NPS ARCHIVE
1961
WILLIAMSON, J.

AN ADAPTIVE DEPTH CONTROL SYSTEM FOR HIGH SPEED SUBMARINES

JOHN PATRICK WILLIAMSON

LIBRARY
U.S. NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

AN ADAPTIVE DEPTH CONTROL SYSTEM FOR HIGH SPEED SUBMARINES

BY

JOHN PATRICK WILLIAMSON

LIEUTENANT, UNITED STATES NAVY

B.S., U.S. NAVAL ACADEMY

(1955)

SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

AT THE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MAY, 1961

Signature of Author ______________________

Certified by ______________________
Thesis Supervisor

Accepted by ______________________
Chairman, Departmental Committee of Graduate Students

NPS Archive
1961
Williamson, J.

Thesis
W6254

Library
U. S. Naval Postgraduate School
Monterey, California

AN ADAPTIVE DEPTH CONTROL SYSTEM FOR HIGH SPEED SUBMARINES

BY

JOHN PATRICK WILLIAMSON

Submitted to the Department of Naval Architecture and Marine Engineering on 20 May 1961 in partial fulfillment of the requirements for the Master of Science degree in Naval Architecture and Marine Engineering and the Professional degree, Naval Engineer.

ABSTRACT

An adaptive control system operating on submarine depth rate with constraints on the maximum values of stern plane deflection angle and hull pitch angle is formulated using a linear compensation technique. The system is adaptive in the sense that it is designed to give near uniform dynamic response over ranges of values of various hull geometry and speed parameters. The formulated system is simulated on a Reeves Electronic Analog Computer, various adjustments made and justified, and results shown in plots of stern plane angle, pitch angle and depth rate error. A simple system for predicting pull-out time is suggested which, when associated with the proposed system, would facilitate rapid, well-damped depth changes.

Thesis Supervisor: George C. Newton, Jr.

Title: Associate Professor of Electrical Engineering

Acknowledgement

The author expresses his appreciation to Mr. J. W. Church of the David Taylor Model Basin for his encouragement and advice in the investigation reported herein. The equations of motion of the hull as used in this study were derived by Mr. Church and his associate Dr. L. Pode. Appreciation is also expressed to Lieutenant M. C. Davis, USN, for his constructive criticisms and suggestions made in the course of many discussions on the general submarine control problem.

Special appreciation is expressed to Dr. G. C. Newton for his help and criticisms throughout the investigation reported herein.

TABLE OF CONTENTS

	Page
Symbols and Nomenclature	i
Chapter I - Introduction	1
General Aspects of the Depth Control Problem	1
Development of Automatic Depth Control Systems	3
Developments in Manual Control Systems	4
The System to be Investigated	7
Chapter II - Procedure	9
Scope	9
Equations of Motion of the Hull	10
Formulation of the Proposed System	14
Chapter III - Results	20
General	20
Evaluation of Results	20
Chapter IV - Discussion of Results	22
Chapter V - A Proposed Pull-out Time Predictor	26
Chapter VI - Conclusions and Recommendations	29
Appendix A - Computer Study	30
Appendix B - Analog Computer Results	32
Appendix C - Bibliography	33

Symbols and Nomenclature

The nomenclature defined in T & R Bulletin No. 1-5 of the Society of Naval Architects and Marine Engineers is used herein where applicable. A right-handed cartesian coordinate system is employed with the origin at the center of gravity of the hull, the positive x axis directed forward, the positive Z axis directed down normal to the base line, and angles measured positive in the counter-clockwise direction. Pitch angle and depth are measured relative to a similar system fixed in space and oriented with the positive Z axis directed vertically down. Quantities measured relative to this fixed system are designated by the subscript g. All quantities are non-dimensionalized, as indicated by the prime, by dividing by appropriate powers of the length of the hull and linear velocity, the mass and mass density.

symbol	non-dimensionalizing formula	definition
I_y	$I'_y = \frac{I_y}{\frac{1}{2}\rho L^5}$	Moment of inertia of hull about Y axis
k_y	$k'_y = \frac{k_y}{L}$	Radius of gyration of hull and added mass of hull about Y axis
k_2	$k'_2 = \frac{k_2}{L}$	Lateral added mass coefficient
k'		Added moment of inertia coefficient
L	$L' = 1$	Characteristic length of hull
m	$m' = \frac{m}{\frac{1}{2}\rho L^3}$	Mass of hull

M_q	$M'_q = \dfrac{M_q}{\frac{1}{2}\rho L^4 U}$	Derivative of moment component with respect to angular velocity component q
$M_{\dot{q}}$	$M_{\dot{q}}' = \dfrac{M_{\dot{q}}}{\frac{1}{2}\rho L^5}$	Derivative of moment component with respect to angular acceleration component $\dot{q}$
M_w	$M'_w = \dfrac{M_w}{\frac{1}{2}\rho L^3 u}$	Derivative of moment component relative to normal velocity component w
$M_{\dot{w}}$	$M_{\dot{w}}' = \dfrac{M_{\dot{w}}}{\frac{1}{2}\rho L^4}$	Derivative of moment component relative to normal acceleration
M_{δ_s}	$M_{\delta_s}' = \dfrac{M_{\delta_s}}{\frac{1}{2}\rho L^3 u^2}$	Derivative of moment component relative to stern plane angle
q	$q' = \dfrac{q}{U}$	Angular velocity component relative to y axis
$\dot{q}$	$\dot{q}' = \dfrac{\dot{q} L^2}{U^2}$	Angular acceleration component relative to y axis
u	$u' = 1$	Velocity of origin of body axes relative to fixed axes in feet per second
w	$w' = \dfrac{w}{U}$	Component of u along Z axis of body
$\dot{w}$	$\dot{w}' = \dfrac{\dot{w} l}{U^2}$	Component of acceleration of origin of body axes along Z axis
$Z_{\dot{q}}$	$Z_{\dot{q}}' = \dfrac{Z_{\dot{q}}}{\frac{1}{2}\rho L^4}$	Derivative of normal force component with respect to angular acceleration component
Z_w	$Z'_w = \dfrac{Z_w}{\frac{1}{2}\rho L^2 U}$	Derivative of normal force component with respect to normal velocity component

$Z_{\delta s}$	$Z'_{\delta s} = \dfrac{Z_{\delta s}}{\frac{1}{2}\rho L^2 U^2}$	Derivative of normal force component with respect to stern plane angle
Z_B	$Z'_B = \dfrac{Z_B}{L}$	metacentric height
δ_s	$\delta_s' = \delta_s$ rad	stern plane angle
θ	$\theta = \theta$ rad	Pitch angle as measured between X axes of body and fixed coordinate systems
ρ	$\rho' = 1$	mass density of water
t	$\tau = t \dfrac{U}{L}$	time in seconds

subscripts

i	desired or commanded quantity
o	actual or output quantity
g	relative to fixed coordinate system

I

INTRODUCTION

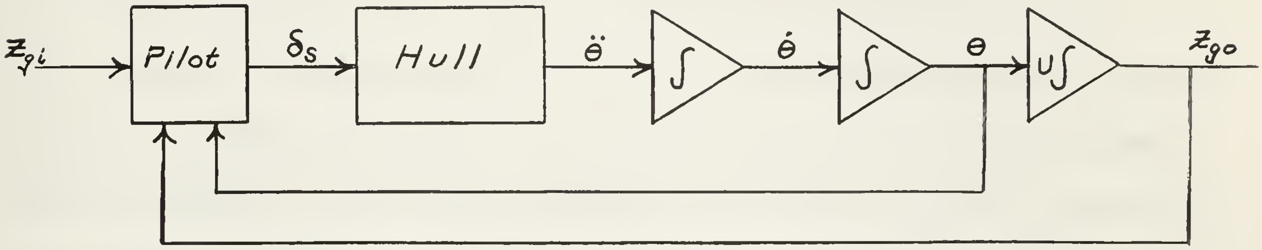
A. General Aspects of the Depth Control Problem

Prior to the closing years of World War II, submarine design features were based primarily on surface performance. As a direct result of this philosophy, submerged speeds, and hence maneuverability, were slow and sluggish. The top speed of a typical boat of this period was only nine knots at the half-hour battery rate. For this reason the crude two-planesman depth control system generally employed since the very earliest days of submarine construction was entirely adequate.

The improved methods of anti-submarine warfare brought about by developments in sonar and radar, the use of carrier-bourne aircraft, and the construction of fast anti-submarine escort ships made higher submerged speeds imperative. Belatedly, submerged performance became the primary consideration. By greatly reducing the amount of superstructure, and fairing the bridge and periscope sheers, hull resistance submerged was reduced by almost a factor of two. This, coupled with a doubling of battery capacity, increased submerged speed by a factor of two. These higher speeds indicated clearly the need for faster, more accurate control of depth. This need is easily recognized when one considers that submarines of this period would collapse at depths little in excess of one ship length. Even present-day submarines with their much higher speeds must confine their motions to a layer of water only a few ship-lengths deep.

The advent of nuclear propulsion plants and the low resistance,

body of revolution hull form developed in the last decade have greatly magnified this depth control problem. Let us consider the situation confronting the submarine pilot controlling the stern planes when only stern planes are used to control pitch angle and depth. This situation is adequately represented by the following block diagram.



Zgi	commanded depth	δ_s	stern plane angle
Zgo	actual depth	θ	pitch angle

Fig. I

From this diagram it is evident that there are three integrations between the immediate effect of the operator's action and the desired result. If the operator is to close the control loop in an optimum manner, he must anticipate the results of these integrations - a matter difficult in itself, but greatly complicated by the long lag between θ and δ_s introduced by the large hydrodynamic mass and small hydrodynamic stiffness of the hull. The operator attempts to overcome this difficulty by introducing a large initial δ_s. This gives him a more rapid indication of the result of his control action, but due to the lag mentioned above, he has no timely indication of when to remove or reverse plane angle. This results in overshooting the desired objective - the behavior of a poorly damped system. Thus it is evident that the operator is required to perform two functions simultaneously in closing the control loop: he must speed up the system response, and he must

provide adequate damping characteristics. This latter skill requires a certain amount of prescience highly dependent not only on the skill of the operator, but also on his physical condition. In this sense, operator reaction is a random variable introduced into the control problem which precludes absolutely consistent performance.

Two basic approaches have been followed to alleviate or avoid these difficulties in depth control. The first, and most apparent, is replacement of the human operator in the control loop by an automatic plane angle computer. The second approach, and the one followed in this investigation, involves relocation of the human operator outside of the closed-loop portion of the system.

B. Development of Automatic Depth Control Systems

The German Navy was the first to practice the new philosophy of submarine design. Their type XXI boats constructed just before the end of World War II in Europe were capable of about twenty knots submerged. These ships clearly indicated the desirability of an automatic depth control system. An attempt was made to meet this need. The system which evolved was really two very similar sub-systems - one for each set of planes.[5] Plane angles were computed as functions of speed, depth, and pitch angle. Depth and pitch angle signals were derived from pressure gauges and pendulums respectively. Variable gain settings in each of the sub-systems permitted ratioing bow and stern plane angles as a function of speed and depth-keeping accuracy requirements. The controlled quantity was depth, so that the overall system was basically a depth regulator rather than an autopilot capable of radical maneuvering.

The United States, profiting from German experience, began modifying the top-hamper and battery capacity of their SS-475 class fleet boats in the late 1940's. Coincident with this Guppy* conversion, development of a semi-automatic depth-keeping system was initiated. The first such system was built by Askania Regulator Company and installed on the U.S.S. Irex (SS-482) in 1948. Although very similar to the German system in most respects, it controlled not only depth, but also boat angle or pitch angle. With this added feature, it provided more maneuvering capability than the German system.[5] The first of these systems were semi-automatic in that the output was an indicated plane angle which the planesman was required to match. Subsequent systems were provided with an automatic follow-up device making them fully automatic.

With the advent of Albacore and submerged speeds in excess of twenty knots, these early systems became inadequate. Present systems are fully automatic, and similar to aircraft autopilots. The Sperry System, installed on most new construction, determines stern and sail plane angles from signals in depth, depth rate, pitch angle, pitch rate, and pitch acceleration to keep the boat on a digitally computed optimum trajectory.

C. Developments in Manual Control Systems

The high submerged speeds and limited depth range of modern submarines make the poor coordination and large time lags inherent in the

*The Guppy (Greater Underwater Propulsive Power) conversion involved streamlining the superstructure and doubling the battery capacity of the SS-475 class boats. These two modifications resulted in a 200% increase in submerged speed. The resulting ships bear an uncanny resemblance to the type XXI boats.

old two-operator, manual control system intolerable. The first step away from the old system was incorporated in Albacore with the substitution of an aircraft-type control column for the old wheel type devices.[11] Two sticks were provided. The main unit is a conventional aircraft steering column in which wheel rotation controls rudder position, and fore and aft motion of the entire column controls bow plane angle. The second stick controls stern plane angle. In the principal mode of operation, stern plane angle command is derived from the bow plane signal via a variable gain amplifier, thus providing single-operator ratioed control. This is the mode of operation greatly preferred by the operators.

This basic system has proven satisfactory in most respects. Subsequent developments have been primarily concerned with providing the operator with the required feed-back information - depth error and boat angle - in the most efficient manner. The first major improvement in this line was the Combined Instrument Panel which displays all the information required by the operator in a cluster of dials arranged in an optimum manner from the human engineering point of view.[8,11] A second, and rather novel, development is the Contact Analog Display developed by the Electric Boat Division of General Dynamics.[8] In essence, this is a television screen picture of the path the operator is required to follow. A three dimensional effect is provided by a ficticious horizon and narrowing-with-distance perspective of the pictured road. This is the only indicator the pilot must concentrate his attention upon. His task is simply to keep the white line of the road properly positioned on the screen.

In anticipation of the performance capabilities to be required of

future high speed submarines, the Bureau of Ships has initiated an extensive study of the over-all submarine control problem. The title of this study is the Submarine Integrated Control Program (SUBIC). The Contact Analog mentioned above originated in this program. As a part of this investigation, Cornell Aeronautical Laboratories conducted a study of the data flow and data processing requirements in effective submarine control.[7] One of the major results of this study was an indication of the desirability of locating the human operator external to a multiple closed-loop system in which the outer loop closure is on depth rate. The advantages of this scheme are readily apparent. In addition to minimizing the effects of erratic human behavior and simplifying the operators' problem by avoiding two of the integrations mentioned in (A) above, the system is easily made fully automatic by substituting a digital computer or programmer in place of the human operator. This system is represented by the following block diagram. The K's indicated are in general non-linear functions of ship speed and

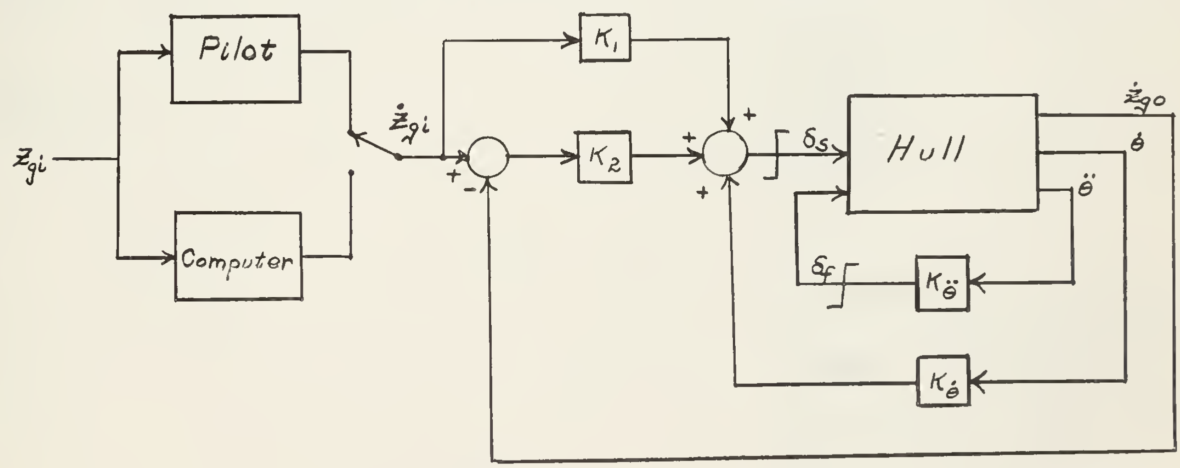


Fig. II

the geometrical parameters of the hull.

D. The System to be Investigated

The major difficulty in submarine control system design is the lack of precise information concerning the values of the various hydroframe parameters. At the present time, there is no satisfactory method of estimating these parameter values within acceptable accuracy from the geometry of the hull as delineated on the lines drawing. Recourse to model and full-scale tests is unavoidable.[12] Further, in order to obtain acceptable performance over the speed range of a given hull, the characteristics of a control system such as that shown in Fig. II must be varied in some pre-determined, generally non-linear manner with speed. It is with this problem that this thesis is concerned.

The basic system under consideration is shown in Fig. III. It is evident from this diagram that no provision is made for a steady state

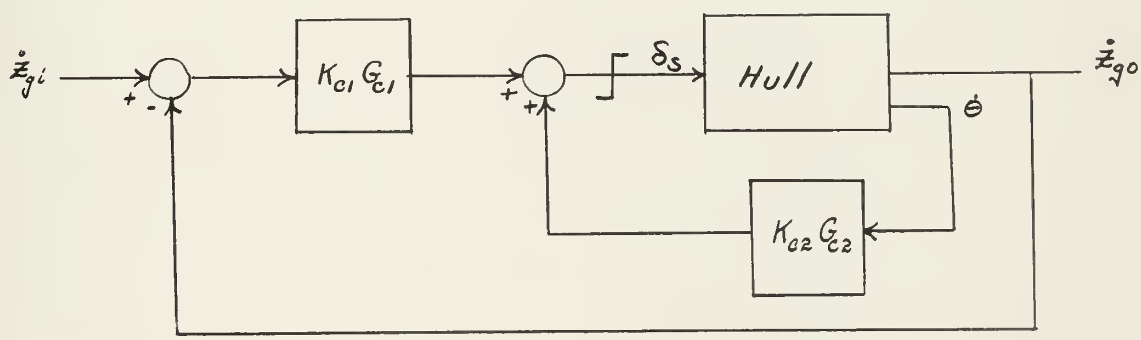


Fig. III

plane angle in a steady dive. This feature would require an auxiliary forward loop from the input to the plane angle summer. This matter is ignored in the following investigation because the effect of such a forward loop is small and decreases with speed roughly as the reciprocal of the speed cubed. The effects of this simplification will be a slight increase in steady state depth rate error at slow speeds. Also, only

stern plane control is considered.

The objective of this investigation is to formulate suitable compensation functions $K_{c1}G_{c1}$ and $K_{c2}G_{c2}$ that will yield a specified performance of the closed loop system over a specified speed range of a given hull configuration, and at the same time minimize the effects of deviations of certain important hull parameters from their specified values. In this sense, the proposed system is an adaptive system.

The problem will be treated on a non-dimensional basis using the linearized force and moment equations of a submerged body in the vertical plane, and standard nomenclature as specified in reference [1]. The system will be simulated on a REAC analog computer to determine its transient and steady state response to a step input of depth rate under various conditions.

II

PROCEDURE

A. Scope

This investigation is concerned with the formulation of a suitable closed-loop system for controlling the depth rate of a deeply submerged submarine subject to constraints on the maximum values of hull pitch angle and plane deflection angle. The principal objective is a system whose dynamic response to an ordered change of depth rate is relatively independent of variations in ship speed and hull geometry. A linear design technique will be employed, and the performance of the resulting system analyzed on an electronic analog computer.

