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MEMORANDUM REPORT M66-12-1

MATHEMATICAL SIMULATION
OF
HELICOPTER EMERGENCY EGRESS TRAJECTORIES

by

LEONARD A. DeSTEFANO

November 1965

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UNITED STATES ARMY
FRANKFORD ARSENAL
PHILADELPHIA, PA.

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Propellant Actuated Devices Division
Components Engineering Directorate
FRANKFORD ARSENAL
Philadelphia, Pa. 19137

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ABSTRACT

The basic equations of motion for a point mass under the influence of gravity, aerodynamic drag, and rocket forces are used to simulate a three-dimensional, three-degree of freedom, helicopter emergency egress trajectory. The resulting equations of motion were solved by a fourth order Runge Kutta method, programmed in Fortran for the Univac Solid State 90 digital computer.

Included in this report is the computer program which was used to obtain a numerical solution to the equations of motion, the solution to three test cases, and a comparison with an experimental trajectory.

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INTRODUCTION

Operational experience with Army helicopters reveals many instances where in-flight hazards to crew personnel may be effectively resolved, with a resultant increase in flight safety, through the use of an emergency escape system.

In this report, the basic equations of motion for a point mass under the influence of gravity, aerodynamic drag, and rocket forces are used to simulate a three-dimensional, three-degree of freedom, helicopter emergency egress trajectory. The resulting equations of motion were solved by a fourth order Runge Kutta method, programmed in Fortran for the Univac Solid State 90 digital computer. The computer program which was used to obtain a numerical solution to the equations of motion is presented in Appendix A.

The purpose of this report is to document the analytical capability necessary to evaluate the egress trajectories associated with such emergency escape systems.

ASSUMPTIONS

1. The seat-man combination is treated as a point mass.
2. Time, $t = 0$, begins at the end of the catapult stroke, at which time the catapult has imparted some initial velocity to the seat-man combination.
3. Aerodynamic drag is proportional to the n^{th} power of the velocity. In the test cases presented, n is 2.
4. Rocket thrust is constant in both magnitude and direction throughout the burn time.
5. The helicopter pitch angle is zero at the time of ejection.
6. Parachute forces are omitted.

DISCUSSION

The helicopter emergency egress trajectory analyzed in this report is accomplished initially by a catapult (which ejects the seat-man laterally) and, after a suitable delay, by a rocket (which raises the escapee to a height sufficient for safe recovery by parachute). The analysis begins at the end of catapult stroke ($t = 0$), at which time the seat-man has acquired an initial velocity due to both the catapult and the velocity of the supporting vehicle. The magnitude and direction of these velocities are inputs to the program.

The trajectory can be thought of in terms of the following three stages:

1. Initial "Free" Flight Stage - The motion of the seat-man, determined by the initial conditions, continues under the influences of only gravity and drag up to time t_1 .
2. Rocket Stage - At time t_1 , a rocket force (R) becomes effective. This force, constant in time and direction, terminates at time $t_1 + t_b$. The delay between ejection ($t = 0$) and rocket initiation (t_1) allows the seat-man sufficient time to clear the rotor blades before being propelled upward. The magnitude and direction of R , t_1 , and t_b are all inputs to the program.
3. Final "Free" Flight Stage - At time $t_1 + t_b$, the seat-man continues its trajectory, influenced only by gravity and drag.

The trajectory is terminated automatically in either of two ways: (1) when ground impact is achieved, i.e., when the vertical coordinate, x_3 , first becomes negative; or (2) when a terminal time read into the computer as input data is reached; whichever occurs first.

THE COORDINATE SYSTEM

A right-handed orthogonal coordinate system (Figure 1) is employed with the mutually orthogonal axes being defined in the following manner.

The $+x_3$ axis is chosen to be in a direction antiparallel to that of the acceleration due to gravity. The roll axis of the helicopter was chosen as the x_1 axis, with the fore end of the helicopter defining the $+$ direction. The x_2 axis is then so oriented as to complete the right-handed orthogonal system. The x_1 , x_2 , and x_3 coordinate axes are referred to as x , y , and z , respectively, in the computer input/output formats.

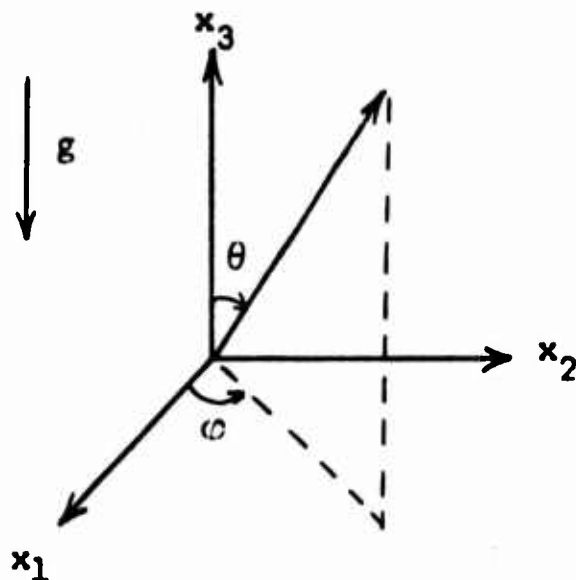


Figure 1. The Coordinate System

All directional inputs to the program are read into the computer in terms of the angles θ and ϕ (the colatitude and azimuth, respectively) referenced with respect to this space set of axes fixed at the instant of ejection.

