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Self-Compensating Carrier Aircraft Recovery System

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Major improvements and expansion of the capabilities of the aircraft recovery systems that are now in service on our aircraft carriers are feasible with existing technology, without any major hardware design change and without jeopardizing the high reliability of the current hydraulic-mechanical arresting gear that was designed in the 1950s. A self-compensating (model-reference adaptive) control system with multiple redundancy and majority voting logic can be developed and installed on our aircraft carriers at a cost less than that of the first aircraft saved by such a system. Feasibility of a "Closed-Loop Control System" that eliminates the risk of aircraft losses due to an erroneous weight preset has been demonstrated by computer simulation. The installation of cable-payout transducers (encoders), of a signal processor, and a servo-actuator that can correct the mis-set of a weight adjustment lever can solve this problem. In addition, an expansion of the current design limits for off-center engagement and for weight and speed of the landing aircraft, as well as a reduction in stress levels and a corresponding increase in service life for aircraft (such as the A-6) and arresting systems, can be achieved by modifications of the cable damper subsystems that are now in service.

Nomenclature

A = aircraft acceleration
A_C = acceleration of cable payout at deck sheave
A_V = orifice area of runout control valve
A_{VO} = initial value of A_V
C = cable payout at deck sheave
C_t = theoretical value of C
F_C = cable tension force
F_H = deceleration force on aircraft hook
G = acceleration of gravity
$K_1..K_6$ = empirical coefficients
M = aircraft mass
R = distance between engagement point and deck sheave
T = aircraft thrust
t_1 = arrival time of longitudinal stress wave at deck sheave
t_2 = arrival time of lateral stress wave at deck sheave
V = aircraft velocity
V_C = velocity of cable payout at deck sheave
V_e = aircraft engagement velocity
X_C = commanded weight adjustment lever (WAL) position
X_{WAL} = WAL position
X_{WS} = WAL Servo position
Y = aircraft runout distance
γ = angular misalignment of velocity vector at engagement
ΔA = aircraft acceleration correction term
ΔC = correction term for cable payout at deck sheave
ΔM = aircraft mass correction term
ε = offcenter distance of engagement
Θ = angle of cable at hook relative to deck centerline
$\hat{}$ = estimate derived by signal processing from sensed data
$\boxtimes$ = multiplication block
$\otimes$ = summing junction

Subscript

r = reference value or value used in generation of reference profiles

Introduction

MANY experts believe that large aircraft carriers will remain an essential mainstay of the U.S. naval power well into the 21st century. As budgetary pressure is increasing on defense spending, we see carrier-based aircraft becoming larger, heavier, faster, equipped with more complex systems and, therefore, more expensive. Their service life must be increased, and a close look is necessary at all options available to reduce risk of aircraft losses due to equipment limitations, human error, electromagnetic interference (EMI), or stress-induced fatigue of structural parts. In addition, potential losses as the result of reduced pilot ability to stay within the present limits of engagement speed magnitude V_e and direction γ as well as off-center distance ε prescribed by design limits of current arresting gear such as the Mark 7 Mod 3 (Fig. 1) are of concern.[1]

Current Status

These arresting systems are designed to achieve "constant runout," but require that the "constant runout control valve" of the main engine be correctly preset to the weight of the arrested aircraft. As a result of human error or EMI, a major mis-set of the "weight adjustment lever" can result in the loss of an aircraft, even if engagement speed and off-center distance are within the design limits.

Another problem area is given by the severe cable-dynamic stress transients ("kinkwave") induced by engaging the aircraft's tailhook with the deck pendant[2]; these transients are reduced by hydraulic cable dampers, but optimum effectiveness cannot be achieved over the full range of aircraft weights, engagement speeds, and off-center distances. In addition, cable strength and cylinder pressure limits are already taxed by some of the heavy, high-speed aircraft in the Navy's inventory.

Projected Improvements

A significant expansion of the capabilities of the current arresting systems can be achieved without compromising their basic design fail-safety and high reliability. The first and major

