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Woods Hole Oceanographic Institution

A COMPUTER PROGRAM FOR THE DESIGN AND STATIC ANALYSIS OF SINGLE-POINT SUBSURFACE MOORING SYSTEMS: NOYFB

by

Donald A. Moller

June 1976

TECHNICAL REPORT

Prepared for the Office of Naval Research under Contract N00014-66-C-0241; NR 083-004.

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Valentine Worthinton, Chairman
Department of Physical Oceanography

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ABSTRACT

This report describes computer program NOYFB: a method of determining the static configuration of sub-surface oceanographic moorings for the purposes of system design and analysis of performance. Operating instructions and the program listing are included as appendices.

The program is written in Fortran II specifically for W.H.O.I. Hewlett-Packard 2100 series shipboard computer systems. The user acts as the computer operator in a decision-making capacity, specifying, evaluating, and modifying the mooring composition and control and environmental parameters. Principle features of the program are:

a) useable both at sea and ashore,

b) real time selection of output formats and devices,

c) standard W.H.O.I. mooring component characteristics are stored in the program with the option of user modification,

d) capable of handling complex, non-uniform current profiles,

e) automatic component length adjustment for depth critical instruments,

f) calculation of launch transients and reserve buoyancy,

g) the ability to imput/output the mooring composition and characteristics from/to punched paper tape.

1.0 INTRODUCTION

During the past six years the Moored Array Project of the Woods Hole Oceanographic Institution has developed and used operationally a subsurface oceanographic mooring system (Ref. 1). Composed of standardized mooring components and instrumentation, these moorings are deployed at a rate of approximately 40 per year. Because of the number involved it was felt that it would be efficient to use modern computer techniques to assist in the routine design of moorings. Each could then be conveniently tailored to specific scientific requirements, water depths, anticipated current regimes and logistical considerations.

Numerous computer programs for determining the static configuration and dynamic response of subsurface moorings exist (Ref. 2) including some highly relevant work produced at Woods Hole (Ref. 3). However, it is judged that on the whole these programs have the undesirable feature, for our application, of being geared to sophisticated engineering evaluation of system performance. This generally requires detailed knowledge of component characteristics, complex input/output procedures and involves considerable time delay in obtaining final or acceptable results.

Computer program NOYFB was written to eliminate the need for procedural complexity and to provide, in real time, a description of the mooring and its performance from an operational point of view.

It is the intent of this report to describe the composition, operation, and utilization of computer program NOYFB.

2.0 OBJECTIVES

The main objective of the program is to provide to the mooring designer and the person responsible for its construction the statistics of the static configuration of W.H.O.I. subsurface single point oceanographic moorings. Secondary objectives are:

- To provide a single program useable both at sea and in the laboratory.
- To permit the operator/designer to act in real time on-line with the computer in a decision-making role, evaluating and modifying successive runs.
- To make the program simple to use with a minimum of training in computer operation.
- To have the program lead the user step by step through successive input and option procedures.

- To provide output in a format directly useable by those responsible for constructing the mooring in commonly used units (pounds, meters, degrees, etc.).

- To produce a permanent record on paper tape or magnetic tape of details of the composition of the mooring.

- To assure a high degree of flexibility so the program would be readily useable for special purpose applications and be easily manipulated by the experienced and sophisticated user.

3.0 APPROACH

3.1 Computer System

The Hewlett-Packard 2100 series computer system was selected for this application. These computers are readily available at W.H.O.I. as standard shipboard systems and as general usage systems ashore. All systems contain 16 K of memory. A variety of peripheral devices (CRT terminals, line printers, paper tape I/O, magnetic tape, cassette, and disc) give the operator flexibility in the method of data input and output. The machines are physically compact and easy to operate with a minimum of instruction.

3.2 Program Language

The program is written in Fortran II. This commonly-used language and the use of frequent annotation in the source program should permit convenient understanding of logic and flow in the event program modification is desired.

3.3 Program Operation

The computer systems are designed for on-line program user control. The program takes advantage of this feature by presenting data to the operator for real time evaluation and provides the means for convenient alteration of control and environmental parameters and of mooring components. This permits rapid optimization of the mooring design and evaluation of its performance. In addition, input errors can be detected and remedied without significant time delay.

To obtain simplicity of operation, all standard mooring component characteristics (buoyancy, area, elastic properties, etc.) are written into the program and stored in arrays at initialization. The user inputs the mooring component type and the program assigns characteristics as appropriate.

In another attempt to obtain simplicity of operation, step by step instructions for program operation are displayed to the user (in English) with the sequence determined by his selection of options. This eliminates the need for a pre-run prepared set of control and input parameters with the attendant likelihood for error.

Flexibility of program application and of operation is attained by providing the option to change any component characteristic either at program initialization or at a subsequent run. Provision is made for the addition of non-standard components with unique elastic properties and coefficients of drag. Proper manipulation of these characteristics and of input parameters permits the program to be used for varied and complex sub-surface mooring systems.

3.4 Features

The program offers the following features:

a. All possible statistics generated by the program of the mooring configuration and the forces acting upon the mooring can be output. The user selects the information to be presented by sense switch option control (see Appendix E for details).

b. I/O flexibility by manual selection of five I/O devices at program initialization. Further, by exercising various options when running, the user can vary the input/output devices within those five devices. Judicious selection of the devices will provide for hard and/or soft copy, manual and/or machine input, and visual and/or machine output.

c. The ability to output to perforated paper tape (or any similar read/write device) the composition and characteristics of a mooring. Similarly, the ability to input a previously designed mooring from paper tape is provided. This feature provides a permanent record of the mooring and a means for efficient and rapid duplication of the mooring for future runs.

d. The ability to input a complex profile of horizontal current varying with depth in both speed and direction, i.e., not co-planar.

e. An omni-directional external force (point force) of any magnitude can be applied to the top of the upper component. This feature provides the ability to model the effects of components which are not integral to the mooring, such as surface markers and tag lines, upon the system.

f. Operator control of the maximum length of segments used in defining the discrete units for the calculation process. In effect, this gives the user the ability to vary the degree of approximation to the true shape of the mooring. It also controls the time required for the completion of each run.

g. Operator comments are written in all output options providing headings and mooring identification.

h. All standard W.H.O.I. mooring components and their characteristics are written into the program and are accessed by code.

i. The operator has the option of altering any component characteristic or input parameter that is written into the program. This can be done both at initialization and after each run.

j. The program displays instructions for the operator to lead him through the proper sequence for initialization and the use of the change options.

k. The program has an automatic component length adjustment feature which places components at specified depths. The lengths of up to ten components will be adjusted so as to place a paired component at a desired depth.

