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# LOCATING DAMAGED MEMBERS IN A TRUSS STRUCTURE USING MODAL TEST DATA: A DEMONSTRATION EXPERIMENT

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## Abstract

On-orbit assessment of large flexible space truss structures can be accomplished, in principle, with dynamic response information, structural identification methods and model correlation techniques which produce an adjusted mathematical model. In a previously developed approach for damage location, an optimal update of the structure model is formed using the response data, then examined to locate damaged members. An experiment designed to demonstrate and verify the performance of the on-orbit assessment approach uses a laboratory scale model truss structure which exhibits characteristics expected for large space truss structures. Vibration experiments were performed to generate response data for the damaged truss. This paper describes the damage location approach, analytical work performed in support of the vibration tests, the measured response of the test article, and some preliminary results.

## Nomenclature

| | |
|---|---|
| [B] | = a matrix |
| $B_{ij}$ | = $ij^{th}$ element of the matrix [B] |
| {B} | = a vector |
| $(B)_j$ | = $j^{th}$ element of {B} |
| [D] | = n x n diagonal weighting matrix |
| $d_i$ | = $i^{th}$ diagonal element of [D] = $\sqrt{k^c_{ii}}$ |
| $\Vert B \Vert_F$ | = matrix Frobenius norm, of a m x n matrix [B] $\left(\sum_{i=1}^{m}\sum_{j=1}^{n}(B)^2_{ij}\right)^{1/2}$ |
| [F] | = $n^2$ x np block diagonal matrix, see Eq. (5) |
| [I] | = identity matrix |
| [K] | = n x n adjusted stiffness matrix |
| $[K_c]$ | = n x n "original model" stiffness matrix |
| [M] | = n x n mass matrix |
| n | = number of degrees of freedom |
| p | = number of measured modes |
| $[P]_i$ | = n x n diagonal projection matrix of 1's and 0's which masks a vector with the sparsity pattern of the $i^{th}$ row of $[K_c]$ |
| sparse (B) | = zero/nonzero pattern of a matrix [B] |
| [S] | = n x p matrix of p expanded mode shape vectors |
| [Y] | = $[M][S][\Omega^2] - [K_c][S]$ |
| {Γ} | = np x 1 partitioned vector of Lagrange multipliers |
| $\{\Gamma_i\}$ | = $i^{th}$ p x 1 subvector of {Γ}, see Eq. (4) |
| {Δ} | = np x 1 partitioned vector, RHS of Eq. (4) |
| $\{\Delta_i\}$ | = $i^{th}$ p x 1 subvector of {Δ}, see Eq. (6) |
| [Π] | = $n^2$ x $n^2$ permutation matrix that converts a columnwise listing of an n x n matrix to a columnwise listing of its transpose, $[\Pi][z_{11}z_{12}\cdots z_{1n}z_{21}\cdots z_{2n}\cdots z_{nn}]^t = [z_{11}z_{21}\cdots z_{n1}z_{12}\cdots z_{n2}\cdots z_{nn}]^t$ |
| $[\Omega^2]$ | = n x n diagonal matrix of squared circular frequencies |

## Introduction

Researchers pursuing the goal to construct large orbiting space structures are considering many issues, including on-orbit assessment of the

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structure integrity. Assurance of adequate stiffness and stability would be aided by the ability to locate individual truss structure members which are damaged. Dynamic response measurements which may be available for use in controlling the structure can be used to indicate damaged members with an approach similar in principle to model correlation methods.

The concept of damage location for a large orbiting space structure is based on using the control system capabilities to, on occasion, excite the structure and measure its dynamic response. These measurements are used in a series of two identification algorithms to produce a model of the structure in its current configuration, which may contain damage. The model is compared to one previously obtained for the undamaged structure to find regions of reduced stiffness which indicate the location of damage. In the context of this paper, a "damaged" structure is one in which a member is removed entirely. However, no limitation in the damage location approach precludes cases where a truss member experiences a reduction in stiffness, while remaining intact.

Simulation studies in previous research demonstrated the potential of this approach to locate damage. However, experimental verification of the method is necessary. To this end, tests of a laboratory truss structure were devised to assess the method performance. The test article exhibits characteristics expected for large space trusses, including closely spaced frequencies and low damping. Dynamic tests conducted with the undamaged structure produced a correlated analysis model, which became the "original model" in the identification process. Tests of the truss in various "damaged" configurations, each with one member removed, provided modal data for the damage location process.

