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Report NATF-EN-1120

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DEVELOPMENT OF A MATHEMATICAL PERFORMANCE PREDICTION MODEL FOR ROTARY-HYDRAULIC-TYPE ARRESTING GEARS

Phase Report
23 March 1972

by

George M. Leask
Computer Division

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DEVELOPMENT OF A MATHEMATICAL PERFORMANCE PREDICTION MODEL FOR ROTARY-HYDRAULIC-TYPE ARRESTING GEARS

Phase Report
23 March 1972

Prepared by: George M Leask
George M. Leask
Computer Division

Reviewed by: William A. Sangtinette
William A. Sangtinette
Head, Computer Division

Approved by: B. F. Kolacz
B. F. Kolacz
Superintendent of Engineering

ABSTRACT

This mathematical model is designed to provide predicted dynamic performance data of shorebased rotary-hydraulic-type aircraft arresting gears. A Navy Model E-28 arresting gear is used for specific comparison between predicted results of the computer solution and actual test results. The simulation of an arrestment of a vehicle under a particular set of conditions is accomplished by putting information (data) into the computer. The input data specifies values for the installation geometry and mechanical properties of the arresting system and the test vehicle. Predicted dynamic values of forces and motions of the test vehicle, purchase system, and tape reel are printed out versus time at a predetermined incremental time.

This report is a phase report on the development of the model and contains the early analytical design approaches, the most current analytical approach with the computer program, and instructions for execution of the computer program.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the efforts of other contributors from the Computer Division who have made significant engineering, mathematical, and/or programming contributions toward the development of this model, namely:

Mr. William Sangtinette

Mr. Norman O'Rorke

Mr. Patrick Stevens

Mr. Wayne Knapp

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I INTRODUCTION

A. The E-28 Mathematical Model was designed and is being developed by the Computer Division, Engineering Department, NATF, to simulate the performance characteristics of the E-28 arresting gear and any similar shorebased rotary-hydraulic arresting gear, such as the BAK-13 or 44B-2D.

B. The ultimate objectives of the design are:

1. To perform parameter predictions which aid in arresting-gear component design, equipment modification, and the determination of gear performance changes due to various proposed and/or actual installation configurations.

2. To reduce the test time of a calibration test program by generating performance data which could act as "fill in" data once the upper and lower limits of the engaging-speed and vehicle gross-weight spectrums have been established through actual arrestments, provided good agreement exists.

C. This report has been prepared to document the model in its current state of development and to discuss the additional capability necessary to achieve the above objectives (paragraphs B1 and B2).

II DESCRIPTION OF THE E-28 ROTARY-HYDRAULIC-TYPE ARRESTING GEAR

A. Purpose: The Navy E-28 arresting gear is a shorebased emergency arresting gear designed to arrest all U.S. Navy arresting-hook-equipped airplanes under conditions of aborted takeoff or landing overrun.

B. Capabilities: An airplane engaging the arresting gear will be stopped within a runout distance of approximately 1,000 feet. The maximum energy absorbing capacity of the gear is 76 million foot-pounds (nominal). Engagements can be made from either runway direction and at points up to 40 feet on either side of the runway centerline.

C. General Description of the Arresting-Gear Operation: As shown in Figure 1, two identical energy absorber units and runway-edge sheaves are located on opposite sides of the runway and are connected, through nylon purchase tapes, to a steel wire-rope deck pendant. Arrestment of a landing aircraft is accomplished by engagement of the aircraft arresting hook with a pendant stretched across the runway. The attached purchase tapes are pulled off the six-foot-diameter drum on each arresting gear. Each drum is splined to a shaft which turns a vaned rotor between vaned stators in a housing filled with a water/glycol mixture. The turbulent fluid resistance caused by the stator and rotor interaction (water brake) decreases the rotational speed of the drums, thereby slowing down the purchase-tape payout which in turn applies a braking force on the aircraft. The ensuing fluid turbulence converts the landing aircraft's kinetic energy into heat. A cooling system is provided to dissipate this heat during rapid-cycle operations. After the aircraft has been safely brought to a stop, and the arresting hook disengaged, the pendant and nylon tapes are returned to battery position by an air-cooled gasoline engine driven retraction system.

III BACKGROUND OF MODEL DEVELOPMENT

A. General: The development of the model from the initial working model to the current model has mainly involved modifications of the pendant/tape geometric configuration that occurs during an arrestment and is used as the basis for parameter generation.

B. Design Progress to Date

1. Initial Design: The initial E-28 mathematical model produced dynamics of the gear directly from the motion of the arresting aircraft. The geometry of the pendant/tape pattern was assumed to be triangular in shape. The pendant/tape was assumed to be in a straight line proceeding from the arresting hook to the runway-edge sheaves throughout the entire arrestment. The early results of model runs indicated that a more sophisticated approach was necessary.

2. Interim Design

a. The kink wave is a triangle-shaped deformation of the runway pendant that is generated from the impact of the arresting hook and represents the motion of stress propagation in the pendant/tape setup.

b. The idea of designing kink-wave phenomenon into the math model originated after studying reports written by F.O. Ringleb (references (a) and (b)) concerning cable dynamics. The addition of kink-wave motion to the program design was necessary to more accurately predict E-28 arresting-gear performance, especially arresting-hook-load and tape-tension values, for the initial part of an arrestment. The introduction of kink-wave geometry into the model forced the dynamics of the arresting system to be generated with respect to the motion of the kink-wave. The various methods that were devised to simulate actual kink-wave paths which hold for the entire simulation of an arrestment are:

(1) arresting-hook-point-to-sheave motion

(2) arresting-hook-point-to-sheave/sheave-to-arresting-hook-point motion

(3) arresting-hook-point-to-sheave/sheave-to-arresting-hook-point/arresting-hook-point-to-sheave motion

3. Most Recent Design: The best results that have been obtained to date are from the current model. This approach assumes that the kink wave travels from arresting-hook point to sheave repeatedly. That is, when the program determines that the kink wave has reached the runway-edge sheave and is ready to "bounce back" toward the hook, program logic forces a new kink wave to emanate from the hook and progress toward the sheave. Although not in agreement with the classical kink-wave motion described by Ringleb in

reference (a), this method has proven to give the most accurate prediction results to date. The results of this method are compared to the results of earlier design approaches in the form of a composite plot of arresting-hook load versus time in Figure 2.

IV ACTUAL ARRESTMENT DESCRIPTION

A. The purpose of the arresting system is to dissipate the engaging kinetic energy of an aircraft. This is accomplished by transmitting the vehicle's energy through the purchase tapes into the tape-reel absorber units where the energy is converted into heat by the action of fluid turbulence. During the course of an arrestment there are, therefore, three main types of motion caused by the action and reaction of the system components:

1. Tape-reel and rotor motion

2. Pendant/tape (kink-wave) motion

3. Vehicle motion

The force interaction between these three types of motion is the principal basis for the mathematical model simulation of an arrestment.

B. The following is an account of how each type of motion changes as the arrestment proceeds:

1. <u>Before Impact</u>

a. Arresting Gear - motionless

b. Pendant/Tape - motionless

c. Vehicle - approaching pendant at a predetermined speed and weight

2. <u>At Impact</u>

a. Arresting Gear - motionless

b. Pendant/Tape - set in motion by action of kink-wave generated upon impact

c. Vehicle - speed at impact is the engaging speed for the arrestment

3. <u>After Impact (period of arrestment)</u>: The initial braking force on the vehicle is slight and is imposed by tensions due to purchase-tape elongation. Once the tape reels are in motion, however, the main retarding (braking) force is due to the hydraulic brake connected to the tape reel. A typical arrestment, therefore, will be described in two sections: the first called the dynamic region where there is only slight retardation of the vehicle due to kink-wave motion causing purchase-tape elongation; and the second called the hydraulic region, where the main retarding forces on the vehicle are encountered.

a. Dynamic Region

(1) Arresting Gear - tape reels start to rotate due to tension instilled by kink waves. Fluid pressure in absorber is still not affected.

(2) Pendant/Tape - kink wave is reflected off of runway-edge sheaves and travels back and forth repeatedly from arresting-hook point to sheave, causing the kink-wave "humps" in the recorded tape-tension values.

(3) Vehicle - speed starting to feel effects of tension pull of tapes.

b. Hydraulic Region

(1) Arresting Gear - tape reels are increasing speed rapidly because they are feeling directly the pull of the vehicle's weight. Fluid pressure in absorber unit increases steadily.

(2) Pendant/Tape - kink waves have more or less damped out although effects on tape tension are still noticeable. Tape tensions are due almost entirely to the retarding force the tape reel fluid has on the vehicle via the purchase tape.

4. End of Arrestment: When all of the vehicle's kinetic energy has been transformed into heat in the absorber units through the action of fluid turbulence, the vehicle comes to a stop and the arrestment is complete. Reel acceleration, arresting-hook load, absorber pressure, and tape tensions reached their maximum values in the hydraulic region of the arrestment and then decreased to their initial pre-impact values[1].

[1]This is generally true although sometimes the maximum values of arresting-hook load and tape tensions can reach their peaks in the dynamic region for certain arrestment runway configurations. Also, due to tape stretch there may be a load in the system when the vehicle is stopped accounting for small arresting-hook-load and tape-tension values.

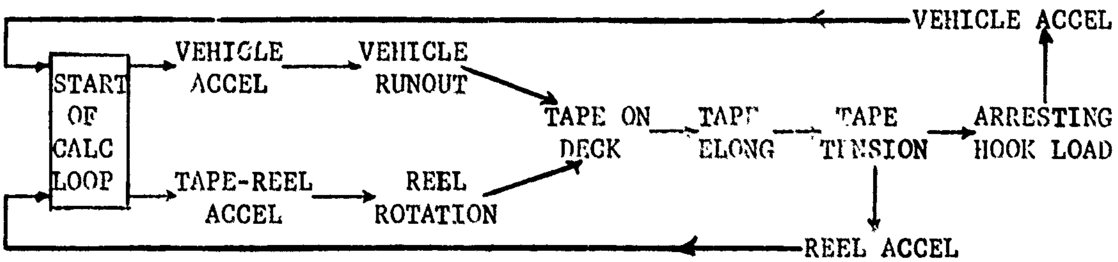
V SIMULATED ARRESTMENT DESCRIPTION

A. General: The computer program developed is a finite incremental analysis of arresting-gear dynamics. The simulation of a test event (aircraft arrestment) is accomplished by relating mathematically the interreactions between vehicle, kink-wave, and tape-reel motions. Parameter computation sections of kink-wave velocity, tape tension and elongation, tape-reel acceleration, etc., which have been developed in separate studies are applied collectively, while conforming to the predetermined shape or pattern of kink-wave design, to obtain performance results.

B. Calculation Section Logic

1. The calculation section logic consists of equation segments which compute specific physical properties of the arrestment such as forces, torques, motions, and distances. Each segment was developed independently and then combined to provide for the calculation of the key motion generation parameters--vehicle and reel accelerations.

2. The logic that begins the calculation loop and generates simulated motion contains equations which are actually simple integration techniques. Values of accelerations (tape reel and vehicle) are provided from the previous pass through the calculation loop. The integration technique is applied which results in values of velocity and speed (tape reel and vehicle), and the procedure is repeated to obtain values for tape-reel revolution and vehicle runout. The basic loop logic is diagrammed below:



3. An explanation illustrating how vehicle speed is obtained from vehicle acceleration follows:

letting V_2 = vehicle speed at end of time increment (VELNS2),

V_1 = vehicle speed at start of time increment (VELNST),

A_2 = vehicle acceleration at end of previous time increment (VACC2),

A_1 = vehicle acceleration at start of previous time increment (VACC),

T = time,

and $\Delta t = \frac{\Delta T}{2}$.

Instantaneous speed can be approximated by a value of average speed or

$$V_2 = V_1 + \Delta t\ (A_1 + A_2).$$

This expression represents an integrated process which utilizes the average of two accelerations, A_1 and A_2, within a specified time increment, ΔT, to obtain an average speed difference, $\Delta V = \Delta t\ (A_1 + A_2)$.

4. Ideally, the most accurate simulation can be obtained when ΔT approaches zero, then $\Delta V = dV$. This program assumes that sufficient accuracy is obtained by letting the time increment Δt = .001 second.

5. Passing through the calculation loop is then a matter of jumping from one logic segment to the next. The calculation loop contains seven main logic segments which compute values for:

a. Reel and vehicle motion

b. Pendant or tape kink-wave velocity

c. Kink-wave coordinates

d. Pendant/tape tensions and elongations

e. Tape-reel inertia and acceleration

f. Arresting-hook load

g. Vehicle acceleration

A detailed description of how each of these segments is designed can be found in Section VI.

VI PROGRAM DESCRIPTION

A. General: The program description format parallels that of the program listing (Appendix A). The description is divided according to the principal sections of program logic. Variable titles used here are identical to those in the program. A complete list of variable names and definitions is presented in Appendix B.

B. Computer Information

1. The program is self-contained and therefore, does not refer to external sources for information. The program language is FORTRAN IV, and the program has been run primarily on the CDC 6600 computer, however, it can also be run on an IBM 360/65 computer. The following is run information for an average run on the CDC 6600:

Compilation time	-	6 seconds
Run time	-	16 to 20 seconds (with .001 second calculation time)
Memory locations used	-	10,000 words (60 bits per word)
Output line limit	-	2,500 lines

2. Data is written on temporary disc storage to minimize running time. Normally, a run is made on priority 6 status which costs 33 cents per system second. If turnaround time is not a critical factor, the cost may be reduced by running on priority 0 at 20 cents per system second.

C. Program Sections

1. Input Section

a. This section contains a dimension statement which defines the linear array, DATUM(32), which is used for program output generation and storage. Every parameter value of output data is allocated a space in this array during calculations. Data values can be recorded on tape or disc storage each time the calculation loop is completed or values can be recorded at a chosen time interval. Presently the recording time interval used is .01 second.

b. The variable JGEOR is initialized to zero. JGEOR is a sequential run indicator and controls the number of program runs performed.

c. Read and format statements of input data complete this section and are separated to distinguish arresting-gear configuration data from event information data. The various input values that are read into the program are listed in Figure 3, which is a sample print-out of all input values.

2. <u>Initialization Section</u>

a. Initial values, that is values of variables that are required for the first pass of the main calculation loop, generally fall into three main catagories:

(1) Deck geometry

(2) Mechancial properties of arresting gear (reel, tape, pendant)

(3) Vehicle and arresting-hook properties

b. The following initialization operations are performed on variables in these categories:

(1) <u>Assignment to the Calculation Variable Names the Value of Zero</u>

(a) All variable names that before pendant impact have the value of zero--such as tape elongation, kink-wave coordinates (angles and distances), arresting-gear motion variables, deck-geometry values, arresting-hook load, tape tensions, etc.--are set equal to zero.

(b) Other variables set equal to zero are TIME, the symmetry flag IFLGSM, the output printer line counter ICOUNT, and the linear array DATUM(32).

(2) <u>Conversion of Units of Input Variables</u>: To simplify the preparation of input values, their units are those of standard, commonly used values. However, to ease calculations through conformity of units, some input values must be converted to units which agree with other variable units. For example, vehicle engaging speed VELENG is normally referred to in knots and is therefore, input this way. For calculations, however, speed in FT/SEC would be more suitable and therefore the conversion is performed.