4.0 COMPUTER PROGRAM SOLUTION

It is the intent of this section to describe the basic equations and logic used to determine the static configuration of subsurface moorings. Since the solution uses generally accepted theories for resolving and balancing the forces acting upon a mooring system, the description of the theoretical background is minimal.

4.1 Parameters Considered

The following parameters are considered in the calculation of the mooring configuration.

a. Component buoyancy, area, and length.

b. Component shape: reflected in the assigned coefficients of drag.

c. Elastic properties of wire and line.

d. Termination length and buoyancy.

e. Method of measuring synthetic lines, i.e., slack or under $200d^2$ tension.

f. Depth of water.

g. Horizontal currents varying with depth in both speed and direction.

h. Maximum tensile loading during launch (launch transients).

i. Anchor weight and effective resistive area.

j. Application of an external load at the top component.

4.2 General Description

The program operates on the premise that subsurface moorings placed in a horizontal current velocity field react to drag-induced forces by spatial displacement with no significant alteration of tension. Horizontal displacement results in a subsequent vertical "dipping" of the mooring in a pseudo-cosine response which alters the position and attitude of the mooring in the forcing current regime. The equilibrium condition of the mooring system is determined in an iterative process in which the mooring configuration is recalculated for successively refined assumed current regimes. An assumed depth of the top component is calculated for each iteration. When the calculated depth and the assumed depth coincide (<2 meters), i.e., the true and assumed current regimes are identical, the resulting mooring configuration is considered to be in a state of equilibrium.

The mooring is composed of individual components of given length which creates non-uniform buoyancy and area distribution over the length of the mooring. For this reason a finite element method is used to establish the equilibrium configuration and the loading of the mooring. Components are divided into discrete units (segments), the maximum length of which is user designated. Segments are treated as inflexible but elastic cylinders with nodes of freedom at each end. The gravity and resistive forces acting on each segment are determined and balanced against the external restraining forces to obtain the equilibrium condition. This is done in an iterative process in which the inclination and azimuth of the segment are evaluated and recomputed (as are the gravity and resistive forces) until the change between successive steps is minimal (<0.1 degree). Segment elongation is calculated, if appropriate, and the X, Y, and Z displacements of the stretched length are determined.

Computation is self-initiated at the termination of input. The measured length of all components is totaled and subtracted from the water depth to establish the assumed depth of the top component in the current profile. The peak loading of each component in a free-falling anchor launch is calculated. Where appropriate this is used in the calculation of segment elongation. Starting at the top component and proceeding sequentially along the mooring, the number of segments in each component is determined. The length, buoyancy, area, and assumed depth of the mid-point of each segment and the current velocity at that depth are computed. With these values the gravity and resistive (drag) forces are determined and the resulting attitude, displacement and loading of the segment are calculated as described above. The displacements of the segments within each component are summed and stored in arrays as are the inclination and axial tension of the lowest segment and the accumulative normal drag and the elongation of the component. These values are the source of the output statistics.

When these computations are complete the calculated depth of the top component is compared to the assumed depth used for those calculations. If the difference exceeds 2 meters a new assumed depth is determined and the configuration is recalculated. When the difference is less than 2 meters, the mooring is considered to be in equilibrium and the routine for automatic component length adjustment is entered. The depths of specified components are evaluated and the lengths of their paired component are adjusted to position them at desired depths. The entire computation sequence is then re-initiated. When all depth requirements are met the statistics are output.

4.3 Specific Description

A description of the significant aspects of the computer solution is given. Sections to be discussed are:

a. Launch transients

b. Current profile and point velocities

c. Gravity and resistive (drag) forces

d. Equilibrium equations

e. Component elongation and elastic properties

f. Displacement of segments and components

g. Automatic component length adjustment

h. Reserve or back-up buoyancy

4.3.1 Launch Transients

The maximum loading of each component of the mooring during free-fall anchor descent is calculated. Transients are considered the history of stress for synthetic lines which is required for the calculation of permanent elongation. Launch transients are calculated in the following manner.

$$T_i = \sum_{1,i} W + V^2 \frac{1}{2}\rho \sum_{1,i} C_D A \qquad (1)$$

where

T_i = tension in component i in pounds

$\sum_{1,i} W$ = sum of the buoyancies of components 1 through i

V = terminal velocity of the anchor in ft/sec

$\sum_{1,i} C_D A$ = sum of drag coefficient times effective area for components 1 through i

ρ = mass density, taken to be 2.0 slugs/ft^3

The terminal velocity* is found as

$$V^2 = \frac{W_a - W_t}{\frac{1}{2}\rho\left[\sum C_D A + C_D A_a\right]} \qquad (2)$$

where

W_a = weight of the anchor in pounds

W_t = net buoyancy of the mooring components at the anchor

$\sum C_D A$ = sum of the drag coefficient times effective area of all components

$C_D A_a$ = drag coefficient times effective area of the anchor

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*The program utilizes one set of drag coefficients for all calculations of hydrodynamic resistance. Coefficients for high velocity regimes are generally lower in value than those representative of low velocity regimes because of associated larger Reynolds numbers. Therefore, the calculated terminal velocity may be in error when the standard (programmed) coefficients of drag are used. However, this fault produces no significant error in the calculated values of launch tension for standard mooring components.

