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THE DYNAMICS OF SPIN STABILIZED SPACECRAFT WITH MOVABLE APPENDAGES - PART II

by

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I. SUMMARY OF RESULTS ACCOMPLISHED DURING PERIOD - MAY 16, 1975 - NOVEMBER 15, 1975

A. Analytical Results

The basic two year study plan is shown in TABLE I. The items indicated by asterisks were proposed for study in the second (present) year. The items indicated by a check mark have been completed during the six month reporting period. Two basic types of movable appendages have been considered throughout the study 1) a hinged type of fixed length whose orientation relative to the main part can change and 2) a telescoping type of varying length which is further subdivided into (a) the case where a large end mass is mounted at the end of an assumed massless boom and (b) where the appendage consists of a uniformly distributed homogeneous mass throughout its length (Fig. 1).

The equations of motion for the hinged system as previously developed have been linearized about the nominal equilibrium position where the booms are orthogonal to the nominal spin axis for the case of two dimensional motion (as simulated by Lang and Honeycutt[1*]) and three dimensional motion. Analytic stability criteria are developed from the necessary condition on the sign of all the coefficients in the system characteristic equation.

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*Please refer to references listed after Table I.

It is seen that, for the general case, for stability some form of active damping must be present and that for limiting cases where the spin axis is an axis of symmetry, certain inequalities relating the hinge point offset coordinates to the moment of inertia ratio must be satisfied. For this same case it is seen that the system characteristic equation separates into two factors - a second order factor describing a mode where both hinged members move in phase as a unit, and the second factor represented by a more complex fourth order polynomial.

To date viscous damping at both hinge points has been included in the mathematical model. Rate damping about the transverse axes will be included since the numerical results indicate that the coupling with only hinge damping present does not result in favorable nutation decay time constants.

Equations of motion have been developed for the telescoping system where: (1) a single boom is linearly offset from the nominal spin axis and (2) two booms are linearly offset from the hub principal axes - one boom from the spin axis and the second from one of the transverse axes. For the latter case, the two booms move at right angles to one another. (Figs. 2a, 2b) These equations of motion have been linearized about two desired equilibrium states: (a) a final spin rate about the nominal spin axis only and (b) a state of zero inertial angular velocity. It is concluded that three-axis control with a single offset boom can not be achieved and that boom offset is required for any control of the linear system.

For a special case of a single boom offset from the hub axis of mass symmetry, it is seen that the optimal control theory for the linear system using a quadratic performance index with unspecified final time can be examined analytically. For such a system the matrix Riccati equation can be solved in closed form and the control law gains obtained without the use of a computer. For this application (involving two axis control) the integrand in the cost functional is assumed to be a weighted function of the transverse angular velocity plus the control.

The problem of optimal control with a minimum time criterion has been examined analytically for the special case of a single offset boom where it is assumed that the initial conditions are such that the system can be driven to the equilibrium (rest) state with only a single switching maneuver in the bang-bang optimal sequence. For this system it is possible to obtain an analytical solution for the switching and final times in terms of the initial conditions and magnitude of the maximum value of the control force.

B. Numerical Results

The nonlinear equations of motion describing the deployment of the hinged system have been programmed for numerical integration using the NOVA computer at Howard University. A few typical results are illustrated in Figs. 3-6. Figs. 3(a) and 3(b) simulate the dynamic response of the system to an initial perturbation in the hinge angles of 0.1 radians with hinge damping absent and then, present, respectively.

For the damped case a damping coefficient of 0.1 lb/ft/sec is selected. The deployment of the system from the position where the hinged members are initially parallel to the local vertical (α=0) is simulated in Fig. 4(a) without damping, and Fig. 4(b) with damping. The 'x' represents the maximum time simulated by Lang and Honeycutt. It is seen that without damping the hinged members exhibit a flapping-type motion as momentum is exchanged between the hinge and spin motions. With the damping coefficient selected the system can be fully deployed in about 10 seconds. An example of the three dimensional hinge-system dynamics is simulated in Fig. 5 (undamped) and 6 (with damping). Initial perturbations in both hinge angles and one of the transverse angular velocities are assumed. Although the hinge damping is effective in reducing the amplitudes of the hinge motion, the time constants associated with the nutation angle decay (Fig. 6(b)) are extremely long. It is clear that an additional form of nutation damping must be added for effective removal of excess transverse rates.

An illustrative numerical example, using the single offset boom as a wobble damper with the gains in the control based on the linear optimal control theory is shown in Fig. 7. The dotted curve shows the response of the nutation angle for such a system where the physical parameters, moments of inertias, masses and offset length are identical to the single control mass system previously analyzed by Edwards and Kaplan.[6,7]

In their application a control law is selected such that the average rate of change of excess rotational kinetic energy is less than zero for each cycle. Using the same value of maximum amplitude (i.e. maximum boom length) it is seen that the nutation decay time constant can be improved by about an order of magnitude by using a control law based on linear optimal control theory.

II. PRESENTATION AND PUBLICATION OF RESULTS

On November 6, 1975 an oral presentation was given at NASA-Langley to Mr. C. W. Martz, the Technical Monitor, Dr. W. Anderson, Head, Stability and Control Branch of the Flight Dynamics and Control Division, and to 6 other members of the Stability and Control Branch. Prior to this date Mr. Martz had been contacted several times by telephone to inform him of the progress. Copies of all visual aids used in the presentation (about 50 in total) were left at Langley. It is anticipated that another presentation will be given during the period December 1975 - January 1976 at which time a draft copy of a follow-on proposal could also be discussed.

During the six month reporting period two papers based on last year's work were accepted:

(1) "Spacecraft Detumbling Using Movable Telescoping Appendages," Peter M. Bainum and R. Sellappan, XXVI th International Astronautical Congress, Lisbon, September 21-27, 1975, Paper No. 75-113.

(2) "Dynamics of Spin Stabilized Spacecraft During Deployment of Telescoping Appendages," by R. Sellappan and Peter M. Bainum, to be presented at the AIAA - 14th Aerospace Sciences Meeting, Washington, D.C., Jan. 26-28, 1976, Paper No. 76-185.

In addition a paper based on a NASA-Grant during the 1973-74 period has been published: "Three Dimensional Motion and Stability of Two Rotating Cable - Connected Bodies," by P.M. Bainum and K.S. Evans, Journal of Spacecraft and Rockets, Vol. 12, No. 4, April 1975, pp. 242-250.

III. PLANS FOR THE NEXT REPORTING PERIOD

Additional numerical simulations of the hinged system during deployment and in response to small perturbations will be made with both hinge damping and nutation damping present, and the results compared with the simulated response with only hinge damping. In the optimal control area, for the more general case of an asymmetrical main hub and one or two offset booms, the matrix Riccati equation will be solved numerically to obtain the control law gains. The dynamics of this system will be simulated numerically using the optimal control law. A comparison in system performance both in a linear and nonlinear region will be made with our previous results where the booms were assumed to extend only along the hub principal axes. Where possible, for the single boom offset case, a comparison will be made with the previous results obtained by Edwards and Kaplan.

It is planned to prepare at least one technical paper based on this research for open publication and/or presentation at a professional society meeting during the next six months. Close liason with NASA - Langley will be maintained. A comprehensive final report will be prepared at the end of the contractual period and a final oral presentation made.