(3) Calculation of Intermediate Input: Parameter variables that are not part of input but have definite values aside from zero and must be introduced into the main calculation loop, are calculated from input data or companion values. An example is the initial vehicle acceleration VACC, which is computed from the vehicle mass, VMASS, and forces of thrust VTHRUS, arresting-hook load VHOOK, and drag VTDRAG.

3. Calculation Section

a. The purpose of this section is to compute prime parameter values as functions of time for output. The parameters that are currently being computed are listed in the output section, page 16.. To compute prime parameter values, many interrelated equations describing

(1) Vehicle distances and motion,

(2) Tape and pendant properties and geometry, and

(3) Tape-reel rotation and motion

are drawn upon to develop changes of the "key" motion generation parameters, vehicle and reel accelerations, with time. These motion generation parameters are the basis of the calculation loop.

b. Time Generation: The impact of the arresting-hook with the pendant is simulated when the calculation loop is entered for the first time. For each pass through the calculation loop, TIME (arrestment time) is increased by one time calculation increment.

c. Port and Starboard Calculations: Port and starboard parameter values can be calculated separately if the arrestment is OFF-CENTER. If the symmetry flag indicates an ON-CENTER arrestment, calculations are performed for port parameters only and set equal to starboard values for each pass through the loop. (See Appendix C, Program Flow Chart, for more details.)

d. Main Loop Calculations

(1) The main calculation loop is separated into five sections:

(a) Program stop logic,

(b) Port parameter calculations,

(c) Setting of port parameter values to starboard parameter values for a symmetrical arrestment,

(d) Starboard parameter calculations, and

(e) Final calculations.

The port and starboard calculations contain the same equations, differing only by the variable name endings, P for port and S for starboard. Therefore, only the port parameter calculations will be described. Variable names that depict parameter values at the end of a time increment end in the number 2.

(2) Program Stop Logic: Two separate tests are performed upon entrance into the main calculation loop to determine if the program has simulated an arrestment completely and to indicate a halt to program calculations:

(a) Port or starboard two-block: The instantaneous radius of outer wrap of the purchase tape on the reel ROWP is compared to the reel-hub radius RHUB to establish if the tape supply on the reel has been depleted.

(b) Vehicle Speed: The instantaneous vehicle speed VELNST is checked to see if it has reached a value of zero which would indicate the end of an arrestment.

(3) Port Parameter Calculations

(a) Motion calculations: In this section, motion of the vehicle and tape reels is simulated. Speed and velocity (vehicle - VELNS2, reel - RSPP2) are obtained by averaging acceleration values of the beginning (vehicle - VACC, reel - RACP) and end (vehicle - VACC2, reel - RACP2) of the last time increment, multiplying by the time increments, and then by adding this value to the speed/velocity values at the end of the previous increment.(vehicle - VELNST, reel - RSPP). Following this same integration logic, vehicle runout VRUNO2 and reel revolutions RPOP2 are obtained from speed/velocity values. The radius of outer wrap of reel tape ROWP is calculated from the amount of tape that has left the reel. The amount of tape on a reel at any time RLTP is determined by the differences of the total length of tape in system TOLENP and the amount on deck TLENP from the last calculation increment. A new value for tape on deck TLENP2 to account for the motion of vehicle and reels is then computed. See Figure 4 for description of variable names of the runway configuration.

(b) Kink-wave location: The location of the kink-wave in the tape-pendant configuration is established. The velocity of the kink wave is a function of the media in which it is traveling. It is necessary, therefore, to determine for each calculation if the kink wave is traveling through the nylon tape or steel pendant so that the proper dynamic equations describing its motion can be employed. This test is accomplished by checking the three-dimensional distance HYPOTP which is the distance from hook to kink against the length of the pendant on the port side of hook engagement through the use of an IF statement.

(c) Kink-wave velocity: The kink-wave velocity for either the pendant or tape is calculated. This velocity is computed in terms of modulus of elasticity (pendant - PENMOD, tape - ETAPEP), longitudinal wave velocity (pendant - CPEND, tape - CTAPEP), and the transverse impact formula approximation (pendant - PENSIG, tape - TASIGP).

(d) Kink-wave three-dimensional coordinate location: The instantaneous location of the kink wave is described by a three-dimensional coordinate system which pinpoints its position by means of angles and linear distances from a fixed reference. See Figure 5 for an illustrated description of this coordinate system. Also, the instantaneous arresting-hook elevation HKELEV, the distance of the kink to the tail hook HYPOTP, and the distance of the kink to the runway-edge sheave RESULP, are computed. See Figure 6 for an illustrated description.

(e) Pendant and tape elongation, tension: Total elongation of the tape/pendant configuration, DELP, is computed by subtracting the length of the tape/pendant on the runway of the previous time increment, TLENP2 and PLENP, from the new length of the tape/pendant on the runway just established from the three-dimensional distances, HYPOTP and RESULP, and SPLITP. See Figures 4 and 6. The tape elongation factor, TELFP, which is the percent tape elongation and is required for substitution into the tape modulus of elasticity equation and the tape tension equation (see pages E-3 and E-4, Appendix E under procedure), is computed by subtracting the pendant elongation PELP from the total elongation DELP, and dividing by the product of the length of tape on the runway TLENP2 and 100. Tape tension, DTENP, is computed and its values used to calculate a new value of pendant elongation PELP2, which is a function of pendant length PLENP, pendant modulus of elasticity PENMOD, pendant cross-sectional area PENX, and tape tension.

(f) Tape-reel acceleration, arresting-hook load: Tape-reel acceleration RACP2, is determined by the relationship between the torques acting on the reel and rotor and the polar moment of inertia of the reel and rotor. (See Appendix F for detailed description of equation derivation.) Arresting-hook load, HOOKP, is established by resolving tape tension into vector components in the direction of hook engagement. (See Figure 7, page 31 for diagram.)

(g) Test to determine if kink wave has reached the sheave: At the end of the port parameter calculation section, a test is performed to determine whether the kink wave has reached the runway-edge sheave. This test is accomplished by comparing XWAVEP, which is the distance from the centerline of engagement to the kink wave, to DHAP, which is the distance from the centerline of engagement to the runway-edge sheave. When the test indicates that these values are equal, the kink wave has reached the sheave and the three-dimensional coordinates and angles at this time must be recorded in order to establish a new path for the next kink wave to follow. If the kink wave has reached the sheave, values of GAMAXP, GAMAYP, GAMAZP, XWAVEP, YWAVEP, ZWAVEP, and HYPOTP are computed.

(4) Arresting Symmetry Check: If the symmetry flag IFLGSM indicates an ON-CENTER arrestment and a completely symmetrical system installation (IFLGSM = 0), port parameter values are set equal to starboard parameter values. This procedure minimizes computational time under computer control when the arrestment is symmetrical. If the arrestment is not symmetrical (IFLGSM = 1), the computer is instructed to enter the starboard calculation section. This test is performed by the use of an IF statement.

(5) Final Calculations

(a) In the final calculation section, VACC2, the vehicle acceleration is calculated and parameter variable values that have been calculated in the port and starboard sections (of present time increment) are stored for reuse upon the re-entrance of the main calculation loop.

(b) Vehicle acceleration is obtained simply by applying Newton's second law of motion and using the fundamental equation, Force = mass x acceleration. Vehicle acceleration is equal to the resultant forces acting on it, thrust (VTHRUS), arresting-hook load (VHOOK), and the total drag force (VTDRAG) divided by its mass (VMASS).

(c) Storage of parameter values for use in the next time increment is accomplished by assigning present increment variable values which are suffixed with the number "2", to the same respective variable names not followed by the number "2".

(6) Saving of Maximum Values: The maximum value of certain parameters is required for most arresting test programs. This section provides a means of obtaining maximum values of desired parameters for an arrestment along with the times that the maximum values occurred. Maximum values are designated by the variable name prefixed by the letter "A". The following maximum values are currently being computed for output:

arresting-hook load	-	AVHOOK
tape tension, port	-	ADTENP
tape tension, stbd	-	ADTENS
vehicle deceleration	-	AVACCG
reel velocity, port	-	ARSPP
reel velocity, stbd	-	ARSPS
reel acceleration, port	-	ARACP
reel acceleration, stbd	-	ARACS

(7) Main Calculation Loop Output Storage: All parameter values that are to be output are stored in the linear array DATUM(32) along with the arrestment time TIME(DATUM (9)), and are recorded on tape. The program listing statement 300 (see Appendix A), shows the parameter names along with their assigned array position.

(8) Run Termination: Run termination is based on elapsed time and occurs when the elapsed time (TIME) exceeds a preset arrestment time limit.

(9) Kink-Wave Coordinate Generation: The last section of the main calculation loop generates the three-dimensional kink-wave coordinate values and the kink-wave velocity for both the port and starboard kink waves along with the corresponding time of arrestment.

4. Output Section

a. Program output consists of five parts:

(1) Record of input,

(2) Kink-wave coordinates,

(3) Maximum values,

(4) Vehicle motion parameters, arresting-hook load and tape tensions, and

(5) Port tape and tape-reel values.

b. The record of input data is output on printed form immediately following the initialization section of the program. See Appendix A for a sample output listing.

c. Kink-wave coordinates are current values that are printed after every calculation iteration until the run is terminated. The kink-wave coordinates, XWAVEP(S), YWAVEP(S), and ZWAVEP(S), are printed along with the corresponding arrestment time TIME for both port and starboard kink waves.

d. The remaining outputs are recorded on magentic tape during the program calculation run and are printed after the calculations are completed. The maximum values are printed as explained in Section III, paragraph E.

e. The vehicle motion parameter values that are printed along with the arrestment time are:

Speed	- VELNS2
Runout	- VRUNO2
Rolling friction	- VROLL
Total drag	- VTDRAG
Acceleration	- VACC2

Also printed out in this output are:

Arresting-hook load	- VHOOK
Port tape tension	- DTENP
Starboard tape tension	- DTENS

The port tape and tape-reel values that are printed out are:

Tape reel velocity	- RSPPR
Tape reel position	- RPOP
Tape wrap radius	- ROWP
Tape on deck	- TLENP
Arresting-hook-point-to-sheave distance	- DLENP
Pendant elongation	- PELP
Total elongation	- DELP
Tape elongation factor	- TELFP
Tape tension	- DTENP
Tape on reel	- RLTP
Total reel inertia	- RTINP
Tape-reel acceleration	- RACPR

VII DISCUSSION

A. Run Verification: One of the most important parameters associated with arrestment test programs is arresting-hook load. It is, therefore, used as a basis of comparison to determine the general accuracy of a computer mathematical model simulation. During the development stages of the mathematical model, arresting-hook-load values obtained from a computer run are plotted against the arresting-hook-load values of actual test data to give an indication of how well a particular program design logic change has affected the predicted results. Other parameters are, of course, analyzed but the arresting-hook load serves as an index of the overall performance of the model.

B. Current Status of Program Performance

1. At the present stage of development, the program computes all required tape-reel and vehicle parameters for ON or OFF-CENTER arrestments from the time of pendant pickup until the vehicle comes to a stop. However, program logic at this point of development is not complete. The basic logic pieces are present and do account for a complete parameter output, but a need exists for refinement in existing logic pieces and also logic supplementation to further improve the accuracy of the model. The problem that exists is the time of peak value occurrence in arresting-hook-load and tape-tension plotted time histories. Peak values are within $\pm$ 5% of the corresponding actual peaks; however, the model calculates them to occur at earlier times than actual data indicated they occur.

2. The current logic piece that is suspected of being the prime cause for the program's generation of peak values being off in time is the determination of tape tension. Tape tensions are calculated as functions of purchase-tape elongation. An equation is derived that expresses tension in terms of percent elongation of the tape by fitting a curve through actual load-percent elongation data. The problem is that with nylon tape the relationship between tension and percent elongation is hysteretic in nature. If a system could be developed to express the load-percent elongation relationship more adequately, the arresting-system physical parameters could be described more accurately by the program.

3. The following is a list of arrestment phenomena that, up to this point in the development of the model, are not yet included:

a. Tape-reel stack slip

b. Angled arrestments where the aircraft or deadload does not engage the pendant perpendicularly.

c. Arresting-hook slip on pendant during OFF-CENTER or angled arrestments

d. Two-block logic which will provide for parameter values after two-block condition.

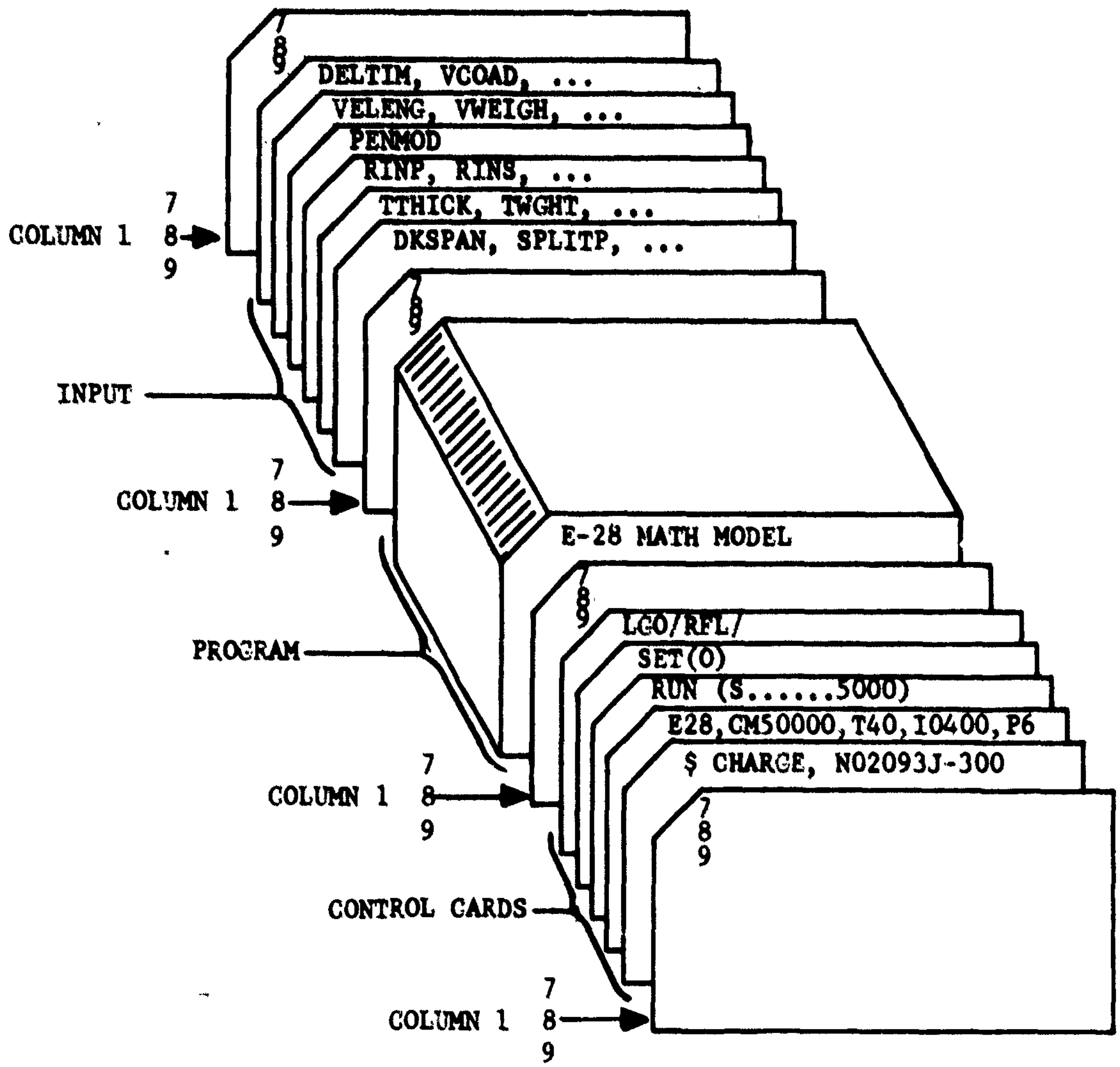
e. Effect that tape/pendant connector has on kink-wave motion

f. Pre-tensioning

g. Logic that would account for energy and momentum of the arresting system with time

VIII PROGRAM USE

A. Program Deck Construction: The following illustrates the setup of a program card deck for a normal run on a CDC 6600 computer:



B. Input Data Preparation: Program input consists of six cards which are divided into two sections: arresting-gear configuration and event information. The cards are placed at the end of the card deck and are separated from the program by a 7, 8, 9 multiple punched card. The input cards variable name location and format are tabulated below:

	INPUT CARD ORDER	VARIABLE NAMES	FORMAT
ARRESTING-GEAR CONFIGURATION INFORMATION	1	DKSPAN, SPLITP, SPLITS, PENLEN, PENX, POFFC PENDEN	7F10.4
	2	TTHICK, TWGHT, TOLENP, TOLENS, C1, C2, C3	7F10.4
	3	RINP, RINS, BRAKEC, RHUB, BRAKEX, TWIDE	6F10.4
	4	PENMOD	1F12.2
EVENT INFORMATION	5	VELENG, VWEIGH, VTHRUS, WINDKT, BARO, TEMPA	6F10.4
	6	DELTIM, VCOAD, DOFFC, HOOKHI, THKLEN	5F10.5

Definitions of variable names can be found in Appendix B. Input values should be obtained from the test engineer and/or the Computer Division.