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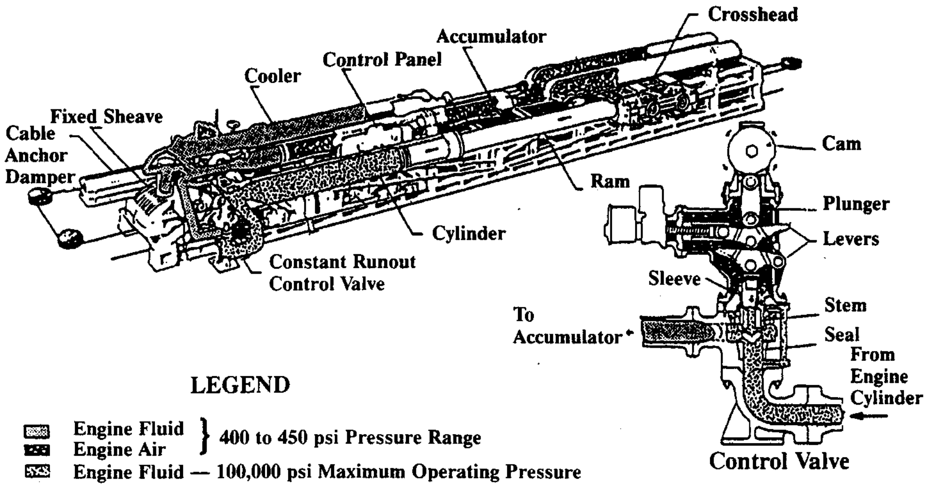


Fig. 1 Mark 7 Mod 3 aircraft arresting system, main engine.

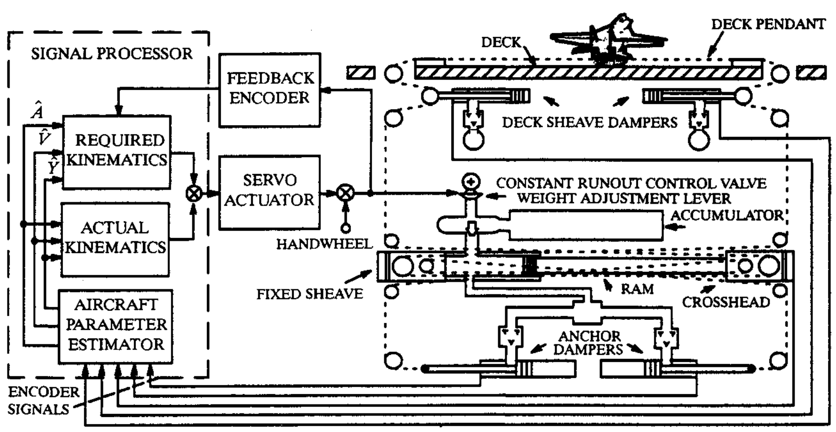


Fig. 2 Closed-loop control system concept.

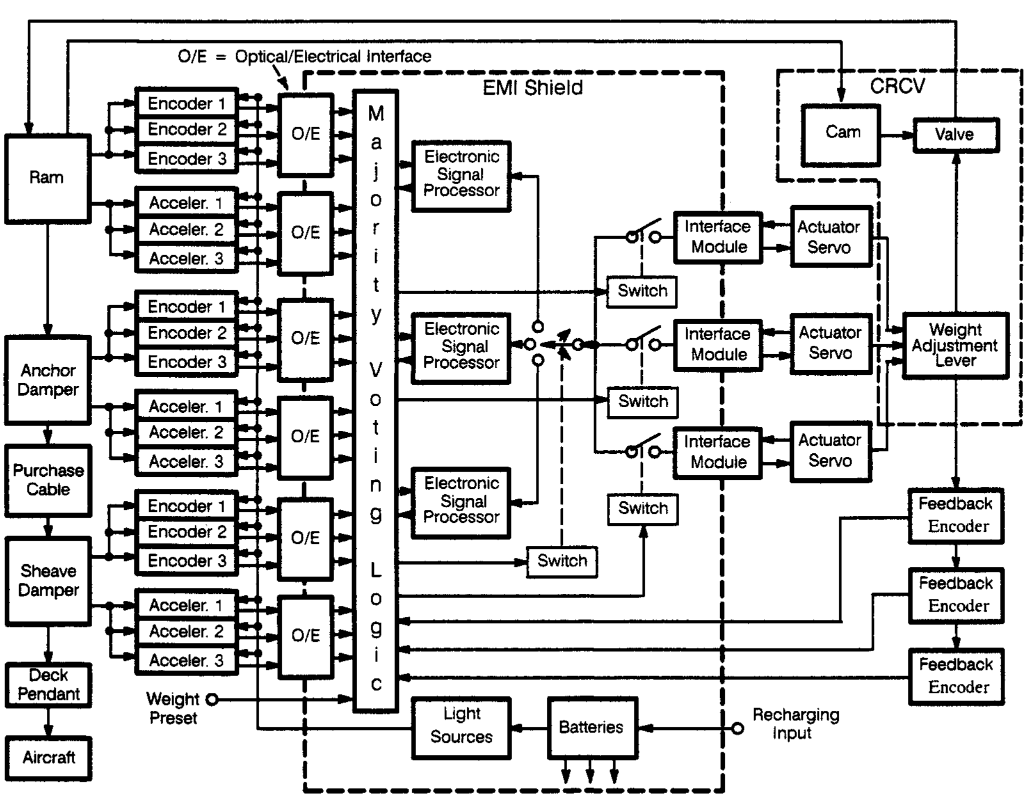


Fig. 3 Triple redundant control system with majority voting logic.

