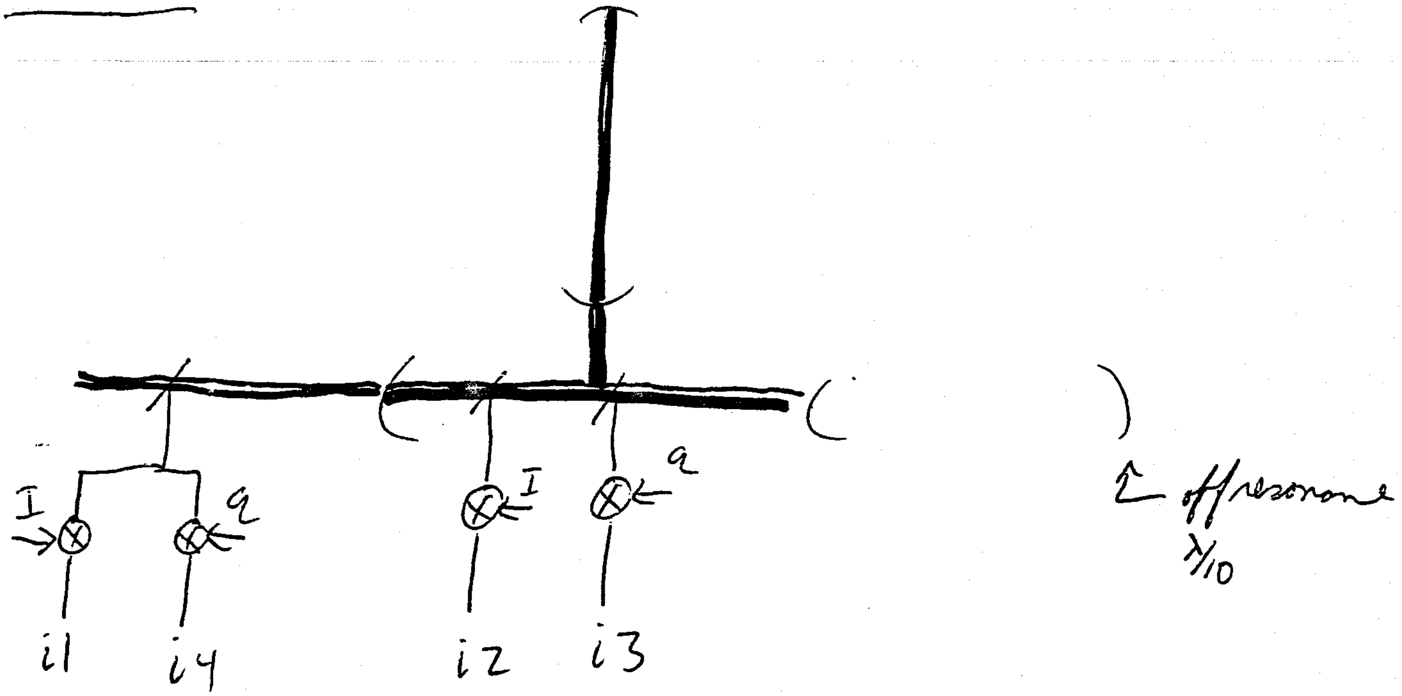

Transfer function from DM to i4
Fit
Recycling Model data
DB
44
42
40
38
36
34
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)



Transfer function from dm to i4
Fit
Recycling Model data
DB
110
100
90
80
70
60
50
40
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Frequency (Hz)

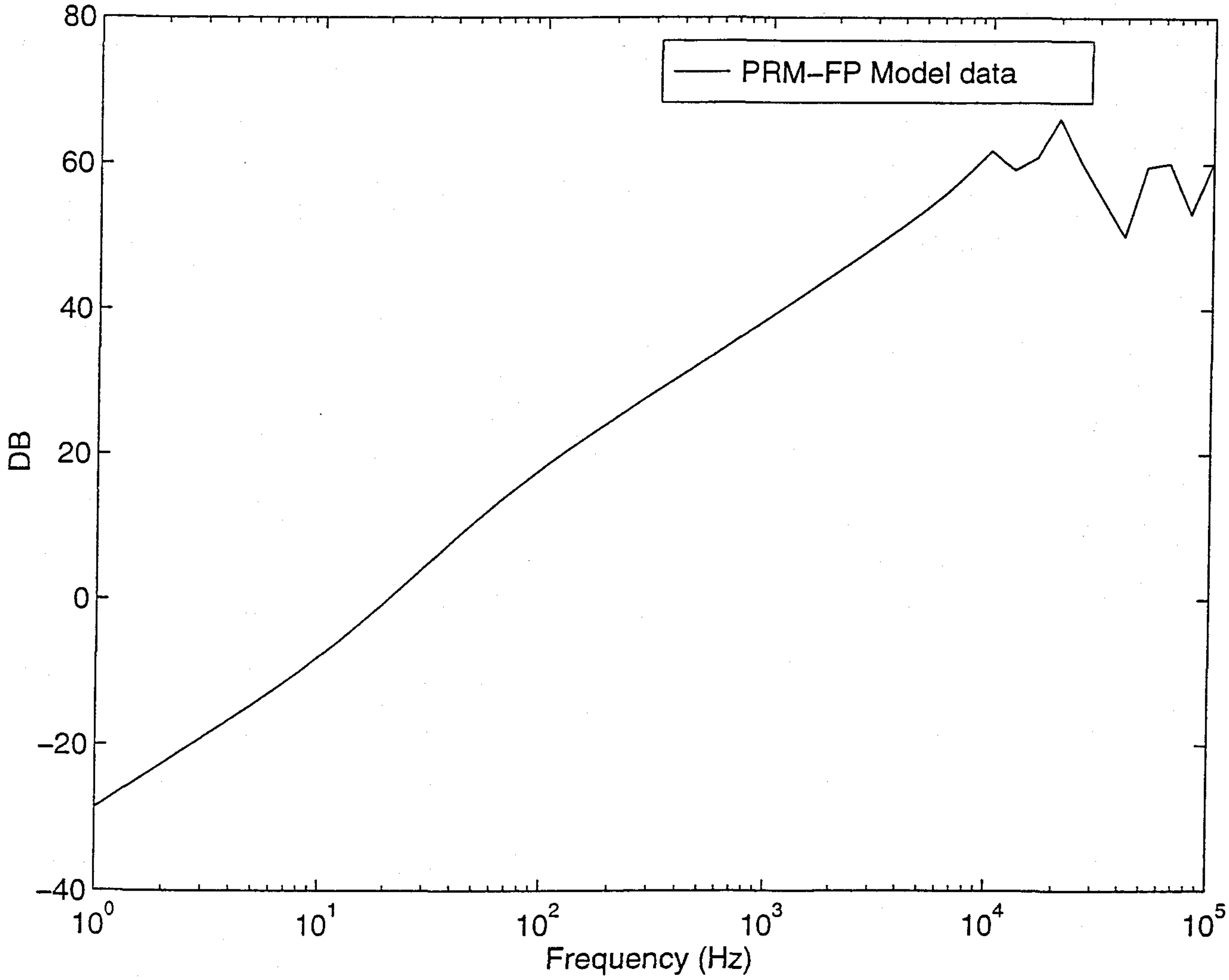

Transfer function from bs to i4
Fit
Recycling Model data
DB
100
90
80
70
60
50
40
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Frequency (Hz)