EQUATIONS OF MOTION

Summing forces (see Appendix B for symbols used)

$$\sum_j F_i^{(j)} = m\ddot{x}_i \quad (1)^*$$

where

$$F_i^{(1)} = \begin{cases} -mg & \text{for } i = 3 \\ 0 & \text{for } i = 1, 2 \end{cases} \quad (\text{Gravity})$$

$$F_i^{(2)} = -k v^n v_i / v = -k v^{n-1} v_i \quad (\text{Drag})$$

$$F_i^{(3)} = \begin{cases} R_i & \text{for } t_1 \leq t \leq t_1 + t_b \\ 0 & \text{otherwise} \end{cases} \quad (\text{Rocket})$$

and

$$\ddot{x}_i = \dot{v}_i \quad (2)$$

$$v = (v_1^2 + v_2^2 + v_3^2)^{1/2} \quad (3)$$

*Dots represent differentiation with respect to time.

Combining Equations 1, 2, and 3 for $n = 2$,

$$m\dot{v}_i = F_i^{(2)} - k v v_i + F_i^{(3)} \quad (4)$$

METHOD OF SOLUTION

Equation 4 represents the three simultaneous differential equations:

$$\dot{v}_1 = -\frac{k}{m} v v_1 + F_1^{(3)}$$

$$\dot{v}_2 = -\frac{k}{m} v v_2 + F_2^{(3)}$$

$$\dot{v}_3 = -g - \frac{k}{m} v v_3 + F_3^{(3)}$$

These three equations, when coupled with

$$\dot{x}_1 = v_1$$

$$\dot{x}_2 = v_2$$

$$\dot{x}_3 = v_3$$

result in six first order differential equations which are integrated numerically using a fourth order Runge Kutta method to obtain the velocities and coordinates as functions of time:

$$v_i = v_i(t)$$

$$x_i = x_i(t).$$

COMPUTER INPUT FORMAT

The data input format for the computer program is listed in Table I. The input data are read into the computer on a series of 18 cards, in the order shown. The first card titles each particular trajectory simulation. This information is punched into the first portion of the card, beginning in column 1. If a title is not desired, a blank card must be substituted. The next 17 cards contain

the necessary input data. Parameter titles are punched into columns 1 through 45. Columns 47 through 90 are reserved for the numerical values of the input, column 46 containing the input sign.

An example of a suggested format is shown in the initial portion of the computer printout (Figure 2) for Test No. 1. The Fortran symbols designating the various inputs to the computer program are also listed in Table I.

TABLE I. Input Data

Test No. _____

<u>Fortran Symbols</u>	<u>Parameter</u>	<u>Unit</u>
D(1)	Initial height	ft
D(2)	Vehicle velocity	ft/sec
D(3)	Catapult velocity	ft/sec
D(4)	Rocket thrust	lb
D(5)	Vehicle colatitude, θ	degree
D(6)	Vehicle azimuth, ϕ	degree
D(7)	Catapult colatitude, θ	degree
D(8)	Catapult azimuth, ϕ	degree
D(9)	Rocket colatitude, θ	degree
D(10)	Rocket azimuth, ϕ	degree
D(11)	Rocket initiation time	sec
D(12)	Rocket burn time	sec
D(13)	Ejected mass	slugs
D(14)	Drag coefficient	lb(sec/ft) ⁿ
D(15)	Drag exponent	dimensionless
D(16)	Time increment	sec
D(17)	Terminal time	sec

Explanation of the input data follows.

D(1) - The initial height of the seat-man configuration.

D(2) - The magnitude of the helicopter velocity at $t = 0$.

D(3) - Magnitude of the velocity imparted to the seat-man by the catapult at $t = 0$.

D(4) - Rocket thrust.

D(5)} The direction of the vehicle velocity at $t = 0$ referenced with
D(6)} respect to the space set of axes.

D(7)} The direction of the catapult velocity referenced with respect
D(8)} to the space set of axes.

HELICOPTER EGRESS TRAJECTORY ANALYSIS

TEST NO. 1

INITIAL HEIGHT (FT) 5.00000
VEHICLE VELOCITY (FT/SEC) 0.00000
CATAPULT VELOCITY (FT/SEC) 60.00000
ROCKET THRUST (LBS) 3400.00000
VEHICLE COLATITUDE, THETA (DEG) 90.00000
VEHICLE AZIMUTH, PHI (DEG) 0.00000
CATAPULT COLATITUDE, THETA (DEG) 90.00000
CATAPULT AZIMUTH, PHI (DEG) 90.00000
ROCKET COLATITUDE, THETA (DEG) 36.25000
ROCKET AZIMUTH, PHI (DEG) 0.00000
ROCKET INITIATION TIME (SEC)30000
ROCKET BURN TIME (SEC)35000
EJECTED MASS (SLUGS) 9.32430
DRAG COEFFICIENT (LBS-(SEC/FT)**N)00600
DRAG EXPONENT (DIM) 2.00000
TIME INCREMENT (SEC)05000
TERMINAL TIME (SEC) 10.00000

T	X	Y	Z	VX	VY	VZ	AX	AY	AZ
0.00	0.00	0.00	5.00	.00	60.00	.00	-.00	-2.31	-32.17
.05	.00	2.99	4.95	.00	59.88	-1.60	-.00	-2.30	-32.11
.10	.00	5.98	4.83	.00	59.76	-3.20	-.00	-2.30	-32.05
.15	.00	8.97	4.63	.00	59.65	-4.81	-.00	-2.29	-31.98
.20	.00	11.95	4.35	.00	59.53	-6.40	-.00	-2.29	-31.92
.25	.00	14.92	3.99	.00	59.42	-8.00	-.00	-2.29	-31.86
.30	.00	17.89	3.55	1.79	59.31	-7.14	215.54	-2.28	262.16
.35	.35	20.85	3.52	12.56	59.19	5.95	215.11	-2.31	261.65
.40	1.25	23.81	4.15	23.30	59.07	19.01	214.61	-2.52	261.07
.45	2.69	26.76	5.42	34.02	58.94	32.05	213.96	-2.85	260.33
.50	4.65	29.70	7.35	44.70	58.78	45.05	213.12	-3.27	259.38
.55	7.15	32.64	9.93	55.33	58.61	57.99	212.07	-3.74	258.18
.60	10.19	35.57	13.15	65.90	58.41	70.86	210.81	-4.24	256.73
.65	13.74	38.48	17.01	76.41	58.18	83.65	209.34	-4.76	255.03
.70	17.65	41.38	21.27	77.88	57.94	84.14	-6.43	-4.79	-39.13
.75	21.53	44.28	25.43	77.56	57.70	82.19	-6.33	-4.71	-38.88
.80	25.40	47.16	29.49	77.24	57.47	80.25	-6.23	-4.63	-38.64
.85	29.26	50.02	33.46	76.94	57.24	78.33	-6.13	-4.56	-38.41