objective is the elimination of a weight preset requirement for the weight adjustment lever of the constant runout control valve (CRCV). This can be achieved by the "Closed-Loop Aircraft Recovery Control System" concept[3] proposed by Martin Marietta in1981 and investigated under contract to the Naval Air Systems Command (NASC) during 1982 and 1983. It was the subject of a simulation and design study program, under contract to the Naval Air Engineering Center (NAEC) from 1985 to 1988.[4]

Results of the (digital) simulation[5] of this "Closed-Loop Control System" (Fig. 2) indicate that additional design change options should be explored that can improve and/or expand the capabilities of current arresting systems in a more general way. This should lead to a reduction of stress transients caused by cable dynamics, to smoothing and optimizing of the deceleration profile for arrested aircraft, and can result in an expansion of the current limits for off-center engagement distance, for engagement velocity magnitude and direction, and for aircraft mass.

Significant improvements are now within reach, and can be based on existing technology without major redesign of the currently installed arresting systems. The modifications can be made fail-safe by providing for an automatic switching function that returns these systems to their present ("open-loop") operating conditions, in case of a malfunction of a self-compensating aircraft recovery system (SCARS) component or subsystem. All functions can be performed by a fully self-contained system that does not rely on external signal inputs.

Implementation

The technologies required for SCARS are available today, as indicated by our proposed closed-loop aircraft recovery control system (CLARCS) mechanization (Fig. 3). Passive optical encoders transmit arresting cable-payout signals to a central signal processor via fiberoptic cables. This processor develops estimates of aircraft position, speed, deceleration, and mass from these signals with the help of stored "model-reference" profiles for selected values of such parameters as ε, V_e, and γ. A weight adjustment lever (WAL) correction can then be made automatically by use of a servo-actuator (Fig. 4) if necessary.

EMI shielding will be required only for the (central) signal processor which can be powered by rechargeable batteries that also power the sensor system's central light source and the WAL-servo electronics. Triple redundancy (as a minimum) and majority voting logic should be employed to provide the fail safety and reliability needed. Potential advantages of emerging technologies are also of interest here: high-speed fluidic signal processing, optical/fluidic interfaces, optical signal processing, and fluidic servo-actuators.[5]

In the proposed SCARS design, the existing single-point failure modes of the present Mark 7 Mod 3 systems would not be eliminated, but modifications of the existing hardware

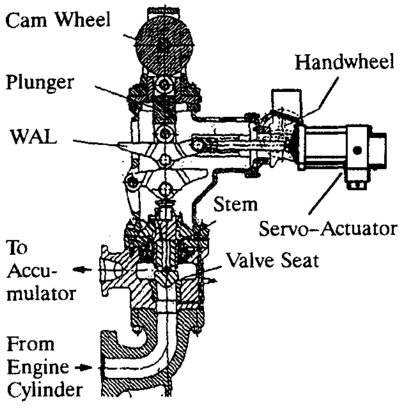


Fig. 4 Constant runout control valve with WAL actuator.

for the purpose of implementing the SCARS concept would be made in such a way that the present safety, reliability, and maintainability (of the "open-loop" system) are not impaired.

The additional risks introduced by the SCARS concept can be reduced (by multiple redundancy) to the point that they are much lower than the risks to crews, aircraft, and equipment that now exist in the operational aircraft arresting systems as the result of 1) major WAL mis-sets caused by human error or EMI; 2) limitations in system capability to cope with engagement velocity and off-center engagement distance errors; and 3) limitations in the cable damper system capability to minimize stress introduced into aircraft and cable systems by cable-dynamic transients.

SCARS Subsystems

A "Self-Compensating Aircraft Recovery System" can be developed along the following conceptual outline:

1) It would encompass "CLARCS" (Fig. 3) that was to be developed under the closed-loop control system (CLCS) program. A cable motion sensor subsystem, a signal generator, and a WAL actuator servo are the major CLARCS elements.

2) SCARS would add to these subsystems a "Damper Control System" that, in essence, increases the damper force output capability (a higher hydraulic pressure limit), and replaces the fixed hydraulic orifice by a servo valve (Fig. 5) that is controlled by a damper control module. This module is itself controlled by the central signal processor that selects an optimum damper response profile on the basis of estimates made for V_e, M, γ, and ε. This profile is used as a command signal to operate the damper's servo valve.

