A STUDY OF THE EFFECT OF DIFFERENT CAM DESIGNS ON MARK 7 MOD 1 --ETC(U)

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A STUDY OF THE EFFECT OF
DIFFERENT CAM DESIGNS ON MARK 7
MOD 1 ARRESTING GEAR PERFORMANCE

Launching and Recovery Division
Ship Installations Engineering Department
Naval Air Engineering Center
Lakehurst, New Jersey 08733

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A Study of the Effect of Different Cam Designs on Mark 7 Mod 1 Arresting Gear Performance

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Computer Program Performance Simulation
Mark 7 Mod 1 Arresting Gear
Control Valve Cam

This report develops a hydraulic simulation program for the Mark 7 Mod 1 Arresting Gear. It also compares theoretical performance with aircraft arrestments using different cam profiles. The present cam, rotated on its dwell, provides as much hydraulic load reduction as any new cam design.
A. PROCEDURES AND RESULTS

1. In order to predict the theoretical performance of the Mark 7 Mod 1 Arresting Gear, a computer program was written that attempted to simulate actual recovery operations. The output of this program was compared to experimental results in order to verify its reliability. Once this check was accomplished, new cam designs as well as the existing K-5 cam, rotated on its dwell, were used as inputs in order to compare the effects of each set of coordinates on recovery gear performance. The table below lists the results for peak operating conditions with the corresponding ram strokes.

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<tr>
<td>K-5 (118&quot;)</td>
<td>50000</td>
<td>111</td>
<td>10000</td>
</tr>
<tr>
<td>Rotated K-5 (122&quot;)</td>
<td>50000</td>
<td>111</td>
<td>9600</td>
</tr>
<tr>
<td>Rotated K-5 (126&quot;)</td>
<td>50000</td>
<td>111</td>
<td>9200</td>
</tr>
<tr>
<td>New Cam Design (122&quot;)</td>
<td>50000</td>
<td>111</td>
<td>9600</td>
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B. CONCLUSIONS

1. Since the rotated K-5 cam provides the same reduction in load as a new cam design, it is not necessary to replace the existing K-5 cam with any new cam.

C. RECOMMENDATIONS

1. Adopt the procedure for rotating cams as outlined in Mark 7 Service Bulletin 300 to all Mark 7 Mod 1 ships.

2. Study the effect of cam rotation on Mark 7 Mod 2 and Mark 7 Mod 3 ships.
PREFACE

The arresting gear systems aboard present ships contain hydraulic engines that develop retarding forces to arrest landing aircraft. The cams, which are driven by the ram stroke of the engine, act as control devices in regulating the fluid flow through the constant runout valve.

The present Mark 7 Mod 1 Arresting Gear has a 118.1-inch ram stroke, at 18:1 reeve ratio, a deck span of 95 feet, and is equipped with a K-5 cam. The maximum allowable MEC pressure is 10,000 psi, and it has an energy absorbing capacity of $31 \times 10^6$ ft-lbs.

The upper balanced constant runout valve insures positive closure and allows for extended ram travel through a rotated cam or new cam design. After the 122-inch radial coordinate, cable stretch provides payout which can be used by rotating the cam to the 126-inch mark. This study shows how the additional service stroke increases the energy absorbing capability of the gear.
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I. INTRODUCTION

This study is intended to investigate the feasibility of new cam configurations aboard Mark 7 Mod 1 ships. Present cam contours on these ships have service strokes of 118 inches. There is, however, within the engine framework additional available ram travel that had been previously used for cross-head battery positioning and two-block safety distance. Since the installation of the upper balanced control valve insures positive closure and limited ram overtravel, allowances for crosshead battery positioning and two-block safety distance can be reduced. Thus, in effect, usable engine ram travel can be increased for operational purposes.
II. EQUIPMENT AND PROCEDURES

The first step in this study was to write a computer program that simulated aircraft arrestments. To do this, the layout of the Mark 7 Mod 1 gear was drawn and the interaction of the various components analyzed. Once these descriptions and interactions were understood, they were formulated into engineering equations, assembled into logical order, and detailed into a computer program.

The computer program was subject to test. Certain relationships, (i.e. mechanical efficiency and velocity coefficients) were unknown and to best approach the values of these variables, a trial and error procedure was used. That is, with the core of the program described mathematically, the unknown variables were used as inputs into the program. Repeated inputs of these variables over a wide range of aircraft velocities and weights finally evolved a set of numbers that, over a select range of aircraft arrestment histories, gave the best hypothetical simulation in comparison to the known experimental results. These "numbers" were then put into a curve-fit program and one equation for each of the relationships was formulated. Mechanical efficiency and velocity coefficients are discussed in the analysis section of this report.

Results from the program proved compatible with existing test data from the RALS. Both sets of data, the theoretical and experimental, considered the K-5 cam as part of the arresting-system configuration. The next step was to develop new cam coordinates over extended strokes and to investigate the effect of these coordinates on recovery gear performance. Various layouts were designed and the coordinates used as inputs. Because of the physical structure of the arresting gear, the tolerances needed for cross-head positioning and safety stops, and the fact that cable stretch occurs during an arrestment, the maximum "new cam design" set of coordinates could be increased to 122 vs. 118." (Cable stretch over the next four inches and rotation of the "new cam design" would provide for the maximum service stroke of 126".) The K-5 cam could be rotated on its dwell 8" from 118 to 126".

The actual layouts of these cam designs, and the pressure cards developed from their use, are shown in the results of this study.
III. ANALYSIS

A. It is intended in this analysis to show the mathematical equations used in the computer program, a theoretical discussion of the unknown variables (i.e. mechanical efficiency, and velocity coefficient) developed in the program, and the design conditions established to improve performance.

1. RUNOUT. Aircraft runout is defined from the point of intersection of the aircraft hook to the final position where the aircraft stops. Given an engaging velocity, ACVEL, aircraft runout is defined as

   a. \[ \text{RUNOUT} = \text{RUNOUT} + \text{ACVEL} \times \text{TIME} \] (PT)

   where (PT) references any variable from a previous time and TIME is the incremental period over which the calculation is made.