IV. POSSIBLE EXTENSION OF THE CURRENT RESEARCH

Referring to TABLE 1, it is hoped to complete all the items related to the hinged system during the next six months.

Because of the success we have had with the application of linear control theory and the need to use the computer both for the solution of the matrix Riccati equation and the simulation of the optimally controlled telscoping system, it is doubtful that much progress can be made with the application of dynamic programing to consider the general problem of time optimal control. This is an item which could be considered in depth during a subsequent one year period. For all simulations involving optimal control laws it is assumed that such a law can be implemented with no time lag and no errors in measuring the state vector components - i.e. angular velocity components and boom lengths. The present work could be extended to include such an estimator problem incorporating the actual expected measurement errors and time lags in obtaining such measurements.

To date all of our results have been obtained by neglecting any and all external perturbations (i.e. in torque - free space). As a tumbling spacecraft is recovered by appropriate maneuvers of the appendages such effects as those due to gravity-gradient torques and solar pressure must be considered. It is hoped to briefly examine the maximum expected magnitudes of these perturbations during the next six months. A more thorough treatment of these two types of perturbations could easily occupy a second graduate student for a one year period if suitable funding were available. And finally the problem of including flexibility effects during deployment of the telescoping appendages, (to the knowledge of the authors) has never been fully treated in the open literature.

This problem is made extremely difficult by the fact that the length of the appendage in its undeformed state is being continually altered according to the particular control law being used.

TABLE I - TWO YEAR PLAN OF STUDY

THE DYNAMICS OF SPIN STABILIZED SPACECRAFT WITH MOVABLE APPENDAGES

CONTENTS

A. MOTION DURING DEPLOYMENT

Spinning spacecraft - small transverse momentum

✓ 1. Hinged Type
- development of equations of motion and stability analysis

2. Telescopic Type

a. End mass moving b. Uniformly distributed mass moving

- Analytical solution for spherical Hub

- Series solution for non-spherical Hub

✓ *3. Effect of Dampers

B. USE OF APPENDAGES TO DETUMBLE SPACECRAFT

1. Telescopic Type
- derivation of kinetic energy

a. Achieve zero inertial angular rate

- Lyapunov Function - Kinetic Energy

b. Achieve spin about principal axis

- Lyapunov function - Modified kinetic energy

✓ *2. Telescoping appendages offset from hub principal axes

3. Appendages + "3" axis boom

C. OPTIMAL CONTROL

✓ *1. Application of linear optimal control theory using different performance indices

*2. Use of gradient technique

D. EFFECT OF PETURBATIONS

*1. Gravity-gradient

*2. Solar pressure

*3. Flexibility with small amplitude

*Proposed for study in second year (Part II)

HINGED SYSTEM

1. Derivation of Kinetic Energy
2. Development of Equations of Motion
3. Two Dimensional Motion Analysis
    a. Small Angle Analysis about Equilibrium State
        (i) Linearization of Equations of Motion
        (ii) Stability Criteria
        (iii) Closed Form Solutions
        (iv) Numerical Results
    b. Large Angle Analysis
        (i) Closed Form Solutions
        (ii) Numerical Results
4. Three Dimensional Motion Analysis
    a. Small Angle Analysis about Equilibrium State
        (i) Linearization of Equations of Motion
        (ii) Stability Criteria
        (iii) Numerical Results
    b. Large Angle Analysis
        (i) Numerical Results

OPTIMAL CONTROL

A. <u>Optimal Control With Quadratic Performance Criterion</u>

I. Theory

II. Applications

1. <u>Single Boom Offset System</u>

   a. Equations of Motion
   b. Linearization
   c. Special case
      (i) Analytical Solution
      (ii) Numerical Results
         - Illustrative Example
   d. General Case
      (i) Numerical Results

2. <u>Two Boom Offset System</u>

   a. Development of Equations of Motion
   b. Linearization
   c. Numerical Results

B. <u>Optimal Control With Minimum Time Criterion</u>

I. Theory

II. Applications

1. <u>Single Boom Offset System</u>

   a. Special Case
      (i) Analytical Solution
      (ii) Numerical Results
   b. General Case
      (i) Numerical Results

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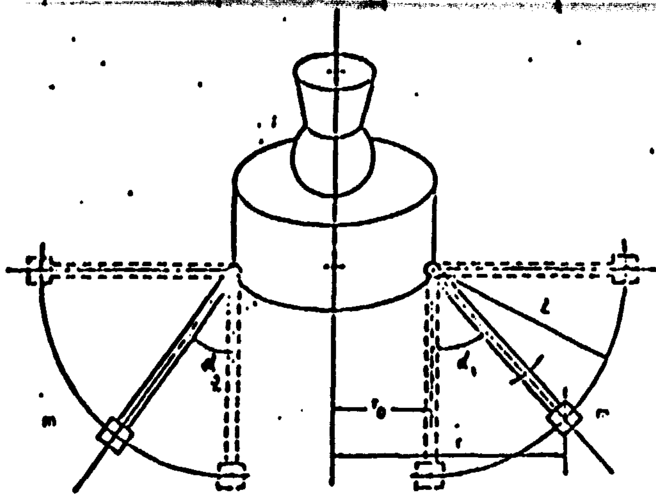
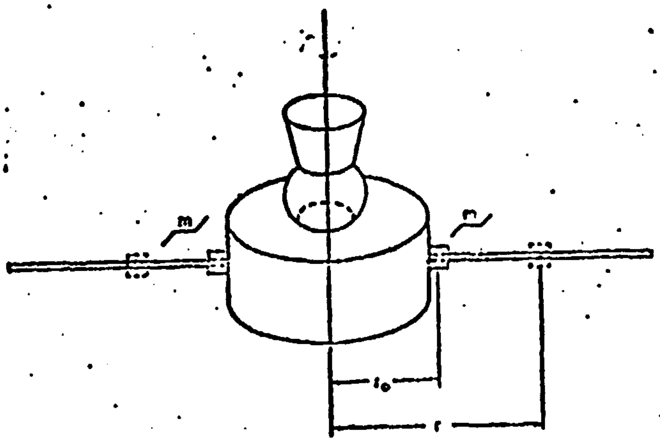
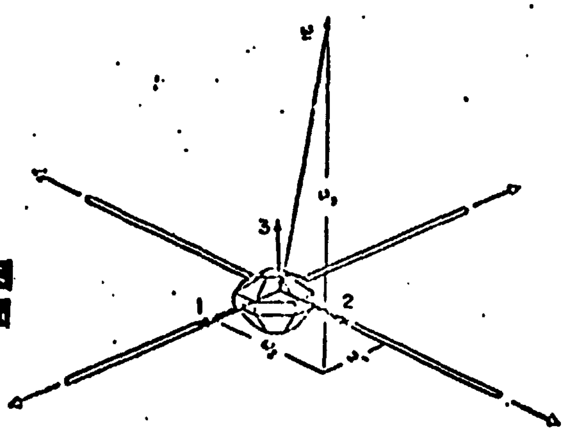