C. Control Card Preparation: There are five control cards which preceed the program in the card deck and are separated from it by a 7, 8, 9 multiple punched card.

1. Charge Card: This card is used for accounting purposes:

```
$ CHARGE, aaaaa C1C2 - UUU
  aaaaa = five-digit charge number
  C1C2  = two check digits
  -     = indicates subcharge number
  UUU   = three-digit subcharge number (optional)
```

2. Scope Job Card: The parameters of this card describe the job's priority, time limits, memory, and peripheral equipment requirements. All parameters are octal values:

```
Job Name  (CMfl, Tt, IO, Pp)

Job Name = To provide user identification of this job.
CMfl     = Loading field length, which specifies the amount
           of memory needed to obtain a control point and
           load the program into memory.
Tt       = Central processor time limit for the job in seconds;
           a maximum of five octal digits.
IO       = Input/Output time limit in seconds.
Pp       = Priority level (P) at which job enters the system.
```

3. Run Card: The FORTRAN compiler is called by this card:

```
RUN (cm, fl, bl, if, of, rf, lc)
Only two parameters are required, cm and lc, the rest are
omitted
cm = Compiler mode option
lc = Line-limit (octal) on the output file of the object
     program
```

4. Set zero card: This card sets equal to zero all storage locations containing variable names and arrays:

```
SET (0)
```

5. Execute Card: This card loads the program into memory and begins execution:

```
LGO/RFL
LGO = Load and go
RFL = Request field length - an option that allows optional
      usage of central memory
```

For more detailed information on preparing the control cards, see references (c) and (d) or consult a programmer from the Computer Division.

IX FUTURE WORK

A. Continued development on the model will be directed to the following areas:

a. Hysteresis representation of the tape modulus of elasticity

b. On-center and off-center angled arrestments

c. Tape stack slip

B. Also, at present, the program outputs data in tabulation form. Plot capabilities should be added to the program.

X REFERENCES

(a) F. O. Ringleb, NAEC Engineering Department Report No. NAEC-ENG-6169 of 27 Dec 1956: Cable Dynamics

(b) F. O. Ringleb, "Basic problems in the dynamics of the aircraft arresting gear", A Decade of Basic and Applied Science in the Navy, Washington, D.C., 1957

(c) Control Data, 6400/6500/6600 Computer Systems, Scope 3 Reference Manual (Up to Revision J)

(d) Control Data, 6400/6500/6600 Computer Systems, Fortran Reference Manual (Up to Revision C)

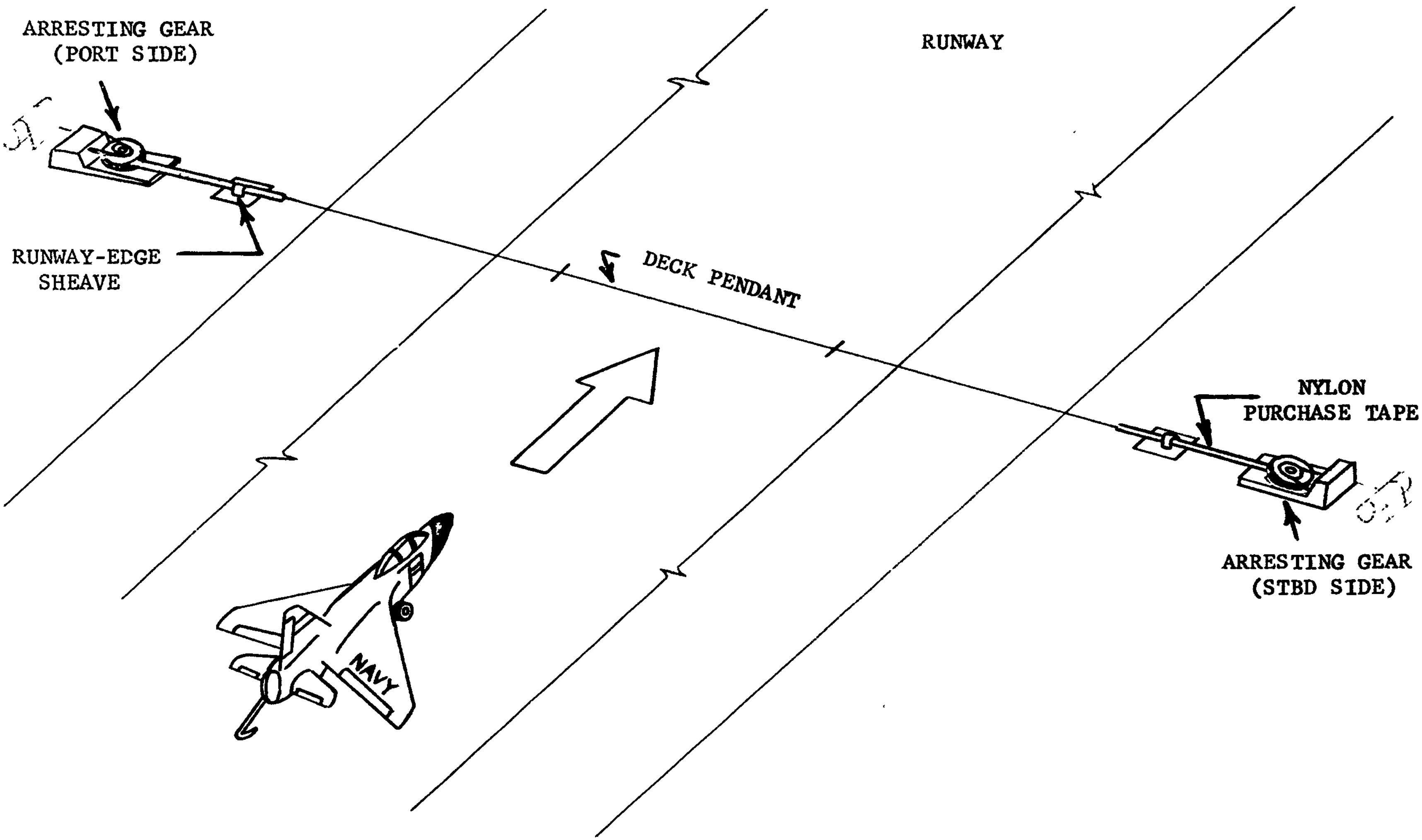


Figure 1 - Typical Shorebased Arresting-Gear Installation Simulated by the E-28 Mathematical Model

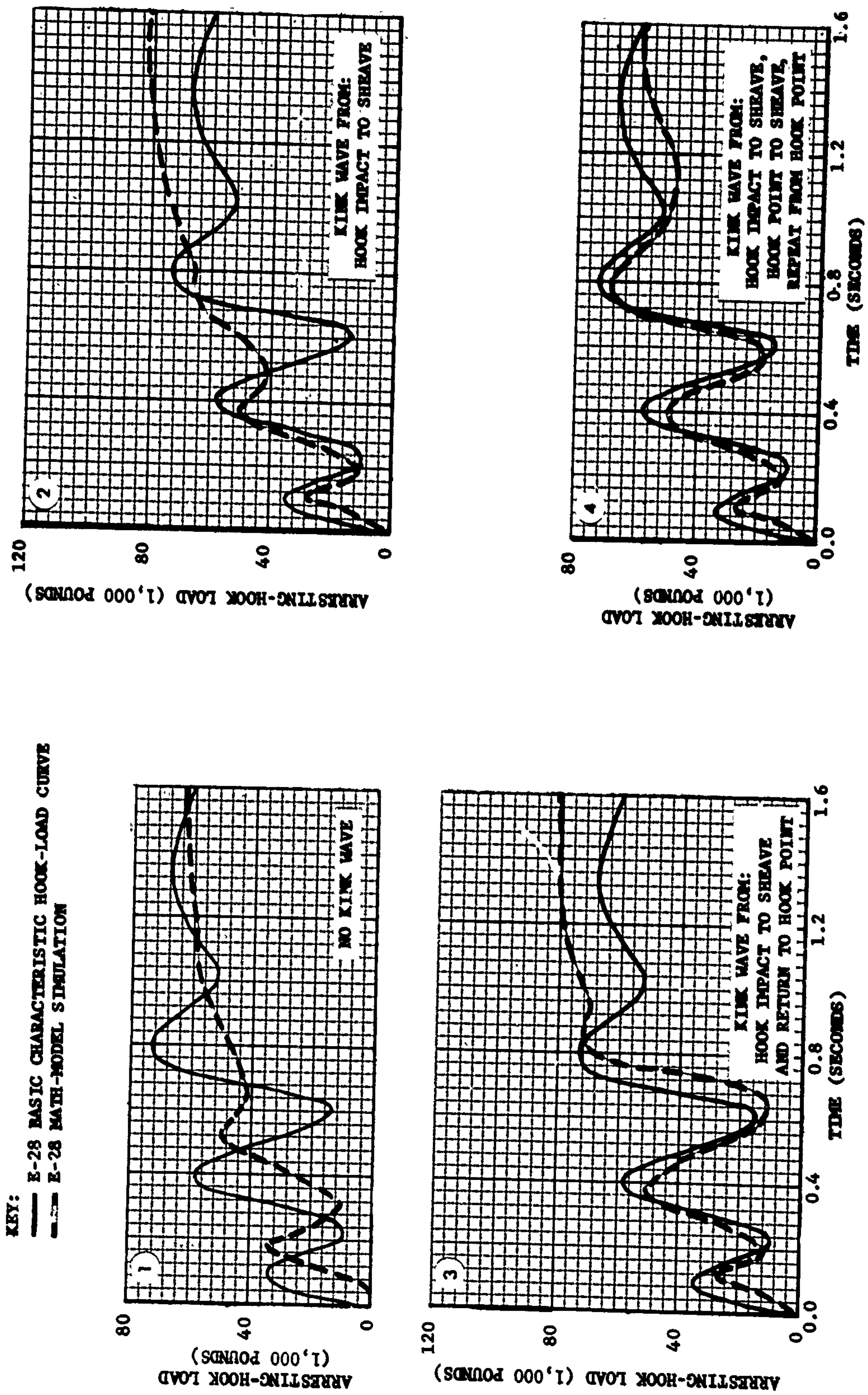


Figure 2 - Arresting-Hook-Load Time Histories of Various E-28 Math-Model Kink-Wave Designs Compared to a Basic Characteristic Hook-Load Curve

ARRESTING-GEAR CONFIGURATION (INPUT VALUES)

PARAMETER NAME	FORTRAN SYMBOL	VALUE	UNITS
DECK SPAN	DKSPAN	164.000	FT
PENDANT LENGTH	PENLEN	154.000	FT
PENDANT MODULUS OF ELAS.	PENMOD	1872000000.000	LB/FT-SQ
PENDANT AREA	PENX	.009	FT-SQ
PENDANT DENSITY	PENDEN	17.890	LB SEC^2/FT^4
PORT SPLIT DISTANCE	SPLITP	49.000	FT
PORT TAPE LENGTH	TOLENP	840.000	FT
PORT REEL INERTIA (METAL)	RINP	114.000	SLUG FT-SQ
BRAKE CONSTANT	BRAKEC	12.310	NONE
TAPE LOAD-% ELONG.COEFF.	C1	1.709	NONE
TAPE LOAD-% ELONG.COEFF.	C2	85.367	NONE
TAPE LOAD-% ELONG.COEFF.	C3	4019.790	NONE
PENDANT OFF-CENTER DISTANCE	POFFC	0.000	FT
PURCHASE TAPE THICKNESS	TTHICK	.344	IN.
PURCHASE TAPE WEIGHT/FOOT	TWGHT	1.000	LB/FT
PURCHASE TAPE WIDTH	TWIDE	8.000	IN.
PURCHASE TAPE AREA	TAREA	2.752	IN.-SQ
STBD SPLIT DISTANCE	SPLITS	49.000	FT
STBD TAPE LENGTH	TOLENS	840.000	FT
STBD REEL INERTIA (METAL)	RINS	114.000	SLUG FT-SQ
BRAKE EXPONENT	BRAKEX	2.000	NONE
HUB RADIUS	RHUB	9.000	IN.