2. CABLE LENGTH. Cable length is the measure of distance of any one cable from the point of engagement to the sheaves on deck.

   a. \[ \text{CBLNTH} = (\text{RUNOUT}^2 + \text{HSPAN}^2)^{\frac{1}{2}} \]

      where HSPAN = 1/2 the deck pendant length.

3. PAYOUT. Cable payout is the amount of cable fed from the engine that is transferred to the carrier deck.

   a. \[ \text{CBLPOU} = \text{CBLNTH} - \text{HSPAN} \] or in terms of cable fed from the engine.

   b. \[ \text{CBLPOU} = 2 \times \text{NSHVES} \times \text{STROKE} \]

      where NSHVES = number of movable sheaves any one cable is attached to, stroke is the ram-stroke of the engine, and (2) is the mechanical advantage of the system.

4. RAMSTROKE. Can be defined as the distance the crosshead moves along its guided tracks and from equation 3b.

   a. \[ \text{STROKE} = \frac{\text{CBLPOU}}{2 \times \text{NSHVES}} \] and from 3a.

   b. \[ \text{STROKE} = \frac{\text{CBLNTH} - \text{HSPAN}}{2 \times \text{NSHVES}} \]

5. RUNOUT ANGLE. Knowing the runout and the length of cable on deck, from a right triangle it is easily seen that

   a. \[ \cos (\theta) = \frac{\text{RUNOUT}}{\text{CBLNTH}} \]
6. CABLE VELOCITY. Given an engaging velocity of the airplane as ACVEL, the velocity of the cable it hooks is

\[ \text{CBLVEL} = \frac{\text{ACVEL}}{\cos(\theta)} \]

7. RAM VELOCITY. The cable, through a system of sheaves whose effect is neglected in this analysis, is connected to the crosshead which drives the ram. The crosshead contains 9 upper and 9 lower sheaves. One cable from the deck is reeved through one set of these sheaves in one bank, and since there are two banks per crosshead

\[ \text{RAMVEL} = \frac{\text{CBLVEL}}{2 \times \text{NSHVES}} \]

8. MAIN ENGINE CYLINDER PRESSURE. With the ram set in motion by the arresting wire rope, there is a subsequent build up of retarding "forces" within the cylinder. This force is actually the cylinder pressure applied over a unit area. The constant runout valve, the cam, and the chain drive system regulate the pressure drop from the main engine cylinder into the accumulator. The "key" to the control valve is the cam. The cam rotates on to a valve stem which fits into the valve seat and at the end of an arrestment is completely closed. The cam is driven by a chain drive which is hooked to the moving crosshead, which, as mentioned before, is driven by the engaged wire rope. Thus, there is an enclosed system. An airplane engages a wire rope which drives a crosshead which forces fluid through a control valve whose stem lift is regulated by a cam which is driven by a chain drive. Complete rotation of the cam will shut the control valve, stop the fluid flow, and bring the aircraft to a stop.

a. Control Valve Area. The cam and its rotational position determines the amount of opening in the control valve. From a geometric layout, taken over an extended series of lifts, the control valve area varies according to the following:

\[ \text{AREORF} = 1.1107 \times (\text{LIFT}) \times (2 \times \text{VALDIA} - \text{LIFT}) \]

(See NAEC MISC. 07352)

b. Valve Stem Lift. The "valve stem lift" is actually the transposition of the cam radial coordinates to the valve stem which effectively regulates cylinder pressure and closes the control valve. It is a function of the ram stroke, and is in essence the primary motive for this report. That is, to determine a set of cam coordinates that over an extended (from previous designs) ram stroke produces the optimum pressure card.

Figure 1 below gives a simple display of \( \text{LIFT} = f(\text{STROKE}) \) for the K-5 Cam.
NOTE: In the computer program, since all calculated strokes didn’t have a corresponding lift from input data, it was necessary to interpolate according to the following equation:

\[
(HH) = \text{LIFT} = \left(\text{STROKE} - \text{STROKE} (L - 1) / \text{STROKE} (L) - \text{STROKE} (L - 1)\right) \\
x \left(\text{LIFT} (L) - \text{LIFT} (L - 1)\right) + \text{LIFT} (L - 1)
\]

(c) Discharge Coefficient, Contraction Coefficient, and Velocity Coefficient. It can be assumed that the constant runout control valve acts similar to a sharp edge orifice.

For this type of device the contraction coefficient is defined as

\[\text{CONCOF} = \frac{A_2}{A_0},\]

where \(A_2\) and \(A_0\) are the respective areas. The velocity coefficient is a measure of loss during contraction, that is, it is a function of the Reynolds Number, \(R\).

\[\text{VELCOF} = f (R)\]

The discharge coefficient is a function of both the Reynolds number and the ratio of the contraction diameter to the conduit diameter. It can be defined by

\[\text{DSHCOF} = \text{CONCOF} \times \text{VELCOF}\]

In order to determine the pressure drop through the orifice it is necessary to apply these equations as well as Bernoulli’s equation for incompressible flow.

Referring to the above diagram

\[
\frac{V^2_{1t}}{2g} + \frac{p_1}{\rho} = \frac{V^2_{2t}}{2g} + \frac{p_2}{\rho}
\]
The continuity equation relates $V_{1t}$ and $V_{2t}$ with the contraction coefficient. That is $V_{1A_1} = V_{2A_0}$ (CONCOF); setting CONCOF = $C_c$

$$V_{1A_1} = V_{2A_0}C_c$$

For the Mark 7 Mod 1 it has been experimentally determined that $C_c = 1.1 A_o - .217$ (NAEC MISC. 07262)

From continuity and Bernoulli's equation

$$\frac{(P_1 - P_2)}{Q} = \left(\frac{V_{2t}^2}{2g}\right) \times \left(1 - C_c \left(\frac{A_o}{A_1}\right)^2\right)$$

solving for $V_{2t}$

$$V_{2t} = \left(\frac{(2g (P_1 - P_2) /Q)}{(1-C_c \left(\frac{A_o}{A_1}\right)^2)}\right)^{0.5}$$