3) A third constituent of SCARS would increase the total cable pay-in capability of the sheave dampers. As indicated in Fig. 5, this option would add cable reeving as part of the deck sheave damper design. It would provide a set of fixed sheaves and would equip the sheave damper piston with the equivalent of a "crosshead" (moving sheaves). As the result, the piston displacement is essentially multiplied by a damper reeving factor.

The cable strength could also be sufficiently increased, so that new cable payout command profiles can be stored as "model references" to achieve optimized cable payout for a wider range of V_e, M, γ, and ε.

The Mark 7 "Constant Runout" System

In contrast to other aircraft recovery concepts such as the "Water-Spray" arresting systems used in some shore installations, and later developed into a "Direct Acting System" (in the 1960s) for the British Royal Navy,[6] the Mark 7 arresting system is based on the concept of constant runout. Table 1 lists its salient design data.

After an initial buildup, the retarding force that is developed by a hydraulic ram is proportional to the square of the ram's velocity and inversely proportional to the relative distance to go. The action of a cam controls the runout control valve orifice area A_V. The cam is operated by a chain drive from the crosshead, so that A_V goes to zero at the end of the runout regardless of aircraft engagement speed (within design limits). The initial value A_{VO}, however, must be preset for aircraft mass M. The result is that for any M (over the WAL design range) the steady-state specific retarding force (force per unit aircraft mass) can be made equal to the deceleration A_r required for constant runout.

The cam also generates a gradually increasing deceleration for the initial part of the runout where cable dynamics introduce high transient loads on the system. The specific hydraulic deceleration force reaches its steady-state value only after these transients have decayed sufficiently. It is expected that these transients can be significantly reduced by the SCARS damper action, permitting a more rapid buildup of aircraft deceleration. This will in turn allow a reduction in the maximum steady-state deceleration level and thereby reduce the

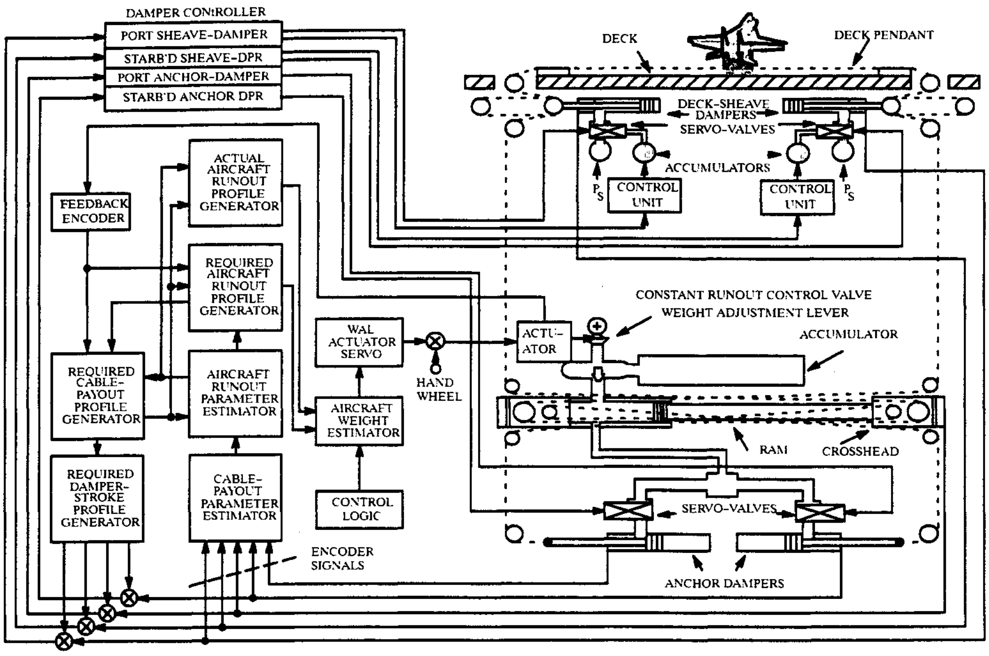


Fig. 5 Self-compensating aircraft recovery system.