Hinged deployment system



Radially telescoping deployment system - type a



Spinning satellite with booms extending - type b

Fig. 1 Different Types of Movable Appendages

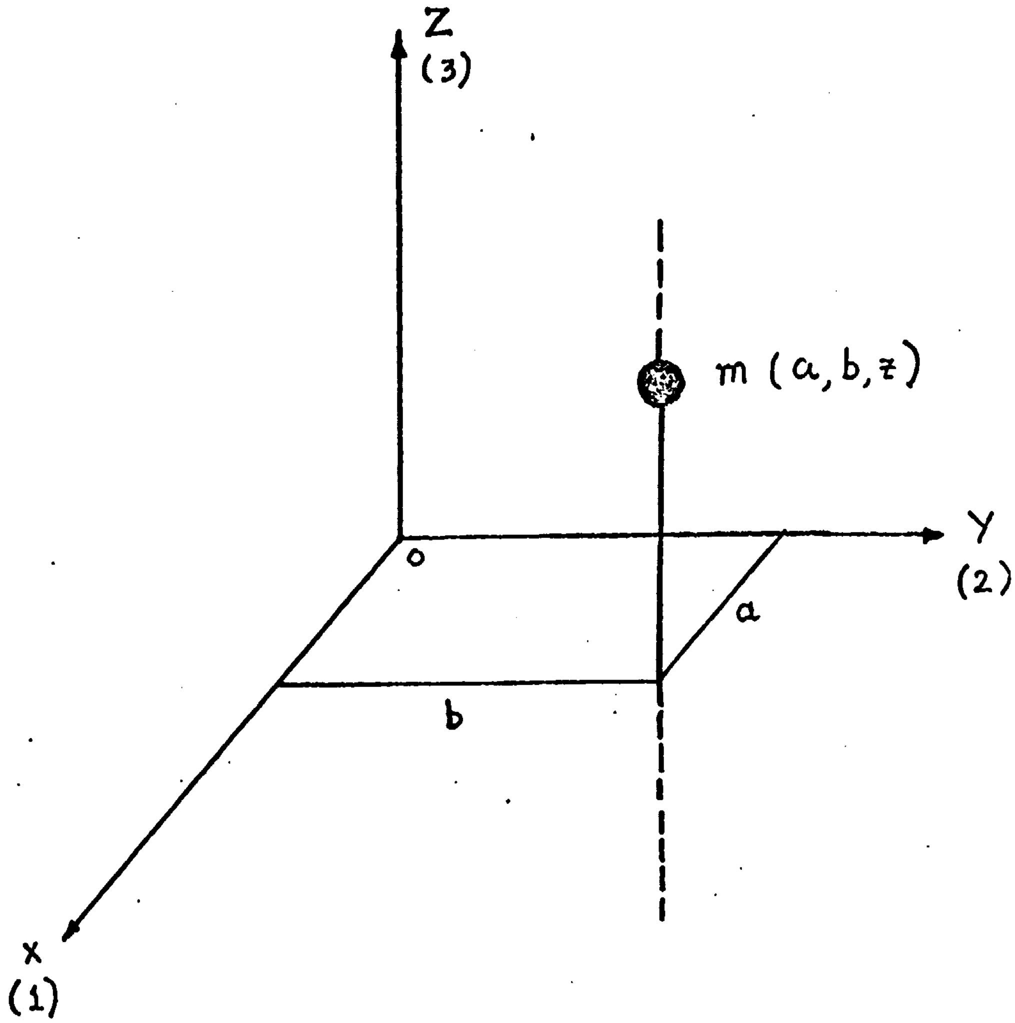


FIG. 2(a) SINGLE BOOM OFFSET SYSTEM

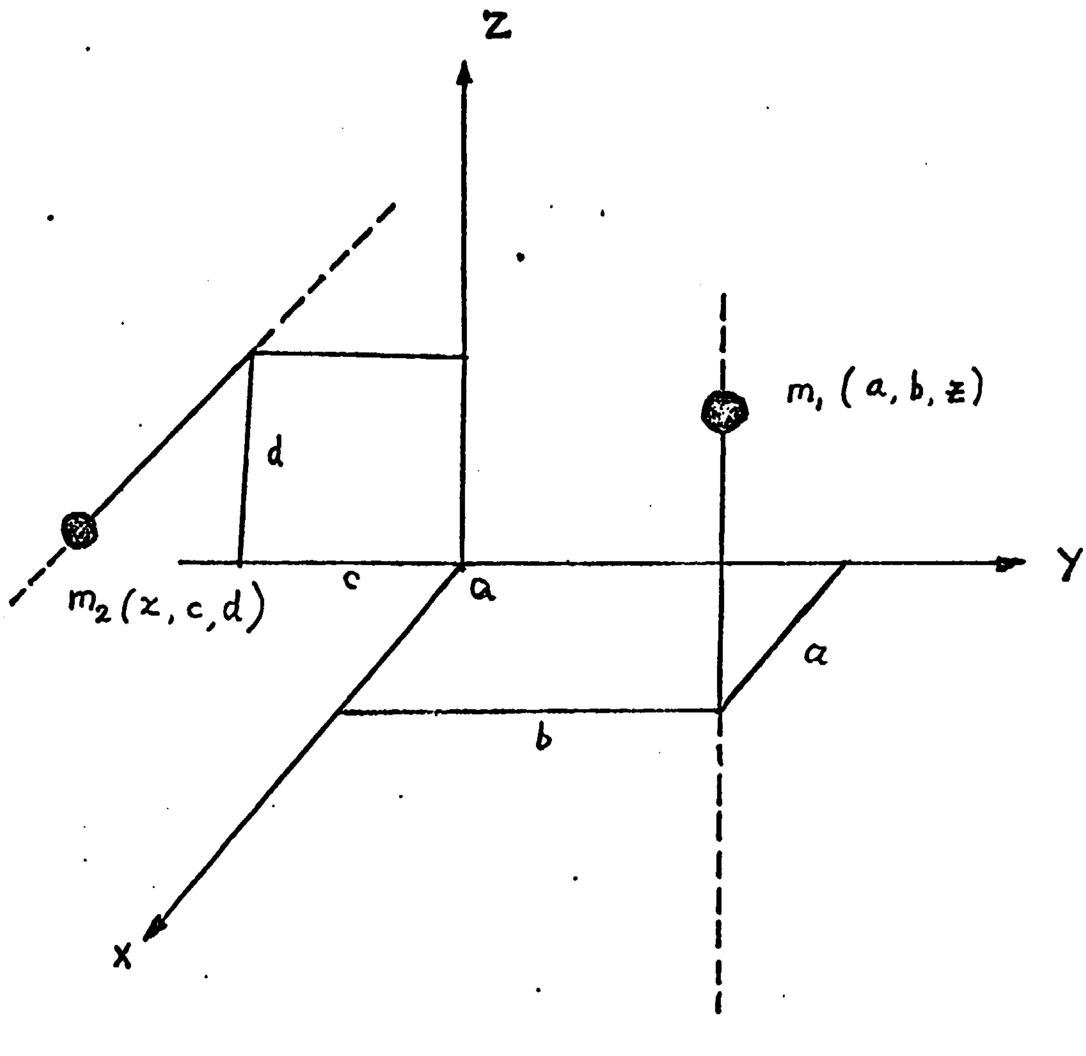