The actual velocity to the theoretical velocity is

$$VELCOF = C_v = V_A / V_T$$

multiplying by $C_v$ to obtain the actual velocity at the vena contracta

$$V_{2A} = C_v x \left(\frac{(2 (P_1 - P_2) /Q)}{(1-C^2_c \left(\frac{A_o}{A_1}\right)^2)}\right)^{0.5}$$

Multiplying by the area of the jet $C_c x A_o$ produces the discharge $Q$.

$$Q = C_c C_v A_o \left(\frac{(2 (P_1 - P_2) /Q)}{(1-C^2_c \left(\frac{A_o}{A_1}\right)^2)}\right)^{0.5}$$

d. Pressure Drop Across Orifice. Since $Q_1 = V_{1A_1}$

$$V_{1A_1} = C_c C_v A_o x \left(\frac{(2 (P_1 - P_2) /Q)}{(1-C^2_c \left(\frac{A_o}{A_1}\right)^2)}\right)^{0.5}$$

$$V_{1A_1}^2 = C_c^2 C_v^2 A_o^2 x \left(\frac{(2 (P_1 - P_2) /Q)}{(1-C^2_c \left(\frac{A_o}{A_1}\right)^2)}\right)$$

$$P_1 - P_2 = \left(\frac{Q V_{1A_1}^2}{2}\right) x \left(\frac{C^2_c}{C^2_v}\right) x \left(1 - \frac{C^2_c}{A_o^2 / A_1^2}\right)$$

Since $A_1 >> A_o$, $(A_o / A_1)^2 \rightarrow 0$ and since $C_d = C_c x C_v$

$$P_1 - P_2 = \left(\frac{Q V_{1A_1}^2}{2}\right) x \left(\frac{C^2_c}{A_o^2 / A_1^2}\right) x \left(1/C_d^2\right) = \text{DPMEC}$$
which is the pressure drop across the control valve orifice.

e. Accumulator Pressure. It is known for most aircraft arrestments, that the pressure in the accumulator varies between 400 and 650 psi over a complete ram stroke. Since it is not known how accumulator pressure varies with cylinder pressure, it was necessary to use these fixed conditions as valid estimates of the accumulator pressure change. Given these initial conditions, the following equation applies:

\[ \text{PACCO} \times \text{VOLACO}^{1.4} = \text{PACCT} \times \text{VOLACT}^{1.4} \]

The original pressure and volumes are known, (PACCO and VOLACO), the new volume (VOLACT) can be calculated as a function of ram stroke*, and so the pressure in the accumulator at any time PACCT can be calculated.

\[ \text{PACCT} = \frac{\text{PACCO} \times \text{VOLACO}^{1.4}}{\text{VOLACT}^{1.4}} \]

*The volume in the accumulator varies with the displacement of fluid from the main engine cylinder. Since it is not an exact function, i.e. varies with piston area and ram stroke, it was necessary to interpolate from the known initial and final conditions to determine how this volume varies.

\[ \text{VOLACT}^{1.4} = (\text{VOLACO} - (\text{SK} \times \text{STROKE}))^{1.4} \]

where SK is the calculated dummy variable that best fits the prescribed conditions.

f. Cylinder Pressure. The pressure in the cylinder is the sum of the drop across the orifice and the increase in accumulator pressure.

\[ \text{PMEC} = \text{DPMEC} + \text{PACCT} \]

9. FORCES ACTING ON THE SYSTEM.

a. Ram Force. The ram force is the build-up of cylinder pressure acting as a unit vector against the piston area

\[ \text{FRAM} = \text{PMEC} \times \text{AREPTN} \]
b. Cable Tension. The arresting gear cables are wrapped around two crossheads, one fixed and one movable. Each crosshead has two banks of sheaves, an upper and lower. Coming down from the top side connection with the deck pendant and wrapped around some intermediate directional sheaves, each cable is wrapped around either both upper banks of sheaves or both lower banks of sheaves. Thus on the movable crosshead the ram force developed by the pressure buildup is equal and opposite to the tension developed by the wrapped around wires.

\[
\text{FRAM} - \text{CBLTEN} = 0
\]

Since one individual cable is wrapped around nine rows of sheaves, applying a force to the top and bottom of the sheaves, the total cable tension in reaction to the ram force is now

\[
\text{FRAM} - (9 \times 2 \times \text{CBLTEN}) = 0
\]

Since there are two cables, one for each bank, the net result is

\[
\text{FRAM} - (9 \times 2 \times 2 \times \text{CBLTEN}) = 0
\]

or \( \text{CBLTEN} = \frac{\text{FRAM}}{36} \) for the Mark 7 Mod 1 arresting gear with a conventional wrap.

In the above discussion, it was noted that the net force acting in the opposite direction to the ram was the cable tension. There is another force, friction drag, which also acts within the system. This force is due to cable drag, cable bounce, slipper friction, etc. It is the summation of all the additional force outside of the main engine cylinder that arrest the aircraft.

\[
\text{CBLTEN} = \frac{\text{FRAM}}{36} + \text{FDRAG}
\]

\[
\text{FDRAG} = (1 - \text{MCHEFF}) \times \text{TOTENG} / 2 \times \text{CBLPOU}
\]

where TOTENG is the total energy of the engagement.

c. Hookload. Hookload is the force transmitted from the cable to the hook. For on center arrestments it is

\[
\text{HKLOAD} = 2 \times \text{CBLTEN} \times \cos(\theta)
\]

d. Thrust. Engine thrust developed by the aircraft acts in the opposite direction to the retarding forces developed by the arresting engine. A standard method of approximating it is .4 to .65 times the weight of the plane.

\[
\text{THRUST} = K \times \text{ACWGT}
\]
e. **Deceleration.** From Newton’s Law, \( F = ma \), the combination of hookload and thrust results in

\[
\text{THRUST} - \text{HKLOAD} = \text{ACWGT} \times \text{DECEL}
\]

\[
\text{ACGTY}
\]