The basic idea underlying the approach to be followed is that hydroframe parameters may be considered to fluctuate from hull to hull as well as for a given hull about certain normal values. Similarly, ship speed may be considered as a deviation from some normal speed. The effects of these deviations is a change in the resonant frequency of the hull and hence of the entire control system. If when its parameters have their so-called normal values, the overall system is so designed that its resonant frequency is much higher than any frequency to which it is normally required to respond, then the change in natural frequency brought about by parameter variations will have a small effect on system performance.

The design specifications for the proposed system are as follows:

1. a non-dimensional natural frequency of the "normal" system in the vicinity of 5 with a damping ratio of about .75.

2. no more than 15% overshoot in pitch angle.*

3. no more than 10% overshoot in depth rate.

4. a rise time to 10° pitch angle for large changes of depth rate close to 1 second in non-dimensional time.

The non-dimensional form of the equations of motion of the hull are employed since this facilitates separation of the dominant parameters from those of lesser importance.

B. Equations of Motion of the Hull[10]

Omitting the cross-acceleration terms $M_{\dot{w}}\ \dot{w}'$ and $Z_{\dot{q}}'\ \dot{q}'$, which are usually quite small,[2] the linearized equations of motion of a submerged body in the vertical plane may be written:[1]

(1) $(m'-Z_{\dot{w}}')\ \dot{w}' - Z_w'\ w' - (m' + Z_q')\ q' = Z_{\delta_s}'\ \delta_s$

(2) $-M_w'\ w' + (I_y' - M_{\dot{q}}')\ \dot{q}' - M_q'\ q' - \triangle'\ Z_B'\ \theta = M_{\delta_s}'\ \delta_s$

The coefficients of the acceleration terms w' and q' are interrelated through the following equations:

$$I_y' = (k_y')^2\ m'$$

$$Z_{\dot{w}}' = -k_2 m'$$

$$M_{\dot{q}}' = -k'\ I_y'$$

k' is simply the non-dimensional radius of gyration of the hull about the y axis. k_2 and k' represent the added mass of the hull. They are usually taken as the theoretical values applying to the ellipsoid of revolution approximated by the hull form.[10]

*It should be noted that the desired glide angle is implicitly included in the commanded depth rate since $\dot{Z}_g = w - u\theta$. Assuming a steady glide with zero normal force, w = o and $\dot{Z}_g = -U\ \theta$. In non-dimensional notation, $Z_g' = -\theta$

Landweber and Johnson of the David Taylor Model Basin have proposed the following relations among the coefficients of the velocity terms for the case under consideration where the only appendage is a tail surface.[12]

$$M'_w = m' - X'_1 \; Z'_w$$

$$Z'_q = X'_2 \; Z'_w$$

$$M'_q = (X'_3)^2 \; Z'_w$$

These relations, although only approximate, give predictions of the indicated parameters which are reasonably close to measured values. x'_1 may be interpreted as the non-dimensional effective moment arm at which the lift due to angle of attack acts. The m' in this relation is taken as an approximation to the Munk moment which appears in the potential flow about the body. X'_2 may be regarded as the non-dimensional effective radius through which the angular velocity q is related to an equivalent normal velocity, i.e. $w' = X'_2 \; q'$. $(X'_3)^2$ may be interpreted as the effective product of the radius relating angular and linear velocities and the moment arm relating moment and force due to angle of attack. Although such a product is not necessarily a square, it seems nearly so and is so defined for convenience.[10]

The coefficient of θ in equation (2) may be reduced to a speed parameter as follows:

$$- \frac{\Delta' \; Z_B'}{m'} = - \frac{\dfrac{mg \; Z_B}{\frac{1}{2}\rho L^2 U^2 \; L}}{\dfrac{m}{\frac{1}{2}\rho l^3}} = - \frac{g \; Z_B}{U^2} = \frac{1}{\tilde{U}^2}$$

This speed parameter $\tilde{U}$ is then dependent not only on the ship speed U, but also on the metacentric height Z_B which is a measure of the ship's

longitudinal static stability. Incorporation of the minus sign in the definition of $1/\tilde{U}$ is done since Z_B is always a negative quantity for ships with positive static stability.

The formulation is further simplified with the introduction of the two quantities

$$K'_s = \frac{Z'_{\delta_s}}{Z'_w}$$

$$X'_s = -\frac{M'_{\delta_s}}{Z'_{\delta_s}}$$

K'_s may be regarded as a measure of the control effectiveness or as the ratio of the lift force generated by the stern planes to the lift force generated by the fixed surfaces of the hull due to angle of attack. X'_s is the non-dimensional effective radius at which the normal force generated by the stern plane acts. The negative sign arises from the coordinate system employed.

Making all of the above substitutions in equations (1) and (2) after dividing through by m' yields the equations of motion of the hull with which we shall be concerned.

$$(3)\quad (1 + k_2)\,\dot{w}' - \frac{Z'_{\dot{w}}\, w'}{m'} - \left(1 + x'_2 \frac{Z'_w}{m'}\right) q' = K'_{\delta} \frac{Z'_w}{m'} \delta_s$$

$$(4)\quad -\left(1 - x'_1 \frac{Z'_w}{m'}\right) w' + (k'_y)^2 (1 + k')\,\dot{q}' - (X_3')^2 \frac{Z'_w}{m'} q' + \frac{\theta}{\tilde{U}^2} = -X'_{\delta} K'_{s} \frac{Z'_w}{m'} \delta_s$$

The utility of this formulation lies in the fact that $\tilde{U}$ is the only speed-dependent parameter of importance, and the number of geometry-dependent parameters has been greatly reduced. If it is assumed that Z_w varies as the first power of the speed, which is not unreason-

able, then it can be seen that Z_w'/m' is independent of speed from the following:

$$Z_{w'} = \frac{\dfrac{Z_w}{\frac{1}{2}\rho L^2 U}}{\dfrac{m}{\frac{1}{2}\rho L^3}} = \frac{Z_w L}{Um}$$

For hulls of normal design, the ranges of variation of k_2, k', and k_y' are very limited. Similarly, the effective moment arms and radii x_1', x_2', and $(x_3')^2$ are confined to sufficiently limited ranges of values that they may be considered to be of secondary importance in this investigation. Accordingly, these parameters are assigned the following normal values and henceforth treated as constants.

$$x_1' = -0.5 \qquad (k_y')^2 = 0.045$$

$$x_2' = 0.5 \qquad k^2 = 0.933$$

$$(x_3')^2 = 0.25 \qquad k' = 0.805$$

$$x_s' = -0.5$$

Then the dynamic characteristics of the hulls to be considered depend upon the three primary parameters $\tilde{U}$, Zw'/m', and K_s'. As noted above, the metacentric height Z_B also enters implicitly as a forth major parameter. These primary parameters will be considered to fluctuate about assigned normal values as follows:

$$\tilde{U} = 5.0 \pm 4.0$$

$$\frac{Zw'}{m'} = -1.5 \pm 0.5$$

$$K_s' = 0.3 \pm 0.1$$

It is considered that the indicated ranges of Zw'/m' and K_s' include most body of revolution hulls existing or to be constructed.

The actual speed range indicated by the range of $\tilde{U}$ depends, of course, on the value of metacentric height selected. This figure normally lies in the range -0.5 to -2.0 feet. For $Z_B = -0.5$ feet, the indicated range of $\tilde{U}$ corresponds to a speed range of 2.3 to 21 knots. For $Z_B = -2.0$ feet, this range corresponds to speeds from 4.7 to 41 knots. Again, it is considered that the range of $\tilde{U}$ considered includes all combinations of Z_B and U of practical significance.

C. Formulation of the Proposed System

By applying Laplace transform operations, in which the operator "s" implies differentiation with respect to non-dimensional time , to equations (3) and (4), one obtains the following transfer functions for the hull.

$$(5) \quad \frac{\theta(s)}{\delta_s(s)} = \frac{(E_1 s + F_1)\, s}{A\, s^3 + B\, s^2 + C\, s + D}$$

$$(6) \quad \frac{\dot{z}_g{}'(s)}{\delta_s(s)} = \frac{N_1\, s^2 - N_2\, s - N_3}{As^3 + Bs^2 + Cs + D}$$

where

$$A = (1+k_2)(k_y{}')^2\,(1+k')$$

$$B = \frac{-Z_w{}'}{m'}\left[(k'_y)^2\,(1+k') + (1+k_2)\,(x_3{}')^2\right]$$

$$C = \left(\frac{Z_w{}'}{m'}\right)^2\left[(x_3{}')^2 + x_1{}'\,x_2{}'\right] - \frac{Z_{w'}}{m'}\,(x_2{}'-x_1{}') + \frac{1+k}{\tilde{U}^2} - 1$$

$$D = -\frac{Z_w{}'}{m'}\,\frac{1}{\tilde{U}^2}$$

$$E_1 = -(1+k_2)\,x_s{}'\,K_s{}'\,\frac{Z_w{}'}{m'}$$

$$F_1 = \frac{Z_w{}'}{m'}\,K_s{}'\left[\frac{Z_w{}'}{m'}\,(x_s{}' - x_1{}') + 1\right]$$

$$N_1 = K_s' \frac{Z_w'}{m'} (k_y')^2 (1+k')$$

$$N_2 = K_s' \frac{Z_w'}{m'} \left\{ \frac{Z_w'}{m'} \left[(x_3') + x_s' x_2' \right] - k_2 x_s' \right\}$$

$$N_3 = K_s' \frac{Z_w'}{m'} \left[(x_s' - x_1') \frac{Z_w'}{m'} - \frac{1}{U^2} + 1 \right]$$

Equations (5) and (6) are rewritten in standard from as follows:

$$(7) \quad \frac{\dot{\theta}(s)}{\delta_s(s)} = \frac{K_1(s+N)s}{s^3 + J_2 s^2 + J_1 s + J_o}$$

$$(8) \quad \frac{\dot{Z}_g'(s)}{\delta_s(s)} = \frac{K_2 (s^2 + E_2 s + F_2)}{s^3 + J_2 s^2 + J_1 s + J_o}$$

where

$$K_1 = \frac{E_1}{A} \qquad K_2 = \frac{N_1}{A}$$

$$N = \frac{F_1}{E_1} \qquad E_2 = \frac{-N_2}{N_1}$$

$$F_2 = \frac{-N_3}{N_1}$$

$$J_2 = \frac{B}{A} \qquad J_o = \frac{D}{A}$$

$$J_1 = \frac{C}{A}$$

Substituting the assigned values of the secondary parameters given above, these coefficients are expressed as functions of the primary parameters as follows:

$$K_1 = 6.16\, K_s' \frac{Z_w'}{m'} \qquad K_2 = 0.517\, K_s' \frac{Z_w'}{m'}$$

$N = 1.034$

$J_2 = -3.6 \dfrac{Z_w'}{m'}$

$J_1 = 6.37\left(\dfrac{1.933}{U^2} - \dfrac{Z_w'}{m'} - 1\right)$

$E_2 = -5.745$

$F_2 = -12.3\left(1 - \dfrac{1}{\tilde{U}^2}\right)$

$J_o = \dfrac{-6.37}{\tilde{U}^2} \dfrac{Z_w'}{m'}$

The following points are now evident concerning the transfer functions defined by equations (7) and (8):

1. both gains are always negative since $\frac{Zw'}{m'}$ is a negative number and K_s' is always positive.
2. both are stable transfer functions in that neither has a right half plane pole.
3. (8) is non-minimum phase since E_2 is negative.

Using these relations, the system to be investigated is represented by the block diagram of Fig. IV.

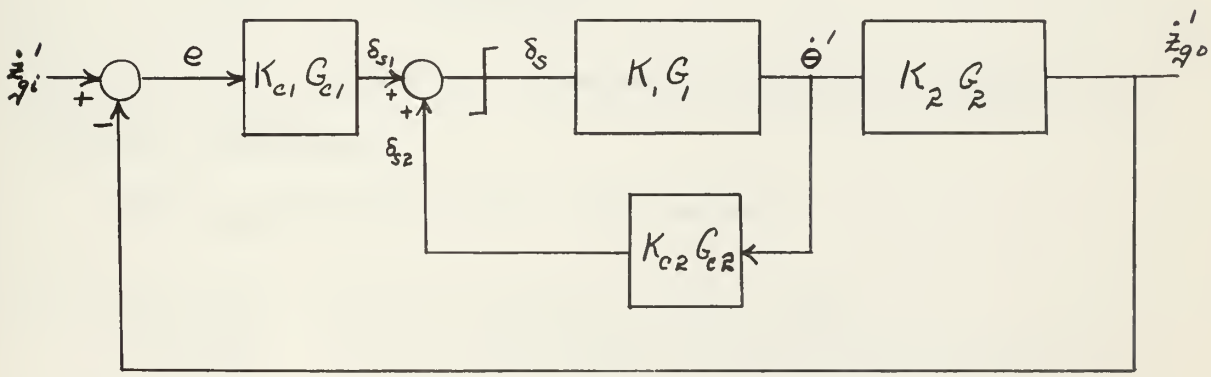


Fig. IV

The open-loop relation for the unity feedback system is:

$$(9) \quad \frac{\dot{z}_g'(s)}{e(s)} = K_{c1} G_{c1}(s) \frac{K_1 G_1(s)}{1 - K_1 K_{c2} G_1 G_{c2}(s)} K_2 G_2(s)$$

where $K_{c1}G_{c1}$ and $K_{c2}G_{c2}$ are the compensation functions to be formulated, and

$$K_1G_1(s) = \frac{K_1(s+N)s}{s^3 + J_2 s^2 + J_1 s + J_o}$$

$$K_2G_2(s) = \frac{K_2(s^2 + E_2 s + F_2)}{K_1(s+N)s}$$

$$e(s) = \dot{Z}'_{gi}(s) - \dot{Z}'_{go}(s)$$

Substituting the expressions for $K_1 G_1(s)$ and $K_2 G_2(s)$ into (9), one obtains

$$(10) \quad \frac{\dot{Z}'_{go}(s)}{e(s)} = \frac{K_{c1} K_2 G_{c1}(s)(s^2 + E_2 s + F_2)}{s^3 + J_2 s^2 + J_1 s + J_o - K_1 K_{c2} G_{c2}(s)(s+N)s}$$

Now we choose $G_{c2}(s)$ to be of the form

$$G_{c2}(s) = \frac{s^2 + a s + b}{s(s+N)}$$

in which we note that N is a constant and therefore independent of parameter variations.

With $G_{c2}(s)$ of this form, (10) becomes

$$(11) \quad \frac{\dot{Z}'_{go}(s)}{e(s)} = \frac{K_2 K_{c1} G_{c1}(s)(s^2 + E_2 s + F_2)}{s^3 + (J_2 - K_1K_{c2})s^2 + (J_1 - K_1K_{c2}a)s + (J_o - K_1K_{c2}b)}$$

and the utility of this selection of $G_{c2}(s)$ is immediately obvious. By suitably choosing K_{c2}, a, and b, the poles of the open-loop relation may be conveniently located in the s plane. (As will be indicated later, the situation is not quite so straightforward due to saturation in δ_s.)

As stated above, the system will be designed with the primary parameters assigned their normal or mid-range values. Inserting these numbers in (11) yields

$$(12) \quad \frac{\dot{Z}'_{go}(s)}{e\,(s)} = \frac{-.233K_{c1}G_{c1}(s)(s^2 - 5.745s - 11.8)}{s^3 + (5.4 + 2.77K_{c2})\,s^2 + (3.68 + 2.77K_{c2}a)\,s + (.382 + 2.77\,K_{c2}b)}$$

For the present, take $G_{c1}(s)$ equal to unity. Then the zeros of the open-loop relations are located at + 7.35 and - 1.61. Since K_{c1} must be positive, we are concerned with variations of the negative gain factor $-.233\,K_{c1}$ as far as stability and performance of the closed-loop system are concerned. The locations of the poles of (12) are determined by experimenting with the root locus plot of this relation to achieve the desired resonant frequency and damping ratio of the dominant pole-pair of the closed-loop function. The resulting configuration is shown in Fig. V. It is to be noted that the most negative pole of (12) is one of the dominant poles.

With the poles of (12) located at -1, -4, and -9 as shown, the denominator of (12) becomes

$$s^3 + 14s^2 + 49s + 36 = s^3 + (5.4 + 2.77K_{c2})s^2 + (3.68 + 2.77\,K_{c2}a)s + (.382 + 2.77K_{c2}b)$$

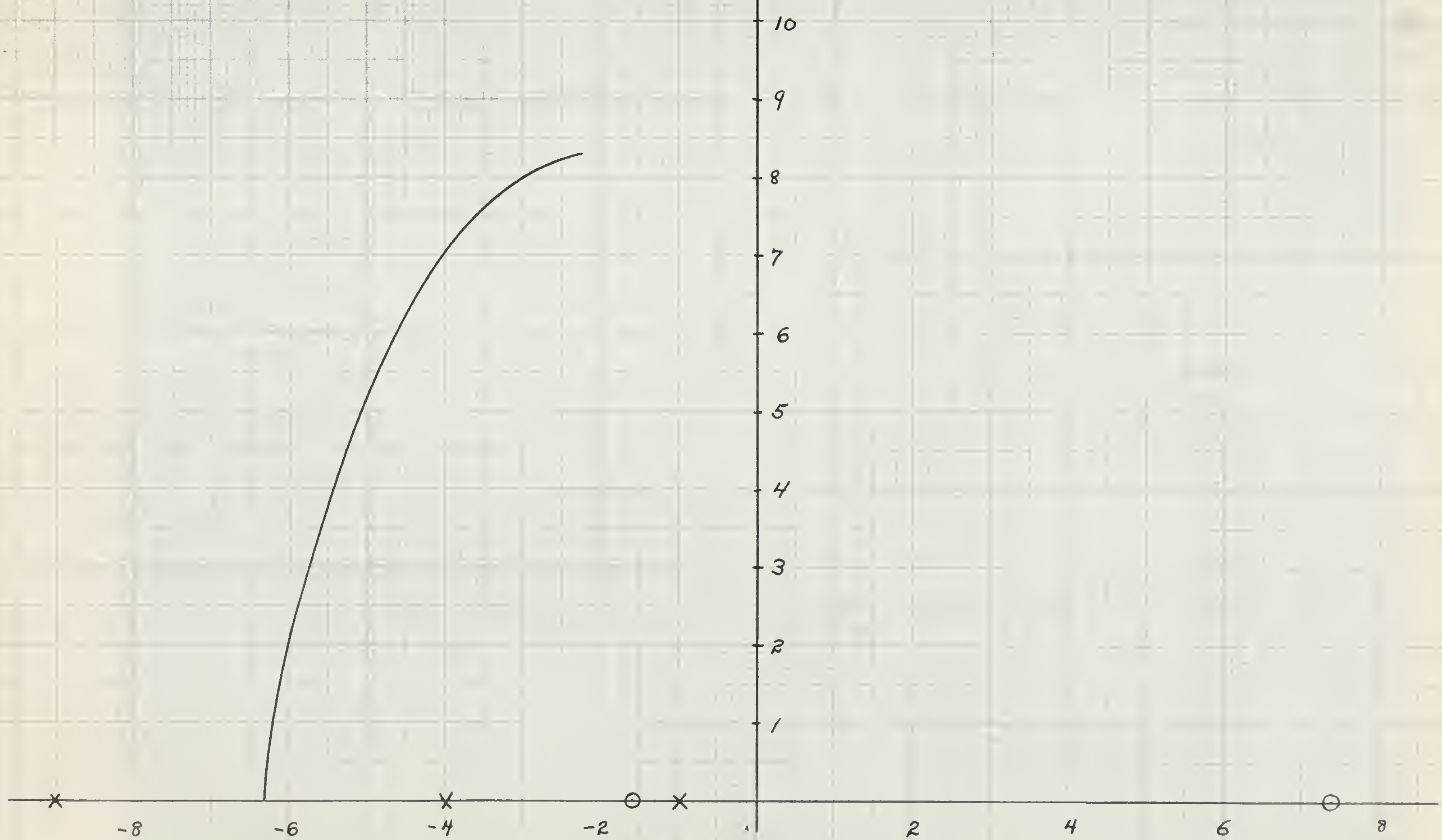
Equating coefficients of the various powers of s yields

