21-追
64

STRUCTURAL SYSTEMS— STATICS, DYNAMICS AND STABILITY

图书资料

STRUCTURAL SYSTEMS—STATICS, DYNAMICS AND STABILITY

Moshe F. Rubinstein

Professor of Engineering and Applied Science
Chairman, Engineering Systems Department
University of California, Los Angeles

Prentice-Hall, Inc.

Englewood Cliffs, New Jersey

PREFACE

The material in this book was developed in teaching a graduate course in structural analysis in the School of Engineering and Applied Science, UCLA, and in a two-week short course for practicing engineers. The purpose of the book is to provide a text for a one-semester (3 hours per week) graduate course in advanced analysis of structures or a one-quarter (4 hours per week) graduate course. One of the primary objectives is to develop a unified approach for the analysis of structural systems which brings together the areas of statics, dynamics and stability analysis. The basic theme of the book is the synthesis of system characteristics from those of the constituent elements in the *Finite Element Method.* Beginning with the concept of coordinates and energy principles, a common basis is established for formulating problems in static, dynamic and stability analysis of structural systems. It is demonstrated that the characteristics of a finite element are synthesized from differential parallelepiped elements in the same way as the characteristics of the total system are synthesized from those of the finite elements. The physical significance of the stiffness matrix, flexibility matrix, mass matrix and stability matrix are emphasized, and the analogy is developed between the concepts employed in static, dynamic and stability analysis. The basic concepts are developed for the formulation and solution of structural systems including frames, plates and shells.

The student using this book is expected to have completed a course in matrix methods of structural analysis comparable to the content of the first nine chapters of *Matrix Computer Analysis of Structures* (Rubinstein, Prentice-Hall, 1966).

The practicing engineer who has already discovered the potential of the digital computer in static analysis will find this book useful in learning how to formulate problems for the static, dynamic and stability analysis of complex structures. He will also gain insight into the efficient decomposition method of solution which provides guides for error detection and control in computer applications.

To assist the student in studying the material and the practicing engineer in using it, summary tables are included at frequent points in the text. The tables show as a group the key equations and key steps in the formulation and solution of problems in statics, dynamics and stability analysis. Summaries also appear at the end of chapter for ease of reference.

To help with the teaching function, worked-out solutions to the problems at the end of each chapter are available upon adoption of the book.

The content of each chapter in the book is as follows:

Chapter 1 develops the concepts of coordinates and coordinate transformations which are central to the subject of the book. Eigenvalues and eigenvectors are introduced in connection with static analysis in order to emphasize the physical significance of these concepts which are used in dynamics and stability analysis.

Chapter 2 provides a complete treatment of energy principles and their engineering implications. The foundation is set for understanding how bounds are established on the solutions in finite element analysis, and the key concepts are developed for stability analysis.

Chapter 3 discusses the subject of static analysis by finite elements. The stiffness and flexibility methods are developed in parallel, to include forces not at the coordinates. The basic approach of synthesizing system characteristics from constituent building blocks is developed. The common basis for generating finite element characteristics is emphasized by showing how to generate the characteristics of the following elements: a plate element in plane stress, a plate element in bending, a tetrahedron element, and a ring element with triangular cross-section.

Chapter 4 treats the solution of linear equations and error analysis through the use of the matrix decomposition approach, which is among the most efficient for computer applications. Error analysis in computer solutions is discussed and guides are suggested for error detection and control. Gradient methods of solution based on minimization of total potential are also presented.

Chapter 5 shows how problems in dynamics can be formulated by beginning with coordinates and constituent elements. The analogy to the static analysis is pointed out. The solution of problems in structural dynamics with *n* coordinates is synthesized from a single coordinate building block using the normal mode method. The engineering implication of this method is emphasized. The solution of dynamic problems by matrix decomposition and iteration is demonstrated.

Chapter 6 establishes the procedure for formulating problems in stability analysis of systems from constituent elements. The analogy to the developments for static and dynamic analysis in Chapters 3 to 5 respectively is emphasized. Stability matrices are derived for a beam and plate element, and the eigenvalue problem is formulated for the stability analysis of a complete system.

