Appendix H

LQTSS

H.1 SIMULINK implementation

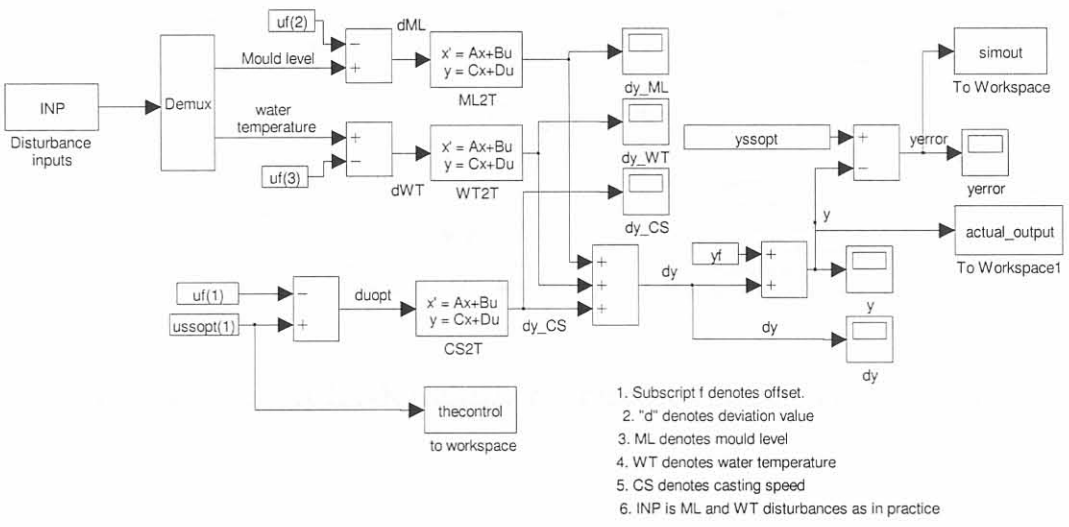

Figure H.1 SIMULINK realization for the MVIV model.

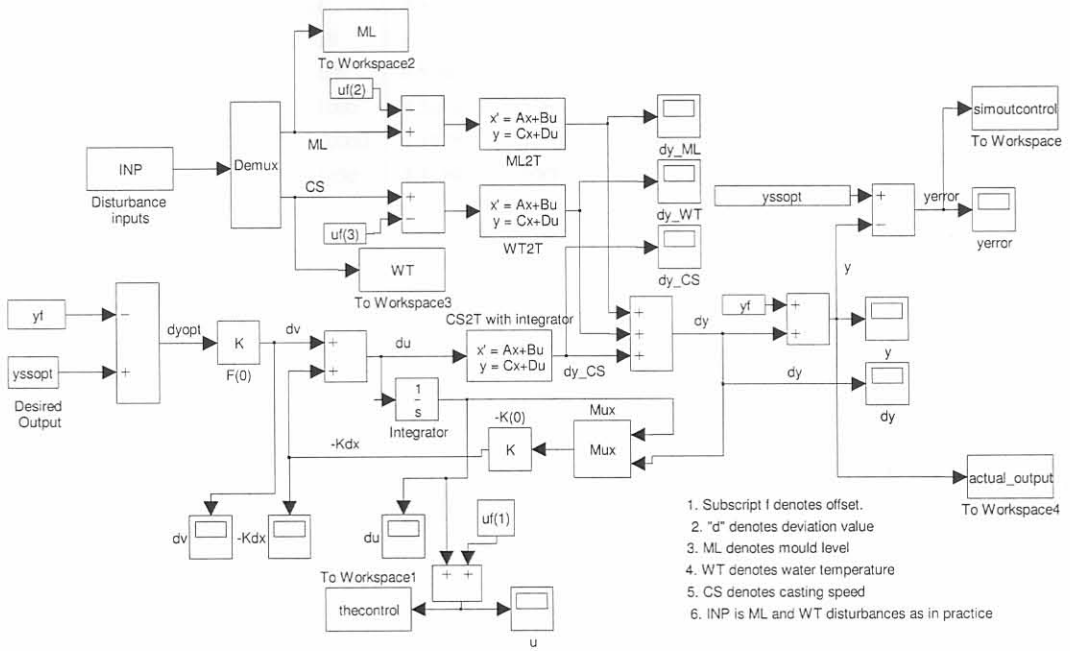

Figure H.2 SIMULINK realization for the LQTSS controller synthesis.

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H.2 1280mm wide slabs results

H.2.1 Tabled results

Table H.1 1280mm wide slab errors, maximum accellaration and maximum speeds for the LQTSS implementation at different values of the q/r ratio.

$\frac{q}{r}$	SMSMSE	$\max\lvert du_1/dt \rvert$	$\max(u_1)$
None	7.1598	0	724.1
0.001	4.727	10.81	927.1
0.01	4.6325	34.64	936.8
0.1	4.5739	75.67	948.4
1	4.5427	142.3	958
10	4.5268	271.5	962.1
100	4.5186	501.4	966
1000	4.5143	918	968.5
10000	4.5122	1620	969.7
1450	4.5139	1000	968.8

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Table H.2 Mean Square Errors for the LQTSS implementation for 1280mm wide slabs at different values of the q/r ratio. $q/r = 1450$ has the maximum accellaration of 1000mm/min^2.

$\frac{q}{r}$	in1u	in1l	in2u	in2l	in3u	in3l	in4u	in4l
None	6	5.06	70.8	92.9	22.2	204	22	550
0.001	10.8	3.27	8.92	8.78	3.73	31.5	5.17	135
0.01	9.37	2.69	6.71	9.36	2.91	34.8	3.78	146
0.1	8.38	2.31	5.13	9.86	2.34	37.2	2.85	153
1	7.81	2.09	4.29	10.2	2.05	38.8	2.32	158
10	7.5	1.97	3.88	10.5	1.9	39.8	2.04	162
100	7.33	1.9	3.68	10.7	1.82	40.4	1.88	163
1000	7.24	1.86	3.58	10.8	1.78	40.7	1.8	165
10000	7.2	1.84	3.52	10.8	1.76	40.9	1.76	165
1450	7.23	1.85	3.57	10.8	1.78	40.8	1.79	165

$\frac{q}{r}$	in5u	in5l	in6u	in6l	in7u	in7l	in8u	in8l
None	3.06	149	44.5	80.9	18.7	56.1	9.72	3.3
0.001	1.92	28.1	4.19	8.35	4.09	10.5	5.88	19.4
0.01	1.53	30.4	3.17	9.05	3.01	10.6	4.8	18.7
0.1	1.24	32.2	2.5	9.61	2.25	10.7	4.06	18.3
1	1.07	33.4	2.15	10	1.84	10.9	3.64	18
10	0.984	34.1	1.98	10.3	1.62	11	3.41	17.9
100	0.937	34.5	1.9	10.4	1.51	11	3.29	17.8
1000	0.911	34.8	1.86	10.5	1.45	11.1	3.23	17.7
10000	0.898	34.9	1.84	10.6	1.42	11.1	3.19	17.7
1450	0.908	34.8	1.86	10.6	1.45	11.1	3.22	17.7

$\frac{q}{r}$	ou1u	ou1l	ou2u	ou2l	ou3u	ou3l	ou4u	ou4l
None	50.1	17.1	12.4	31.4	40	93.2	2.82	36.7
0.001	7.68	3.89	14.7	2.96	4.55	6.59	10.2	4.3
0.01	5.48	2.94	12.3	1.98	3.35	7.17	9.11	4.48
0.1	4	2.34	10.5	1.37	2.55	7.66	8.35	4.64
1	3.2	2	9.5	1.03	2.14	8.04	7.9	4.77
10	2.79	1.81	8.94	0.86	1.93	8.3	7.64	4.86
100	2.57	1.71	8.64	0.767	1.82	8.46	7.49	4.92
1000	2.46	1.65	8.48	0.717	1.77	8.56	7.41	4.95
10000	2.4	1.62	8.4	0.691	1.74	8.61	7.37	4.97
1450	2.44	1.64	8.46	0.712	1.76	8.57	7.4	4.96

$\frac{q}{r}$	ou5u	ou5l	ou6u	ou6l	ou7u	ou7l	ou8u	ou8l
None	5.93	38.2	NA	NA	0.89	1.17	1.64	1.33
0.001	9.04	2.03	NA	NA	24.2	21.8	32.2	18.8
0.01	7.75	2.18	NA	NA	22.5	20.1	30.6	17.2
0.1	6.87	2.33	NA	NA	21.3	18.9	29.5	16.1
1	6.35	2.45	NA	NA	20.6	18.2	28.9	15.5
10	6.06	2.53	NA	NA	20.2	17.8	28.5	15.1
100	5.9	2.59	NA	NA	20	17.5	28.3	14.9
1000	5.81	2.62	NA	NA	19.9	17.4	28.2	14.8
10000	5.77	2.64	NA	NA	19.8	17.3	28.1	14.7
1450	5.8	2.63	NA	NA	19.9	17.4	28.2	14.8

$\frac{q}{r}$	nl1u	nl1l	nl2u	nl2l	nr1u	nr1l	nr2u	nr2l
None	168	3.12	14.6	1.45	2.06	4.31	70.5	12.3
0.001	6.31	54.1	116	62.5	72.6	52.9	9.86	22.2
0.01	3.88	49.7	112	59.1	69.5	50.9	7.05	19.4
0.1	2.57	46.8	110	56.8	67.5	49.6	5.31	17.6
1	1.91	45	108	55.4	66.3	48.7	4.34	16.5
10	1.58	44	107	54.5	65.6	48.2	3.8	15.8
100	1.42	43.3	107	54	65.1	47.9	3.5	15.5
1000	1.33	43	107	53.8	64.9	47.7	3.34	15.3
10000	1.29	42.8	106	53.6	64.8	47.7	3.25	15.2
1450	1.32	42.9	107	53.7	64.8	47.7	3.32	15.2

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Table H.3 Feedback gain matrix $\mathbf{K}_\infty$ for 1280mm wide slabs at $q/r = 1450$.