$$K_{c2} = 3.1$$

$$a = 5.26$$

$$b = 4.14$$

The phase-magnitude plot of the open-loop relation incorporating



ROOT LOCUS WITHOUT G_{c1}

FIG. V

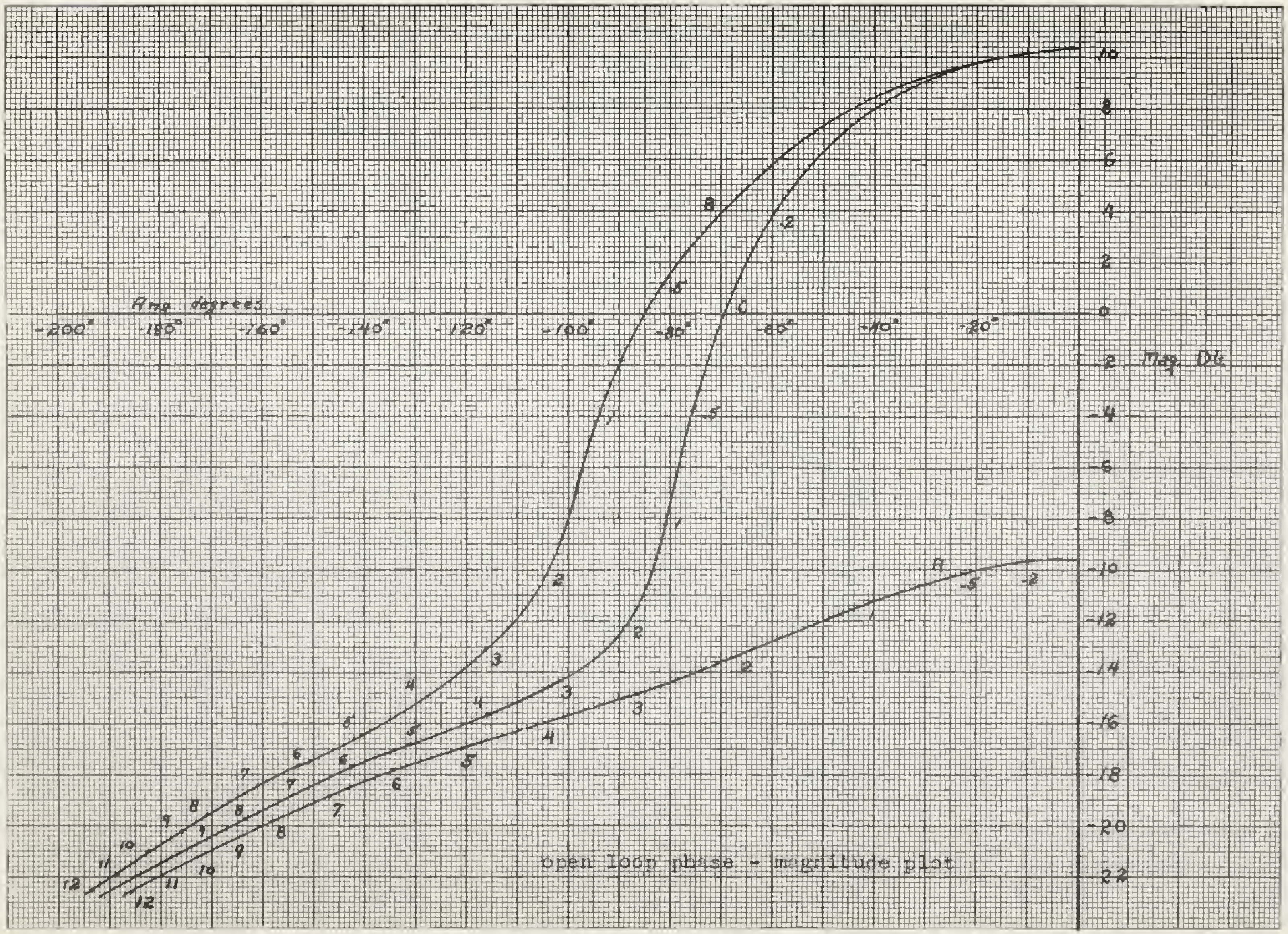

Ang degrees
-200°
-180°
-160°
-140°
-120°
-100°
-80°
-60°
-40°
-20°
Mag Db
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
A
B
C
open loop phase - magnitude plot

FIG VI

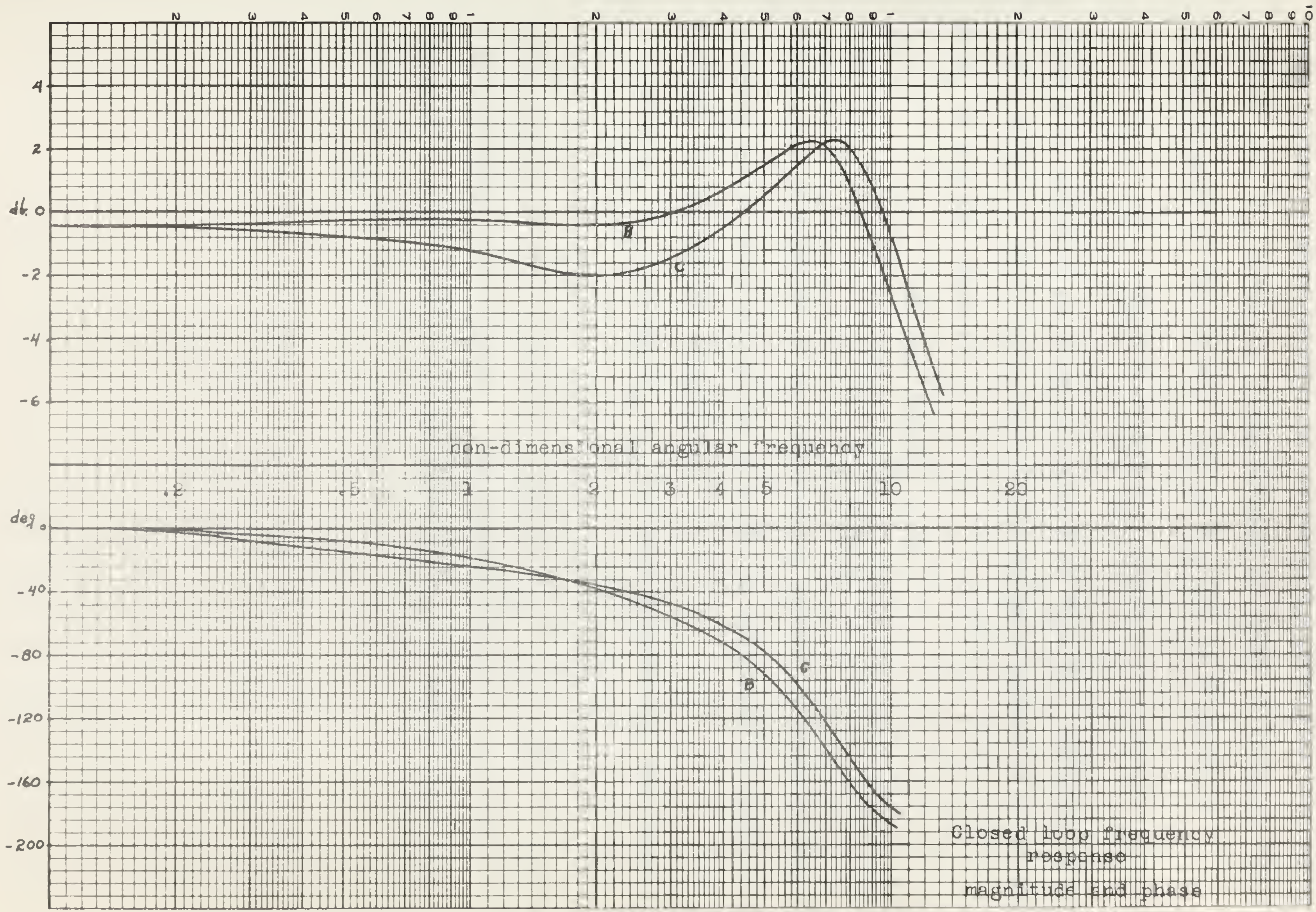

db
dег
non-dimensional angular frequency
Closed loop frequency response
magnitude and phase
B
C

FIG. VII

these values is shown in Fig. VI as curve A. From this plot it is evident that G_{c1} should be a lag network in order to increase the low frequency gain of the system. Taking $G_{c1}(s)$ to be given by

$$G_{c1}(s) = \frac{s + 2}{s + .2}$$

curve A is modified as shown in curve B of Fig. VI. Applying curve B to a Nichol's chart indicates a required gain factor of 14 db for an M_p of 2.3 db. That is

$$20 \log .233\, K_{c1} = 14$$

$$K_c' = 21.4$$

The frequency response of the closed-loop system is shown in Fig. VII. A steady state error of -.4 db, or 4.5%, is indicated in depth rate, but this is considered acceptable.

With $K_{c1}\, G_{c1}(s)$ and $K_{c2}\, G_{c2}(s)$ thus determined, the overall system was simulated on a Reeves Electronis Analog Computer. As will be indicated, it was necessary to modify $G_{c1}(s)$ in order to realize a satisfactory step response. The computer set-up is described in Appendix A, and the plotted responses in δ_s, θ, and e for a step input of Z'_{gi} are shown in Appendix B.

III

RESULTS

A. General

The proposed system was simulated on a Reeves Electronic Analog Computer as described in Appendix A. A constraint of plus and minus 25 degrees or .436 radians was placed on the maximum stern plane angle permissible. The input to the system was chosen to be a step function.

$$\dot{Z}'_{gi} = .5\, u_{-1}(r)$$

This choice was made on the basis that in a steady glide w' should be desirably zero making

$$\dot{Z}'_{q} = -\theta$$

where θ is the maximum permissible steady pitch angle. This value of θ was taken to be -.5 radian or -28.6°. 30° is usually taken as the maximum allowable value of θ in medium speed submarines. The actual peak value of θ indicated in the results of Appendix B are only approximate due to the assumption that $\theta = \sin\theta$. The error introduced by this approximation is justified in the sense that using a high value of θ permitted observing the system's general performance in the most extreme condition normally encountered.

B. Evaluation of Results

With the system as designed in Chapter II set up on the computer, and the primary parameters assigned their normal values, it was observed that the overshoot in θ and e were of the order of thirty percent. This was due to excessive lag introduced by G_{c1} and saturation in δ_s. Accordingly, the locations of the pole-zero pair of the lag network were

shifted to -0.1 and -1.0 respectively by changing the setting of potentiometer number 15. This corresponded to changing the value of k in the lag function representation given in Appendix A from 1 to .5. The effect of this adjustment on the phase-magnitude plot of the open-loop function and on the closed-loop response are shown in Curve C of Figs. VI and VII. After this adjustment, the system performed satisfactorily. Plotted results are shown in Appendix B.

The following observations are to be noted concerning these results:

1. the system specifications are met for values of $\frac{Z_{w'}}{m'}$ of -1.5 and -2.0 for all values of $\tilde{U}$ greater than 2.0 and all values of K_s' considered.
2. the system does not function satisfactorily for $\frac{Z_w'}{m'}$ =-1.0.

At values of $\tilde{U}$ of 1.0 and 2.0, the system either responds very slowly and with large steady-state error, or shows very little response at all, especially for low values of K_s'. This is due directly to the small lift force generated by the stern planes at slow speed and cannot be taken as a failure of the plane angle control system. At these speeds, δ_s takes on a maximum value and retains this value as would be expected. For this reason values of $\tilde{U}$ less than 3.0 are not considered in the results.

IV

DISCUSSION OF RESULTS

It was noted that the system did not function satisfactorily for Z_w'/m' equal to -1.0. The reason for this becomes apparent when the effects of this parameter and of saturation is δ_s on the locations of the open-loop poles of the system are considered. Limiting the maximum value of δ_s is equivalent to limiting the effectiveness of the compensation gains K_{c1} and K_{c2}. It is recalled that the open-loop poles of the system were moved further out into the left half of the s plane by a suitable choice of K_{c2}. The effect of saturation in δ_s is, therefore, to constrain these poles to lie to the right of their desired locations. The effect is aggravated by the tendency of J_1 as well as J_o to approach zero as $\tilde{U}$ increases when Z_w'/m' equals -1.0. For values of Z_w'/m' between zero and -1.0, J_1 approaches a negative number. In the extreme case, two of the poles fall between the origin and the zero of the lag network, and these become the dominant pole pair. The net result is a lowering of the closed-loop natural frequency and damping for a given gain. Two possible remedies present themselves. First, the pre-saturation gain K_{c1} may be decreased to keep the system in the linear region of δ_s longer, with a resultant decrease in steady-state accuracy. Fig. XXVI of Appendix B shows this result for $K_{c1} = 9.25$ instead of 21.4. A second approach lies in increasing the post-saturation gain of the hull via K_s'. This is equivalent to supplying more control surface area. Figs. VIII through XIII of Appendix B indicate this tendency.

A more detailed discussion of the effects of saturation indicated would require a non-linear analysis of the system and will not be attempted here.

The question immediately arises as to why these effects were not predominant at the higher values of Z_w' investigated. The necessity of shifting the zero of the lag network to the right mentioned above indicates that these effects were present when Z_w'/m' equalled -1.5, but a suitable remedy was quite simply achieved. The effect is not so pronounced simply because J_1 and J_o assume larger values and the hull gain is larger for these values of Z_w'/m'.

This failure of the system at low values of Z_w' is not considered a serious limitation on the basic approach presented. For normal hull forms, the magnitude of $Z_{w'}/m'$ is rarely less than 1.2.[15] The results simply confirm the known fact that hulls with little directional stability must be provided with larger control surfaces.

The remainder of the plotted results of Appendix B for values of Z_w'/m' of -1.5 and -2.0 are considered to justify the method presented. The behavior of pitch angle, a critical quantity, in the dive entry maneuver simulated is considered to be quite satisfactory. The error in steady state depth rate is maintained less than eight percent in all instances, and the overshoot is negligible. It will be recalled that the calculated steady state error of the system as compensated was four and one-half percent. From Fig. XVII, the steady state error of the system as designed is seen to be four percent. Since $\tilde{U}$ appears in the denominator of the expressions for J_1 and J_o, decreasing $\tilde{U}$ will move the poles of the open-loop relations to the left and

thus increase the steady state error, an effect clearly shown in the plotted results. The converse is true when $\tilde{U}$ is increased. It is seen from the plots that this effect is made quite small by the compensation technique employed.

It will be recalled that the requirement for a steady-state plane angle to counteract the metacentric righting moment was neglected in the system formulation. From the results, it is seen that this requirement is almost completely satisfied by the system due to the effect of metacentric righting moment on depth rate. For low values of $\tilde{U}$, an appreciable steady state plane angle exists but there is still a small pitch rate.

It is noted that the effect on steady state error due to changes in hull gain through variations in K'_s and Z_w'/m' are smaller than the effect of metacentric moment noted above. However, several runs were made with K_{c1} adjusted to correct for this change in hull gain. The runs were made only for the case U = 5.0, but the results shown in Figs. XXVII and XXVIII indicate that a slight improvement in steady state error results.

In the basic system presented, it was assumed that an infinite plane rate, $\dot{\delta}_s$, was available. This is not the case in practice. The compensation method presented, however, can easily be extended to handle the case when plane actuator dynamics are included in the K_1G_1 function. For example, if these dynamics are representable by a transfer function of the form $\frac{1}{p\,s+1}$, addition of the term (p s+1) in the numerator of both G_{c1} and G_{c2} would cancel this function and require minor changes in the constants associated with $K_{c1}G_{c1}$ and

$K_{c2}G_{c2}$. Again, complete cancellation would be achieved only in the linear region of stern plane operation.

It is becoming common practice to evaluate performance of a proposed submarine control system in terms of the comparison between the trajectories achieved for step inputs to the system and experimentally determined minimum time or limit trajectories. Due to time and computer capacity limitations, such a direct comparison was not carried out in this investigation. It is maintained, however, that on the basis of the indicated behavior of stern plane angle the plotted trajectories of depth rate error and pitch angle for the cases of interest closely approach those observed in the limit dive entry. In the results of Appendix B for the cases in which Z_w'/m' assumes the values of -1.5 and -2.0, δ_s shows at most one complete reversal from its initial maximum value before it quickly settles out to its steady state value. This behavior is necessarily characteristic of a minimum time trajectory. More will be said on this point in the following chapter.

V

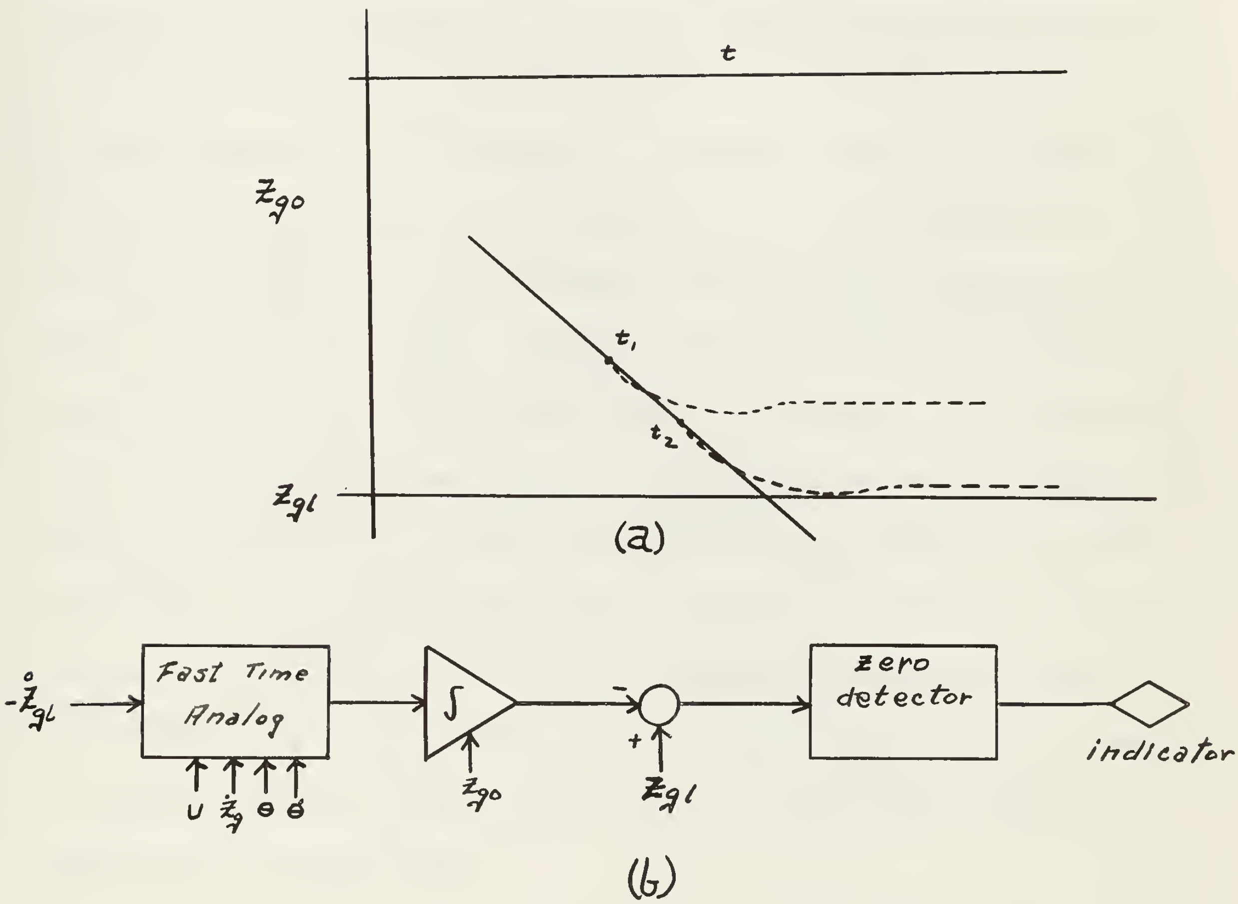
A PROPOSED PULL-OUT TIME PREDICTOR

The proposed system functions satisfactorily in carrying the ship through a dive or rise entry phase and maintaining the required dive or rise, but it cannot inform a human operator when to pull out to achieve a desired depth. As was indicated, a computer or programmer could be substituted for the human operator, but a simpler solution would be desirable. In the course of the investigation reported herein, a simple analog method of computing pull-out time presented itself. The basic idea stems from an optimum controller concept proposed by Lieutenant M. C. Davis USN in his doctoral thesis on multi-dimensional random processes.[17] This technique is considered worthy of note and further investigation as an auxiliary component of the proposed system.

