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ACCELEROMETER PLACEMENT FOR THE INTERNATIONAL SPACE STATION NODE MODAL TEST

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Abstract

Accelerometer location analysis for the modal survey test of the International Space Station Node is described. Three different approaches were utilized: 1. Guyan reduction, 2. iterative Guyan reduction, and 3. the average driving point residue (ADPR) method. Both Guyan approaches worked well, but poor results were observed for the ADPR method.

Although the iterative Guyan approach appears to provide the best set of sensor locations, it is intensive computationally, becoming impractical for large initial location sets. While this is computer dependent, it appears that initial sets larger than about 1500 degrees of freedom are impractical for the interative technique.

Test Configuration and Fixtures

The modal survey test of the International Space Station Node (Fig. 1) was one of the largest known tests in regard to the volume of instrumentation required, utilizing over 400 triaxial accelerometers and more than 1200 data channels. A primary reason for the large number of accelerometers was the requirement of including numerous components interior to the Node shell (Fig. 2). Great care was taken in all phases of test planning, pre-test analysis, and conduct of the test due to the importance of the Node as the first U.S.-built component of the Space Station to be launched.

Testing was done in a large fixed-base fixture developed specifically for Space Station modules, but which can be used for any trunnion- and keel-mounted Space Shuttle payload (Ref. 1). Figure 1 shows the Node mounted in the fixture. The test fixture utilizes flexure mechanisms to simulate the Shuttle Orbiter payload constraints. These mechanisms constrain translational motion in two degrees of freedom (DOF) at each primary trunnion, and one DOF at each secondary trunnion and the keel (Fig. 2). Reference 1 provides a description of the flexure mechanisms and their development.

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Description of Approaches Used for Sensor Location Analysis

Sensor location analysis for modal testing begins with engineering judgment supplemented by analysis to determine an initial set of measurement locations. Of course, locations that are not accessible, as well as rotational DOF, can be immediately removed from consideration. This initial set is much smaller than the full finite element model, but considerably larger than a practical final set of locations. The initial set of locations can partly be determined by visual inspection of the structure's geometry and mode shapes to determine critical regions of the structure for instrumentation. Critical regions will have well-defined motion in one or more of the target mode shapes, or provide paths by which loads are transmitted into the structure. Kinetic energy and mass-to-stiffness ratio calculations can also be used to help locate or verify critical locations.

Once the analyst has determined the character of the mode shapes and identified several important areas to be instrumented, the initial set of sensor locations includes these areas and also provides generally good coverage of the structure to define the mode shapes. A lot of conservatism can be utilized in the choice of the initial set to make sure that all possible regions of interest are covered. For example, initial sets of size greater than 2000 DOF may be reasonable for large complex structures. The next step in the process is to use analytical techniques to reduce the large initial set to a realistic size, which can be on the order of 200-400 locations or more for very large modal tests.

Several analytical techniques are commonly used for determining measurement locations, including kinetic energy sorting, iterative Guyan reduction (Refs. 2-3), and effective independence (Ref. 4). Reference 3 provides a good overview of these first three methods. Other techniques that have been investigated include use of flexibility shapes and genetic algorithms, as discussed in Refs. 5-7. Listed below are several techniques that were determined to be of interest for selection of measurement locations for the Node modal test.

Kinetic Energy Sorting

As described in Ref. 8, kinetic energy sorting involves an examination of each DOF's contribution of kinetic energy to each mode shape. By summing the energy over all the modes for each DOF, those coordinates having the greatest contribution or most energy can be indentified and retained in a candidate set.

Reference 8 indicates that a problem with this approach lies in its inability to recognize when many DOF have approximately equal kinetic energies, and that it cannot retain one such coordinate without retaining them all.

Guyan Reduction

Standard or noniterative Guyan reduction (Ref. 2) involves examining each DOF in the full model to determine which DOF have the largest diagonal mass to diagonal stiffness ratio. That is, the locations on the structure where inertia forces are large compared to elastic forces are to be retained. A sorting procedure can be used for finding the N degrees of freedom with the largest diagonal M/K ratio in descending order.