Figure 2. Initial Portion of Computer Printout for Test 1

- D(9) } Direction of rocket thrust referenced with respect to the
D(10) } space set of axes.
- D(11) - Rocket initiation time.
- D(12) - Rocket burn time.
- D(13) - Mass of seat-man combination.
- D(14) - Drag coefficient equal to $\rho AC_D/2$, where ρ is the air density (slugs/ft³); A, the seat area (ft²); and C_D , an aerodynamic coefficient (dimensionless) taken equal to 1.
- D(15) - Velocity exponent in the velocity dependent drag force.
- D(16) - Compute and print interval.
- D(17) - Time at which the program terminates if ground impact has not occurred.

RESULTS OF COMPUTER ANALYSIS

Approximately twelve computer tests were run; the results of three (tests 1, 5, and 6) are given in Figures 3, 4, and 5. The input for these tests is presented in Table II.

The computer simulation was compared to data from experimental trajectories.* Test 1 is such a comparison. The input values were chosen to correspond to those of the actual ejection. Figure 2 is the initial portion of the computer printout for this test. Coordinates (x, y, z) are expressed in feet; velocities (v_x , v_y , v_z), in ft/sec; and accelerations (A_x , A_y , A_z), in ft/sec². The trajectory is referenced with respect to the point of ejection. Comparison between experimental and computer results is presented in Table III.

Tests 5 and 6 were run using the same aerodynamic and rocket data, but with different initial heights and vehicle velocities.

A suitable method of graphically portraying the three-dimensional trajectory is shown in Figures 3, 4, and 5. Two graphs (A and B) determine each trajectory. The first (A) is a graph of altitude (z) vs time (t), with the various events indicated along the time axis. The second (B) is a graph of the horizontal components x vs y, again with the various events indicated. The two graphs are sufficient to determine the complete space-time trajectory.

* M. Weinstock, "Emergency Escape Systems for Army Helicopters," Aerospace Medicine, Vol 36, No. 3, March 1965.