\( \text{DECEL} \) = rate of change of aircraft velocity. Since the engaging velocity is known, it is possible, through the computer program, and assuming a constant aircraft acceleration during each time step, to calculate the new velocity at the end of the time increment. That is

\[
\text{DECEL} = \frac{\text{VELIN} - \text{VELOF}}{\text{TIME}}
\]

and

\[
\text{VELOF} = \text{VELIN} + \text{ACGTY} \left( \text{THRUST} - \text{HKLOAD} \right) \frac{\text{ACWGT}}{\text{ACWHT}}
\]

10. **MECHANICAL EFFICIENCY.** Mechanical efficiency is defined as the energy absorbed by the main engine cylinder taken as a percentage of the total energy of the arrestment. Since previous experimental calculations of mechanical efficiency neglected aircraft thrust, it was necessary to make theoretical approximations using the computer program as to its actual value. The equation developed from these approximations is similar to the experimental result obtained from the Mark 7 Mod 3 gear, and in fact, was effective in producing suitable hydraulic pressure cards for the Mark 7 Mod 1.

\[
\text{MCHEFF} = .201 \left( \text{TOTENG} \right)^{.084}
\]

11. **VELOCITY COEFFICIENT.** The velocity coefficient is a measure of the viscous losses during contraction of the fluid. Actual velocity coefficients for any type orifice can be only determined experimentally. It was necessary, therefore, to apply the same theoretical procedure for approximating velocity coefficients as with mechanical efficiency. The range of velocity coefficients was known. For different weights and speeds, different coefficients were substituted until suitable hydraulic cards were developed. For the sake of simplicity in the computer program, an equation for velocity coefficients was developed as a function of aircraft weight.

\[
\text{VELCOF} = 3.126 \times \left( \text{ACWHT} \right)^{-1.111}
\]

12. **DESIGN CONDITIONS.**

   a. **Hydraulic Ram Stroke.**

      (1) The following diagrams compare the present operating conditions with the proposed changes.
MARK 7 MOD 1 ARRESTING GEAR
AVAILABLE RAM TRAVEL

PROPOSED CHANGES IN RAM TRAVEL

Present Conditions  Proposed Conditions

A - Total Ram Travel 118"  122"
A' - Total Ram Travel

B - Initial Crosshead Location 9"  7"
B' - Initial Crosshead Location

C - Two-Block Safety Distance 4 5/8"  2 5/8"
C' - Two-Block Safety Distance

D - Two-Block Stopper 2 1/4"  2 1/4"

E - Length of Two-Block Stroke 133 7/8"  133 7/8"

The reduction of the two-block distance from 4 5/8" to 2 5/8" and the placement of the crosshead at the 7" mark, allows for a total ram travel of 122". As the cable stretches, and the crosshead moves towards the crosshead stop, additional ram travel can be utilized by further rotation of the cam.
b. Mean Cylinder Pressure Drop

Maximum Cylinder Pressure - 10,000 psi  
Present Ram Travel - 118.1 inches  
Proposed Ram Travel - 122.0 inches  
Piston Area - 314.16 sq. in.  
Total Energy Absorbed = 10,000 psi \times \frac{118.1 \text{ in.}}{12} \times 314.16 \text{ sq. in.}

= 30.9 \times 10^6 \text{ ft-lbs.}

Mean Cylinder Pressure Drop = \frac{(10,000 - dp) \times 122 \times 314.16}{12} = 30.9 \times 10^6 \text{ ft-lbs.}

dp = 320 psi

The Mean Cylinder Pressure range is 87 inches. So the drop over this range is \frac{122 \times 320}{87} = 450 psi.

Assuming an 85% efficiency after maximum conditions.

\frac{.85 \times 450}{12} = 380 psi

For 122" ram travel, the design condition is 400 psi.

c. New Engaging Velocity. From NAEC MISC 09344, a 50,000 lb. aircraft @ 111 knots, develops a 10,000 psi MEC pressure. The 400 psi drop due to the extended ram travel corresponds to a velocity change of 3 knots. The new engaging velocity is now theoretically 114 knots.

d. New Dial Curve. An aircraft dial curve has been developed for the 122" ram stroke. (See Figure 25). The effect of the new cam coordinates on a wide range of pressure cards is shown in Figures 26-29.
IV. RESULTS AND DISCUSSION

The reliability of the MK 7 Mod 1 hydraulic simulation program was established by pressure simulations of actual aircraft test events. The experimental and theoretical plots showed similar trends. (See Figures 1-8).

The aircraft weight dial settings used in the simulation were from the actual test settings. Velocity coefficients and mechanical efficiency values (See Figure 10) were taken from the theoretical equations derived specifically for the Mod 1 gear. The thrust ratings used in the A-3 performance simulations and the development of the aircraft weight settings were .4 times the weight of the aircraft. In the development of simulations for 118.1 inch stroke, the thrust ratings varied according to projected aircraft capability. (This was necessary because over an extended runout a variance of .1 to .2 percentage points for the K factor results in a significant total energy difference).

The main engine cylinder pressure limit of the Mod 1 is 10,000 psi. Aircraft calibration test reports for the Mod 1 gear show that a 50,000 lb. aircraft at 111 knots will develop this peak cylinder pressure. (The A-3 was used because it is the heaviest in the fleet. The F-4J also develops critical loads because of its specific aircraft requirements). Figure 9 shows the simulation of this condition.

Figures 11 and 12 are comparison plots of the pressure trends for the 122" cam designs and the 118" K-5 cam. The simulations were made for the A-3 aircraft at various engaging speeds. (See Figures 13-24). The trends meet the 400 psi design criteria throughout the range of engaging velocities.

Figure 25 shows the aircraft dial settings for the extended stroke and the K-5 cam. Figures 26-29 show the development of the dial settings for the new cam design.