If the optimum trajectory in depth is specified to be one executed in minimum time with no overshoot, then the optimum controller applies maximum control effort throughout the entry and pull-out phases.[16] Consider a ship controlled by the proposed system to be in some steady dive. In pull-out, the operator could simply return his control column to the zero position, commanding zero depth rate, or he could command varying amounts of negative depth rate to speed up the pull-out. But we have seen that the system presented in this paper approaches the performance of the optimum controller itself when the input is the desired step change in depth rate. Therefore, commanding a negative depth rate in pull-out cannot give a faster response than simply

returning the control column to zero. The problem, then, is determining when the operator should zero his control column to level out at a desired depth.

Th problem and an indication of a possible solution are shown in the following figures. In (a), the ship is shown in some steady dive,



as indicated by the solid line, which will carry it through the desired depth Z_{gi}. At successive instants, t_i, the present state of the system as determined by speed, depth, depth rate, pitch, and pitch rate are introduced as initial conditions into a fast time analog of the system, shown in (b). The input to the analog is a step function of equal magnitude but opposite sign to the existing commanded depth rate, a step function returning commanded depth

rate to zero. The computing periods, in real time, are short relative to the response time of the hull. The output of the analog is integrated to yield, in fast time, the trajectory in depth which would result if the control column were zeroed at the associated sampling instant t_i. This projected depth response is subtracted from the desired depth, represented by a constant quantity, and the difference is supplied to a zero-crossing detector. At the first zero-crossing of this difference, the indicator is actuated. Now it is noted from the dashed representations of the projected trajectories in (a) that at the first zero in this difference both the depth error and its first derivative are zero. That this will be the case is indicated by the plots of depth rate error response in Appendix B. This simplifies the operator's task since if he zeroes his control column at the first indication of a zero crossing he will come out on depth with depth rate passing through zero. Then he need only correct for the error in depth due to the small overshoot of the depth rate control system. Note that pullout time is based on the projected depth at peak overshoot in depth rate so that in a dive this error will always be on the safe side.

VI

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the results shown in Appendix B, it is concluded that the system presented is entirely feasible and worthy of further investigation and implementation. It is noted that this system possesses the following very desirable characteristics from the operator's viewpoint:

1. the system adjusts itself to any steady dive or rise commanded by the operator in a minimum time.
2. response becomes faster as speed increases, but does not become oscillatory or unstable.
3. pitch angle takes care of itself within the system, leaving the operator concerned only with the primary quantity, depth rate.
4. the control system minimizes the effects of speed and hull geometry variations by increasing the natural frequency of the control loop by a factor of at least five.

It is considered that this system, in conjunction with a pull-out time indicator discussed in the preceeding chapter, will provide near optimum depth changing and depth-keeping capability. Due to its broadband nature, one system of this type will provide adequate control characteristics in a variety of hulls, obviating the need to tailor-design a control system for each new ship.

APPENDIX A

COMPUTER STUDY

A. Computer Simulation of the Proposed System

The system as shown in Fig. IV was simulated on the analog computer in the following manner. To avoid loosing sight of the basic problem, the force and moment equations of the hydroframe as given in equations (3) and (4) were used to represent the hull. To facilitate the computer solution, these equations were rewritten in the following form

$$(3a) \quad 100\frac{dw'}{dr} = .517\left\{100\frac{d\theta}{dr} - 10\ \ .1\left|\frac{Z_w'}{m'}\right|\left[.5\left(100\frac{d\theta}{dr}\right) + K_s'(10\ \ _s) + .1(100_w')\right]\right\}$$

$$(4a) \quad 100\frac{d^2\theta}{dr^2} = .123\left\{100w' - \frac{1000}{U^2} - 10\ \ .1\left|\frac{Z_w'}{m'}\right|\left[.25\left(1000\frac{de}{dr}\right) + .5(100w') + .5K_s'(10)(10\ \ _s)\right]\right\}$$

where $r = 10\tau$

$$\frac{d}{d\tau} = 10\frac{d}{dr} \qquad \frac{d^2}{d\tau^2} = 100\frac{d^2}{dr^2}$$

A point concerning the analog treatment of the lag network is worthy of note. Writing the defining relations of this component in the following form,

$$\frac{\delta_{sl}(s)}{e(s)} = \frac{K_{cl}(s + 2K)}{s + .2K}$$

and carrying through the indicated operations and change of time base yields

$$10\frac{d\delta_{sl}}{dr} = K_{cl}\left(10\frac{de}{dr}\right) + K(2K_{cl}e - .2\ \ _{sl})$$

Integrating once since $\frac{de}{dr}$ is unavailable, and noting that the initial conditions on the integration are zero yields

$$10\,\delta_{s1} = K_{c1}\ (10\ e) + K \int \left[2K_{c1}\ e - .2\ \delta_{s1} \right] dr$$

or

$$\delta_{s1} = .01K_{c1}\ (100\ e) + .1K \int \left[.02K_{c1}\ (100\ e) - .2\delta_{s} \right] dr$$

Now the coefficient of the integral will appear in the computer diagram simply as a potentiometer for values of K between 0 and 10. K determines the location of the pole-zero pair of the lag network along the negative real axis of the s plane relative to the selected position at -2 and -.2, the ratio of their distances from the origin remaining constant. This facilitates a simple method of experimentally varying the phase shift introduced by the lag network without affecting the steady state error of the system.

The feedback compensation is represented by the following:

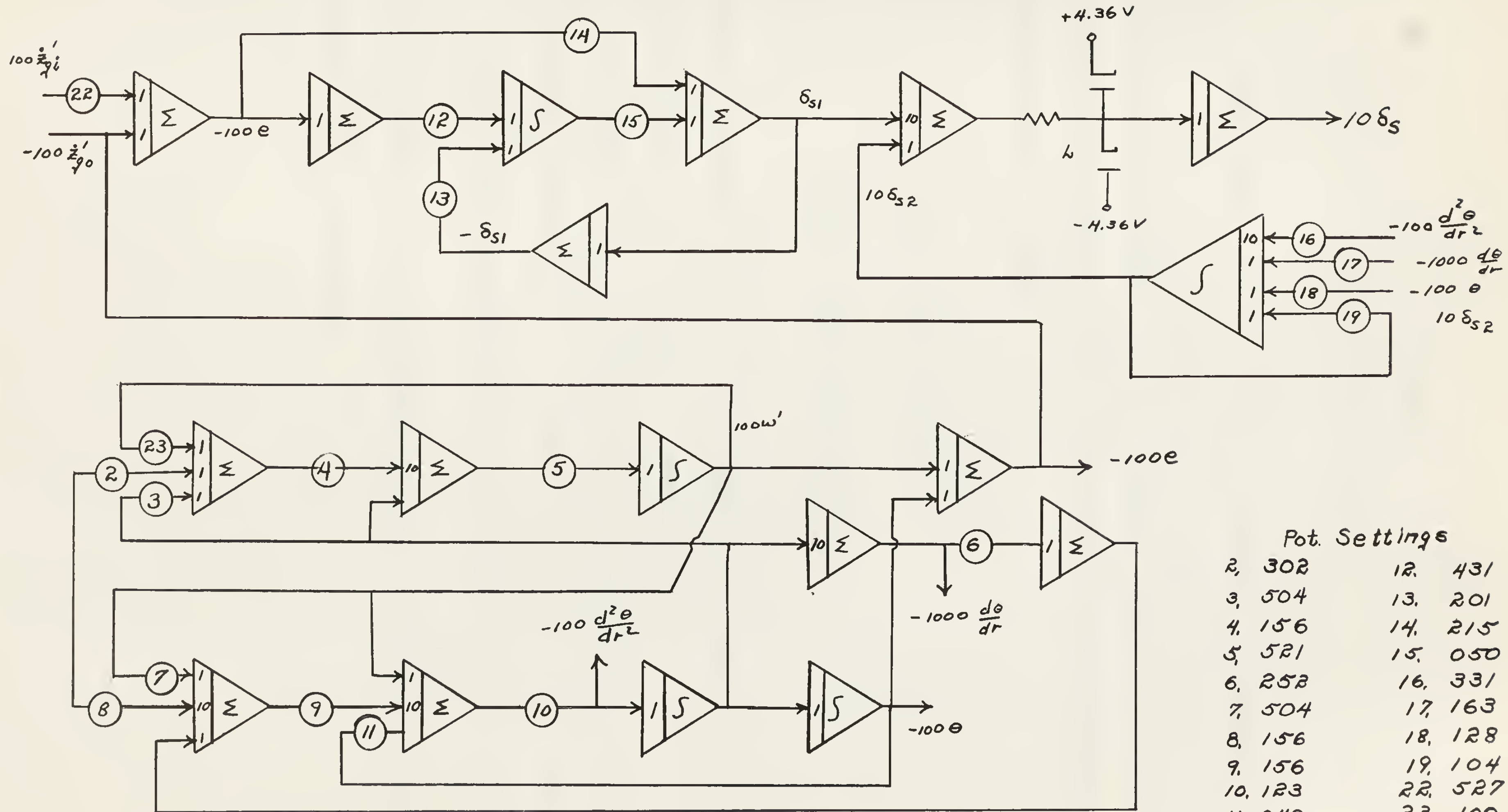
$$\frac{10\ d\delta_{s2}}{dr} = .310\ \left(1000\ \frac{d^2\theta}{dr^2}\right) + .163\ \left(1000\ \frac{d\theta}{dr}\right) + .128\ (100\ \theta) - .104\ (10\,\delta_{s2})$$

A limiter is employed to restrict the maximum value of $\delta_s = \delta_{s1} + \delta_{s2}$ to $\pm$ 25° or .436 radian.

$\dot{Z}'_{go}$ is computed from the relation

$$100\ \dot{Z}'_{go} = 100\ \dot{w}' - 100\ \theta$$

The complete computer diagram is shown on Plate I.



Pot. Settings

2,	302	12.	431
3,	504	13.	201
4.	156	14.	215
5,	521	15.	050
6.	252	16.	331
7.	504	17.	163
8.	156	18.	128
9.	156	19.	104
10.	123	22.	527
11.	040	23.	100

REAC CIRCUIT

PLATE I

APPENDIX B

ANALOG COMPUTER RESULTS

Figs. VIII through XXV show the results of the analog computer study of the proposed system as plots of δ_s, θ, and e vs the non-dimensional time parameter τ for various values of the three primary parameters K_s', Z_w'/m', and $\tilde{U}$. The values of these parameters considered are as follows:

$\tilde{U}$	3.0, 5.0, 7.0, 9.0
K_s'	0.2, 0.3, 0.4
$\frac{Z_w'}{m'}$	-1.0, -1.5, -2.0

Curves for each value of $\tilde{U}$ are shown on one plot for each pair of the parameters K_s' and $\frac{Z_w'}{m'}$ considered.

Fig. XXVI shows the performance of the system in pitch angle and depth rate for $Z_w'/m' = -1.0$, $U = 5.0$, $K_s' = 0.3$, and $K_{cl} = 9.25$

Figs. XXVII and XXVIII show this data for $\frac{Z_w'}{m'}$ of -1.5 and -2.0 and all values of K_s' considered with K_{cl} adjusted to maintain the product $K_{cl}\,K_2$ constant.

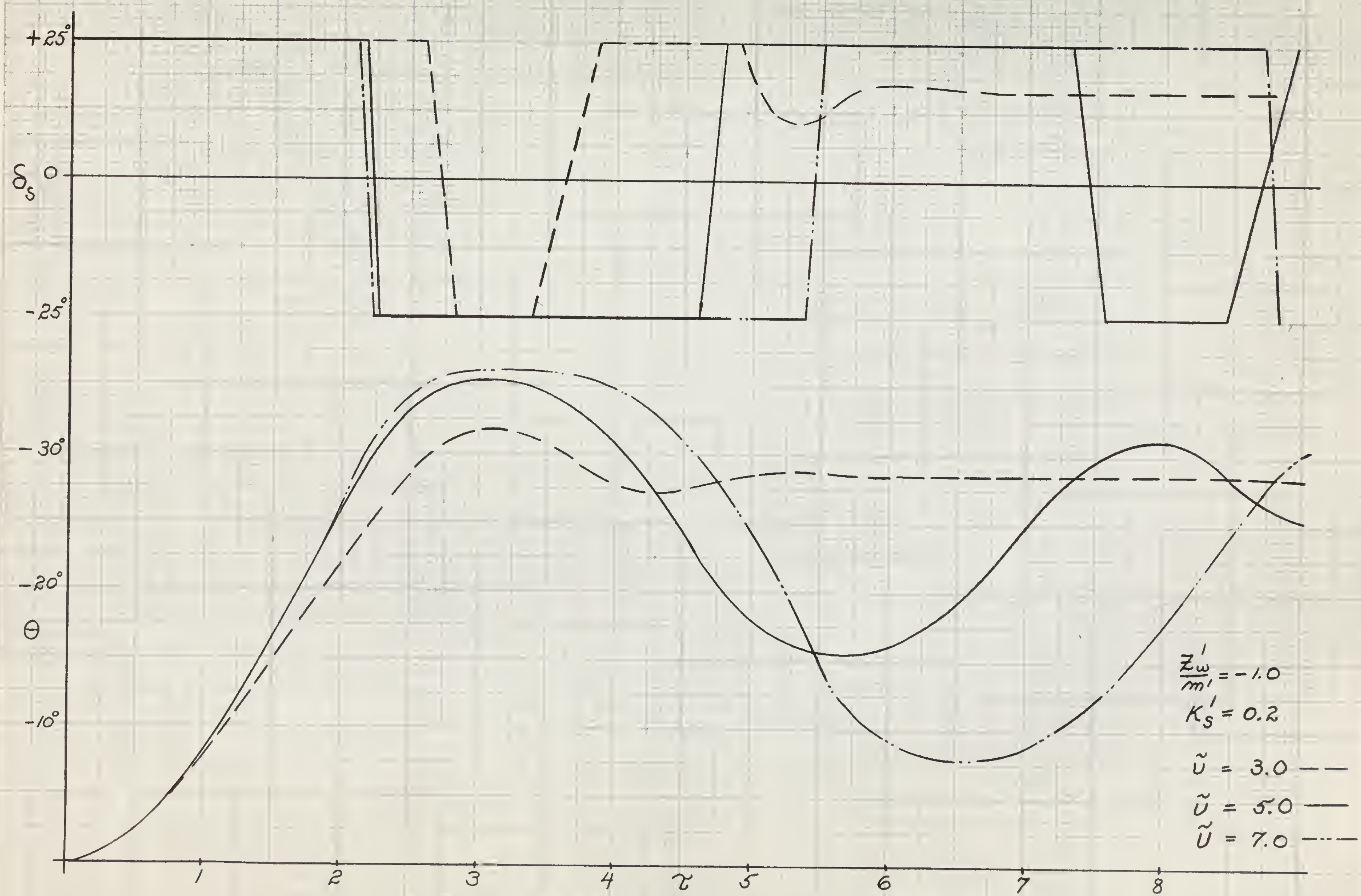
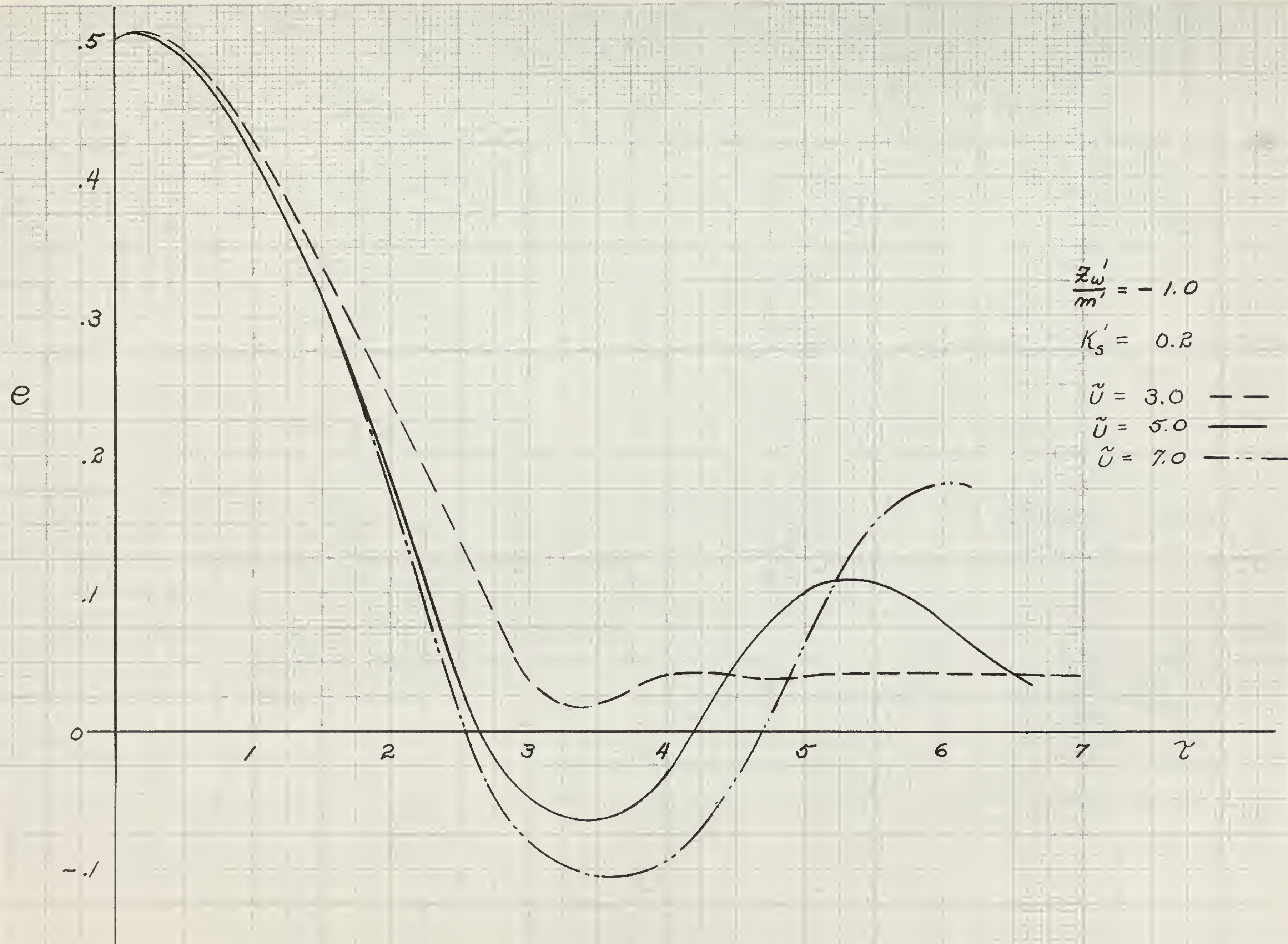