Table 1 Mark 7 arresting gear characteristics

Cable	
Diameter	1.375 or 1.4375 in.
Breaking strength	
Deck pendant	
(6 × 30 flattened strand)	188,000 lb
Purchase cable	
(6 × 25 round strand)	175,000 lb
Reeving ratio	18 to 1
Arresting engine	
Length	50 ft
Weight	43 tons
Engine fluid	Hydraulic fluid
Ram diameter	20.000 in.
Length of service stroke	163 in.
Accumulator	
Operating medium	Hydraulic fluid-air
Working pressure	400 to 650 psi
Type of coolant	Sea water
Cable anchor damper	
Piston service stroke	15 ft 8 in
Reliability	0.99998
Duration of operation	<3.5 s
Deceleration	<3.5 *G*
Energy absorption capacity	47.5 × 10[6] ft-lb
Engaging speed limit	145 knots
Aircraft weight range	10,000–50,000 lb
Deck runout for deck pendant system	345 ft
Off-center engagement capability	20 ft
Retraction time	15 s
Continuous operation rate	2 arr./min[a]
Maximum operating load (based on 55% breaking strength of 1.375 in. diameter cables)	95,000 lb
Service life,	
Purchase cable	2,000 arr.[a]
Deck pendant	100 arr.[a]
Kinetic energy range	(8–47.5) × 10[6] ft-lb
Deck pendant pretension	3500 lb

[a]arr. = arrestments.

stress levels in aircraft and arresting gear, with a corresponding increase in service life.

Closed-Loop Aircraft Recovery Control System

The CLARCS concept (Fig. 2) is essentially based on the following five considerations:

1) Given a fixed "runout" distance, the minimum steady-state aircraft deceleration required for a safe landing is proportional to the square of the engagement velocity, but independent of the aircraft weight.

2) Aircraft position, velocity, and deceleration can be derived internally (without an external data link) by use of existing technology, from encoder signals that measure cable payout.

3) Comparison of the "actual" aircraft runout deceleration profile with a stored "model reference" profile can then provide the basis for a "model reference adaptive" control system for the arresting gear that eliminates the need for a correct weight preset.

4) The existing weight adjustment level can be controlled by a servo-actuator (Fig. 4), without major redesign of the CRCV.

5) Line replaceable units, in a modular system design, make it possible to use and maintain such a system without the need for increased skill levels aboard the aircraft carriers.

Discrete Closed-Loop Control System (DCLCS)

There are basically two approaches available to generate an aircraft weight estimate from cable system sensor data:

1) The system can be instrumented to derive both the force F_H that is acting on the tailhook and the deceleration A applied to the aircraft. The ratio of the two is then the weight (mass) estimate.

2) The alternate approach uses stored reference information: an aircraft for which the WAL is preset to M_r correctly will follow the (stored) built-in "required" deceleration profile A_r. If it does not, then we can obtain the necessary WAL correction ΔM, as a first approximation, from ΔA, since

$$\frac{MA}{M_r A_r} = \left(1 - \frac{\Delta M}{M_r}\right)\left(1 + \frac{\Delta A}{A_r}\right) = \frac{F_H - T}{F_{Hr} - T_r} \qquad (1)$$

In general, $F_H \neq F_{Hr}$, so we must go one step further (Fig. 6) and state (T is aircraft thrust)

$$\frac{F_H}{F_{Hr}} = \frac{F_c \sin\Theta + T}{F_{Cr} \sin\Theta_r + T_r} = \frac{f(V,T,M)}{f(V_r,T_r,M_r)} \qquad (2)$$

This results in a system that relies on kinematic data (A_r, V_r, A, V) generated with the help of encoders in the cable system, and on the comparison of "actual" kinematic profiles (A, V) with stored reference profiles of the same parameters (A_r, V_r).

This approach avoids the problems that come with attempts to reliably measure forces or to derive them from transducer data, and the associated calibration difficulties, in a very severe environment. The main issues to be resolved for the DCLCS concept (Fig. 7) were, therefore 1) demonstrate that there is adequate time available to estimate aircraft weight (after engagement) and to make the WAL servo correction safely and timely; and 2) demonstrate that the weight estimate can be made sufficiently accurate (design goal: ±5%) within the available time span.

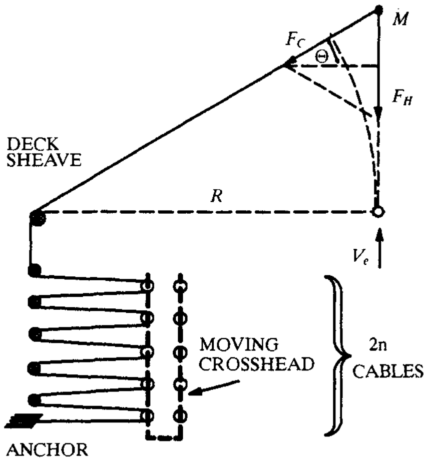


Fig. 6 Reeving schematic.