Appendix 2 PRM-FP* Transfer Fctns

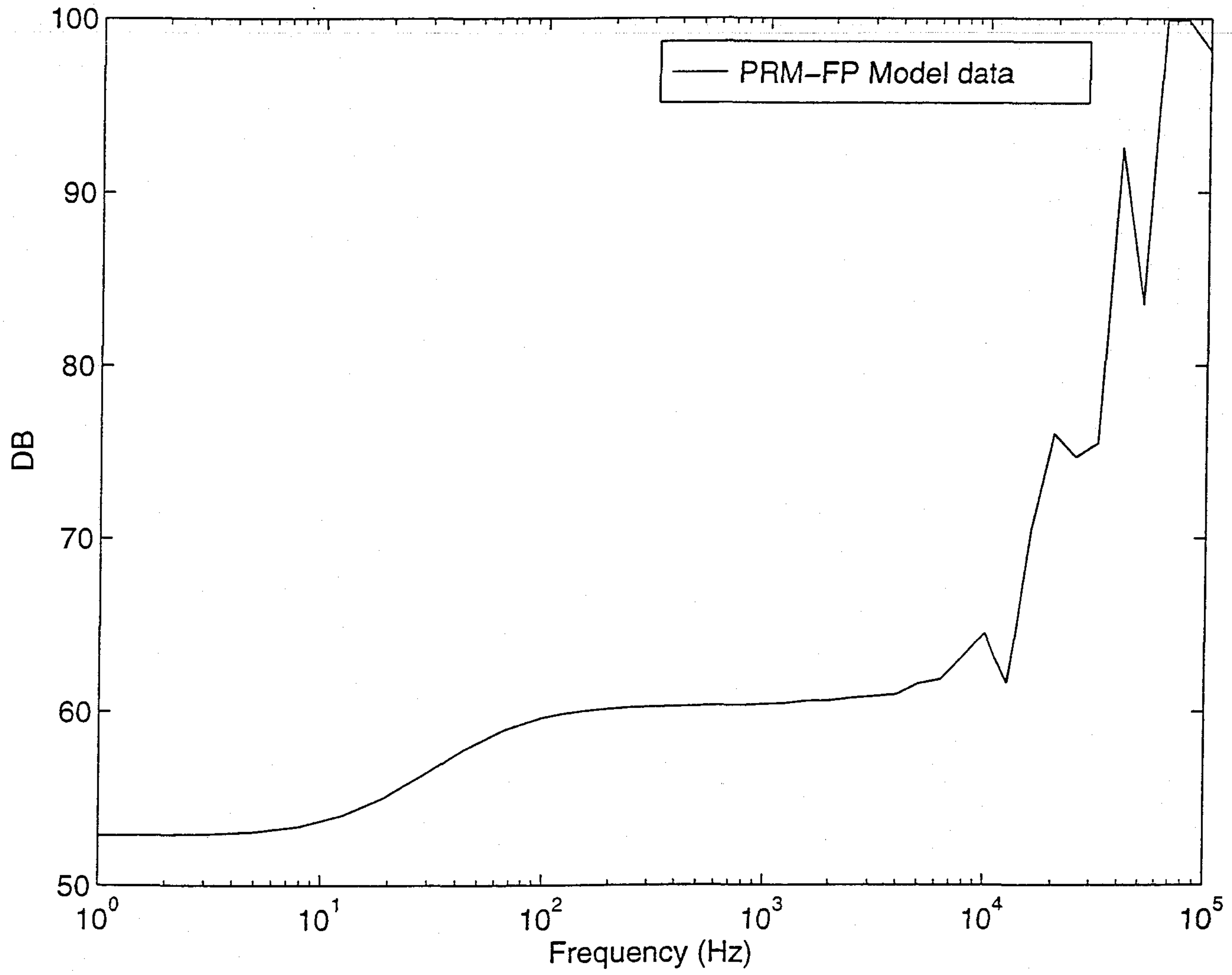


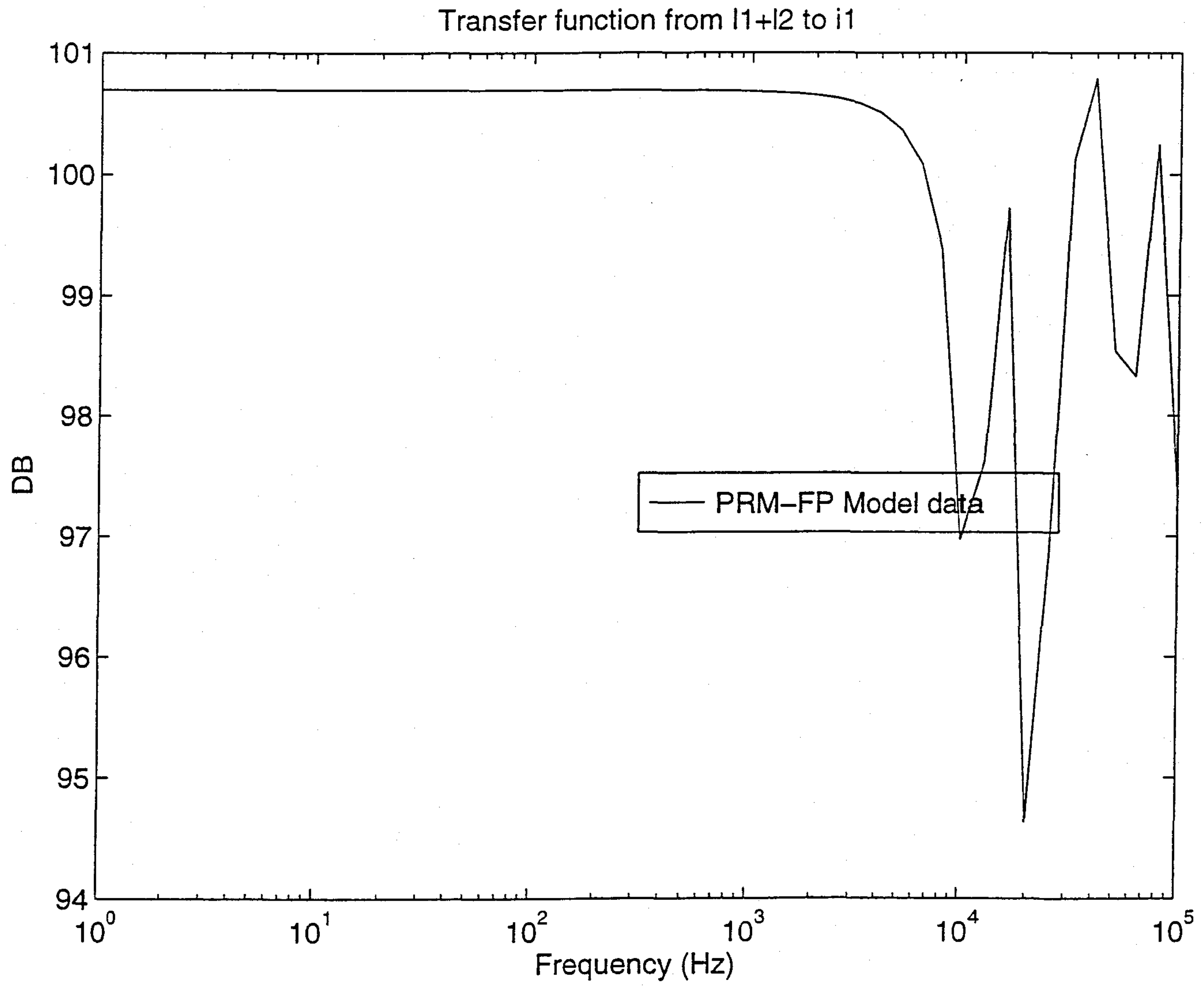
*PRM-FP stands for the configuration where the sidebands are resonant in the Power Recycled Michelson and the carrier is resonant in one of the arms Fabry Perot cavities

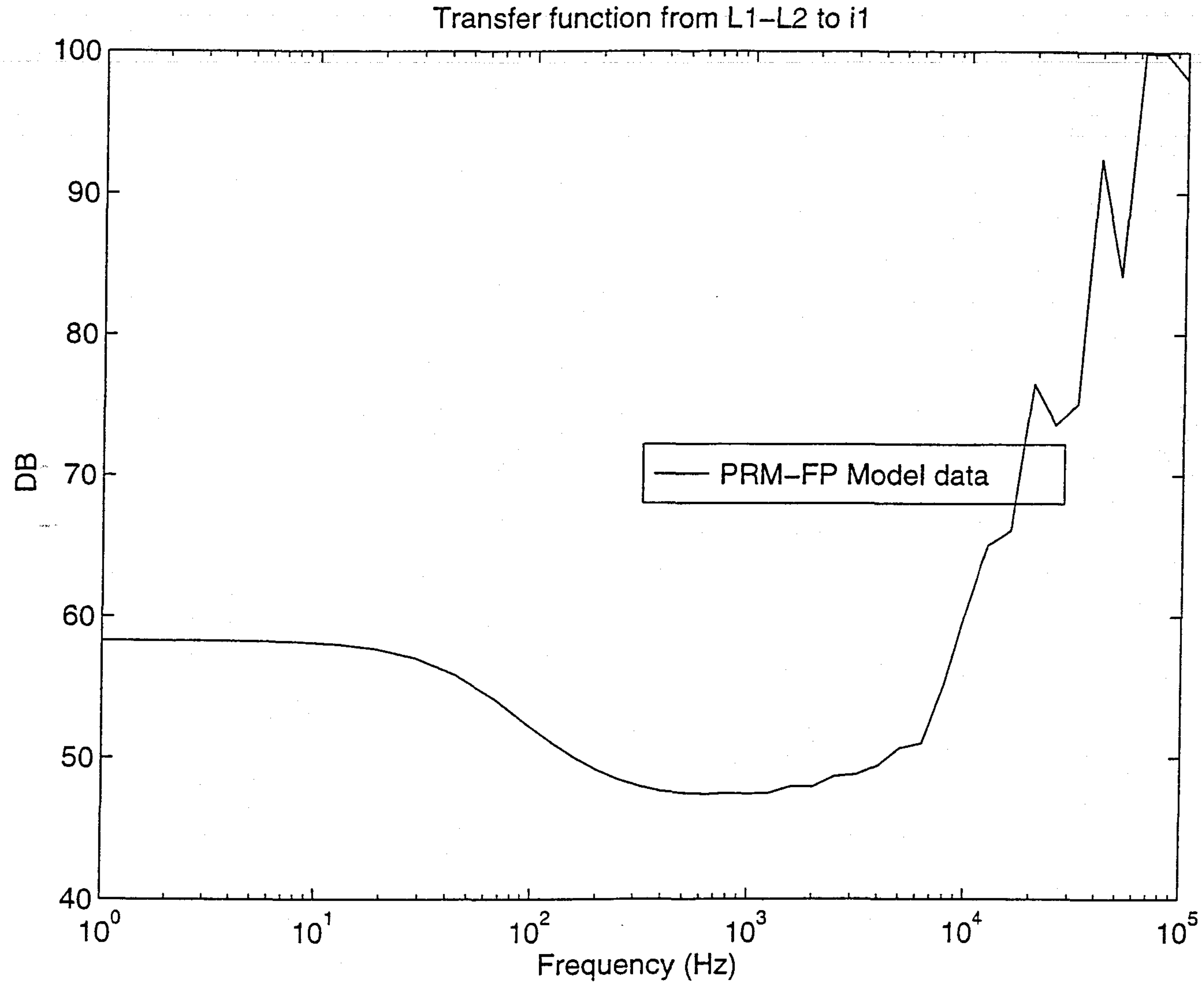
Transfer function from Source Phase to i1