The gain of the integrator state is $k_\infty = 0.221$.

in1u	in1l	in2u	in2l	in3u	in3l	in4u	in4l
8.04	3.47	9.06	4.8	5.22	4.99	6.17	6.86
in5u	in5l	in6u	in6l	in7u	in7l	in8u	in8l
4.15	4.1	6.13	4.17	5.98	3.94	5.83	2.14
ou1u	ou1l	ou2u	ou2l	ou3u	ou3l	ou4u	ou4l
8.18	4.45	11.6	5.23	6.27	4.82	5.37	3.11
ou5u	ou5l	ou6u	ou6l	ou7u	ou7l	ou8u	ou8l
6.21	3.29	NA	NA	7.7	4.77	5.69	4.25
nl1u	nl1l	nl2u	nl2l	nr1u	nr1l	nr2u	nr2l
8.96	7.34	8.27	6.88	10.7	6.66	7.91	7.67

Table H.4 Feedforward gain matrix $\mathbf{F}$ for 1280mm wide slabs at $q/r = 1450$.

in1u	in1l	in2u	in2l	in3u	in3l	in4u	in4l
4.52	3.35	7.08	6.34	4.22	8.23	5.47	12.1
in5u	in5l	in6u	in6l	in7u	in7l	in8u	in8l
2.46	6.54	5.58	5.75	4.5	4.16	4.21	2.3
ou1u	ou1l	ou2u	ou2l	ou3u	ou3l	ou4u	ou4l
7.04	4.98	5.91	5.67	5.7	6.72	4.17	3.82
ou5u	ou5l	ou6u	ou6l	ou7u	ou7l	ou8u	ou8l
4.54	4.59	NA	NA	4.96	4.95	4.45	4.76
nl1u	nl1l	nl2u	nl2l	nr1u	nr1l	nr2u	nr2l
12.6	7.91	6.35	6.5	6.51	4.98	9.46	6.9

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H.2.2 Time-domain results

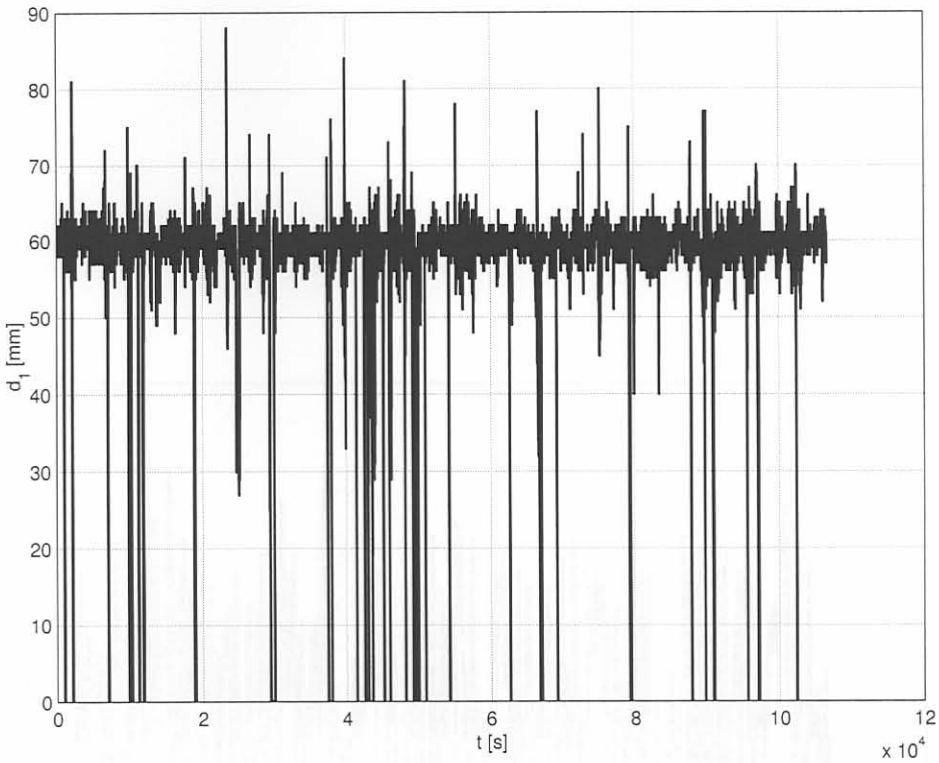

Figure H.3 Mould level disturbance ($d_1(t)$) used for the simulation of the 1280mm wide slab system.

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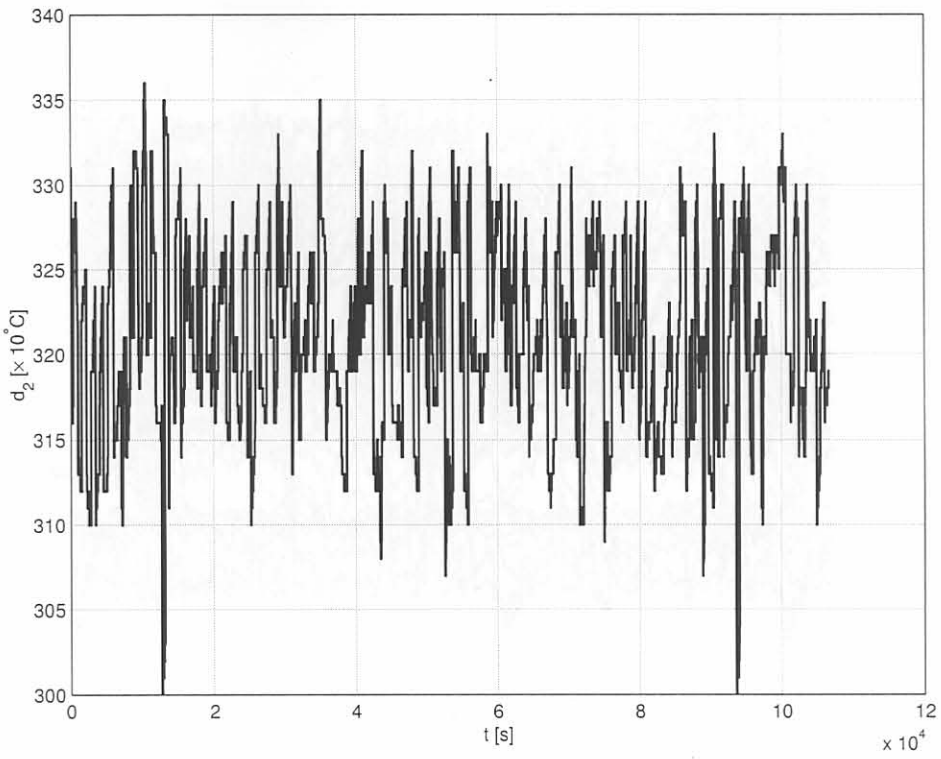

Figure H.4 Water temperature ($d_2(t)$) disturbance used for the simulation of the 1280mm wide slab system.

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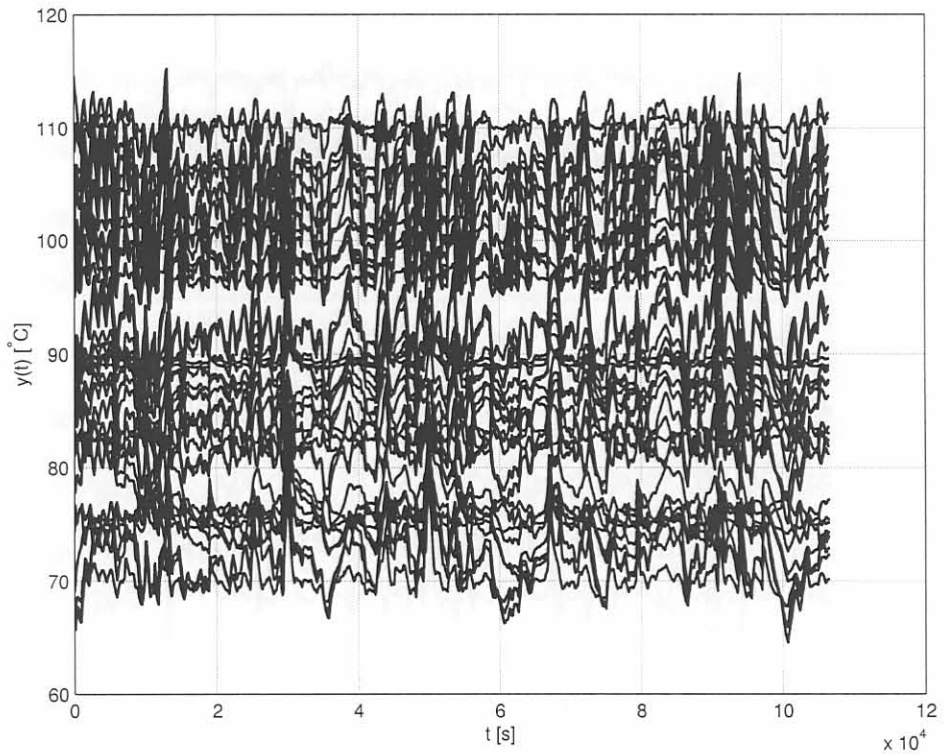

Figure H.5 Outputs ($\mathbf{y}(t)$) of the system without the LQTSS controller for 1280mm wide slabs.

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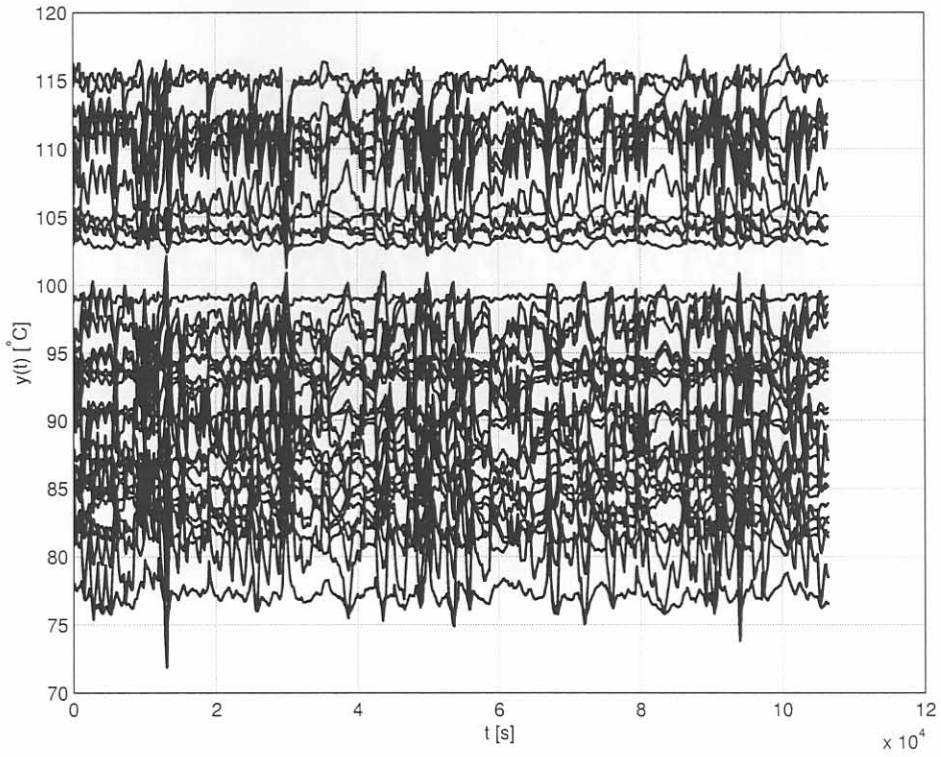

Figure H.6 Outputs ($\mathbf{y}(t)$) of the system with the LQTSS controller for 1280mm wide slabs.