FIG. 2(b) Special Case of Two Boom Offset Orientation System

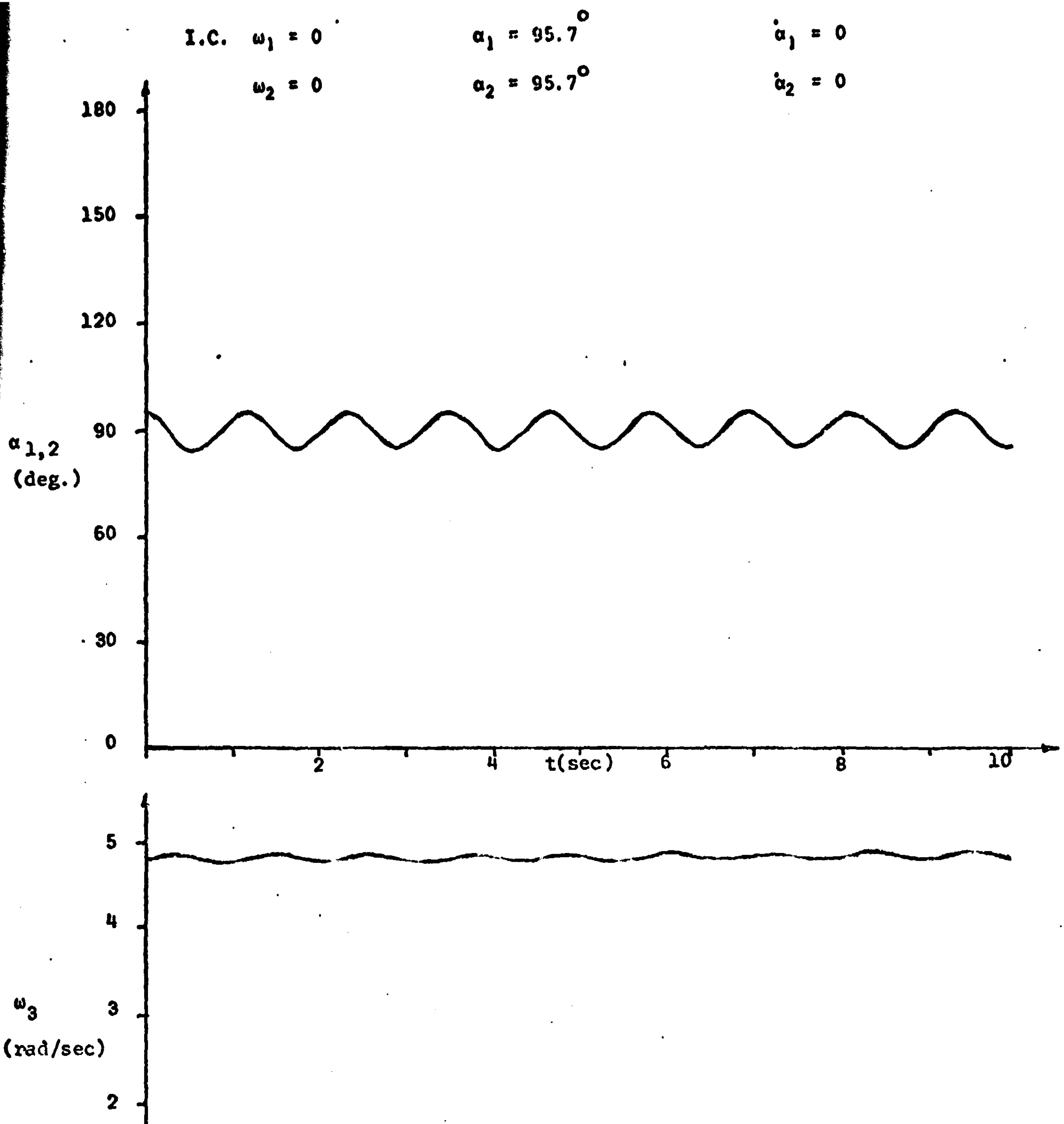


FIG. 3(a) DYNAMICS OF THE SYSTEM ABOUT 90° EQUILIBRIUM POSITION (NO DAMPING).

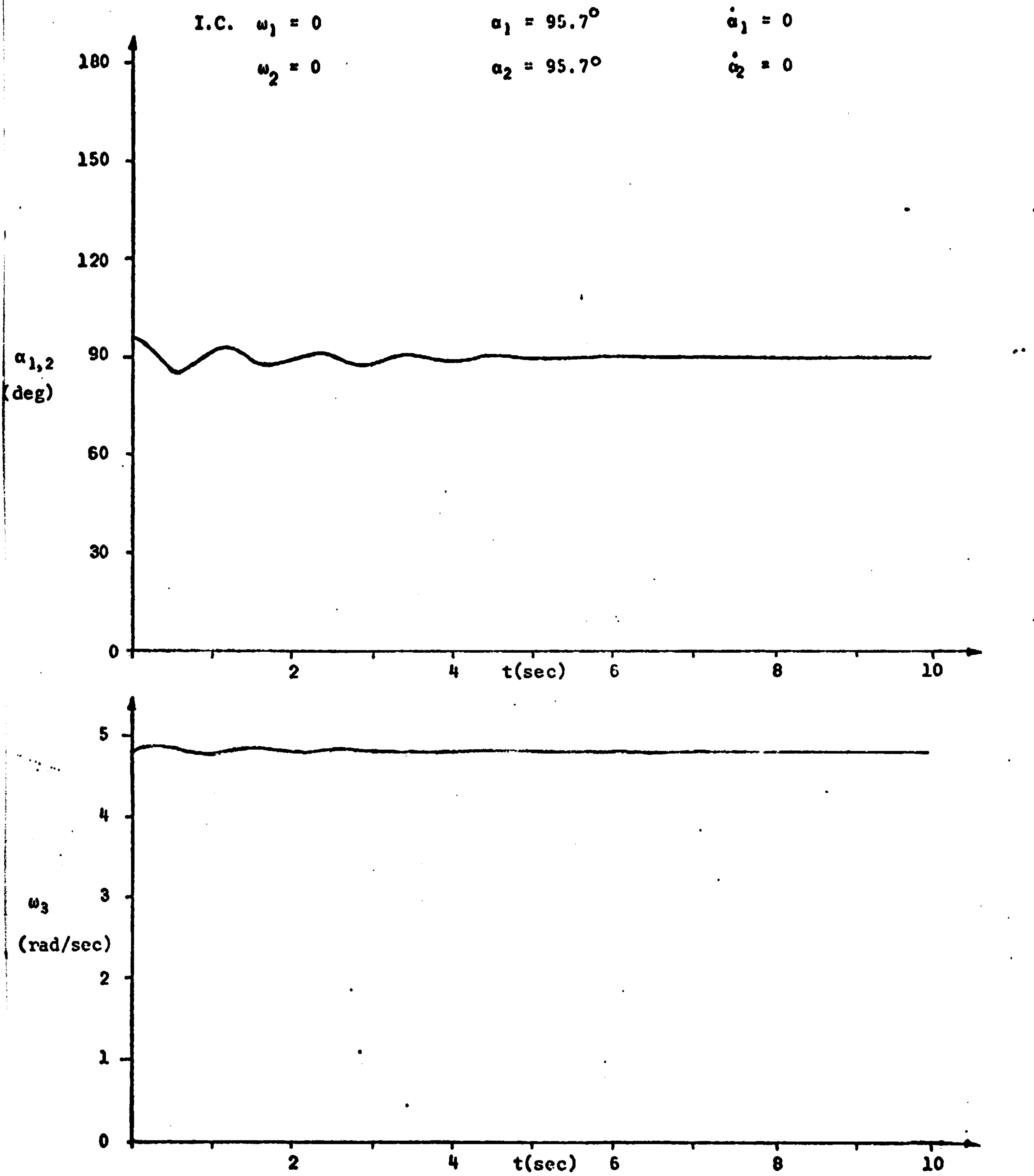


FIG. 3(b) DYNAMICS OF THE SYSTEM ABOUT 90° EQUILIBRIUM POSITION WITH DAMPING.