EVENT INFORMATION (INPUT VALUES)

VEHICLE ENGAGING SPEED	VELENG	150.000	KN
VEHICLE WEIGHT	VWEIGH	53000.000	LB
VEHICLE THRUST	VTHRUS	0.000	LB
HEAD WIND	WINDKT	0.000	KN
BAROMETRIC PRESSURE	BARO	30.000	IN. HG A
AMBIENT TEMPERATURE	TEMPA	68.000	DEG F
CALCULATION INCREMENT	DELTIM	.001	SEC
AERO DRAG COEFFICIENT	VCOAD	.041	LB SEC^2/FT^2
DECK OFF-CENTER DISTANCE	DOFFC	0.000	FT
ARRESTING-HOOK HEIGHT	HOOKHI	2.313	FT
ARRESTING-HOOK LENGTH	VHKLEN	6.167	FT

Figure 3 - Sample Output of Input

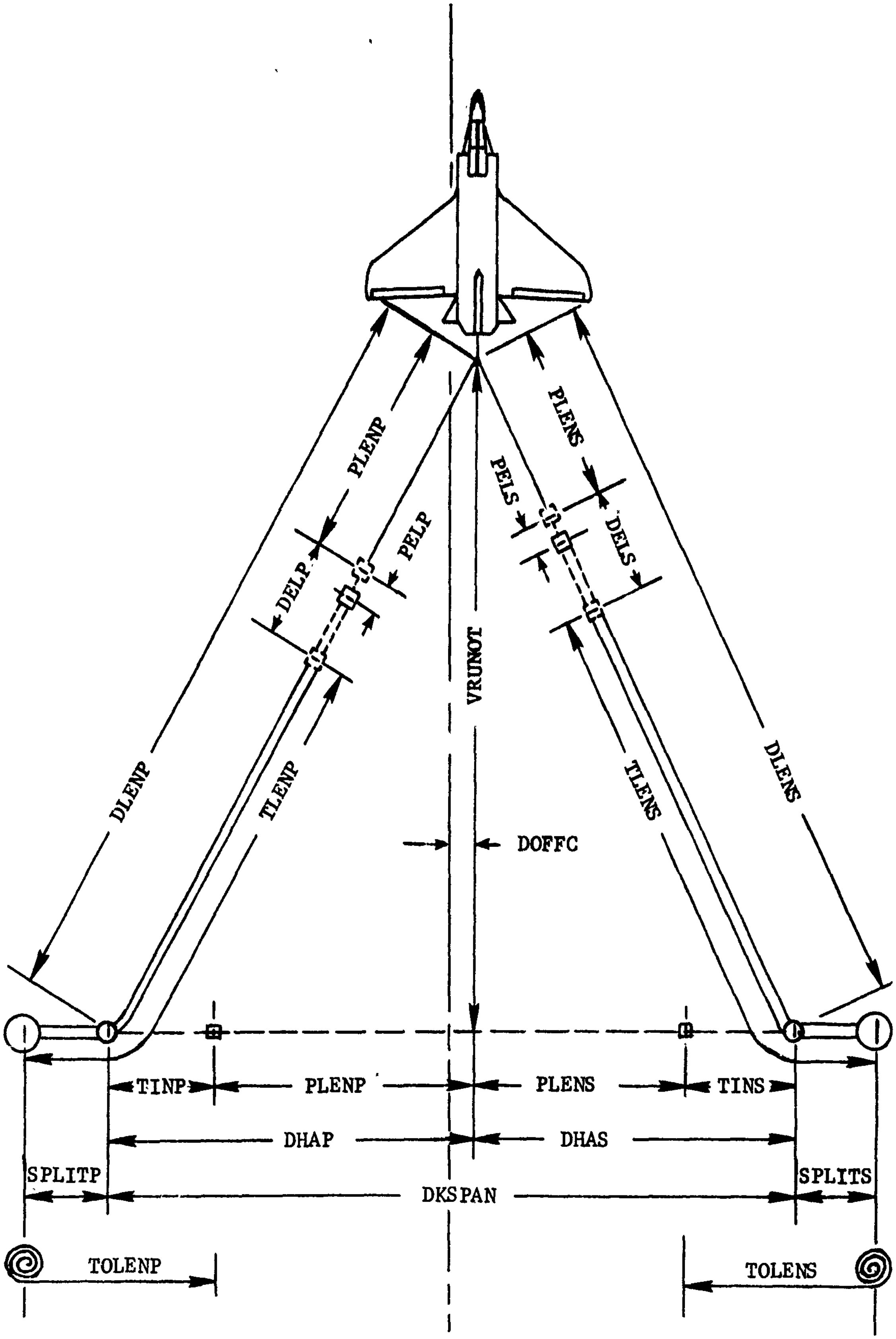


Figure 4 - Schematic of Runway Installation With Variable Name Descriptions

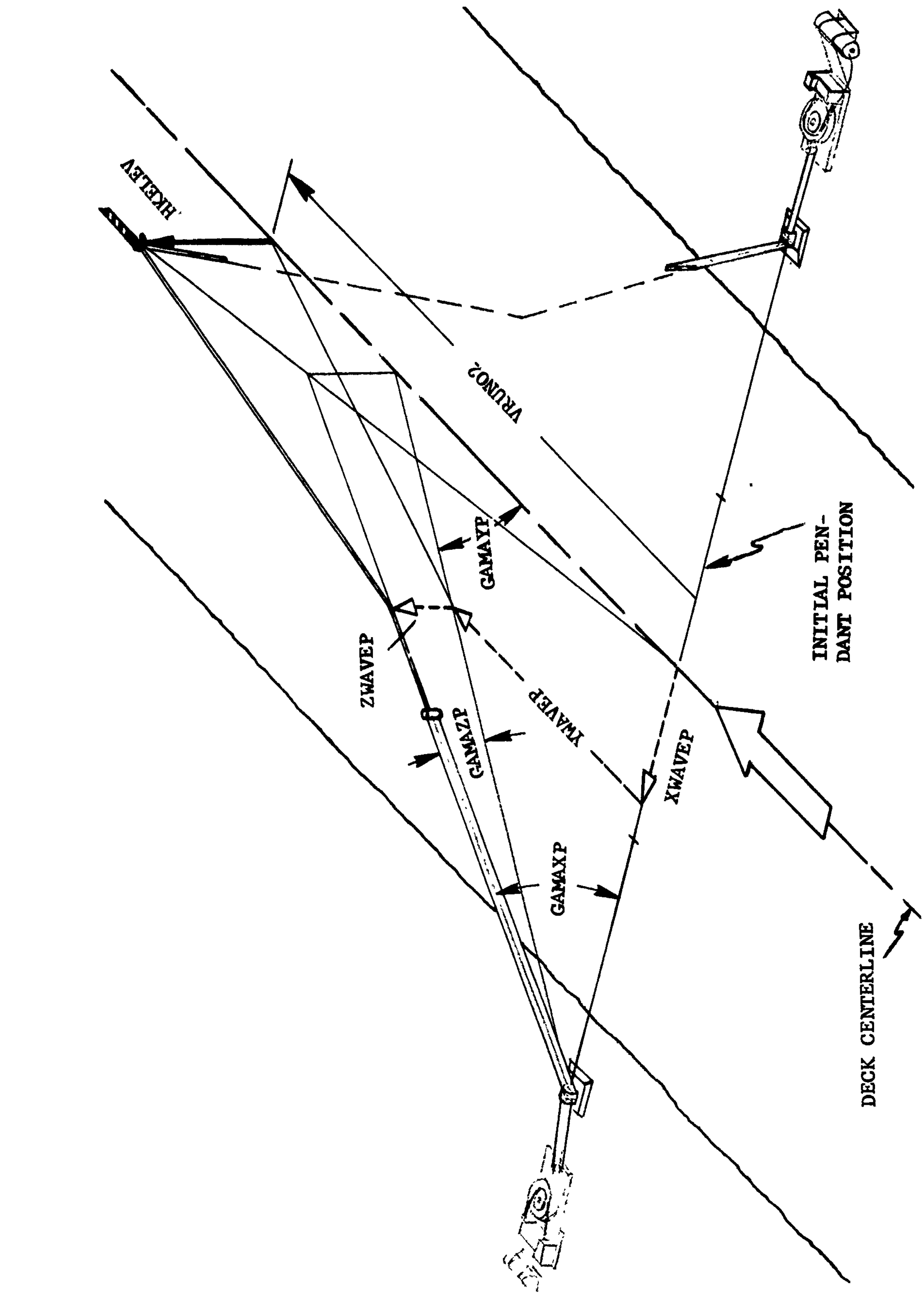


Figure 5 - Three-Dimensional Kink-Wave Coordinates

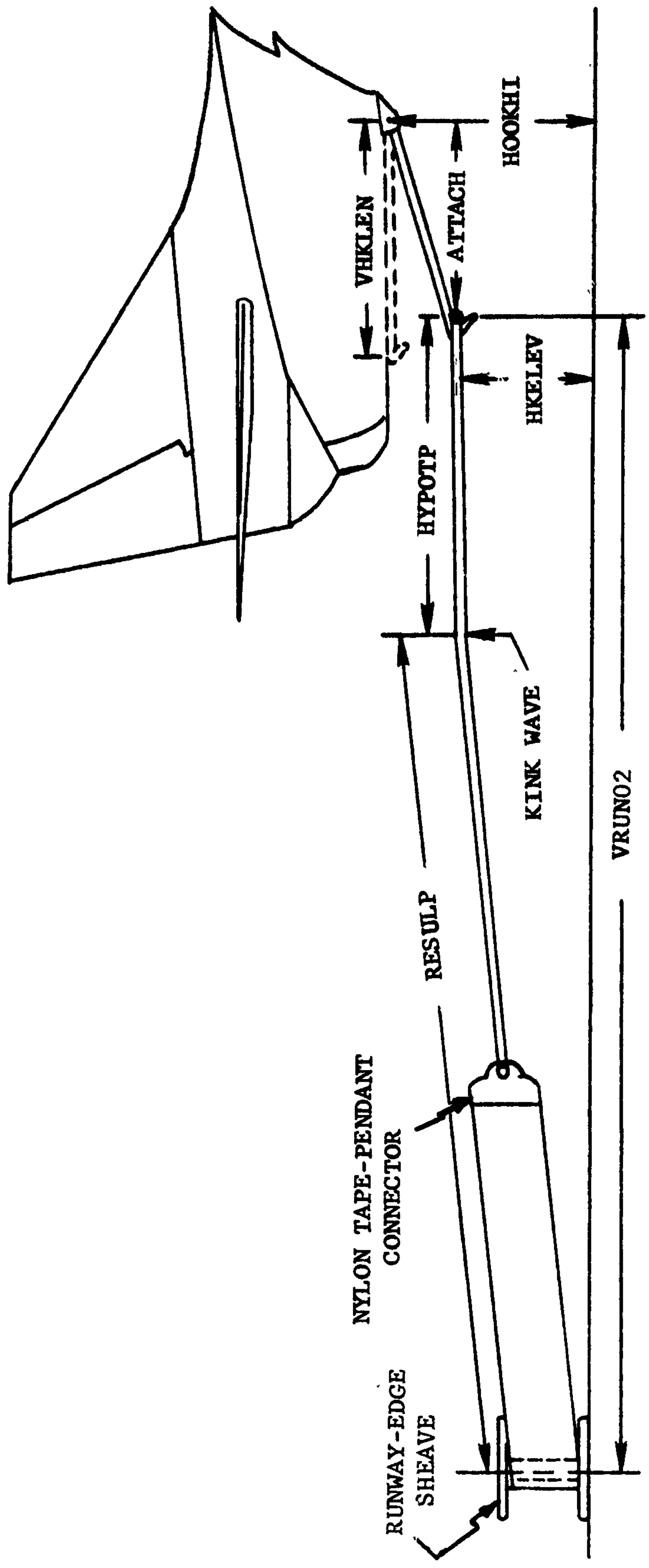
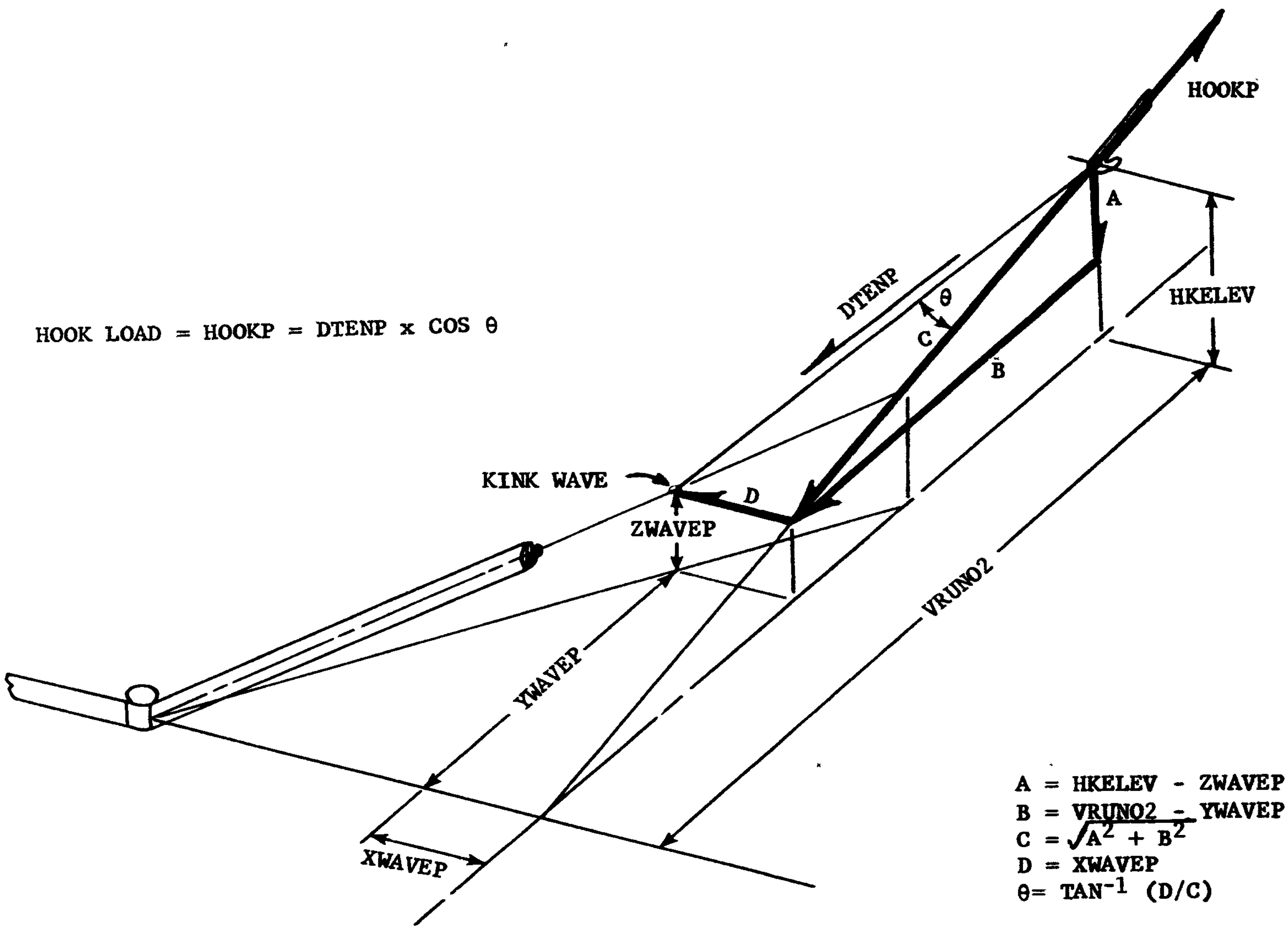


Figure 6 - Runway and Arresting-Hook Measurements

HOOK LOAD = HOOKP = DTENP x COS θ



$A = HKELEV - ZWAVEP$

$B = VRUNO2 - YWAVEP$

$C = \sqrt{A^2 + B^2}$

$D = XWAVEP$

$\theta = TAN^{-1}\ (D/C)$

Figure 7 - Arresting-Hook Load Determination (Port Side Component Breakdown)