The F-4J is a 38,000 lb. plane with an afterburner thrust to weight ratio of .63. Figure 30 shows the cylinder pressures developed in the F-4 using the standard .4 ratio. Figures 31 and 32 show pressure simulations for an F-4J under its landing conditions.

The hydraulic cards for the F-4J show underset conditions. The MEC pressure limit is not exceeded, but the limits for cable tension and hookload are with the afterburner thrust ratings. (See Figures 33-36).
V. CONCLUSIONS

1. The new cam design and the standard K-5 cam rotated on its dwell develop significant pressure reductions in MK 7 Mod 1 arresting gear recovery operations.

2. Peak cable tensions and hookloads should also be reduced with the extended ram stroke, but in order to determine this a more detailed dynamic analysis of the Mod 1 system is necessary.

3. NATF Report R-172 verifies the trends of this study.

4. A rotated cam or a new cam design shows the same theoretical performance of the MK 7 Mod 1 Arresting Gear.

5. The MK 7 program can adequately simulate the hydraulic loads in an aircraft operation.
VI. RECOMMENDATIONS

1. Establish 122" as the operating service stroke for the Mark 7 Mod 1 Arresting Gear with an upper balanced control valve and with a new reeve of purchase cable.

2. Achieve the increased service stroke (from the present 118 inches to 122 inches) by rotation of the existing control valve cam, P/N 502715-1P.
VII. REFERENCES

(a) DD 979 – Mark 7 Mod 1 Arresting Gear – K-5 Cam Coordinates by R. R. Hood

(b) NAEF MISC. 07262 – Geometrical and Effective Flow Area vs. Stem Lift: Mark 7 Mod 2-3 Arresting Gear Control Valve

(c) NAEC MISC. 09335 – Mark 7 Mod 1 Arresting Gear Hydraulic Performance Charts

(d) NAEC-ENG-7511 – Performance Analysis of Mark 7 Mod 3 Recovery System Based on Aircraft Calibration Tests by J. Zurzolo

(e) Aircraft Recovery Equipment Handbook – Mark 7 Mod 1, 2, and 3, NAVAIR Publications 51-5BAA-1, 51-5BBA-1, 51-5BCA-1

(f) NATF Report R-172; Evaluation of Mark 7 Arresting Gear Service Changes No. 307 and 320 with the RALS Mark 7 Mod 1 Arresting Gear
CYLINDER PRESSURE VS. RAM STROKE SIMULATION
EVENT 36579
MARK 7 MOD 1 ARRESTING GEAR
K-5 CAM-118.1" STROKE
A-4 A/C WEIGHT-13900 LBS.
ENGAGING VELOCITY-100.0 KNOTS

FIGURE 1
CYLINDER PRESSURE VS. RAMSTROKE SIMULATION
EVENT 36589
MARK 7 MOD I ARRESTING GEAR
K-5 CAM-118.1" STROKE
A-4 A/C WEIGHT 14000 LBS.
ENGAGING VELOCITY-113.4 KNOTS

FIGURE 2
CYLINDER PRESSURE VS. RAMSTROKE SIMULATION
EVENT 36574
MARK 7 MOD I ARRESTING GEAR
K-5 CAM-118.1" STROKE
A-7 A/C WEIGHT 25200 LBS.
ENGAGING VELOCITY-110.4 KNOTS

- Cylinder pressure vs. ramstroke simulation graph.
- Actual arrestment notation.
- Pressure simulation notation.
CYLINDER PRESSURE VS. RAM STROKE SIMULATION
EVENT 36575
MARK 7 MOD I ARRESTING GEAR
K-5 CAM-118.1" STROKE
A-7 A/C WEIGHT 25100 LBS.
ENGAGING VELOCITY-105. KNOTS

FIGURE 4
CYLINDER PRESSURE VS. RAMSTROKE SIMULATION
EVENT 36667
MARK 7 MOD I ARRESTING GEAR
K-5 CAM-118.1" STROKE
F-4J A/C WEIGHT 37200 LBS.
ENGAGING VELOCITY-93.0 KNOTS"
CYLINDER PRESSURE VS. RAM STROKE SIMULATION
EVENT 36668
MARK 7 MOD I ARRESTING GEAR
K-5 CAM 118.1" STROKE
F-4J A/C WEIGHT 36800 LBS.
ENGAGING VELOCITY-108.9 KNOTS
CYLINDER PRESSURE VS. RAMSTROKE SIMULATION
EVENT 36644
MARK 7 MOD I ARRESTING GEAR
K-5 CAM-118.1" STROKE
A-3 A/C WEIGHT 49200 LBS.
ENGAGING VELOCITY-90 KNOTS

FIGURE 7
CYLINDER PRESSURE VS. RAMSTROKE SIMULATION
EVENT 36649
MARK 7 MOD I ARRESTING GEAR
K-5 CAM-118.1" STROKE
A-3 A/C WEIGHT 49500 LBS.
ENGAGING VELOCITY-105.4 KNOTS

FIGURE 8

PRESSURE SIMULATION

ACTUAL ARRESTMENT
CYLINDER PRESSURE VS. RAM STROKE SIMULATION
MARK 7 MOD I ARRESTING GEAR
K-5 CAM-118.1" RAMSTROKE
A-3 A/C WEIGHT 50000 LBS.
ENGAGING VELOCITY-111.0 KNOTS
DIAL SETTING-3.16

Maximum main engine cylinder pressure for mode I arresting gear 50000 LBS A/C 611 KNOTS.
MARK 7 MOD I ARRESTING GEAR
MECHANICAL EFFICIENCY VS. TOTAL ENERGY

MECH. EFF = 201 (T/R)^0.6

TOTAL ENERGY = FT-185 x 10^6

MARK 7 MOD I ARRESTING GEAR
VELOCITY COEFFICIENT VS. AIRCRAFT WEIGHT

Cv = 3.126 x (WT)^-1.04

FIGURE 10
MARK 7 MOD 1 ARRESTING GEAR
PEAK CYLINDER PRESSURE VS. ENGAGING VELOCITY
COMPARATIVE PERFORMANCE PLOTS
A-3 AIRCRAFT