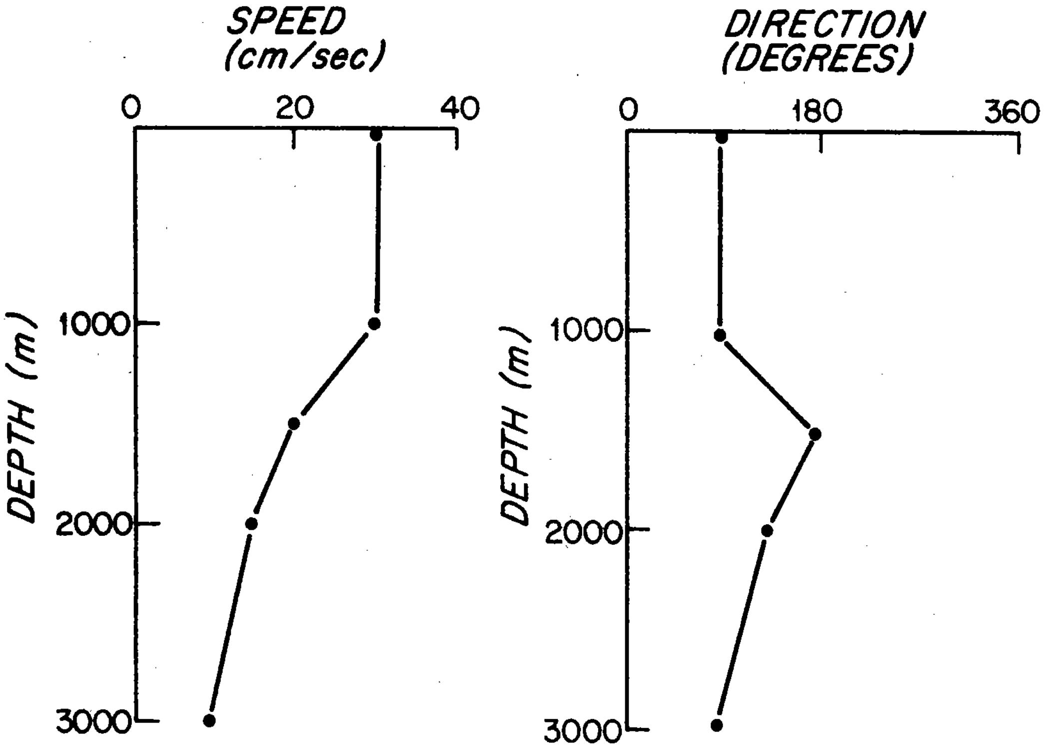


Fig. 1. Horizontal Current Profile Input.

4.3.2 Current Velocity

Horizontal current induced drag forces are the prime source of perturbation to subsurface mooring systems. Ocean current velocities can vary over the length of the mooring in a complex manner. The horizontal current field is an input parameter which is entered as a vertical profile of current velocities (see Fig. 1). The velocity profile is input as speed and direction at specified depths. The velocity at any point in the profile is obtained by linear interpolation between inclusive input values and is indexed by the assumed depth of the mid-point of the segment under consideration.

The velocity of a given point is broken into two components (see Fig. 2); one, V_u, lying in the plane of the segment, which tends to incline, and one, V_v, normal to the plane of the segment, which tends to rotate. The equations are

$$V_u = V_T \cos \gamma \quad \text{or} \quad V_T \cos (\beta - \theta) \qquad (3)$$

$$V_v = V_T \sin \gamma \quad \text{or} \quad V_T \sin (\beta - \theta) \qquad (4)$$

where

V_T = current vector speed

β = current vector direction (relative to north)

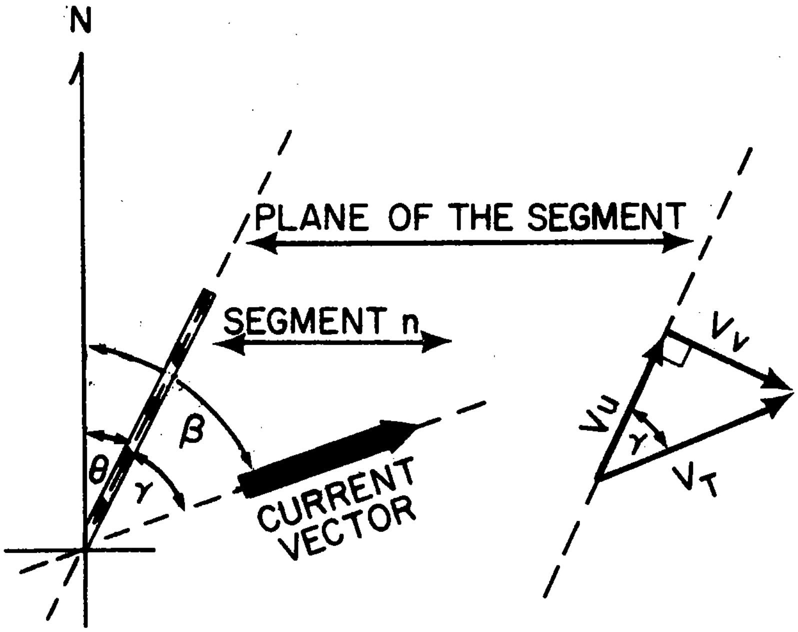
θ = azimuth of segment n

γ = current direction relative to the plane of segment n

V_u = tangential component of velocity (incline)

V_v = normal component of velocity (rotate)

V_u and V_v are recalculated with a new θ for each segment iteration.



$$V_u = V_T \cos(\gamma)$$

$$V_v = V_T \sin(\gamma)$$

Fig. 2. Resolution of Current Vector Components.

4.3.3 Gravity and Resistive Forces

Two forces act on the segments of the mooring: gravity and hydrodynamic resistance (drag).* Gravity forces act in the vertical plane and the drag forces act in the horizontal plane. Each is broken into components relative to the vertical plane of the segment n (see Fig. 3).