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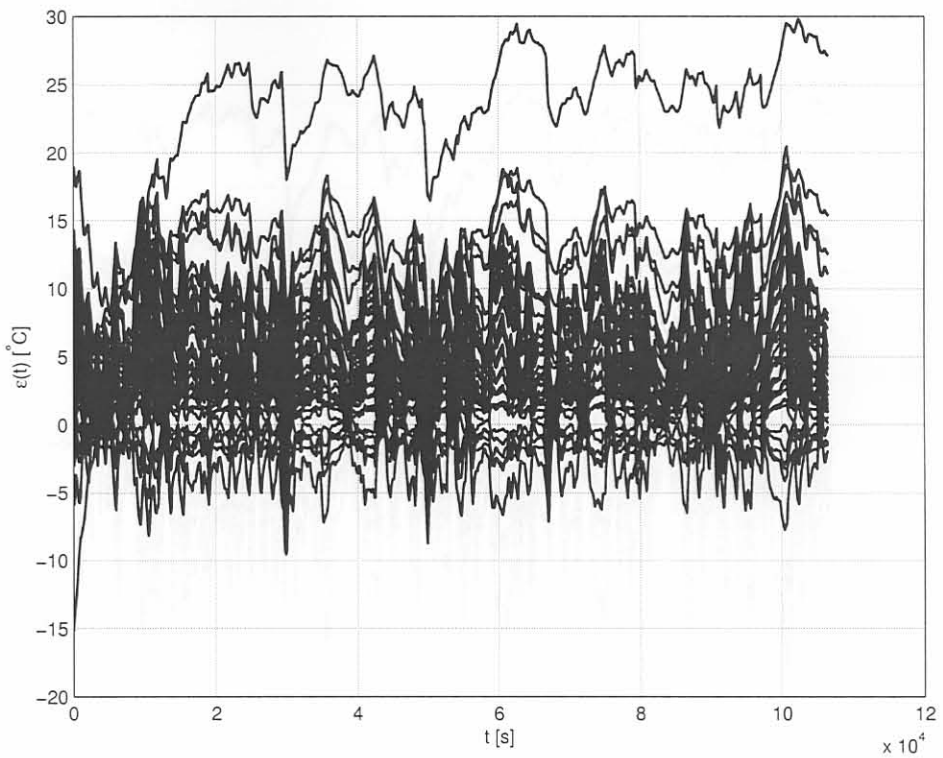

Figure H.7 Tracking errors of the system without the LQTSS controller for 1280mm wide slabs.

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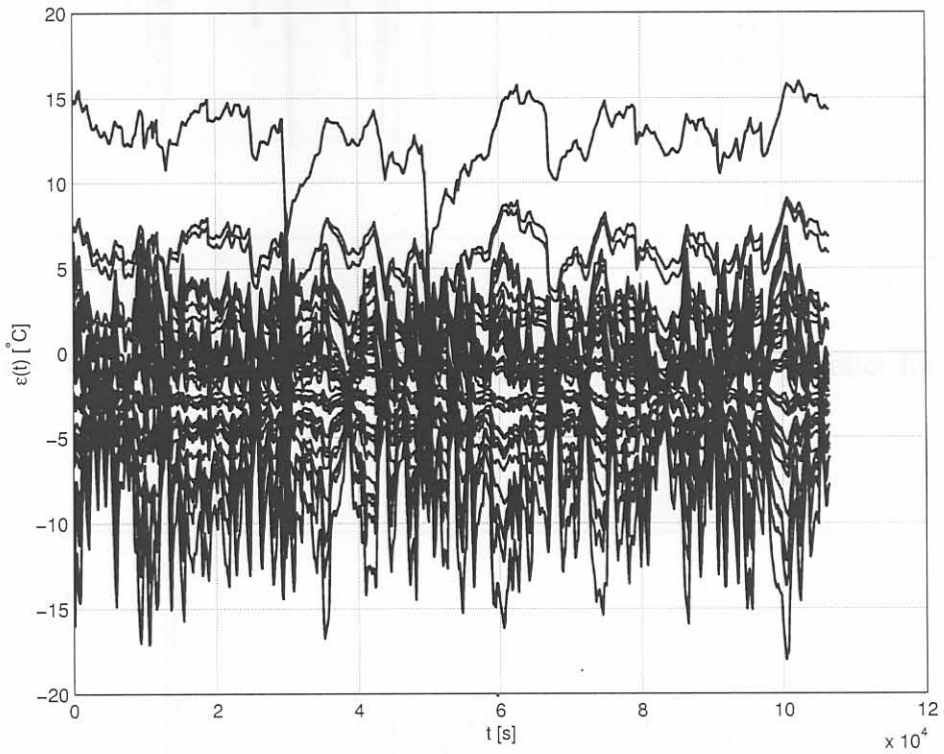

Figure H.8 Tracking errors of the system with the LQTSS controller for 1280mm wide slabs.

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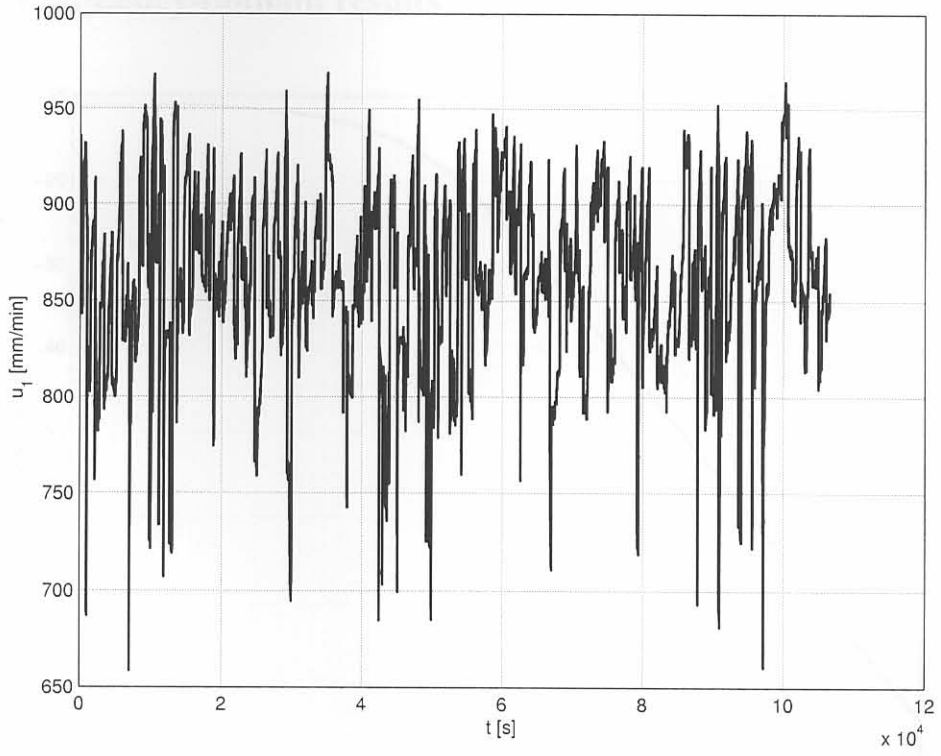

Figure H.9 Casting speed (casting speed, $u_1(t)$) for the LQTSS controller for 1280mm wide slabs.

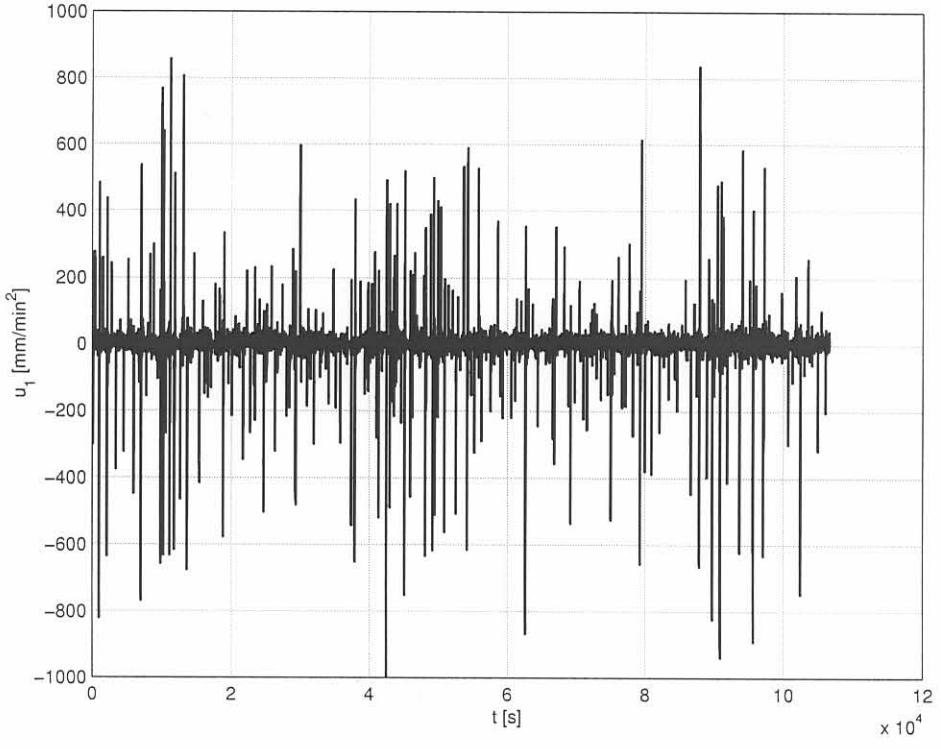

Figure H.10 Casting accellaration for the LQTSS controller for 1280mm wide slabs.

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H.2.3 Frequency-domain results

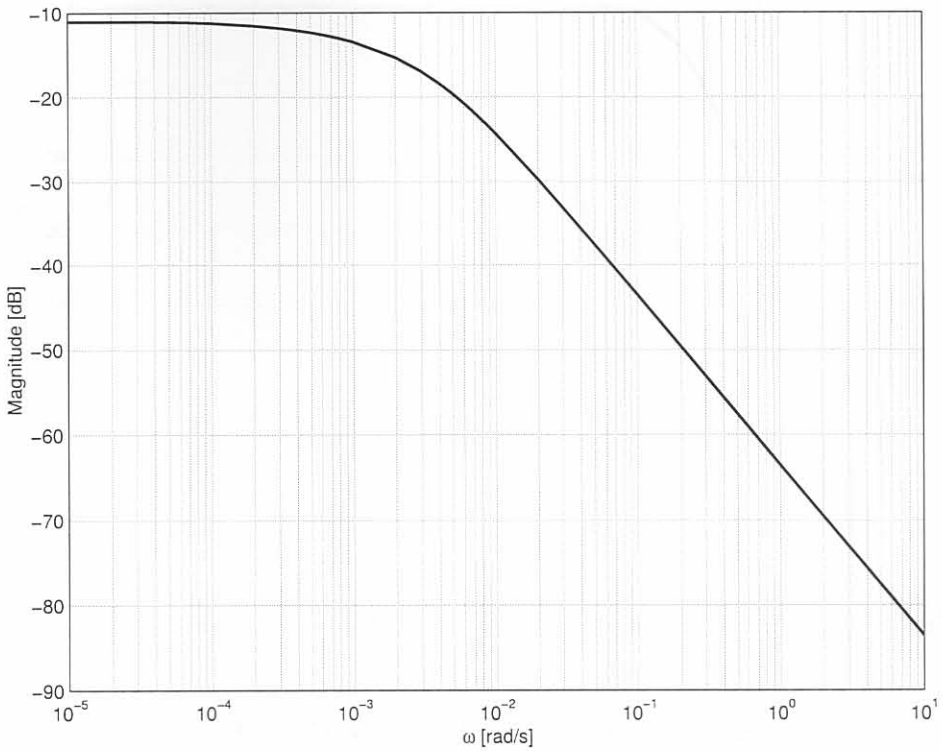

Figure H.11 Open-loop SVD plot of casting speed to the thermocouple temperatures without control ($\mathbf{g}(s)$).