FIGURE 11
MARK 7 MOD 1 ARRESTING GEAR
PEAK CYLINDER PRESSURE VS. ENGAGING VELOCITY
COMPARATIVE PERFORMANCE PLOTS
A-3 AIRCRAFT

FIGURE 12
CYLINDER PRESSURE VS. RAM STROKES SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
NEW CAM DESIGN-122" RAMSTROKE
A-3 A/C WEIGHT 50000 LBS.
ENGAGING VELOCITY-80 KNOTS
DIAL SETTINGS-3.3
CYLINDER PRESSURE VS. RAM STROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
NEW CAM DESIGN-122" RAMSTROKE
A-3 A/C WEIGHT-50000 LBS.
ENGAGING VELOCITY-90.0 KNOTS
DIAL SETTING-3.3
CYLINDER PRESSURE VS. RAMSTROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
NEW CAM DESIGN-122° RAMSTROKE
A-3 A/C WEIGHT-50000 LBS.
ENGAGING VELOCITY-100 KNOTS
DIAL SETTING-3.3
CYLINDER PRESSURE VS. RAMSTROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
NEW CAM DESIGN-122" RAMSTROKE
A-3 A/C WEIGHT-50000 LBS.
ENGAGING VELOCITY-110.0 KNOTS
DIAL SETTING-3.3
CYLINDER PRESSURE VS. RAMSTROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
NEW CAM DESIGN-122" RAMSTROKE
A-3 A/C WEIGHT-50000 LBS.
ENGAGING VELOCITY-111.0 KNOTS
DIAL SETTING-3.3

FIGURE 17
Cylinder Pressure vs. Ramstroke Simulation

Mark 7 Mod 1 Arresting Gear

New Cam Design-122" Ramstroke

A-3 A/C Weight-50000 LBS.

Engaging Velocity-114.0 Knots

Dial Setting-3.3

Figure 18
CYLINDER PRESSURE VS. RAM STROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
K-5 CAM ROTATED 4" ONTO DWELL-122" RAMSTROKE
A-3 A/C WEIGHT-50000 LBS.
ENGAGING VELOCITY-80.0 KNOTS
DIAL SETTING-3.16

FIGURE 19
CYLINDER PRESSURE VS. RAMSTROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
K-5 CAM ROTATED 4" ONTO DWELL-122" RAMSTROKE
A-3 A/C WEIGHT-50000 LBS.
ENGAGING VELOCITY-90.0 KNOTS
DIAL SETTING-3.16
CYLINDER PRESSURE VS. RAM STROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
K-5 CAM ROTATED 4" ONTO DWELL-122" RAMSTROKE
A-3 A/C WEIGHT-50000 LBS.
ENGAGING VELOCITY-100.0 KNOTS
DIAL SETTING-3.16

FIGURE 21
CYLINDER PRESSURE VS. RAMSTROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
K-5 CAM ROTATED 4" ONTO DWELL-122" RAMSTROKE
A-3 A/C WEIGHT-50000 LBS.
ENGAGING VELOCITY-110.0 KNOTS
DIAL SETTING-3.16
CYLINDER PRESSURE VS. RAM STROKE SIMULATION
MARK 7 MOD - ARRESTING GEAR
K-5 CAM ROTATED 4" ONTO DWELL-122" RAMSTROKE
A-3 A/C WEIGHT-500000 LBS.
ENGAGING VELOCITY-111.0 KNOTS.
DIAL SETTING-3.16

FIGURE 23
CYLINDER PRESSURE VS. RAMSTROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
K-5 CAM ROTATED 4" ONTO DWELL-122" RAMSTROKE
A-3 A/C WEIGHT-50000 LBS.
ENGAGING VELOCITY-114 KNOTS
DIAL SETTING-3.16
CYLINDER PRESSURE VS. RAMSTROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
K-5 CAM ROTATED 8" ONTO DWELL-126" RAMSTROKE
A-3 A/C WEIGHT-50000 LBS.
ENGAGING VELOCITY-111 KNOTS
DIAL SETTING-3.16

FIGURE 24a
CYLINDER PRESSURE VS. RAMSTROKE
MARK 7 MOD 1 ARRESTING GEAR
NEW CAM DESIGN—122" RAM STROKE
A/C WEIGHT—13000 LBS.
ENGAGING VELOCITY—110.0 KNOTS
DIAL SETTING—1.25
CYLINDER PRESSURE VS. RAMSTROKE
MARK 7 MOD 1 ARRESTING GEAR
NEW CAM DESIGN-122" RAMSTROKE
A/C WEIGHT-20000 LBS.
ENGAGING VELOCITY-110.0 KNOTS
DIAL SETTING-1.80

MAXIMUM CYLINDER PRESSURE DEVELOPED
K-5 CAM
CYLINDER PRESSURE VS. RAMSTROKE
MARK 7 MOD 1 ARRESTING GEAR
NEW CAM DESIGN-122" RAMSTROKE
A/C WEIGHT-30000 LBS.
ENGAGING VELOCITY-110.0 KNOTS
DIAL SETTING-2.4

MAXIMUM CYLINDER PRESSURE DEVELOPED
K & Q DAM
CYLINDER PRESSURE VS. RAM STROKE
MARK 7 MOD 1 ARRESTING GEAR
NEW CAM DESIGN-122" RAMSTROKE
A/C WEIGHT-40000 LBS.
ENGAGING VELOCITY-110.0 KNOTS
DIAL SETTING-2.9

MAXIMUM CYLINDER PRESSURE DEVELOPED
CYLINDER PRESSURE VS. RAMSTROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
NEW CAM DESIGN-122" RAMSTROKE
F-4J A/C WEIGHT-37000 LBS.
ENGAGING VELOCITY-116 KNOTS
DIAL SETTING-2.75
THRUST-.4 WEIGHT