I have many persons to thank. Professor Walter C. Hurty contributed significantly to my education in years of fruitful association. Professor Vladimir Simonče read the manuscript and made helpful suggestions. Antone Sayegh and Patricia Schottkoefer assisted me during the production of the book. My students solved problems, pointed out errors and helped clarify the presentation.

As I think of my students in the years of teaching which paved the way for this book, I find it most appropriate to fall back on a paraphrase of an old Talmudic proverb: ***I have learned much from my teachers, more from my friends, but most from my students.***

SYMBOLS

The symbols listed have also the same meaning in the following texts:

Dynamics of Structures by W. C. Hurty and M. F. Rubinstein, Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1964.

Matrix Computer Analysis of Structures by M. F. Rubinstein, Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1966.

$[A]$	matrix associated with finite element displacement functions; matrix of coefficients
A	area
$[a]$	system flexibility matrix
$[B]$	matrix associated with the expression for element strains, force transformation matrix
$[b]$	transformation matrix in equations of equilibrium
$[C]$	matrix associated with element displacement, displacement transformation matrix
$[c]$	system damping matrix
c	velocity of light; constant
$[\mathscr{c}]$	element damping matrix
$[D]$	dynamical matrix
DLF	dynamic load factor (dynamic amplification of static displacement)
$\lceil D \rfloor$	diagonal matrix in decomposition
E	Young's modulus
e	natural base of logarithms
$\{e_i\}$	base vector with $e_i = 1$, $e_j = 0$ $(j \neq i)$
F	force
F_D	system damping force
f_D	element damping force
G	shear modulus $G = E/2(1 + \nu)$
$[G]$	transformation matrix used in synthesis of element stability matrix [Eq. (6.9-10)]
$[H_q]$	Hessian matrix

此为试读，需要完整PDF请访问：www.ertongbook.com

h	Planck's constant
I	moment of inertia
$[I]$	identity matrix
i	$\sqrt{-1}$
$[k]$	system stiffness matrix
$[L]$	lower triangular matrix
l	length
M	moment
m_{rel}	relativistic mass
$[m]$	system mass matrix
$[\mathscr{M}]$	element mass matrix
$m(x)$	moment per unit length
$[N]$	matrix relating stress and strain
N	force, generalized force in normal coordinates
N_{xx}, N_{yy}, N_{xy}, N_{yx}	in-plane forces for plate element
$O(\delta^3)$	symbol for third-order variation and higher
P	element force
$\{P\}^0_{FNC}$	element force vector at the fixed coordinate state due to forces not at the coordinates
$\{P\}^0_{ID}$	initial element forces at the fixed coordinate state due to initial displacements.
$p(x)$	distributed force function
$p_s(x, y, z)$	force per unit area at (x, y, z)
$p_v(x, y, z)$	force per unit volume at (x, y, z)
$\mathscr{P}$	element momentum
p	system momentum
$\{p\}_i$	vector in direction of iteration in gradient methods
Q	force
q	displacement
R_i	residual in ith equation of relaxation
R	dissipation function
$\{r\}_i$	residual force vector in gradient methods
r	radius, correlation coefficient
s_a^2	sample variance of variable a
s_b^2	sample variance of variable b
s_{ab}	sample covariance of variables a and b
$[s]$	system stability matrix
$[S]$	upper triangular matrix with 1's on principal diagonal
$[\mathscr{s}]$	element stability matrix
$[T]$	coordinate transformation matrix