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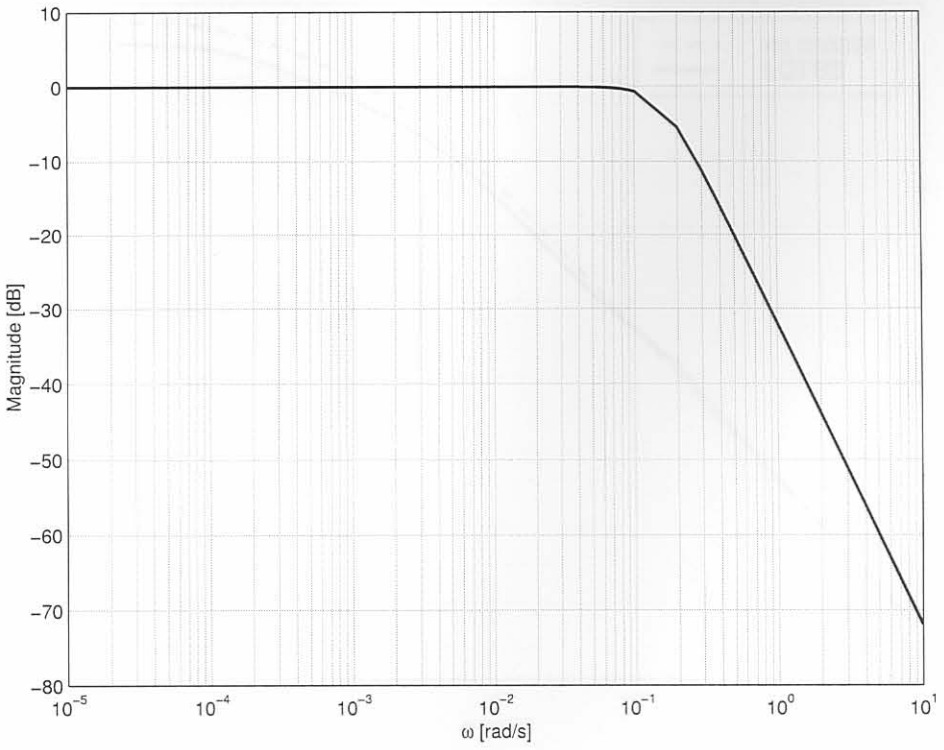

Figure H.12 Closed-loop SVD plot, $\mathbf{T}(s)$, of the system.

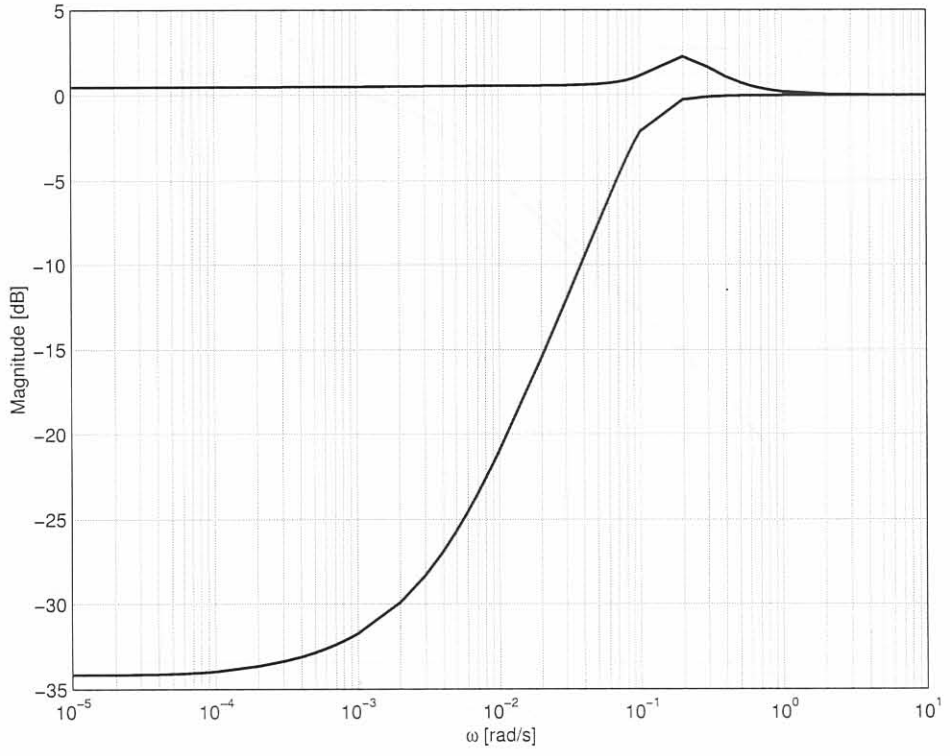

Figure H.13 Sensitivity function for the system.

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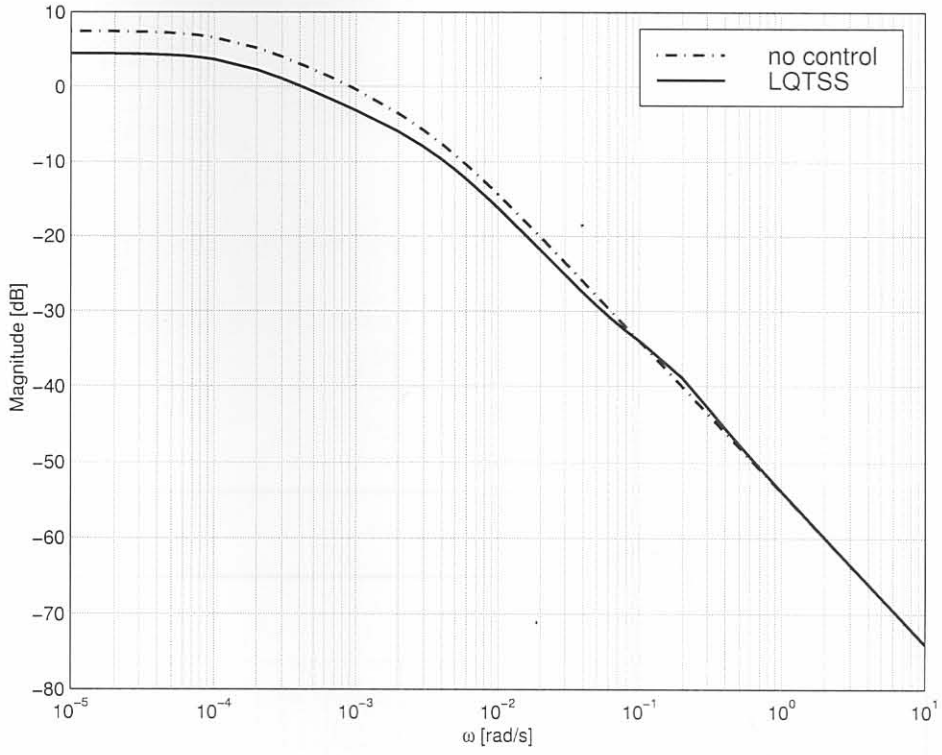

Figure H.14 Reduction in the effect of mould level disturbance on the output temperatures.

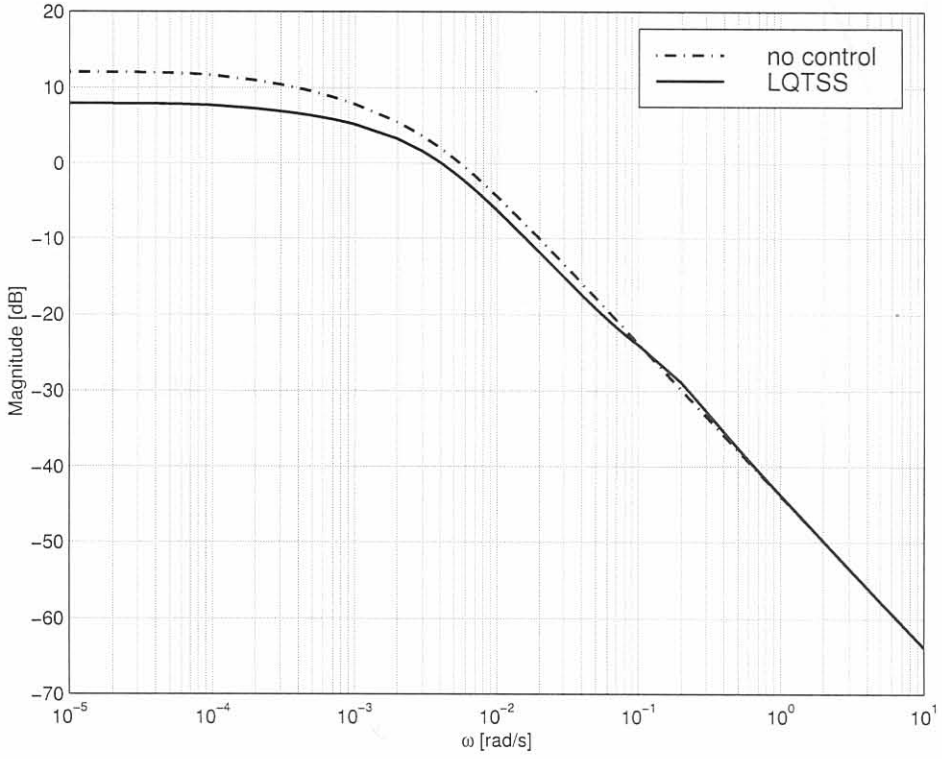

Figure H.15 Reduction in the effect of water temperature disturbance on the output temperatures.

