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# AUTOMATED DYNAMIC RELAXATION SOLUTION ALGORITHMS FOR COMPLIANT SYSTEMS

***ABSTRACT*** Tensioned or compliant structures, such as fabric shelter systems and ocean cable systems, are composed of very flexible structural components that exhibit a high degree of geometrical nonlinearity and analytical complexity. Structural analysis of these systems is a two-phase procedure: (1) the determination of the static equilibrium configuration or prestressed state of the structure; and (2) the determination of structural response relative to the equilibrium configuration due to static and dynamic in-service loads. This report addresses static solution algorithms for reliable phase-one solution procedures. In contrast to the standarad Newton-Raphson (NR) incremental/iterative algorithm, the automated dynamic relaxation (ADR) solution algorithm is a pure iterative algorithm and it is also simple to implement. The ADR algorithm's performance is globally convergent in test problems having multiple solutions, whereas NR algorithms are known to be only locally convergent. The ADR algorithm can be successfully utilized to form the basis of structural analysis software for specialized, highly nonlinear problems involving tensioned structures.

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# METRIC CONVERSION FACTORS

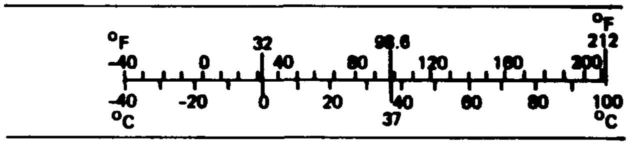
### Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2,000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.


### Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1,000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



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Tensioned or compliant structures, such as fabric shelter systems and ocean cable systems, are composed of very flexible structural components that exhibit a high degree of geometrical nonlinearity and analytical complexity. Structural analysis of these systems is a two-phase procedure: (1) the determination of the static equilibrium configuration or prestressed state of the structure; and (2) the determination of structural response relative to the equilibrium configuration due to static and dynamic in-service loads. This report addresses static solution algorithms for reliable phase-one solution procedures. In contrast to the standarad Newton-Raphson (NR) incremental/iterative algorithm, the automated dynamic relaxation (ADR) solution algorithm is a pure iterative algorithm and it is also simple to implement. The ADR algorithm's performance is globally convergent in test problems having multiple solutions, whereas NR algorithms are known to be only locally convergent. The ADR algorithm can be successfully utilized to form the basis of structural analysis software for specialized, highly nonlinear problems involving tensioned structures.

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CONTENTS

# INTRODUCTION

The problem addressed in this research is the lack of a robust computational procedure for determining the initial equilibrium configuration and prestress state of tensioned structures. The solution of this problem is widely regarded as a deterrent to efficient engineering design and analysis of tensioned structures in the Navy (i.e., ocean cable and membrane structures and land-based expeditionary and architectural/tensioned fabric structures). Several authors have discussed and documented this technical problem; they include Webster (1977, 1984), Liu (1977), Peyrot and Goulois (1979), Shields and Zueck (1984), and Shugar (1987). Compliant structures such as these generally may not be handled by linear analysis methods, and successful nonlinear analysis methods usually require modified solution algorithms.

A promising algorithm for application to structures that exhibit strong nonlinear structural behavior was addressed in this investigation. It is known as the automated dynamic relaxation (ADR) algorithm. The ADR algorithm was compared to existing solution algorithms for tensioned structures. It possesses some attractive features which provide for monitoring and control of the stability of the solution process. Often the solution process exhibits pathological behavior when a tensioned structure approaches a slack configuration.

Existing solution algorithms based upon the Newton-Raphson method have a subjective nature. They require that a guess be made for the pretension in the structure to begin the solution procedure. The robustness of these methods is adversely affected by this requirement because convergence to the correct solution sometimes depends on the accuracy of the guess. This runs contrary to the goal of a foolproof algorithm.

A set of cable test problems was designed to numerically evaluate the robustness of the algorithms studied. In these problems, the starting conditions were designed purposely to be onerous to test the ability of the algorithms to seek the correct static equilibrium position when starting from rather arbitrary configurations. In some cases, multiple static equilibrium solutions exist, and the goal is to find the global solution.

## Objective

The objective of this report is to present the automated dynamic relaxation solution algorithms for nonlinear static problems in a manner suitable for implementation into structural analysis software. This report is largely based on a previous paper (Shugar, 1988) but also includes additional background information, discussion of different ADR algorithms, and additional numerical comparison studies with general purpose ocean cable analysis computer programs.

## Background

The technology of computational methods in ocean structural engineering was reviewed by Shugar and Armand (1986) in which solution methods for geometrically nonlinear ocean cable structures were discussed. In particular, the solution of static mooring system problems has largely motivated this study of the dynamic relaxation solution method. Hence, a lengthy discussion of several existing numerical solution procedures and mooring computer programs is included in the appendix. The computer programs discussed include:

MOORING (NAVFAC DM-26.5, 1985)
FLEETMOR (Palo and Karnoski, 1986)
STATMOOR (Cox, 1982)
SOUPLE (Peyrot, 1980)
SEADYN (Webster, 1976)
SEASTAR (Pawsey and Nour-Omid, 1988)

Three classes of computer programs are defined as follows: (1) programs limited to standard Navy ship mooring practice, (2) programs suited to special purpose mooring problems, and (3) general purpose finite element programs aimed at a wide class of structural analysis problems.

The last two types of programs listed above are more closely related than the first in that they are based on the direct stiffness method from the theory of matrix analysis of structures, which provides them with the potential for general purpose capability. The first type is very specialized and limited to ship mooring problems in shallow water where mooring line hydrodynamic drag force is insignificant. With respect to the static mooring problem, however, all three types of programs have the common requirement of solving a nonlinear system of static equilibrium equations.

The Newton iteration solution algorithm is most commonly employed to solve the nonlinear system of equations in the computer programs discussed. None of these programs employ the dynamic relaxation solution algorithm, although it has been used successfully, mostly in the U.K., for general purpose static analysis of very flexible or compliant structures including tensioned fabric structures and offshore riser and cable structures. Mathematical and engineering descriptions of the dynamic relaxation method are given by Crisfield (1986), although the context is restricted to the solution of linear equations.

## DERIVATION OF DYNAMIC RELAXATION INTEGRATION FORMULAS

It is presumed that a continuous cable structural system has been spatially discretized using standard simple straight truss or curved isoparametric finite elements. Then, the system of N static nonlinear algebraic equations to be solved for the unknown, N-dimensional displacement vector $\underset{\sim}{x}$ is:

$$\underset{\sim}{F}_i(\underset{\sim}{x}) = \underset{\sim}{F}_e \qquad (1)$$

where $\underset{\sim}{F}_i(\underset{\sim}{x})$ is the internal force vector which is a function of structural system configuration $\underset{\sim}{x}$, and $\underset{\sim}{F}_e$ is the applied, static external force vector acting on the structural system.

The dynamic relaxation method begins by converting the static problem (Equation 1) into a structural dynamics problem using a psuedo time variable, t, and a step load form for the static load vector, $\underset{\sim}{F}_e(t)$. Thus,

$$\underset{\sim}{M}\,\ddot{\underset{\sim}{x}}\,(t) + \underset{\sim}{C}\,\dot{\underset{\sim}{x}}\,(t) + \underset{\sim}{F}_i\left[\underset{\sim}{x}\,(t)\right] = \underset{\sim}{F}_e\,(t) \tag{2}$$

Here $\underset{\sim}{M}$ and $\underset{\sim}{C}$ are, respectively, artificial mass and artificial damping matrices which are defined arbitrarily as:

$$\underset{\sim}{M} = \rho\,\underset{\sim}{I} \tag{3a}$$

$$\underset{\sim}{C} = c\,\underset{\sim}{I} \tag{3b}$$

where $\underset{\sim}{I}$ is the NxN identity matrix, and the scalars $\rho$ and c are artificial mass and artificial damping parameters, respectively. These parameters will subsequently be chosen to control convergence of the dynamic relaxation iterative procedure. The artificial inertia and artificial damping forces are stabilizing terms for the left-hand side of Equation 2. When calculation of the internal force becomes numerically ill-conditioned, these terms serve to temporarily regularize the calculation. The psuedo equation of motion (Equation 2) is to be integrated for $\underset{\sim}{x}(t)$. After sufficient time has elapsed, the dynamic solution $\underset{\sim}{x}(t)$ is expected to converge to the static solution sought which is denoted by $\underset{\sim}{x}$.

Temporal integration is accomplished by discretizing Equation 2 using the following central difference approximation formulas,

$$\dot{x}(t_{n-1/2}) \approx \dot{\underset{\sim}{x}}^{n-1/2} = \frac{1}{h}\,(\underset{\sim}{x}^{n} - \underset{\sim}{x}^{n-1}) \tag{4a}$$

and,

$$\ddot{x}(t_n) \qquad \ddot{\underset{\sim}{x}}^{n} = \frac{1}{h}\left(\dot{\underset{\sim}{x}}^{n+1/2} - \dot{\underset{\sim}{x}}^{n-1/2}\right) \tag{4b}$$

where h is the time step size. Also, averaging the discrete velocities in Equation 4a time steps n+1/2 and n-1/2 yields:

$$\dot{x}(t_n) \qquad \dot{\underset{\sim}{x}}^{n} = \frac{1}{2}\left(\dot{\underset{\sim}{x}}^{n+1/2} - \dot{\underset{\sim}{x}}^{n-1/2}\right) \tag{4c}$$

Substituting Equation 4 into Equation 2 yields a two-term recursion formula for updating the velocity:

$$\dot{\underset{\sim}{x}}^{n+1/2} = \left(\frac{2 - ch/\rho}{2 + ch/\rho}\right) \dot{\underset{\sim}{x}}^{n-1/2} - \left(\frac{2\ h/\rho}{2 + ch/\rho}\right) \underset{\sim}{r}^{n} \tag{5}$$

where $\underset{\sim}{r}^n$ is the residual force vector and is defined as the difference between the *approximated internal* and external force vectors after n time steps:

$$\underset{\sim}{r}^{n} = \underset{\sim}{F}_i(\underset{\sim}{x}^{n}) - \underset{\sim}{F}_e(t^{n}) \tag{5a}$$

The displacement is updated by replacing n with n+1 and solving for $\underset{\sim}{x}^{n+1}$ in Equation 4a:

$$\underset{\sim}{x}^{n+1} = \underset{\sim}{x}^{n} + h\ \dot{\underset{\sim}{x}}^{n+1/2} \tag{6}$$

Substituting Equation 5 into Equation 6 and using Equation 4a to eliminate $\dot{\underset{\sim}{x}}^{\,n-1/2}$ yields a three-term recursion formula (see Papadrakakis, 1982) for updating the displacement vector:

$$\underset{\sim}{x}^{n+1} = \left(\frac{4}{2 + ch/\rho}\right) \underset{\sim}{x}^{n} - \left(\frac{2 - ch/\rho}{2 + ch/\rho}\right) \underset{\sim}{x}^{n-1} - \left(\frac{2\ h^2/\rho}{2 + ch/\rho}\right) \underset{\sim}{r}^{n}, \ (n > 0) \qquad \ldots (7)$$

This is the primary formula for the dynamic relaxation method. It can be seen that the central difference integration method results in an explicit formulation for marching through time, since the vectors on the right-hand side of Equation 7 are known. The vectorization apparent in Equation 7 implies certain data structure advantages over standard Newton methods which are matrix-based formulations. Papadrakakis (1986) refers to this as a vector iteration method.

Equation 7 does not apply when n = 0, for the displacement at $\underset{\sim}{x}^{-1}$ is unknown. Therefore, an additional formula is needed to start the iteration (see Shugar, 1987) as follows:

$$\underset{\sim}{x}^{1} = \underset{\sim}{x}^{0} - \frac{h^2}{2\rho} \underset{\sim}{r}^{0} \qquad (8)$$

This is a consistently derived starting formula for the dynamic relaxation method. Equations 7 and 8 generally agree with the dynamic relaxation formulas given by Papadrakakis (1981a) and Underwood (1983).*

It should be emphasized that the calculation of the residual $\underset{\sim}{r}^{n}$ in Equation 7 is computationally straightforward using its definition (Equation 5a). All that is required is to calculate and sum the unbalanced forces existing at each node point in the structural model at the known, current configuration $\underset{\sim}{x}^{n}$. The internal force calculation for each element may be simply based on the conventional linear portion of the finite element stiffness matrix, so long as the cable structure behavior is restricted to small axial strains. Otherwise, nonlinear

*P.G. Underwood investigated dynamic relaxation methods for applications to nonlinear buckling problems in structural analysis. In this regard, the reader is also referred to Papadrakakis (1981b) and Tong (1986a, 1986b).

stiffness terms may be derived to handle large axial strains, as shown by Zienkiewicz (1977). Large displacements of cable elements are permitted naturally by the displacement update formula (Equation 7). It is not necessary to use a geometric stiffness matrix as in Newton-based methods. The residual force vector is calculated on the updated, local, or element level. No assembly is needed, nor is it necessary to compute the tangent stiffness matrix of the system as required for the Newton-based procedures.