Gravity forces act only in the plane of the segment. They are defined as the buoyancy (+/-) per unit length (lbs/meter) of the immersed component i. The buoyancy of the segment is

$$W_n = W_i ds \tag{5}$$

and

$$W_N = W_n \sin \phi_n \tag{6}$$

$$W_T = W_n \cos \phi_n \tag{7}$$

where

W_n = buoyancy of segment n in pounds

W_i = buoyancy per unit length of component i

ds = length of segment n in meters

W_N = normal component of buoyancy

W_T = tangential component of buoyancy

ϕ_n = angle of inclination to the vertical of segment n.

Drag forces are considered to be uniform over the length of the segment and are separated into three orthogonal components relative to the axis of the segment: one, D_{Nu}, normal to the

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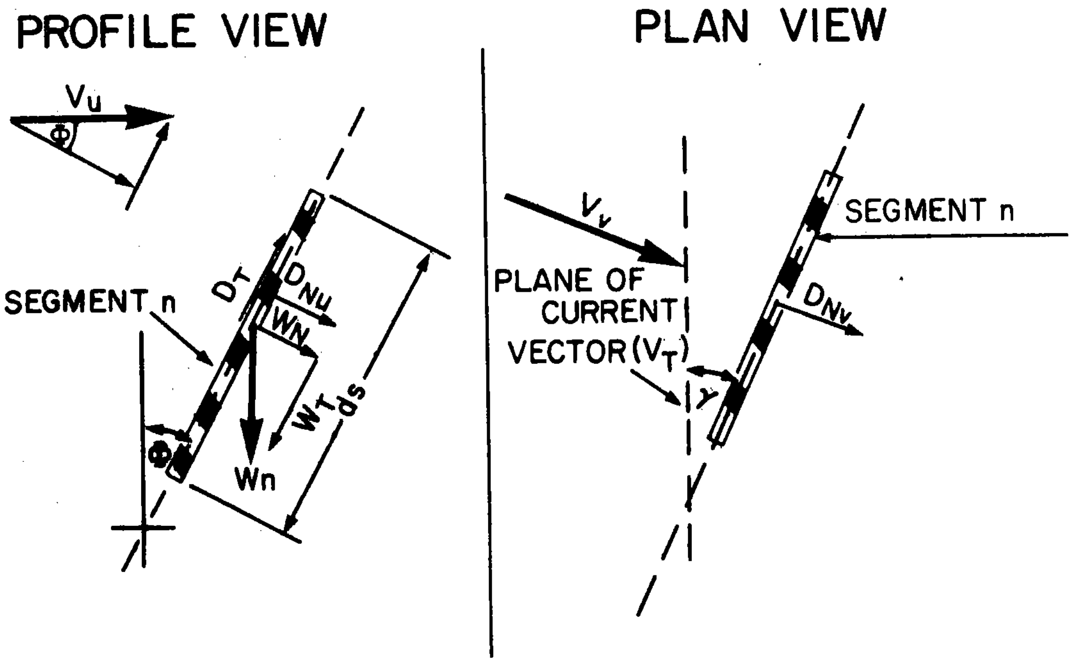
*A third force, the external point force, is not relevant to this discussion.



$$W_N = W_n \sin \Phi$$

$$W_T = W_n \cos \Phi$$

$$D_{Nu} = 1/2\, \rho\, C_{DN}\, ds\, A \left| V_u \cos \Phi \right| V_u \cos \Phi$$

$$D_{Nv} = 1/2\, \rho\, C_{DN}\, ds\, A \left| V_v \right| V_v$$

$$D_T = 1/2\, \rho\, C_{DT}\, \pi\, ds\, A \left| V_u \sin \Phi \right| V_u \sin \Phi$$

Fig. 3. Normal and Tangential Components of Hydrodynamic Resistance and Gravity Forces.

segment <u>in</u> the vertical plane of the segment; one, D_{Nv}, normal <u>to</u> the vertical plane of the segment; and one, D_T, tangential to the segment (see Fig. 3). The expressions defining these components are

$$D_{Nu} = \frac{1}{2}\rho\ C_{DN}\ ds\ A\left|V_u \cos \phi_n\right| V_u \cos \phi_n \tag{8}$$

$$D_{Nv} = \frac{1}{2}\rho\ C_{DN}\ ds\ A\left|V_v\right| V_v \tag{9}$$

$$D_T = \frac{1}{2}\rho\ C_{DT}\ \pi\ ds\ A\left|V_u \sin \phi_n\right| V_u \sin \phi_n \tag{10}$$

where

D_{Nu} = normal component of drag in the plane of the segment (acting to incline)

D_{Nv} = component of drag normal to the plane of the segment (acting to rotate)

A = area per unit length (m^2/m)

D_T = tangential component of drag (axial)

ρ = mass density of the fluid (assumed to be 2.0)

C_{DN} = coefficient of normal drag

C_{DT} = coefficient of tangential drag.

Variations in the shape of mooring components are reflected in the values assigned to C_{DN} and C_{DT} permitting the use of a single set of expressions for drag calculations. W_N, W_T, D_{Nu}, D_{Nv}, and D_T are reclaculated for each iteration.

4.3.4 Equilibrium Equations (see Fig. 4)

A mooring is composed of components which are, for calculation purposes, subdivided into discrete units of varied length known as segments. The equilibrium condition of each segment is calculated in an iterative process where gravity