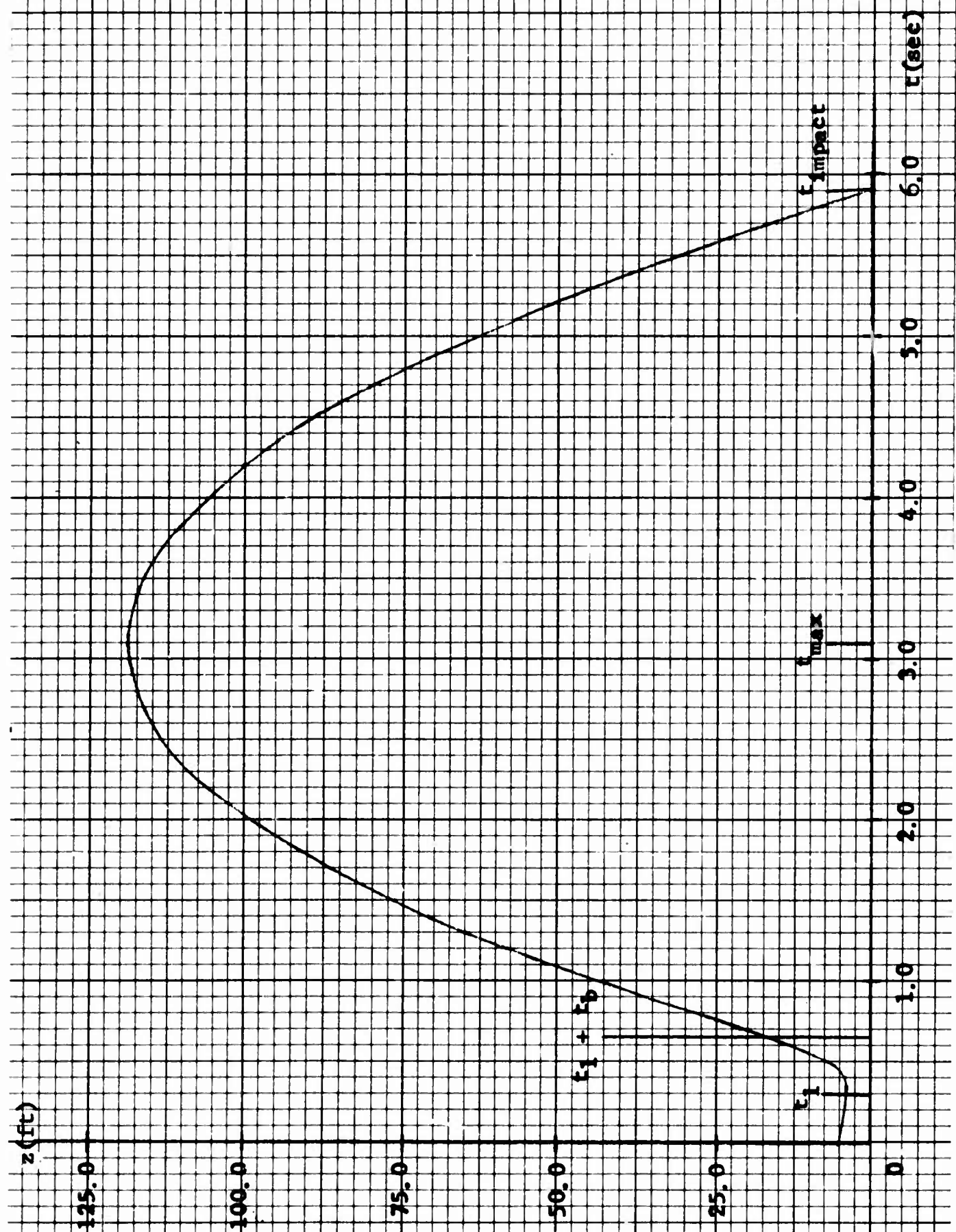


Figure 3. A - Graph of z vs t , test No. 1

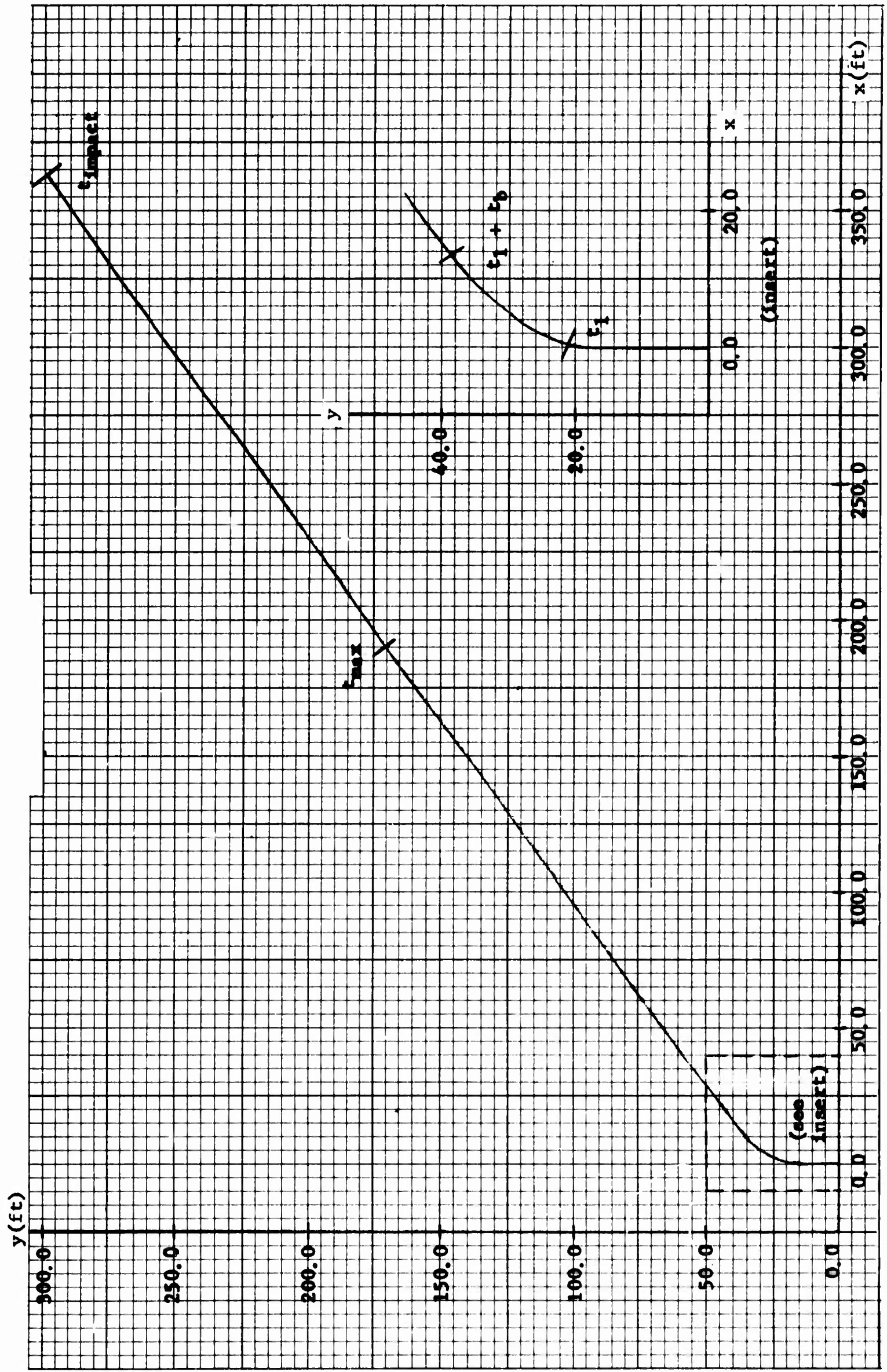


Figure 3. B - Graph of x vs y , test No. 1

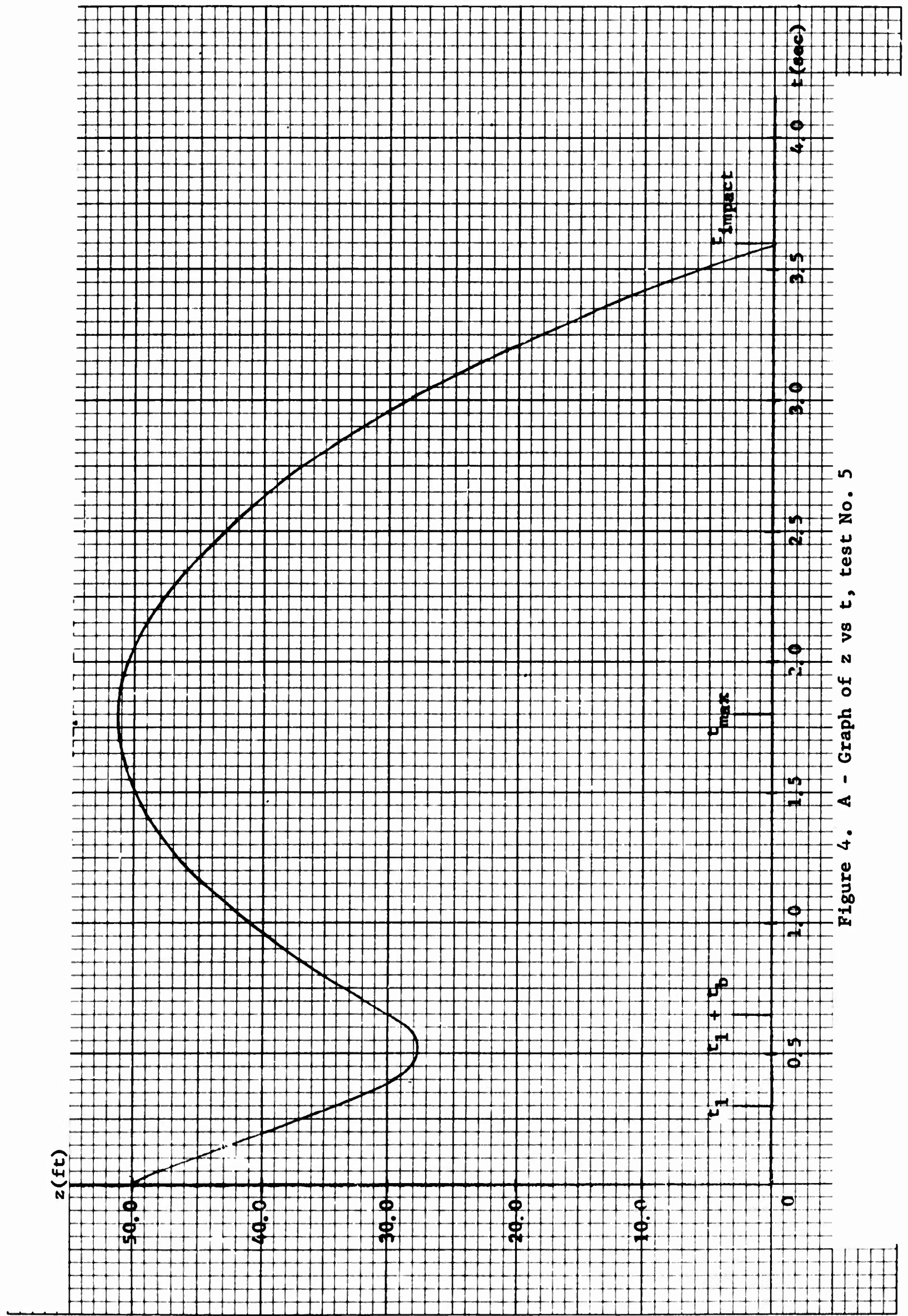


Figure 4. A - Graph of z vs t , test No. 5

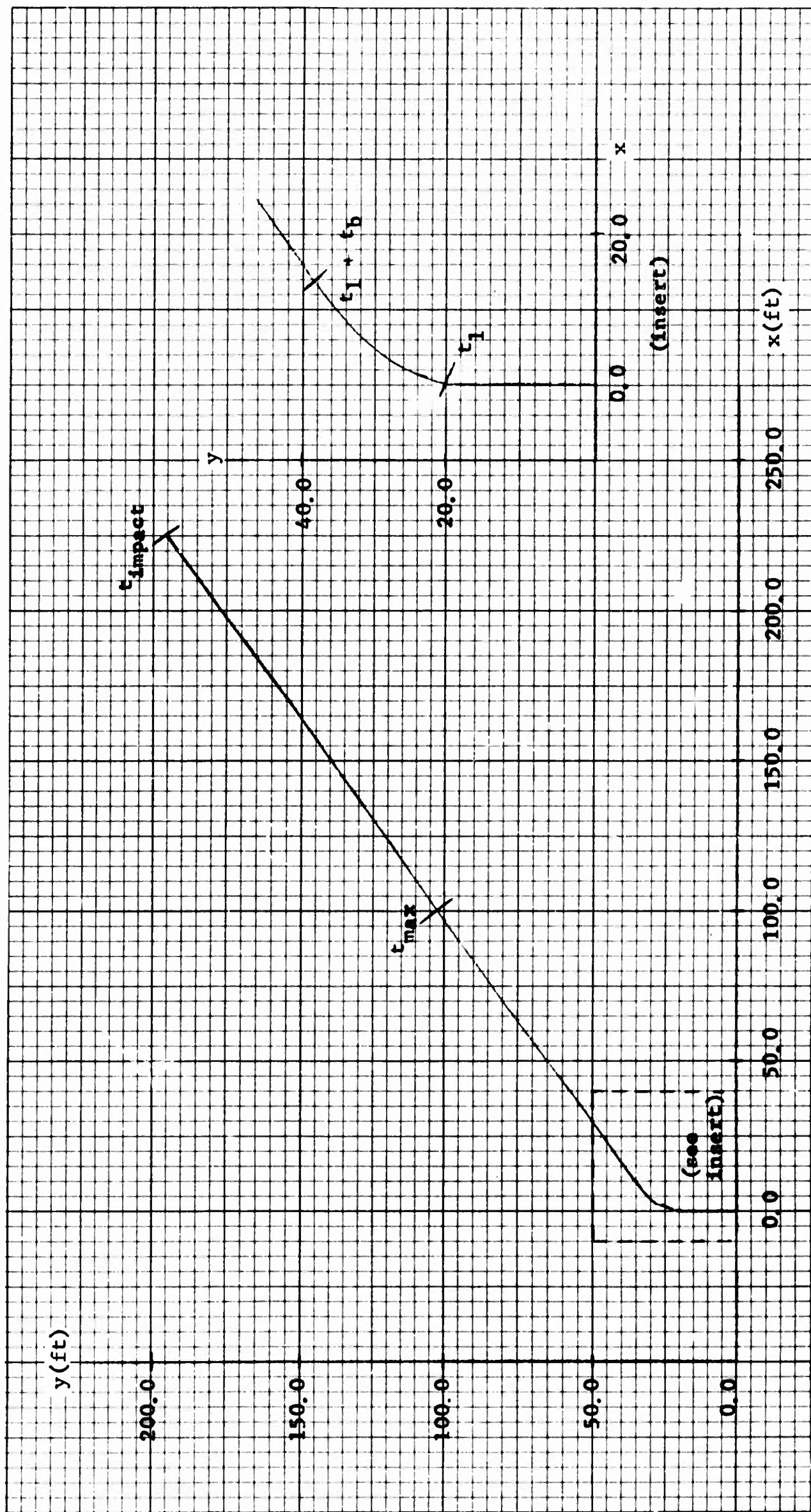


Figure 4. B - Graph of x vs y , test No. 5

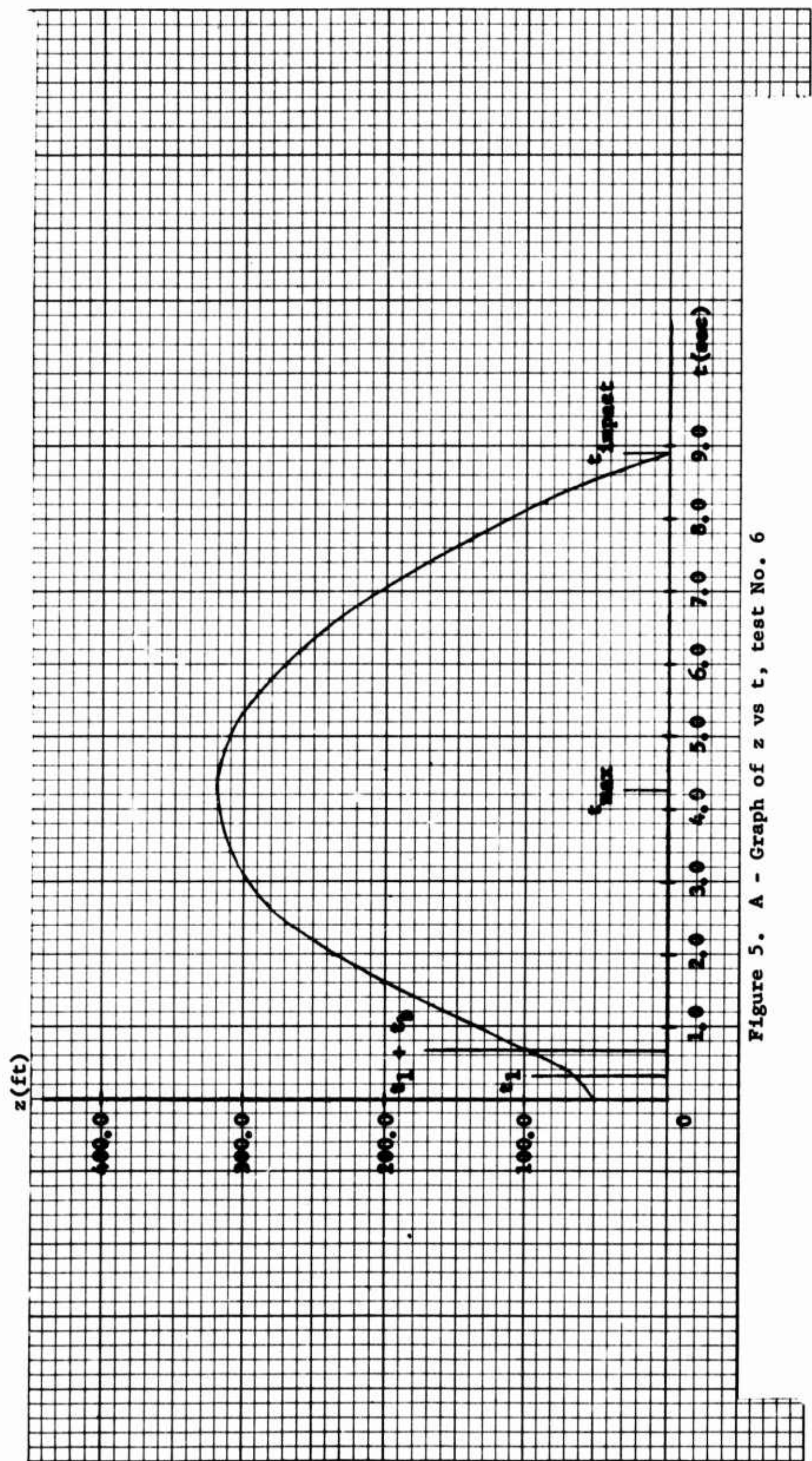


Figure 5. A - Graph of z vs t , test No. 6

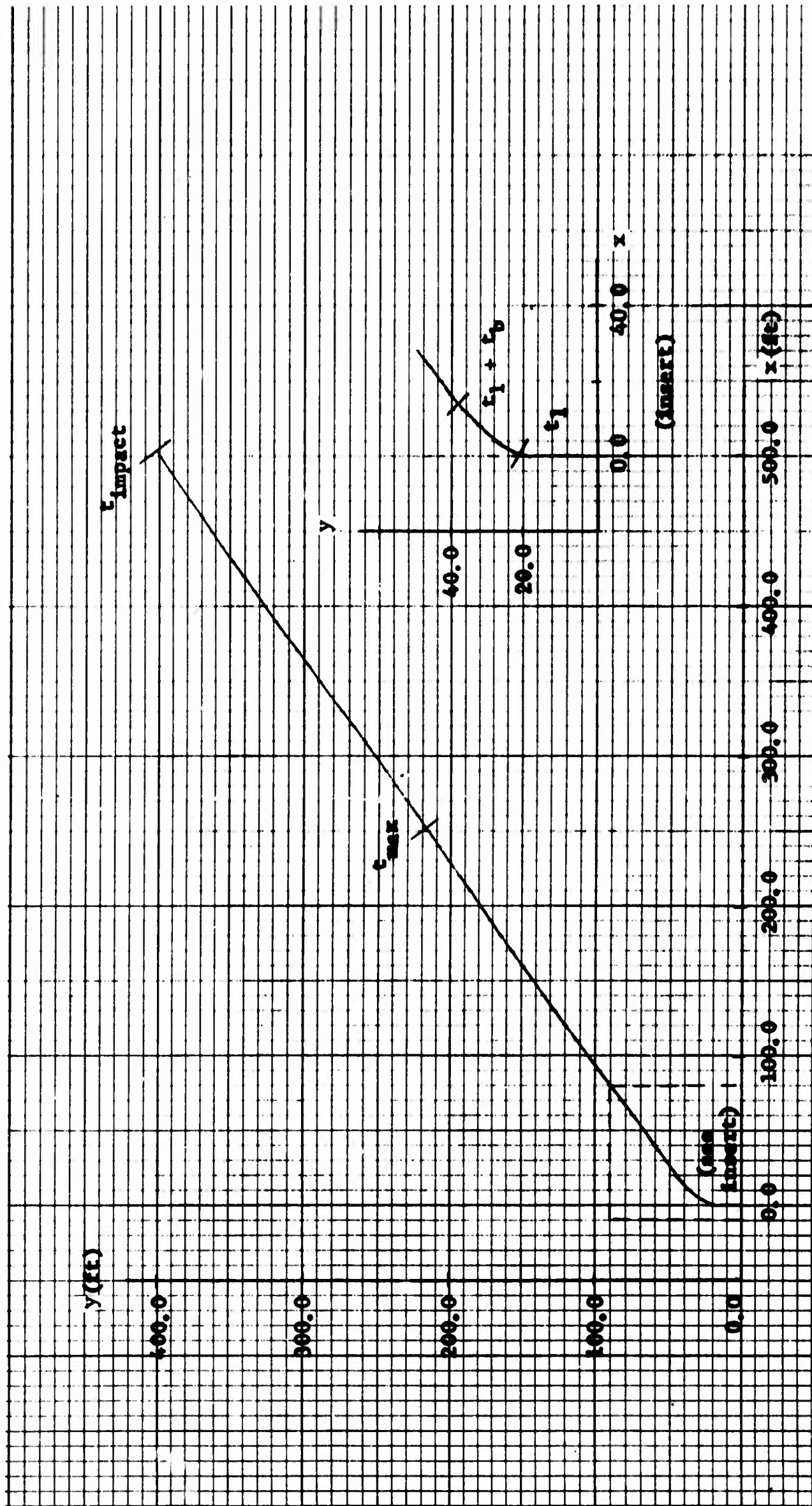


Figure 5. B - Graph of x vs y , test No. 6

TABLE II. Input for Tests 1, 5, and 6

<u>Parameter</u>		<u>Test 1</u>	<u>Test 5</u>	<u>Test 6</u>