## DERIVATION OF OPTIMAL ITERATION PARAMETERS

Since the artificial inertia and artificial damping forces appearing in the psuedo equation of motion (Equation 2) are arbitrary, one is at liberty to choose any values for the parameters $\rho$ and c. The objective is to develop formulas for these parameters so that they may be adaptively controlled (during the solution) in such a way as to promote optimum convergence for the dynamic relaxation iterative procedure.

One assumes that any difficulty in achieving convergence is due to numerical ill-conditioning in the tangent stiffness matrix $\underset{\sim}{K}(\underset{\sim}{x})$. Such ill-conditioning may arise for valid physical reasons, such as when cables approach slack conditions. Since a well-behaved tangent stiffness matrix is important to stability of the numerical process, whatever the desired optimizing formulas are, it makes sense to anticipate that they should somehow reflect the numerical condition of the tangent stiffness matrix during the solution process.

To examine systematically the convergence of the method, Lynch (1968) transformed the iterative process into a standard eigenvalue problem for the error vector:

$$\underset{\sim}{\varepsilon}^n = \underset{\sim}{x}^n - \underset{\sim}{x} \tag{9}$$

Following this approach, subtract the true solution $\underset{\sim}{x}$ from Equation 7 and rewrite it using the error definition (9) to get the relationship between successive error vectors:

$$\underset{\sim}{\varepsilon}^{n+1} = [\beta \underset{\sim}{I} - \gamma \underset{\sim}{B}] \underset{\sim}{\varepsilon}^{n} - \alpha \underset{\sim}{\varepsilon}^{n-1} \qquad (10)$$

where: $$\beta = \frac{2 - ch/\rho}{2 + ch/\rho} + 1 \qquad (10a)$$

$$\gamma = \frac{2\ h^2/\rho}{2 + ch/\rho} \qquad (10b)$$

$$\alpha = \beta - 1 \qquad (10c)$$

In Equation 10 the matrix $\underset{\sim}{B}$ is a preconditioned tangent stiffness matrix,

$$\underset{\sim}{B} = \underset{\sim}{W}^{-1} \underset{\sim}{K}(\underset{\sim}{x}^{n}) \underset{\sim}{W}^{-T} \qquad (11)$$

where the preconditioning matrix $\underset{\sim}{W}$ (see Papadrakakis, 1986) is:

a. $\underset{\sim}{W} = \underset{\sim}{I}$. This is the standard dynamic relaxation scheme which has been presented above in deriving Equation 7.

b. $\underset{\sim}{W} = \underset{\sim}{D}^{1/2}$. Here, $\underset{\sim}{D}$ is a diagonal matrix composed of the entries on the main diagonal of the tangent stiffness matrix. This method is also called diagonal scaling since the entries on the main diagonal of the coefficient matrix, formed from the triproduct matrix, $\underset{\sim}{W}^{-1}\underset{\sim}{K}(\underset{\sim}{x}^{n}) \underset{\sim}{W}^{-T}$, are unity.

Letting the rate at which the error vector decays in the dynamic relaxation process be denoted by $\lambda_{DR}$, then:

$$\underset{\sim}{\varepsilon}^{n+1} = \lambda_{DR} \underset{\sim}{\varepsilon}^{n} \qquad (12)$$

Clearly, the modulus of $\lambda_{DR}$ should remain less than unity for the dynamic relaxation process to converge with increasing n.

Following Lynch (1968), one wishes to investigate what influences the decay rate $\lambda_{DR}$. An equation for $\lambda_{DR}$ is obtained by substituting Equation 12 into Equation 10. One can then obtain:

$$\left[\left(\frac{\lambda_{DR}^2 - \beta\,\lambda_{DR} + \alpha}{\gamma\,\lambda_{DR}}\right)\underset{\sim}{I} + \underset{\sim}{B}\right]\underset{\sim}{\varepsilon}^n = \underset{\sim}{0} \tag{13}$$

Now, the standard eigenvalue problem for the eigenpairs $(\lambda_B, \underset{\sim}{\varepsilon}^n)$ of the matrix $\underset{\sim}{B}$ is written as:

$$(-\,\lambda_B\,\underset{\sim}{I} + \underset{\sim}{B})\,\underset{\sim}{\varepsilon}^n = \underset{\sim}{0} \tag{14}$$

If one identifies the scalar coefficient of $\underset{\sim}{I}$ in Equation 13 with the scalar coefficient of $\underset{\sim}{I}$ in Equation 14, one can arrive at:

$$\frac{\lambda_{DR}^2 - \lambda_{DR}\,\beta + \alpha}{\lambda_{DR}\,\gamma} + \lambda_B = 0 \tag{15}$$

In Equation 15, one has related the decay rate $\lambda_{DR}$ of the dynamic relaxation process to the eigenvalues $\lambda_B$ of the structure's tangent stiffness matrix. This is the type of relationship that was anticipated. Furthermore, the condition of the structural stiffness matrix can be tracked by monitoring its eigenvalues by some method yet to be described.

Solving Equation 15 for $\lambda_{DR}$ one obtains the quadratic equation:

$$\lambda_{DR}^2 - (\beta - \gamma\,\lambda_B)\,\lambda_{DR} + \alpha = 0 \tag{16}$$

So, for each of the N eigenvalues of $\underset{\sim}{B}$ there are two solutions for $\lambda_{DR}$:

$$\lambda_{DR} = \frac{1}{2}(\beta - \gamma\,\lambda_B) \pm \frac{1}{2}\sqrt{(\beta - \gamma\,\lambda_B)^2 - 4\,\alpha} \tag{17}$$

There are three cases for these roots.

Case 1. The roots of the quadratic are complex when:

$$4\alpha > (\beta - \gamma \lambda_B)^2 \tag{18}$$

The modulus of the decay rate $|\lambda_{DR}|$ for this case is:

$$|\lambda_{DR}| = \sqrt{\frac{2 - ch/\rho}{2 + ch/\rho}} \tag{19}$$

The decay rate modulus is seen to be independent of the eigenvalue $\lambda_B$ in the case of complex roots, and, therefore, this case is of no particular use.

Case 2. The roots are real and equal when:

$$4\alpha = (\beta - \gamma \lambda_B)^2 \tag{20}$$

The roots are:

$$\lambda_{DR} = \frac{1}{2 + ch/\rho}\left(2 - \frac{h^2}{\rho}\lambda_B\right) \tag{21}$$

For this case, one also finds that the square of the convergence parameter $ch/\rho$ has the following relationship with $\lambda_B$:

$$\left(\frac{ch}{\rho}\right)^2 = \frac{\lambda_B h^2}{\rho}\left(4 - \frac{\lambda_B h^2}{\rho}\right) \tag{22}$$

Case 3. The roots are real and unequal when:

$$4\alpha < (\beta - \gamma \lambda_B)^2 \tag{23}$$

The larger of the two roots is found to be:

$$\lambda_{DR} = \frac{1}{2 + ch/\rho} \left[ \left( 2 - \frac{h^2 \lambda_B}{\rho} \right) + \sqrt{\frac{\lambda_B{}^2 h^4}{\rho^2} - \frac{4 \lambda_B h^2}{\rho} + \frac{c^2 h^2}{\rho^2}} \right]$$

From the definition of $\lambda_{DR}$ in Equation 12, one can see that it is important to promote the smallest value possible for this parameter, and to require that its modulus never exceed unity.

With that in mind, the behavior of the modulus $|\lambda_{DR}|$ is studied by graphing it versus $ch/\rho$ using Equation 24, while holding the parameter $(h^2/\rho)\ \lambda_B$ constant (Figure 1). One can see that for any value of $(h^2/\rho)\ \lambda_B$, the smallest value of $\lambda_{DR}$ occurs for Case 2, the equal-roots case. Thus, for any value of $(h^2/\rho)\ \lambda_B$, the appropriate choice for $ch/\rho$ comes from Equation 22.

However, note that there are N values of $\lambda_B$ and, thus, N values of $(h^2/\rho)\ \lambda_B$. To help resolve this, the behavior of $|\lambda_{DR}|$ versus $(h^2/\rho)\ \lambda_B$ is similarly graphed in Figure 2, while holding constant the parameter $ch/\rho$. Not shown is the region where $\lambda_{DR}$ exceeds unity when $(h^2/\rho)\ \lambda_B >$ 4.0. This region is to be avoided if convergence is to be promoted. Moreover, a strategy for selecting $(h^2/\rho)\ \lambda_B$ is suggested from this figure.

Assume that for any $\underset{\sim}{B}$, the maximum eigenvalue $\lambda_{Bmax}$ and the minimum eigenvalue $\lambda_{Bmin}$ have been calculated. Then a value of $h^2/\rho$ that promotes convergence can be calculated by centering $(h^2/\rho)\ \lambda_{Bmin}$ and $(h^2/\rho)\ \lambda_{Bmax}$ symmetrically about the abscissa value of 2. The appropriate equation is therefore:

$$\left(\frac{h^2}{\rho}\right)_{opt} = \frac{4}{\lambda_{Bmax} + \lambda_{Bmin}} \qquad (25)$$

Using this equation avoids the region $(h^2/\rho)\ \lambda_{Bmax} > 4.0$, and assures stability of the dynamic relaxation procedure. Furthermore, substituting Equation 25 into Equation 22 leads to the optimal choice for $ch/\rho$ for promoting a faster convergence rate for the dynamic relaxation procedure:

$$\left(\frac{ch}{\rho}\right)_{opt} = \frac{4}{\lambda_{Bmax} + \lambda_{Bmin}} \sqrt{\lambda_{Bmax} \cdot \lambda_{Bmin}} \qquad (26)$$

## ESTIMATING THE MAXIMUM AND MINIMUM EIGENVALUES

To ensure stability one needs only to ensure that the inequality $|\lambda_{DR}| < 1$ is maintained during iteration with the dynamic relaxation method. Thus, if one is able to calculate an upper bound for the maximum eigenvalue, then one is assured that when its product with $h^2/\rho$ is taken to be less than four, the product of $\lambda_{Bmax}$ with $h^2/\rho$ will also be less than four and thereby satisfy $|\lambda_{DR}| < 1$. Papadrakakis (1981a) suggests the following method.

The Gerschgorin theorem is available to calculate an upper bound of the maximum eigenvalue of a square matrix. Applying it, one can write:

$$|\lambda_{Bmax}| < \max_{i} \sum_{j=1}^{N} |B_{ij}| \qquad (27)$$

where the $B_{ij}$ are the entries in the scaled stiffness matrix $\underset{\sim}{B}$. This states that the maximum over all rows of $\underset{\sim}{B}$ of the sum of the entries (their absolute values) in each row is an upper bound of $\lambda_{Bmax}$. An implementation of this simple inequality must involve an algorithm that recognizes that the matrix $\underset{\sim}{B}$ is never formed explicitly in the dynamic relaxation method. Thus, the coefficients $B_{ij}$ are calculated at the element level to preserve the advantage of a vector iteration method.

Calculation of the minimum eigenvalue is less critical than the calculation of the maximum eigenvalue for it cannot directly affect the stability of the iteration process. Exact methods for its calculation are not required, and bounds are not necessary for its estimation. The minimum eigenvalue must only satisfy:

$$0 < \lambda_{Bmin} < \lambda_{Bmax} \tag{28}$$

Its value, along with that for the maximum eigenvalue, does affect the rate of convergence of the solution. Numerical experience has shown that poor estimates can adversely affect the rate of convergence, though they cannot directly cause a solution to blow up. Good estimates of the minimum eigenvalue should therefore be sought.

It is noted that Equations 27 and 28 are only needed on occasions when progress toward a solution is not satisfactory. Then they are employed along with the optimal formulas (Equations 25 and 26) to adjust the solution parameters in Equation 7.