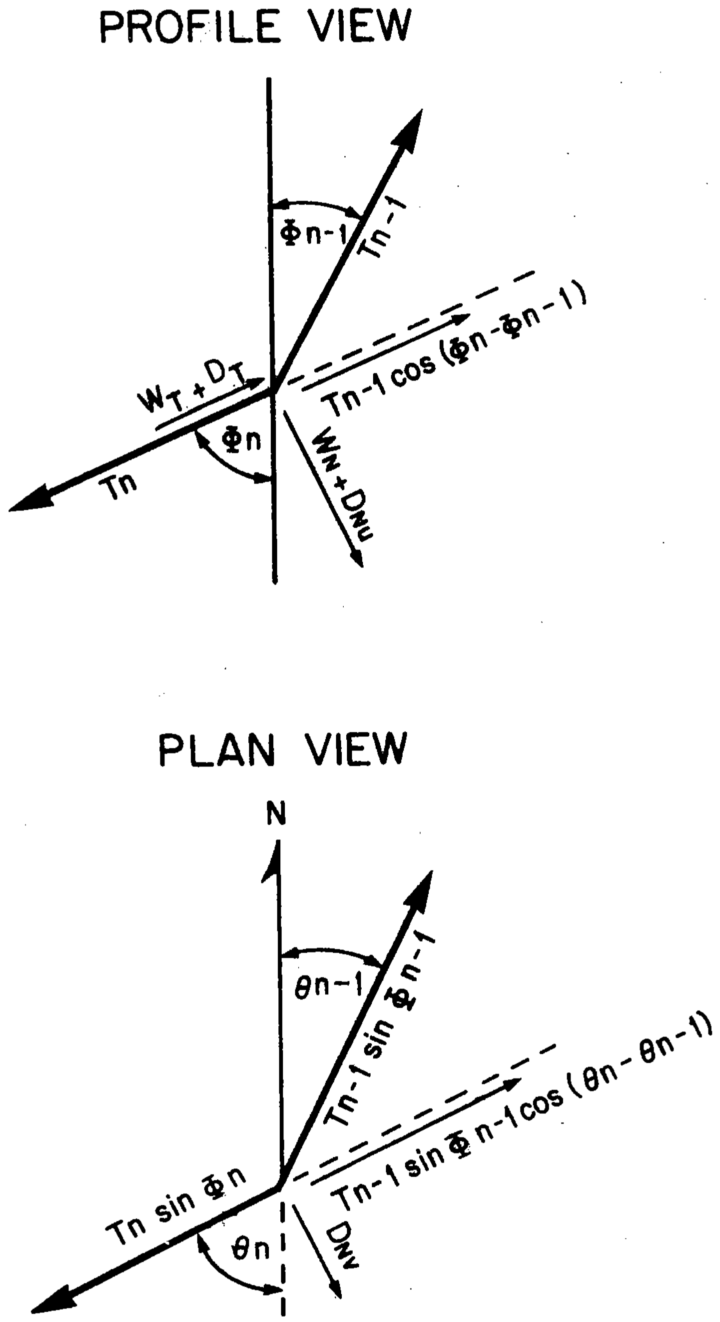


Fig. 4. Equilibrium Conditions - The Balance of Forces.

and resistive forces are balanced against external restraining forces. The equilibrium conditions are

$$W_T + D_T = T_n - T_{n-1} \cos (\phi_n - \phi_{n-1}) \tag{11}$$

$$W_N + D_{Nu} = T_{n-1} \sin (\phi_n - \phi_{n-1}) \tag{12}$$

$$D_{Nv} = T_{n-1} \sin \phi_{n-1} \sin (\theta_n - \theta_{n-1}) \tag{13}$$

where

T = axial tension

ϕ = inclination of the segment

θ = azimuth of the segment.

The state of equilibrium is described by the attitude of the segment in terms of axial tension, inclination to the vertical and azimuth. The program converges to the balance of forces by the following expressions:

$$\phi_n = \Delta\phi' + \phi' \tag{14}$$

$$\theta_n = \Delta\theta' + \theta' \tag{15}$$

where

ϕ' and θ' = the inclination and azimuth from the immediately preceding iteration

$\Delta\phi'$ and $\Delta\theta'$ = the change in inclination and azimuth between successive iterations

Substituting ϕ' and θ' for ϕ_n and θ_n in expressions (11), (12), (13), and by further substituting the transposed expressions (11), (12), (13) for $\Delta\phi'$ and $\Delta\theta'$, the following equations result.

$$T_n = T_{n-1} \cos (\phi' - \phi_{n-1}) + D_T + W_T \tag{16}$$

$$\phi_n = \tan^{-1} \left[\frac{D_{Nu} + W_N - T_{n-1} \sin(\phi' - \phi_{n-1})}{T_n} \right] + \phi' \tag{17}$$

$$\theta_n = \tan^{-1} \left[\frac{D_{Nv} - T_{n-1} \sin(\phi_{n-1}) \sin(\theta' - \theta_{n-1})}{T_n \sin \phi_n} \right] + \theta' \tag{18}$$

Gravity and drag force components are recalculated for each iteration using the values ϕ' and θ'. Therefore, the values of $\Delta\phi'$ and $\Delta\theta'$ tend to converge to zero. The equilibrium condition is considered to exist when $\phi_n - \phi'$ and $\theta_n - \theta'$ are <0.1 degree.

At the start of each iteration procedure ϕ' and θ' are set equal to ϕ_{n-1} and θ_{n-1}.

At program initialization T_{n-1}, ϕ_{n-1}, θ_{n-1} are set equal to the input values of the external point force at the top component.

4.3.5 Elongation and Elastic Properties

The elastic responses of mooring cables are considered in this study. Elastic components fall into two categories: wire rope and synthetic line.

When stressed, wire rope elongates by mechanical deformation of the cable structure and by the elastic response of its metallic components.

Structural elongation is found by

$$\varepsilon_m = \frac{T}{RBS} \cdot K \tag{19}$$

Elastic elongation is found by (Hooke's Law)

$$\varepsilon_e = \frac{\sigma}{E} \quad \text{or} \quad \varepsilon_e = \frac{T}{Aw \cdot E} \tag{20}$$

Expressions (19), (20) are combined in the equation:

$$\varepsilon_T = \left(\frac{T}{RBS} \cdot K + \frac{T}{Aw \cdot E}\right) \times L_o \tag{21}$$

where

ε_T = total strain or elongation (meters)

ε_m = structural strain as percent elongation

ε_e = elastic strain as percent elongation

σ = stress on the wire or tension/area (psi)

E = modulus of elasticity (psi)

T = axial tension on the wire segment (lbs)

RBS = rated breaking strength (lbs)

K = coefficient of structural stretch

Aw = metallic cross-sectional area of the wire (in^2)

L_o = slack or measured length of the wire (meters).