The objective of the experiment is to demonstrate and verify a previously developed approach for locating damaged members in a truss structure. This paper describes, in detail, the finite element analysis and dynamic test results for both the undamaged and damaged laboratory truss. A review of the damage location method is presented and the numerical implementation is discussed. Some difficulties encountered in processing the data for damage location are outlined, along with plans to complete the demonstration experiment.

## Background

### Damage Location Approach

The approach for locating damaged members in large space truss structures was developed by Smith and Hendricks,[1,2] then improved by Beattie and Smith.[3] A flow chart illustrating the approach is presented in Figure 1. In this chart, each vertical arrow represents a process that produces the results in the subsequent block. Several algorithms exist as possible candidates for each process. A comparison study of various algorithms and their effect on overall performance was not part of the scope of the current work.

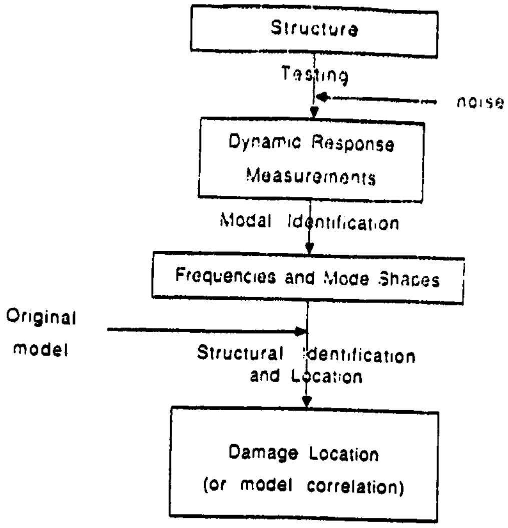



Figure 1. Damage Location Approach

The key identification algorithm, labeled "structural identification," produces an optimally adjusted stiffness matrix for the structure using an original model and modal data. Then the damage location algorithm, which uses graph theory for matrices, finds any regions of reduced stiffness to locate the damaged member.

The "original model," correlated to the undamaged truss, consists of the mass and stiffness matrices from a finite element model. Modal data, namely frequencies and a measured subset of the mode shapes, are obtained from sensor outputs using a second identification algorithm, labeled "modal identification." The mode shapes are expanded for use in the structural identification algorithm.

An overview of identification methods which produce frequencies and mode shapes from measured data is presented in Chapter 5 of Reference 4. Mode shape expansion is discussed by Berman and Nagy[5] as part of their Analytical Model Improvement (AMI) method. Also, a more recent approach for mode shape expansion is presented in Reference 10 as part of an equivalent reduced system model technique.

Kabe's[6] method of stiffness matrix adjustment was originally used in the work of Reference 2 as the key structural identification algorithm. Difficulties which arose in the numerical solution for large truss structure problems led to development and use of a new method (Beattie and Smith[3]) for this process of the damage location approach.

The Multiple Secant Marwil Toint (MSMT) method of Beattie and Smith is presented in detail in Reference 3. Briefly, the stiffness matrix is adjusted from an original form to a "closest" stiffness matrix which reproduces the measured frequencies and mode shapes as eigensolutions of the adjusted model.

The measure of "closeness" is a cost functional weighting the difference of the stiffness matrix elements

$$\|[D]^{-1}([K] - [K_c])[D]^{-1}\|_F^2 \qquad (1)$$

where

$$[D] = \text{diag}\ (d_i) = \text{diag}\ (\sqrt{K^c_{ii}})$$

Constraints are imposed with the method of Lagrange multipliers to represent the dynamic response, to ensure symmetry and to preserve the sparsity as follows:

$$[K][S] = [M][S][\Omega]^2,$$
$$[K] = [K]^t, \qquad (2)$$
$$\text{Sparse}\ ([K]) = \text{Sparse}\ ([K_c]).$$

Preservation of the zero/nonzero pattern of the original stiffness matrix enables successful identification of large structural models with relatively few modes. In addition this constraint equation maintains the correspondence between the physical structure and the model, since unrealistic load paths are precluded in the adjusted stiffness matrix. This is a key factor in the ability to locate damaged members.