## AUTOMATED DYNAMIC RELATION ALGORITHM

A procedural description of the automated dynamic relaxation solution method is given by the following algorithm:

Given $h = 1$ and $\mathbf{F}_{ext}$, $\frac{h}{2\rho}$, $\frac{ch}{\rho}$, $n_{max}$

0. Initialize $n \leftarrow 0$, $\mathbf{x} \leftarrow$, $\mathbf{F}_{int} \leftarrow \mathbf{0}$

1. $\mathbf{r}^0 \leftarrow \mathbf{F}^0_{int} - \mathbf{F}_{ext}$

2. $\mathbf{x}^1 \leftarrow \mathbf{x}^0 - \frac{h}{2\rho}\,\mathbf{r}^0$ and $\mathbf{x}^{-1} \leftarrow \mathbf{x}^1$

3. $\mathbf{x}^{n+1} \leftarrow \left(\frac{4}{2+ch/\rho}\right)\mathbf{x}^n - \left(\frac{2-ch/\rho}{2+ch/\rho}\right)\mathbf{x}^{n-1} - \left(\frac{2h^2/\rho}{2+ch/\rho}\right)\mathbf{r}^n$

4. If convergence OK, then output $\tilde{x}^{n+1}$ and stop.

5. If $n = n_{max}$ then output error message and stop.

6. $n \leftarrow n + 1$

7. $\tilde{x}^{n} \leftarrow \tilde{x}^{n-1}$ and $\tilde{x}^{n-1} \leftarrow \tilde{x}^{n-2}$

8. Calculate $\tilde{F}^{n}_{int}$

9. $\tilde{r}^{n} \leftarrow \tilde{F}^{n}_{int} - \tilde{F}_{ext}$

10. If convergence rate OK, then go to step 3.

11. Estimate upper bound of maximum eigenvalue and estimate minimum eigenvalue.

12. Update parameters $ch/\rho$ and $h^2/\rho$.

13. Go to step 3.

## KINEMATIC DAMPING ALGORITHM

Cundall (1976), when examining the application of explicit integration methods to problems in geomechanics, suggested that the kinetic energy of the structure be constantly monitored, and that when an energy peak is detected all the current velocities be set to zero. For a system oscillating in one mode, the state of stress at the energy peak would correspond to the static equilibrium position. However, for practical problems with many degrees of freedom, the process must be repeated through further peaks, eliminating the kinetic energy for all modes, until the required degree of accuracy is obtained.

Using this method, the viscous damping coefficient of Equation 2 is set to zero and the equation of motion becomes:

$$\underset{\sim\sim}{M}\ddot{\underset{\sim}{x}} + \underset{\sim}{F}_i(\underset{\sim}{x}) = \underset{\sim}{F}_e(t) \qquad (29)$$

Integrating Equation 29, using central difference approximations in the same way as Equation 2, we get:

$$\dot{\underset{\sim}{x}}^{n+1/2} = \dot{\underset{\sim}{x}}^{n-1/2} - (h/\rho)\, \underset{\sim}{r}^{n} \qquad (30)$$

and,

$$\underset{\sim}{x}^{n+1} = 2\underset{\sim}{x}^{n} - \underset{\sim}{x}^{n-1} - (h^2/\rho)\, \underset{\sim}{r}^{n} \qquad (31)$$

Following the same process for derivation of optimal iteration parameters as before, the optimum value for $(h^2/\rho)$ is:

$$(h^2/\rho)_{opt} = \frac{4}{\lambda_{Bmin} + \lambda_{Bmax}} \qquad (32)$$

It is also recommended the the sum of $\lambda_{Bmin}$ and $\lambda_{Bmax}$ be replaced by the Gerschgorin bound in Equation 27.

When the time increment h is kept constant throughout the iteration process, an energy peak can be detected at each successive time step, and in this case the structure is oscillating about the equilibrium state with a constant frequency. To overcome this difficulty, the time step is reduced to half of its value every time an energy peak is detected at each time step until the iteration process returns to its normal convergence. Once this has been achieved, the time increment is reset to its original value. A flow chart of the method is shown in Figure 3.

Papadrakakis (1988) believes this version of dynamic relaxation may have better behavior than the classical viscous damping version of dynamic relaxation, presented here, for the class of problems studied. This would seem to be corroborated by the success of Barnes and coworkers (in the U.K.) who have used the kinetic damping version of dynamic relaxation for problems involving compliant structures. For example, flexible risers were studied by Soltanahmadi and Barnes (1987), prestressed nets and membranes were studied by Barnes (1987), and various other membranes and tensioned fabric structures have been solved by Wakefield (1987). Much of the success of ADR in the design office environment is ascribed to the simplicity of the kinetic damping algorithm. It is pointed out that the inherent dynamic analogy of the method also facilitates understanding and engenders control of the solution procedure by practicing engineers when solving complex problems.

## RESULTS FROM NUMERICAL EXPERIMENTS

In the following numerical experiments, results from the standard Newton iteration algorithm and the ADR algorithm applied to nonlinear static cable problems are compared. These results are abstracted from Shugar (1987). Further results comparing the performance of the ADR algorithm with existing cable analysis computer programs are also presented.

A set of simple, two-dimensional cable test problems was designed primarily to test an algorithm's ability to seek the correct static equilibrium solution from an initial cable configuration that is arbitrarily prescribed. The robustness of the algorithm is addressed by deliberately specifying onerous initial nonequilibrium configurations. Furthermore, multiple solutions are possible in some cases due to specification of a simple cable element that can support axial compression force and has no bending stiffness.

### Fixed-Span Suspended Cable Problem

The fixed-span suspended cable test problem consists of a cable that is suspended between two supports and is acted on by lateral, unit forces at each node. The unstrained length of the cable is 100 units, and the span is 60 units. The cable length is uniformly divided into 10 elements. The rigidity of the cables, EA, is 1000. Table 1 compares the convergence results of the full Newton and ADR algorithms for four initial configuration cases. The results indicate that convergence to the correct solution was achieved successfully by both algorithms for all cases except the third, the kinked initial configuration case.

This case consists of an initial configuration where all the elements lie on a straight line across the span, and the two innermost elements overlap (though they are shown parallel with) adjacent elements. The expected equilibrium solution for this problem is presented in Figure 4. Also shown is the unexpected, kinked equilibrium position found by the full Newton algorithm for certain prescribed initial prestress forces -- a requirement with this algorithm to avoid an initially singular system. In this solution the two overlapped elements are sustaining compressive forces. It is expected that all algorithms would find the expected solution if provision for tension-only element behavior were made, since this constraint would eliminate the alternative equilibrium states. However, the ADR algorithm requires no such provision, and furthermore, is independent of initial prestress force. Therefore, it exhibits greater robustness in seeking the expected solution.

**Cable Snap-Through Problem**

The cable snap-through test problem consists of a six-element suspended cable with an unstrained length of 60 units. The cable is considered weightless, has an EA value of 1000, and is subjected to concentrated horizontal and vertical forces, as shown in Table 2. The horizontally loaded end support is free to move in the horizontal direction, beginning from either of two prescribed initial configuration cases, until a static equilibrium configuration is reached. In the second case, the six cable elements are initially coiled on top of one another such that their nodes possess exactly the same initial coordinate values. As the solution algorithm seeks equilibrium, the cable tends to uncoil and snap through from left to right.

The ADR algorithm converges to the expected equilibrium solution, which is shown in Figure 5, from either initial configuration. However, in the first case, the final calculated span was short by 9 percent. (This is an anomalous result; in the other 13 test problems no similar inaccuracy occurred with the ADR algorithm.) The accuracy of the full Newton algorithm was good in this case. In the second case, however, the full Newton algorithm did not always converge to the expected solution; again, this behavior depended on the value of the required initial prestress force. The ADR algorithm is independent of this quantity, and converged to the expected solution accurately.

Two unexpected, alternative equilibrium states found by the full Newton algorithm are shown in Figures 5b and 5c. Once again these states include elements sustaining compression forces.

### Varying-Span Suspended Cable Problem

The varying-span suspended cable test problem consists of a horizontally suspended cable with one of the two supports free to slide horizontally. The cable is acted upon by uniform lateral load forces and a concentrated, horizontal reaction force, both of which cause one support to slide until the system reaches equilibrium. The unstrained cable is 200 feet long and is uniformly subdivided into 10 elements. This test problem was used by Webster (1979) in a similar study of solution algorithms for ocean cable systems.

The three initial configuration cases studied are shown in Table 3 along with the problem parameters. In the first two cases, the cable is initially aligned horizontally along the span. Case 1 is labeled taut because its initial configuration is such that the cable will remain in tension throughout the solution process. Case 2 is labeled slack because the cable must pass from a compression state to a tension state during the solution, thus traversing a zero-tension state. In Case 3, a completely sagged cable is represented wherein all elements initially lie along a common vertical line; the cable should otherwise remain in tension throughout the solution process.

The ADR algorithm converged to the expected equilibrium solution, shown in Figure 6, in all three cases. However, in Case 2, the full Newton algorithm did not always converge to this solution; its behavior was like that already discussed for the previous problems. Whether the expected solution was found or not depended on the value of the prescribed prestress force. Webster (1979) showed that the full Newton algorithm failed to converge for this test case. Here, it was learned that it may or may not converge to the expected solution. In general, however, these results are in agreement with those of Webster's concerning the unreliability of the full Newton algorithm for this class of problems.

The ADR algorithm is more robust than the full Newton algorithm in seeking the expected equilibrium solution in the varying-span suspended cable problem. Once again, this behavior is correlated with whether or not a slack cable configuration arises in the solution process.

Also the results from Cases 1 and 3 show that the ability of either algorithm to converge is not dependent on the degree of cable sag present in the initial configuration. Thus, for numerical conditioning, it seems to matter whether cable slackness (zero tension) is present, but not to what degree cable sag is present.

**Comparison with SEADYN and SEASTAR**

In Table 4, the results of the preceding numerical experiments are summarized for comparison with the results of further experiments on the same set of test problems using two different nonlinear, displacement-based finite element programs which are currently in practice for static cable analysis applications, SEADYN and SEASTAR. Both of these programs were evaluated over the set of 14 (problem 7 is actually four similar problems) test problems, but did not perform quite as well as the ADR solution algorithm.

The results from SEASTAR, using its Newton-Raphson solution option* (the default option), are very similar to the results presented earlier for the test code written for this study which uses the same solution algorithm (thus this similarity is to be expected). SEASTAR was able to converge to the expected stable equilibrium solution for each problem. However, it was also able to converge to unexpected cable equilibrium positions as well. The difference is a consequence of having specified different values of certain input parameters. The parameters with the most noticeable influence were the initial pretension of the cable elements, the load step or increment size, and whether the cable elements were allowed to sustain compression.

When a load step size of 1.0 was prescribed (i.e., all the load is applied at once), SEASTAR converged to the expected equilibrium solution. However, in test problem 3, application of the external load in increments instead of all at once, a common and reasonable strategy for nonlinear problems, resulted in convergence to only metastable solutions. Figures 7a and 7b show this outcome when the total load was applied in two and four increments, respectively. The unexpected solution obtained by SEASTAR for test problem 6 was similar to the profile obtained before (see Figures 4 and 5) and is omitted.

In test problem 10, application of the total load in one step resulted in convergence to the expected equilibrium solution, as shown in Figure 8a. Unfortunately this behavior seems unpredictable, for application of the load in four increments and 20 increments again resulted in convergence to only metastable solutions, as shown in Figures 8b and 8c, respectively. Prescribing a zero pretension load is not necessarily the answer in this test problem as indicated by the result in Figure 8d.

*SEASTAR is a modified version of a computer program called ANSR III which was written for general purpose, nonlinear finite element, structural analysis applications. As such, it has additional advanced options for solving nonlinear static problems (Simons and Powell, 1982). These options must be used with caution and require experience for they are based on intricate modifications of the Newton-Raphson algorithm aimed at overcoming its inherent unreliability in structural buckling problems.

The evolution of the unexpected solution (Figure 8d) is presented in Figure 8e, which shows four intermediate plots depicting initial progress toward the converged unexpected solution. Load increments 1 through 5 applied 5 percent of the total load of each increment. From 5 percent to 100 percent of the load at increments of 5 percent, the unexpected solution was locked in. Thus, the unexpected solution locked in early.

The results from SEADYN's viscous relaxation solution algorithm (called VRR) are perfect except for test problem 6 where only the unexpected, or metastable equilibrium solution was obtained.

## SUMMARY AND CONCLUSIONS

The automated dynamic relaxation (ADR) algorithm possesses some attractive theoretical features for solving ill-conditioned numerical models of static ocean cable structures. A major feature is the ability to control the stability of the solution process automatically. Typically, when seeking a prestressed, equilibrium configuration from an arbitrary starting configuration, the structure stiffness matrix will exhibit pathological behavior when slack conditions in the cable structure arise during the solution process. The alternative Newton algorithm has no provision for controlling the condition of the structure stiffness matrix and may therefore be defeated by slack cable behavior.

The Newton algorithm requires that a cable pretension force be arbitrarily prescribed to avoid a singularity condition in the cable structure's stiffness matrix at the beginning of the solution process. This study has shown that robustness is adversely affected by this requirement. Convergence to the expected equilibrium solution sometimes depended on the value of the arbitrarily prescribed pretension force when multiple equilibrium solutions were present. Input data requirements that affect convergence in this way run contrary to the goal of a foolproof solution algorithm.