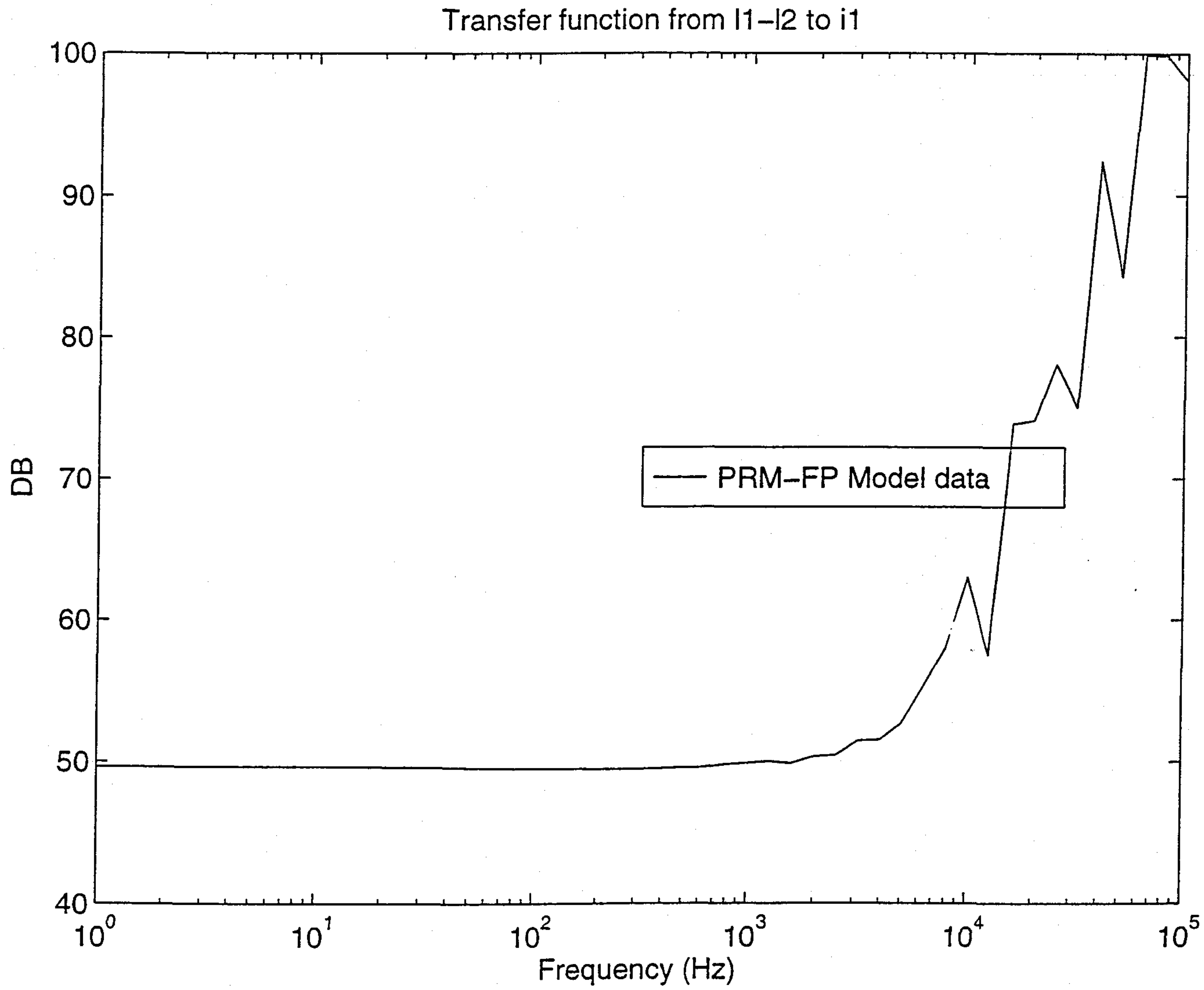


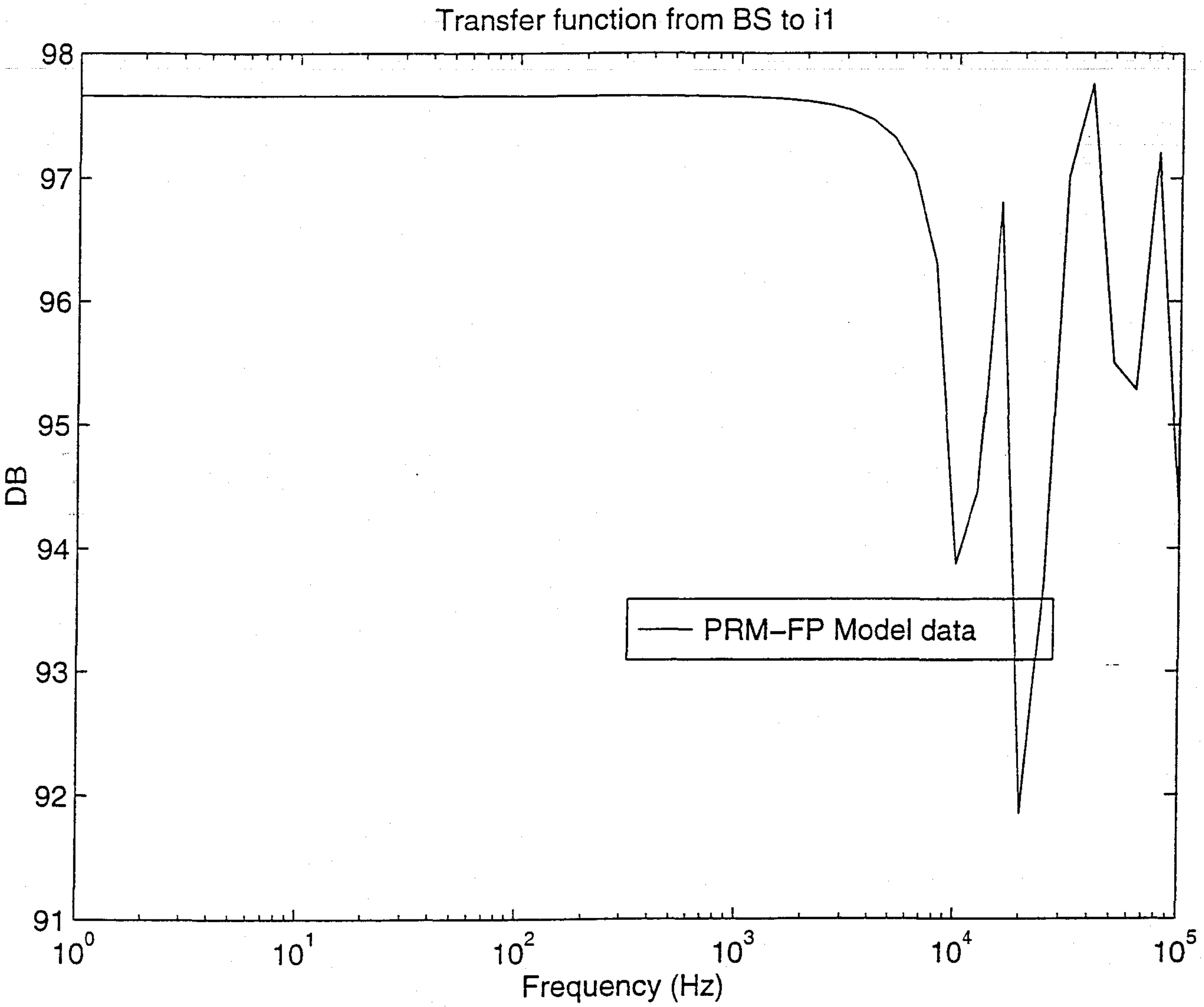
Transfer function from L1+L2 to i1

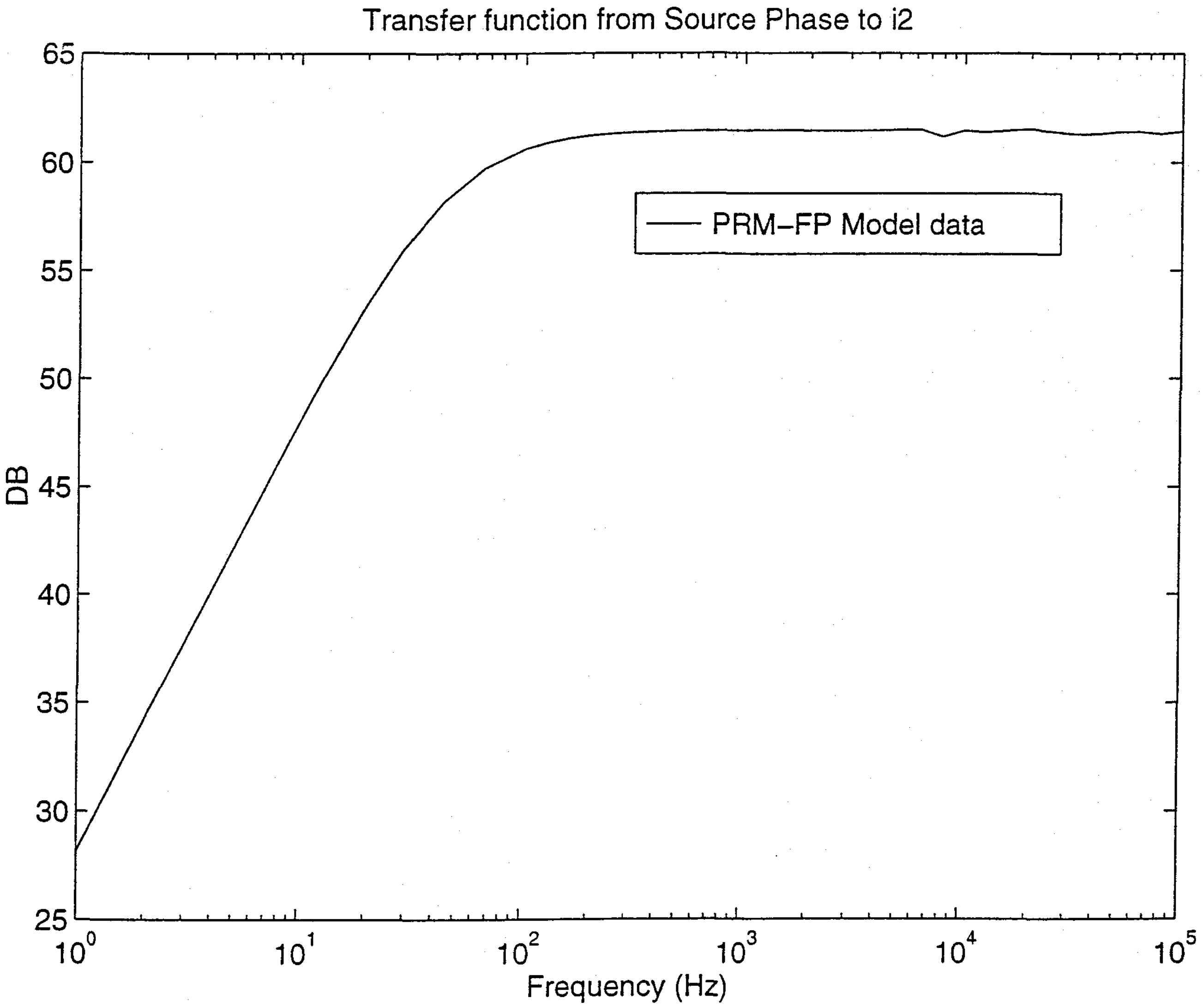


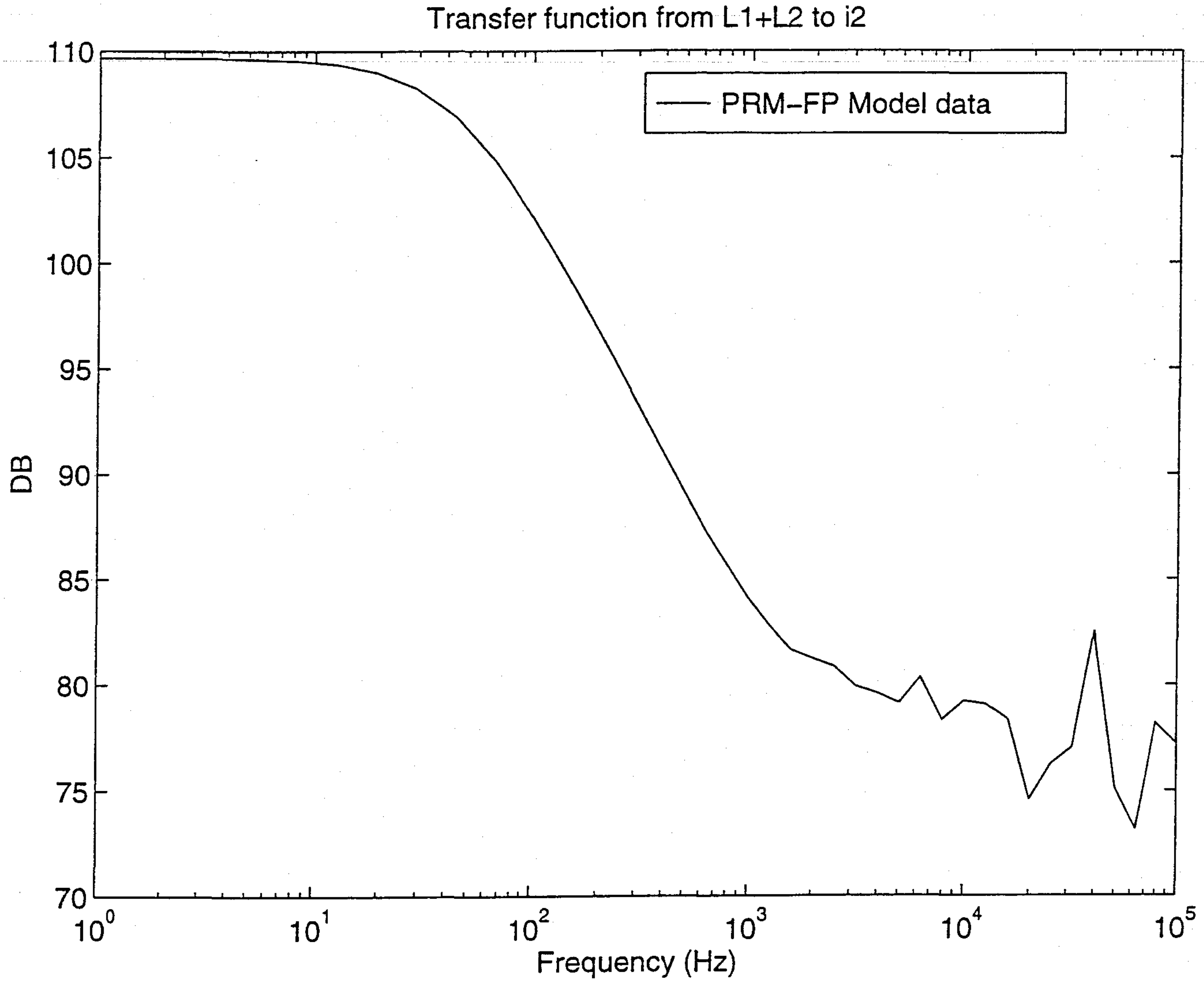

Transfer function from l1+l2 to i1
101
100
99
98
97
96
95
94
DB
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)
PRM−FP Model data

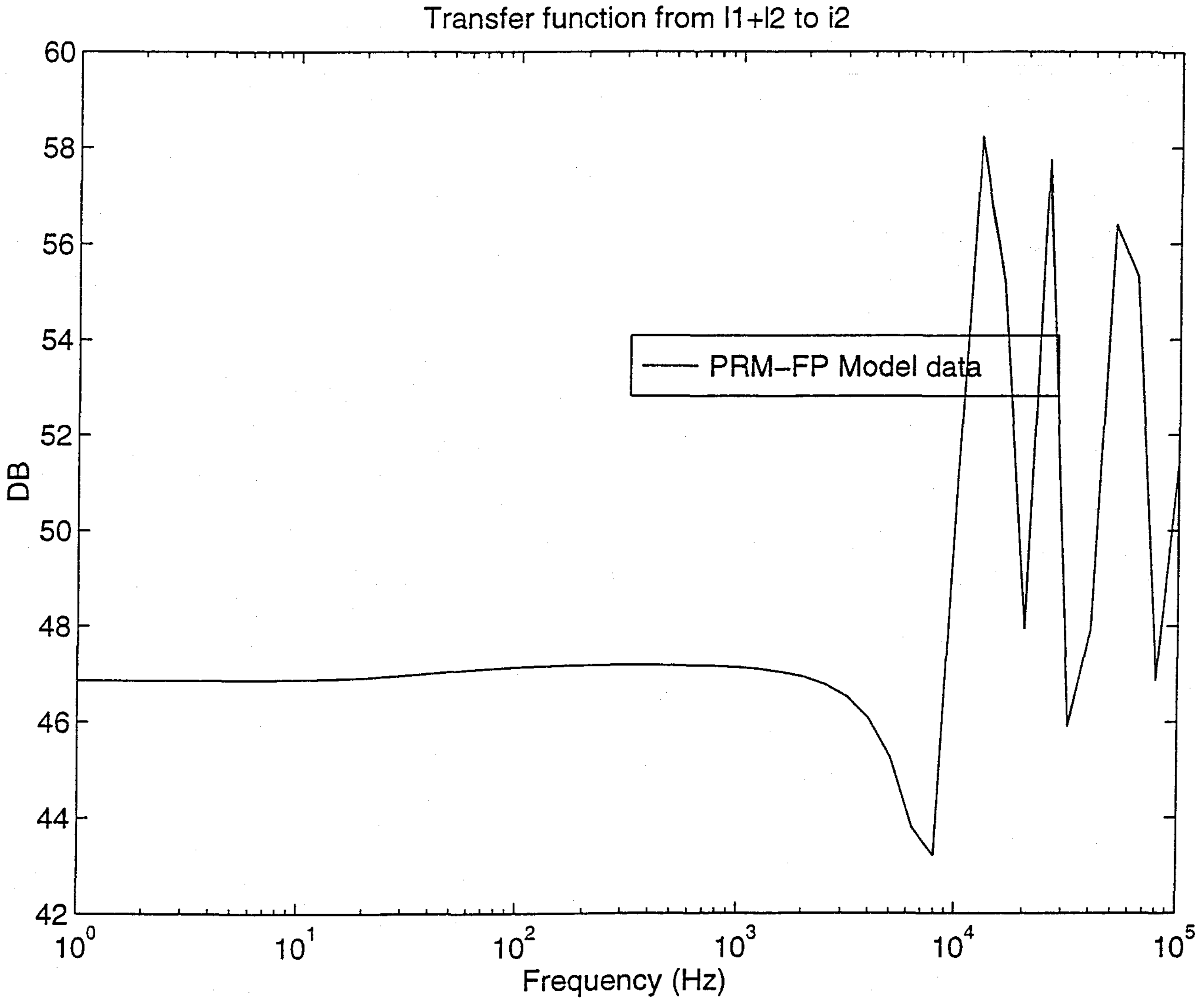

Transfer function from L1−L2 to i1
DB
Frequency (Hz)
PRM−FP Model data
100
90
80
70
60
50
40
10^0
10^1
10^2
10^3
10^4
10^5