In the program, K and E are considered stretch characteristic constants of wire and are stored in an array as E(1) and E(2) respectively.

Standard W.H.O.I. mooring wire is manufactured by U. S. Steel. Structural stretch at the elastic limit (70% of RBS) is approximately 1% and is assumed to decrease linearly to zero at no load. The modulus of elasticity (Youngs) of the wire is 20.5×10^6. Therefore,

$$E(1) = 0.01/.7 \quad \text{or} \quad 1.43 \times 10^{-2}$$

$$E(2) = 20.5 \times 10^6$$

The stretch of synthetic line in response to tensile loading is the sum of permanent and elastic elongation. Permanent elongation represents the residual deformation or strain resulting from the "history" of stress. Elastic elongation represents the additional strain caused by elastic response to instantaneous loading. Elongation is defined in terms of percent of measured length.

A single expression is used to define the relationship of tension to both permanent and elastic elongation of all synthetic line. Measurement at $200d^2$ is assumed.*

$$\frac{T}{d^2} = A\left[\left(\frac{L-L_o}{L_o}\right)\right]^B \tag{22}$$

where

T = tension in pounds

d = diameter of the line in inches

L = stretched length of the line

L_o = slack or measured length of the line

A = linear coefficient of elongation

B = exponential coefficient of elongation

Elongation of the line is found by

$$\varepsilon_T = \left(\frac{T_m}{d^2 A_p}\right)^{\frac{1}{B_p}} + \left(\frac{T_i}{d^2 A_e}\right)^{\frac{1}{B_e}} \tag{23}$$

where

ε_T = total strain or percent elongation

T_m = maximum stress in the history of the line (lbs)

T_i = instantaneous tension (lbs)

d = diameter of the line (inches)

A_p = linear coefficient (permanent)

B_p = exponential coefficient (permanent)

A_e = linear coefficient (elastic)

B_e = exponential coefficient (elastic).

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*In order to standardize procedures for relaxed measurement of synthetic line manufacturers have adopted the technique of loading the line to a tension in pounds equal to $200d^2$ where d is the nominal diameter of the line in inches.

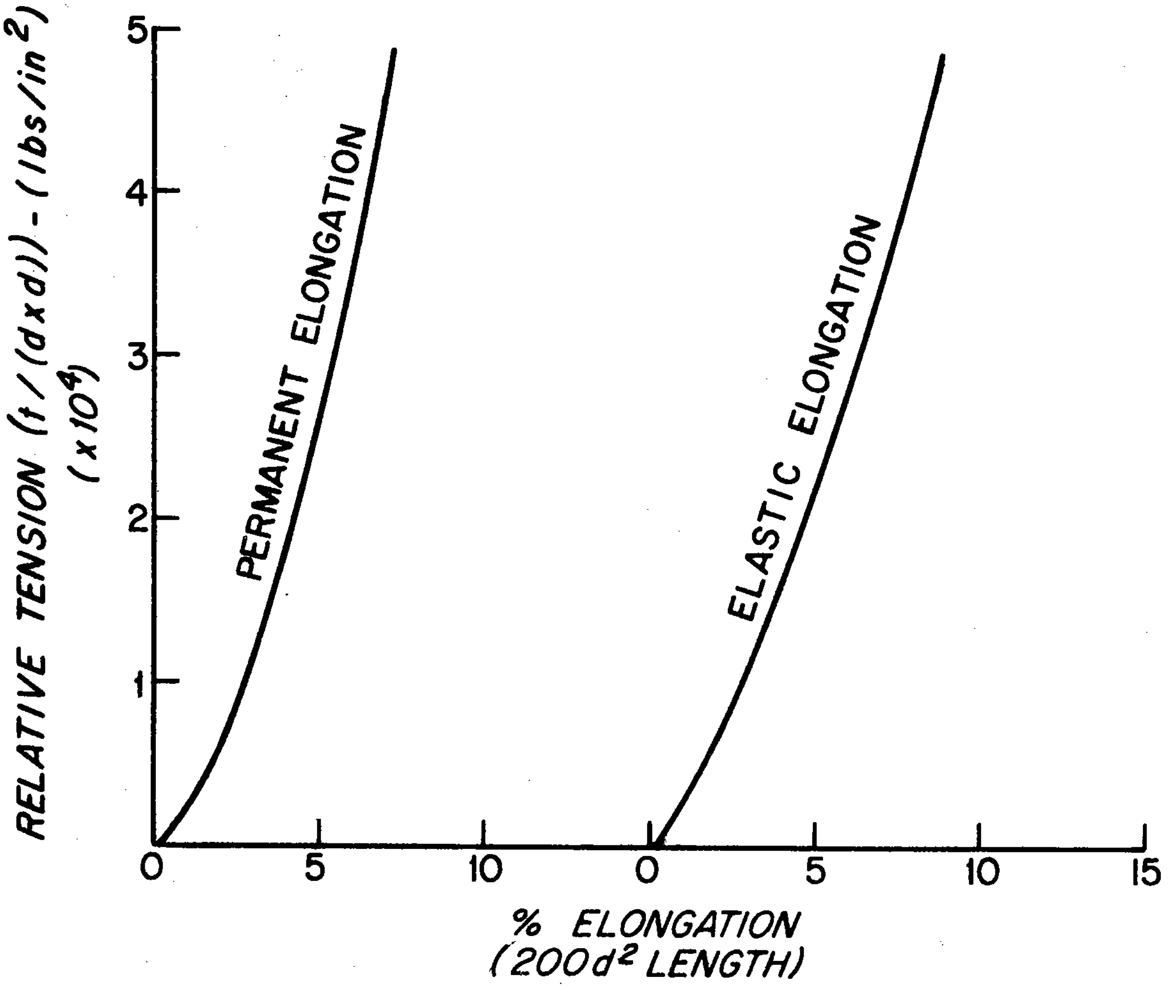

Fig. 5. General Stress-Strain Relations - DACRON (components 6-10)