The result of this process is that a reduced model is generated that accurately preserves the dynamic characteristics of the structure at the lower frequencies (Refs. 3-4). If some higher-order modes are of interest for model correlation, then a larger set should be retained, a different technique should be used, or the results should be modified using engineering judgment.

Iterative Guyan Reduction

In this approach (Refs. 3-4), the ratio of diagonal mass to diagonal stiffness is again examined, but the DOF with the smallest ratio is removed. The mass and stiffness matrices are reduced, and the process is repeated. This procedure is continued until the desired model size and accuracy are achieved. The advantage of this iterative process is that the effects of each removed DOF are distributed to the remaining DOF, providing greater accuracy than the standard or non-iterative approach (Ref. 3).

Average Driving Point Residue (ADPR) Method

This approach is utilized in commercial software for modal testing and model correlation (Ref. 9). As described in Ref. 3, it uses an average magnitude or amplitude of mode shapes. Degrees of freedom with the highest average driving point residue, or highest weighted average modal magnitude, could make up a measurement set. A sorting procedure can be used to list these DOF in descending order.

Previous Comparative Studies

As stated in Ref. 6, "...no one method stands out as the clear choice. Methods which perform well in one instance may give completely unacceptable results in another." However, the authors of Ref. 6 go on to point out that the commonly used methods such as iterative Guyan reduction, kinetic energy sorting, and effective independence typically give reasonable results. Results of some comparative studies of several techniques are described in this section.

The comparative study in Ref. 6 describes selection of sensor locations for the Pegasus launch vehicle constrained at attach locations to the carrier aircraft. The full model had approximately 30,000 DOF, and the initial candidate measurement set consisted of 150 locations and 450 DOF. Several commonly-used methods (kinetic energy sorting, iterative Guyan reduction, and effective independence) were evaluated for the problem and compared to results using flexibility shapes. The methods were compared for a reduction of the measurement set to 150 DOF (300 coordinates eliminated), and 24 target modes to 50 Hz were selected. For that particular application, kinetic energy sorting, mass weighted effective independence, and iterative Guyan reduction performed best.

A second comparative study is described in Ref. 8, where kinetic energy sorting, iterative Guyan reduction, effective independence, and genetic algorithm methods were evaluated for four structural models. The test structures evaluated were a general-purpose spacecraft model, 10-bay space truss, avionics box, and satellite model. Size of the full models ranged from 360 DOF for the 10-bay truss to about 22,000 DOF for the satellite model. The initial set size varied from 168 to 576 DOF, and the final accelerometer set size was typically on the order of 30-75 DOF. Results consistently showed good performance of all four methods, but the genetic algorithm seeded with results of the other algorithms did best followed by iterative Guyan reduction.

Reference 3 compares the iterative Guyan reduction and ADPR methods for a cantilever beam, free-free H-frame, 2-D truss pinned at one end, and a free-free plate. Generally, the iterative Guyan procedure gave the best results, particularly for constrained structures with no rigid body modes. For free-free structures or those with one or more rigid body modes, the ADPR approach seemed to work better, but iterative Guyan also did an adequate job. Both methods are easily implemented.

In conclusion of comparative studies, iterative Guyan reduction fares very well generally for different boundary conditions, though kinetic energy sorting and mass-weighted effective independence also did quite well. The ADPR method appears to work well for free-free structures, or those with rigid body modes. Newer approaches such as genetic algorithms show great potential, but do not appear to be as easily implemented as the the more commonly used methods, and apparently must be seeded with results of the other algorithms. Based on these findings, Guyan reduction was given considerable attention in the accelerometer location analysis for the Space Station Node, as described in the remainder of the paper.

Application Of Methods to the International Space Station Node

The general approach taken for accelerometer placement for the Node external shell included the following steps: 1. Begin with a fairly large set based mainly on visual inspection of the structure geometry and analytical mode shapes, but also based on kinetic energy sorting, 2. Add locations known to be paths by which loads are transmitted to the structure, and other locations that appear to be of interest, such as trunnion and keel support structures, shell reinforcing rings, and end cones, 3. Run iterative Guyan reduction, beginning with the set described in 2., to reduce the number of locations for the Node external shell to about 190, 4. Use standard non-iterative Guyan reduction and ADPR reduction to also obtain candidate sets of measurement coordinates, 5. Run eigenvalue analyses for the reduced models and a reference Craig-Bampton model (Ref. 6) or full model, and form cross-orthogonality of the resulting modes normalized with respect to the reduced mass matrix.