APPENDIX A - MATHEMATICAL PERFORMANCE PREDICTION MODEL PROGRAM LISTING

```
      THIS PROGRAM WAS REDESIGNED TO REFLECT A REVISED APPROACH. NEW
      LOGIC INCLUDES A 3-DIMENSIONAL KINK WAVE FORM,INCREMENTAL COMPUT-
      ATION OF THE KINK VELOCITY TO ACCOUNT FOR THE VARYING MODULUS OF
      ELASTICITY OF THE NYLON TAPE AND LOCATION OF THE KINK (I.E. IN
      TAPE OR STEEL PENDANT), AND NEW LOGIC FOR KINK2 WHICH ASSUMES THE
      FORMATION OF A NEW KINK EMINATING FROM THE HOOK AS KINK1 IMPACTS
      THE SHEAVE.
      DIMENSION DATUM(32)
      READ IN ALL DATA PERTINENT TO THE ARRESTING GEAR CONFIGURATION
      JGEOR = 0
    1 READ 2, DKSPAN,SPLITP, SPLITS, PENLEN, PENX, POFFC, PENDEN
      READ 2, TTHICK, TWGHT, TOLENP, TOLENS, C1, C2, C3
      READ 3,  RINP,  RINS,   BRAKEC, RHUB, BRAKEX, TWIDE
      READ 4, PENMOD
    2 FORMAT (7F10.4)
    3 FORMAT (6F10.4)
    4 FORMAT (1F12.2)
    5 FORMAT(5F10.5)
      READ IN ALL DATA PERTINENT TO EVENT INFORMATION
      READ 3, VELENG, VWEIGH, VTHRUS, WINDKT, BARO, TEMPA
      READ 5, DELTIM, VCOAD,DOFFC, HOOKHI, VHKLEN
      INITIALIZATION OF VARIABLES
      IGL = 0
      DTENP=DTENS=RSPPR=RSPSR=0.0
      DELP=DELS=RACPR=RACSR=0.0
      VKINKP=VKINKS=0.0
      VRUNOT=RSPP=RSPS=RACP=RACS=RPOP=RPOS=RELP2=RELS2=RACP2=RACS2=0.0
      AVHOOK = ADTENP = ADTENS = AVACCG = ARSPP = ARSPS =ARACP=ARACS=0.0
      XWAVEP  = YWAVEP  = ZWAVEP  = XWAVES = YWAVES = ZWAVES = 0.0
      ICOUNT = 0.0
      TIME  = 0.0
      VMASS  = VWEIGH / 32.174
      THDEL  = DELTIM / 2.0
      WINDFT = WINDKT * 1.6878
      VELNST = VELENG * 1.6878
      VROLL  = .00045 * VELENG * VWEIGH
      DRAGK = 17.3262 * ( BARO / ( TEMPA + 459.4 )) * VCOAD
      VADRAG = (VELNST + WINDFT)**2 * DRAGK
      VTDRAG = VADRAG + VROLL
      HOOKP  = HOOKS = 0.0
      VHOOK = HOOKP + HOOKS
      VACC=VACC2=(VTHRUS-VHOOK-VTDRAG)/VMASS
      VACCG  = VACC / 32.174
      HYPOTP = HYPOTS = 0.0
      TELFP  = TELFS  = 0.0
      PELP2  =  0.0
      GAMAYP = GAMAYS = 1.5708
      GAMAXP = GAMAZP = GAMAXS = GAMAZS = 0.0
      ATTACH = SQRT  (VHKLEN **2 - HOOKHI **2)
      DHAP = .5 * DKSPAN * DOFFC
```

```
      DHAS = .5 * DKSPAN - DOFFC
      DLENP = DHAP
      DLENS = DHAS
      TINP = .5 * (DKSPAN - PENLEN ) + POFFC
      TINS = .5 * (DKSPAN - PENLEN ) - POFFC
      PLENP = DHAP - TINP
      PLENS = DHAS - TINS
      TLENOP = TLENP * SPLITP + TINP
      TLENOS = TLENS * SPLITS + TINS
      RLTP = TOLENP - TLENP
      RLTS = TOLENS - TLENS
      RNUIP   = (-TTHICK - 2*RHUB + SQRT ((TTHICK + 2*RHUB)**2 +
     1( 4 * TTHICK * (( TOLENP - TLENP ) * 12)/3.1416 ))) / (2*TTHICK)
      ROWP    = RHUB +(TTHICK * RNUIP)
      RNUIS   = (-TTHICK - 2*RHUB + SQRT ((TTHICK + 2*RHUB)**2 +
     1( 4 * TTHICK * (( TOLENS - TLENS ) * 12)/3.1416 ))) / (2*TTHICK)
      ROWS    = RHUB + (TTHICK * RNUIS)
      CA      = TTHICK / 6.2832
      PEAP    = PLENP / (PENMOD * PENX)
      PEAS    = PLENS / (PENMOD * PENX)
      CD      = ( RHUB / 12.0 )**2
      CE      = TWGHT / 64.348
      LTCONT = 0
      TAREA = TTHICK * TWIDE
      IO = 0
      DATUM(32) = 0.0
      JTIME = 1
      TAPDEN = TWGHT/(32.17*(TAREA/144.0))
      TEST FOR ON CENTER ENGAGEMENT AND SYMETRICAL A.G. CONFIGURATION
      IFLGSM = 0
      JSYMVP = DHAP*TINP*SPLITP*TOLENP*RINP
      JSYMVS = DHAS*TINS*SPLITS*TOLENS*RINS
      IF(JSYMVP-JSYMVS)19,18,19
   18 IFLGSM = 1
   19 CONTINUE
   20 FORMAT(1H1,///46X,28HARRESTING GEAR CONFIGURATION)
   21 FORMAT (/28X,7HFORTRAN,52X,7HFORTRAN)
   22 FORMAT(6X,14HPARAMETER NAME,8X,6HSYMBOL,8X,5HVALUE,3X,5HUNITS,11X,
     114HPARAMETER NAME,8X,6HSYMBOL,8X,5HVALUE,3X,5HUNITS)
   23 FORMAT(/10H DECK SPAN,18X,6HDKSPAN,1X,F14.3,1X,2HFT,9X,24HPENDANT
     1OFF CENTER DIST.,3X,5HPOFFC,2X,F14.3,1X,2HFT)
   24 FORMAT (15H PENDANT LENGTH,13X,6HPENLEN,1X,F14.3,1X,2HFT,9X,23HPUR
     1CHASE TAPE THICKNESS,4X,6HTTHICK,1X,F14.3,1X,2HIN)
   25 FORMAT (25H PENDANT MODULUS OF ELAS.,3X,6HPENMOD,1X,F14.3,1X,8HLB/
     1FT*SQ,3X,25HPURCHASE TAPE WEIGHT/FOOT,2X,5HTWGHT,2X,F14.3,1X,5HLB/
     2FT)
   26 FORMAT (13H PENDANT AREA,15X,4HPENX,3X,F14.3,1X,5HFT-SQ,6X,19HPURC
     1HASE TAPE WIDTH,8X,5HTWIDE,2X,F14.3,1X,2HIN)
   27 FORMAT (16H PENDANT DENSITY,12X,6HPENDEN,1X,F14.3,11HLB SEC2/FT4,
     11X,18HPURCHASE TAPE AREA,9X5HTAREA,2X,F14.3,1X,5HIN-SQ)
```

```
28 FORMAT (20H PORT SPLIT DISTANCE,8X,6HSPLITP,1X,F14.3,1X,2HFT,9X,
  119HSTBD SPLIT DISTANCE,8X,6HSPLITS,1X,F14.3,1X,2HFT)
29 FORMAT (17H PORT TAPE LENGTH,11X,6HTOLENP,1X,F14.3,1X,2HFT,9X,
  116HSTBD TAPE LENGTH,11X,6HTOLENS,1X,F14.3,1X,2HFT)
30 FORMAT (26H PORT REEL INERTIA (METAL),2X,4HRINP,3X,F14.3,1X,
  110HSLUG FT-SQ,1X,25HSTBD REEL INERTIA (METAL),2X,4HRINS,3X,
  2F14.3,1X,10HSLUG FT-SQ)
31 FORMAT (15H BRAKE CONSTANT,13X,6HBRAKEC,1X,F14.3,1X,4HNONE,7X,
  114HBRAKE EXPONENT,13X,6HBRAKEX,1X,F14.3,1X,4HNONE)
32 FORMAT (25H TAPE LOAD-%ELONG. COEFF.,3X,2HC1,5X,F14.3,1X,4HNONE,
  17X,10HHUB RADIUS,17X,4HRHUB,3X,F14.3,1X,2HIN)
33 FORMAT (25H TAPE LOAD-%ELONG. COEFF.,3X,2HC2,5X,F14.3,1X,4HNONE)
34 FORMAT(25H TAPE LOAD-(FLONG. COEFF.,3X,2HC3,5X,F14.3,1X,4HNONE,7X,
  125HARRESTMENT IS SYMMETRICAL)
35 FORMAT(///51X,17HEVENT INFORMATION)
36 FORMAT(/32X,14HPARAMETER NAME,10X,6HSYMBOL,8X,5HVALUE,3X,5HUNITS)
37 FORMAT(/29X,25HVEHICLE ENGAGING VELOCITY,2X,6HVELENG,1X,F14.3,1X,
  15HKNOTS)
38 FORMAT(29X,14HVEHICLE WEIGHT,13X,6HVWEIGH,1X,F14.3,1X,3HLBS)
39 FORMAT(29X,14HVEHICLE THRUST,13X,6HVTHRUS,1X,F14.3,1X,3HLBS)
40 FORMAT(29X,8HHEADWIND,19X,6HWINDKT,1X,F14.3,1X,5HKNOTS)
41 FORMAT(29X,19HBAROMETRIC PRESSURE,8X,4HBARO,3X,F14.3,1X,7HIN HG A)
42 FORMAT(29X,19HAMBIENT TEMPERATURE,8X,5HTEMPA,2X,F14.3,1X,5HDEG F)
43 FORMAT(29X,21HCALCULATION INCREMENT,6X,6HDELTIM,1X,F14.3,1X,3HSEC)
44 FORMAT(29X,21HAERO DRAG COEFFICIENT,6X,5HVCOAD,2X,F14.3,1X,11HLB S
  1EC2/FT2)
45 FORMAT(29X,24HDECK OFF CENTER DISTANCE,3X,5HDOFFC,2X,F14.3,1X,2HFT
  1)
46 FORMAT(29X,15HTAILHOOK HEIGHT,12X,6HHOOKHI,1X,F14.3,1X,2HFT)
47 FORMAT(29X,15HTAILHOOK LENGTH,12X,6HVHKLEN,1X,F14.3,1X,2HFT)
48 FORMAT(25H TAPE LOAD-(FLONG. COEFF.,3X,2HC3,5X,F14.3,1X,4HNONE,7X,
  129HARRESTMENT IS NOT SYMMETRICAL)
   PRINT 20
   PRINT 21
   PRINT 22
   PRINT 23,DKSPAN,POFFC
   PRINT 24,PENLEN, TTHICK
   PRINT 25,PENMOD,TWGHT
   PRINT 26,PENX,TWIDE
   PRINT 27,PENDEN,TAREA
   PRINT 28,SPLITP,SPLITS
   PRINT 29,TOLENP,TOLENS
   PRINT 30,RINS,RINP
   PRINT 31,BRAKEC,BRAKEX
   PRINT 32,C1,RHUB
   PRINT 33,C2
   IF(IFLGSM.EQ.1)49,50
49 PRINT 34,C3
   GO TO 51
50 PRINT48,C3
```

```
 51 PRINT 35
    PRINT 36
    PRINT 37,VELENG
    PRINT 38,VWEIGH
    PRINT 39,VTHRUS
    PRINT 40,WINDKT
    PRINT 41,BARO
    PRINT 42,TEMPA
    PRINT 43,DELTIM
    PRINT 44,VCOAD
    PRINT 45,DOFFC
    PRINT 46,HOOKHI
    PRINT 47,VHKLEN
    PRINT 88
 88 FORMAT ( 1H1, 32X, 55HPORT AND STARBOARD KINK WAVE COORDINATES AND
   1 VELOCITIES)
    PRINT 89
 89 FORMAT ( 1H0, 11X, 6HPORT-X, 4X, 6HPORT-Y, 4X, 6HPORT-Z, 4X,
   1 6HVKINKP, 5X, 4HTIME, 15X, 6HSTBD-X, 4X, 6HSTBD-Y, 4X, 6HSTBD-Z,
   2 4X, 6HVKINKS, 5X, 4HTIME)
    PRINT 90 , XWAVEP, YWAVEP, ZWAVEP, VKINKP, TIME, XWAVES, YWAVES,
   1 ZWAVES, VKINKS, TIME
 90 FORMAT ( 10X, 5F10.3, 10X, 5F10.3)
    DATUM(1)=VELNST$DATUM(9) =TIME $DATUM(17)=TELFP$DATUM(25)=DLENS
    DATUM(2)=VRUNOT$DATUM(10)=RSPPR$DATUM(18)=RLTP $DATUM(26)=PELS2
    DATUM(3)=VHOOK $DATUM(11)=RPOP $DATUM(19)=RTINP$DATUM(27)=DELS
    DATUM(4)=VROLL $DATUM(12)=ROWP $DATUM(20)=RACPR$DATUM(28)=TELFS
    DATUM(5)=VTDRAG$DATUM(13)=TLENP$DATUM(21)=RSPSR$DATUM(29)=RLTS
    DATUM(6)=DTENP $DATUM(14)=DLENP$DATUM(22)=RPOS $DATUM(30)=RTINS
    DATUM(7)=DTENS $DATUM(15)=PELP2$DATUM(23)=ROWS $DATUM(31)=RACSR
    DATUM(8)=VACCG $DATUM(16)=DELP $DATUM(24)=TLENS$DATUM(32)=0.0
    WRITE (7) DATUM
    MAIN COMPUTATION LOOP BEGINS AT STATEMENT 100
 99 CONTINUE
100 LTCONT = LTCONT + 1
    TIME = DELTIM * LTCONT
    TEST FOR PORT TWO-BLOCK
    IF ( RHUB .LE. ROWP ) 101,1000
    TEST FOR STBD TWO-BLOCK
101 IF ( RHUB .LE. ROWS ) 102,1000
    TEST FOR INSTANTANEOUS VEHICLE VELOCITY = 0
102 IF ( VELNST .LE. 0.0 ) 1000, 103
    STATEMENT 103 BEGINS PORT CALCULATIONS
103 VELNS2 = VELNST + THDEL * (VACC + VACC2)
    VRUNO2 = VRUNOT + THDEL * (VELNST + VELNS2)
    RSPP2  = RSPP   + THDEL * (RACP   + RACP2 )
    RPOP2  = RPOP   + THDEL * (RSPP   + RSPP2)
    ROWP2  = ROWP   +  CA   * (RPOP   - RPOP2)
    RLTP = TOLENP - TLENP
    TLENP2 = TLENP  - ROWP2 * (RPOP   - RPOP2 )  / 12.0
```

```
      IF ( HYPOTP.GE.PLENP) 104,105
  104 IF(TELFP.LE..50)TELFP = .50
      ETAPEP = -160.635*TELFP**2 + 4079800.0*TELFP - 1919200.0
      CTAPEP = SQRT  (ETAPEP / TAPDEN )
      TASIGP = .5 ** .667 * (VELNS2 / CTAPEP ) ** 1.33
      VKINKP = CTAPEP * (SQRT  (TASIGP)+ TASIGP) -(TLENP2 - TLENP) /
     1 DELTIM
      GO TO 106
  105 PENMOD = PENMOD
      CPEND  = SQRT  ( PENMOD / PENDEN)
      PENSIG = .5 ** .667 * ( VELNS2 / CPEND ) ** 1.33
      VKINKP = CPEND * (SQRT  (PENSIG) - PENSIG) - (TLENP2 - TLENP ) /
     1 DELTIM
  106 XWAVEP = XWAVEP + (VKINKP * DELTIM * COS  ( GAMAXP ))
      YWAVEP = YWAVEP - (VKINKP * DELTIM * COS  ( GAMAZP) *COS (GAMAYP))
      ZWAVEP= ZWAVEP - (VKINKP * DELTIM * SIN ( GAMAZP))
      HKELEV = HOOKHI - VHKLEN * COS (1.5708-ATAN (HOOKHI/(ATTACH +
     1 VRUNO2)))
      HYPOTP = SQRT  (XWAVEP**2+ (VRUNO2-YWAVEP)**2+ (HKELEV-ZWAVEP)**2)