Initial height	(ft)	5.0	50.0	50.0
Vehicle velocity	(ft/sec)	0.0	50.0	50.0
Catapult velocity	(ft/sec)	60.0	60.0	60.0
Rocket thrust	(lb)	3400.0	3400.0	3400.0
Vehicle colatitude	(degree)	90.0	180.0	0.0
Vehicle azimuth	(degree)	0.0	0.0	0.0
Catapult colatitude	(degree)	90.0	90.0	90.0
Catapult azimuth	(degree)	90.0	90.0	90.0
Rocket colatitude	(degree)	36.25	36.25	36.25
Rocket azimuth	(degree)	0.0	0.0	0.0
Rocket initiation time	(sec)	0.3	0.3	0.3
Rocket burn time	(sec)	0.35	0.35	0.35
Ejected mass	(slugs)	9.3243	9.3243	9.3243
Drag coefficient	(lb/sec/ft) ⁿ	0.006	0.006	0.006
Drag exponent	(dimensionless)	2.0	2.0	2.0
Time increment	(sec)	0.05	0.05	0.05
Terminal time	(sec)	10.0	10.0	10.0

TABLE III. Comparison between Experimental and Computed Trajectory

	<u>Max Height</u> <u>(ft)</u>	<u>Max v_x</u> <u>(ft/sec)</u>	<u>Max v_y</u> <u>(ft/sec)</u>	<u>Max v_z</u> <u>(ft/sec)</u>
Experimental	120 to 130	72	60	100
Computed	119	78	60	84

No horizontal displacement data are available for comparison, and no meaningful comparison between acceleration levels is possible because of the following assumptions made in the analysis:

1. The catapult which, in the experimental trajectory, caused the maximum acceleration is assumed to impart an initial velocity only;
2. Rocket thrust is assumed constant over the burn time.

CONCLUSIONS

Comparison with experimental data indicates that the analysis presented in this report adequately simulates experimental helicopter egress trajectories.

RECOMMENDATIONS

It is recommended that

1. The analytical capability provided here be utilized in future analyses of helicopter egress trajectories and any other trajectory simulation fulfilling the stated assumptions.
2. This analysis be extended to include the effect of parachute forces and rotation in the pitch plane.