Results of frequency comparisons and cross-orthogonality calculations were used as the figures-of-merit or standards by which each candidate set and reduction technique was evaluated. In Tables 1 and 2, the cross-orthogonality values are shown for two initial sets, one with nearly 500 external shell locations and 1500 DOF and the second with approximately 800 locations and 2400 DOF. It was found that the iterative Guyan approach provided measurement sets that compared very well with the reference model. Table 3 shows the cross-orthogonality values for a set reduced to 195 locations and 577 DOF. Comparison with Tables 1 and 2 verifies the good performance of the iterative Guyan approach. Poor results in all cases for modes 19-22 were found to be due to improper constraints for some internal connections in the Node finite element model. When the constraints were corrected, good orthogonality and frequency comparisons were obtained for modes 19-22.

The ADPR method did not perform well for the Node structure, as seen in Table 4. Possible this is because the Node test was a fixed-boundary configuration. Results in Ref. 3 suggest that the ADPR approach works better for free-free test configurations.

It was also found in this study that the kinetic energy sorting method as a stand-alone sensor location procedure did not work well. It was discovered that the method provided locations on the structure that are heavy and stiff, and not a good distribution of desirable measurement points.

Summary and Conclusions

This paper describes results of accelerometer placement analysis for the International Space Station Node fixed-base modal survey test. It was found that the iterative Guyan reduction method performed very well, yielding a measurement set with good frequency and cross-orthogonality comparisons to the reference model. However, the iterative method was computationally intensive, requiring long run times (about 4 hours wallclock time for the initial 1500 DOF set, and 2 weeks for the initial 2400 DOF set). Although the run times are dependent on computer platform and workload, it is clear that the iterative approach becomes impractical for initial candidate sets larger than about 1500 DOF.

Standard non-iterative Guyan reduction also provided a good measurement set, but the ADPR technique gave poor results for the Node structure in a constrained configuration.

Acknowledgments

Steven Woletz of Boeing Company in Huntsville, Alabama determined initial candidate accelerometer locations for the Node exterior, as well as the final set used in the modal test. Bobby Evars, also of the Boeing Company in Huntsville, determined sensor locations for the Node interior components.