$\omega_1 = 0$ $\alpha_1 = 0$ $\dot{\alpha}_1 = 0$

$\dot{\omega}_2 = 0$ $\alpha_2 = 0$ $\dot{\alpha}_2 = 0$

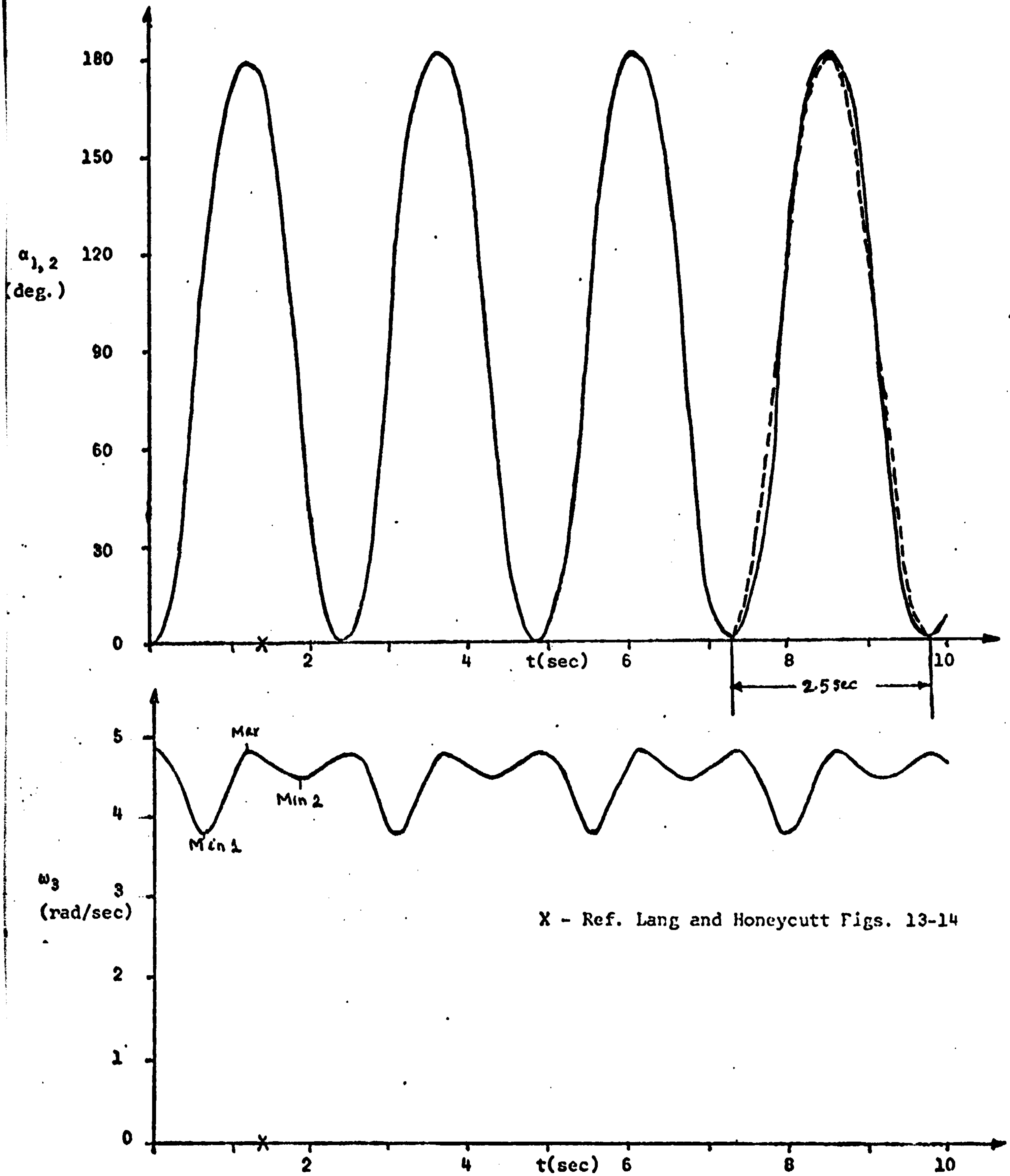


FIG. 4(a) DEPLOYMENT DYNAMICS OF THE SYSTEM (ZERO I-CS).