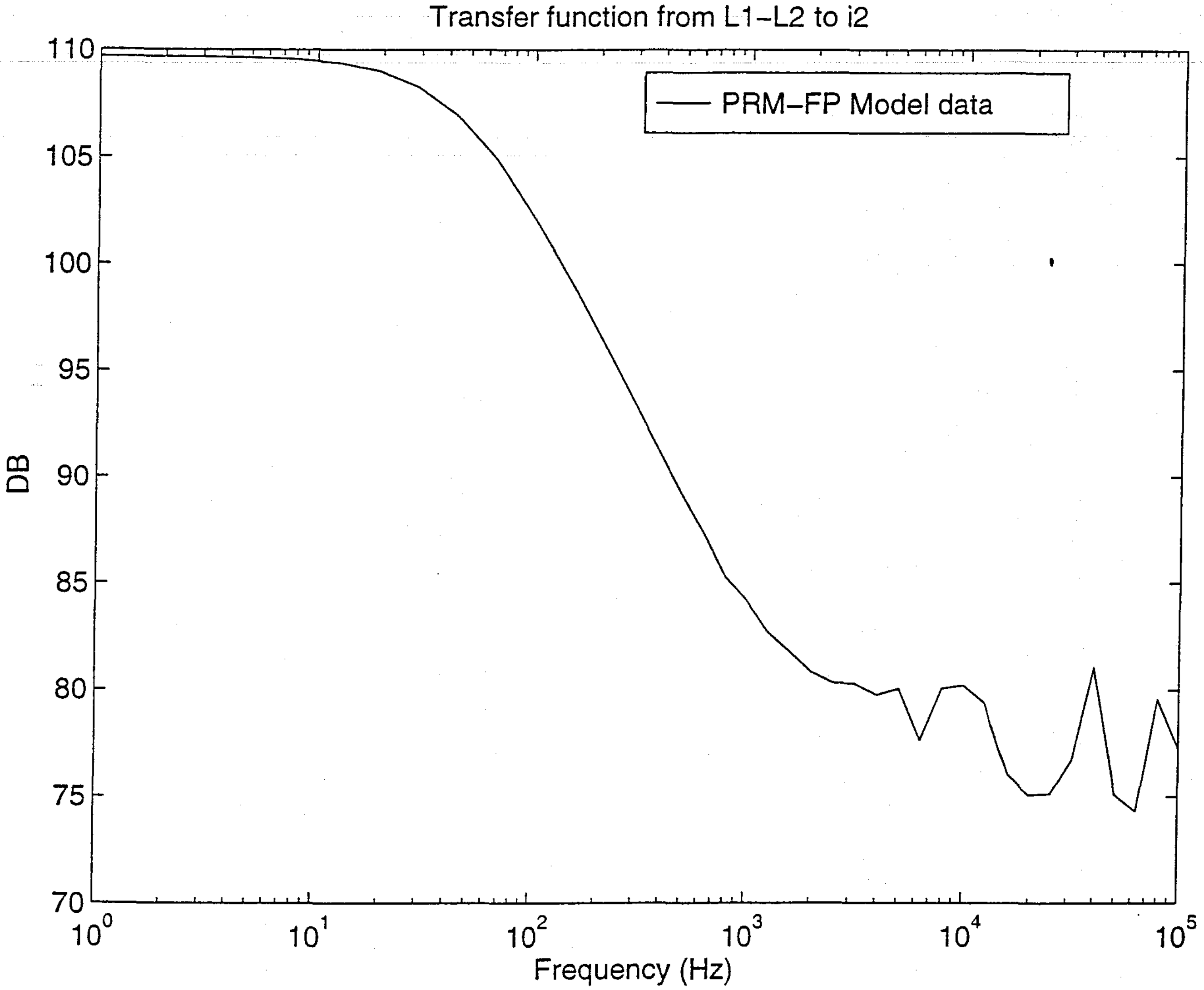

Transfer function from I1−I2 to i1
DB
100
90
80
70
60
50
40
Frequency (Hz)
10^0
10^1
10^2
10^3
10^4
10^5
PRM−FP Model data

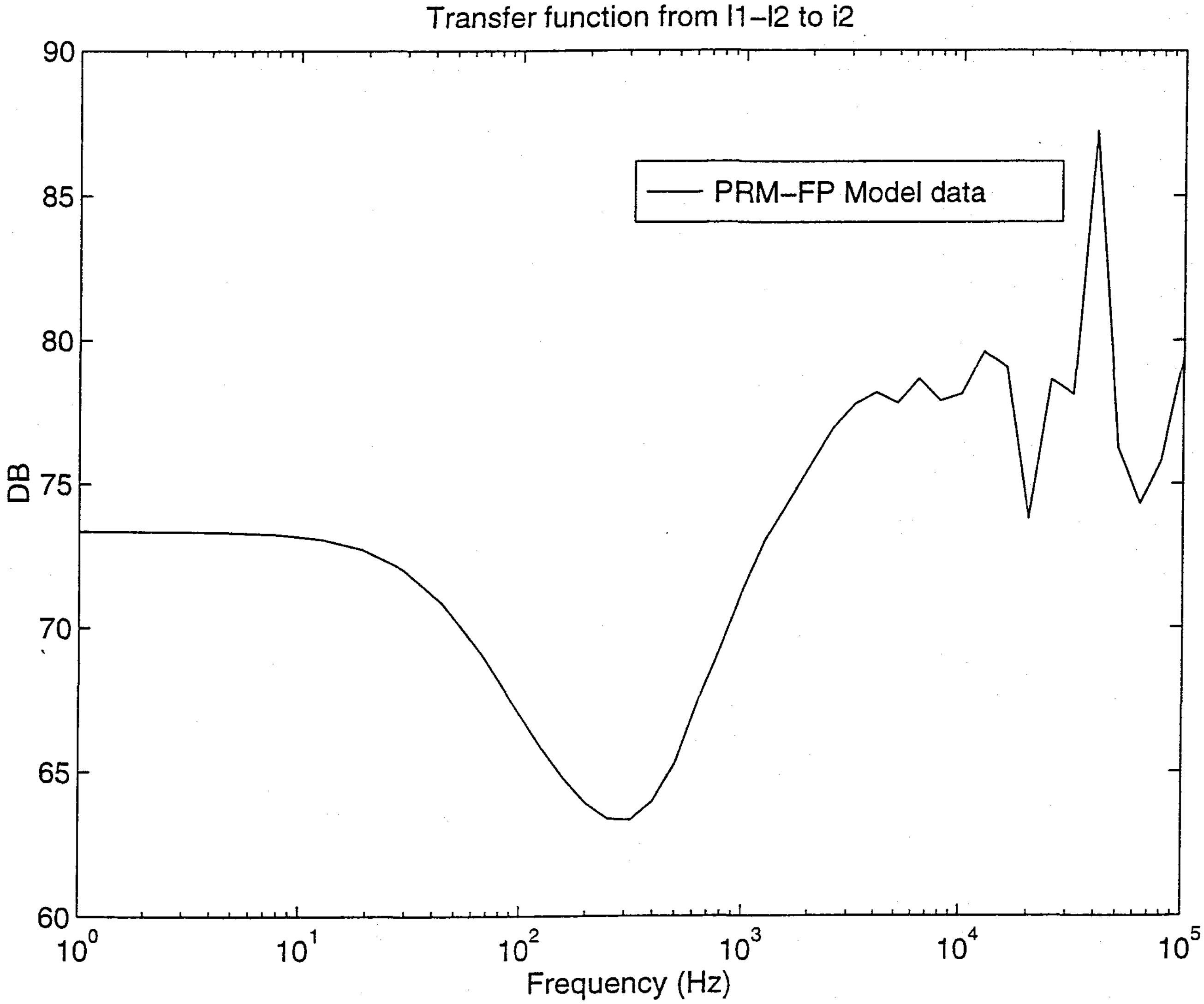

Transfer function from BS to i1
98
97
96
95
94
93
92
91
DB
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)
PRM−FP Model data

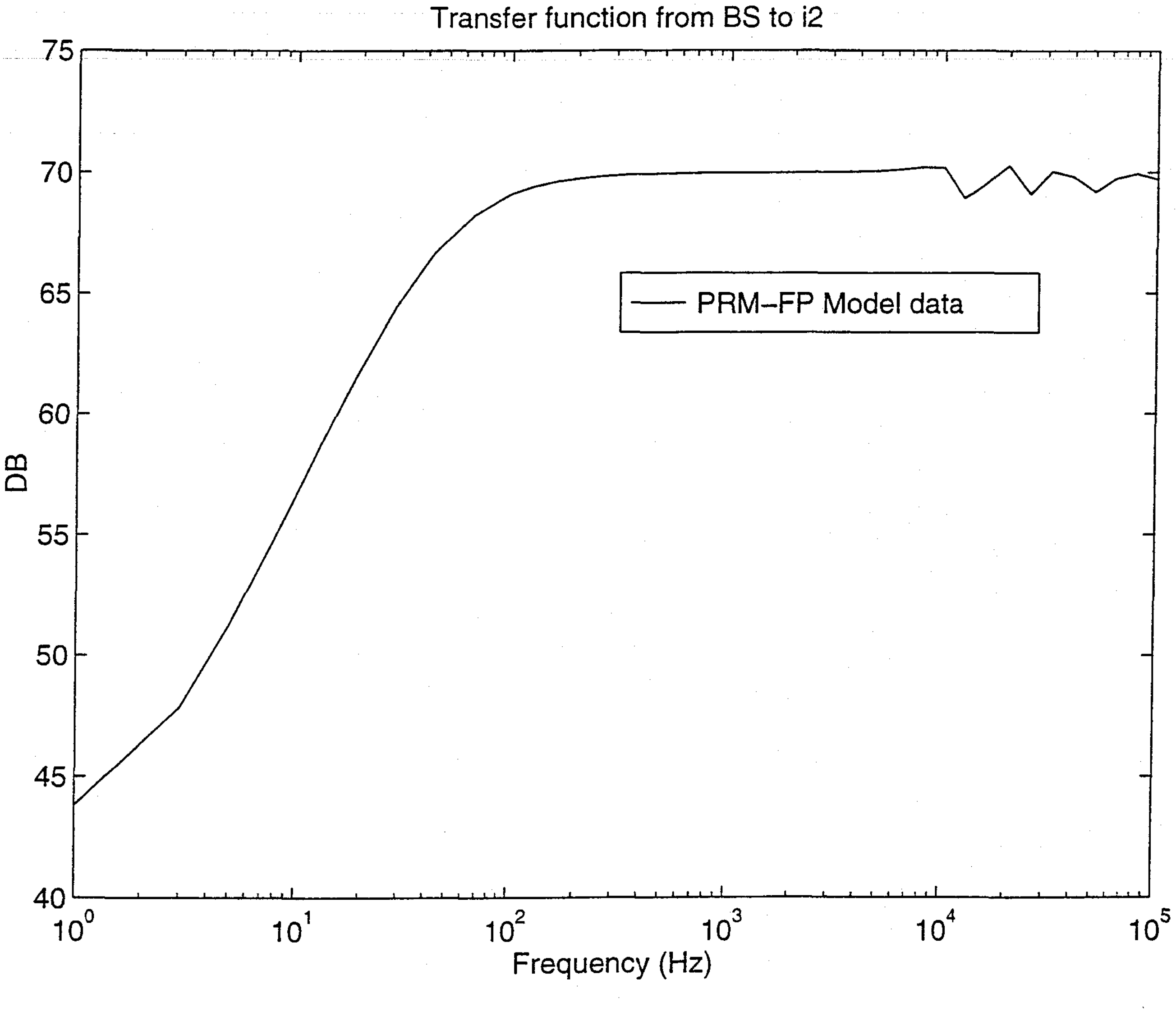

Transfer function from Source Phase to i2
PRM−FP Model data
DB
65
60
55
50
45
40
35
30
25
Frequency (Hz)
10^0
10^1
10^2
10^3
10^4
10^5