Elements of the adjusted stiffness matrix are formed from the original stiffness matrix as

$$K_{ij} = K^c_{ij} + d_i d_j [([P]_i[D][S]\{r_i\})_j + ([P]_j[D][S]\{r_j\})_i] \text{ for } i,j = 1,2..n. \qquad (3)$$

The diagonal matrix $[P]_i$ contains only ones and zeros to mask the mode shape vectors in [S] with the sparsity pattern of the ith row of $[K_c]$. The partitioned vector $\{r\}$ is the solution of an auxiliary system of linear equations in the form $[A]\{x\} = \{b\}$.

The auxiliary problem is constructed from the original model and measured modal data to give

$$[F]^t([I] + [\Pi])[F]\begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_n \end{bmatrix} = \begin{bmatrix} \Delta_1 \\ \Delta_2 \\ \vdots \\ \Delta_n \end{bmatrix}. \qquad (4)$$

[F] is a block diagonal matrix of weighted masked modal vectors using the same projection matrix $[P]_i$,

$$[F] = \text{diag}\begin{bmatrix} [P]_1[D][S] & & \\ & [P]_2[D][S] & \\ & & \ddots [P]_n[D][S] \end{bmatrix} \qquad (5)$$

which is combined with the identity matrix I and a reordering matrix $[\Pi]$ to form the auxiliary problem coefficient matrix. The right-hand-side vector $\{\Delta\}$ is another partitioned vector formed with the original model and measured data as

$$\{\Delta_i\} = d_i^{-1}\begin{bmatrix} Y_{i1} \\ Y_{i2} \\ \vdots \\ Y_{ip} \end{bmatrix} \qquad (6)$$

weighting each row of $[Y] = [M][S][\Omega^2] - [K_c][S]$.

Implementation of the method can be accomplished by assembling the full symmetric positive semidefinite system and solving for $\{r\}$. However the dimension of the system is np × np which can lead to excessive computer storage requirements for a large structure. Iterative methods for solving Equation 4 take advantage of the repetitive substructure patterns and never assemble the coefficient matrix explicitly. A classical conjugate gradient method was used for solution of the auxiliary problem and required no more storage than that for the original stiffness matrix.[3]

A classical conjugate gradient solution for this auxiliary system may not converge since the system is only positive semidefinite. An error compensating version of the MSMT method produces a positive definite auxiliary system, which guarantees convergence.

## Experiment Hardware

The truss structure used for this investigation was constructed to demonstrate and verify various technologies for testing scale models of large flexible space structures. It is one in a series of structures designed for research into dynamic scale model ground testing of large space structures at NASA Langley Research Center.[7]

The test article is ten-bays long, cantilevered, and has an attached mass at its tip as shown in Figure 2. Each truss bay is a cube 1.64 feet on a side, for a total beam length of 16.4 feet.[8] The tip weight accounts for approximately 60 percent of the total structural weight of 147 pounds. The truss dimensions are such that the overall bay geometry is 1/10 scale of that proposed for the Space Station. However, individual truss components are not geometrically scaled. Constructed of aluminum erectable joints

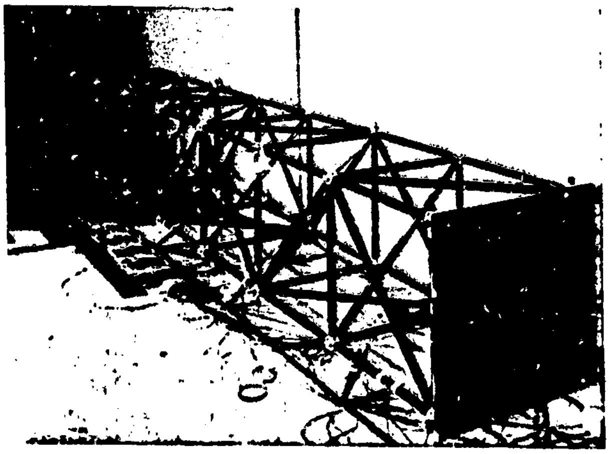


Figure 2. Ten-bay Generic Scale Model Truss Structure

and struts, a variety of truss member arrangements are possible.