T^*	kinetic coenergy
T	kinetic energy
t	time, thickness
U	strain energy
U^*	complementary strain energy
$[U]$	upper triangular matrix
U_e	potential of external forces
u	displacement
V	total potential
V^*	total complementary potential
v	displacement
W_N	work done by axial forces
W_Q	work done by forces Q at the coordinates
W^*	complementary work
W	work
w	displacement
x	position coordinate
Y	constant
y	position coordinate
Z	force
z	position coordinate
$[\alpha]$	element flexibility matrix
α	coefficient in gradient methods algorithms
$[\beta]$	transformation matrix in equations of compatibility
β	damping coefficient, coefficient in conjugate gradient algorithm
ν	Poisson's ratio
Δ	symbol for "total variation of . . ."; area of triangle; second-order displacement in stability analysis
δ	element displacement
$\{\delta\}^0_{FNC}$	element displacement vector at the free coordinate state due to forces not at the coordinates
$\{\delta\}^0_{ID}$	initial displacements in free coordinate state.
δ^1	symbol for "first-order variation of . . ."
δ^2	symbol for "second-order variation of . . ."
ϵ	strain
$\{\epsilon\}^0_{FNC}$	strain vector in the free coordinate state due to forces not at coordinates
$\{\epsilon\}^0_{IS}$	initial strain vector in the free coordinate state due to thermal expansion or lack of fit
ζ	displacement; fraction of critical damping $\left(\zeta = \frac{\beta}{\omega} = \frac{C}{2m\omega}\right)$

η	normal coordinate of displacement
$[\kappa]$	element stiffness matrix
λ	eigenvalue
ξ	displacement
$\sum$	summation operator
σ	stress; standard deviation
$\{\sigma\}^0_{FNC}$	stress vector in the fixed coordinate state due to forces not at the coordinates
$\{\sigma\}^0_{IS}$	initial stress vector in the fixed coordinate state required to reduce to zero strain $\{\epsilon\}^0_{IS}$ in the free coordinate state
σ_{xp}	covariance of variables x and p
σ^2_x	variance of variable x
σ^2_p	variance of variable p
τ	time
$\phi(x)$	displacement function
$[\Phi]$	orthogonal transformation matrix; modal matrix
ω	circular natural frequency
ω_d	circular natural frequency of damped system
∇	symbol for "gradient of . . ."; del operator

CONTENTS

此为试读，需要完整PDF请访问：www.ertongbook.com

1

COORDINATES AND LINEAR VECTOR SPACES

1.1 INTRODUCTION

The fundamental conditions that govern the behavior of structural systems can be considered in three parts:

1. Displacement constraints ≡ *Compatibility.*
2. Force constraints ≡ *Equilibrium.*
3. Force–displacement relations ≡ *Hooke's law* (for linear elastic structures).

To establish the above conditions and relate them to a particular structure it is essential to construct a device for identifying forces and displacements. A *coordinate system* is such a device. The concept of coordinates is central to the subject of this book and is considered in this chapter.

1.2 COORDINATES[1,2]†

Consider the structure of Fig. 1.2-1 in the plane of the paper. The 12 numbered arrows are the *coordinates* of the structure. The coordinates are used to describe events such as a displaced configuration that exists at a given time, or a force group that is applied at a given time. The information

†Superscript numerals refer to bibliographical items cited in the section of references at the end of the book.

obtained from the description of these events is limited to the arrows where coordinates are defined. The description of any event is considered complete only when the information is known at all coordinates.

In Fig. 1.2-1, a displaced configuration is described by a displacement vector $\{u\}$ consisting of 12 components, in which each component u_i $(i = 1, 2, \ldots, 12)$ is the magnitude of the displacement at coordinate i. The word displacement includes rotation. Similarly, a force group acting on the structure of Fig. 1.2-1 is described by a vector $\{F\}$ in which each component F_i $(i = 1, 2, \ldots, 12)$ is the magnitude of the force at coordinate i. The word force includes torque and moment.

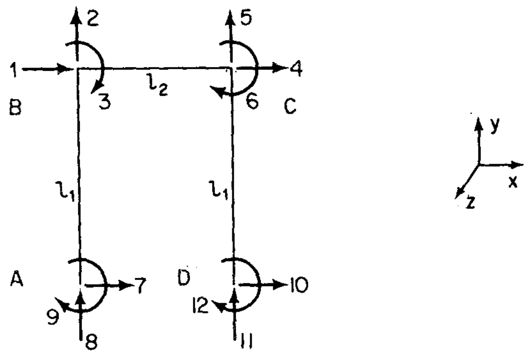

Fig. 1.2-1 Coordinates.