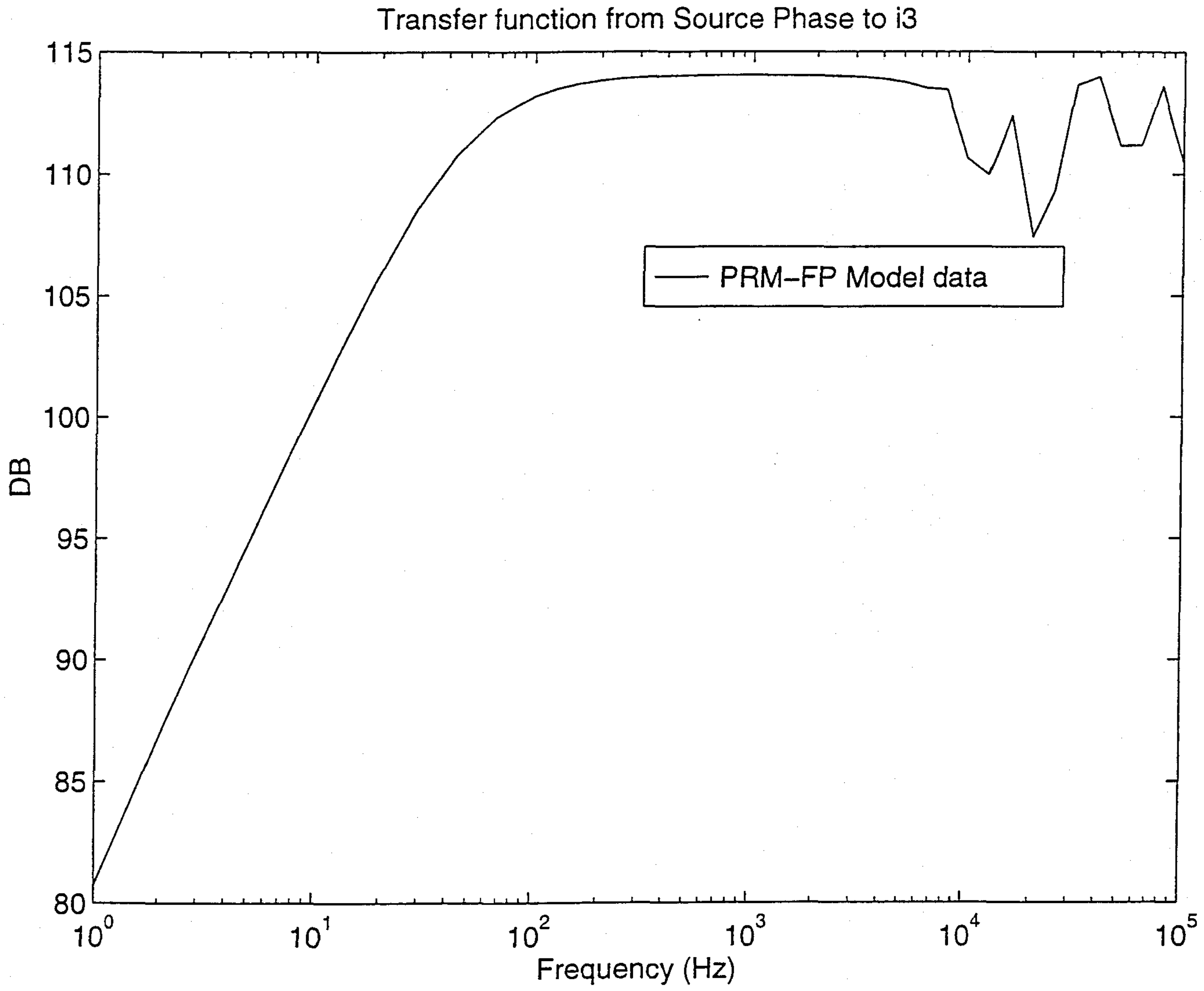

Transfer function from L1+L2 to i2
PRM−FP Model data
DB
110
105
100
95
90
85
80
75
70
Frequency (Hz)
10^0
10^1
10^2
10^3
10^4
10^5

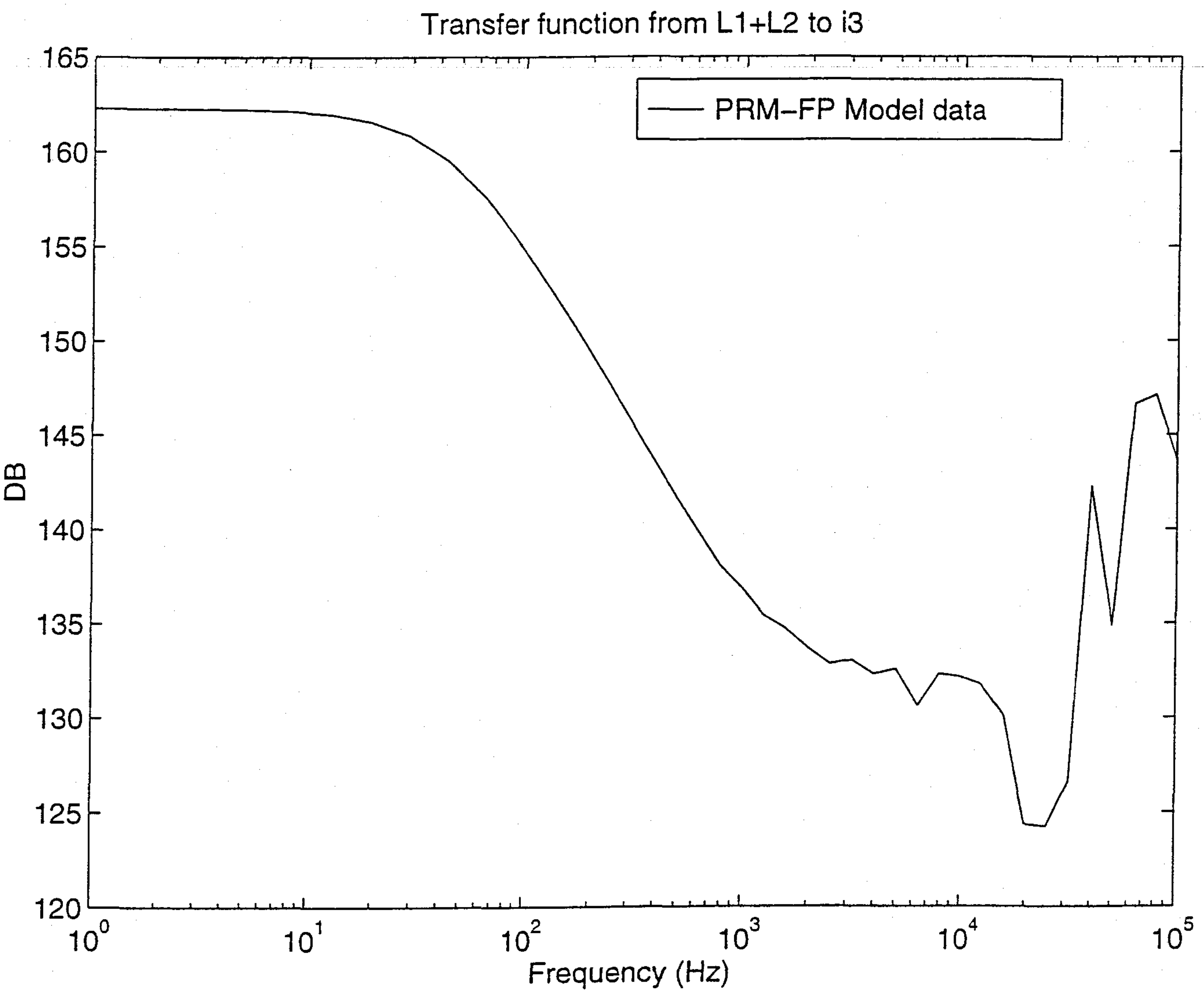

Transfer function from I1+I2 to i2
60
58
56
54
52
50
48
46
44
42
DB
PRM−FP Model data
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

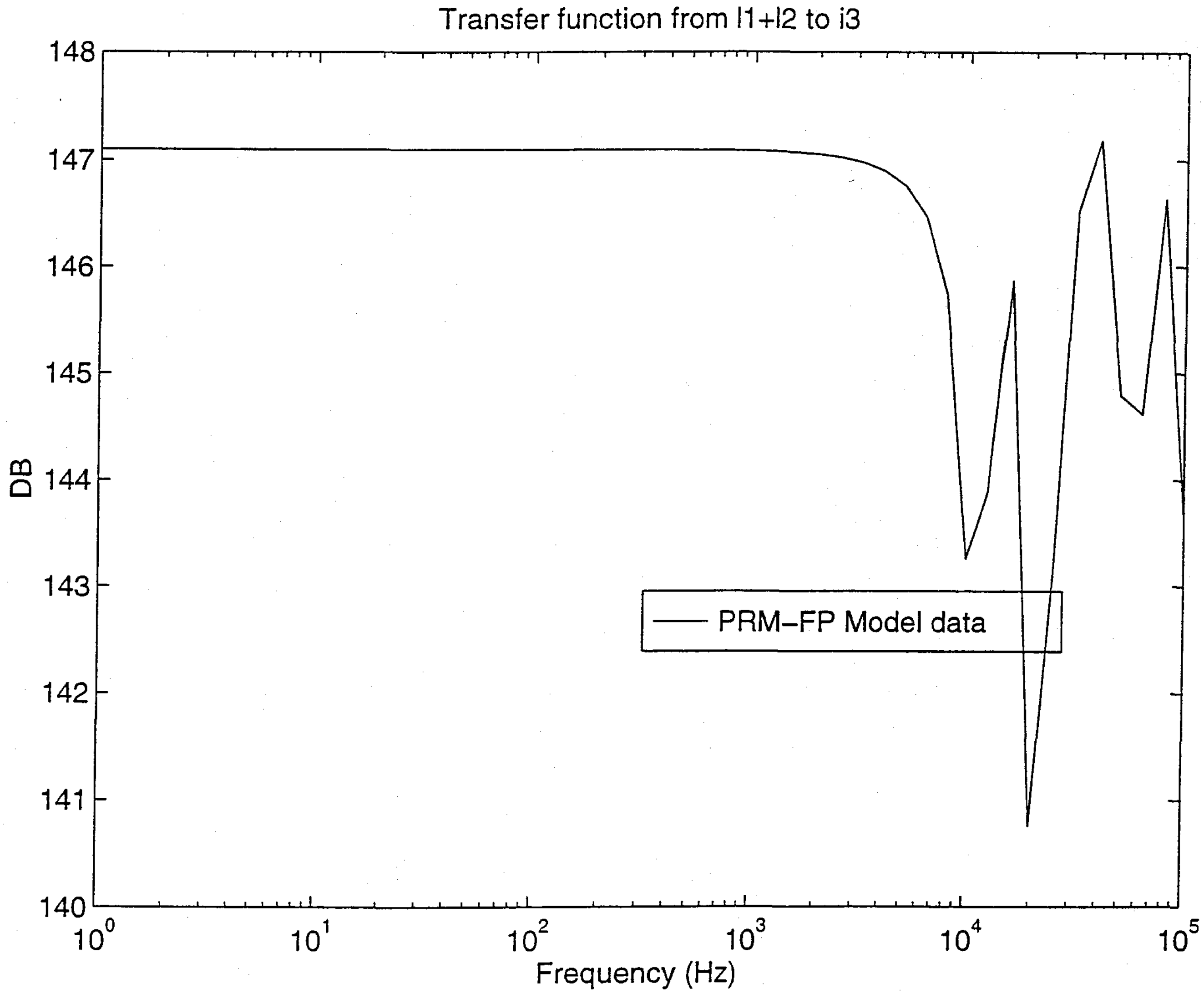

Transfer function from L1−L2 to i2
PRM−FP Model data
DB
110
105
100
95
90
85
80
75
70
Frequency (Hz)
10^0
10^1
10^2
10^3
10^4
10^5