+25°
δ_s 0
-25°
-30°
-20°
Θ
-10°
1
2
3
4
τ
5
6
7
8
$\frac{Z'_w}{m'} = -1.0$
$K'_s = 0.2$
$\tilde{U} = 3.0$
$\tilde{U} = 5.0$
$\tilde{U} = 7.0$

FIG VIII



.5
.4
.3
.2
.1
0
-.1
e
1
2
3
4
5
6
7
τ
$\frac{Z_w'}{m'} = -1.0$
$K_s' = 0.2$
$\tilde{U} = 3.0$
$\tilde{U} = 5.0$
$\tilde{U} = 7.0$

FIG. IX

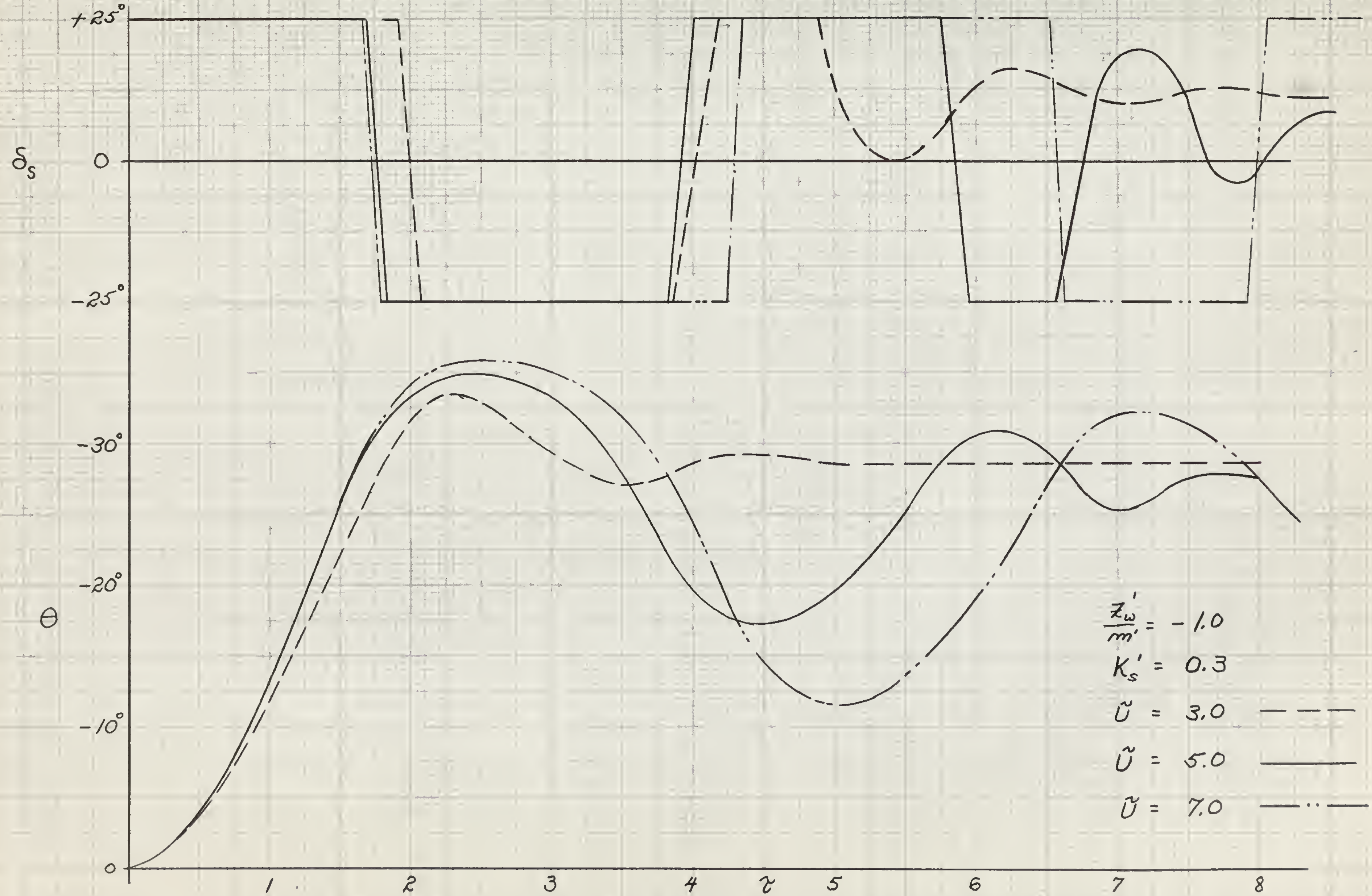
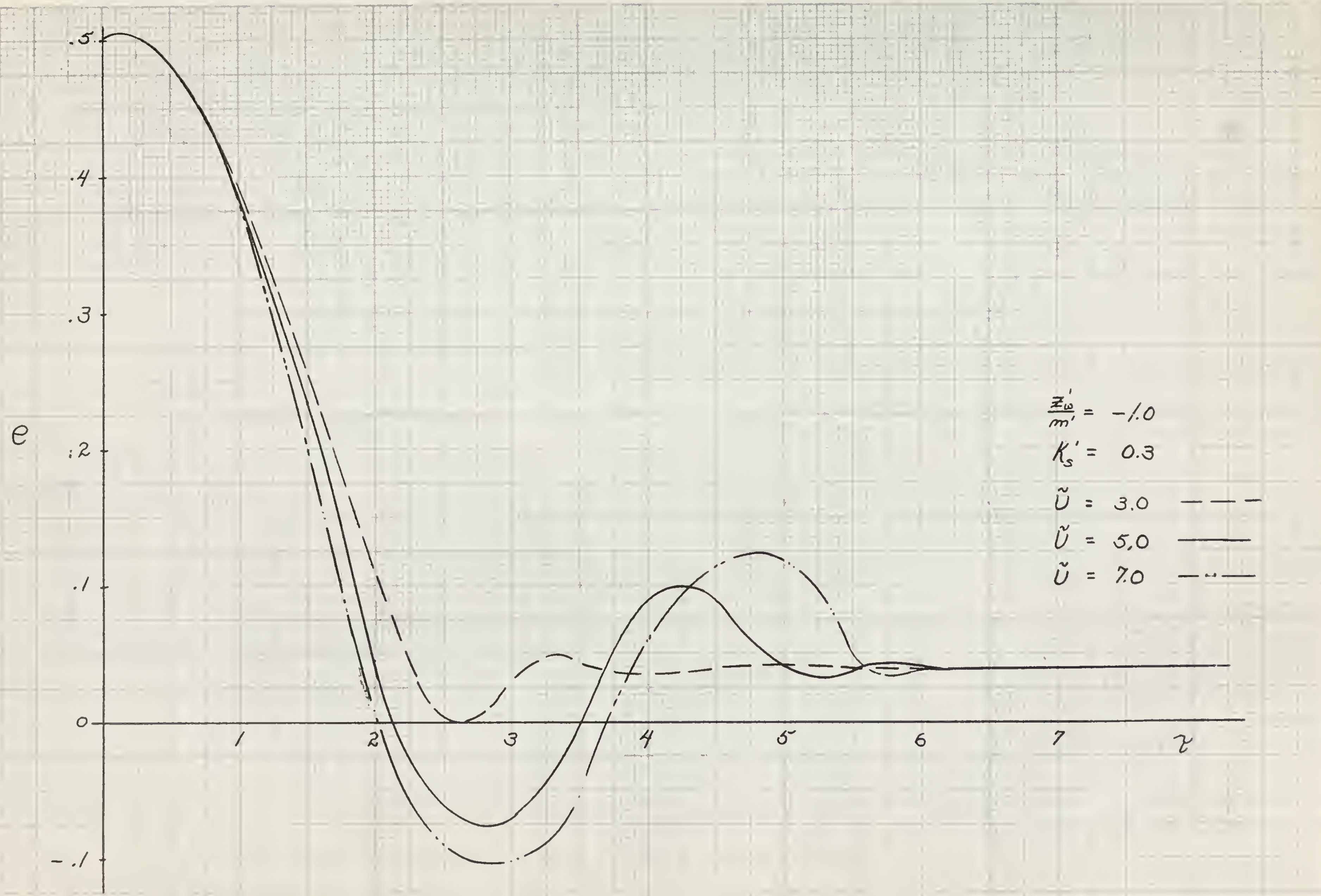

+25°
δ_s
0
-25°
-30°
-20°
θ
-10°
0
1
2
3
4
τ
5
6
7
8
$\frac{Z_w'}{m'} = -1.0$
$K_s' = 0.3$
$\tilde{U} = 3.0$
$\tilde{U} = 5.0$
$\tilde{U} = 7.0$

FIG. X



.5
.4
.3
.2
.1
0
-.1
e
1
2
3
4
5
6
7
τ
$\frac{Z_w'}{m'}$ = -1.0
K_s' = 0.3
$\tilde{U}$ = 3.0
$\tilde{U}$ = 5.0
$\tilde{U}$ = 7.0

FIG. XI

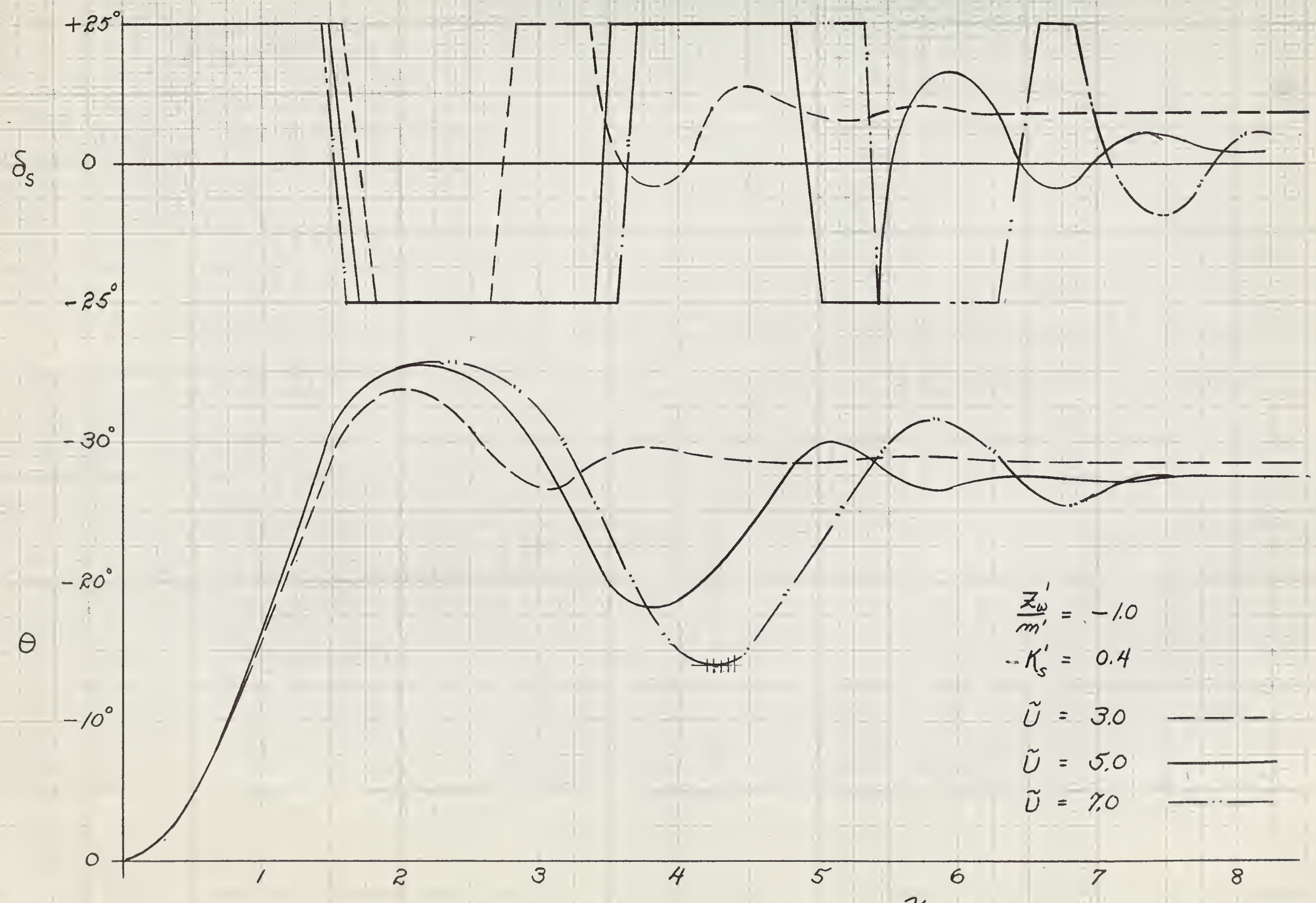

+25°
0
-25°
-30°
-20°
-10°
0
δ_s
Θ
1
2
3
4
5
6
7
8
τ
$\frac{Z_w'}{m'} = -1.0$
$-K_s' = 0.4$
$\tilde{U} = 3.0$
$\tilde{U} = 5.0$
$\tilde{U} = 7.0$

FIG. XII

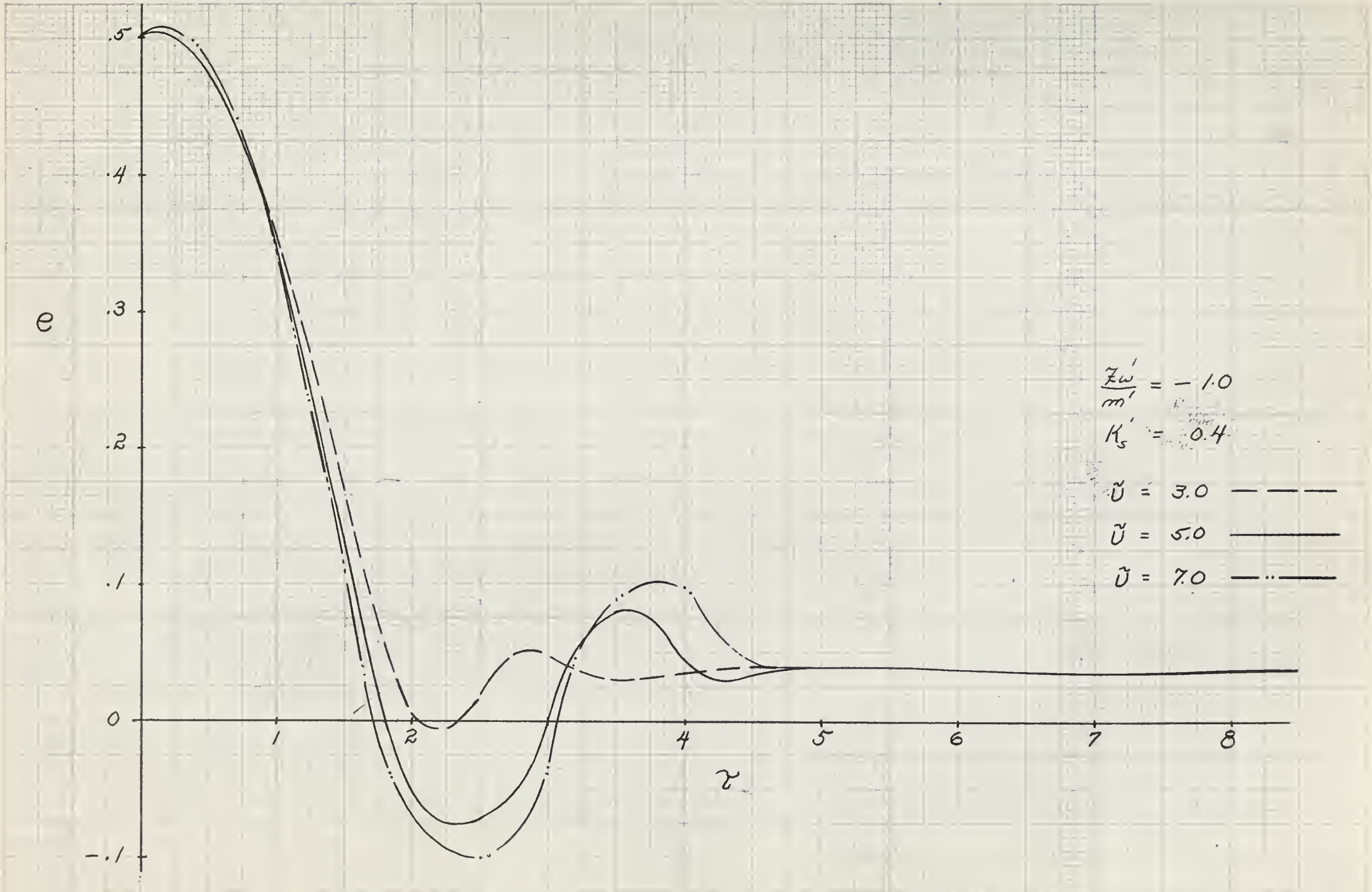


FIG. XIII

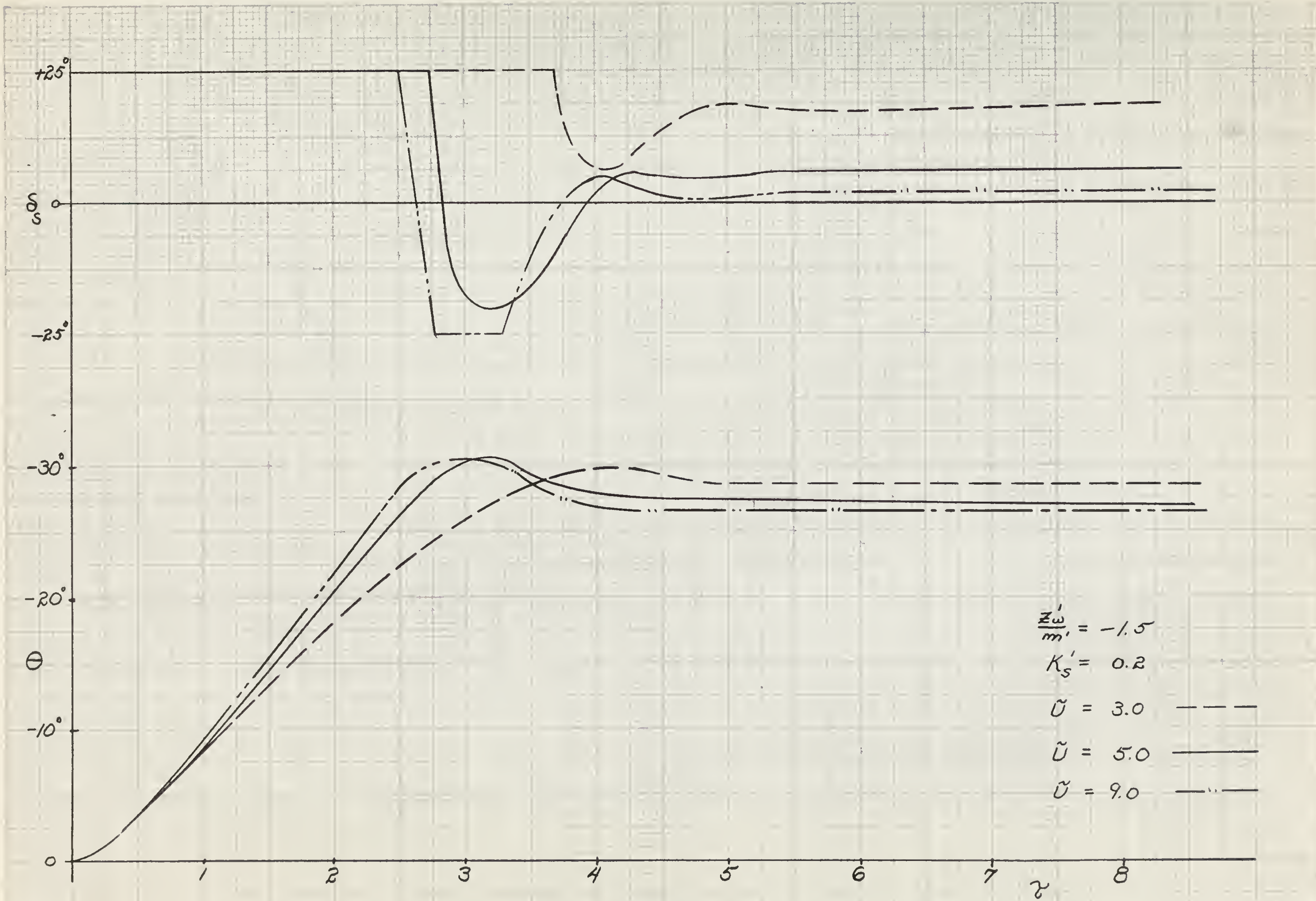

+25°
δ_s 0
-25°
-30°
-20°
Θ
-10°
0
1
2
3
4
5
6
7
8
τ
$\frac{Z'_w}{m'} = -1.5$
$K_s' = 0.2$
$\tilde{U} = 3.0$
$\tilde{U} = 5.0$
$\tilde{U} = 9.0$