For the current study, the truss member arrangement is slightly different than that proposed for the Space Station. In this case, the outer diagonals on all four faces are alternating in a Warren truss direction, while the interior diagonals are all in one direction. For the purposes of demonstrating the damage location process, the choice of diagonal arrangement is immaterial.

The presence of a large concentrated mass on a relatively light, distributed weight structure is one similarity of this test article to proposed space structures. Characteristics of the response exhibited by the test article resemble those for large space trusses, as well. The truss responds with low, closely-spaced frequencies and light damping.

Impact testing was used to determine the dynamic response of the scale model truss. An instrumented hammer was used as an excitation source. Acceleration responses were simultaneously measured at various locations on the truss. Each accelerometer and the force hammer were calibrated to achieve accurate mode shape estimations.

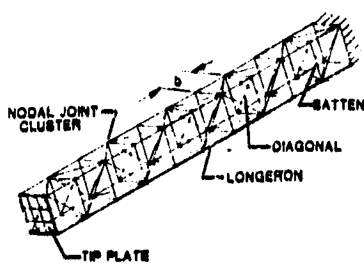
The number of acceleration measurements was selected to be approximately 10% of the total number of truss degrees-of-freedom. This is representative of the situation expected on-orbit where a relatively small number of measurements will be available to characterize the structures. Accelerometers were placed at the truss midplane and at the tip, in both the lateral and vertical directions. Six of the first seven global vibration modes were identified. The seventh mode (sixth in terms of frequency) is an axial mode, which was not of significant interest for the current work.

A GenRad 2515 dynamic test system was used to acquire and reduce all of the test data. Accelerometer and force measurements were processed with standard modal analysis techniques (ModalPlus software, Reference 11). Due to the close spacing of some modes, some tests were repeated using different operating bandwidths in order to achieve the required resolution to separate and identify the modes. Resonant frequencies and mode shapes were extracted from frequency response functions computed in the modal analysis. In order to obtain the best estimate of the structure's modal properties, a number of excitation and response locations and impact ensemble averages were used.

## Analysis

NASTRAN finite element analyses were used to predict the vibration modes of the undamaged truss structure. This provided the stiffness and mass matrices for the "original model" of the damage location process. In addition, correlation of the analyses with tests of the undamaged truss provided confidence in test procedures.

Figure 3 presents the model mesh and properties used to construct the model. Each truss member was modeled as a rod element, with an




| Truss Properties | |
|---|---|
| total weight | 147.40 lb |
| tip weight | 86.28 lb |
| nodal joint cluster weight | 1.097 lb |
| strut EA | $1.139 \times 10^6$ lb |
| b | 19.7 in |
| total length | 197.0 in |
| $\rho$ diag | 0.0731 lb/in$^3$ |
| $\rho$ long | 0.0785 lb/in$^3$ |

Figure 3. Ten-Bay Truss Model Mesh and Properties

effective axial stiffness to account for the presence of the nodal joint. For the purpose of identifying global vibration modes, a rod element model produces essentially the same results as a beam element model. Concentrated masses were added to represent the nodal joint clusters. The tip weight was modeled as a number of interconnected plate elements to accurately account for rotational inertia.

It should be noted that the stiffness properties of the finite element models employed herein were previously verified at the component and subassembly level (reference 8). Thus, the truss properties were accurately known, a priori. This contributed to the excellent test/analysis agreement of the undamaged truss.

Table 1 and Figure 4 present analysis results for the undamaged truss. Frequency results and mode descriptions are listed in the table, while the corresponding mode shapes are shown in the figure. Two closely-spaced bending mode pairs (B1 and B2), two torsional modes (T1 and T2) and one axial mode (A1) are depicted.

Analysis of the damaged truss was conducted to reveal cases of interest for damage testing. Results for the damaged truss are presented in the next section for comparison with the test results.

## Tests

For tests of the undamaged truss, observed frequencies and modes were compared to those predicted by analysis. Percent difference comparisons of test and analysis frequencies provided one method of correlation. In addition, the Modal Assurance Criterion (MAC) parameter[9] was used to indicate the correspondence of test and analysis mode shapes. A MAC parameter of 1.0 indicates perfect correlation of two shapes within a scale factor. Orthogonal modes produce a MAC parameter of 0.