PEAK CYLINDER PRESSURE- 118.7" RAMSTROKE DEVELOPED
CYLINDER PRESSURE VS. RAM STROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
NEW CAM DESIGN-122" RAMSTROKE
F-4J A/C WEIGHT-37000 LBS.
ENGAGING VELOCITY-116 KNOTS
DIAL SETTINGS-2.75
THRUST-.63 WEIGHT

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CYLINDER PRESSURE VS. RAMSTROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
K-5 CAM ROTATED 4" ONTO DWELL-122" RAMSTROKE
F-4J A/C WEIGHT-37000 LBS.
ENGAGING VELOCITY-116 KNOTS
DIAL SETTING-2.55
THRUST-.63 WEIGHT

FIGURE 32
CABLE TENSION VS. RAMSTROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
NEW CAM DESIGN-122" RAMSTROKE
F-4J A/C WEIGHT-37000 LBS.
ENGAGING VELOCITY-116 KNOTS
DIAL SETTING-2.75
THRUST-.4x WEIGHT

PEAK CABLE TENSION - K-54AM - 118" STROKE

FIGURE 33
HOOKLOAD VS. RAMSTROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
NEW CAM DESIGN-122" RAMSTROKE
F-4J A/C WEIGHT-37000 LBS.
ENGAGING VELOCITY-116 KNOTS
DIAL SETTING-2.75
THRUST-.4x WEIGHT
CABLE TENSION VS. RAMSTROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
NEW CAM DESIGN-122" RAMSTROKE
F-4J A/C WEIGHT-37000 LBS.
ENGAGING VELOCITY-116 KNOTS
DIAL SETTING-2.75
THRUST-.63x WEIGHT

PEAK HYDRAULIC CABLE TENSION- K-SCAM-118" RAMSTROKE

Figure 35
HOOKLOAD VS. RAMSTROKE SIMULATION
MARK 7 MOD 1 ARRESTING GEAR
NEW CAM DESIGN-122" RAMSTROKE
F-4J A/C WEIGHT-37000 LBS.
ENGAGING VELOCITY-116 KNOTS
DIAL SETTING-2.75
THRUST-.63x WEIGHT

PEAK HYDRAULIC HOOKLOAD VS. CAM-18" RAMSTROKE
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Geometrical vs. Effective Flow Area, Mk 7 Mod 1 Arresting Gear

![Graph showing geometrical vs. effective flow area for Mk 7 Mod 1 arresting gear]

- Geometrical area vs. lift, A = 1100 ft²
- Effective vs. geometrical area, CA = \( \frac{CA}{CA} \)

For use in Equation (n), where CA = 105 B.

\[ CA = 11A - 217 = CC \]

\[ CC = \text{Contraction Coefficient} \]
Figure 39

**Notes:**

1. This chart is based on actual aircraft test data up to 50000 lbs. (Cam/Valve/Weight).
2. Extrapolation of test parameter Eq. for WTs above 50000 lbs.
3. Assumption that an optimum cam is designed and used for ideal cam and valve programming.
4. Max. allowable cylinder pressure = 13000 psi.
5. Max. allowable cable tension = 90000 lbs. for 1/8" cable.

**Performance Chart**

Engaging Velocity (knots)

Aircraft Weight = 16000 pounds

\[ P = \left( 2.262 \times 10^{-6} \right) \times V \times V \]

\[ V = \frac{1}{2} \times \sqrt{\frac{P}{2.262 \times 10^{-6}}} \]

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Figure 42
<table>
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<th>MOD 3</th>
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<td>210</td>
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<tr>
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<td>T.B.D.</td>
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<tr>
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<td>0.201(ETA=0.99)</td>
<td>T.B.D.</td>
<td>0.148(ETA=0.99)</td>
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TABLE 5

MARK 7 MOD 1 SIMULATION PROGRAM

DIMENSION S(I), M(I)

DIMENSION IR(I), IP(I), IT(I), IF(I), IM(I), IS(I)

DATA IR/*RAM STROKE-INCHES*/ IP/*CYLINDER PRESSURE PSI*/

DATA IT/*VELOCITY-KNOTS*/

DATA IR/*CABLE TENSION LBS*/

DATA IF/*HOCK LOAD LBS*/

DATA IS/*LIFT-INCHES*/

DATA IS/*TIME-SECONDS*/

IC=0

OPEN 25,1,900,0

CALL PLOTS(0,0,6)

DO 70 I=1,100

READ(10,1)S(I),M(I)

IF(S(I)*EQ.999) GO TO 72

CONTINUE

70 CONTINUE

72 READ(10,2)VAK, HT, D

READ(10,3)ST, CS, RR, AP, DIA, SW, SK

READ(10,5)M, TI

READ(10,6)C, EX

READ(10,12)JJ

READ(10,14)CV

READ(10,16)EFF

READ(10,18)FB

READ(10,20)TMS(CW

READ(10,22)THC

VAO=84000.0

L=1

PR=0.0

SR=0.0

SX=0.0

PY=400.0

PAO=400.0

Rx=0.0

EAB=0.0

EFHL=0.0

FHR=0.0

FHL=0.0

DT=0.0

VX=VAK*1.689*12.0

PO=2.0*TMS*ST

RO=((((PO+DS/2.0)**2-(DS/2.0)**2))**.5)/12.0

TH=THC*WT

ETA=.0443*WT*(VAK**2)+(TH*RO)

FD=1.0-EFF)*ETA/(2.0*PO/12.0)

CV=3.126*(MT**(-.111))

EFF=.201*(ETA**.084)

DO 21 I=1,M

DT=DT+TI

RS=RX

RY=RS

RX=RX+(VX*TI)

DRX=RX-RY

CL=((RX**2+(DS/2.0)**2))**.5
SR=SX
SY=SR
SX=(CL-(DS/2.0))/(2.0*TMS)
DSX=SX-SY

33 IF (S(L).GE.SX) GO TO 75
L=L+1
IF(L.GT.JJ) GO TO 54
GO TO 33

75 MH=(H(L)-H(L-1)+H(L-1))-(S(X)-S(L-1))/(S(L)-S(L-1))
MA=MH/D
COST=RX/CL
VLC=VX*COST
VRA=VLC/(2.0*TMS)
AO=1.1107*HA*(2*(DIA)-HA)
CO=C*(AO**EX)**CV
PA=(PAO*(VAO**1.4))/((VAO-ISK)**1.4)
DPX=(SX/(24.0*G))**((VRA**2)**((AP/AO)**2)/(CD**2))
PR=PX
PY=PR
PX=PA+DPX
X=PX+PY