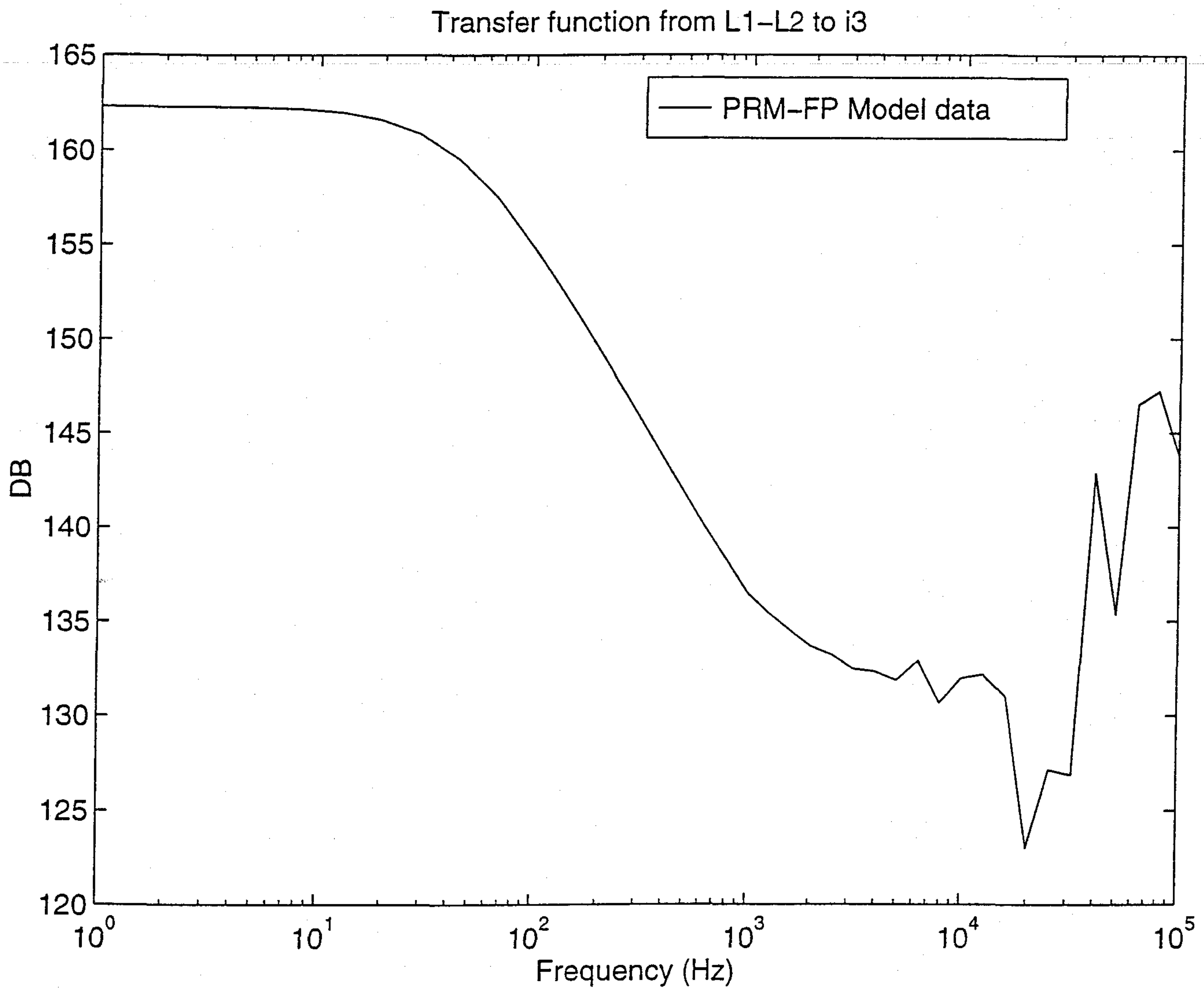

Transfer function from I1−I2 to i2
PRM−FP Model data
DB
90
85
80
75
70
65
60
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

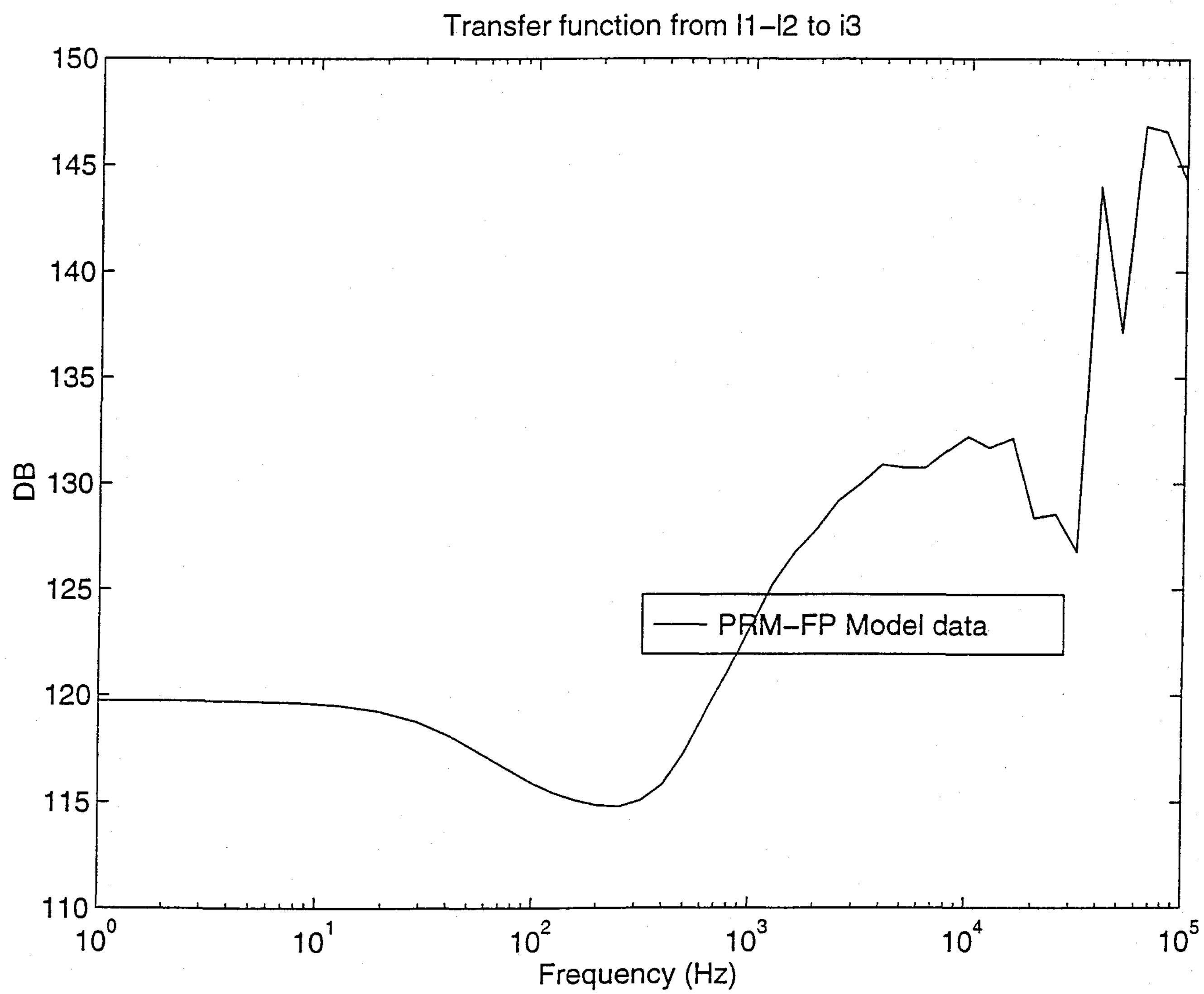

Transfer function from BS to i2
75
70
65
60
55
50
45
40
DB
PRM–FP Model data
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

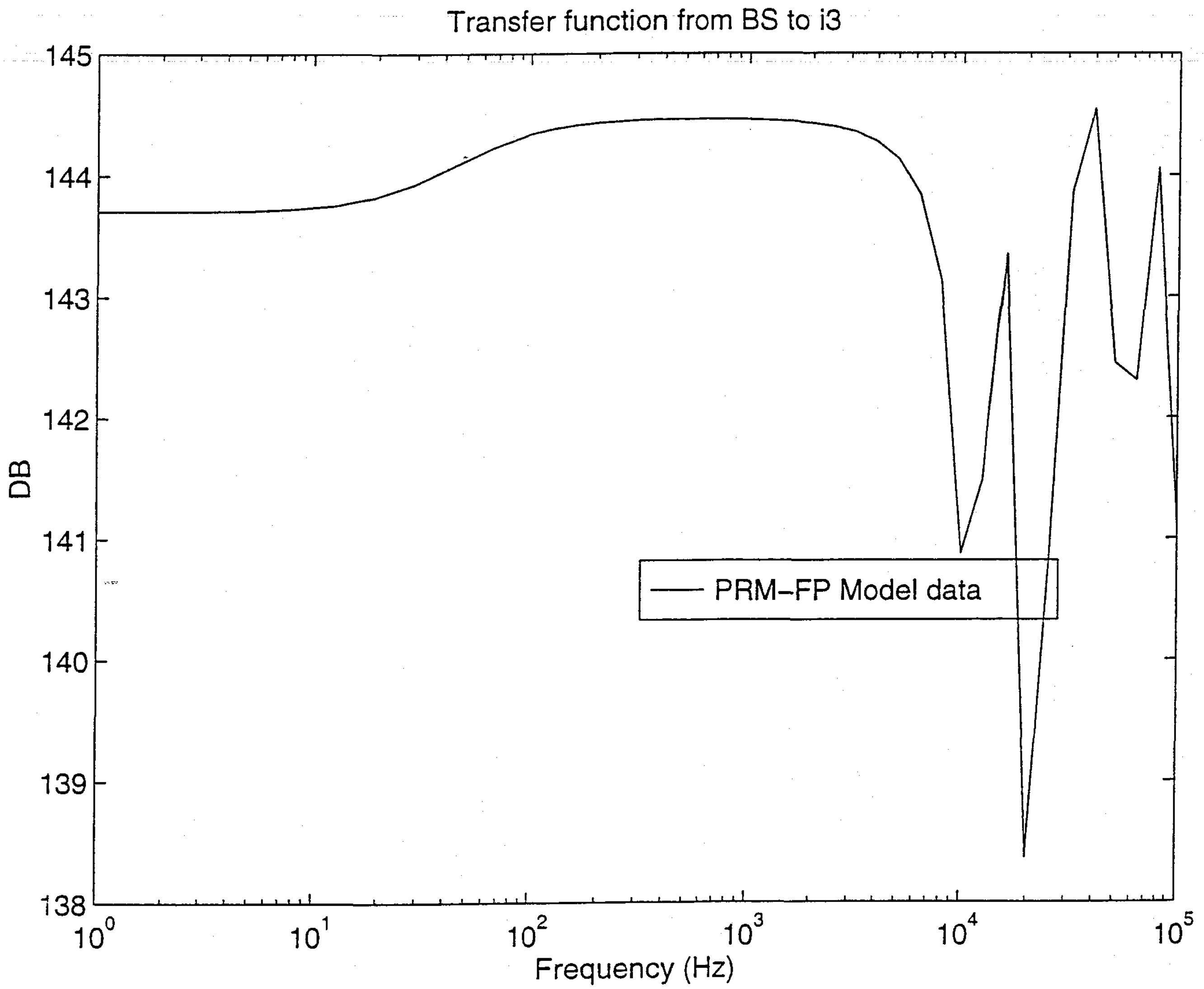

Transfer function from Source Phase to i3
115
110
105
100
95
90
85
80
DB
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)
PRM–FP Model data