The ADR algorithm proved to be more robust than the full Newton algorithm and the solution algorithms in SEASTAR and SEADYN for the class of problems studied. It converged to the expected static equilibrium configuration in every test problem. Conversely, solution algorithms based on the full Newton method sometimes failed to converge to the expected solution, and instead converged to unexpected and sometimes meaningless alternative equilibrium states in those cases where the solution process encountered slack cable behavior.

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Table 1. Numerical Results of Fixed-Span Suspended Cable

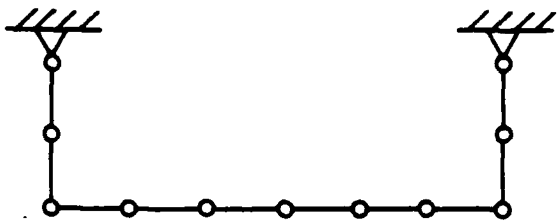
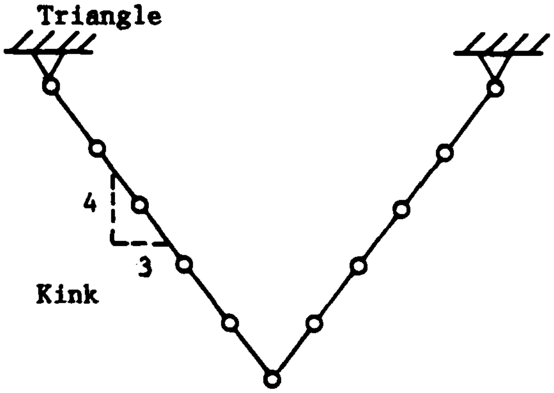
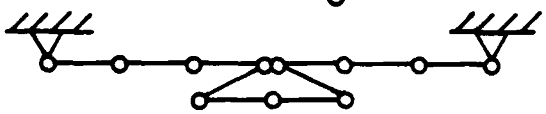
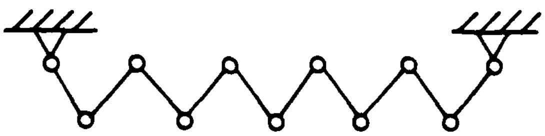
| Case No. | Initial Configuration | Algorithms: Full Newton | Algorithms: ADR |
|---|---|---|---|
| 1 | Rectangle  | Converged | Converged |
| 2 | Triangle   | Converged | Converged |
| 3 | Kink  (all elements are colinear) | Can converge to unexpected solution | Converged |
| 4 | Saw tooth  | Converged | Converged |

Table 2. Numerical Results - Cable Snap Through

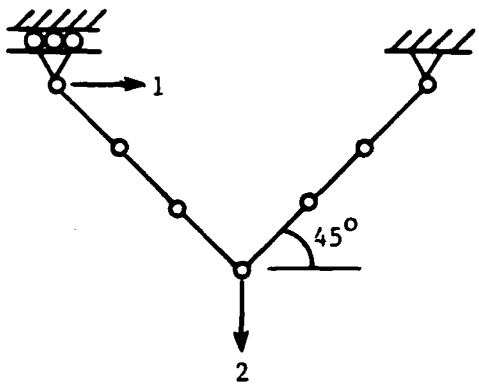
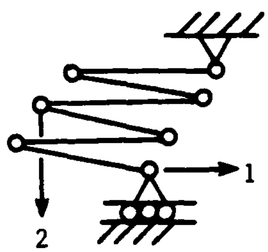
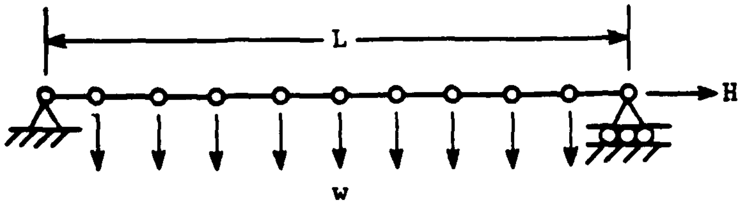
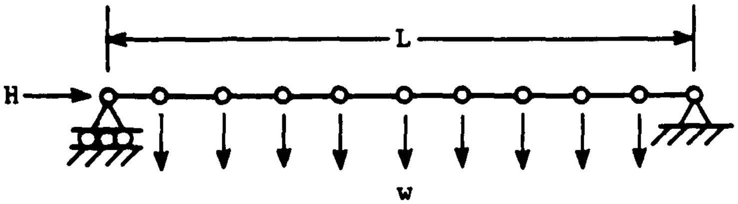
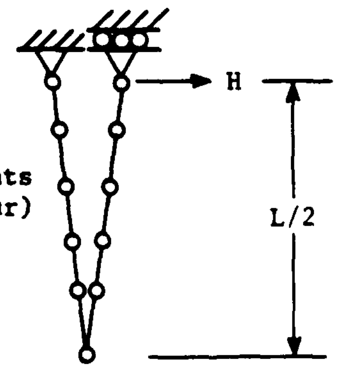
| Case No. | Initial Configuration | Algorithms: Full Newton | Algorithms: ADR |
|---|---|---|---|
| 1 | Triangle<br> | Converged | Converged with poor accuracy |
| 2 | Coil<br><br>(all elements are colinear) | Can converge to unexpected solution | Converged |

Table 3. Numerical Results - Varying-Span Suspended Cable

<table>
<tr><th rowspan="2">Case No.</th><th rowspan="2">Initial Configuration</th><th colspan="2">Algorithms</th></tr>
<tr><th>Full Newton</th><th>ADR</th></tr>
<tr><td>1</td><td>Taut<br><br></td><td>Converged</td><td>Converged</td></tr>
<tr><td>2</td><td>Slack<br><br></td><td>Can converge to unexpected solution</td><td>Converged</td></tr>
<tr><td>3</td><td>Sag<br>(all elements are colinear)<br><br></td><td>Converged</td><td>Converged</td></tr>
</table>

$L = 200$ ft<br>
$H = 5.77$ lb<br>
$w = 0.1$ lb/ft<br>
$EA = 1 \times 10^{3}$ lb

Table 4. Summary of Numerical Convergence Performance for Various Algorithms

| Test Problem | Initial Configuration | Newton-Raphson | ADR | SEADYN VRR | SEASTAR N-R |
|---|---|---|---|---|---|
| 1 | Rectangle, suspended cable | E | E | E | E |
| 2 | Triangle, suspended cable | E | E | E | E |
| 3 | Kink, suspended cable | E,U | E | U | E,U |
| 4 | Sawtooth, suspended cable | E | E | E | E |
| 5 | Triangle, cable snap-through | E | E | E | E |
| 6 | Coil, cable snap-through | E,U | E** | E | E,U |
| 7 | Inverted sag, four mooring cables | E | E | E | E |
| 8 | Taut mooring cable | E | E | E | E |
| 9 | Zero sag, varying cable span | E | E | E | E |
| 10 | Slack, varying cable span | E,U | E | E | E,U |
| 11 | Max sag, varying cable span | E | E | E | E |

Key: U = Converged to an unexpected or metastable equilibrium solution.
E = Converged to the expected, stable equilibrium solution.
** = Converged but with 9% error in final span--anomalous result.

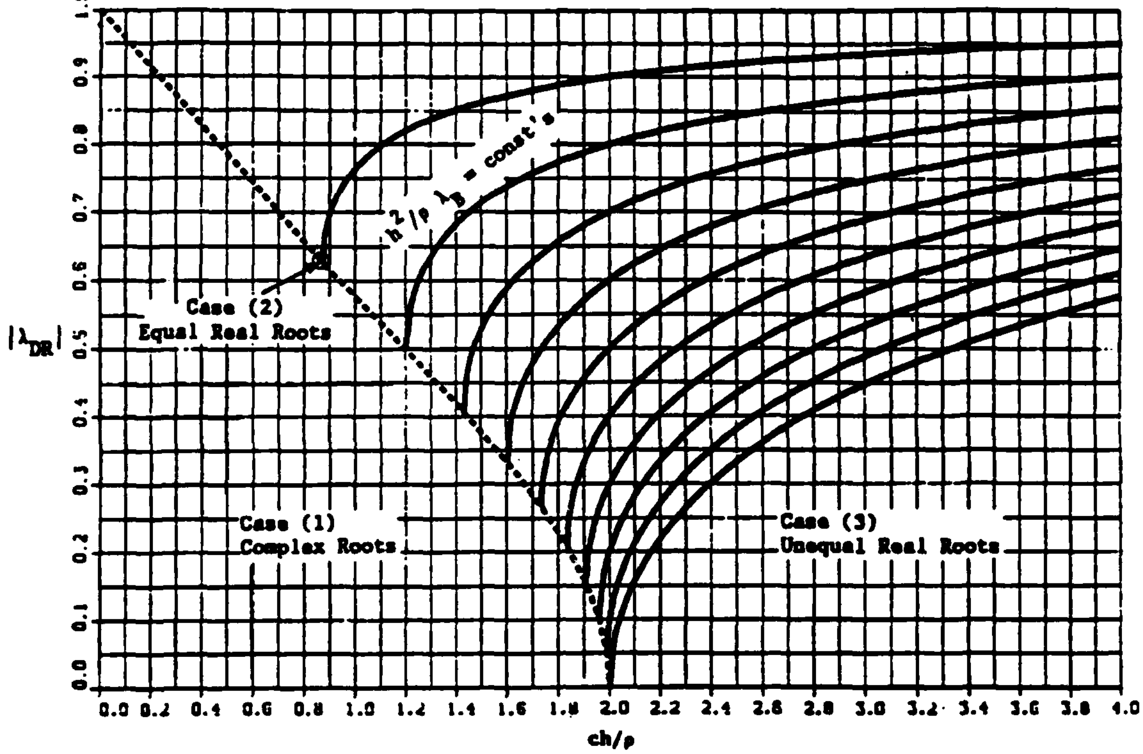



Figure 1. Dynamic relaxation -- relation between convergence and ch/ρ.

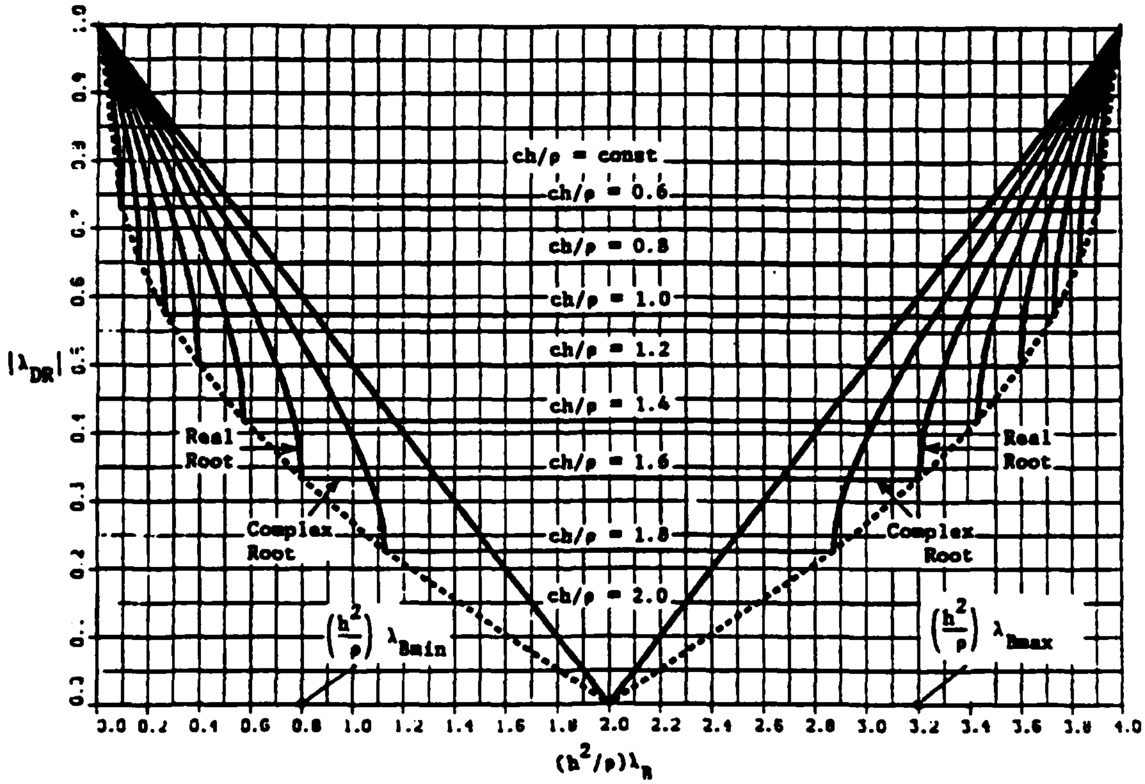



Figure 2. Dynamic relaxation -- relation between convergence and $(h^2/\rho)\lambda_B$.