Table 1 presents test results with analysis predictions for the undamaged truss. Excellent test/analysis correlation is indicated by the frequency and MAC parameter comparisons. Since the analysis model for the undamaged truss provided modal predictions in agreement with the test results, the "original model" was established.

Each case of damage consists of removing a single member from the truss. Figure 5 shows the members removed for the damaged cases considered. Table 2 presents the mode(s) most affected for

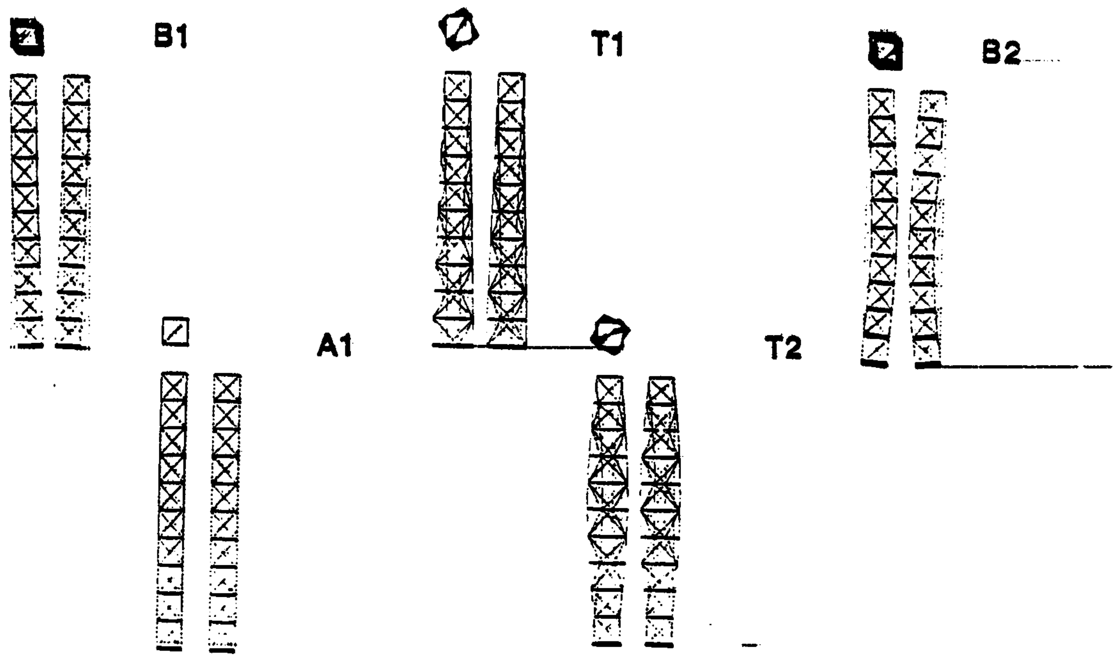



Figure 4. Ten-Bay Truss Analysis Mode Shapes

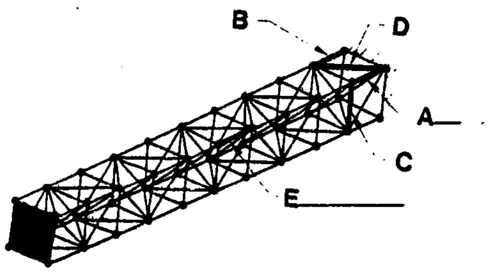



Figure 5. Selected Damage Test Cases for the Ten-Bay Truss

each damage case. Maximum frequency change and affected mode (as predicted by analysis) are included along with the corresponding test results for frequency changes. In cases that involve the removal of a longeron, the truss bending modes are most affected. Likewise, torsion modes are affected by the removal of a diagonal member.

The removal of the vertical member for case C did not significantly affect the bending or torsion modes under consideration. The axial mode is most affected, but its frequency change was slight. No displacement measurements were available in the axial direction, therefore Case C was eliminated as a test case.

Typical results for a particular damage case are shown in Table 3 which summarizes the frequencies for the undamaged truss alongside those for damage case A. Results from both analysis and test are presented. Again correlation of the test results to analysis predictions is excellent.