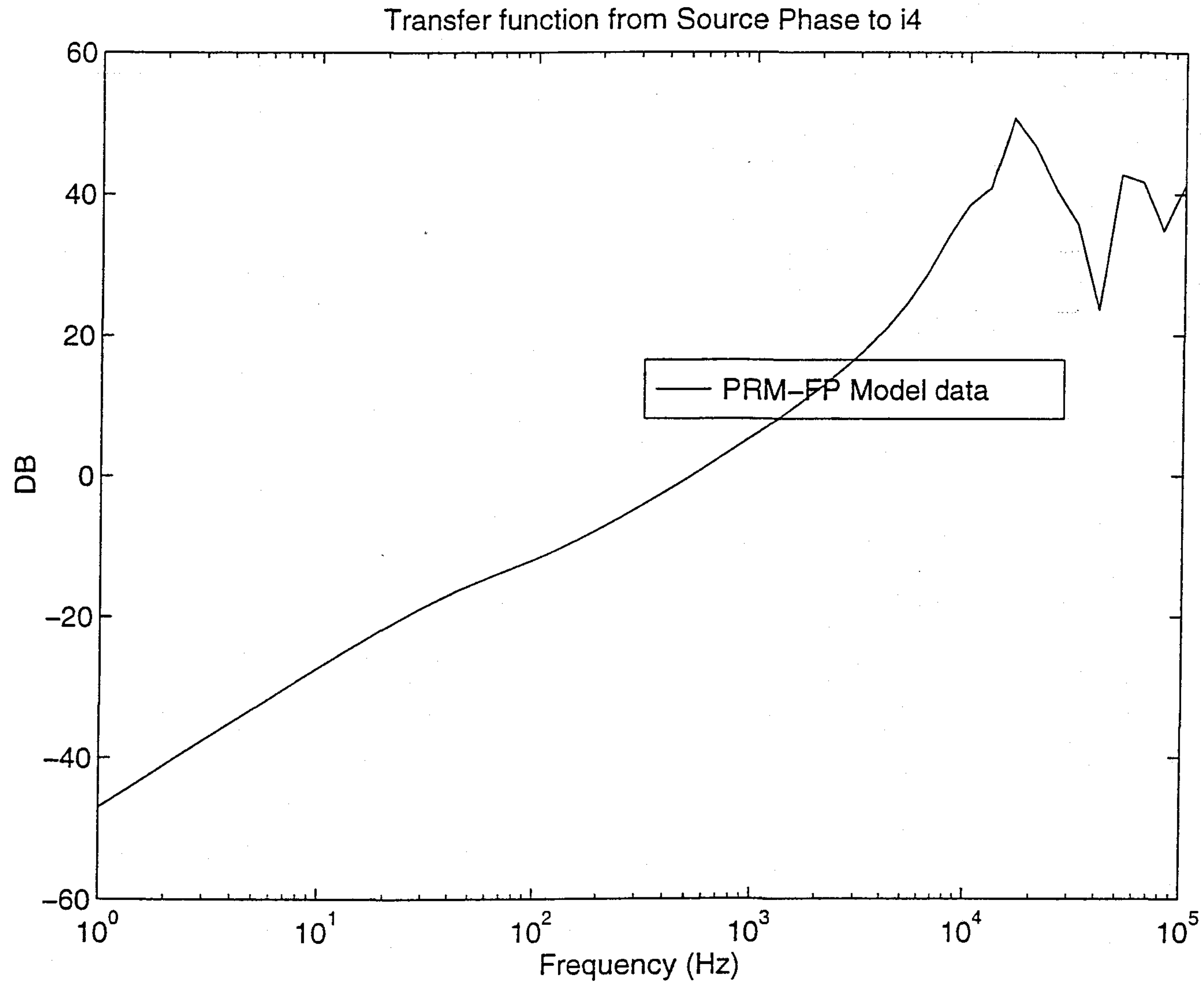

Transfer function from L1+L2 to i3
PRM–FP Model data
165
160
155
150
145
140
135
130
125
120
DB
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)

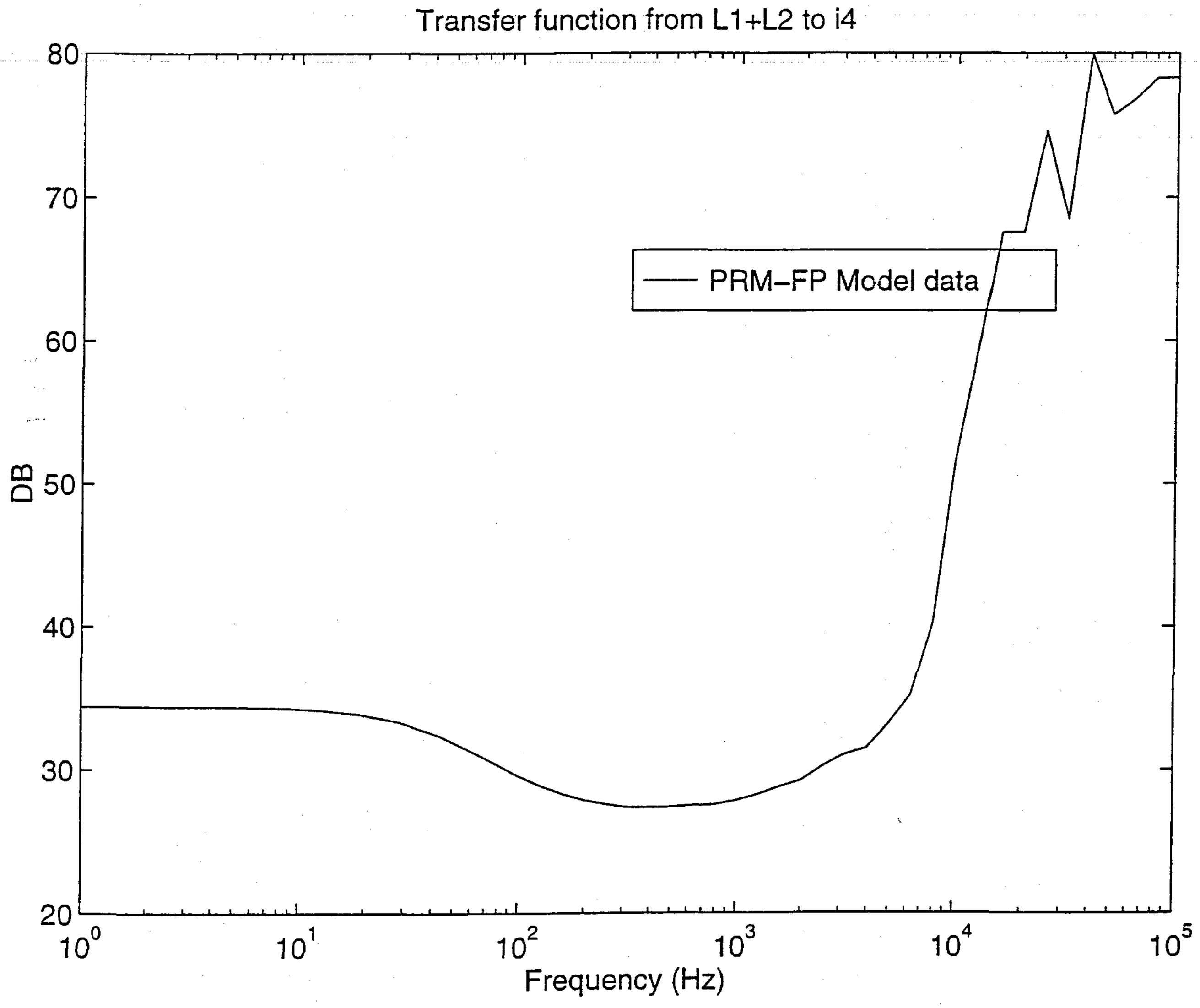

Transfer function from I1+I2 to i3
148
147
146
145
144
143
142
141
140
DB
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)
PRM-FP Model data

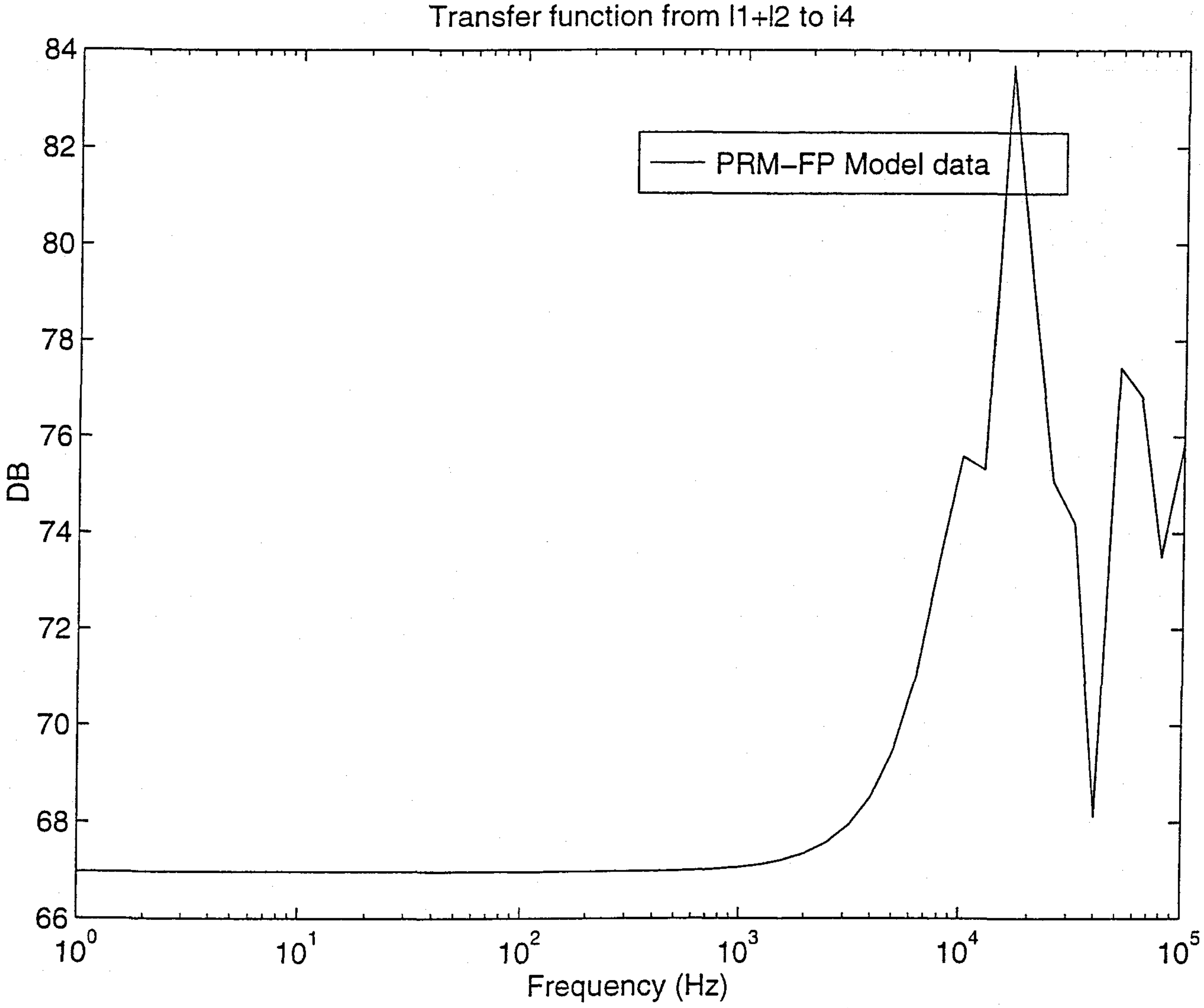

Transfer function from L1−L2 to i3
PRM−FP Model data
DB
Frequency (Hz)
165
160
155
150
145
140
135
130
125
120
10^0
10^1
10^2
10^3
10^4
10^5