FIG XIV

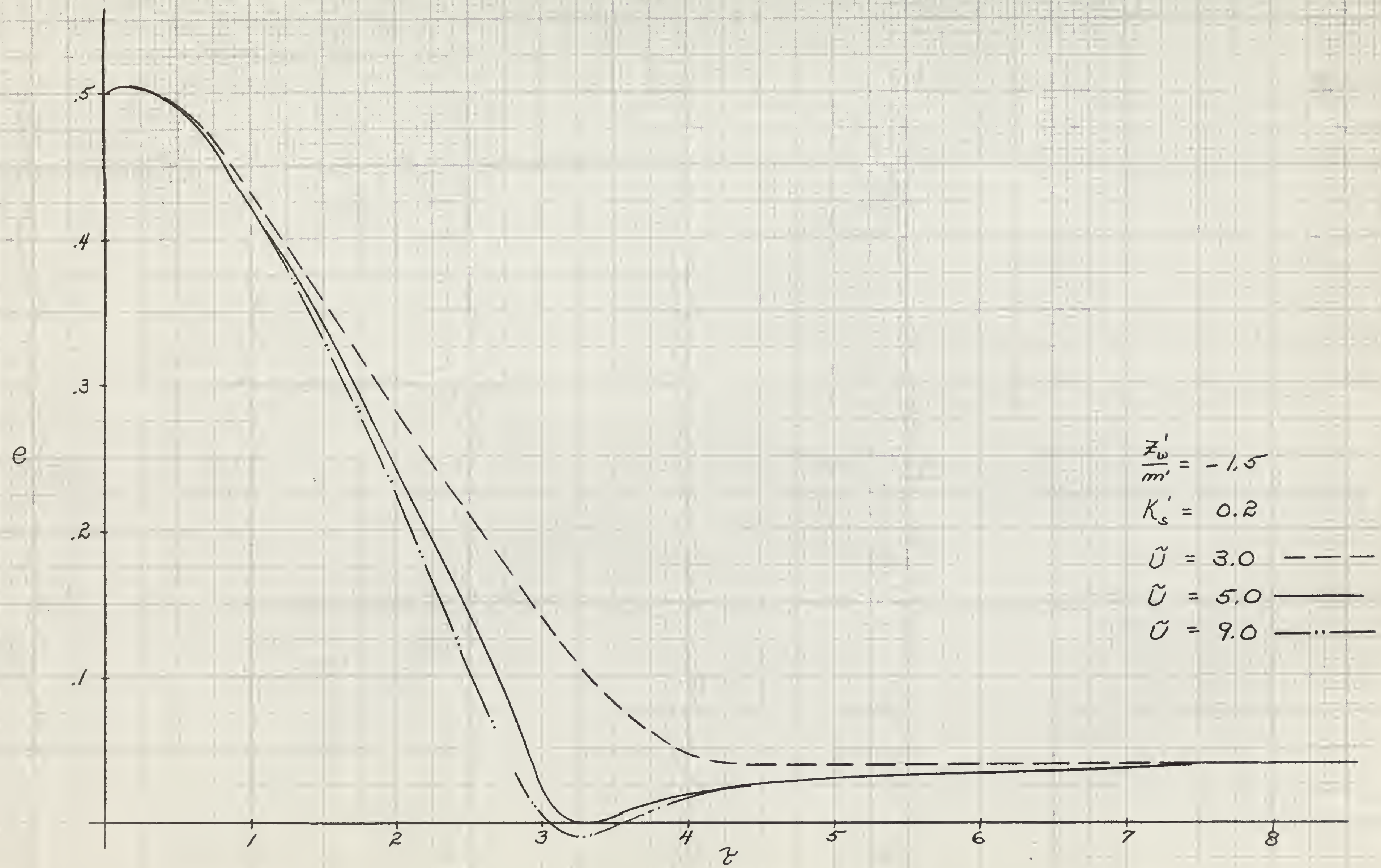

e
.5
.4
.3
.2
.1
1
2
3
4
5
6
7
8
τ
$\frac{Z_w'}{m'} = -1.5$
$K_s' = 0.2$
$\tilde{U} = 3.0$
$\tilde{U} = 5.0$
$\tilde{U} = 9.0$

FIG. XV

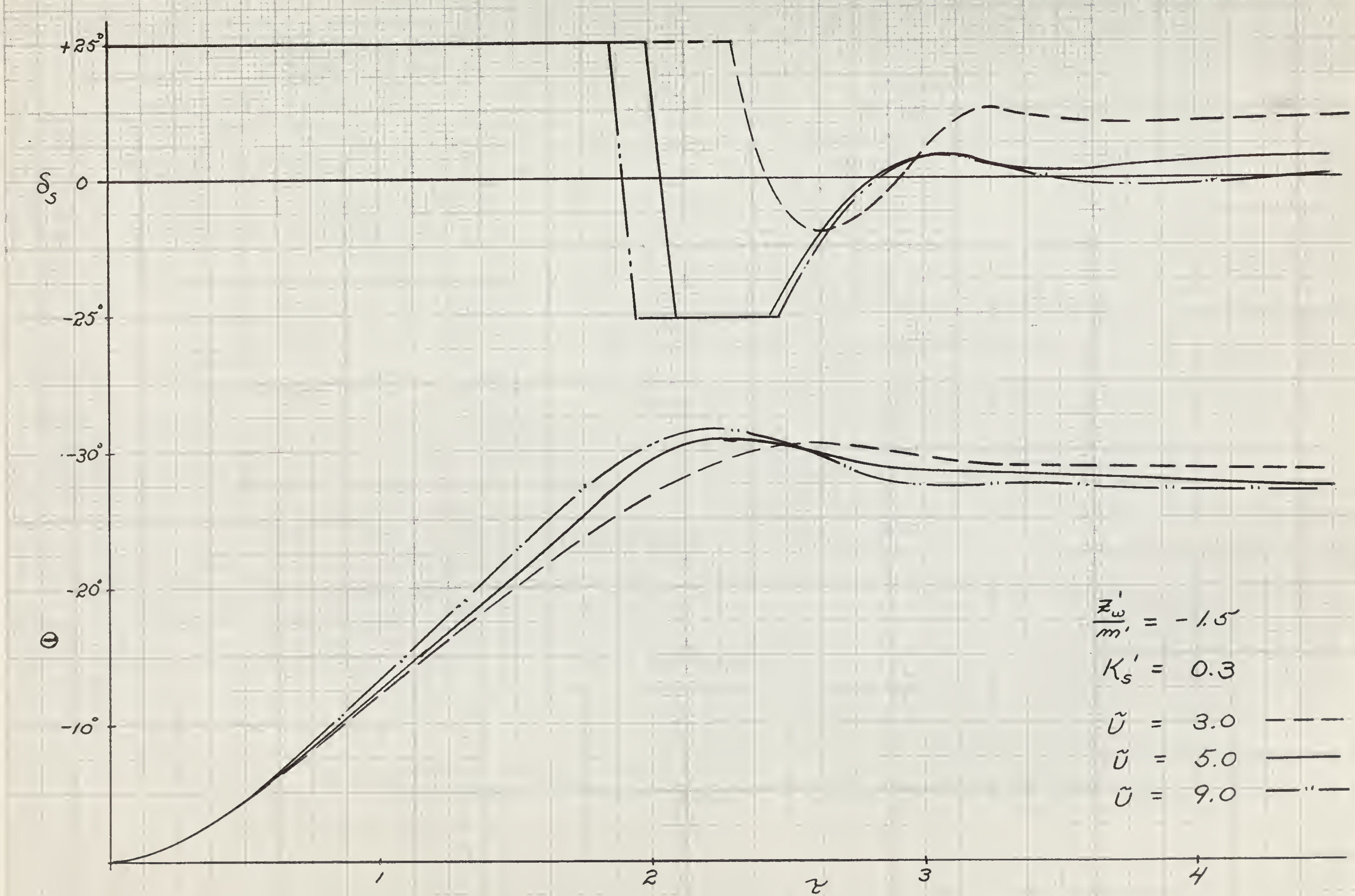

+25°
δ_s
0
-25°
-30°
-20°
Θ
-10°
1
2
3
4
τ
$\frac{Z'_w}{m'} = -1.5$
$K_s' = 0.3$
$\tilde{U} = 3.0$
$\tilde{U} = 5.0$
$\tilde{U} = 9.0$

FIG. XVI

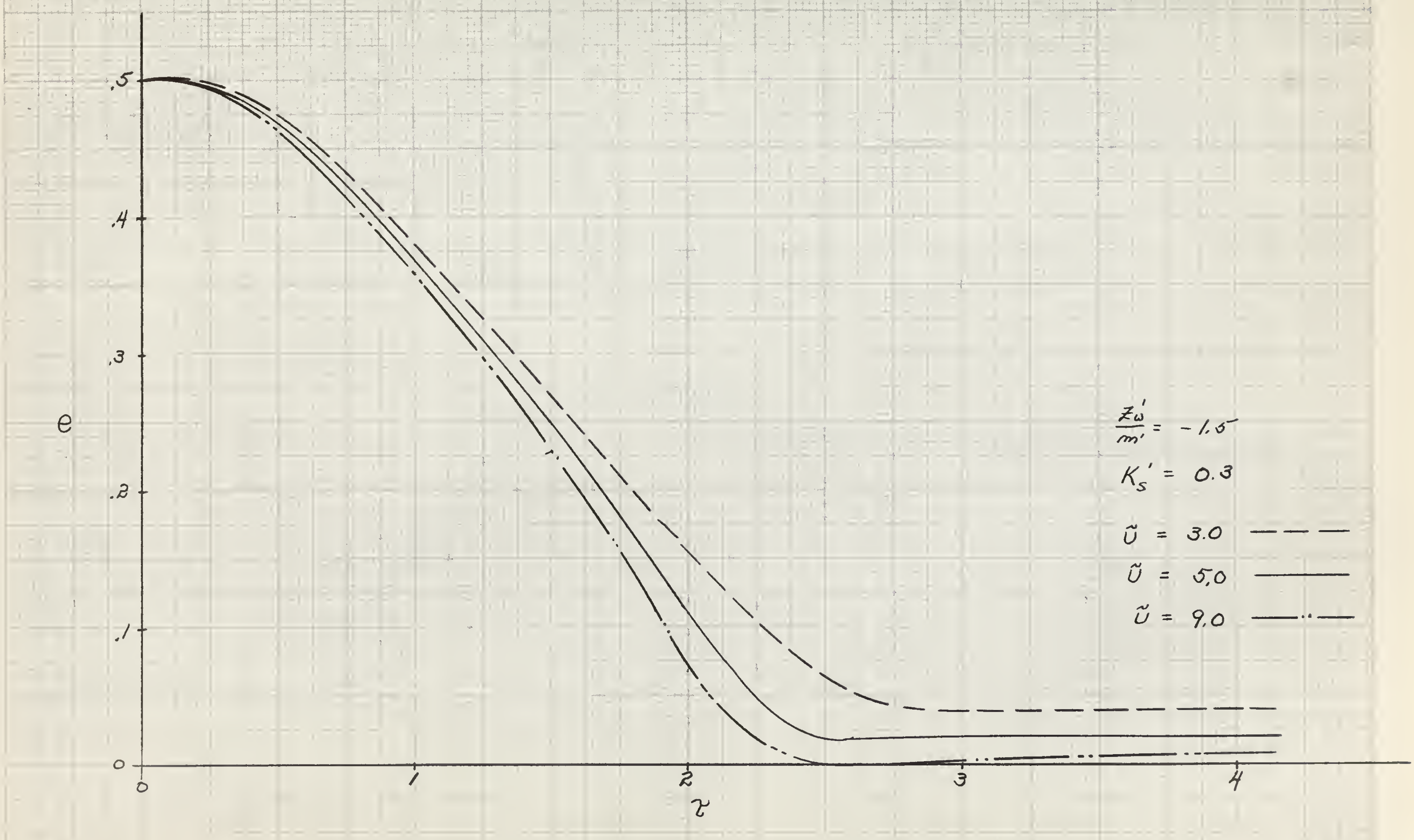


FIG. XVII

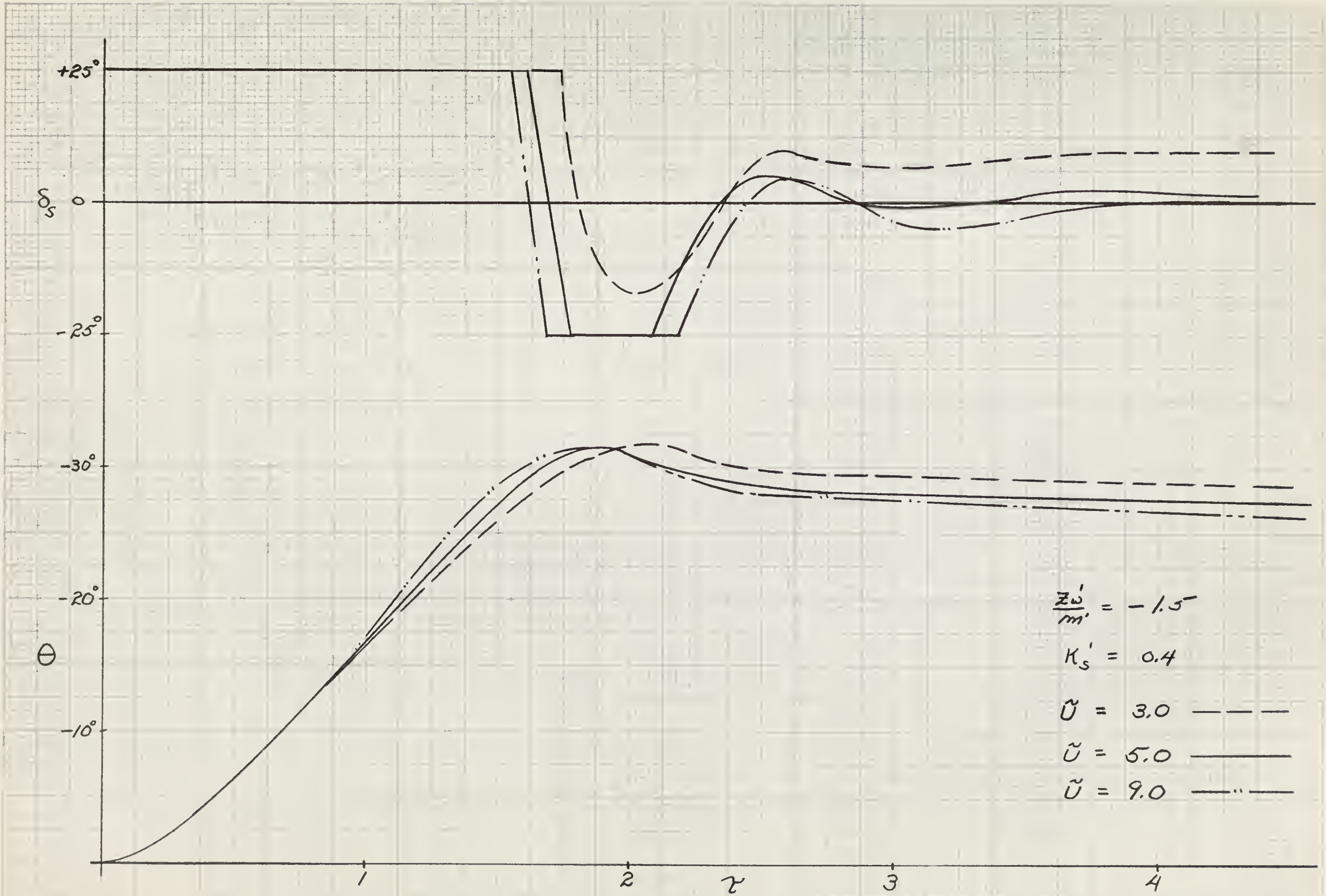
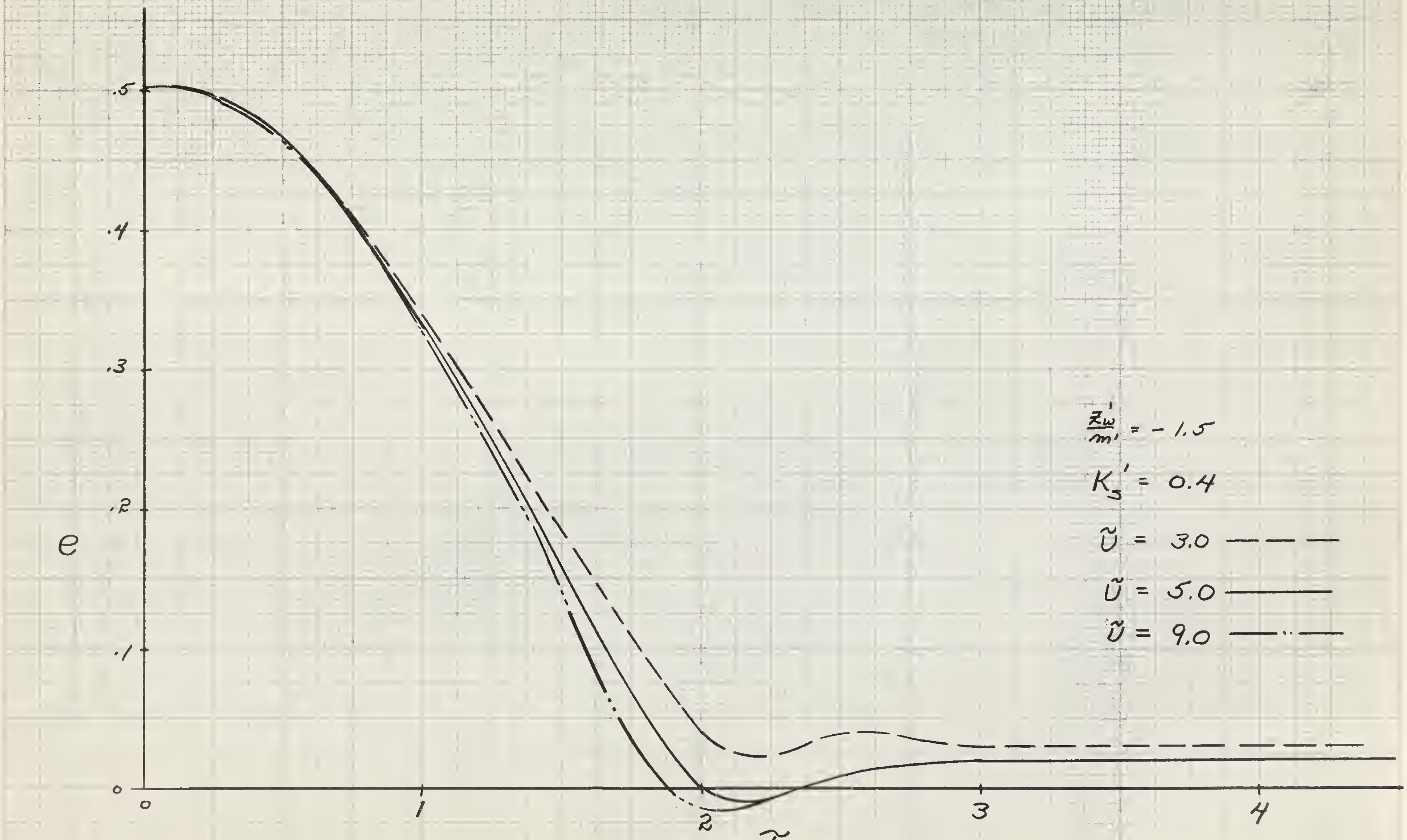