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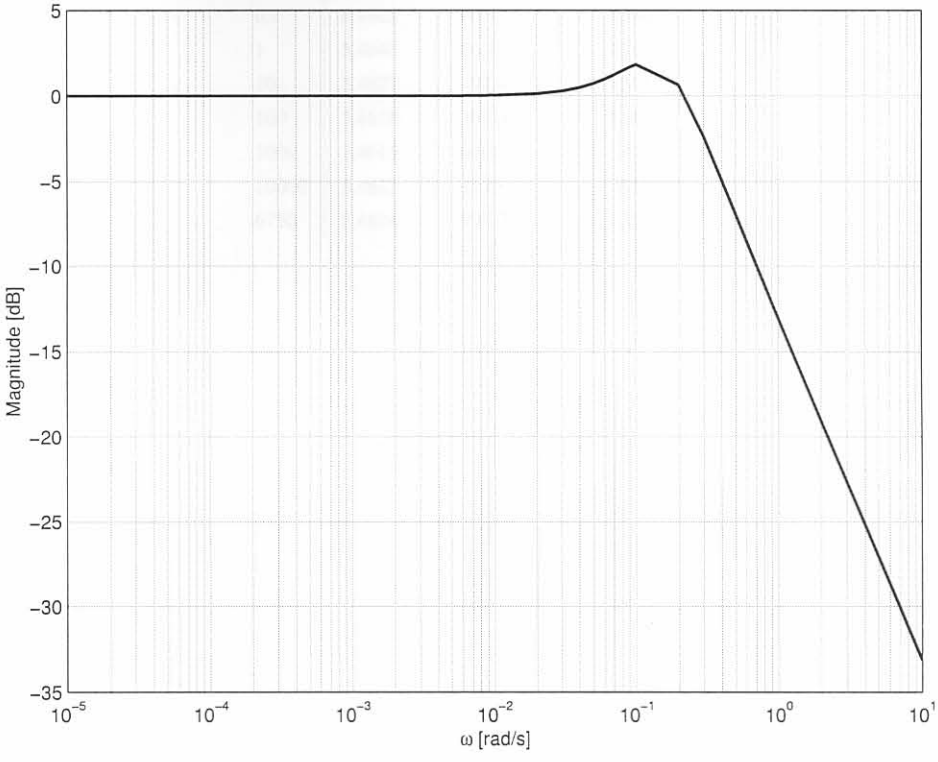

Figure H.16 Bode plot of the transfer function of $p(s) = h(s)v(s)$.

H.3 1575mm wide slabs results

H.3.1 Tabled results

Table H.5 1575mm wide slab errors, maximum accellaration and maximum speeds for the LQTSS implementation at different values of the q/r ratio.

$\frac{q}{r}$	SMSMSE	$\max\lvert du_1/dt \rvert$	$\max(u_1)$
None	5.5005	0	1255
0.001	5.5002	7.123	1304
0.01	5.4817	15.96	1311
0.1	5.4702	40.38	1330
1	5.4648	86.87	1339
10	5.4627	192.4	1345
100	5.4618	359.3	1349
1000	5.4615	640.9	1351
10000	5.4613	1115	1353
6750	5.4614	999.7	1353

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Table H.6 Mean Square Errors for the LQTSS implementation for 1575mm wide slabs for different values of the q/r ratio. $q/r = 6750$ has the maximum accellaration of 1000 mm/min^2.

$\frac{q}{r}$	in1u	in1l	in2u	in2l	in3u	in3l	in4u	in4l
None	2.94	61.4	12	20.1	5.15	25.8	1.78	48.6
0.001	3.59	63.8	11.2	20.1	3.97	25.9	2.01	49.9
0.01	3.55	61.9	12.4	19.1	3.51	24.3	1.7	49.8
0.1	3.56	60.6	13.4	18.3	3.16	23.1	1.49	49.8
1	3.58	59.7	14.1	17.8	3.01	22.3	1.37	49.8
10	3.6	59.2	14.6	17.5	2.97	21.9	1.31	49.8
100	3.61	58.9	14.8	17.4	2.96	21.6	1.28	49.8
1000	3.61	58.7	15	17.3	2.96	21.5	1.26	49.8
10000	3.62	58.7	15	17.2	2.96	21.4	1.25	49.8
6750	3.62	58.7	15	17.3	2.96	21.4	1.25	49.8

$\frac{q}{r}$	in5u	in5l	in6u	in6l	in7u	in7l	in8u	in8l
None	17.7	8.21	3.07	42.6	9.2	38.7	21.2	39.5
0.001	13.6	7.57	3.07	43.5	9.26	39.6	22.1	39.9
0.01	12.6	6.63	2.49	43.3	7.98	38.6	21	37.8
0.1	11.8	5.93	2.07	43.1	7.03	37.8	20.1	36.2
1	11.5	5.51	1.82	43	6.47	37.3	19.6	35.2
10	11.3	5.28	1.69	42.9	6.16	37	19.3	34.6
100	11.2	5.15	1.62	42.9	5.99	36.8	19.1	34.3
1000	11.2	5.08	1.58	42.8	5.89	36.7	19	34.1
10000	11.1	5.04	1.56	42.8	5.84	36.7	19	34
6750	11.1	5.04	1.57	42.8	5.85	36.7	19	34

$\frac{q}{r}$	ou1u	ou1l	ou2u	ou2l	ou3u	ou3l	ou4u	ou4l
None	27.4	62.1	9.73	36.7	1.63	41.7	0.918	65.8
0.001	28.5	65.9	9.4	37.3	2.11	43.6	1.36	67.3
0.01	28	64.9	7.92	35	1.99	42.5	1.39	67.3
0.1	27.6	64.3	6.75	33.3	1.94	41.7	1.44	67.2
1	27.3	63.9	6.06	32.3	1.92	41.2	1.49	67.2
10	27.2	63.6	5.68	31.7	1.91	40.9	1.52	67.2
100	27.1	63.5	5.48	31.3	1.91	40.7	1.54	67.2
1000	27	63.4	5.37	31.1	1.91	40.6	1.55	67.2
10000	27	63.4	5.32	31	1.91	40.6	1.56	67.2
6750	27	63.4	5.32	31	1.91	40.6	1.56	67.2

$\frac{q}{r}$	ou5u	ou5l	ou6u	ou6l	ou7u	ou7l	ou8u	ou8l
None	4.08	9.33	NA	NA	11.4	6.67	3.38	59.1
0.001	2.97	10.1	NA	NA	10.7	5.55	3.81	60
0.01	2.29	9.89	NA	NA	11.7	4.7	3.45	57.4
0.1	1.8	9.76	NA	NA	12.5	4.09	3.19	55.4
1	1.53	9.67	NA	NA	13.1	3.74	3.05	54.2
10	1.39	9.62	NA	NA	13.5	3.55	2.96	53.5
100	1.33	9.59	NA	NA	13.7	3.44	2.92	53.1
1000	1.29	9.57	NA	NA	13.8	3.38	2.9	52.8
10000	1.27	9.56	NA	NA	13.9	3.35	2.88	52.7
6750	1.27	9.56	NA	NA	13.9	3.35	2.88	52.7

$\frac{q}{r}$	nl1u	nl1l	nl2u	nl2l	nr1u	nr1l	nr2u	nr2l
None	33.9	84.8	104	31.7	25.5	4.25	60.4	107
0.001	33.6	83.2	100	30.8	25.3	4.06	60.4	105
0.01	34.5	85.1	104	32	26.9	5.01	62.1	108
0.1	35.4	86.6	106	32.9	28.2	5.79	63.5	110
1	35.9	87.6	108	33.5	29.1	6.31	64.3	111
10	36.2	88.1	109	33.9	29.5	6.63	64.8	112
100	36.4	88.5	110	34.1	29.8	6.82	65.1	113
1000	36.5	88.7	111	34.2	30	6.92	65.3	113
10000	36.5	88.8	111	34.3	30.1	6.98	65.4	113
6750	36.5	88.8	111	34.3	30.1	6.98	65.4	113

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Table H.7 Feedback gain matrix $\mathbf{K}_\infty$ for 1575mm wide slabs at $q/r = 6750$.

The gain of the integrator state is $k_\infty = 0.316$.

in1u	in1l	in2u	in2l	in3u	in3l	in4u	in4l
17	10.2	23.6	8.22	22.8	13.3	13.9	0.146
in5u	in5l	in6u	in6l	in7u	in7l	in8u	in8l
20.4	11.3	13.9	1.9	17	7.93	14.1	14.3
ou1u	ou1l	ou2u	ou2l	ou3u	ou3l	ou4u	ou4l
8.25	4.86	19.2	13.3	13.1	8.05	13.3	0.362
ou5u	ou5l	ou6u	ou6l	ou7u	ou7l	ou8u	ou8l
15.8	2.87	NA	NA	19.3	12.5	12.5	13.1
nl1u	nl1l	nl2u	nl2l	nr1u	nr1l	nr2u	nr2l
8.29	9.74	19.7	11.2	11.1	16.1	7.47	10.3

Table H.8 Feedforward gain matrix $\mathbf{F}$ for 1575mm wide slabs at $q/r = 6750$.

in1u	in1l	in2u	in2l	in3u	in3l	in4u	in4l
12.4	12.7	16.2	9.02	17.6	11.3	12.7	0.211
in5u	in5l	in6u	in6l	in7u	in7l	in8u	in8l
24.1	12.8	13.7	2.35	17.2	8.51	13.1	13
ou1u	ou1l	ou2u	ou2l	ou3u	ou3l	ou4u	ou4l
8.02	7.32	16.3	19.4	12.7	10	12.4	0.5
ou5u	ou5l	ou6u	ou6l	ou7u	ou7l	ou8u	ou8l
17.4	4.33	NA	NA	15.2	15.2	12.5	14.8
nl1u	nl1l	nl2u	nl2l	nr1u	nr1l	nr2u	nr2l
6.96	11.6	21	11	13.3	17.1	9.25	14.6

H.3.2 Time-domain results

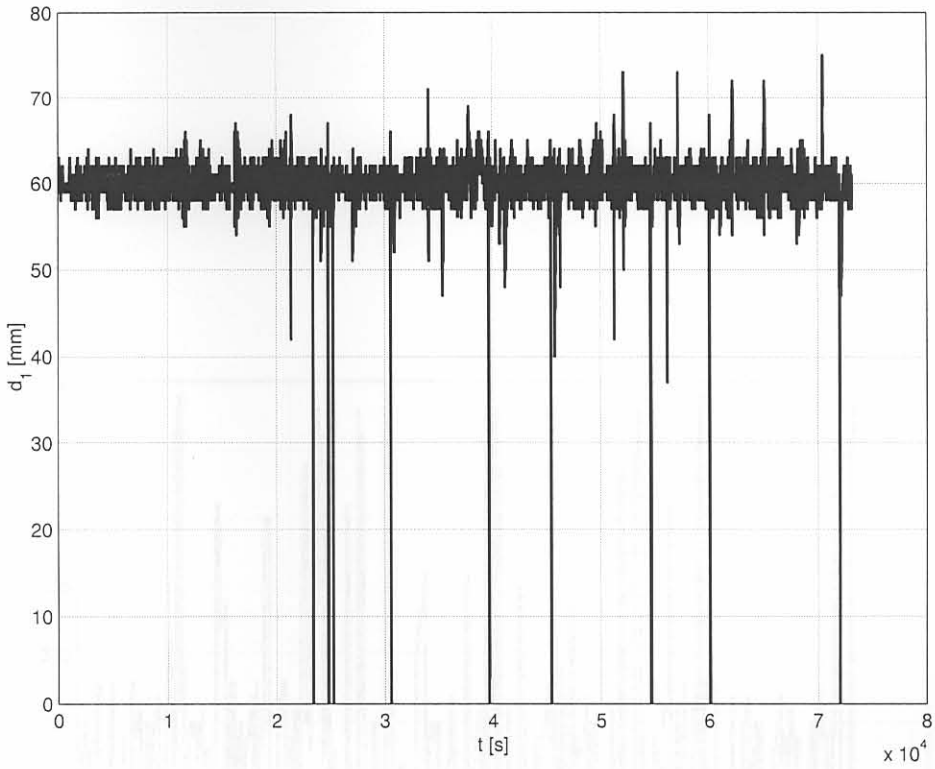

Figure H.17 Mould level disturbance ($d_1(t)$) used for the simulation of the 1575mm wide slab system.