Any arbitrary displacement vector $\{u\}$ in Fig. 1.2-1 can be written

$$\{u\} = \sum_{i=1}^{12} u_i \{e\}_i, \tag{1.2-1}$$

in which $\{e\}_i$ is a vector representing a displacement configuration with a displacement of unity at coordinate i and zero displacements at all other coordinates. u_i is the amplitude of configuration $\{e\}_i$. Hence, *vector* $\{e\}_i$ *identifies coordinate i and* u_i *is its amplitude or magnitude.*

Similarly, any arbitrary force vector $\{F\}$ in Fig. 1.2-1 can be written

$$\{F\} = \sum_{i=1}^{12} F_i \{e\}_i, \tag{1.2-2}$$

in which $\{e\}_i$ represents a force group with a force of unity at coordinate i and zero forces at all other coordinates. F_i is the amplitude of force group $\{e\}_i$. Here again, $\{e\}_i$ *identifies coordinate i, and* F_i *gives its amplitude or magnitude.*

Note that in Eqs. (1.2-1) and (1.2-2) the amplitudes of 12 vectors $\{e\}_i$ must be specified in order to completely describe any arbitrary vector $\{u\}$ or $\{F\}$ for the 12 coordinates in Fig. 1.2-1.

1.3 DEPENDENCE AND INDEPENDENCE[2]

In the system of Fig. 1.2-1 constraints may be imposed on the forces or displacements at the coordinates. Constraints inhibit the freedom of arbitrary choice and bring about a reduction in the number of quantities required to describe an event.

Constrained Displacements ≡ Compatibility. In Fig. 1.2-1 the displacements are independent and can be assigned any arbitrary values u_i in Eq. (1.2-1). Suppose now that station D, where coordinates 10, 11, and 12 are defined, is held so that no displacements can take place there. In this case the following three equations of constraints are written:

$$\left.\begin{aligned} u_{10} &= 0 \\ u_{11} &= 0 \\ u_{12} &= 0. \end{aligned}\right\} \qquad (1.3\text{-}1)$$

Equations (1.3-1) are equations of *external connectivity—or displacement compatibility at the boundaries of the structure.*

Further constraints can be introduced, for example, by considering the members of the structure in Fig. 1.2-1 infinitely stiff along their axial directions, so that their lengths cannot be changed. The corresponding equations of constraints are

$$\left.\begin{aligned} u_1 - u_4 &= 0 \\ u_2 - u_8 &= 0 \\ u_5 - u_{11} &= 0. \end{aligned}\right\} \qquad (1.3\text{-}2)$$

Equations (1.3-2) are *equations of internal connectivity—or displacement compatibility internal to the structural system.*

Equations (1.3-1) and (1.3-2) reduce the 12 independent displacements of Fig. 1.2-1 to 6. Now a complete description of a displaced configuration (considering only stations where coordinates are defined) consists of 6 independent quantities, for instance, u_i for $i = 3, 4, 6, 7, 8, 9$ or u_i for $i = 1, 2, 3, 6, 7, 9$.

Constrained Forces ≡ Equilibrium. When the forces are assigned arbitrary values at the coordinates in Fig. 1.2-1, a net force may act on the structure, and, according to Newton's second law of motion, acceleration may result. If the structure is not to accelerate, the forces acting on it must be constrained so that no net force results. For the structure of Fig. 1.2-1, three such equations must be written (moments are taken about A):

$$\left.\begin{aligned} F_1 + F_4 + F_7 + F_{10} &= 0 \\ F_2 + F_5 + F_8 + F_{11} &= 0 \\ F_3 + F_6 + F_9 + F_{12} + F_1 l_1 + F_4 l_1 - F_5 l_2 - F_{11} l_2 &= 0. \end{aligned}\right\} \qquad (1.3\text{-}3)$$

Equations (1.3-3) are *equations of equilibrium*. For structures in three-dimensional physical space, six equations of equilibrium must be written.