+25°
0
-25°
-30°
-20°
-10°
δ_s
Θ
1
2
3
4
τ
$\frac{Z_w'}{m'} = -1.5$
$K_s' = 0.4$
$\tilde{U} = 3.0$
$\tilde{U} = 5.0$
$\tilde{U} = 9.0$

FIG. XVIII



e
.5
.4
.3
.2
.1
0
0
1
2
3
4
$\tilde{\tau}$
$\frac{Z_w'}{m'} = -1.5$
$K_s' = 0.4$
$\tilde{U} = 3.0$
$\tilde{U} = 5.0$
$\tilde{U} = 9.0$

FIG. XIX

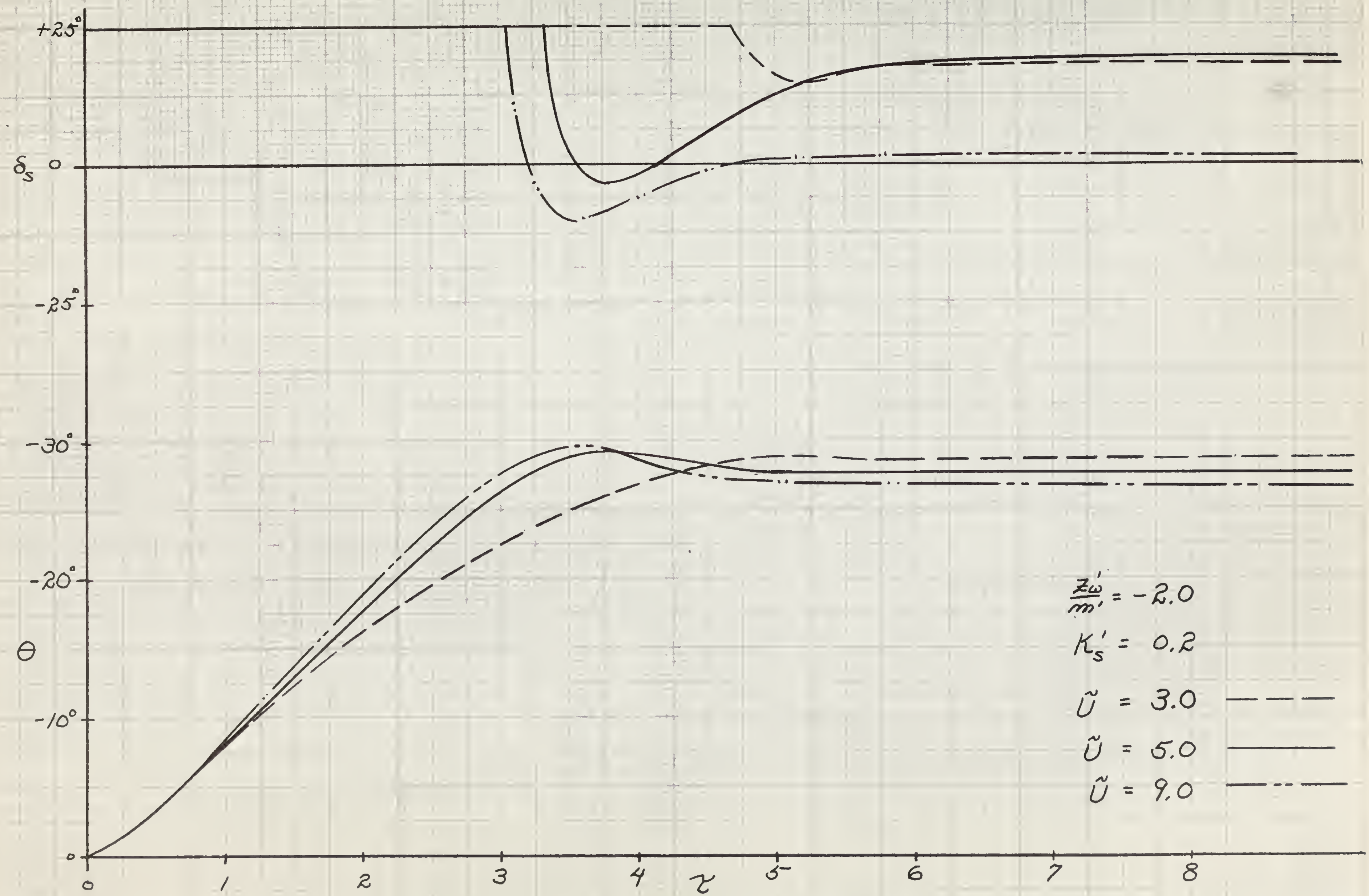


FIG XX

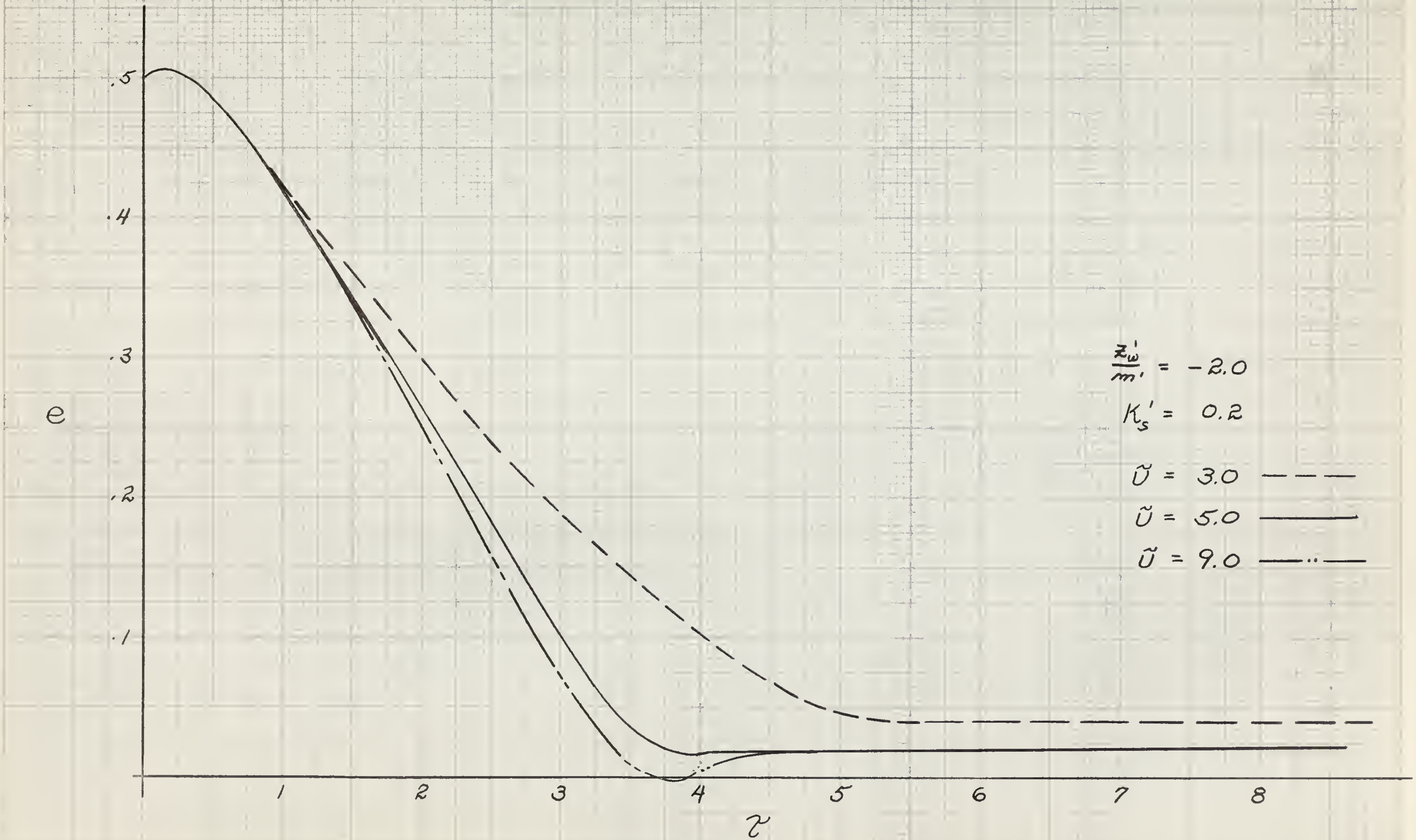


FIG. XXI

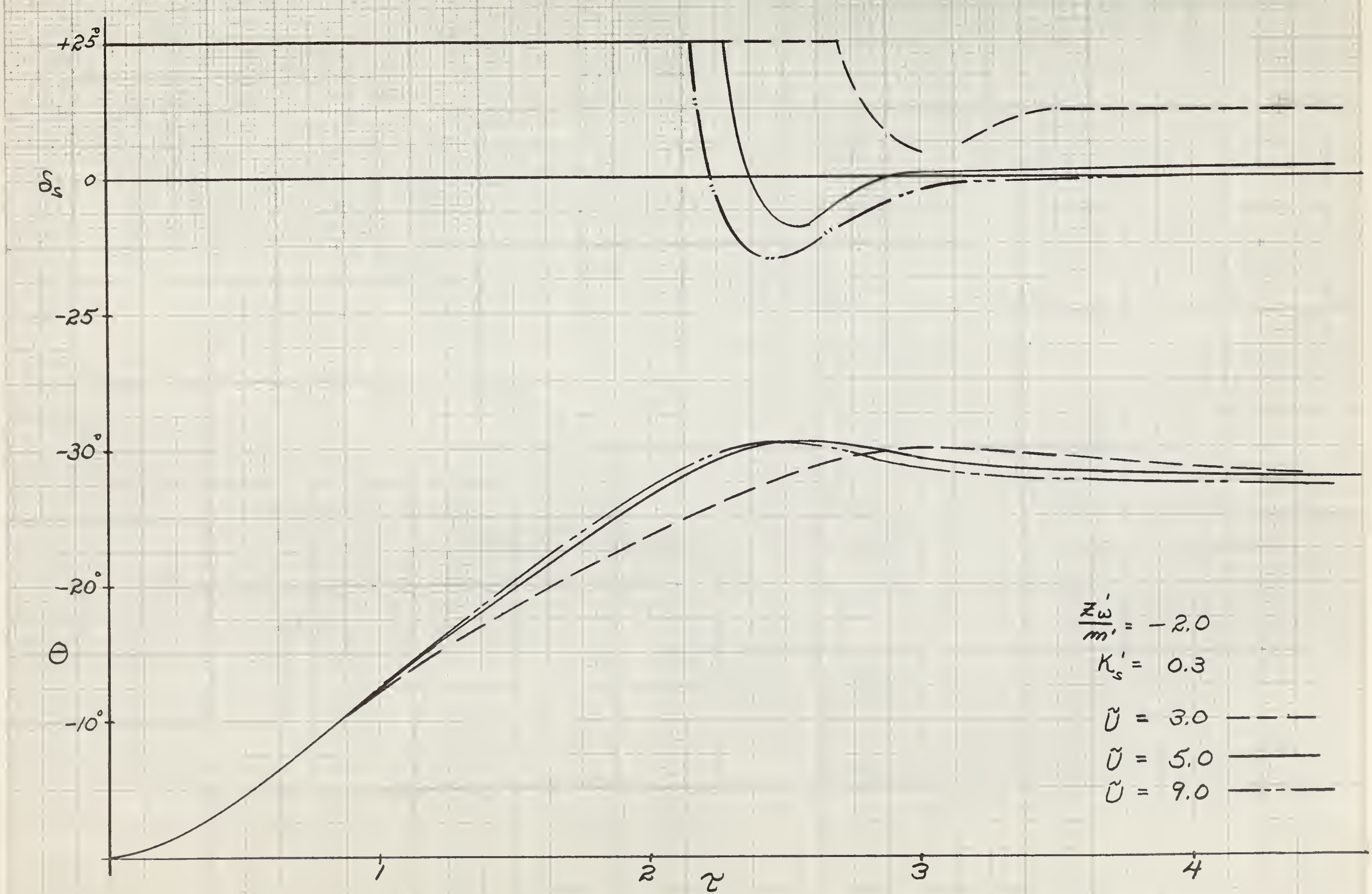

+25°
δ_s
0
-25
-30°
-20°
Θ
-10°
1
2
3
4
τ
$\frac{Z_{\dot{w}}'}{m'} = -2.0$
$K_s' = 0.3$
$\tilde{U} = 3.0$
$\tilde{U} = 5.0$
$\tilde{U} = 9.0$

FIG. XXII

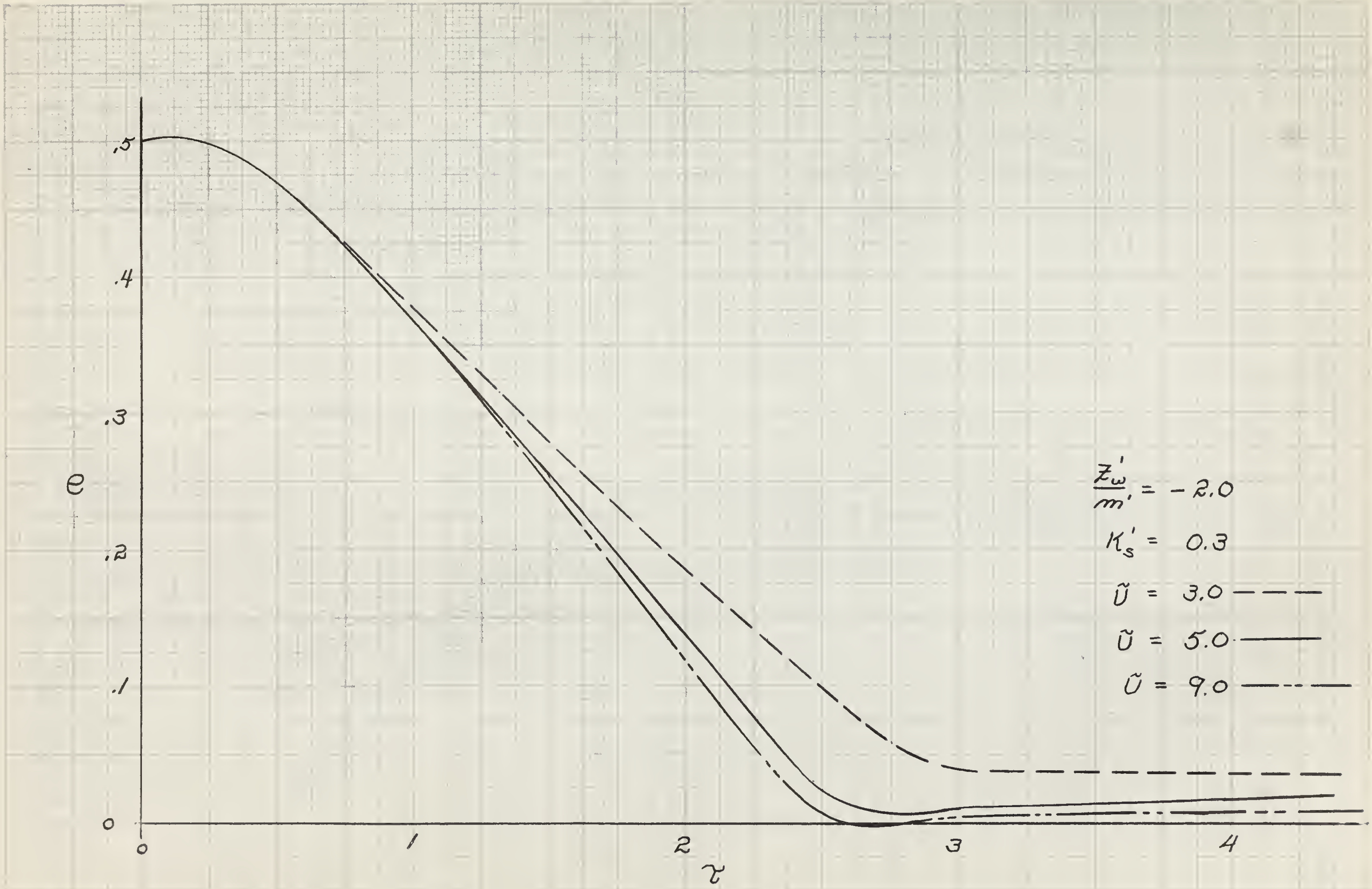

.5
.4
.3
.2
.1
0
e
0
1
2
3
4
τ
$\frac{Z'_w}{m'} = -2.0$
$K'_s = 0.3$
$\tilde{U} = 3.0$
$\tilde{U} = 5.0$
$\tilde{U} = 9.0$