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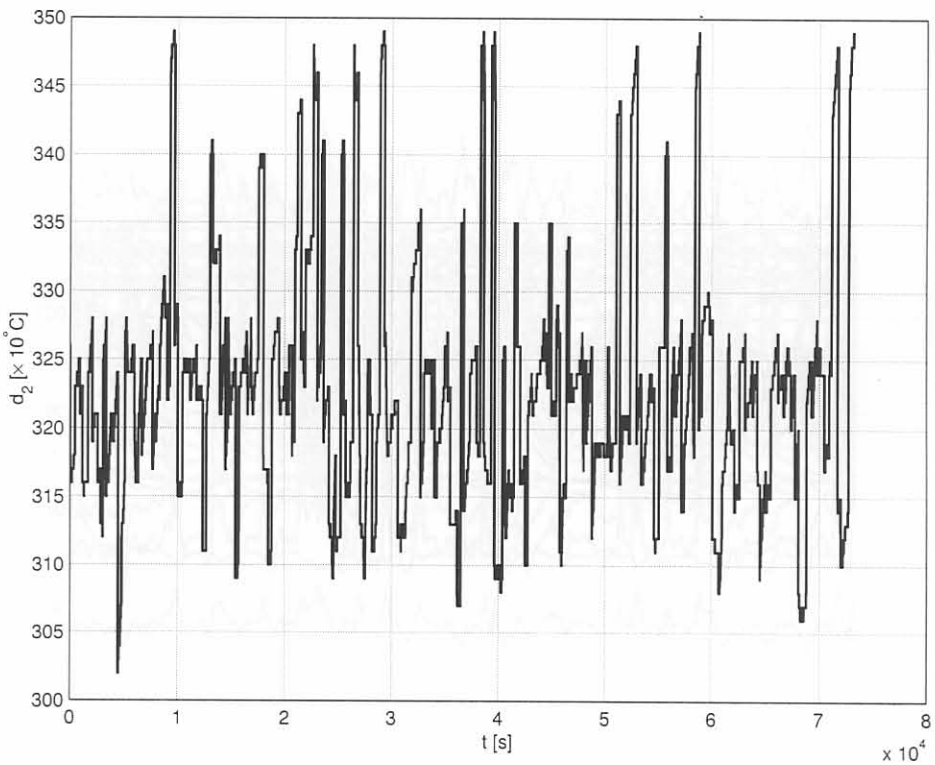

Figure H.18 Water temperature ($d_2(t)$) disturbance used for the simulation of the 1575mm wide slab system.

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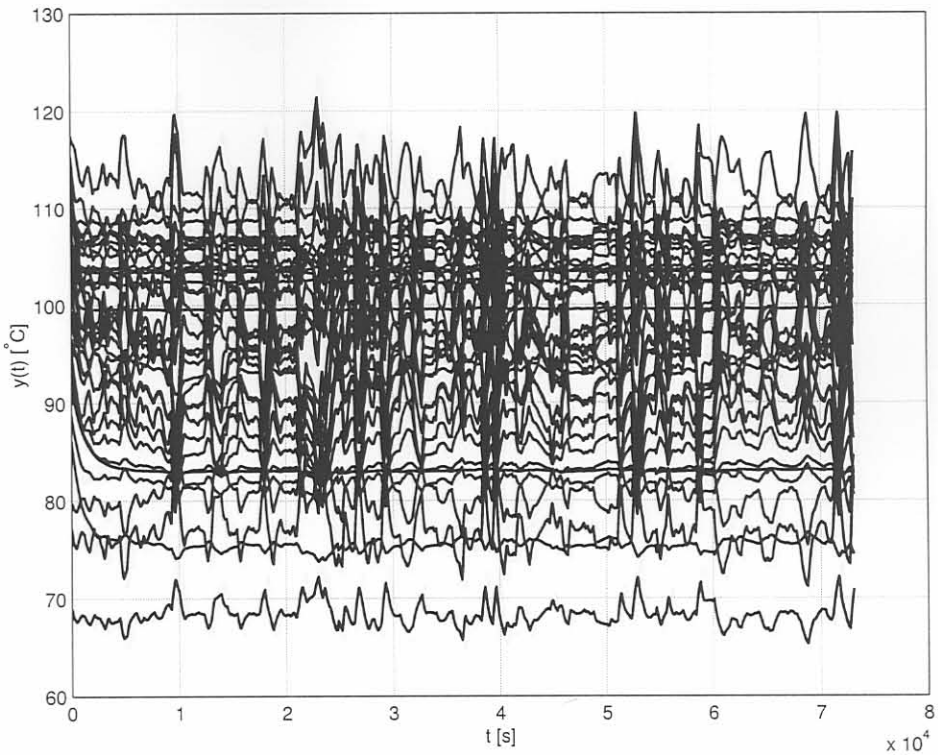

Figure H.19 Outputs $(\mathbf{y}(t))$ of the system without the LQTSS controller for 1575mm wide slabs.

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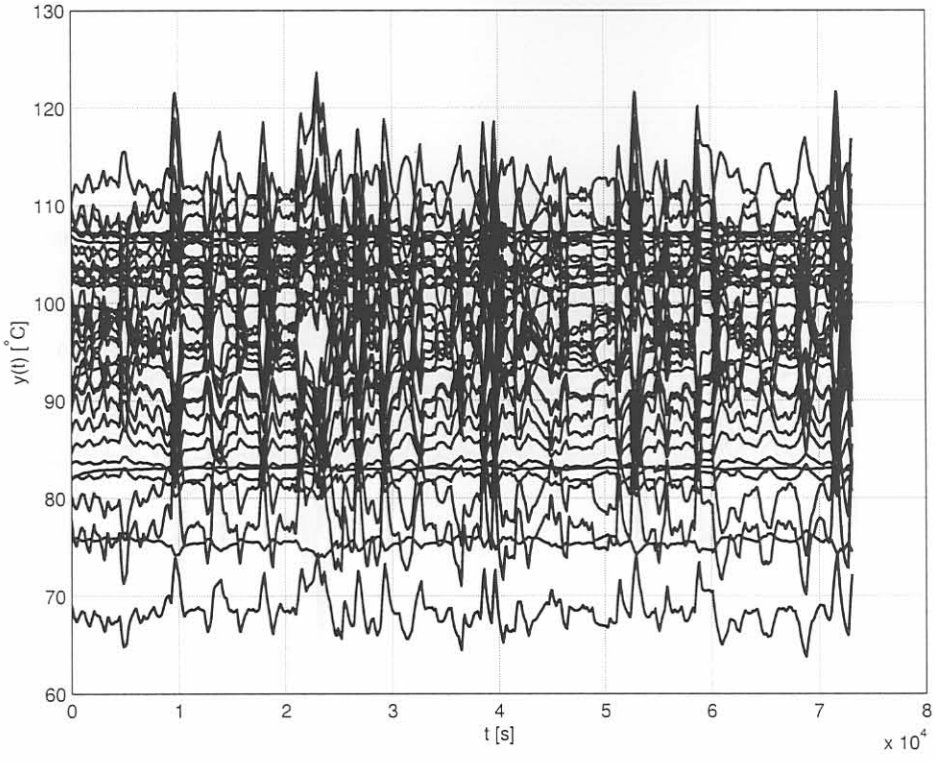

Figure H.20 Outputs $(\mathbf{y}(t))$ of the system with the LQTSS controller for 1575mm wide slabs.

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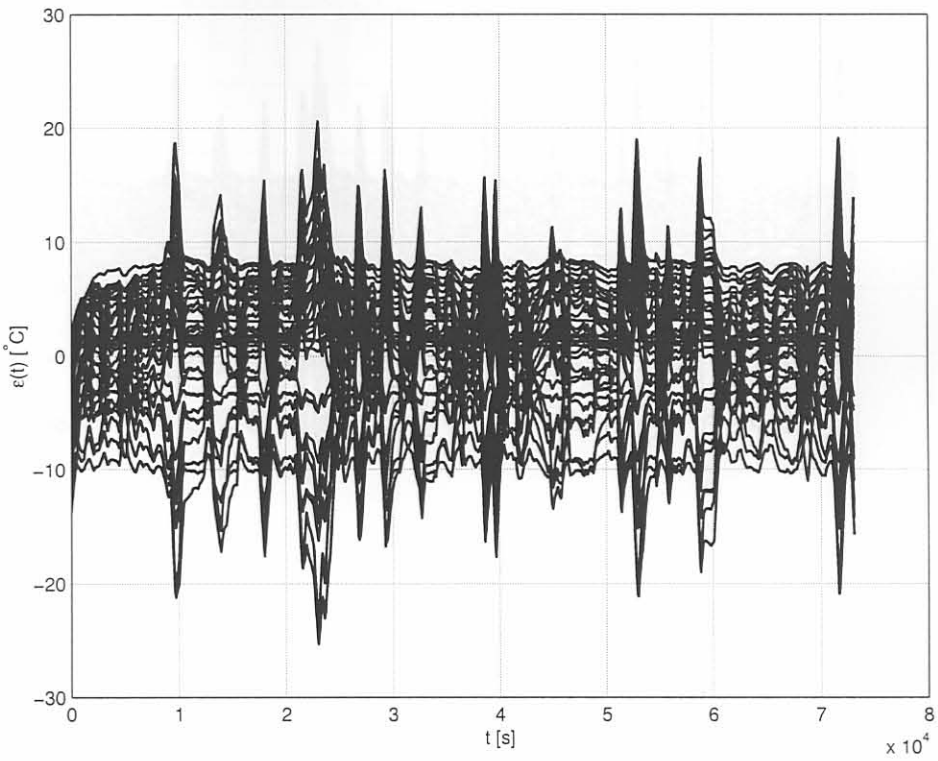

Figure H.21 Tracking errors of the system without the LQTSS controller for 1575mm wide slabs.