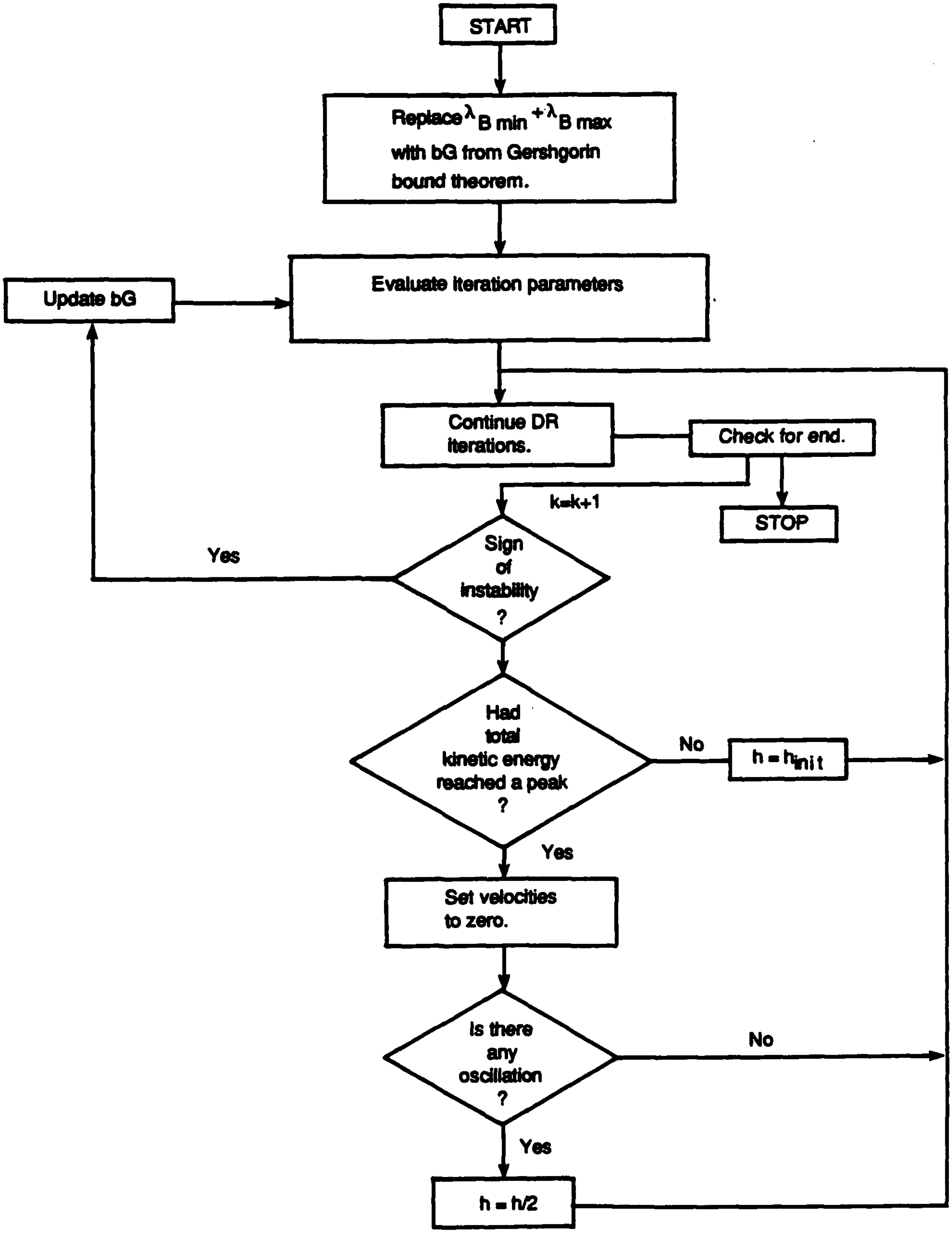



Figure 3. Flow chart for dynamic relaxation with kinetic damping (Papadrakakis, 1988).

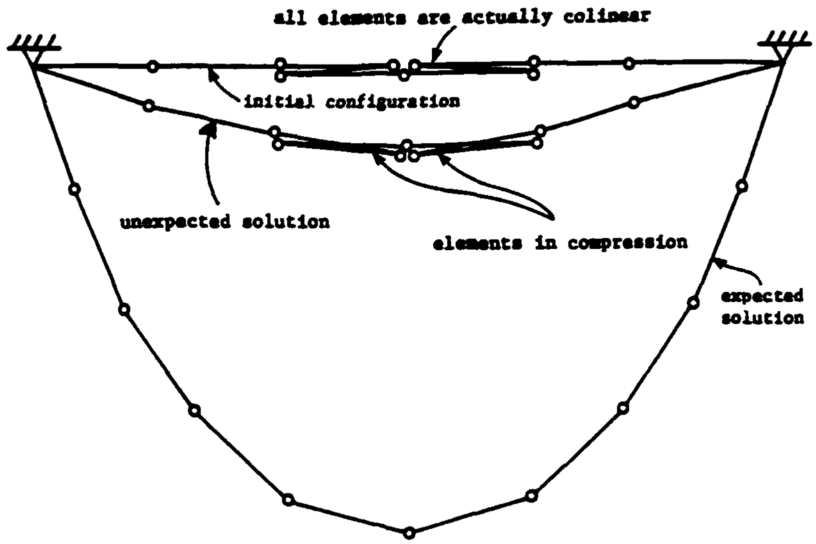



Figure 4. Expected and unexpected equilibrium configuration for initially kinked cable.

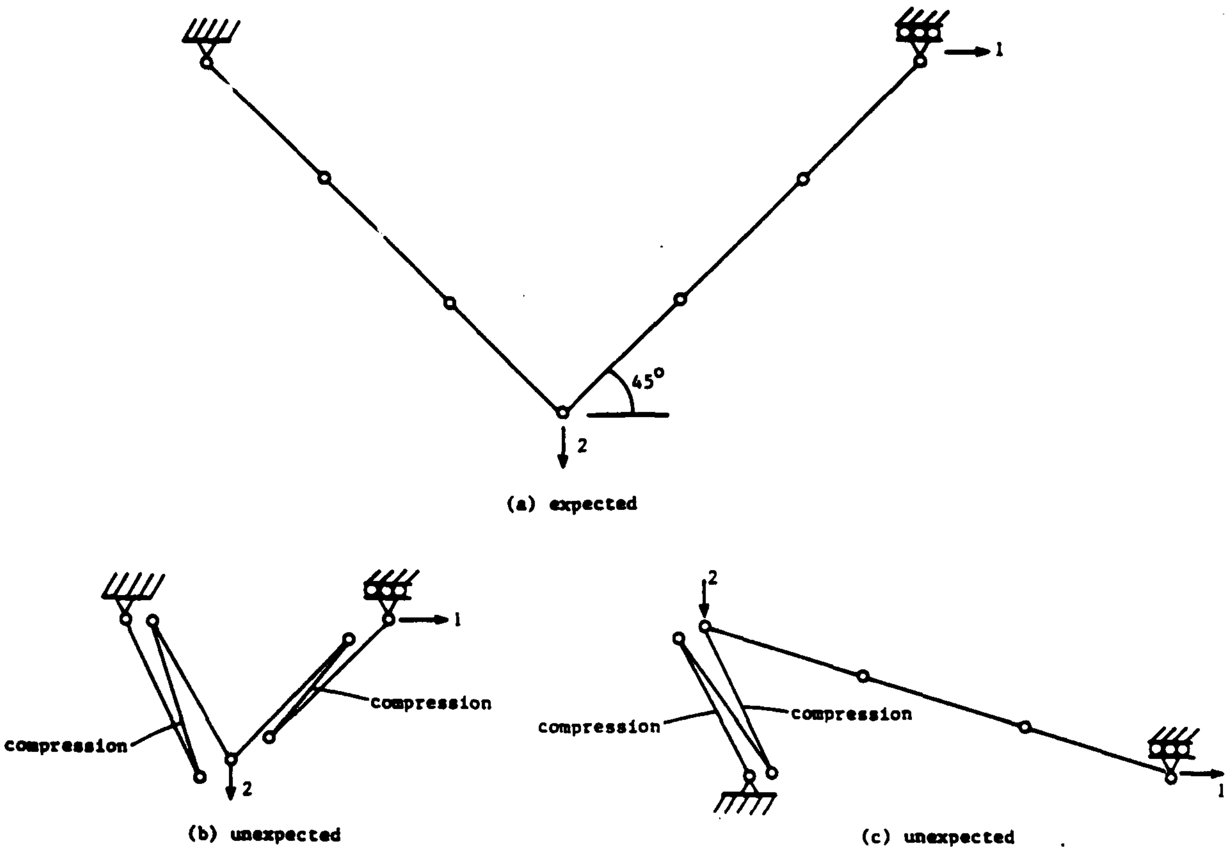



Figure 5. Expected and unexpected equilibrium configurations for initially coiled cable.

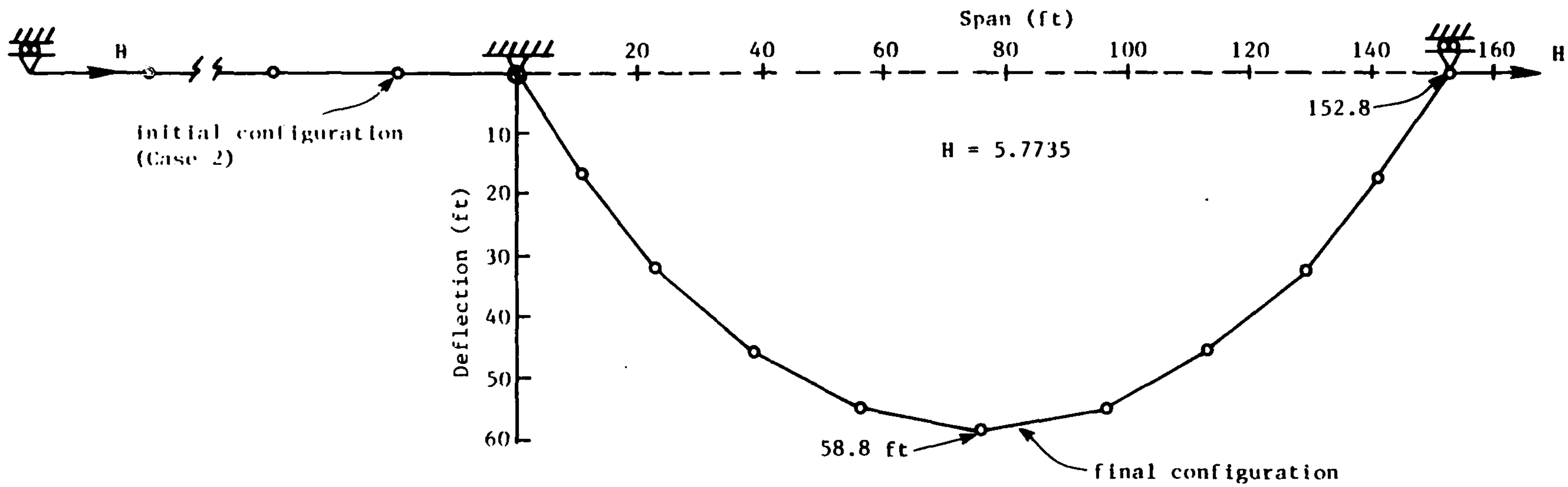



Figure 6. Expected equilibrium configuration for varying span problem.