      RESULP = SQRT  ((DHAP - XWAVEP)**2 + YWAVEP**2 + ZWAVEP**2)
      DLENP  = HYPOTP + RESULP
      DELP   = HYPOTP + RESULP + SPLITP - TLENP2 - PLENP
      IF ( DELP .LT. 0 )107,108
  107 DELP = 0.0
  108 PELP  =  PELP2
      TELFP =  (DELP - PELP ) / TLENP2 * 100.0
      IF ( TELFP  .LE.  0  ) 109,110
  109 DTENP = TELFP = PELP2 = 0.0
  110 DTENP = C1 * TELFP **3 + C2 * TELFP **2 + C3 * TELFP
      IF (DTENP.LT. 0)      DTENP = 0
      PELP2 = PEAP  * DTENP
      RTINP = RINP + CE * (TOLENP - TLENP2 )*( CD + ( ROWP2 / 12.0)**2)
      RACP   = RACP2
      RACP2 = (DTENP * ROWP2 / 12.0 - BRAKEC * RSPP2**BRAKEX) / RTINP
      HOOKP = DTENP*COS  ( ATAN  ( XWAVEP / SQRT  (( HKELEV-ZWAVEP)
     1 **2 + (VRUNO2 -YWAVEP) **2 )))
      ALL PORT CALCULATIONS DONE - TEST NEXT FOR KINK WAVE LOCATION
      IF(XWAVEP.GE.DHAP)111,1112
  111 GAMAXP = ATAN  ( SQRT  ( HKELEV**2 + VRUNO2**2)/XWAVEP)
      GAMAYP = ATAN  ( XWAVEP / VRUNO2 )
      GAMAZP = ATAN  ( HKELEV / SQRT  ( VRUNO2**2 + XWAVEP**2 ))
      XWAVEP = 0.0
      YWAVEP = VRUNO2
      ZWAVEP = HKELEV
      HYPOTP = 0.0
 1112 IF(IFLGSM.EQ.0)112,1111
 1111 RSPS2 = RSPP2
      RPOS2 = RPOP2
      ROWS2 = ROWP2
      RLTS = RLTP
```

```
      TLENS2 = TLENP2
      VKINKS = VKINKP
      XWAVES = XWAVEP
      YWAVES = YWAVEP
      ZWAVES = ZWAVEP
      DLENS = DLENP
      DELS = DELP
      TELFS = TELFP
      DTENS = DTENP
      PELS2 = PELP2
      RACS2 = RACP2
      HOOKS = HOOKP
      GAMAXS = GAMAXP
      GAMAYS = GAMAYP
      GAMAZS = GAMAZP
      GO TO 130
C     STATEMENT 112 BEGINS STARBOARD CALCULATIONS
  112 RSPS2  = RSPS  + THDEL * ( RACS + RACS2 )
      RPOS2  = RPOS  + THDEL * ( RSPS + RSPS2 )
      ROWS2 = ROWS + CA    * ( RPOS - RPOS2 )
      RLTS = TOLENS - TLENS
      TLENS2 = TLENS - ROWS2 * ( RPOS - RPOS2 ) / 12.0
      IF (HYPOTS .GE. PLENS) 113,114
  113 IF(TELFS.LE..50)TELFS = .50
      ETAPES = -160.635*TELFS**2 + 4079800.0*TELFS - 1919200.0
      CTAPES = SQRT  (ETAPES / TAPDEN)
      TASIGS = .5 ** .667 * (VELNS2 / CTAPES ) ** 1.33
      VKINKS = CTAPES *(SQRT  (TASIGS)- TASIGS) - (TLENS2 - TLENS) /
     1DELTIM
      GO TO 115
  114 PENMOD = PENMOD
      CPEND  = SQRT  ( PENMOD / PENDEN )
      PENSIG = .5 ** .667 * ( VELNS2 / CPEND ) ** 1.33
      VKINKS = CPEND * (SQRT  (PENSIG) - PENSIG) - (TLENS2 - TLENS ) /
     1DELTIM
  115 XWAVES = XWAVES + (VKINKS * DELTIM * COS ( GAMAXS ))
      YWAVES = YWAVES - (VKINKS * DELTIM * COS  (GAMAZS) * COS (GAMAYS))
      ZWAVES = ZWAVES - (VKINKS * DELTIM * SIN  ( GAMAZS))
      HYPOTS = SQRT  (XWAVES**2+(VRUNO2-YWAVES)**2 +(HKELEV-ZWAVES)**2)
      RESULS = SQRT  (( DHAS - XWAVES)**2 + YWAVES**2 + ZWAVES**2)
      DLENS  = HYPOTS + RESULS
      DELS   = HYPOTS + RESULS + SPLITS - TLENS2 - PLENS
      IF(DELS .LT. 0 ) 116,117
  116 DELS   = 0.0
  117 PELS   = PELS2
      TELFS  = (DELS - PELS ) / TLENS2 * 100.0
      IF (TELFS .LE. 0 ) 118,119
  118 DTENS = TELFS = PELS2 = 0.0
  119 DTENS = C1 * TELFS **3 + C2 * TELFS **2 + C3 * TELFS
      IF (DTENS.LT. 0)     DTENS = 0
```

```
      PELS2 = PEAS + DTENS
      RTINS = RINS + CE * ( TOLENS - TLENS2)*( CD + (ROWS2 / 12.0 )**2)
      RACS  = RACS2
      RACS2 = ( DTENS * ROWS2 / 12.0 - BRAKEC * RSPS2** BRAKEX) /RTINS
      HOOKS = DTENS*COS  ( ATAN  ( XWAVES / SQRT  ((HKELEV-ZWAVES)
     1 **2 + (VRUNO2-YWAVES) **2 )))
      ALL STBD CALCULATIONS DONE / TEST NEXT FOR KINK WAVE LOCATION
      IF ( XWAVES .GE. DWAS ) 120,130
  120 GAMAXS = ATAN  ( SQRT  ( HKELEV**2 + VRUNO2**2)/XWAVES)
      GAMAYS = ATAN  ( XWAVES / VRUNO2 )
      GAMAZS = ATAN  ( HKELEV / SQRT  ( VRUNO2**2 + XWAVES**2 ))
      XWAVES = 0.0
      YWAVES = VRUNO2
      ZWAVES = HKELEV
      HYPOTS = 0.0
      STATEMENT 130 BEGINS FINAL CALCULATIONS
  130 VHOOK  = HOOKP + HOOKS
      VFRICT = .0002666 * VELNS2
      IF ( VFRICT .LE. .018 ) 131,132
  131 VFRICT = .018
  132 VROLL  = VFRICT * VWEIGH
      VADRAG = ( VELNS2 + WINDFT)**2 * DRAGK
      VTDRAG = VADRAG + VROLL
      VACCG  = VACC2 / 32.174
      VACC   = VACC2
      VACC2  = ( VTHRUS - VHOOK - VTDRAG)/ VMASS
      RPOP   = RPOP2
      RPOS   = RPOS2
      ROWP   = ROWP2
      ROWS   = ROWS2
      TLENP  = TLENP2
      TLENS  = TLENS2
      VELNST = VELNS2
      VRUNOT = VRUNO2
      RSPP   = RSPP2
      RSPS   = RSPS2
      RSPPR  = RSPP * 9.5493
      RSPSR  = RSPS * 9.5493
      RACPR  = RACP * 57.29578
      RACSR  = RACS * 57.29578
      SAVE MAXIMUM VALUES BEGINS AT STATEMENT 200 , ENDS AT 215
  200 IF ( AVHOOK .LT. VHOOK) 201,202
  201 AVHOOK = VHOOK                      $ ATHOOK  = TIME
  202 IF ( ADTENP .LT. DTENP) 203,204
  203 ADTENP = DTENP                      $ ATDENP  = TIME
  204 IF ( ADTENS .LT. DTENS) 205,206
  205 ADTENS = DTENS                      $ ATDENS  = TIME
  206 IF ( AVACCG .GT. VACCG) 207,208
  207 AVACCG = VACCG                      $ ATVACG  = TIME
  208 IF ( ARSPP  .LT. RSPPR) 209,210
```

```
  209 ARSPP  = RSPPR                       $ ATRSPP  = TIME
  210 IF ( ARSPS  .LE. RSPSR) 211,212
  211 ARSPS  = RSPSR                       $ ATRSPS  = TIME
  212 IF ( ARACP  .LT. RACPR) 213,214
  213 ARACP  = RACPR                       $ ATRACP  = TIME
  214 IF ( ARACS  .LT. RACSR) 215,216
  215 ARACS  = RACSR                       $ ATRACS  = TIME
C     MAIN LOOP OUTPUT AND TAPE STORE LOGIC BEGINS HERE
  216 CONTINUE
      IF(TIME.EQ.0)GO TO 300
      IGL = IGL + 1
      IF(IGL.EQ.10)402,400
  402 IGL = 0
  300 DATUM(1)=VELNSTSDATUM(9) =TIME $DATUM(17)=TELFPSDATUM(25)=DLENS
      DATUM(2)=VRUNOTSDATUM(10)=RSPPRSDATUM(18)=RLTP $DATUM(26)=PELS2
      DATUM(3)=VHOOK $DATUM(11)=RPOP $DATUM(19)=RTINPSDATUM(27)=DELS
      DATUM(4)=VROLL $DATUM(12)=ROWP $DATUM(20)=RACPRSDATUM(28)=TELFS
      DATUM(5)=VTDRAGSDATUM(13)=TLENPSDATUM(21)=RSPSRSDATUM(29)=RLTS
      DATUM(6)=DTENP $DATUM(14)=DLENPSDATUM(22)=RPOS $DATUM(30)=RTINS
      DATUM(7)=DTENS $DATUM(15)=PELP2SDATUM(23)=ROWS $DATUM(31)=RACSR
      DATUM(8)=VACCG $DATUM(16)=DELP $DATUM(24)=TLENSSDATUM(32)=0.0
      WRITE (7) DATUM
  400 IF(TIME.LE.3.0)301,304
  301 IF(LTCONT-10*JTIME)304,302,302
  302 PRINT 90 , XWAVEP, YWAVEP, ZWAVEP, VKINKP, TIME, XWAVES, YWAVES,
     1  ZWAVES, VKINKS, TIME
  303 JTIME = JTIME + 1
  304 GO TO 99
C     MAIN COMPUTATION LOOP DONE FINAL OUTPUT BEGINS WITH STATEMENT 1000
 1000 REWIND 7
C     PRINT OUT MAXIMUM VALUES OF PARAMETERS AND TIME OF OCCURANCE
      PRINT 1001
 1001 FORMAT (43X,7HMAXIMUM, 24X, 4HTIME )
      PRINT 1002, AVHOOK, ATHOOK
 1002 FORMAT (10H HOOKLOAD, 28X, F12.4, 3H LB, 13X, F10.4, 4H SEC)
      PRINT 1003, ADTENP, ATDENP
 1003 FORMAT (19H  TAPE TENSION-PORT,19X,F12.4,3H LB,13X,F10.4,4H SEC)
      PRINT 1004, ADTENS, ATDENS
 1004 FORMAT (19H  TAPE TENSION-STBD,19X,F12.4,3H LB,13X,F10.4,4H SEC)
      PRINT 1005, AVACCG, ATVACG
 1005 FORMAT (22H  VEHICLE DECELERATION, 16X, F12.4, 4H G S, 12X, F10.4,
     1 4H SEC)
      PRINT 1006, ARSPP, ATRSPP
 1006 FORMAT (17H  REEL SPEED-PORT,21X,F12.4,4H RPM,12X,F10.4, 4H SEC)
      PRINT 1007, ARSPS, ATRSPS
 1007 FORMAT (17H  REEL SPEED-STBD,21X,F12.4,4H RPM,12X,F10.4, 4H SEC)
      PRINT 1008, ARACP, ATRACP
 1008 FORMAT (24H  REEL ACCELERATION-PORT, 14X, F12.4, 7H RPM SQ, 9X,
     1 F10.4, 4H SEC)
      PRINT 1009, ARACS, ATRACS
```

```
1009 FORMAT (24H  REEL ACCELERATION-STBD, 14X, F12.4, 7H RPM SQ, 9X,
    1 F10.4, 4H SEC)
1010 JTIME = 1
1050 JCOUNT = 0
     PRINT 1052
1052 FORMAT (9H1 VEHICLE)
     PRINT 1054
1054 FORMAT (106H0   VELOCITY     RUNOUT    HOOKLOAD    ROLL FRICT  TOT
    1AL DRAG  TENSION/P    TENSION/S  ACCELERATION   TIME)
     PRINT 1056
1056 FORMAT (106H     FT/SEC        FT          LB          LB
    1 LB          LB          LB         G            SEC,//)
1058 READ (7) DATUM
1060 LTCONT = DATUM(9)*1000.0
     IF(LTCONT-10*JTIME)1058,1064,1064
1064 PRINT 1066, ( DATUM (I) , I = 1,9 )
     IF(DATUM(9).GE.2.0)1063,1065
1063 JTIME = JTIME + 10
     GO TO 1068
1065 JTIME = JTIME + 1
1066 FORMAT (7F12.2,F12.4,F12.8)
1068 TIM = TIME-.01
     IF(DATUM(9).GE.TIM)1072,1070
1070 JCOUNT = JCOUNT + 1
     IF ( JCOUNT .GE. 50 ) 1050,1058
1072 REWIND 7
1073 JTIME = 1
1074 JCOUNT = 0
     PRINT 1076
1076 FORMAT (11H1 PORT SIDE)
     PRINT 1078
1078 FORMAT (108H    REEL     REEL     RADIUS    TAPE    HOOK PT    PEND
    1 TOTAL    ELONG      TAPE    TAPE ON      TOTAL         REEL)
     PRINT 1080
1080 FORMAT (116H   SPEED   POSITION    WRAP   ON DECK TO SHEAVE  ELONG
    1 ELONG  FACTOR    TENSION    REEL     INERTIA       ACC      TIME)
     PRINT 1082
1082 FORMAT (116H    RPM       RAD          IN       FT         FT       FT
    1  FT       %         LB         FT    SLUG-FT SQ   RPM SQ     SEC)
1084 READ (7) DATUM
1086 LTCONT = DATUM(9)*1000.0
     IF(LTCONT - 10*JTIME)1084,1090,1090
1090 PRINT 1092, ( DATUM(I), I=10,17 ), DATUM(6), DATUM(18),
    1 DATUM(19), DATUM(20), DATUM(9)
     IF(DATUM(9).GE.2.0)1087,1091
1087 JTIME = JTIME + 10
     GO TO 1094
1091 JTIME = JTIME + 1
1092 FORMAT (F9.3,F10.3,F9.3,F8.2,F9.3,2(F8.3),F8.4,F10.1,F8.2,F12.3,
    1F11.3,F8.3)
```

```
1094 TIM = TIME-.01
     IF(DATUM(9).GE.TIM)1098,1096
1096 JCOUNT = JCOUNT + 1
     IF ( JCOUNT .GE. 50 ) 1074,1084
1098 REWIND 7
     JGEOR = JGEOR + 1
2000 STOP
     END
```