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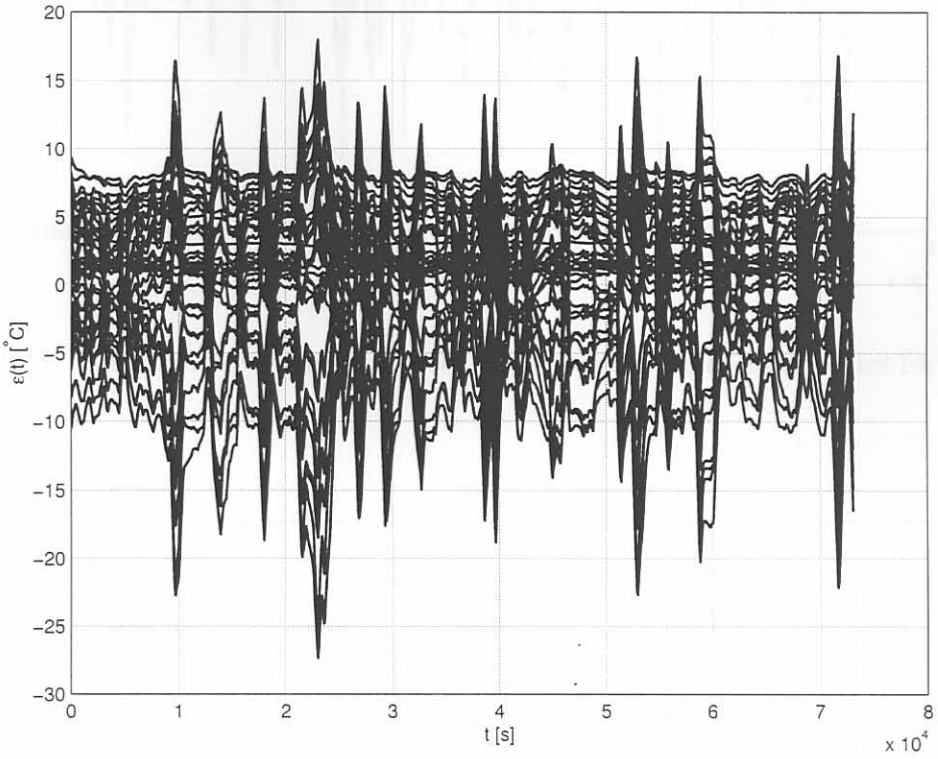

Figure H.22 Tracking errors of the system with the LQTSS controller for 1575mm wide slabs.

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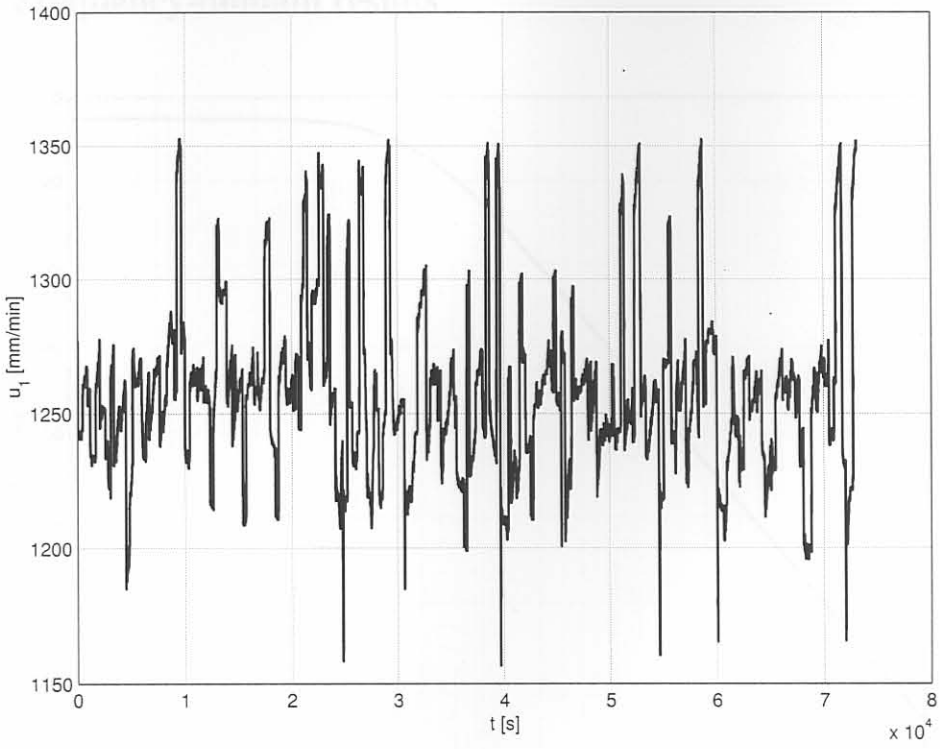

Figure H.23 Casting speed (casting speed, $u_1(t)$) for the LQTSS controller for 1575mm wide slabs.

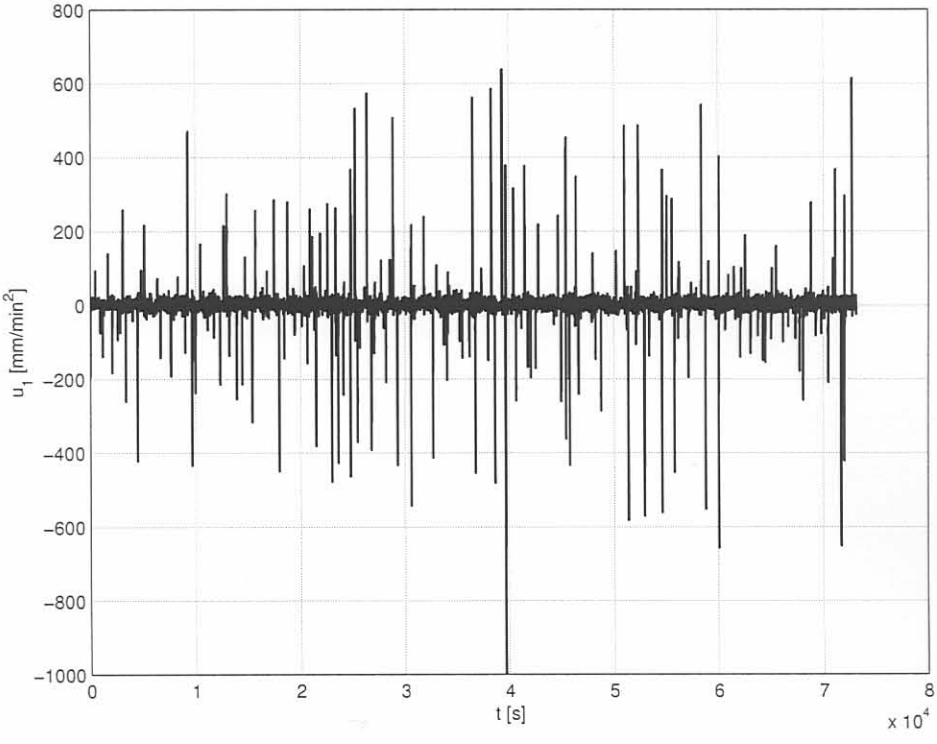

Figure H.24 Casting accellaration for the LQTSS controller for 1575mm wide slabs.

H.3.3 Frequency-domain results

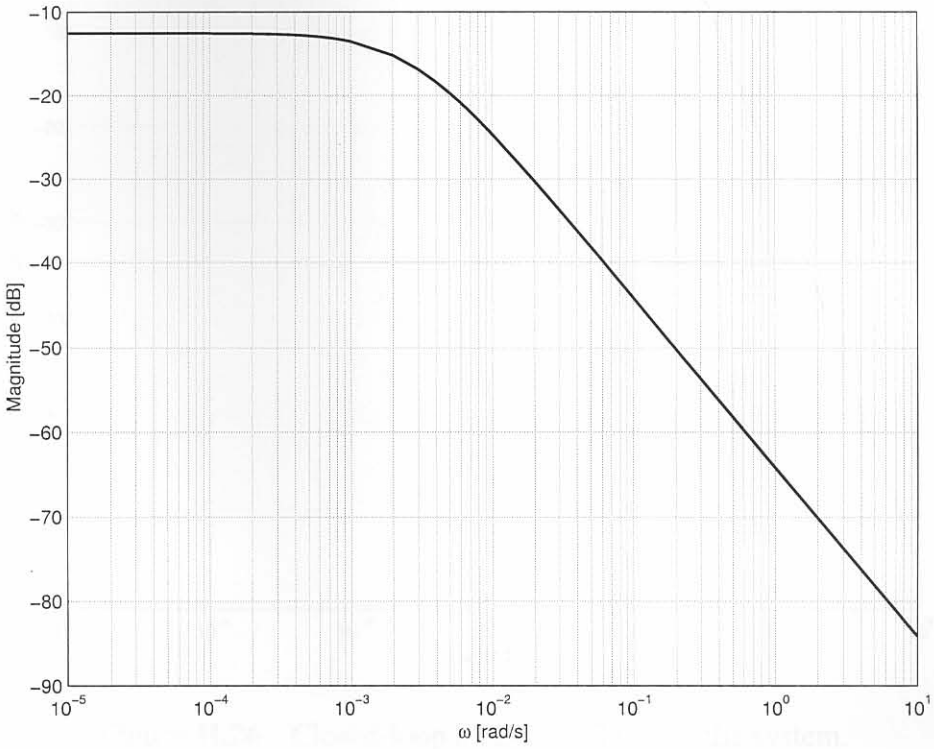

Figure H.25 Open-loop SVD plot of casting speed to the thermocouple temperatures without control ($\mathbf{g}(s)$).