FIG XXIII

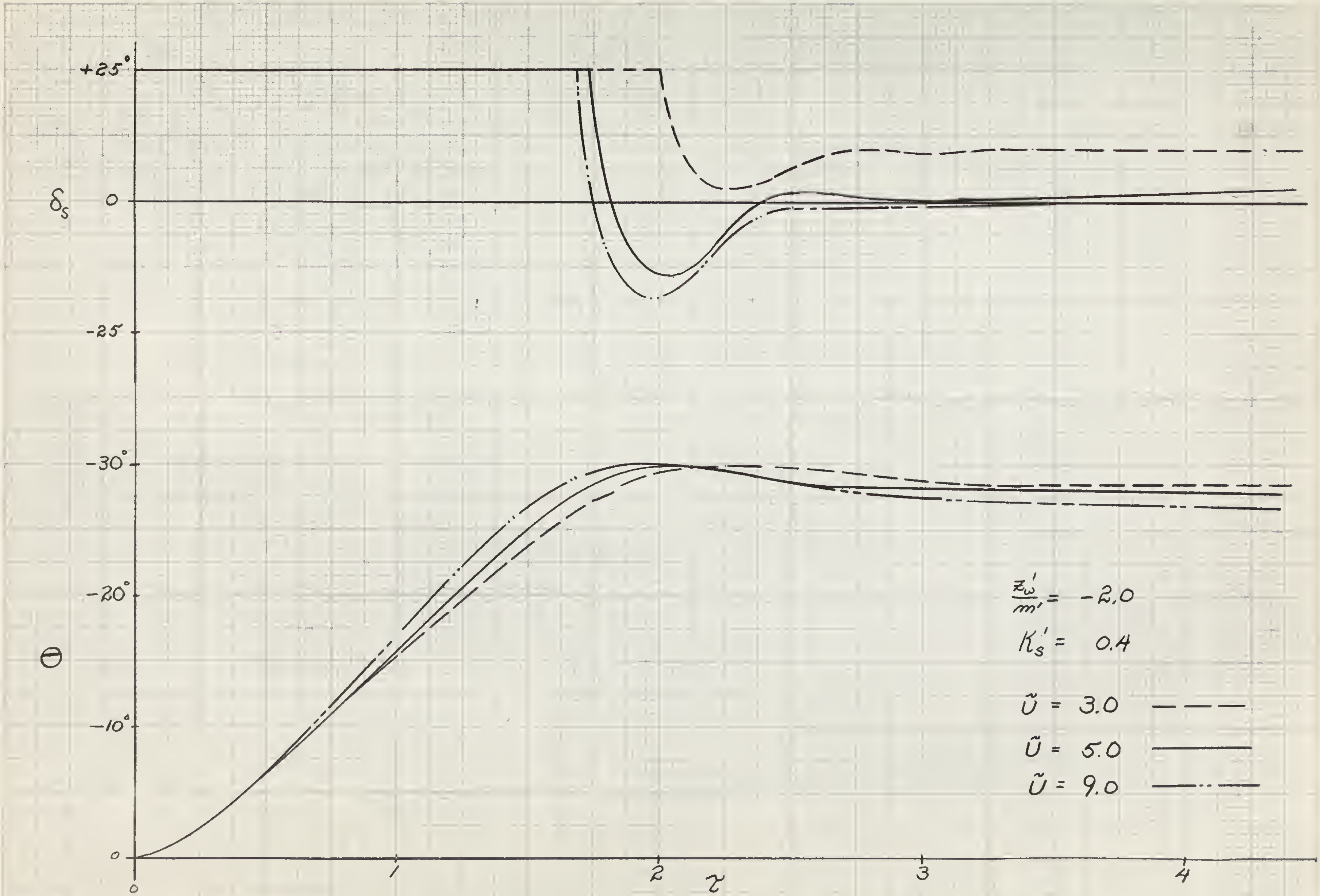


FIG. XXIV

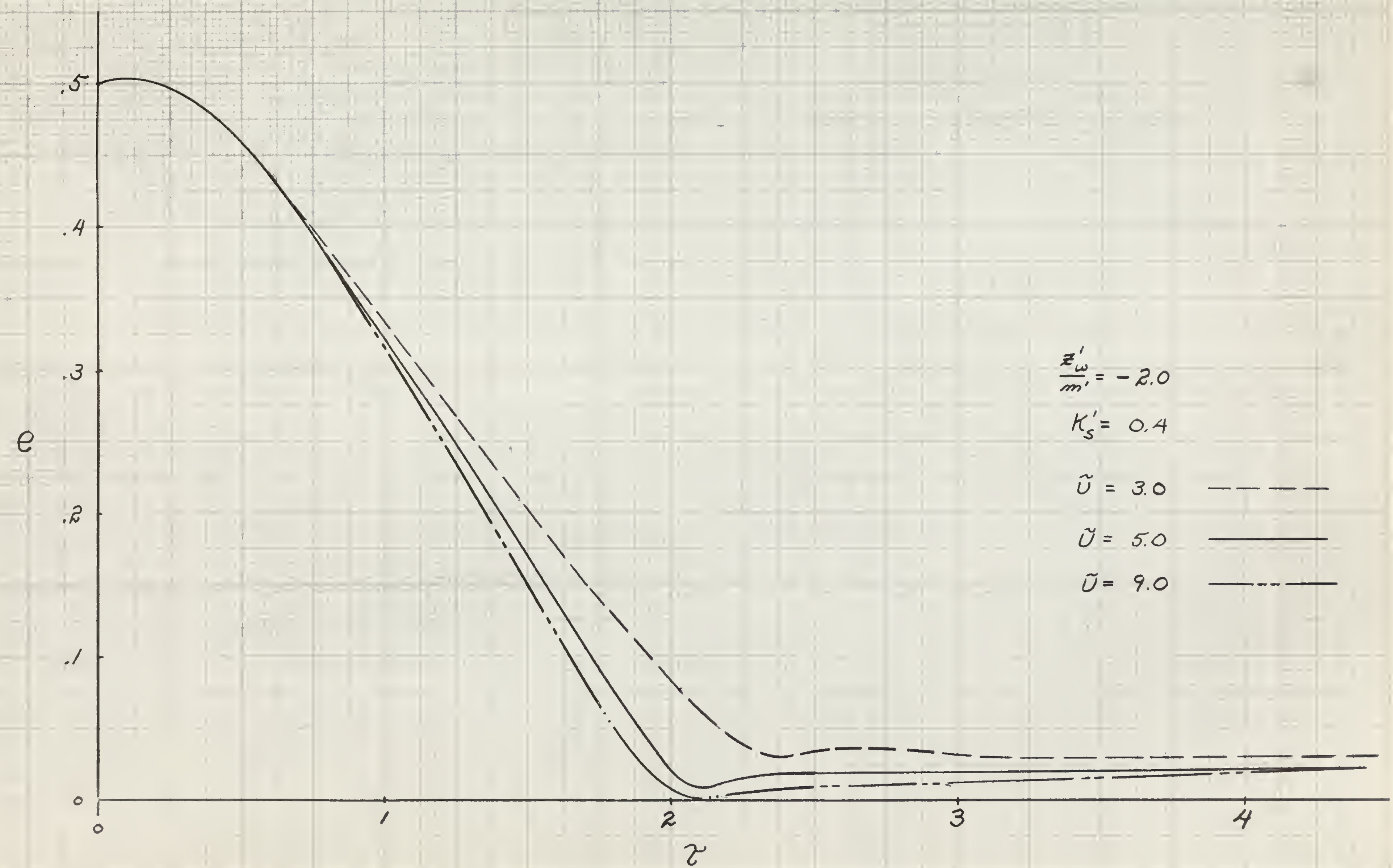


FIG. XXV

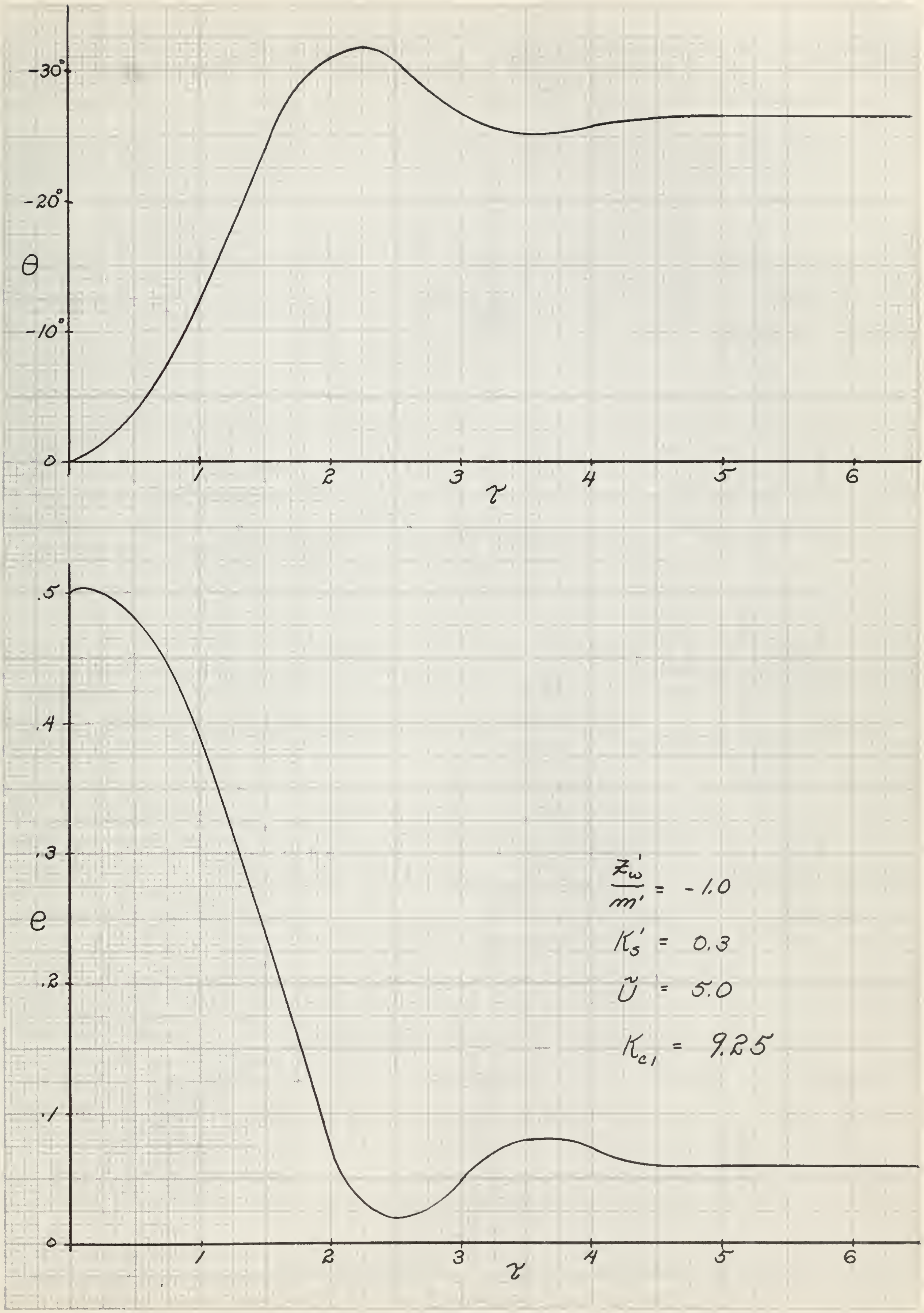


FIG. XXVI

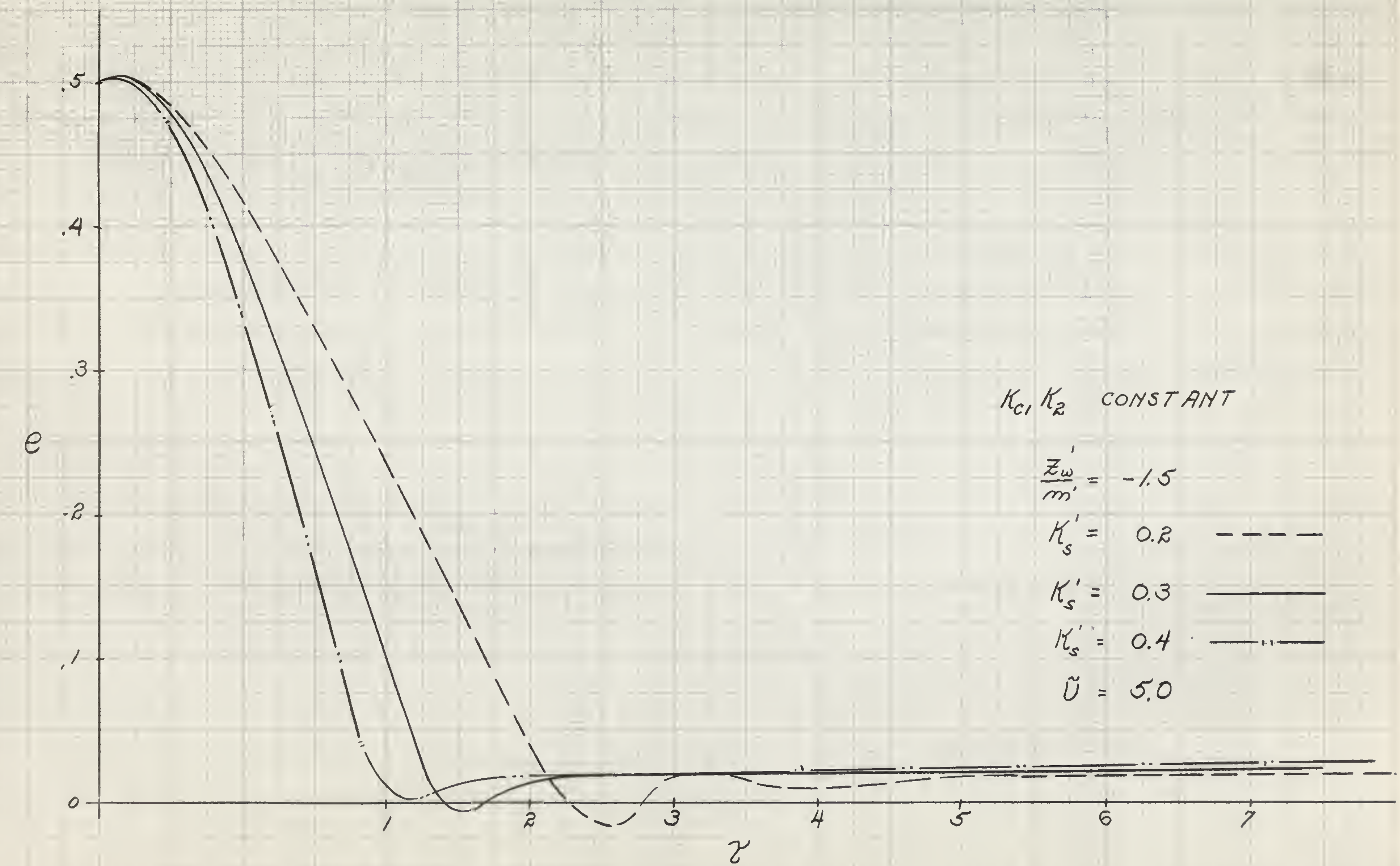
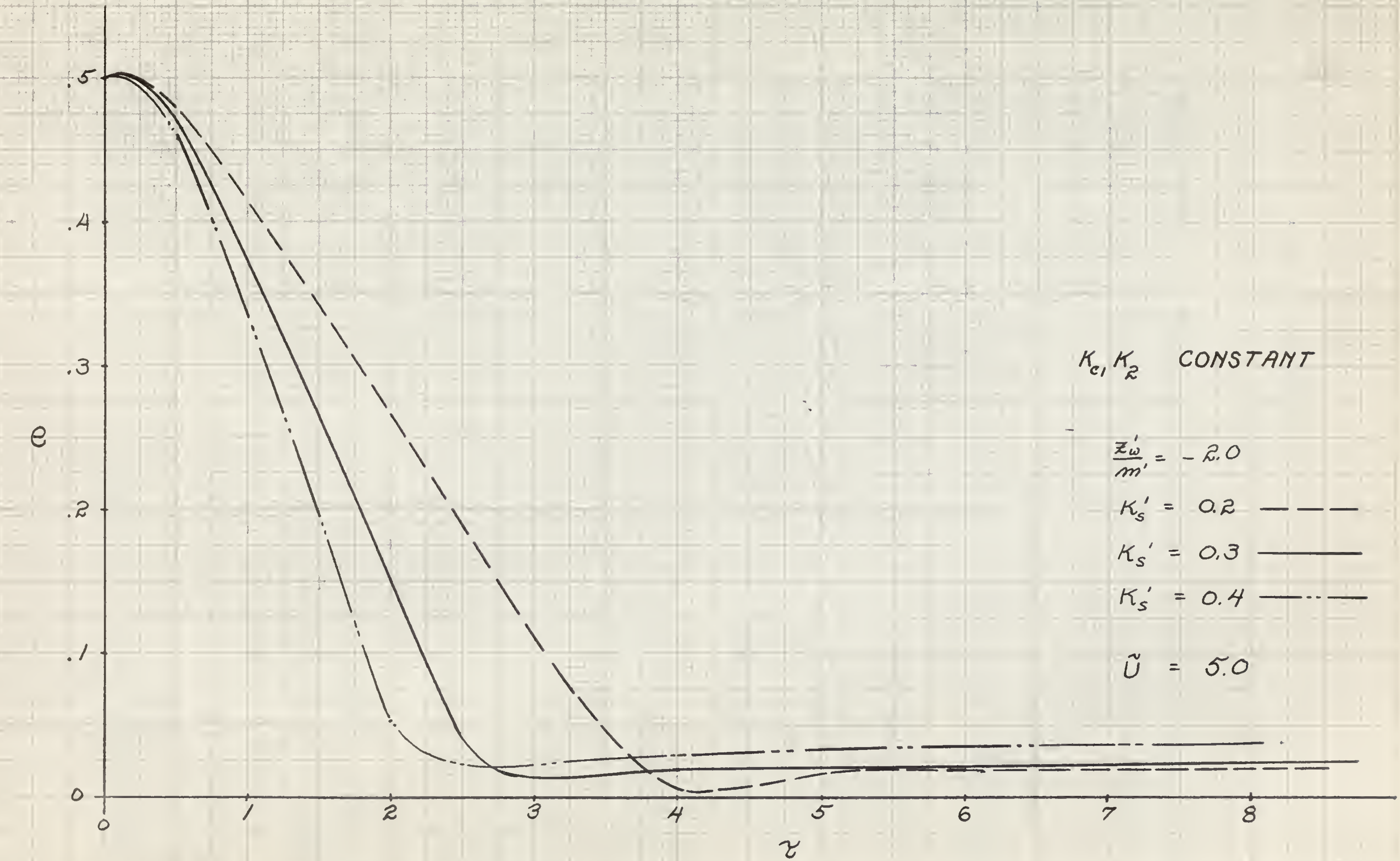


FIG. XXVII



.5
.4
.3
.2
.1
0
e
0
1
2
3
4
5
6
7
8
τ
Kc1, K2 CONSTANT
Zẇ'/m' = - 2.0
Ks' = 0.2
Ks' = 0.3
Ks' = 0.4
Ũ = 5.0

FIG. XXVIII

APPENDIX C

BIBLIOGRAPHY

1. "Nomenclature for Treating the Motion of a Submerged Body Through a Fluid," The Society of Naval Architects and Marine Engineers, Technical and Research Bulletin No. 1-5 (Apr. 1950).
2. Hoyt, E. D. and Imlay, F. H., "The Influence of Metacentric Stability on the Dynamic Longitudinal Stability of a Submarine", Taylor Model Basin Report C - 158 (Unclassified)
3. Segalin, V. G., "An Analytical Formulation of the Synthesis Problem of Corrective Devices in Linear Servosystems," Automation and Remote Control (USSR), vol. XIX, No. 2, Feb. 1958.
4. J. G. Truxal, "Automatic Feedback Control System Synthesis", McGraw-Hill Book Company, Inc., 1955.
5. Thornbury, J. W. and Kauffman, H. A., "Automatic Depth Control for Submarines", MIT: M. S. Thesis 1949 (Declassified)
6. Williamson, R. R. and Peters, B. H., "Trajectory Analysis of the Relationship of Stability to Maneuverability in the Manual Control of Submarines", Report No. 389, Experimental Towing Tank, Stevens Institute of Technology, 1949. (Declassified)
7. "Final Report Ship Control Information Study (SUBIC)", Report No. IM - 1306 - V - 2, Cornell Aeronautical Laboratory Inc. (1959).
8. "SUBIC Progress Broshure, 1 October 1960", Electric Boat Co.
9. Pode, L. and Church, J. W., "A Representation of the Submerged Dynamic Behavior of Submarines Proposed for the Special Devices Center Submarine Simulator", DTMB Report C -661 (CONFIDENTIAL)

10. Pode, L. and Church, J. W., "A Study of the Effects of Stability and Control Parameters on the Performance and Stability of Submarines in Pitching Motion", DTMB Report C -626 (CONFIDENTIAL)

11. Centner, R. M., "Manual Depth Control of the AGSS 569 Submarine", MIT; M. S. Thesis 1957 (CONFIDENTIAL)

12. Landweber, L. and Johnson, J. L., "Prediction of Dynamic Stability Derivatives of an Elongated Body of Revolution", DTMB Report C - 359, 1951. (CONFIDENTIAL)

13. Westbrook, C. B. and McRues, D. T., "Handling Qualities and Pilot Dynamics", Aero/Space Engineering vol. 18, No. 5, May 1959.

14. Chestnut, H. and Mayer, R. W., "Servo Mechanisms and Regulating System Design", Vol. I, John Wiley and Sons, New York (1957).

15. "Stability and Control Data for Current Submarine Design", David Taylor Model Basin Miscellaneous Report 105 (1949) (CONFIDENTIAL)

16. Preston, J. S. "Non-linear Control of a Saturating Third Order Servomechanism", MIT; M. S. Thesis 1954.

17. Davis, M. C., "Models, States, and Dimensions in Random Processes", MIT; Sc. D. Thesis 1961.

thesW6254
An adaptive depth control system for hig
3 2768 001 90107 7
DUDLEY KNOX LIBRARY