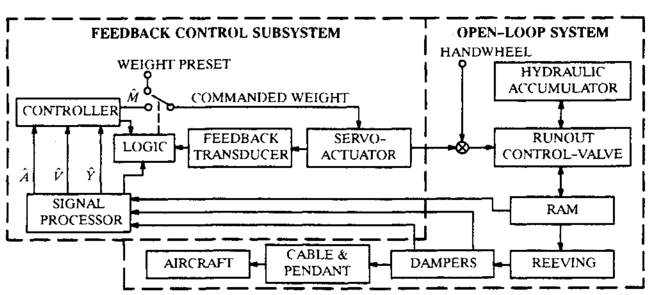


Fig. 7 Discrete closed-loop control system concept.

Simulation results show that adequate time is available for weight estimation. Figure 8 illustrates the range of deceleration amplitudes over consecutive 40-ft intervals of runout for a 32,400 lb aircraft landing at 200.9 ft/s resulting from different WAL mis-sets and correction delay intervals. Missets of 50,000 and 12,000 lb and correction delay intervals of 0.25–0.35, 0.50–0.60, and 0.75–0.85 s are simulated. No significant increase in peak deceleration (or cable tension or engine pressure) is realized with WAL corrections made prior to 0.6 s using a DCLCS that is represented schematically by the block diagram of Fig. 9. A noticeable increase with the 0.75–0.85 s corrections appears, however, for a 50,000 lb aircraft. The weight-estimate accuracy is mostly a function of the V_e estimate accuracy, and our studies indicate that ±5% appears to be an achievable design goal. As shown below, the weight estimate can be made within 0.5 s after engagement: this leaves adequate time to complete the required WAL servo correction within 0.6 s.

Aircraft Weight (Mass) Estimation

Inertia forces (acceleration of sheaves, cable and attached masses) represent only initial transient effects. For a first approximation, the retarding force F_H at the tailhook of the aircraft can be expressed as a second-order polynomial in V

$$\begin{aligned} F_H &= F_C \sin\Theta + T \\ &= (K_1V^2 + K_2V + K_3M + K_4)\sin\Theta + T \qquad (3) \end{aligned}$$

If we assume that the individual cable system component velocities are all, as a first approximation, proportional to aircraft velocity V, then we obtain

$$\begin{aligned} \frac{F_H(Y)}{F_{Hr}(Y_r)} &= \left(\frac{M}{M_r}\right)\left(\frac{A(Y)}{A_r(Y_r)}\right) \\ &= \frac{F_C(Y)\sin(\Theta(Y)) + T}{F_{Cr}(Y_r)\sin(\Theta_r(Y_r)) + T_r} \\ &= \frac{T + \sin(\Theta(Y))(K_1V^2(Y) + K_2V(Y) + K_3M + K_4)}{T_r + \sin(\Theta_r(Y_r))(K_1V_r^2(Y_r) + K_2V_r(Y_r) + K_3M_r + K_4)} \qquad (4) \end{aligned}$$

This equation relates stored data profiles collected under reference conditions $[V_r(Y_r), A_r(Y_r), M_r, Y_r]$ to corresponding

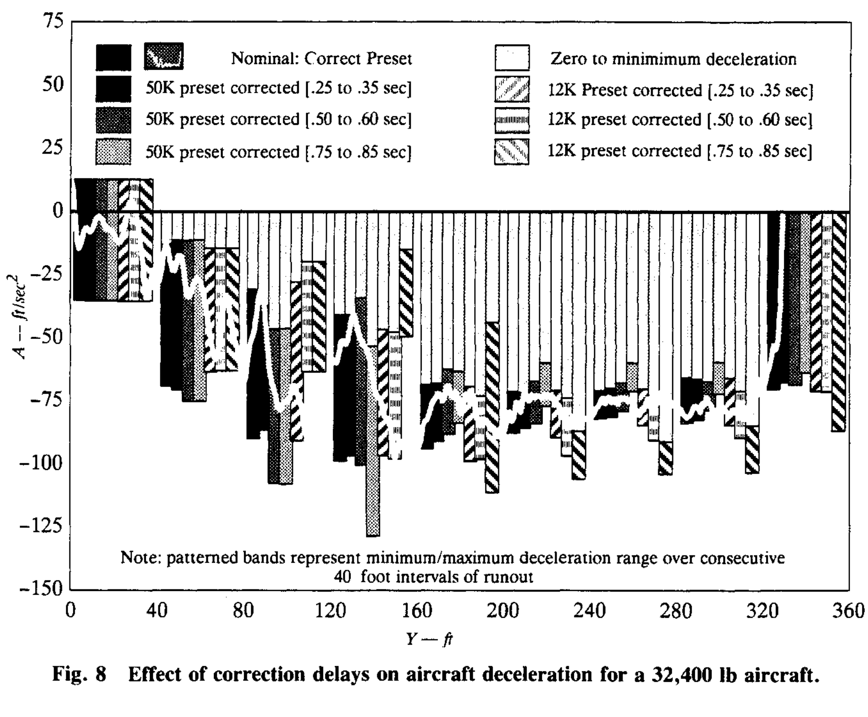


Fig. 8 Effect of correction delays on aircraft deceleration for a 32,400 lb aircraft.