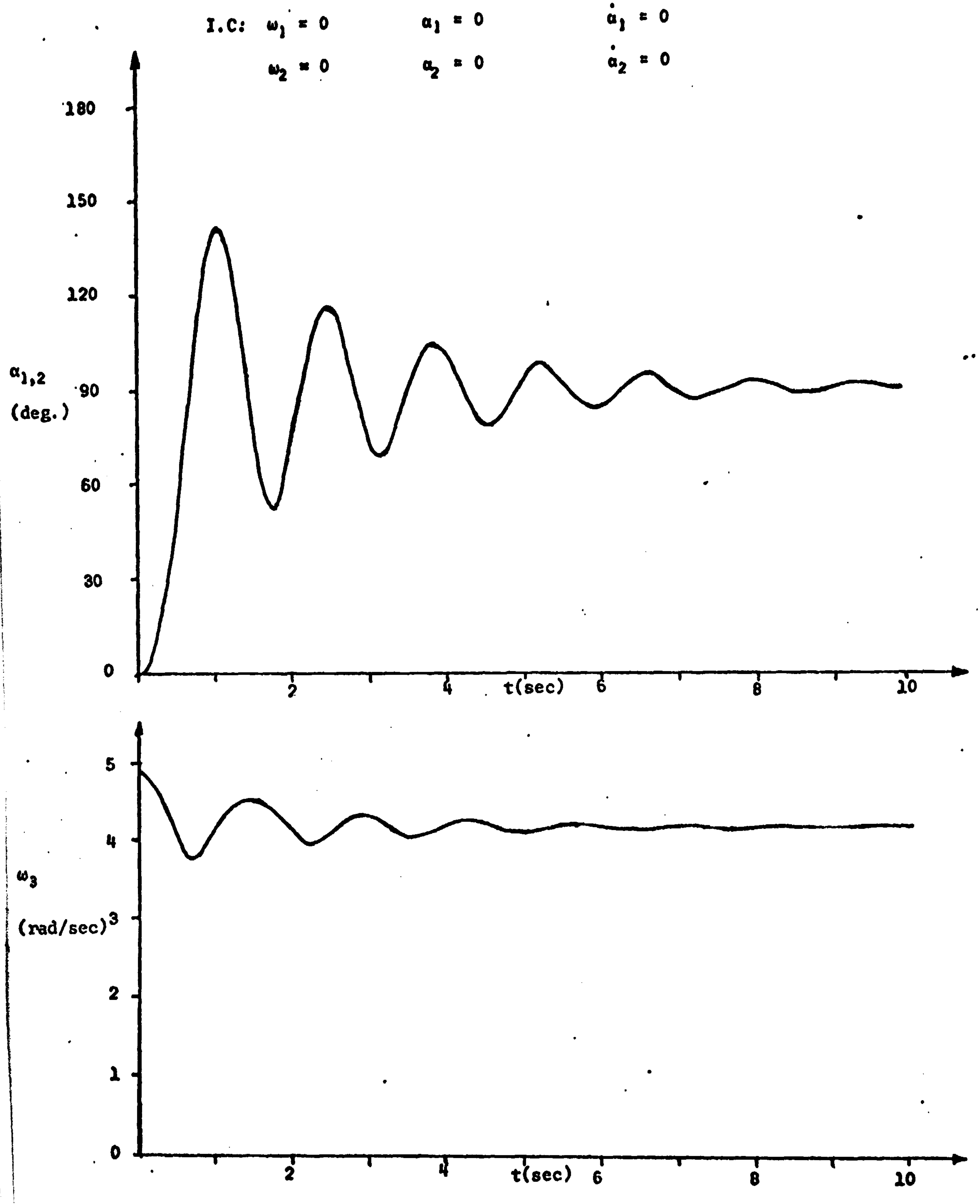


FIG. 4(b) DEPLOYMENT DYNAMICS OF THE SYSTEM WITH DAMPING (ZERO I-CS).

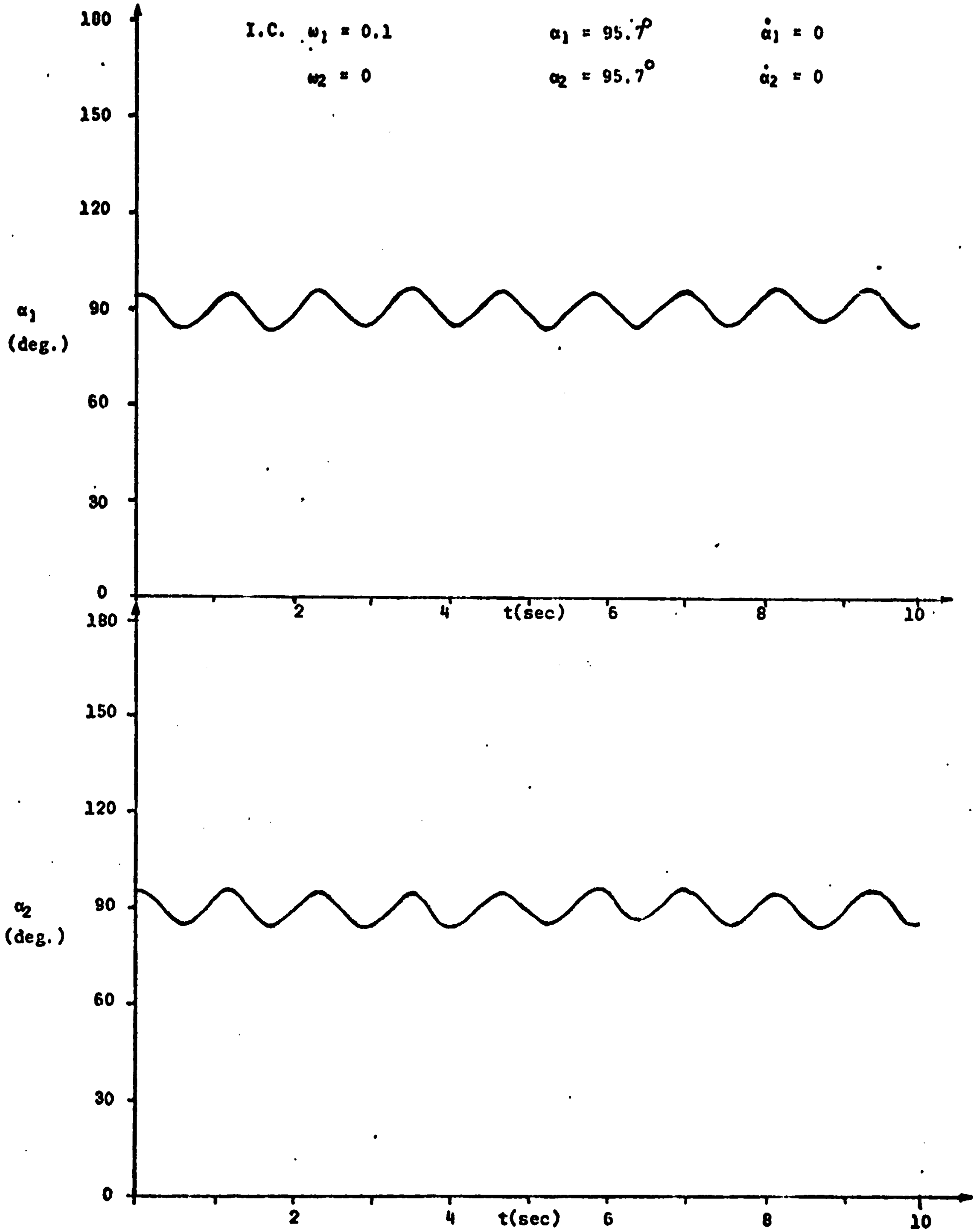


FIG. 5(a) TIME RESPONSE OF HINGE ANGLES (ABOUT 90° EQUILIBRIUM STATE) WITH INITIAL TRANSVERSE RATE (NO DAMPING).