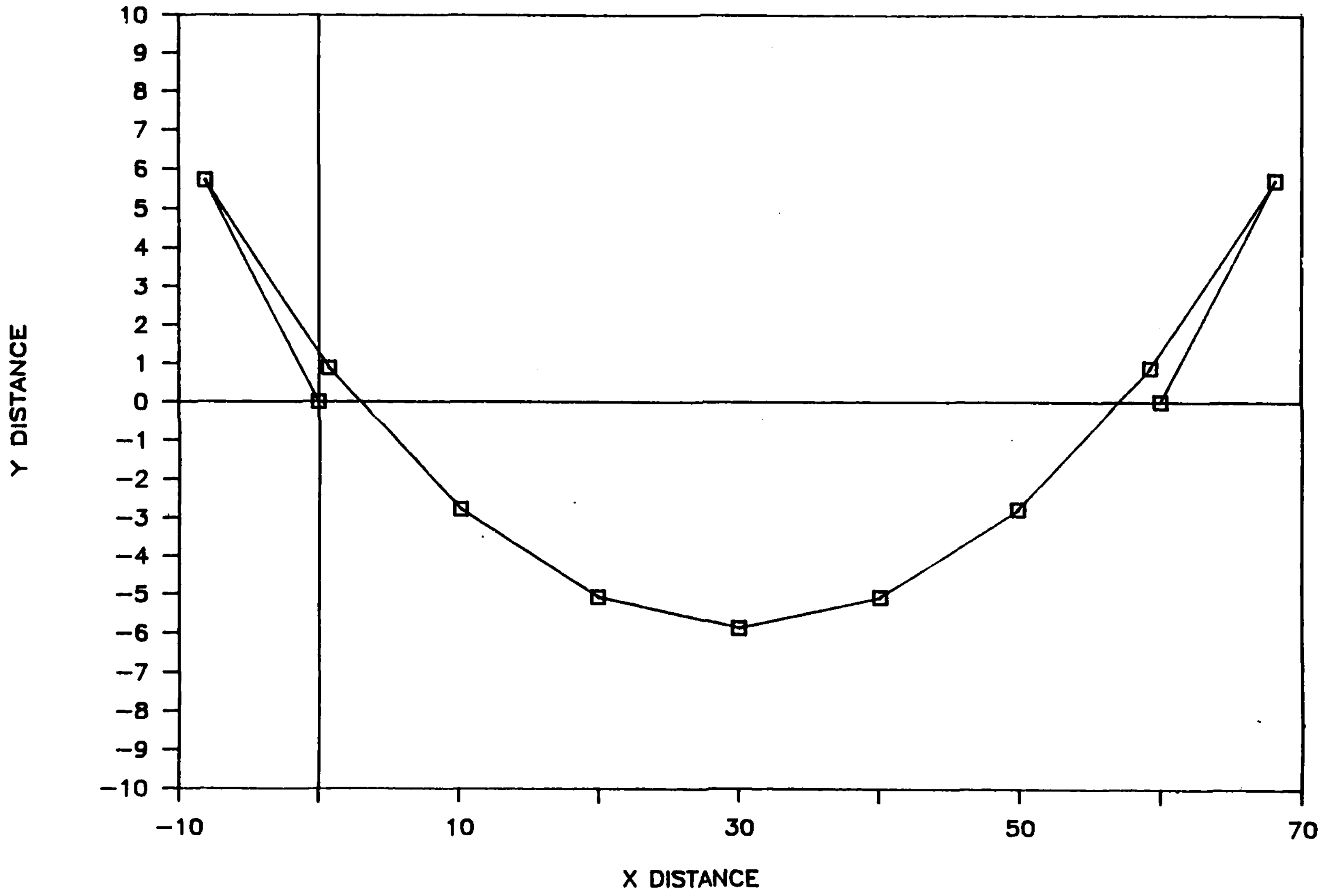



Figure 7a. Fixed-span suspended cable, kink start. Initial load = 0, load step = 0.5.

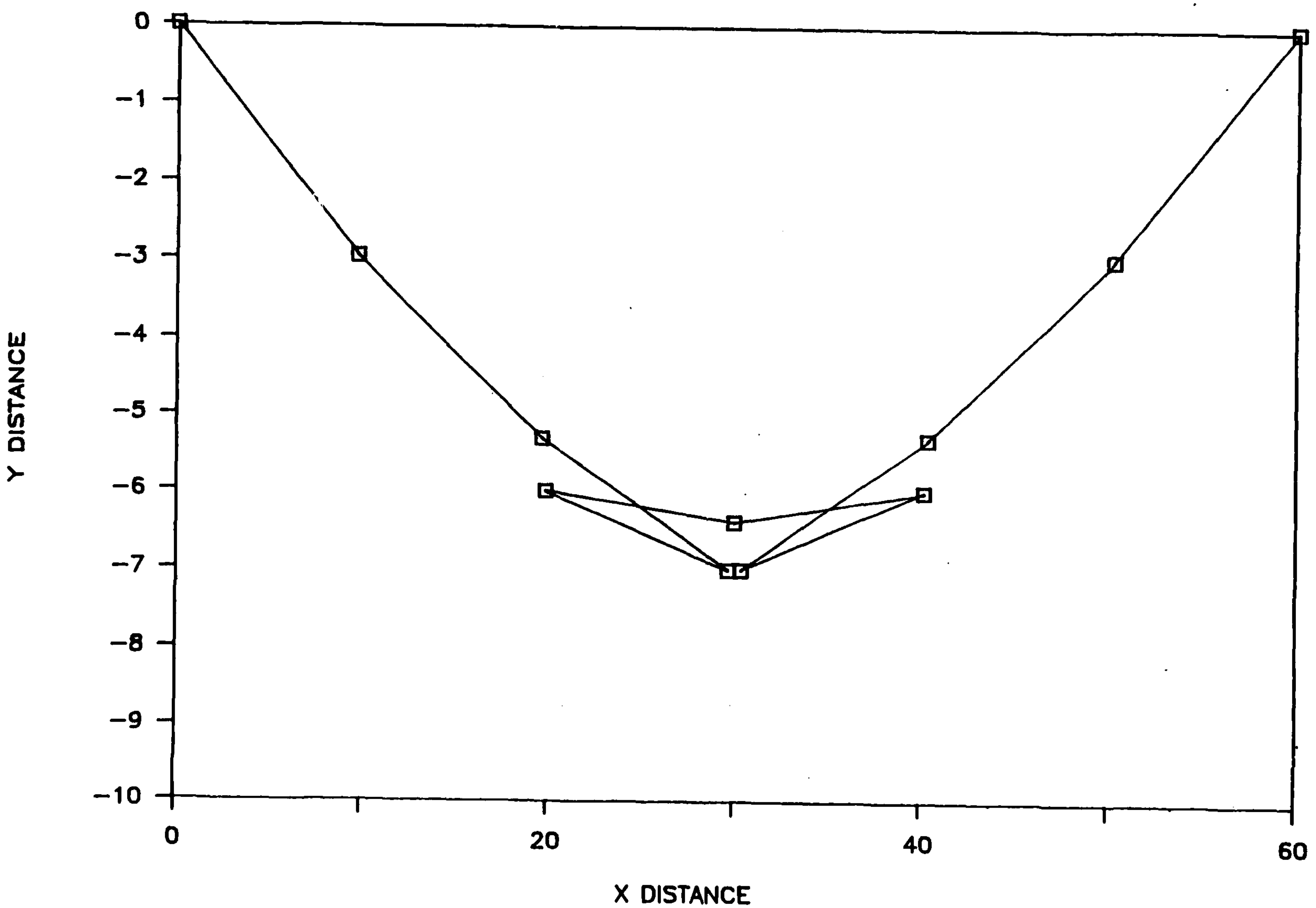



Figure 7b. Fixed-span suspended cable, kink start. Initial load = 0, load step = 0.25.

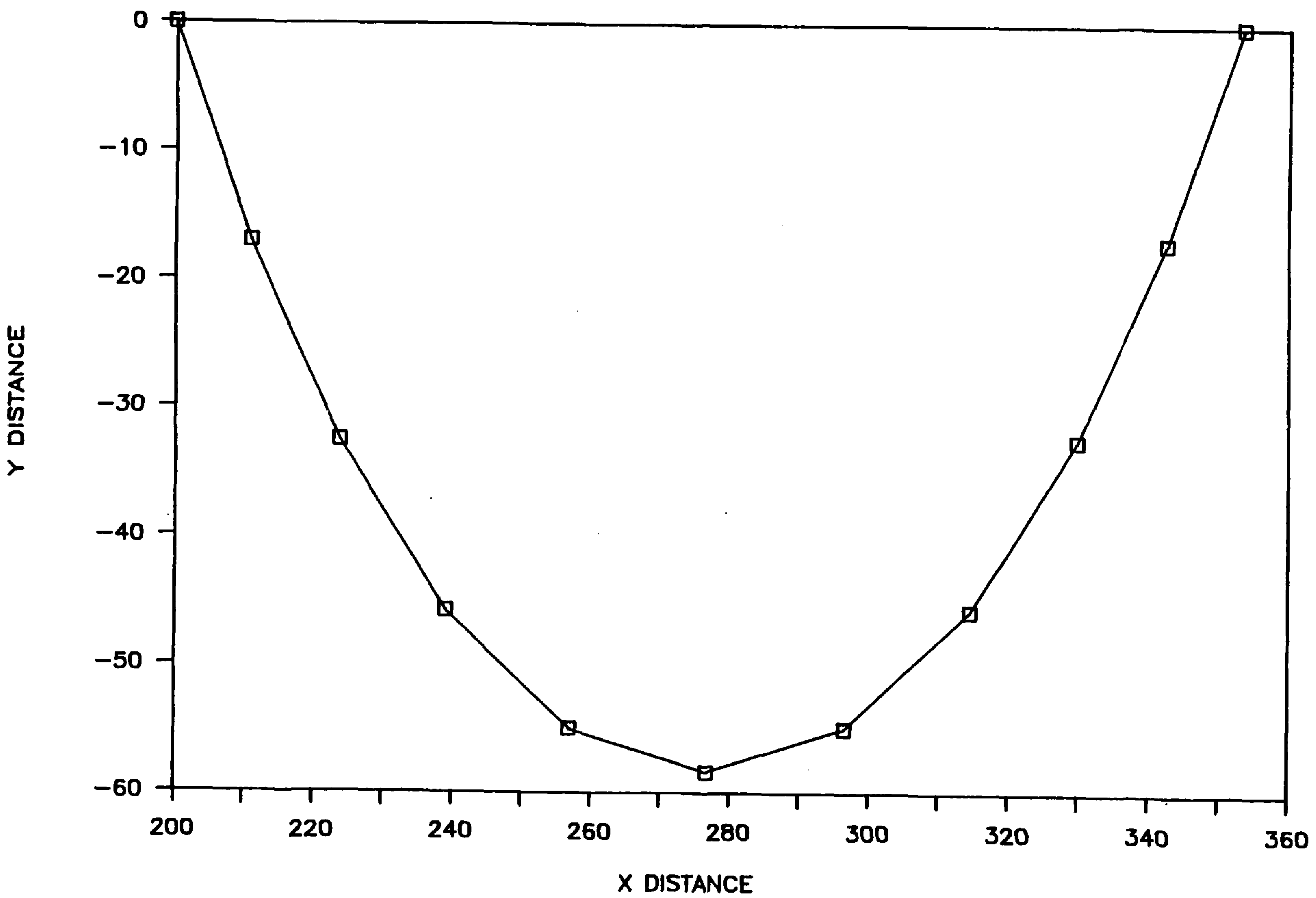



Figure 8a. Varying-span cable, case 2 - slack. Initial force = 0.1, load step = 1.0.

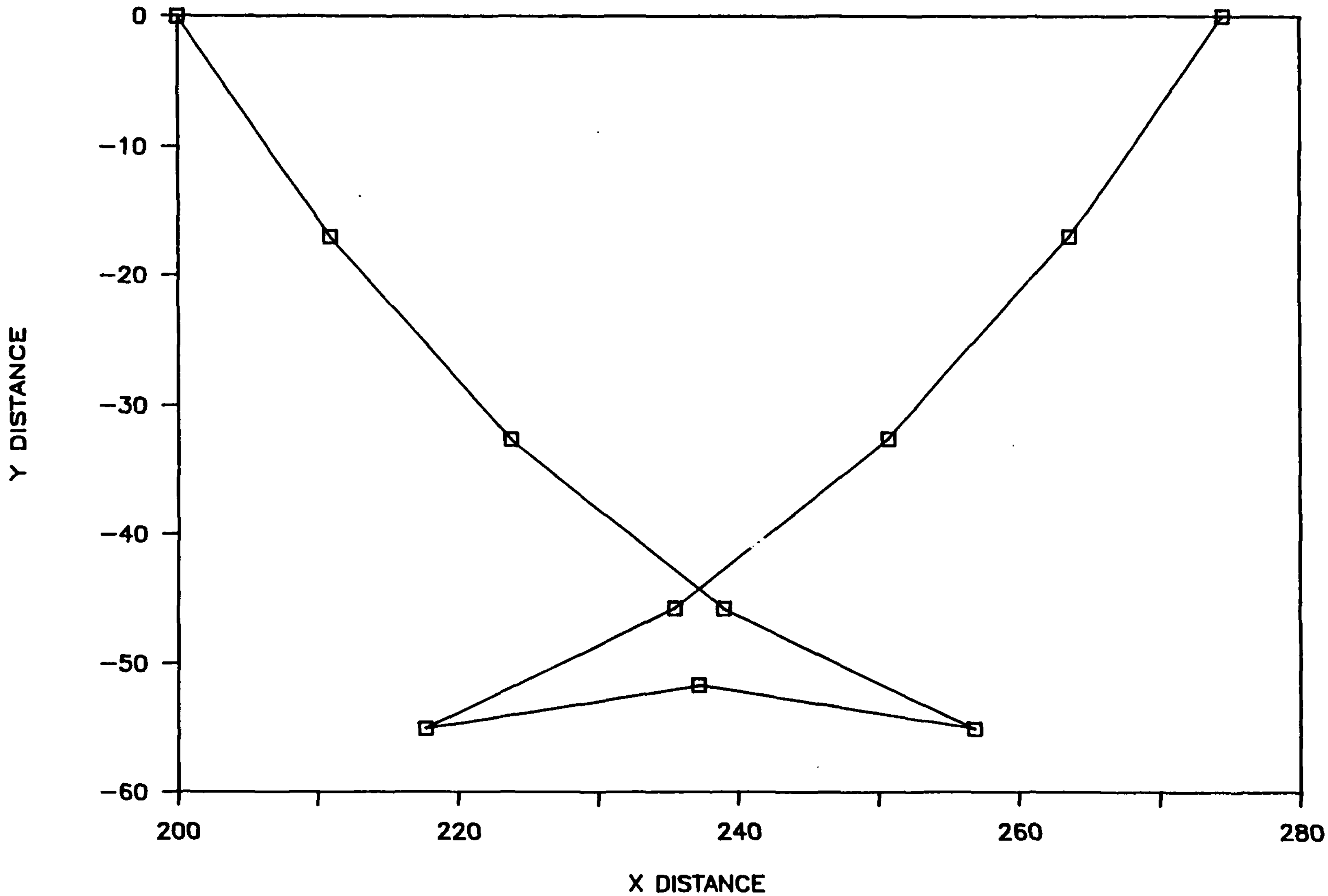



Figure 8b. Varying-span cable, case 2 - slack. Initial load = 0.1, load step = 0.25.