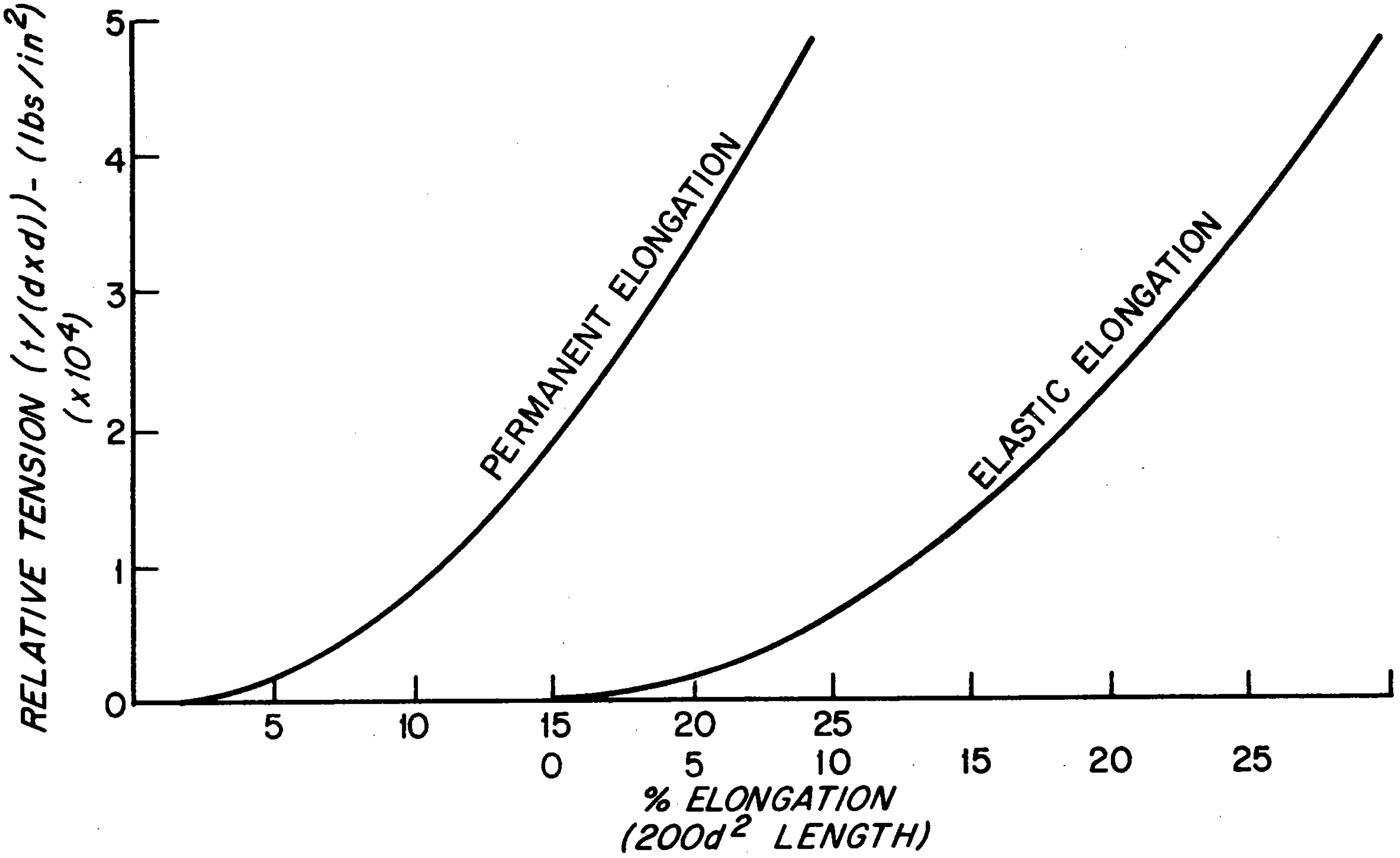

Fig. 6. General Stress-Strain Relations - NYLON (components 11-15)