Table 4 combines the frequency results for the remaining damage cases. Analysis predictions and test results are presented for each case. Again, excellent correlation between analysis and test is evident. The MAC parameters reported in Table 3 for Case A are typical for these three damage cases as well and are not reported.

Each of the four remaining damage cases present a unique situation for damage detection. Cases A and B each involve one model of the first bending mode pair, but due to the member arrangement the truss is more sensitive to the damage of Case A. Case D damage affects more than one mode significantly. Both torsion modes are sensitive to Case D damage. Finally, Case E involves a longeron positioned in bay 5 that will allow comparisons with the results of Case A damage.

## Damage Location

Simulated damage problems studied in Reference 2 demonstrated that for a similar truss structure only three modes are needed for unique structural identification. Kabe[6] showed that including additional modes improved the results when the modes were corrupted with noise. Here six modes, excluding the axial mode, are available for use in the damage location approach.

With measured frequencies and partial mode shapes from the testing and modal analysis, expansion of the mode shapes is required before proceeding with damage location. In the flow chart of Figure 1, this process is not illustrated specifically. However it plays a more important role than originally envisioned.

The original model contains 120 degrees of freedom and the modal displacements for only 14 of these were determined from the testing and modal identification. Berman and Nagy's[5] expansion technique or the System Equivalent Reduction/Ex-

Table 2. Effect of Removed Members on Scale Model Truss

| case no. | removed member** | % max freq change (analysis) | mode affected | % max freq change (test) |
|---|---|---|---|---|
| 1 | A | 30.0 | 2 (B1) | 29.3 |
| 2 | B | 21.4 | 1 (B1) | 21.1 |
| 3 | C | 1.6 | 6 (A1) | * |
| 4 | D | 19.6, 15.4 | 7, 3 (T2, T1) | 16.9,12.5 |
| 5 | E | 18.1, 14.0 | 5, 2 (B2, B1) | 20.0,13.8 |

*did not attempt to measure
**see Figure 5

Table 3. Results for Damaged Truss (Damage Case A*)

| mode no. | mode desc. | frequency (Hz) undamaged analysis | undamaged test | damaged analysis | damaged test | percent change analysis to analysis | percent change test to test |
|---|---|---|---|---|---|---|---|
| 1 | B1 | 4.10 | 3.94 | 4.10 | 3.93 | 0.0 | 0.25 |
| 2 | B1 | 4.16 | 4.00 | 2.92 | 2.83 | 29.8 | 29.3 |
| 3 | T1 | 26.1 | 26.1 | 26.1 | 26.0 | 0.00 | 0.38 |
| 4 | B2 | 36.2 | 36.0 | 36.2 | 36.0 | 0.00 | 0.0 |
| 5 | B2 | 38.1 | 37.8 | 34.3 | 34.3 | 9.9 | 9.3 |
| 6 | A1 | 47.2 | 45.9 | 45.9 | 45.1 | 2.8 | 1.7 |
| 7 | T2 | 86.6 | 90.4 | 86.6 | 90.4 | 0.00 | 0.0 |

note: bending mode pairs switched places
*see Figure 5

Table 4. Results for Damaged Truss (Damage Cases B, D, E**)

| mode no. | mode desc. | frequency (Hz) Case B analysis | Case B test | Case D analysis | Case D test | Case E analysis | Case E test |
|---|---|---|---|---|---|---|---|
| 1 | B1 | 3.22 | 3.09 | 4.07 | 3.94 | 3.58 | 3.50 |
| 2 | B1 | 4.16 | 3.99 | 4.15 | 3.99 | 4.10 | 3.98 |
| 3 | T1 | 26.1 | 26.0 | 22.1 | 22.5 | 26.1 | 26.1 |
| 4 | B2 | 31.7 | 31.7 | 34.0 | 34.0 | 31.2 | 31.4 |
| 5 | B2 | 38.1 | 37.8 | 37.4 | 37.1 | 36.3 | 36.4 |
| 6 | A1 | 46.5 | * | 47.0 | * | 45.7 | * |
| 7 | T2 | 86.6 | 90.5 | 69.6 | 72.3 | 86.8 | 90.4 |

*did not attempt to measure
**see Figure 5

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15. Supplementary Notes

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16. Abstract

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