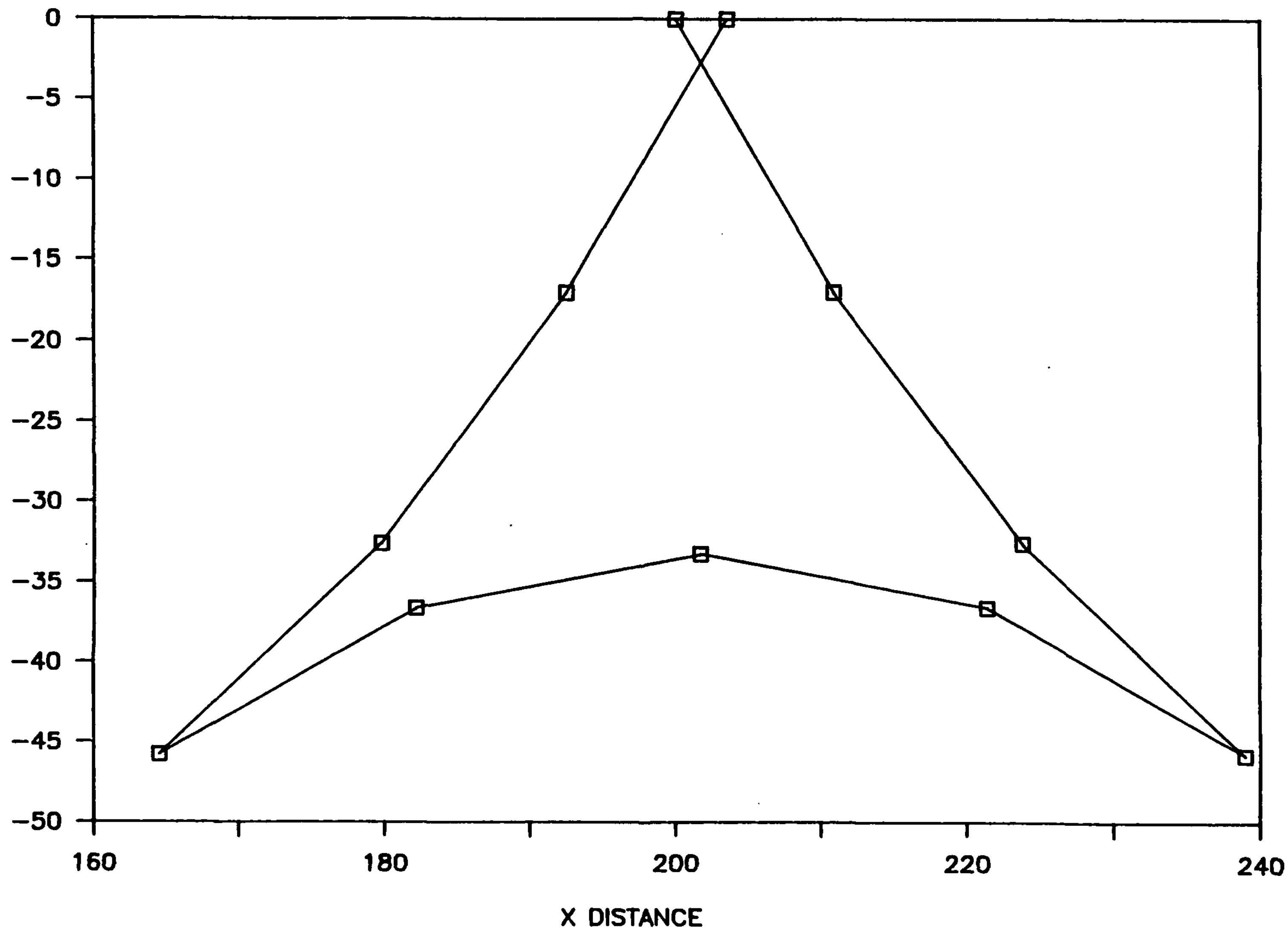



Figure 8c. Varying-span cable, case 2 - slack. Initial load = 0.1, load step = 0.05.

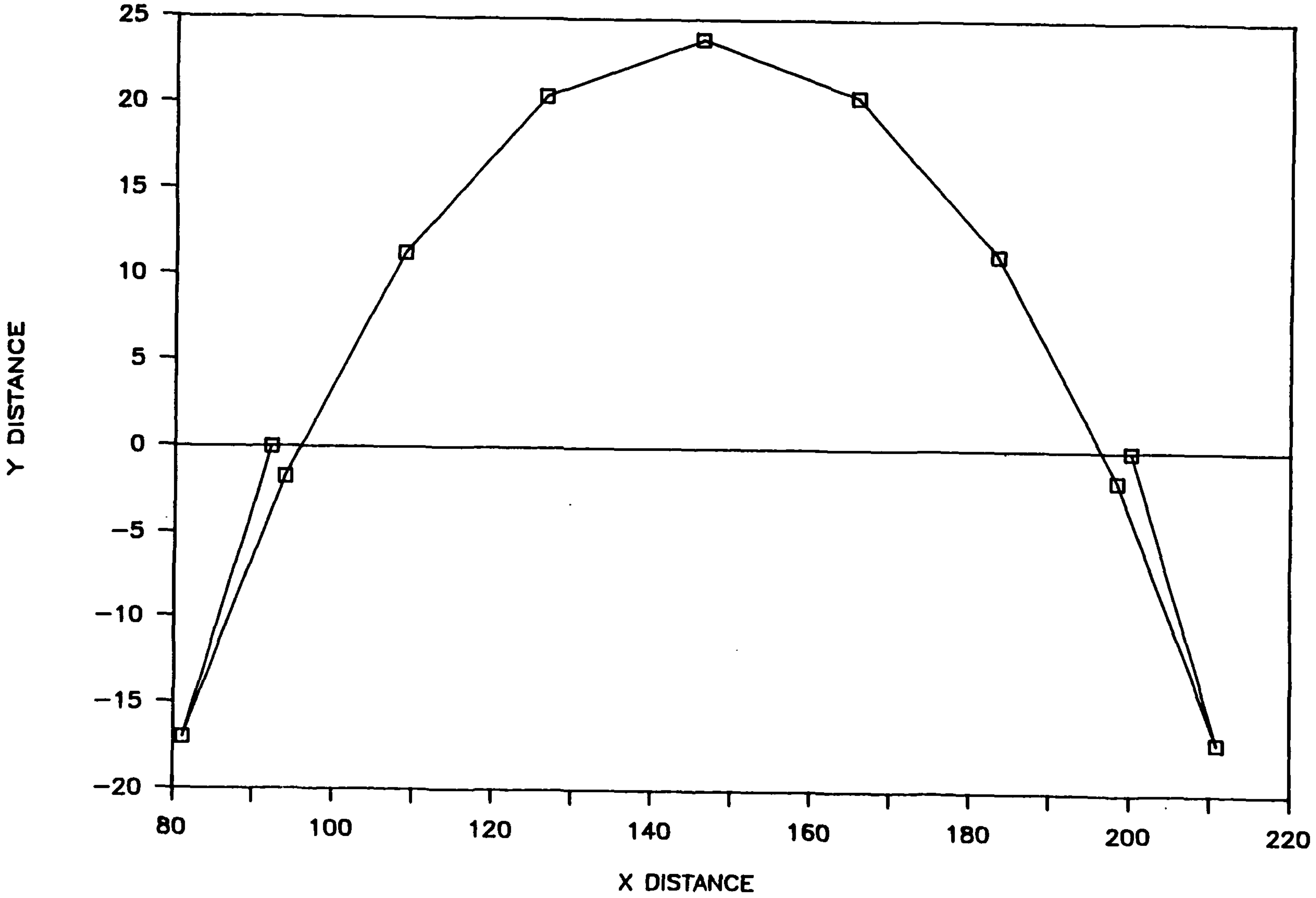



Figure 8d. Varying-span cable, case 2 - slack. Initial load = 0.0, load step = 0.05.

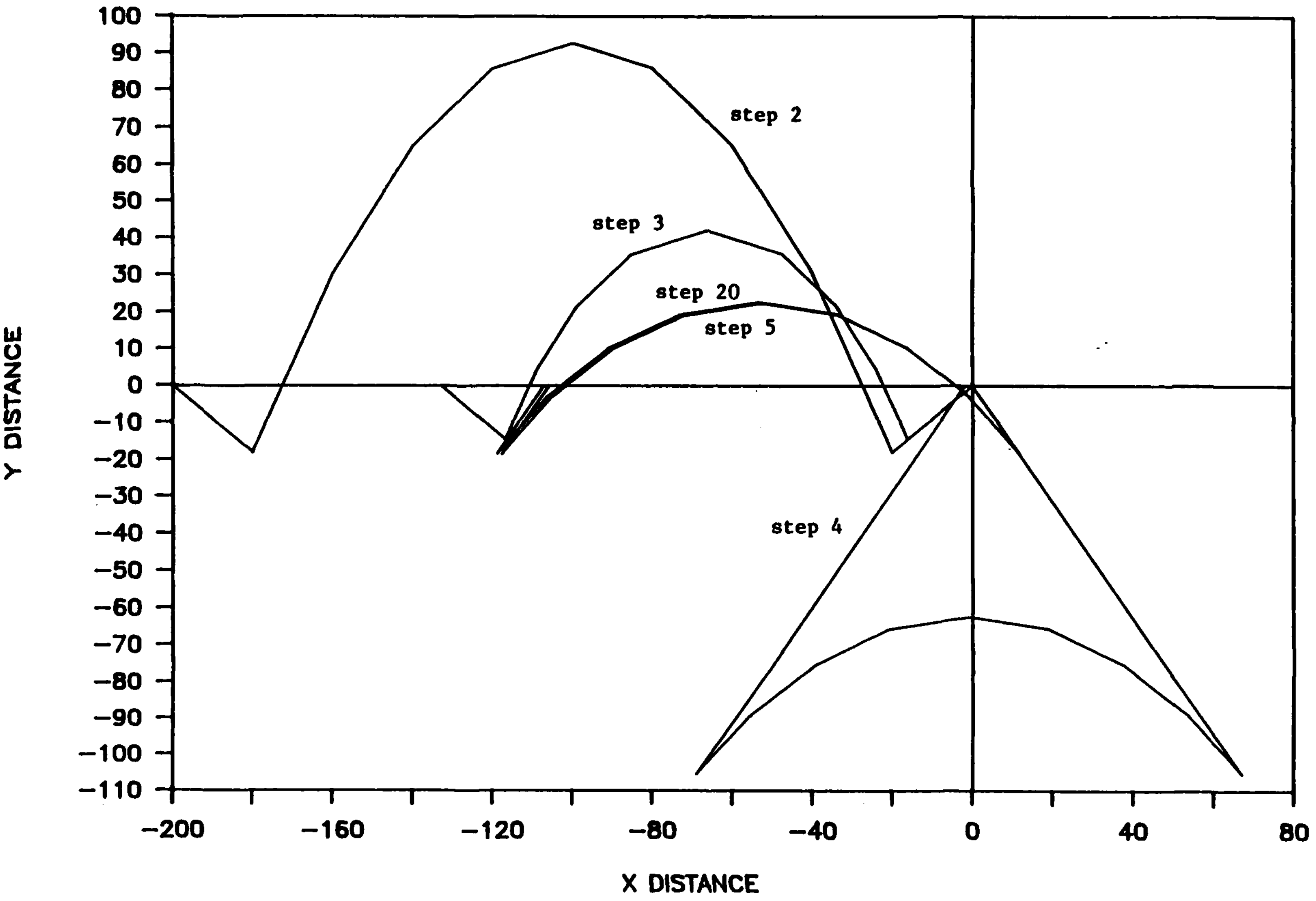



Figure 8e. Varying-span cable, case 2 - slack. Initial load = 0.0, load step = 0.05.