APPENDIX A

THE COMPUTER PROGRAM

```

C   HELICOPTER EGRESS TRAJECTORY ANALYSIS
    DIMENSION A(10),B(10),C(10),D(25),F(10),HED(9),S(10),U(10)
    PRINT 402,
    PRINT 401,
    READ 202,HED
    PRINT 203,HED
    PRINT 401,
    DO 300 I#1,17
    READ 200,HED,D(I)
300 PRINT 204,HED,D(I)
    PRINT 401,
    PRINT 400,
C   CONSTANTS
    T2#D(11)+D(12)
    D(9)#D(9)-90.
    D(10)#D(10)-90.
    DO 60 I#5,10
60  D(I)#.017453*D(I)
    DO 70 I#5,8
70  A(I)#SIN(D(I))
    DO 80 I#5,8
80  B(I)#COS(D(I))
    C1#SIN(D(7)+D(9))
    C2#COS(D(7)+D(9))
    C3#SIN(D(8)+D(10))
    C4#COS(D(8)+D(10))
    C5#D(2)*A(5)*B(6)
    C6#D(2)*A(5)*A(6)
    C7#D(2)*B(5)
    C8#D(3)*A(7)*B(8)
    C9#D(3)*A(7)*A(8)
    C10#D(3)*B(7)
    C11#D(4)*C1*C4/D(13)
    C12#D(4)*C1*C3/D(13)
    C13#D(4)*C2/D(13)
    C14#-D(14)/D(13)
    C15#2.*D(16)
    C16#.5*D(16)
C   INITIAL CONDITIONS
    J#1
    T#0.
    XD#C5+C8
    YD#C6+C9
    ZD#C7+C10
    X#0.
    Y#0.
    Z#D(1)
    F(1)#XD
    F(2)#YD
    F(3)#ZD
    F(4)#X
    F(5)#Y
    F(6)#Z

```

```

C      ENTER EVALUATION ROUTINE
100 XD#F(1)
    YD#F(2)
    ZD#F(3)
    XF#F(4)
    YF#F(5)
    ZF#F(6)
    V#SQRT(XD*XD+YD*YD+ZD*ZD)
    IF(T-D(11))2,1,1
1  IF(T-T2)3,3,2
2  RX#0.
    RY#0.
    RZ#0.
    GO TO 4
3  RX#C11
    RY#C12
    RZ#C13
4  VC14#C14*V**(D(15)-1.)
    S(1)#VC14*XD+RX
    S(2)#VC14*YD+RY
    S(3)#VC14*ZD+RZ-32.174
    S(4)#XD
    S(5)#YD
    S(6)#ZD
    F(1)#S(4)
    F(2)#S(5)
    F(3)#S(6)
    F(4)#X
    F(5)#Y
    F(6)#Z
    IF(T)6,5,6
5  PRINT 201,T,F(4),F(5),F(6),F(1),F(2),F(3),S(1),S(2),S(3)
C      EXIT EVALUATION ROUTINE
6  GO TO (10,20,30,40,50),J
C      ENTER RUNGE KUTTA ROUTINE
10 DO 11 I#1,6
    U(I)#F(I)
    C(I)#D(16)*S(I)
11 F(I)#U(I)+.5*C(I)
    T#T+C16
    J#2
    GO TO 100
20 DO 21 I#1,6
    C(I)#C(I)+C15*S(I)
21 F(I)#U(I)+C16*S(I)
    J#3
    GO TO 100
30 DO 31 I#1,6
    C(I)#C(I)+C15*S(I)
31 F(I)#U(I)+D(16)*S(I)
    T#T+C16
    J#4
    GO TO 100

```

```

40 DO 41 I#1,6
41 F(I)#U(I)+(C(I)+D(16)*S(I))/6.
   J#5
   GO TO 100
C   EXIT RUNGE KUTTA ROUTINE
50 PRINT 201,T,F(4),F(5),F(6),F(1),F(2),F(3),S(1),S(2),S(3)
   J#1
   IF(Z)102,102,101
101 IF(T-D(17))100,102,102
102 STOP
200 FORMAT(9A5,                                     F16.5)
201 FORMAT(10F13.2)
202 FORMAT(9A5)
203 FORMAT(59X,9A5)
204 FORMAT(34X,9A5,                                     F16.5)
400 FORMAT(10X,1HT,12X,1HX,12X,1HY,12X,1HZ,12X,2HVX,11X,2HVV,11X,2HVZ,
   111X,2HAX,11X,2HAY,10X,2HAZ)
401 FORMAT(2/)
402 FORMAT(46X,37HHELICOPTER EGRESS TRAJECTORY ANALYSIS)
   END

```

APPENDIX B

SYMBOLS USED IN DERIVATION OF EQUATIONS OF MOTION

<u>Symbol</u>	<u>Definition</u>	<u>Unit</u>
F	Force	lb
g	Acceleration due to gravity	ft/sec ²
i	Subscript having values 1, 2, 3, corresponding to the three mutually perpendicular coordinate directions	dimensionless
j	Superscript having values 1, 2, 3, referring to the various force contributions	dimensionless
k	Drag coefficient	lb(sec/ft) ⁿ
m	Mass of seat-man	slugs
n	Drag exponent	dimensionless
R	Rocket thrust	lb
t	Time	sec
t ₁	Rocket initiation time	sec
t _b	Rocket burn time	sec
v	Velocity	ft/sec
x	Displacement	ft

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11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY	
13. ABSTRACT The basic equations of motion for a point mass under the influences of gravity, aerodynamic drag, and rocket forces are used to simulate a three-dimensional, three-degree of freedom, helicopter emergency egress trajectory. The resulting equations of motion were solved by a fourth order Runge Kutta method, programmed in Fortran for the Univac Solid State 90 digital computer. Included in this report is the computer program which was used to obtain a numerical solution to the equations of motion, the solution to three test cases, and a comparison with an experimental trajectory.			

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Helicopter Egress Trajectories Egress Trajectory Analysis Computer Programming Propellant Actuated Devices Escape Systems						

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