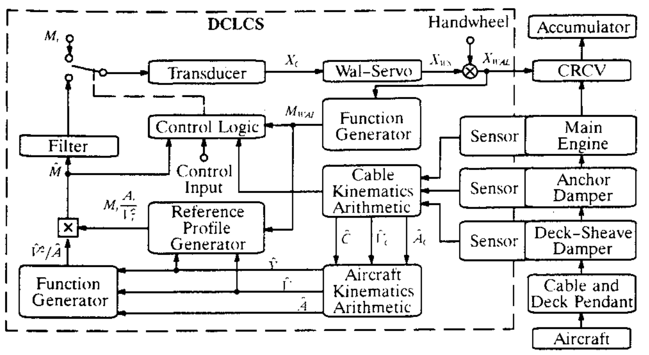
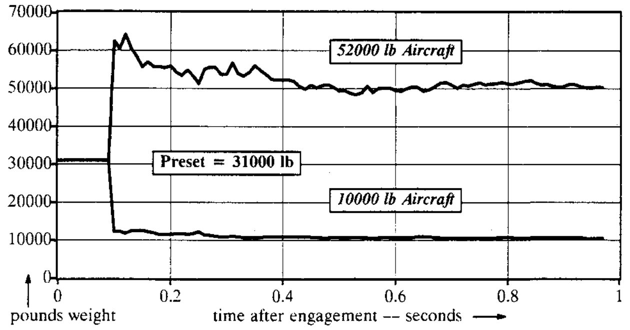


Fig. 9 Discrete closed-loop control system block diagram.



Reference Conditions Interpolated from Profiles Stored for Engagement Speeds of 191.5 ft/sec and 211.5 ft/sec

Fig. 10 Weight estimates for 52,000 lb and 10,000 lb aircraft with 31,000 lb WAL preset and 200.9 ft/s engagement speed.

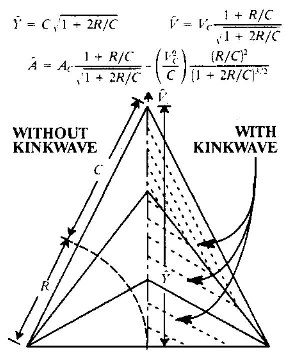


Fig. 11 Deck-cable payout geometry with and without kinkwave.

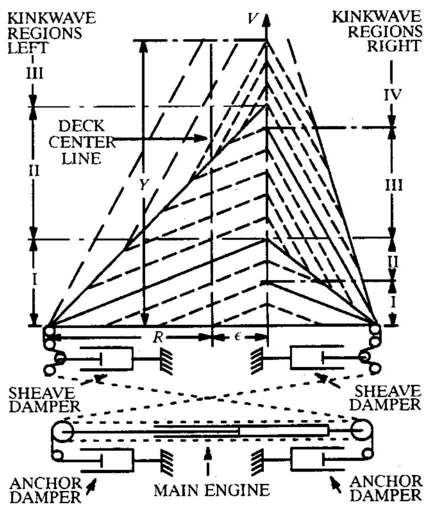


Fig. 12 Off-center runout geometry.

profiles of the same type generated at the aircraft runout position $Y = Y_r$, during the runout for which M is to be estimated. With some manipulation and simplification,[3] we can convert Eq. (4) into the following mass-estimation algorithm:

$$M = M_r\left(\frac{A_r - T_r/M_r}{A - T/M}\right)\left(\frac{V}{V_r}\right)^2\left(1 - K_5\frac{\Delta V}{V^2}\right)(1 + K_6\Delta M) \qquad (5)$$

where T/M and T_r/M_r are the military rated thrust acceleration of the aircraft (typically 0.4 G). The factor K_5 makes allowance for viscous drag effects and K_6 for dry friction: both represent correction terms applied to the major hydraulic force which is proportional to V^2. We have also assumed that $\Theta = \Theta_r$, which is confirmed as acceptable by the results of the simulation runs made so far.