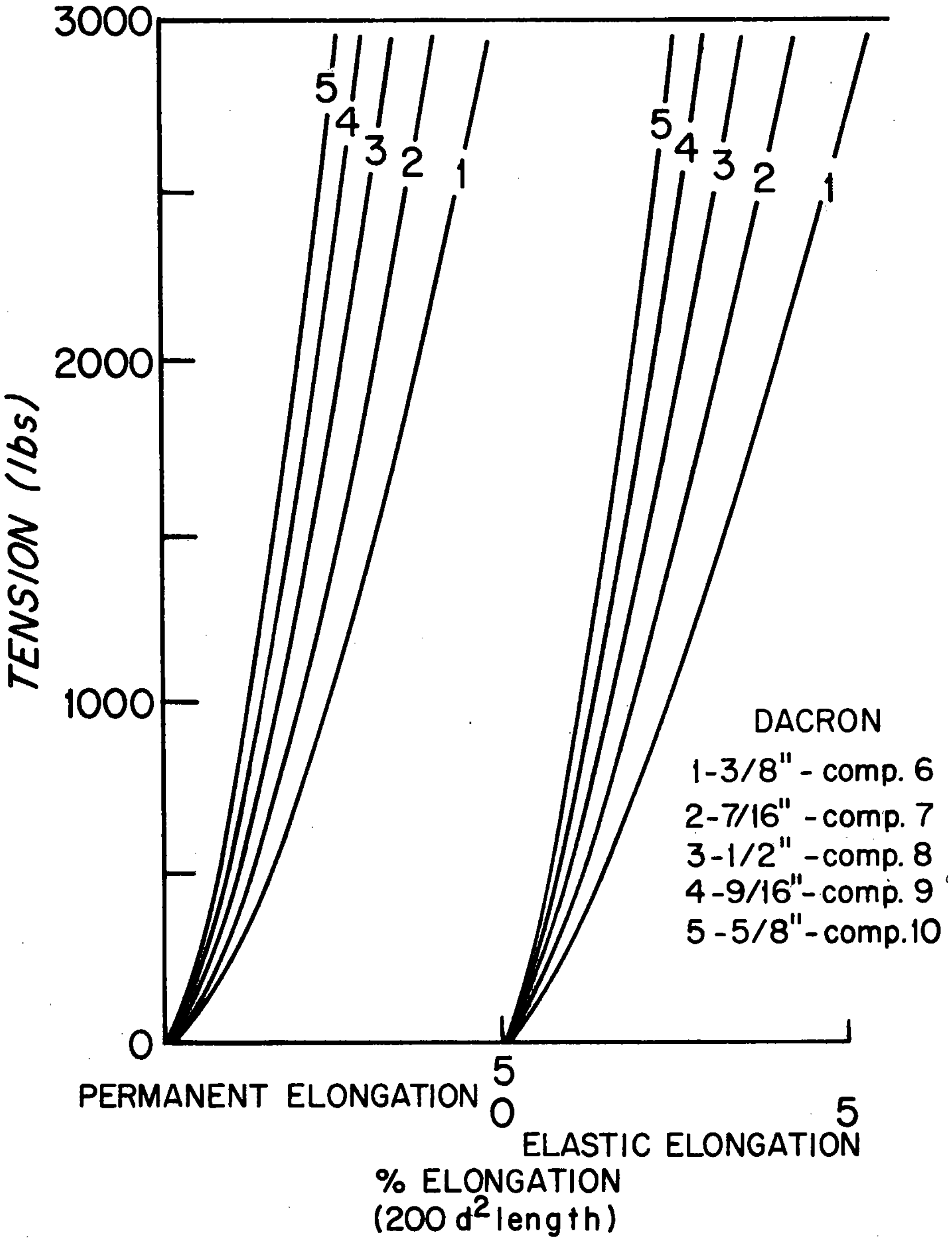

Fig. 7. Stretch Curves - DACRON
(components 6-10)

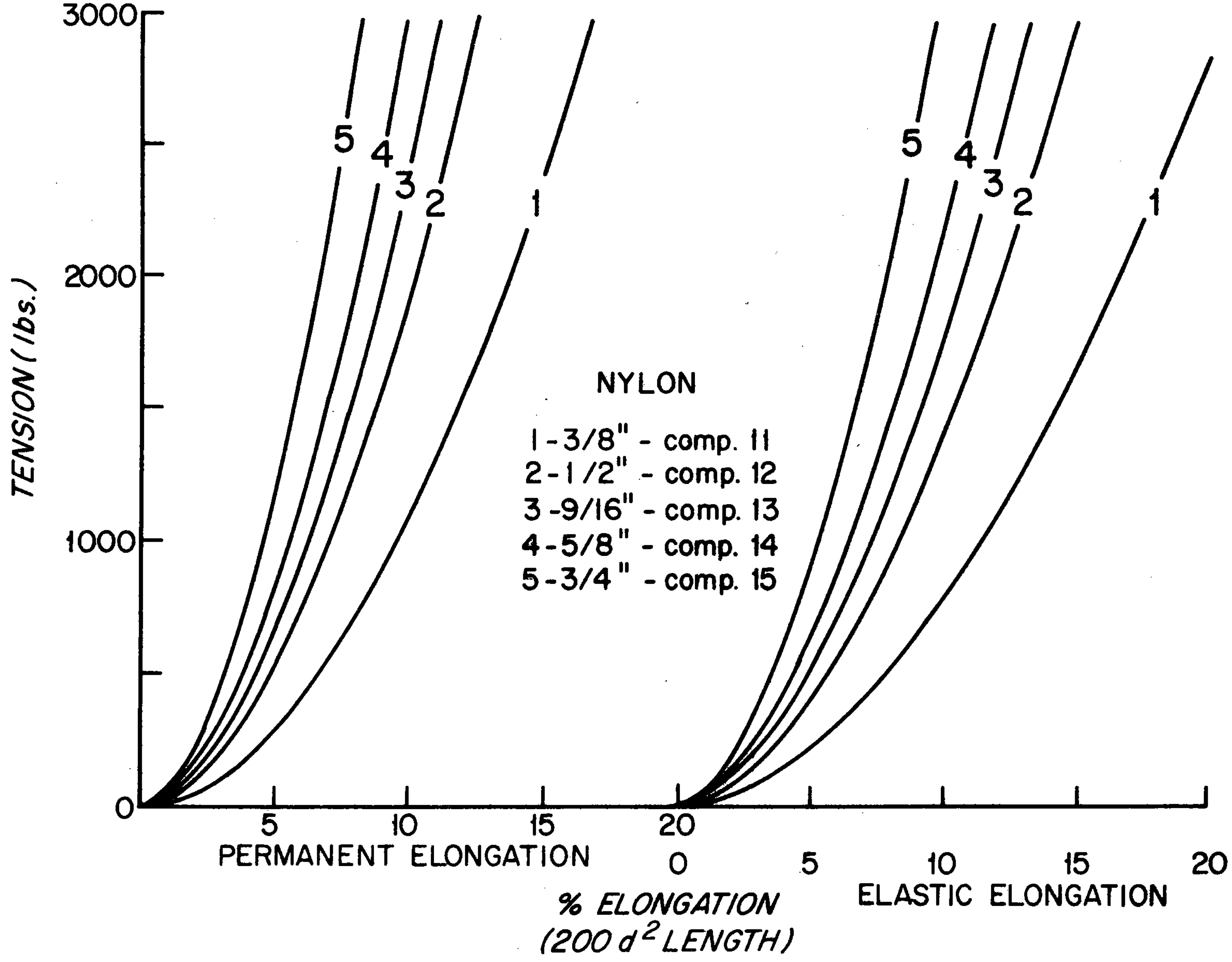

Fig. 8. Stretch Curves - NYLON
(components 11-15)