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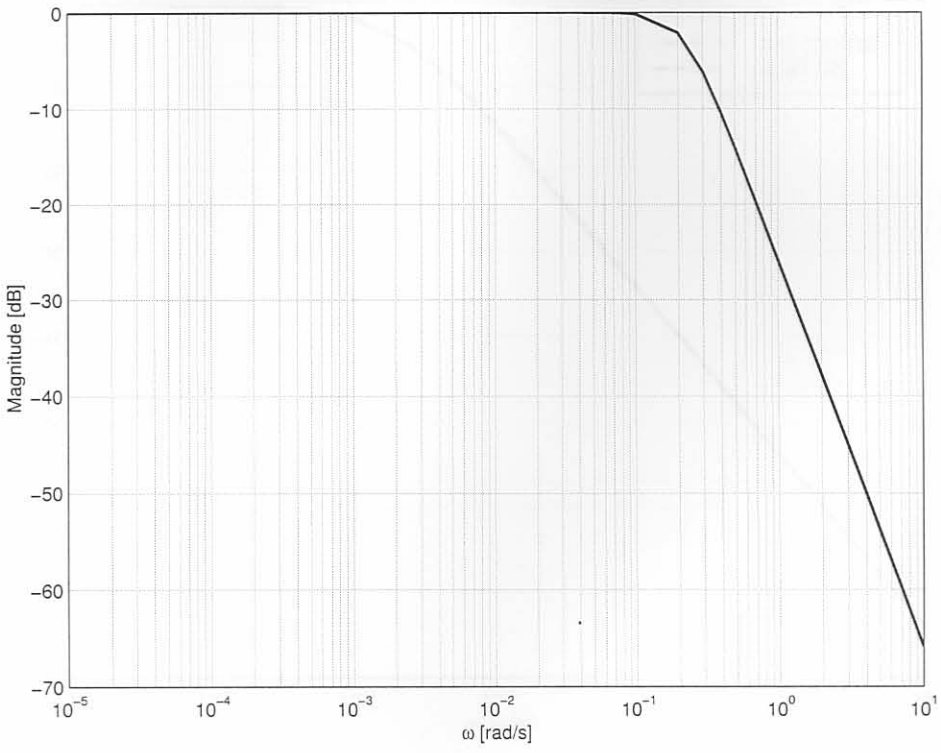

Figure H.26 Closed-loop SVD plot, $\mathbf{T}(s)$, of the system.

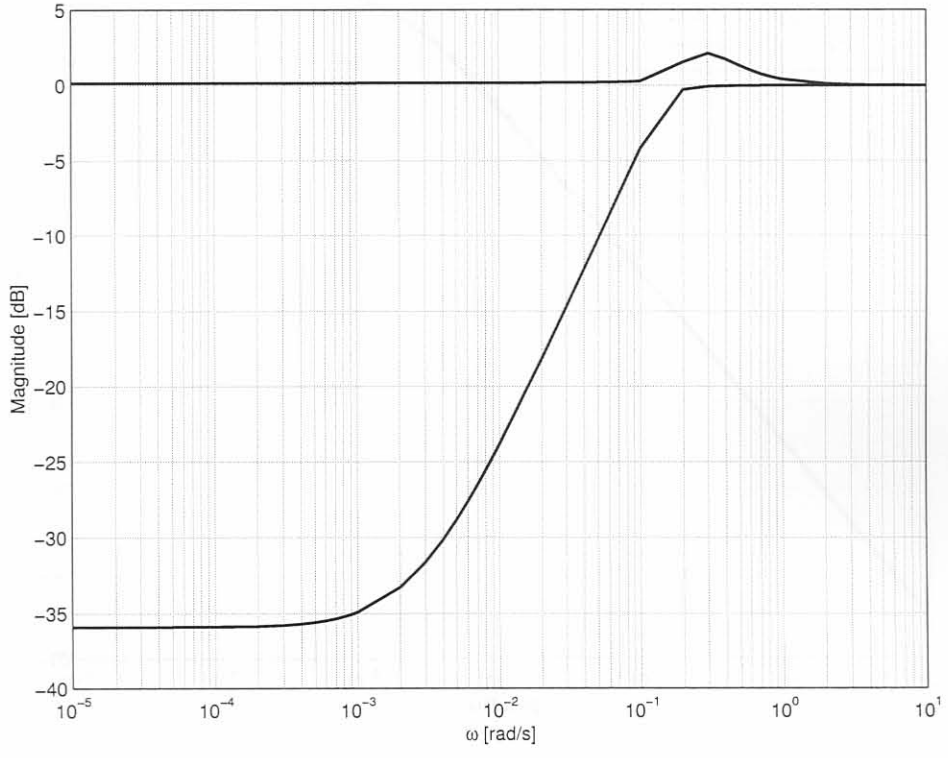

Figure H.27 Sensitivity function for the system.

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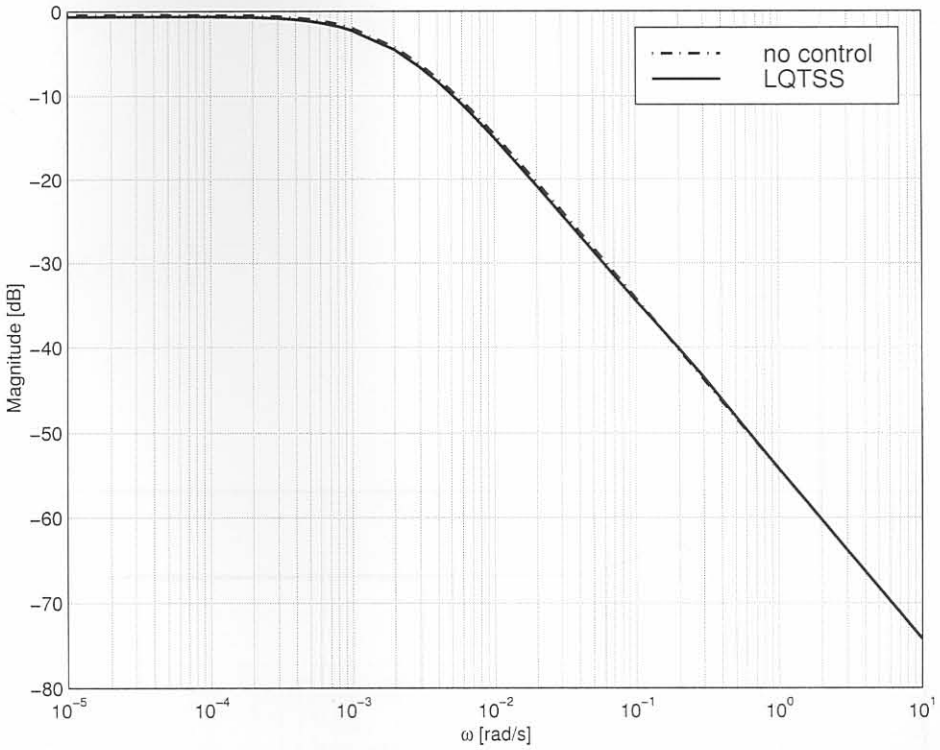

Figure H.28 Reduction in the effect of mould level disturbance on the output temperatures.

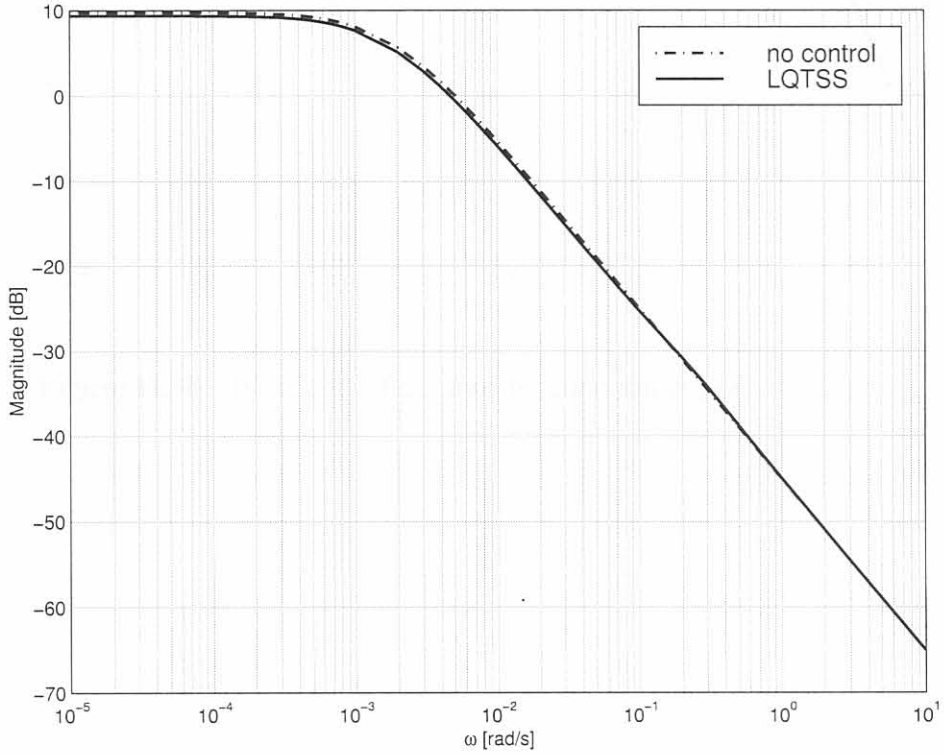

Figure H.29 Reduction in the effect of water temperature disturbance on the output temperatures.

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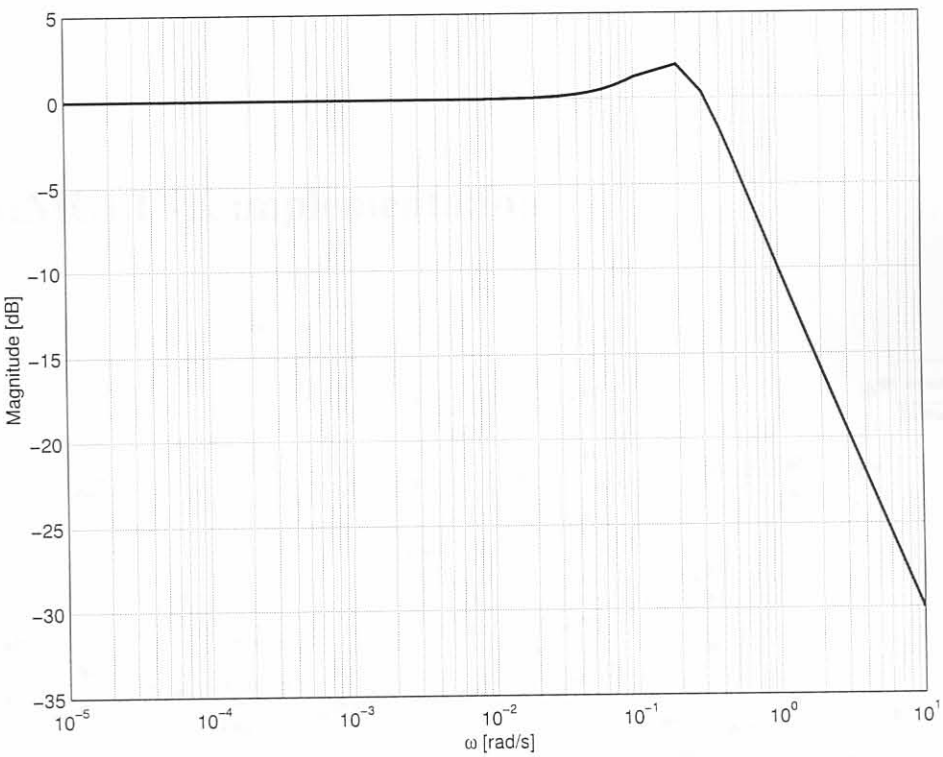

Figure H.30 Bode plot of the transfer function of $p(s) = h(s)v(s)$.