APPENDIX B - VARIABLE NAMES, TYPES, DEFINITIONS, AND UNITS (NAMES ENDING WITH THE LETTER "P" REPRESENT PORT SIDE VALUES; THOSE ENDING IN "S" REPRESENT THE CORRESPONDING STARBOARD VALUES)

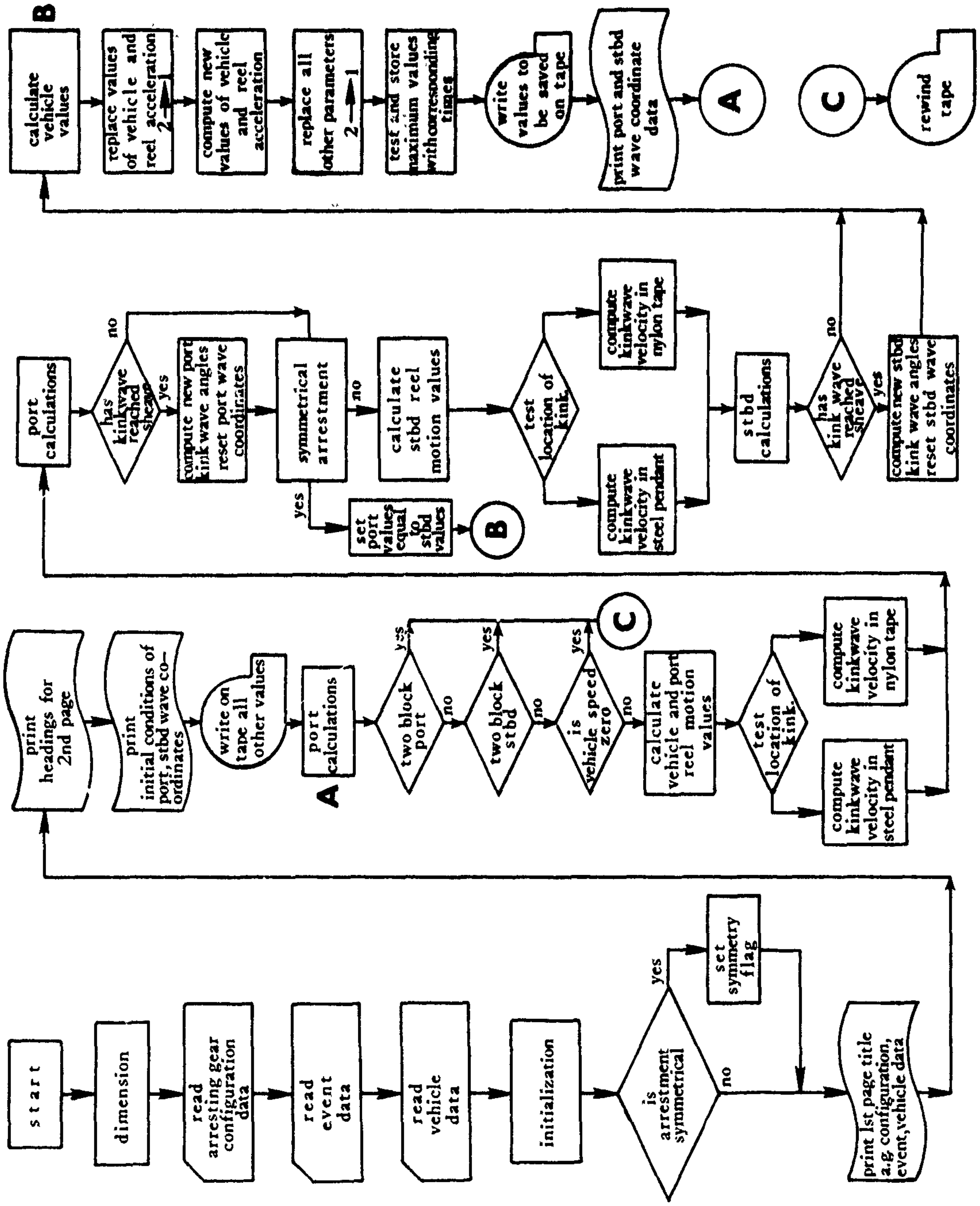
Variable Name	Type: Input	Type: Output	Type: Intermediate	Definition	Units
ADTENP(S)		X		Maximum tape tension	Lb
ARACP(S)		X		Maximum reel angular acceleration	Rad/Sec^2
ARSPP(S)		X		Maximum reel angular velocity	Rad/Sec
ATDENP(S)		X		Time at which AVHOOK occurs	Sec
ATHOOK		X		Time at which ADTENP(S) occurs	Sec
ATRACP(S)		X		Time at which ARACP(S) occurs	Sec
ATRSPP(S)		X		Time at which ARSPP(S) occurs	Sec
ATVACG		X		Time at which AVACCG occurs	Sec
AVACCG		X		Maximum vehicle acceleration	G
AVHOOK		X		Maximum vehicle arresting-hook axial load	Lb
BARO	X			Barometric pressure	In. Hg
BRAKEC	X			Tape reel brake constant	None
BRAKEX	X			Water brake exponent	None
C1	X			Coefficient for tape tension equation	None
C2	X			Coefficient for tape tension equation	None
C3	X			Coefficient for tape tension equation	None
CA			X	$\frac{\text{Tape thickness}}{2\pi}$	In.
CD			X	$\left(\frac{\text{Hub radius}}{12}\right)^2$	Ft^2
CE			X	$\frac{\text{Tape weight per foot}}{2g}$	$\frac{Lb\text{-}Sec^2}{Ft}$
CPEND			X	Stress propagation velocity-pendant	Ft/Sec
CTAPEP(S)			X	Stress propagation velocity-tape	Ft/Sec
DATUM(32)			X	Linear array dimension	None
DELP(S)			X	Total elongation (tape and pendant)	Ft
DELTIM	X			Incremental time for each calculation	Sec
DHAP(S)			X	Distance - sheave to point of engagement	Ft
DKSPAN	X			Distance between runway-edge sheaves	Ft
DLENP(S)			X	3D distance, hook-point-to-kink-to-sheave	Ft
DOFFC	X			OFF-CENTER engaging distance (starboard +)	Ft
DRAGK			X	Drag factor	$\frac{Lb\text{-}Sec^2}{Ft^2}$
DTENP(S)			X	Tension in tape and pendant	Lb

Variable Name	Type: Input	Type: Output	Type: Intermediate	Definition	Units
ETAPEP(S)			X	Tape modulus of elasticity	Lb/Ft^2
GAMAXP(S)			X	Angle, initial pendant position-to-sheave-to-kink	Deg
GAMAYP(S)			X	Angle, intersection of line of engagement and projection of line from sheave to kink	Deg
GAMAZP(S)			X	Angle, kink-to-sheave-to-projection of kink on deck	Deg
HKELEV			X	Hook point elevation at any instant	Ft
HOOKHI	X			Elevation of hook attach point on vehicle	Ft
HOOKP(S)			X	Component of arresting-hook axial load	Lb
HYPOTP(S)			X	3D distance, hook point to kink	Ft
ICOUNT			X	Output printer line counter	None
IFLGSM			X	Engagement symmetry flag	None
IGL			X	Output generation increment counter	None
JCOUNT			X	Line counter	None
JGEOR			X	Program sequential run indicator	None
LTCONT			X	Calculation increment counter	None
PEAP(S)			X	Used to segment pendant elongation equation	$\frac{1}{Lb\text{-}Ft^3}$
PELP(S)			X	Pendant elongation	Ft
PENDEN	X			Pendant density	$\frac{Lb\text{-}Sec^2}{Ft^4}$
PENLEN	X			Total unelongated pendant length (eye-to-eye)	Ft
PENMOD	X			Modulus of elasticity of the pendant	Lb/Ft^2
PENSIG			X	Transverse impact equation approximation for pendant	None
PENX	X			Pendant cross-sectional area	$In.^2$
PLENP(S)			X	Pendant length (unelongated)	Ft
POFFC	X			Pendant off-center distance (starboard +)	Ft
RACP(S)			X	Reel angular acceleration	Rad/Sec^2
RACP(S)R			X	Reel angular acceleration	Rev/Min^2
RESULP(S)			X	3D distance, kink to sheave	Ft
RHUB	X			Tape reel hub radius	In.
RINP(S)	X			Tape-reel inertia (metal)	$Slug\text{-}Ft^2$
RLTP(S)			X	Length of tape on reel (not on deck)	Ft
RNUIP(S)			X	Initial number of tape wraps on reel	None

Variable Name	Type: In-put	Out-put	Inter-me-diate	Definition	Units
ROWP(S)			X	Tape outer wrap radius	In.
RPOP(S)			X	Reel angular position (beginning of time increment)	Rad
RPOP2(S2)			X	Reel position (end of time increment)	Rad
RSPP(S)			X	Reel angular velocity	Rad/Sec
RSPP(S)R			X	Reel angular velocity	Rev/Min
RTINP(S)			X	Total reel inertia	Slug-Ft^2
SPLITP(S)	X			Split distance (from runway sheave to tape reel)	Ft
TAPDEN			X	Tape density	$\frac{\text{Lb-Sec}^2}{\text{Ft}^4}$
TAREA			X	Tape cross-sectional area	In.^{2}
TASIGP(S)			X	Transverse impact equation approximation for tape	None
TELFP(S)			X	Tape elongation factor	%
TEMPA	X			Temperature (ambient)	$^\circ$ F
THDEL			X	$\frac{\text{DELTIM}}{2}$	Sec
THETAP(S)			X	Kink angle	Deg
TIME			X	Absolute accumulative time	Sec
TINP(S)			X	Initial length connector to sheave	Ft
TLENOP(S)	X			Initial tape on deck	Ft
TLENP(S)			X	Tape on deck at beginning of time increment	Ft
TLENP2(S2)			X	Tape on deck at end of time increment	Ft
TOLENP(S)			X	Total purchase-tape length	Ft
TTHICK	X			Purchase-tape thickness	In.
TWGHT	X			Purchase-tape unit weight	Lb/Ft
TWIDE	X			Purchase-tape width	In.
VACC			X	Vehicle acceleration at the beginning of the time increment	Ft/Sec^2
VACC2			X	Vehicle acceleration at the end of the time increment	Ft/Sec
VACCG			X	$\frac{\text{Vehicle acceleration}}{32.17}$	G
VADRAG			X	Vehicle aerodynamic drag	Lb
VCOAD	X			Vehicle coefficient of aerodynamic drag	None
VELENG	X			Vehicle engaging speed	Kn
VELNST			X	Vehicle speed at beginning of time increment	Ft/Sec
VELNS2			X	Vehicle speed at end of time increment	Ft/Sec
VFRICT	X			Coefficient of rolling resistance	None
VHKLEN	X			Vehicle arresting-hook length	Ft
VHOOK			X	Vehicle arresting-hook axial load	Lb

Variable Name	Type: In-put	Type: Out-put	Type: Inter-me-diate	Definition	Units
VKINKP(S)			X	Kink-wave velocity	Ft/Sec
VMASS			X	Vehicle mass	$\frac{Lb\text{-}Sec^2}{Ft}$
VROLL			X	Vehicle rolling resistance load	Lb
VRUNOT			X	Vehicle runout at beginning of time increment	Ft
VRUNO2			X	Vehicle runout at the end of time increment	Ft
VTDRAG			X	Vehicle total drag	Lb
VTHRUS	X			Vehicle thrust	Lb
VWEIGH	X			Vehicle weight	Lb
WINDFT			X	Head-wind velocity	Ft/Sec
WINDKT	X			Head-wind velocity	Kn
XWAVEP(S)			X	Kink X-distance from point of engagement	Ft
YWAVEP(S)			X	Kink Y-distance from point of engagement	Ft
ZWAVEP(S)			X	Kink Z-distance from point of engagement	Ft

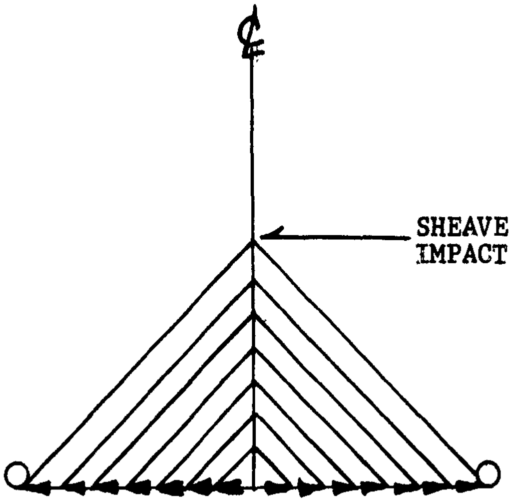
APPENDIX C - GENERAL FLOW CHART

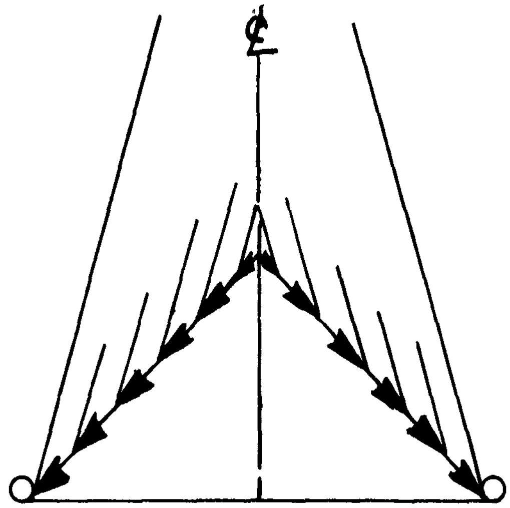


APPENDIX D - DETERMINATION OF KINK-WAVE VELOCITY

1. The location of the kink wave with time is an important factor in the mathematical model design. The kink wave's position on the runway determines the overall pendant/tape geometry which governs the operation of the program. The change in runway geometry directly affects the two most important arrestment parameters: tape tension and arresting-hook load.

2. The location of the kink wave is determined by its velocity alone because its path is predetermined by model design. In this model, the kink wave, upon hook impact with the pendant, follows a straight line path from the position of hook impact to the runway-edge sheave (kink one). Upon impact on the sheave, it then follows a new path which is a straight line from the position of the hook at sheave impact to the runway-edge sheave (kink two). The establishment of kink-wave paths is illustrated below:





3. The approach to the problem of determining kink-wave velocity is based on information presented in "Cable Dynamics" by F. O. Ringleb (reference (a) of basic text), and the method of solution presented here follows from his work.

4. It is assumed that the arresting hook of the aircraft engages the pendant perpendicularly and results in transverse impact. A triangle-shaped deformation is formed in the pendant due to impact. A stress wave propagates along the pendant toward the sheaves with a finite

velocity ahead of and faster than the deformation. The velocity at which the kink wave propagates along the pendant while this is happening is established below:

NOTE: Ringleb's analysis applies only to an infinitely long cable. The assumptions made in the model design are: 1, The calculation of the kink-wave velocity in the purchase-tape media follows the same principles that pendant calculations are based on and 2, the equations of motion described are used even after kink one reflects off of the runway-edge sheave and the pendant/tape configuration no longer appears to be like an infinitely long cable.