The use of runout profiles instead of time profiles is appropriate because the energy-dissipation process is characterized by $(V_e)^2 = 2\int A(Y)dY$ which forms the basis for this analysis. For a given V_e, and with a correct "preset" M_r, all aircraft will follow the standard Mark 7 "required" deceleration profile $A_r(Y_r)$. Therefore, a set of profiles for $[(A_r - T_r/M_r)/(V_r)^2]$ as function of Y_r is generated and stored, for a set of five engagement velocities that are equally spaced over the required range from 150–250 ft/s. During the first 0.2 s of a runout (immediately following engagement), an estimate for V_e is made so that the appropriate profile $[(A_r - T_r/M_r)/(V_r)^2]$ (for a V_{er} value that is closest to the actual V_e value) can be used in the mass-estimation algorithm of Eq. (5).

As a first step, we derived estimates for the parameters Y, V, and A from the simulation parameter C which is cable payout at the deck sheave. These estimates $\hat{Y}$, $\hat{V}$, and $\hat{A}$ were then used in the mass-estimation algorithm, Eq. (5), and we obtained results such as those shown in Fig. 10.

Derivation of Aircraft Parameter Estimates from Cable-Payout Sensor Data

To simplify the computation, we used a mathematical model that assumes an idealized cable payout without any kinkwave transients (Fig. 11). A cable-payout correction term ΔC is derived from stored reference profiles; this term is added to the actual (sensed) cable payout C with the result that $C_t = C + \Delta C$ represents the (theoretical) cable payout that would prevail/occur if the cable (kinkwave) dynamics had been completely removed by a 100% effective cable damper system. This (theoretical) parameter C_t is applied to the simplified mathematical model, for the purpose of deriving $\hat{Y}$, $\hat{V}$, and $\hat{A}$ (see Fig. 11), avoiding the complex kinkwave computations. The SCARS damper control subsystem would actually attempt to achieve this optimized cable payout by minimizing the kinkwave transients.

This specific cable-payout correction term ΔC is generated from stored reference data for the same engagement velocities that are selected for the $[(A_r - T_r/M_r)/(V_r)^2]$ profiles. As a result, the basic pattern of cable-dynamic transients is merely compressed in time (or expanded) when V_e (and therefore, V_K) is increased (or reduced); a stored ΔC_r pattern for V_{er} can be "time-skewed" to obtain a good approximation of the actual ΔC transient pattern for V_e within limited ranges $V_{er} \pm \Delta V_e$.

The cable-dynamic transients are generated by reflections of the "kink" that is formed in the deck pendant at the time of tailhook engagement; this kink travels with the "kinkwave" velocity V_K along the cable between tailhook and deck sheave. As a first approximation for the Mark 7 Mod 3 arresting gear, the kinkwave velocity is related to the aircraft engagement velocity by the equation

$$V_K = 220 + \frac{5}{3}V_e \qquad \text{(ft/s)} \qquad (6)$$

for the V_e range of interest here (150–250 ft/s), and for a cable modulus of elasticity $E = 12.5 \times 10^6$ psi.

Derivation of Engagement Velocity Estimate

There are at least two promising options available for deriving an estimate of V_e from sensors in the cable system:

1) Accelerometers can be placed in the deck sheaves to pick up the two events that define the "kink wave velocity" V_K: arrival (at $t = t_1$) of the "longitudinal" stress wave[2] that travels with very high velocity, and arrival (at $t = t_2$) of the slower "lateral" or "kinkwave." This allows us to derive V_e from Eq. (6), using an estimate for $V_K = R/(t_2 - t_1)$, where R is the distance between engagement point and deck sheave. Since both deck sheaves would have to be instrumented, these calculations can also determine the off-center engagement distance ε (see Fig. 12).

2) As an alternate option, one can derive V_e from the initial cable-payout velocity V_C. The cable is initially being payed out to allow the "kink" to travel from the tailhook to the deck link (which connects the deck pendant to the purchase cable) in a simple triangular geometry so that, during this time interval

$$(V_K + V_C)^2 = V_K^2 + V_e^2 \tag{7}$$

Conclusions

The studies performed since 1981 indicate clearly that it is feasible and cost-effective to convert the present Mark 7 Mod 3 arresting gear into a "closed-loop" system that does not require a weight preset for the landing aircraft. In addition, other benefits such as stress reduction and extension of service life for aircraft and arresting gear, and increased ranges of ε, M, γ, and V_e appear feasible, based on the damper control concepts that have been outlined here. Other potential applications of fully automated, self-adjusting arresting systems based on the concepts presented here may well be of practical value and should warrant study.

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