## Appendix

## DISCUSSION OF EXISTING NUMERICAL PROCEDURES FOR MOORING AND OCEAN CABLE SYSTEMS

The design of mooring systems is generally governed by static load behavior. The mooring problem described here is a static force problem in the horizontal plane for which the conditions of static equilibrium are imposed by three equations of equilibrium. Single-point mooring problems are statically determinant and multipoint mooring problems are statically indeterminant. For the single-point mooring problem, there are available the three equations of equilibrium in the plane to solve for the three unknowns; the ship heading angle, the hawser force, and the hawser heading angle. This problem can therefore be solved directly without resorting to the force-displacement relation and compatibility condition for the compliant mooring line. For multipoint mooring problems, each additional mooring leg, beyond the first, contributes two more unknowns (either two rectangular components of the restoring force or the restoring force and its angle) to the mooring problem. For an m-point mooring problem, the order of redundancy is therefore 2(m-1). Thus, 2(m-1) compatibility equations are required, in addition to the three equations of equilibrium, to solve the statically indeterminant problem.

The required compatibility equations are provided by the displacement constraints imposed by the rigid ship deck and by the compliant mooring lines. In numerical procedures, these constraints are formed from two sets of input data for each mooring leg; the coordinates of the anchor point and chock, where the mooring line is assumed to terminate, and the force-deflection relationship of the mooring legs. Thus, the relative distances among the chocks are known to the computer program and remain fixed in the horizontal plane according to the first set of data, and the displacement of the chocks relative to the anchor points can be calculated using the second set of data. From this information, the displacement of the ship and the displacements of the mooring lines are calculated such that compatibility is satisfied. The mooring line forces which act on the ship are calculated consistent with the ship displacement.

The Naval Facilities Engineering Command (NAVFAC) promogates a catenary mooring analysis computer program called MOORING to calculate the position of a fleet moored ship and the forces in the mooring lines due to wind and current loads. The analysis and design procedure, as well as this program, are described in NAVFAC Design Manual DM-26.5 (see the list of references). This program is a simple microcomputer program for both fleet and fixed mooring design. It is written in Microsoft GBASIC language and operates under the CPM operating system. It is currently being rewritten in FORTRAN. There are several attractive user-oriented features in the program, and it is apparently convenient for the design of standard moorings.

MOORING pertains to a specific anchor leg definition which is limited to a certain configuration and to two different types of materials. An anchor leg configuration may include a hawser from the ship to a surface buoy, a riser chain from the buoy to a ring or sinker, and up to three ground leg chains extending from the ring to three anchor points. Any combination or portion of this pattern may be prescribed for each leg of the mooring system. Length, submerged weight, and breaking strength of each line component is prescribed, and zero is entered where any generic component in the anchor leg definition is to be omitted. The nonlinear load-displacement curve for each prescribed anchor chain configuration is precomputed according to catenary equations and saved for subsequent use in solving the nonlinear static equilibrium equations governing the offset position of the moored vessel. Both the mooring leg configuration prescriptions and the catenary solutions are accomplished by running a subprogram CATZ.

The solution to the nonlinear static equilibrium equations provides the position of the moored vessel in terms of three degrees of freedom; they are the surge, sway, and yaw displacements relative to an assumed, prescribed initial position for the vessel. The Newton-Raphson solution method is employed. It has been noted that on occasion, convergence to the solution does not occur, and the computation is automatically terminated after a preset number of iterations. It is interesting that, according to the documentation in DM-26.5, this happens when the mooring system is exceptionally slack.

Calculations with MOORING were compared to calculations with another ship mooring program, FLEETMOR (Palo and Karnoski, 1986), and both were compared to measurements of moored ships made in the Carquinez Straits just northeast of San Francisco (Karnoski and Palo, 1986). The results showed that FLEETMOR was more accurate than MOORING. One reason is that FLEETMOR allows the wind and current loads on the moored vessel to vary according to changing position of the vessel during the solution process, whereas MOORING assumes the loads to remain constant and independent of vessel displacement.

Like MOORING, FLEETMOR is also intended to be an easy to use microcomputer program for analysis of standard ship mooring systems. It computes the static offset position of the moored ship due to wind, current, and wave drift force loads. It models up to 24 mooring legs with each leg comprised of up to three cable segments and a buoy or sinker. Line stretch is included to simulate the elongation of synthetic lines. Either surface or subsurface buoys may be simulated.

As in MOORING, the force-deflection relationship for each prescribed mooring leg subsystem in FLEETMOR is precomputed using two-dimensional catenary formulas and stored on disc file for later retrieval by the program's solution routine. Mooring leg configurations anticipate and are limited to standard Navy ship mooring practice. Arbitrary mooring configurations for buoys, ships, platforms, risers, etc., are not provided for in these programs. No cable drag forces are allowed, and therefore so-called mooring dominated systems cannot be analyzed with these programs. MOORING and FLEETMOR are not intended for general purpose mooring system analysis.

FLEETMOR is coded in FORTRAN using the Professional FORTRAN compiler for the IBM-AT (with math coprocessor) version and the Supersoft FORTRAN compiler for the Zenith version. It also has graphics routines written in BASIC. Program modification must be anticipated if other FORTRAN compilers are used when porting the program.

Like MOORING, FLEETMOR includes user-oriented editing features. However, unlike MOORING, FLEETMOR also computes the applied wind, current, and wave drift force loads from user-prescribed environmental data, and for user-prescribed Navy vessels. Accomodating the fact that these forces vary with the ship's heading relative to the direction of the environment adds substantially to the degree of nonlinearity in the static equations of equilibrium to be solved. As such, FLEETMOR solves a more difficult problem than MOORING, but it yields a more accurate prediction for the static offset position. That is, to the extent that the ship's assumed initial heading is different from its final heading in the static offset position, FLEETMOR's predictions of the offset position and mooring line tensions will be more accurate than MOORING's predictions. In this sense, a solution obtained by MOORING can be regarded as only an approximation to a solution obtained by FLEETMOR given the same assumed initial headings. The differences should be small for standard ship mooring applications which tend to be relatively stiff or taut multipoint systems, but for more flexible systems or for single-point mooring systems, the differences could be significant.

The solution method for the nonlinear static equations in FLEETMOR is based on a simple bisection technique (method of false position). It iteratively finds the heading angle of the ship that corresponds to a zero value of the residual moment acting on the ship. This method has a slower rate of convergence than the Newton-Raphson solution method used in MOORING. However, it may also be more robust for difficult mooring problems.

The solution routine in FLEETMOR is in fact derived from the bisection solution routine in another microcomputer program called STATMOOR (Cox, 1982). This program was written for single-point mooring analysis of Navy ships. It has no provision for mooring leg data and does not compute a static offset position for the moored ship. Thus, STATMOOR is not intended to be a mooring analysis program per se.

In single-point moorings the equilibrium heading of the ship depends only on the directions of the environmental loads and is not a function of the mooring leg restoring force. STATMOOR calculates this heading in the same way that FLEETMOR does for multipoint mooring cases, the only difference being that no restoring force from the mooring leg exists in the residual moment equation. The equilibrium heading found by the bisection routine corresponds to equilibrium among the forces acting on the ship due to environmental loading, which are also coded to vary as a function of heading, as in FLEETMOR.

Once the equilibrium heading is calculated, STATMOOR calculates the hawser force and heading necessary to hold the static offset position, but not the coordinates of the position itself. FLEETMOR, has the necessary mooring leg data to also calculate the static offset position. In fact, FLEETMOR contains the STATMOOR code and defers to this section of the program when a user flags the single-point mooring option. It then computes the equilibrium heading and hawser force as well as the static offset position.

For deep water mooring applications where the drag force on the mooring line becomes a consideration in the equilibrium of the system, and for general-purpose mooring and ocean cable analysis, none of the above Navy ship mooring computer programs are suitable. A general-purpose mooring analysis capability is required for practical solutions in these types of problems. Two general-purpose computer programs are in use for Navy applications, SEADYN (Webster, 1976, and Webster and Palo, 1982) and SEASTAR (Pawsey and Nour-Omid, 1988). These computer programs are displacement-based finite element programs, and it is this technology that provides for general-purpose capability. Cables are modeled as a series of one-dimensional finite elements which may be subjected to hydrostatic or hydrodynamic loads, and they may be assembled into an entire mooring leg or arbitrarily into many legs, and they may be networked in arbitrary geometrical configurations. SEADYN and SEASTAR would seem more suitable for mooring and ocean cable system analysis than alternative commercially available general-purpose, nonlinear finite element programs (MARC, ADINA, ABAQUS, ANSYS, MSCNASTRAN)* because they have been specified to ocean engineering problems. Their nonlinear analysis features are, however, too extensive to be appropriate for current microcomputer implementation.

One computer program called SOUPLE (Peyrot, 1980) is implemented on IBM-AT microcomputers and provides general-purpose mooring and cable analysis capability. This program is based on the catenary formulas given by O'Brien and Francis (1964) for use in modeling mooring legs as in MOORING and FLEETMOR, but the catenary force-deflection relationship is cast (Peyrot and Goulois, 1979) as a flexibility relationship as described in the theory of matrix analysis of structures. This relationship is then simply inverted to obtain a stiffness relationship so that it behaves like a super cable finite element. This is so that the standard, direct stiffness algorithm may be used to assemble arbitrary networks of these elements, as well as other structural elements, into a structural model of a mooring or cable system. Depending on the problem, either a single catenary element or a series of catenary elements are used to model each mooring leg. Thus, SOUPLE is a displacement-based structural analysis computer program which has been specified to ocean engineering problems (Peyrot, 1980 and 1989).

Hydrodynamic loads are distributed to the cable elements in such a way that the catenary equations (classically associated with gravity loading only) upon which they are based remain valid. In a sense, the loads are treated as an artificial gravity force component distributed along a cable, but in the direction of the normal drag force component instead of in the vertical direction typical of conventional catenary mooring legs. The tangential drag force component is neglected.

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*Some of these programs (ABAQUS, for example) do provide for ocean cable analysis including hydrodynamic loads and spectral analysis capability. They should be considered where they are available when solving ocean structural analysis problems because they are user-oriented, commercially-tested products.

SOUPLE does not provide for variable hydrodynamic forces on a moored ship as does FLEETMOR, and therefore it would not be as appropriate in ship mooring problems where the specification of such forces is important. However, it can be recommended for use in other or more advanced problems when the larger general-purpose programs SEADYN and SEASTAR would otherwise be employed; because it is microcomputer-based, it should be simpler to use, and because the mooring legs are modeled using catenary formulas, convergence to the equilibrium solution should be more reliable.

The solution algorithm coded in SOUPLE is the Newton-Raphson method. Significantly, the algorithm has been modified to enhance convergence performance. The modification consists of an addition of artificial stiffness to the mooring system's structural stiffness matrix. The amount of artificial stiffness added is variable in two respects. First, the user is required to make decisions on the appropriate amount of artificial stiffness during the input data phase based on his/her experience in the use of the program to solve more difficult and highly nonlinear problems. For more well-behaved problems a default value may be selected. Second, the amount of artificial stiffness diminishes automatically after each iteration of the solution procedure so that only a minimum amount of artificial stiffness exists when convergence is achieved.

SOUPLE does have its limitations in static problems, and it looses some of its formulation elegance when handling cable inertia forces in dynamic problems. In static problems, the catenary elements used to model a mooring leg must each remain in their own plane, so if the vertical current profile is not coplanar, the mooring leg must be modeled as a series of smaller elements each deforming as a catenary in its own plane. Even when the vertical profile is coplanar, but not uniform, the user must anticipate the use of a series of elements to model the variation of drag forces with depth. This can be done easily enough by specifying the load variation on the mooring leg in its initial configuration. However, if the mooring leg's vertical position changes during displacement from the initial position to the final position, SOUPLE will not accomodate the changes because the load on each element will remain constant irrespective of the changing depth of the element.

The situation in dynamic problems is similar because the inertia forces on a mooring leg will vary spatially. Thus, when using SOUPLE to solve dynamic problems, a significantly larger number of catenary elements will be needed to model the variation in inertia forces with fidelity. This mitigates the advantage that SOUPLE would normally have over SEADYN* and SEASTAR due to its super catenary element formulation in contrast to a traditional finite element formulation for modeling compliant structures.

*While SEADYN also has this catenary element, its architecture is not designed around it. SOUPLE has a smaller architecture which permits a microcomputer implementation.

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