Letting:

E = modulus of elasticity of pendant (tape)

ρ = mass density of pendant (tape)

σ = stress

σ_0 = initial stress

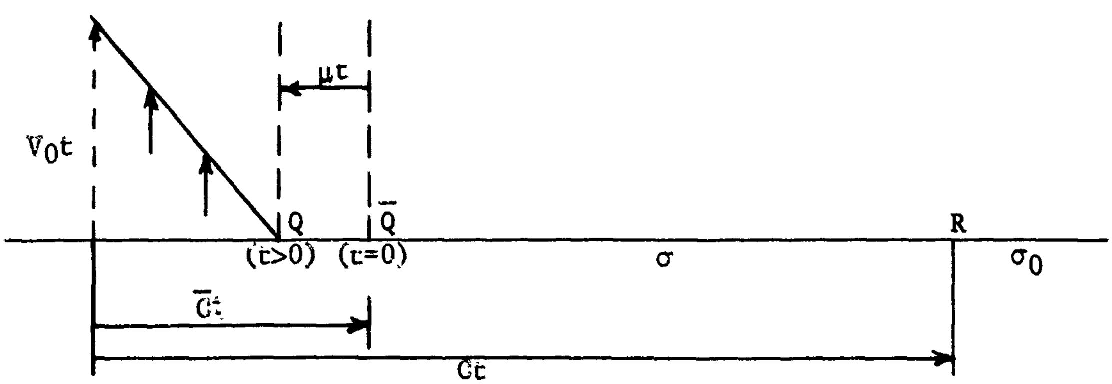
Then from the classical theory of a vibrating string, the longitudinal wave velocity C is:

$$C = \sqrt{\frac{E}{\rho}}$$

and the transverse wave velocity $\bar{C}$ is

$$\bar{C} = \sqrt{\frac{\sigma}{\rho}} .$$

C is the velocity of stress propagation in the medium of concern, and $\bar{C}$ is the velocity that the deformation propagates with respect to a particular defined mass point in the media (pendant) at time of impact ($t = 0$). The following diagram shows a segment of the pendant impact:



In the preceding diagram, the motion of a point mass $\overline{Q}$ of the pendant at time 0 is analyzed to define kink-wave motion. After impact, t >0, this point mass is designated Q and marks the location of the kink wave on its way toward the sheave. R represents the point that the stress has reached at t > 0. The point $\overline{Q}$ moves toward the right with the transverse wave velocity $\overline{C}$ while the pendant segment QR moves toward the left with a velocity μ (from the longitudinal impact formula $\sigma - \sigma_0/E = \mu/C$). Thus the velocity of the kink wave, W, is given by the relationship $W = \overline{C} - \mu$. Now, $\overline{C}$ can be expressed in terms of E and σ since

$$C = \sqrt{\frac{E}{\rho}} \text{ it follows that } \frac{1}{\sqrt{\rho}} = \frac{C}{\sqrt{E}}$$

so that substituting $\frac{C}{\sqrt{E}}$ for $\frac{1}{\sqrt{\rho}}$ into the formula for $\overline{C}$ gives

$$\overline{C} = \sqrt{\frac{\sigma}{\rho}} = \sqrt{\frac{1}{\rho}} \times \sqrt{\sigma} = \frac{1}{\sqrt{\rho}} \times \sqrt{\sigma} = \frac{C}{\sqrt{E}} \times \sqrt{\sigma} = C\sqrt{\frac{\sigma}{E}},$$

the kink-wave velocity can therefore be expressed as

$$W = C\left(\sqrt{\frac{\sigma}{E}} - \frac{\sigma - \sigma_0}{E}\right).$$

5. An expression for the term $\frac{\sigma-\sigma_0}{E}$, which represents an approximation of the transverse impact formula (reference (a) of main text), is given as,

$$\frac{\sigma - \sigma_0}{E} = \left(\frac{1}{2}\right)^{2/3} \left(\frac{V_0}{C}\right)^{4/3},$$

where V_0 is the impact velocity. So that finally, the kink-wave velocity for an infinitely long cable is:

$$W = C\left(\sqrt{\frac{\sigma}{E}} - \left(\frac{1}{2}\right)^{2/3} \left(\frac{V_0}{C}\right)^{4/3}\right).$$

NOTE: The kink-wave velocity in this model is computed with this equation modified with an additive factor accounting for the tape "feed in" velocity as the tape reel responds to the acceleration forces during an actual arrestment.

APPENDIX E - DETERMINATION OF THE MODULUS OF ELASTICITY

1. The value of modulus of elasticity for both steel (pendant) and nylon (tape) is required in the program to account for kink-wave motion. The value for the pendant is a constant value and is input into the program. The value for nylon tape varies with tape stretch and an expression must be derived to represent it. Therefore, a mention of elasticity theory and the method of derivation of an appropriate modulus equation for nylon tape follows.

2. The modulus of elasticity is a measure of the effect that tension has on a material. Many materials exhibit a stretching (deformation) in direct proportion to the amount of tension applied (loading). This relationship is given by Hooke's law:

$$E = \frac{S}{\epsilon} .$$

where E = modulus of elasticity lb/in.^{2},

S = stress lb/in.^{2},

and ϵ = strain in./in.

If L = original length of material,

A = original area of material,

P = applied tension load,

and δ = elongation of material,

then

$$S = P/A \text{ and } \epsilon = \delta/1$$

so that

$$E = \frac{PL}{A\delta} .$$

Plotting P/A against δ/L, we obtain the typical stress-strain curve:

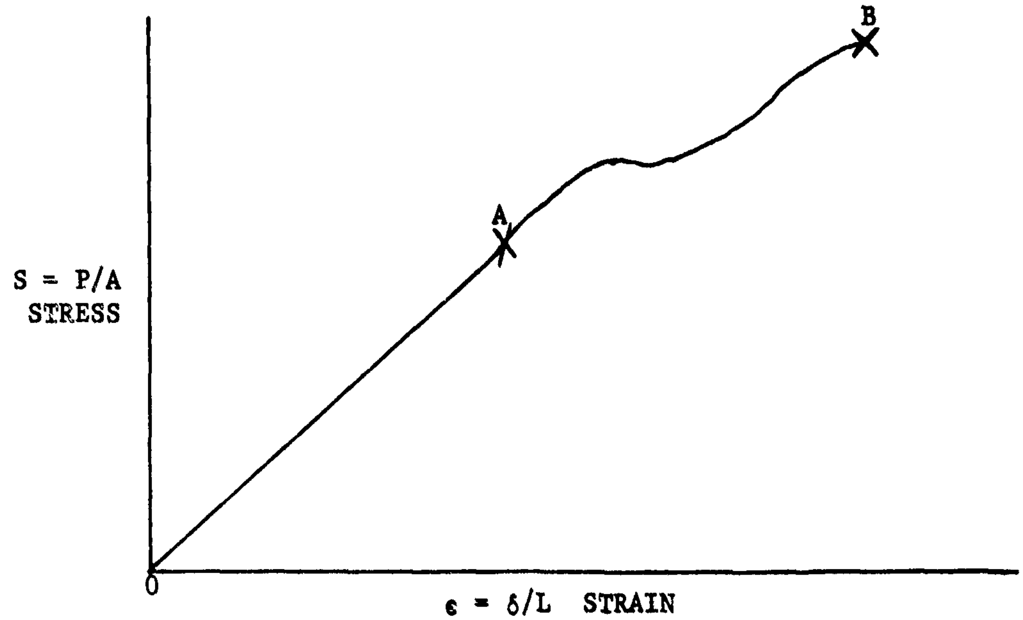


Figure E1

Line OA is linear and represents the elastic range of a material. In this range, no permanent deformations are produced by stresses. Hooke's law applies only in this region. Curve AB represents the plastic range of a material. Here, permanent deformations or sets occur upon applied loading. Point B shows where the test material fails. The slope of the line OA is the modulus of elasticity of the material. Stresses and strains along this line follow the "linear theory of elasticity".

3. Modulus of Elasticity of Steel Pendant: The stress-strain diagram for a steel pendant closely resembles that of Figure E1. The value of modulus used in the program is taken from data for steel wire cables with hemp core containing 6 strands with 19 wires each. The value is $E = 13{,}000{,}000\ \mathrm{lb/in.}^2$ (page 13 of reference (a) of basic text). This value varies considerably from that of steel--$E = 30{,}000{,}000\ \mathrm{lb/in.}^2$--indicating that a pendant of this type is less stiff than a corresponding solid element.

4. <u>Modulus of Elasticity of Nylon Tape</u>: Due to the inhomogeneity of the nylon threads and the fabric nature of nylon tapes, the stress-strain diagram representing the tensile test of a piece of nylon tape differs considerably from that of Figure E1:

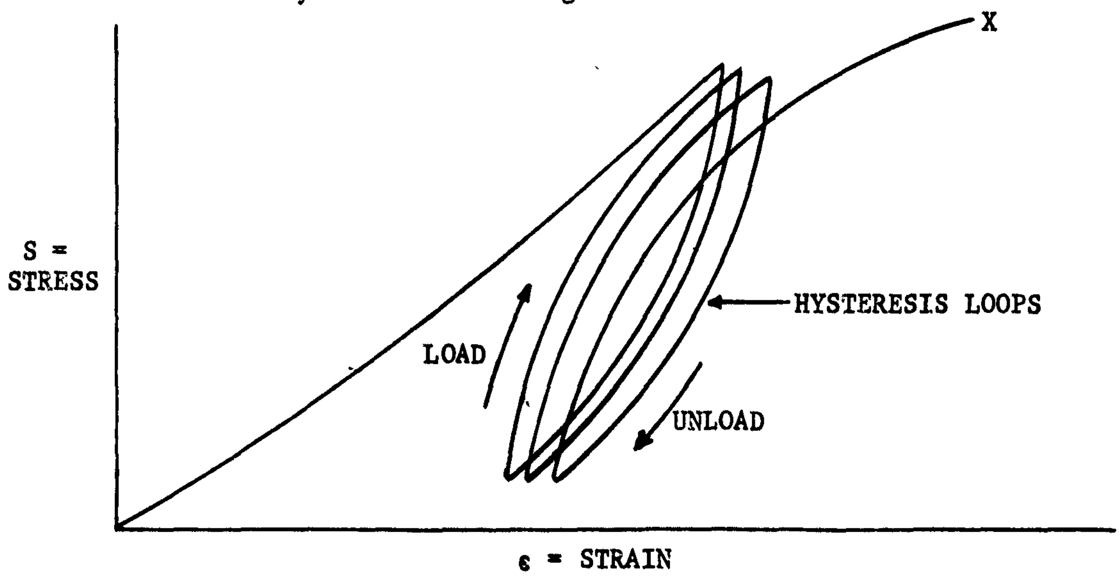


Figure E2

Nylon tape used on the arresting gears are actually plastic in nature. When a load is applied to a specimen in stepped increments and then unloaded, the curve representing this action does not return to where it originated but shows evidence of permanent tape elongation. Upon repeated loadings and unloadings, loops are formed representing the tape's inelasticity. After the initial pull, the loops that are generated originate in approximately the same area. Also, the plastic deformations are somewhat predictable and therefore can be thought of as uniform plastic deformations. For these reasons, a value for modulus of elasticity of nylon tape can be obtained by considering the uniform plastic deformation to be elastic in nature and thereby obtain an approximate value for the modulus by applying elastic theory methods (modulus is slope of stress-strain curve) to the curves.

5. <u>Procedure</u>

a. Obtain pull-test data for particular nylon tape from the NAVAIRTESTFAC Engineering Department Recovery Division (load lb - stretch in.).

b. Convert data to a stress-percent tape elongation curve.

c. Curve fit best 3rd-degree curve through data to obtain equation that represents stress as a function of strain.

d. Differentiate equation to obtain a new equation that represents the slope of the stress-strain curve and is the modulus of the tape as a function of tape elongation.

APPENDIX F - DETERMINATION OF TAPE-REEL ACCELERATION

1. Tape-reel acceleration is one of the key "motion producing" parameters of the program (see Simulated Arrestment Description, Section V of main text). The importance of this parameter necessitates an explanation of the equations that represent it.

2. Tape-Reel Acceleration: The equation for angular acceleration of the tape reel is obtained from the relationship:

$$\Sigma T = I\alpha,$$

where ΣT = sum of the torques acting on the reel and rotor,

I = polar moment of inertia of the rotating reel,

and α = angular acceleration of the reel and rotor.

a. The ΣT term is the sum of the torque created by the tape tension force applied at the radius of the outer wrap of the tape (T_{tt}) and the retarding torque developed in the water brake (T_{wb}),

or $$\Sigma T = T_{tt} + T_{wb}$$

(1) $T_{tt} = T_t\ R_t$

where T_t = purchase-tape tension

and R_t = radius of outer tape wrap on the reel.

(2) $T_{wb} = B \cdot w^n$

where B = hydrodynamic brake constant,

w = angular velocity of reel and rotor,

and n = brake exponent (constant).

The two constants, B and n, are obtained from actual test data of a particular type gear. When the value of angular velocity w reaches its maximum value for a test event, then the angular acceleration is minimized. Assuming that it becomes zero, $\alpha = 0$ and $w = w_m$ (maximum angular acceleration), from the original equation,

$$\Sigma T = I\alpha = 0$$

so that $$\Sigma T = T_t\ R_t + B\ w_m^n = 0,$$

or $$T_t\ R_t = B\ w_m^n\ .$$

The values of T_t and R_t are obtained from the test data at the time corresponding to the maximum angular velocity W_m. The values of B and n are then obtained by using the method of least squares.

b. The I term is the sum of the tape-reel (metal) inertia I_m and the instantaneous tape inertia I_t $I = I_M + I_t$.

(1) The value of tape-reel inertia I_M is a constant value and is equal to 114 slug - ft for the E-28 arresting gear.

(2) The value of the tape inertia I_t varies as the tape is pulled off of the reel and is obtained by the expression

$$I_t = \frac{1}{2}M\ (R_H^2 + R_t^2)$$

where M = instantaneous tape weight / g,

R_H = reel hub radius,

and R_t = instantaneous radius of outer tape wrap.

c. Upon rearrangement of the described terms in the original equation, the expression for tape-reel acceleration, α, is:

$$\alpha = \frac{\Sigma T}{I} = \frac{T_{tt} + T_{wb}}{I_M + I_t} = \frac{T_t\ R_t + Bw^n}{I_M + \frac{1}{2}M\ (R_H^2 + R_t^2)}\ .$$

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13. ABSTRACT

This mathematical model is designed to provide predicted dynamic performance data of shorebased rotary-hydraulic-type aircraft arresting gears. A Navy Model E-28 arresting gear is used for specific comparison between predicted results of the computer solution and actual test results. The simulation of an arrestment of a vehicle under a particular set of conditions is accomplished by putting information (data) into the computer. The input data specifies values for the installation geometry and mechanical properties of the arresting system and the test vehicle. Predicted dynamic values of forces and motions of the test vehicle, purchase system, and tape reel are printed out versus time at a predetermined incremental time.

This report is a phase report on the development of the model and contains the early analytical design approaches, the most current analytical approach with the computer program, and instructions for execution of the computer program.

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