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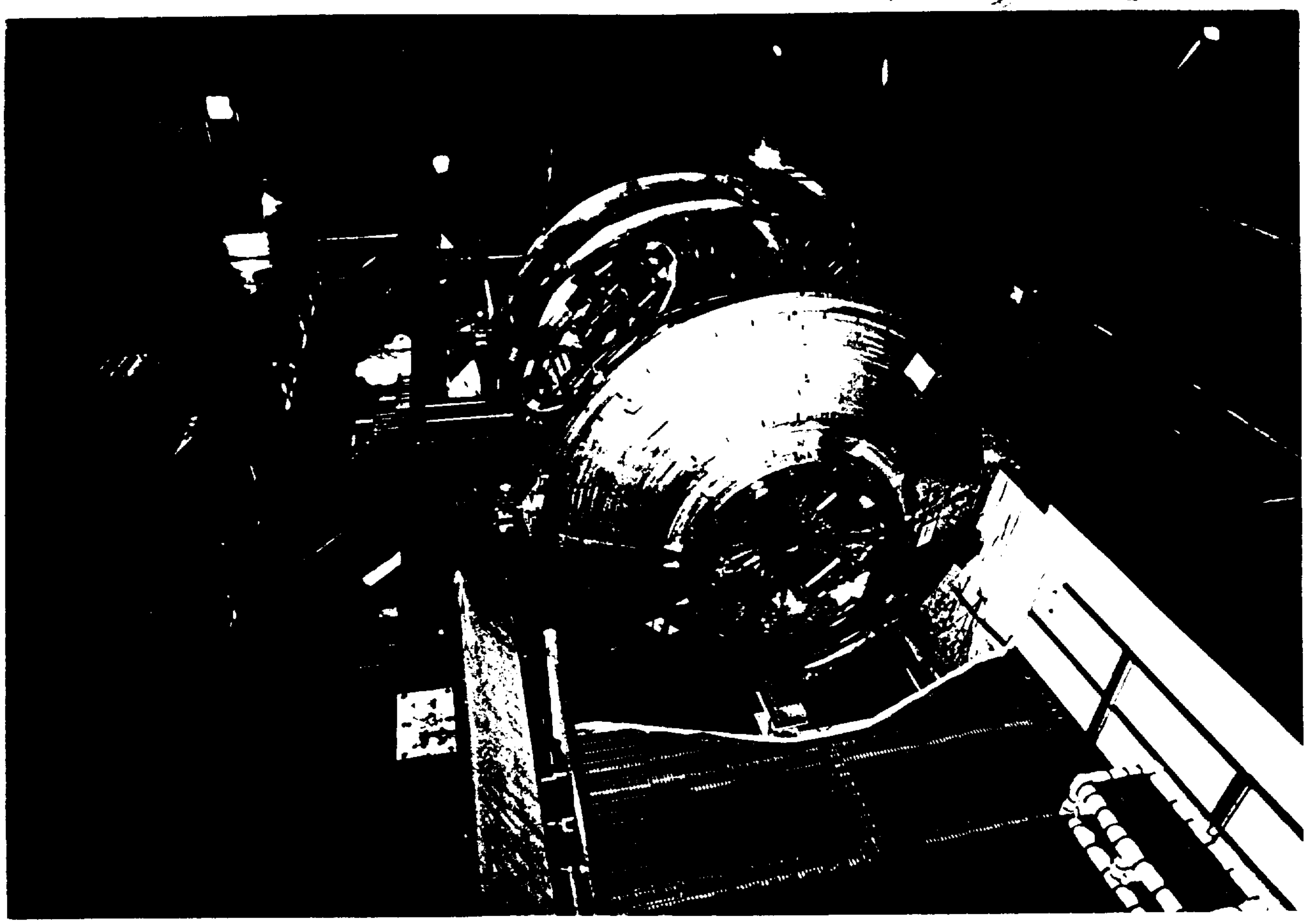