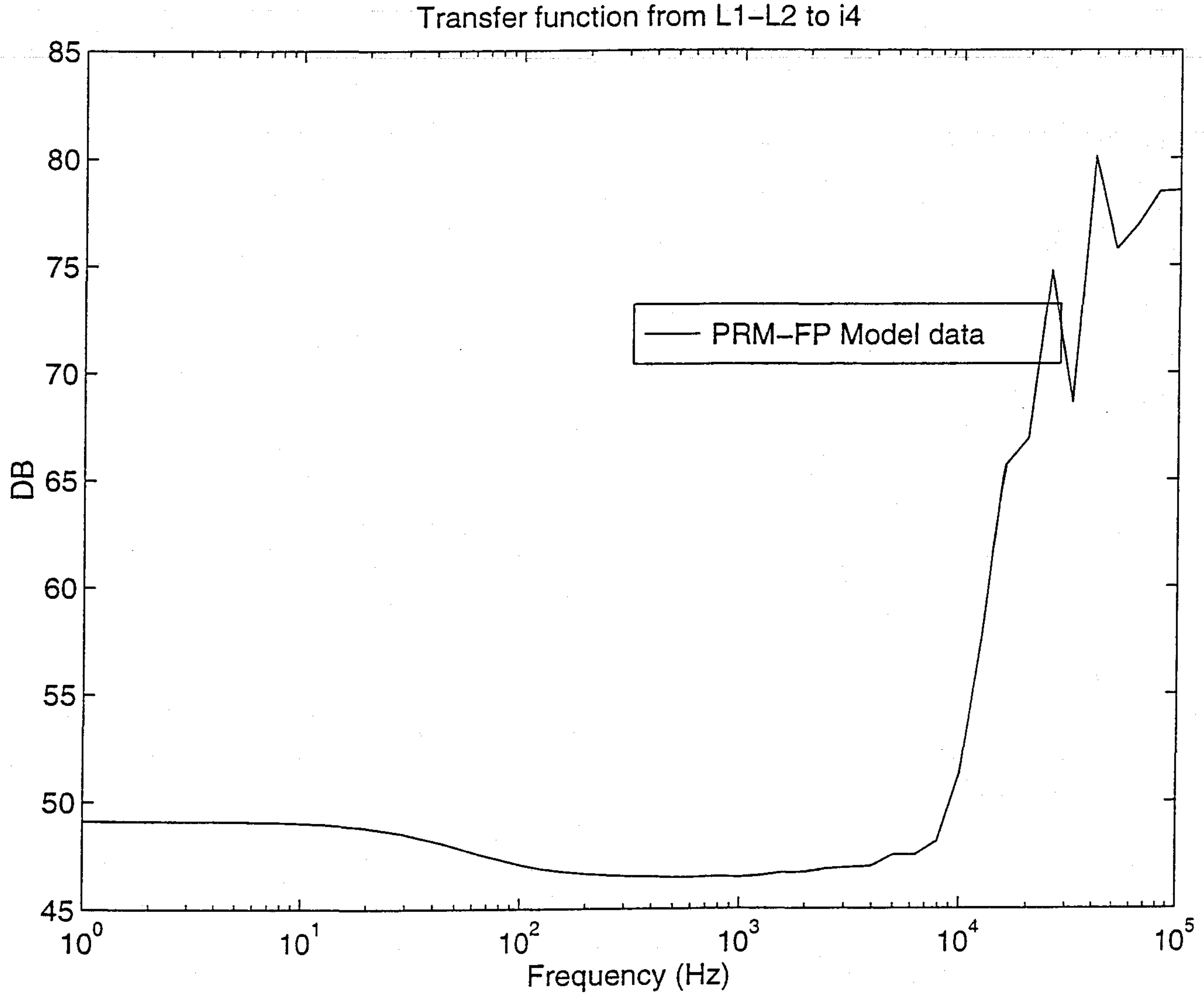

Transfer function from I1–I2 to i3
DB
150
145
140
135
130
125
120
115
110
Frequency (Hz)
10^0
10^1
10^2
10^3
10^4
10^5
PRM–FP Model data

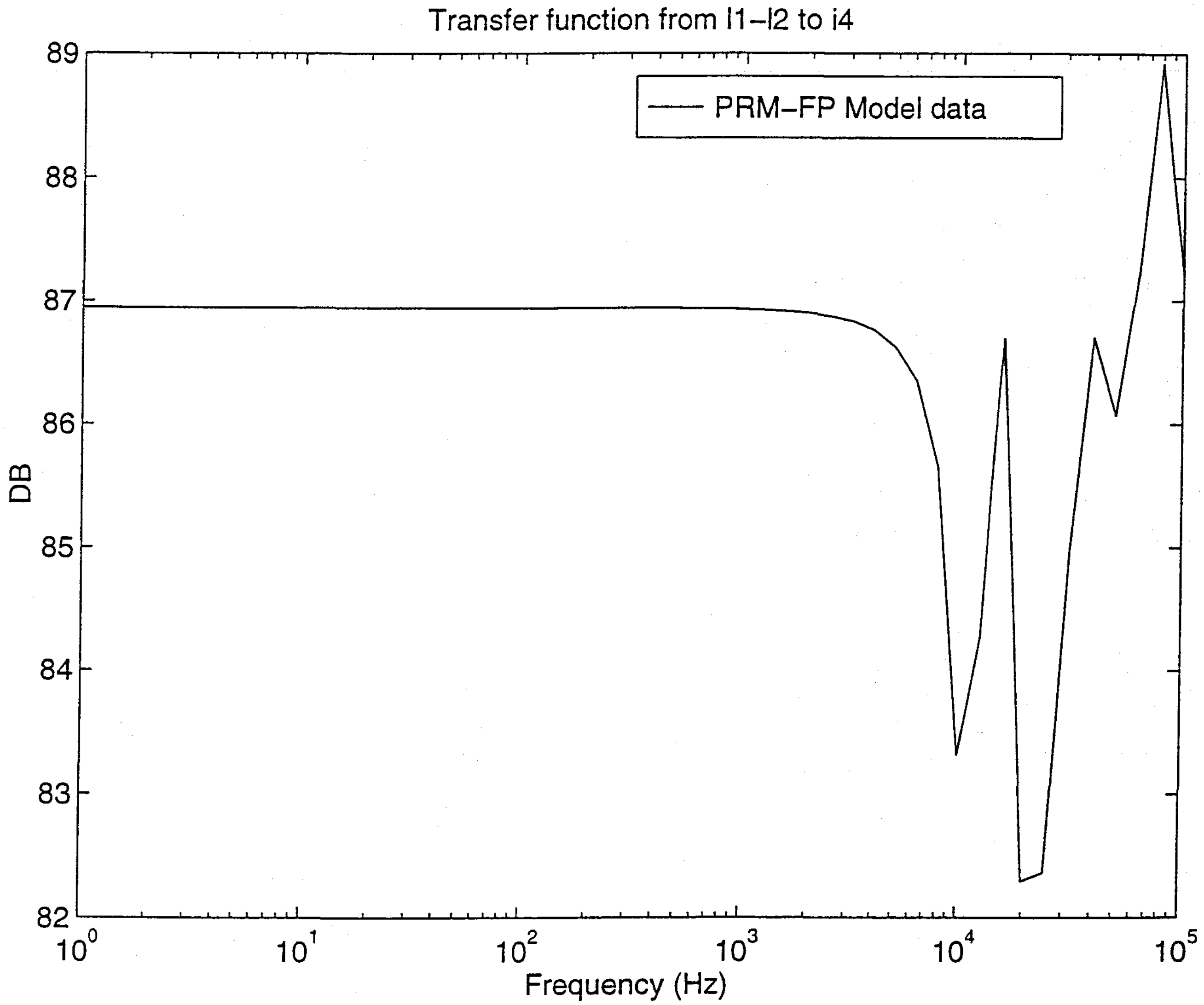

Transfer function from BS to i3
145
144
143
142
141
140
139
138
DB
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)
PRM–FP Model data

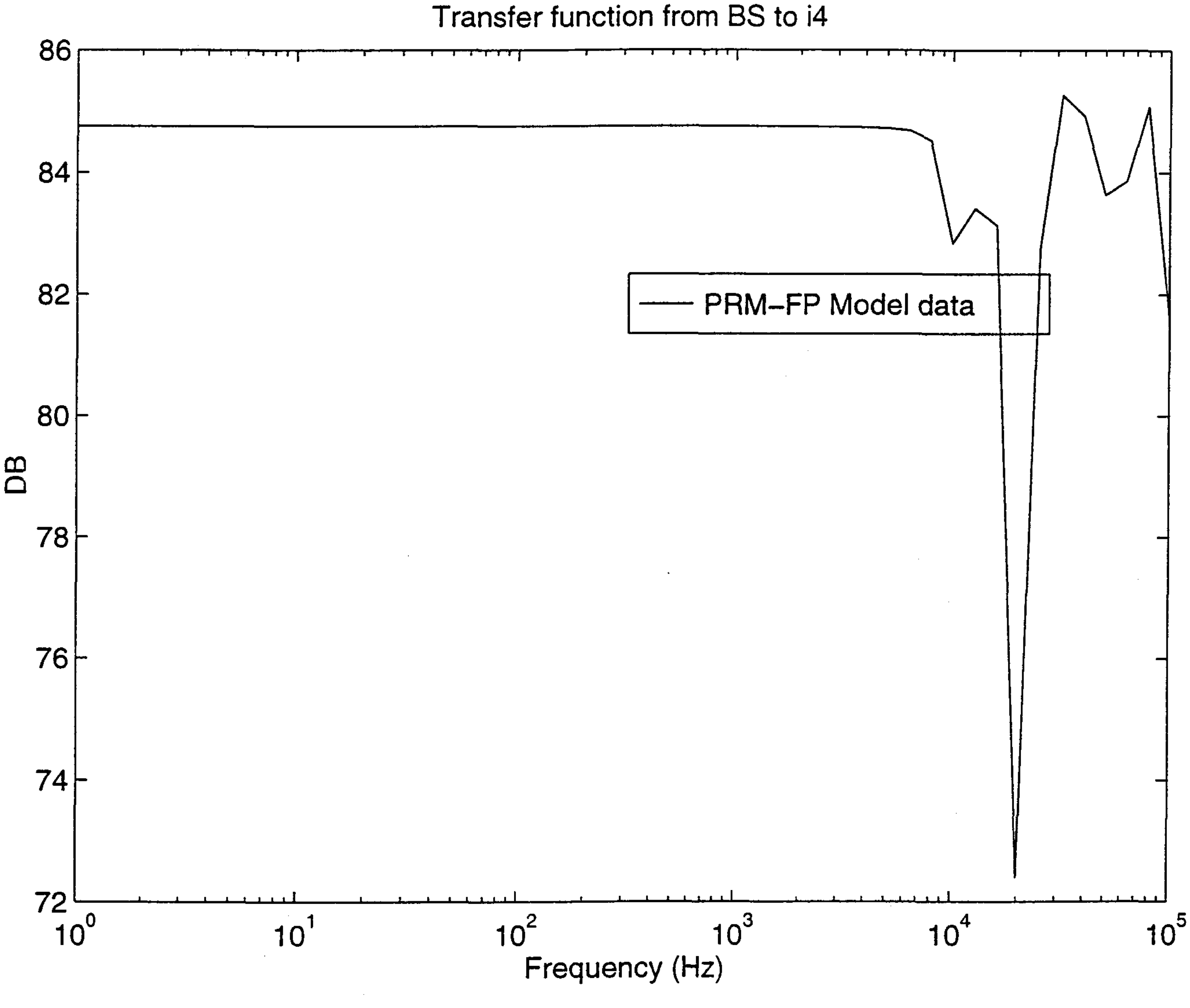

Transfer function from Source Phase to i4
60
40
20
0
−20
−40
−60
DB
PRM−FP Model data
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)


Transfer function from L1+L2 to i4
80
70
60
50
40
30
20
DB
PRM−FP Model data
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)


Transfer function from I1+I2 to i4
PRM−FP Model data
DB
84
82
80
78
76
74
72
70
68
66
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)


Transfer function from L1–L2 to i4
85
80
75
70
65
60
55
50
45
DB
PRM–FP Model data
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)


Transfer function from I1−I2 to i4
PRM−FP Model data
DB
89
88
87
86
85
84
83
82
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)


Transfer function from BS to i4
86
84
82
80
78
76
74
72
DB
10^0
10^1
10^2
10^3
10^4
10^5
Frequency (Hz)
PRM−FP Model data