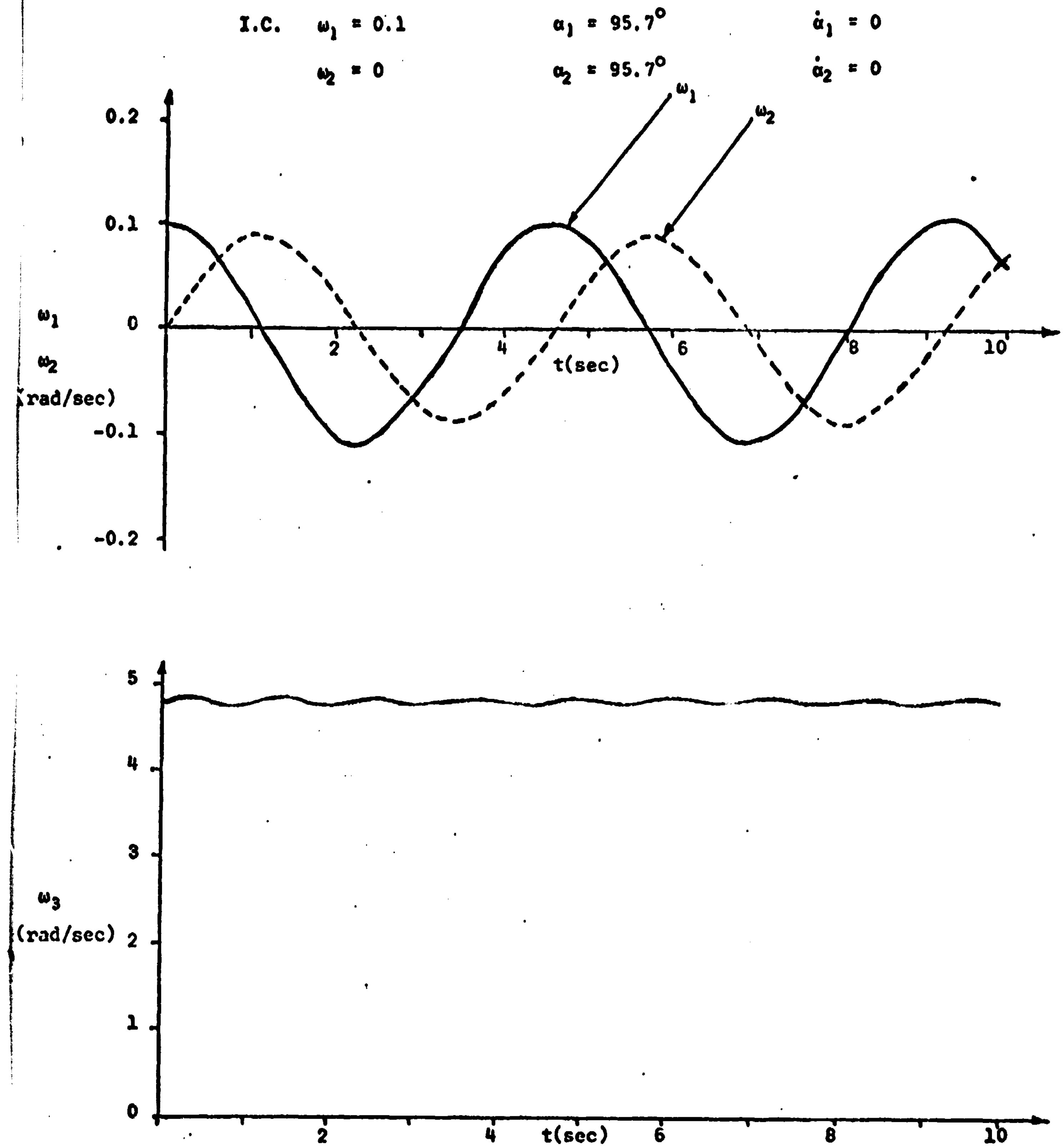


FIG. 5 (b) TIME RESPONSE OF ANGULAR RATES (ABOUT 90° EQUILIBRIUM STATE) WITH INITIAL TRANSVERSE RATE (NO DAMPING).

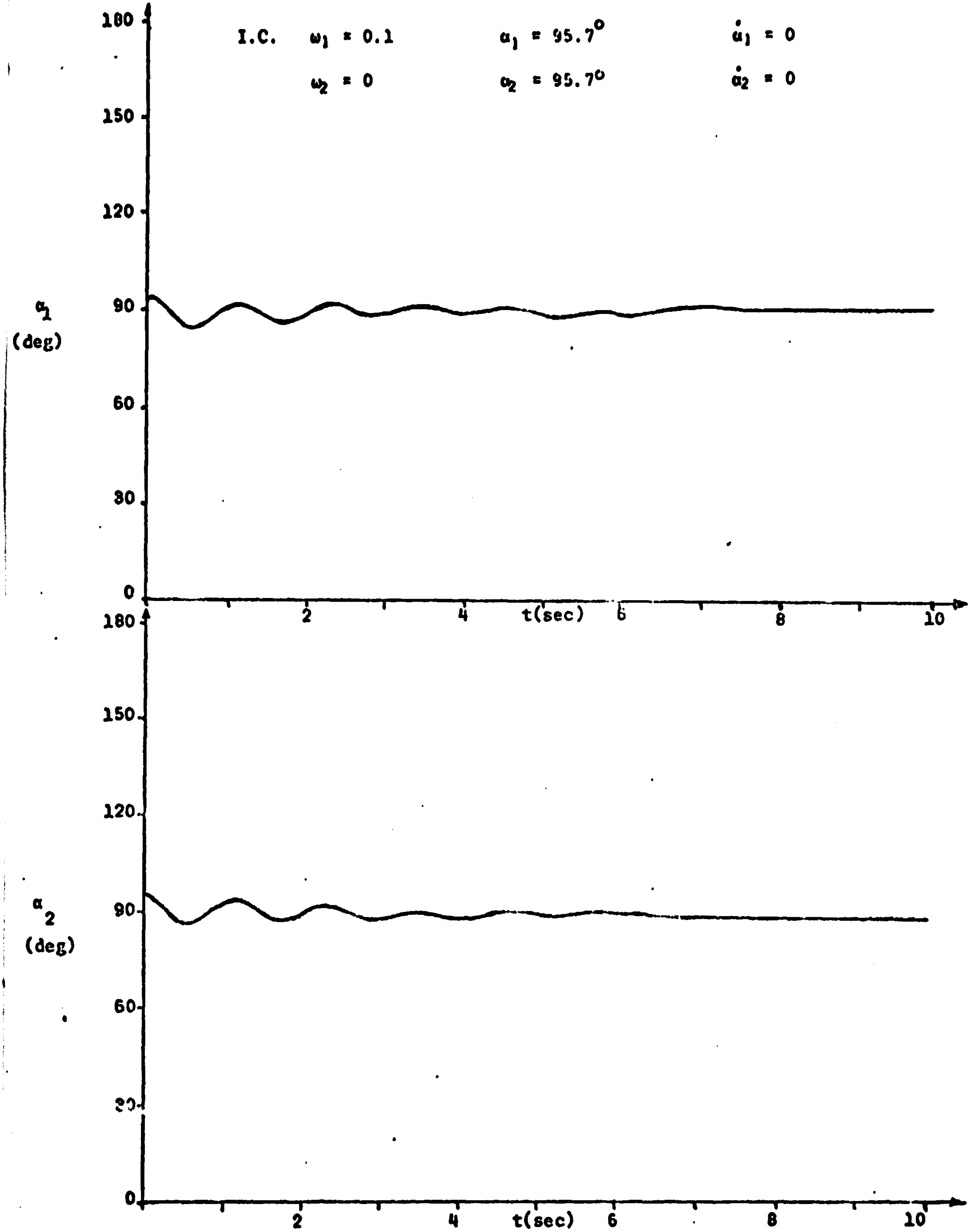


FIG. 6(a) TIME RESPONSE OF HINGE ANGLES - SAME AS IN FIG. 5 (a) - WHEN DAMPING IS PRESENT.