Figure 1. International Space Station Node in Modal Test Configuration

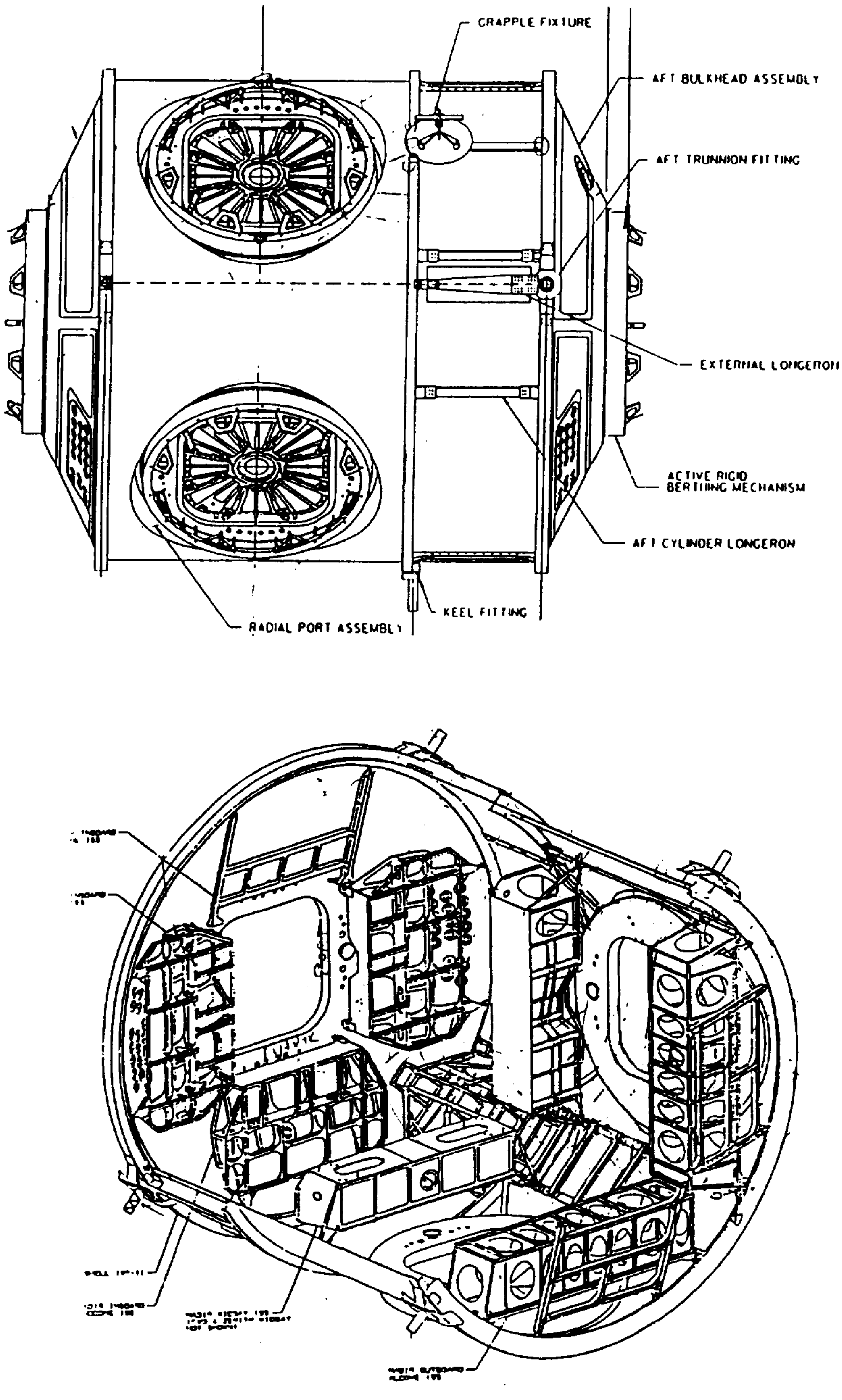

Figure 2. Space Station Node External Shell and Internal Structure

Table 1. Constrained Frequency and Mode Comparisons for 1500 DOF Initial Set and Full Model

	Full		Reduced	Correl.
1	7.3152	1	7.3161	-1.00000
2	10.7081	2	10.7113	1.00000
3	11.4486	3	11.4549	-1.00000
4	14.6754	4	14.6805	1.00000
5	17.8832	5	17.8851	-1.00000
6	18.1015	6	18.1042	0.99999
7	18.7835	7	18.7913	-0.99999
8	21.0240	8	21.1234	-0.99908
9	21.1056	9	21.2139	-0.99919
10	21.3428	10	21.4625	-0.99983
11	22.3180	11	22.3595	-0.99666
12	22.5698	12	22.6420	0.98907
13	22.6876	13	22.7260	-0.99202
14	23.2005	14	23.2457	-0.99932
15	24.0261	15	24.0306	-0.99970
16	24.2233	16	24.2530	0.99909
17	24.9343	17	24.9727	0.99507
18	25.5143	18	25.7124	-0.98312
19	25.7490	19	26.5827	-0.63343
20	25.8087	21	27.4732	-0.43050
21	25.8489	22	28.1236	0.24650
22	25.9833	18	25.7124	0.75599
23	26.5815	19	26.5827	-0.99812
24	26.7932	20	26.8195	-0.99944
25	27.3517	21	27.4732	-0.99831
26	28.0258	22	28.1236	-0.98411
27	28.1892	23	28.2791	-0.81537
28	28.2009	24	28.3412	0.78309
29	28.3107	25	28.3923	-0.99533
30	28.3453	26	28.4274	0.99176

Table 2. Frequency and Mode Shape Comparisons for 2400 DOF Initial Set and Full Model