76 FRA=PX*AP
CT=((FRA)/(2.0*TMS*CW))+FD
FHR=FHL

FHY=FHR
FHL=(2.0*CT*COST)
DFHL=FHY+FHL
EFHL=EFHL+(DFHL*DRX*5)/12.0
VX=((12.0*G)/WT)**(1+((TH-FB=FHL)**VX)
VFT=VX/1.689/12.0
EAB=EAB+((XPA*5)*DSX*(AP/12.0))
WRITE(12,4)DT,SX,RX,PA,CD,HA,VFT,AO,FHL,CT,EAB
IC=IC+1
WRITE(25)IC,DT,SX,RX,PA,CD,HA,VFT,AO,FHL,CT,EAB
IF(VX.LT.0.) GO TO 54

21 CONTINUE

54 EFC=EAB/ET
WRITE(12,8)TH,FD,RO,ETA,EFF,CV,EFC,EFHL
WRITE(12,2)VAT,WT,D

58 CONTINUE
CALLAXIS(0.0,0.0,IR,-17,10.0,0.0,0.0,0.0,0.0,0.0,0.0,20.)
CALLAXIS(0.0,0.0,IP,21,6.0,90.0,0.0,0.0,2000.)
DO 101 K=1,IC
READ(25(K),4)DT,SX,RX,PA,CD,HA,VFT,AO,FHL,CT,EAB
X=SX/20.
Y=VFT/40.
IF (K.EQ.1) CALL FLCT(X,Y,3)

101 CALL PLOT (X,Y,2)

CALL PLOT (12.0,0.0,0.-3)
CALLAXIS(0.0,0.0,IR,-17,10.0,0.0,0.0,0.0,0.0,0.0,0.0,20.)
CALLAXIS(0.0,0.0,IV,15.6,0.90,0.0,0.0,0.0,40.)
DO 100 K=1,IC
READ(25(K),4)DT,SX,RX,PA,CD,HA,VFT,AO,FHL,CT,EAB
X=SX/20.
Y=VFT/40.
IF (K.EQ.1) CALL PLOT (X,Y,3)

100 CALL PLOT (X,Y,2)

CALL PLOT (12.0,0.0,0.-3)
CALLAXIS(0.0,0.0,IT,-17,14.0,90.0,0.0,0.0,2000.)
CALLAXIS(0.0,0.0,IR,-17,10.0,0.0,0.0,0.0,20.)
DO 102 K=1,IC
READ(25(K),4)DT,SX,FX,PX,PA,CD,HA,VFT,AO,FHL,CT,EAB
X= SX/20.
Y=CT/40000.
IF(K.EQ.1) CALL PLOT(X,Y,3)
102 CALL PLOT((X,Y,2)
CALL PLOT (12.0,0.0,-3)
CALL AXIS(0.0,0.0,IR,17.10.0,90.0,0.00,12000.0)
DO 104 K=1,IC
READ(25(K),4)DT,SX,FX,PX,PA,CD,HA,VFT,AO,FHL,CT,EAB
X= SX/20.
Y=CT/40000.
IF(K.EQ.1) CALL PLOT(X,Y,3)
104 CALL PLOT((X,Y,2)
CALL PLOT (12.0,0.0,-3)
CALL AXIS(0.0,0.0,IR,17.20.0,0.00,20.0)
DO 106 K=1,IC
READ(25(K),4)DT,SX,FX,PX,PA,CD,HA,VFT,AO,FHL,CT,EAB
X= SX/10.
Y=HA/(.100)
IF(K.EQ.1) CALL PLOT(X,Y,3)
106 CALL PLOT((X,Y,2)
CALL PLOT (22.0,0.0,-3)
CALL AXIS(0.0,0.0,IN,17.20.0,0.00,250)
CALL AXIS(0.0,0.0,IR,17.10.0,90.0,0.00,20000.0)
DO 110 K=1,IC
READ(25(K),4)DT,SX,FX,PX,PA,CD,HA,VFT,AO,FHL,CT,EAB
X= DT/250.
Y=CT/20000.
IF(K.EQ.1) CALL PLOT(X,Y,3)
110 CALL PLOT((X,Y,2)
CALL PLOT (22.0,0.0,-3)
CALL AXIS(0.0,0.0,IN,17.20.0,0.00,250)
CALL AXIS(0.0,0.0,IR,17.10.0,90.0,0.00,20.0)
DO 112 K=1,IC
READ(25(K),4)DT,SX,FX,PX,PA,CD,HA,VFT,AO,FHL,CT,EAB
X= DT/250.
Y= SX/20.0
IF(K.EQ.1) CALL PLOT(X,Y,3)
112 CALL PLOT((X,Y,2)
CALL PLOT (22.0,0.0,-3)
CALL PLOT(0.0,0.999)
STOP
1 FORMAT(2F10.4)
2 FORMAT(F6.1,F6.0,F7F6.3)
3 FORMAT(F6.1,F6.0,F3.0,F6.1,F4.1,F6.4,F6.2,F6.1)
4 FORMAT(F7.3,F11.3,3F10.0,2F10.4,2F10.4,3F14.0)
5 FORMAT(F14.6,3)
6 FORMAT(2F6.3)
8 FORMAT(F8.1,3F14.0,3F9.3,F14.0)
12 FORMAT(12)
14 FORMAT(F6.3)
16 FORMAT(F6.3)
18 FORMAT(F9.1)
20 FORMAT(F4.1,F3.1)
22 FORMAT(F5.3)
END
A. LIST OF SYMBOLS IN ANALYSIS

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