Generalization. We define a set of displacement measurements u_i, identified by coordinates i, as *linearly dependent* if at least one linear equation of constraint can be written in the form

$$\sum_i c_i u_i = 0, \tag{1.3-4}$$

in which c_i are arbitrary constants with not all $c_i = 0$. This definition applies to all the measurements identified by the coordinates. For example, the forces F_i are linearly dependent if at least one equation of constraint can be written in the form†

$$\sum_i c_i F_i = 0, \tag{1.3-5}$$

with not all $c_i = 0$. If no equations of the above form can be written, that is, no arbitrary constants c_i other than $c_i = 0$ for all i can be found which satisfy Eq. (1.3-4), then displacements u_i are independent. Similarly, if Eq. (1.3-5) does not exist, the forces F_i are independent. Such independent u_i and F_i are referred to as *generalized displacements* and *generalized forces*, respectively.

1.4 RIGID BODY MOTION

Equations (1.3-1) and (1.3-3) have the common objective of preventing rigid body motion. In Eqs. (1.3-1) three displacements are set equal to zero in a way that prevents rigid body motion of the structure as a whole in the plane of the paper. The choice of displacements in Eq. (1.3-1) is not unique; any of the three displacements at A, B, or C can be selected for the same purpose, or other combinations of displacements, such as, for instance, u_1, u_5, u_{10} (but not u_1, u_4, u_{10}, why?). The equilibrium equations (1.3-3) also prevent rigid body motion, because with zero net force, the center of mass of the structure does not displace from its rest position. The dependent forces in Eq. (1.3-3) corresponding to the constraints expressed by Eq. (1.3-1) are F_{10}, F_{11}, F_{12}. These forces cannot be applied arbitrarily, and their magnitudes depend on the arbitrary values assigned to the remaining 9 force components. Note, however, that no constraints on the forces correspond to the internal connectivity constraints of Eqs. (1.3-4).

In general, a minimum of three equations of constraint are required to prevent rigid body motion in two-dimensional physical space, and a minimum of six are required in three-dimensional physical space.

†The coefficients c_i in Eqs. (1.3-4) and (1.3-5) are not necessarily the same.

1.5 DISCRETE AND DISTRIBUTED COORDINATES[1]

Discrete Coordinates. Consider the cantilever beam with four mass points at a, b, c, and d and four coordinates as shown in Fig. 1.5-1. The vectors $\{u\}$ and $\{F\}$ describe displacement configurations and force groups associated with the four mass points. The components of $\{u\}$ and $\{F\}$ represent amplitudes of displacement configurations and force groups identified at discrete points. For instance, u_1 amplifies the shape identified by $\begin{Bmatrix}1\\0\\0\\0\end{Bmatrix}$, and F_3 amplifies a force group identified by $\begin{Bmatrix}0\\0\\1\\0\end{Bmatrix}$. No information identifies the displacements or forces at points other than at the discrete points a, b, c,

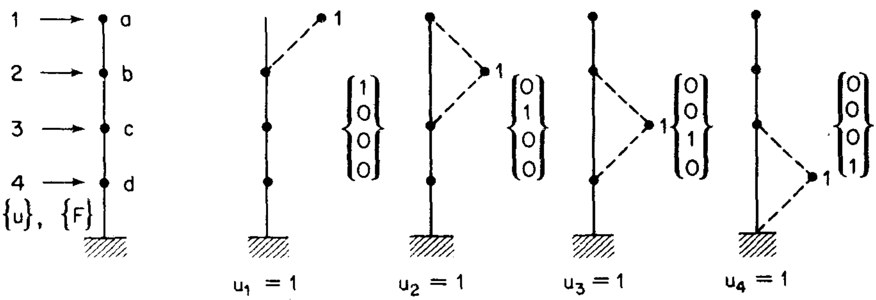

Fig. 1.5-1 Discrete coordinates u_i.

and d (the dashed lines between mass points in Fig. 1.5-1 can have an arbitrary shape).

Coordinates that identify information at discrete points will be referred to as *discrete coordinates.*

Distributed Coordinates. Figure 1.5-2 shows the structure of Fig. 1.5-1, but here the displacement configuration associated with $u_1 = 1$ is a distributed function $\phi_1(x)$ with

$$\phi_1(x_a) = 1$$
$$\phi_1(x_b) = 0$$
$$\phi_1(x_c) = 0$$
$$\phi_1(x_d) = 0.$$

此为试读，需要完整PDF请访问：www.ertongbook.com