	Full		Reduced	Correl.
1	7.2171	1	7.2180	1.00000
2	10.6779	2	10.6811	-1.00000
3	11.4250	3	11.4314	1.00000
4	14.6389	4	14.6438	-1.00000
5	17.7590	5	17.7607	1.00000
6	17.9636	6	17.9662	-1.00000
7	18.7371	7	18.7451	-0.99999
8	21.0096	8	21.1164	0.99965
9	21.1045	9	21.2092	0.99993
10	21.3496	10	21.4598	0.99993
11	22.0088	11	22.0379	-0.99962
12	22.3737	12	22.4292	0.99339
13	22.5631	13	22.6261	0.99183
14	22.9024	14	22.9506	-0.99825
15	23.6325	15	23.6373	-0.99981
16	23.8722	16	23.9002	0.99933
17	24.6049	17	24.6218	-0.99864
18	25.3699	18	25.5671	0.99471
19	25.7425	19	26.5074	0.63960
20	25.8066	21	27.4022	0.43516
21	25.8478	22	28.0672	0.25581
22	25.9583	18	25.5671	-0.66351
23	26.5134	19	26.5074	0.99578
24	26.7016	20	26.7220	-0.99949
25	27.2882	21	27.4022	0.99865
26	27.9624	22	28.0672	-0.97481
27	28.1374	24	28.2892	0.95073
28	28.1636	23	28.2482	0.99463
29	28.3037	25	28.3845	-0.99634
30	28.3365	26	28.4180	0.99306

Table 3. Comparison of Model Reduced Using Iterative Guyan Reduction to 577 DOF and Full Model

	Full		Reduced	Correl.
1	7.2196	1	7.2205	1.00000
2	10.6819	2	10.6850	1.00000
3	11.4300	3	11.4363	1.00000
4	14.6456	4	14.6507	1.00000
5	17.7610	5	17.7628	1.00000
6	17.9643	6	17.9670	1.00000
7	18.7479	7	18.7561	-0.99999
8	21.0198	8	21.1186	0.99916
9	21.1021	9	21.2103	-0.99929
10	21.3405	10	21.4601	0.99984
11	22.0126	11	22.0415	0.99969
12	22.3859	12	22.4425	0.99368
13	22.5785	13	22.6385	0.99201
14	22.9062	14	22.9541	-0.99816
15	23.6384	15	23.6431	0.99982
16	23.8784	16	23.9065	0.99935
17	24.6093	17	24.6257	0.99872
18	25.3845	18	25.5880	-0.99470
19	25.7470	19	26.5738	0.64030
20	25.8082	21	27.4616	0.43106
21	25.8482	22	28.1058	0.25143
22	25.9622	18	25.5880	0.67523
23	26.5742	19	26.5738	0.99852
24	26.7992	20	26.8268	0.99937
25	27.3403	21	27.4616	-0.99836
26	28.0028	22	28.1058	0.97190
27	28.1451	24	28.2998	0.89959
28	28.1937	23	28.2781	-0.94853
29	28.3062	25	28.3876	0.99487
30	28.3393	26	28.4217	0.99090

Table 4. Results for Model Reduced Using ADPR Method in Comparison to Full Model

	Full		Reduced	Correl.
1	7.2185	1	7.2957	-1.00000
2	10.6796	2	11.2582	0.92248
3	11.4261	3	11.7480	0.89365
4	14.6400	4	16.8584	0.94562
5	17.7593	5	17.8977	0.77481
6	17.9637	6	18.2141	0.74335
7	18.7400	7	21.3759	0.41561
8	21.0186	8	21.4238	0.64090
9	21.1018	7	21.3759	0.62388
10	21.3409	8	21.4238	-0.60177
11	22.0095	10	22.0903	-0.61034
12	22.3766	12	22.8021	0.72083
13	22.5662	12	22.8021	0.54391
14	22.9037	13	23.3842	-0.70360
15	23.6353	14	23.6921	0.72775
16	23.8746	15	24.0488	-0.68995
17	24.6069	16	24.8842	0.83705
18	25.3765	16	24.8842	0.56847
19	25.7443	17	26.4460	-0.62584
20	25.8077	19	27.2857	0.41153
21	25.8481	29	29.9961	-0.21809
22	25.9603	16	24.8842	-0.30521
23	26.5249	17	26.4460	-0.95181
24	26.7178	18	26.7485	0.99338
25	27.3099	19	27.2857	0.91490
26	27.9739	20	28.1439	-0.63554
27	28.1436	22	28.2872	0.79567
28	28.1739	24	28.4429	-0.57695
29	28.3052	23	28.4286	0.59759
30	28.3383	23	28.4286	-0.72719