I.C. $\omega_1 = 0.1$ $\qquad \alpha_1 = 95.7^\circ$ $\qquad \dot{\alpha}_1 = 0$

$\omega_2 = 0$ $\qquad \alpha_2 = 95.7^\circ$ $\qquad \dot{\alpha}_2 = 0$

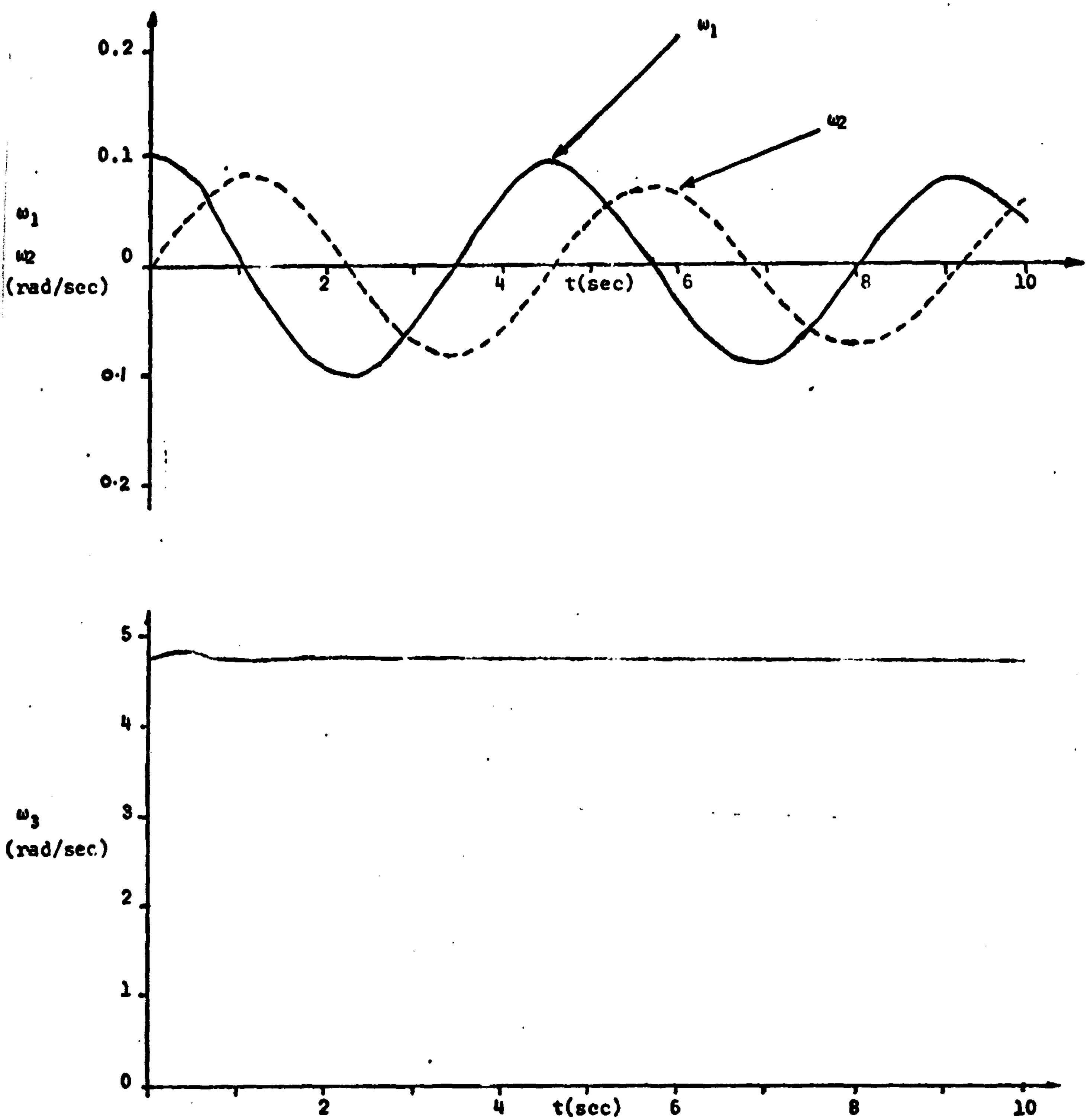


FIG. 6(b) TIME RESPONSE OF ANGULAR RATES - SAME AS IN FIG. 5 (b)- WHEN DAMPING IS PRESENT.

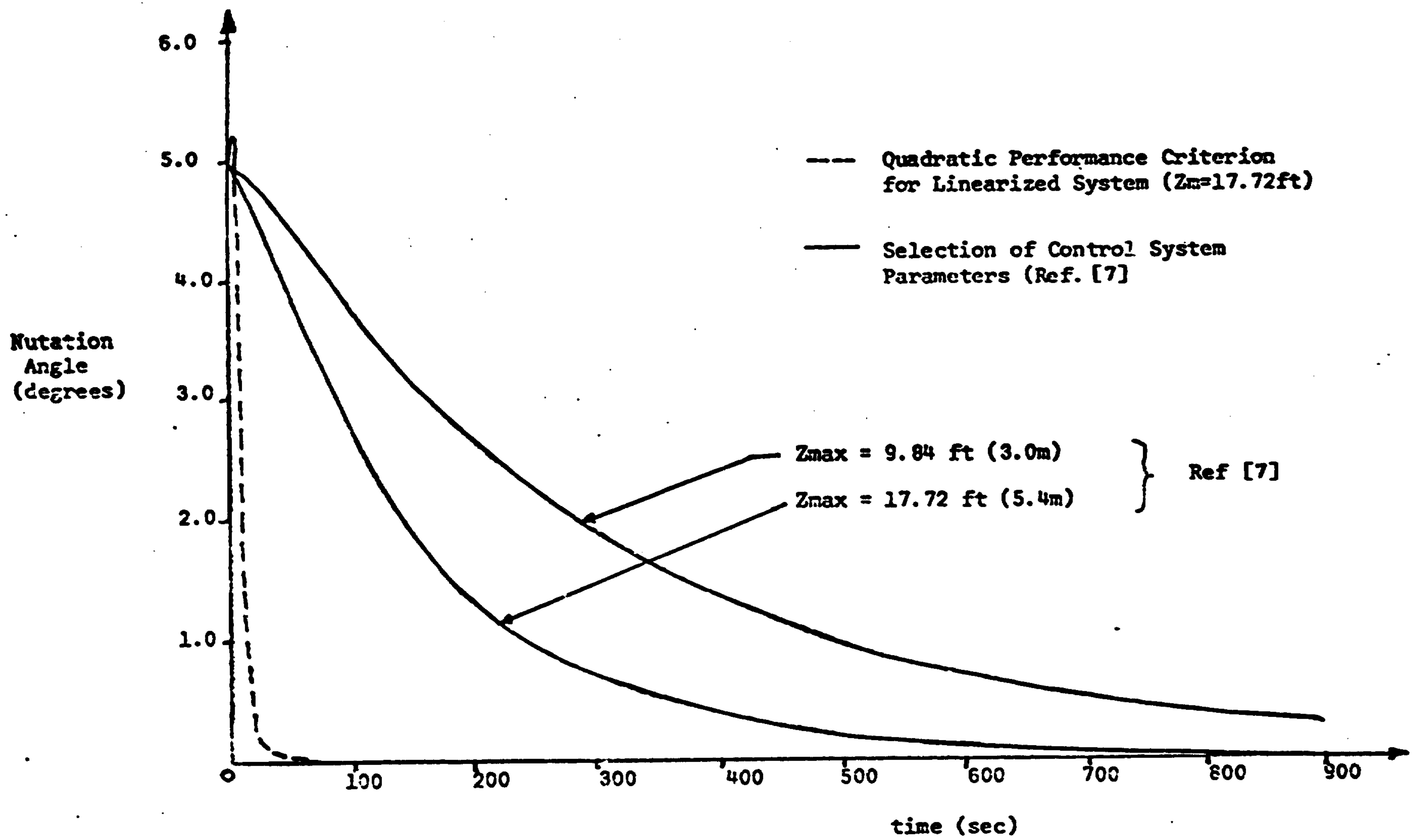


FIG. 7 Decay of Nutation Angle With Different Control Laws.