from these results. For high vehicle speeds, the power required to drive the air compressors [(first term of Eq. 20) and represented by power at zero speed in Fig. 10] is less than the power required to overcome the momentum drag associated with the ingestion of air required for the air cushions [second term of Eq. (20)]. This fact gives the two-stage air cushion a power advantage at high speeds. For example, the required compressor output for the set of two single-stage air cushions is 85 lb_m/sec at 16.41 psia; for the set of two two-stage air cushions the required compressor output is 42 lb_m/sec at 17.29 psia. The compressor power required for the two-stage air cushion is only slightly less than that required for a single stage air cushion. However, since the power required to overcome momentum drag is proportional to the quantity of air ingested, this power for a two-stage air cushion is approximately half that required for a single stage air cushion.

The significance of the power required to overcome momentum drag has important implications related to the comparison of multiple stage air cushions with other advanced air cushion concepts. One of these concepts[3] has multiple peripheral jets, but has a separate air supply for each peripheral jet. This type of air cushion can provide an equivalent lift with slightly greater compressor power as the multiple stage air cushion described in this paper. However, the quantity of air required for a two stage peripheral jet with separate air supplies is nearly twice that required for the air cushion described in this paper; therefore the power required to overcome momentum drag would be expected to be twice as great for separate air supplies as for the air cushion described in this paper.

The other significant result shown in Fig. 10 is the importance of the inherent roll stability of the two-stage air cushion. Both the compressor power and the power required to overcome momentum drag are significantly reduced by using a single two-stage air cushion across the entire width of the vehicle.

Conclusion

The operation of multiple stage air cushions for tracked air cushion vehicles has been examined both analytically and experimentally. The theoretical and experimental results are sufficiently close so that the analytical model may be used for further analysis. The multiple stage air cushion is a promising concept for reducing the power required for levitation for tracked air cushion vehicles. The inherent roll stability of multiple stage air cushions allows a significant reduction in the power required for levitation of TACV's.

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Arrested Landing Studies for STOL Aircraft

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This paper describes a computer simulation study of the motion of a STOL aircraft after touchdown, when the runout of the aircraft is shortened by engaging an extendable arresting cable. A set of second-order nonlinear differential equations is solved numerically to simulate the time history of the aircraft motion. The results show that the arresting gear is a very promising containment device for STOL ports, especially at elevated sites.

Nomenclature

C = damping constant of the water twister
$C(S)$ = the transfer function of the controlled vehicle dynamics
F_{hx}', F_{hy}' = arresting hook forces in x' and y' directions
h_1 = cable thickness
$H(S)$ = human operator transfer function
$I(S)$ = system input
I_{zz} = moment of inertia in z' direction
K_p = gain of the pilot
L_R, L_L = extended lengths of right-hand and left-hand cables
l_h = distance from aircraft c.g. to hook
$\Sigma L', \Sigma M', \Sigma N'$ = total rolling, pitching and yawing moments
m = aircraft mass
$O(S)$ = system output signal
$P(S)$ = pilot's control signal
R = yawing rate of the aircraft ($\dot{\Psi}$)
R_R, R_L = varying drum radius of the right-hand and left-hand water twister
T_D, T_I, T_L, T_N = coefficients of the human operator's transfer function
u, v = longitudinal and lateral velocities of the aircraft
x, y, x = fixed axis coordinates (runway coordinates)
x', y', z' = body axis coordinates (aircraft coordinates)
x_h, y_h = x' and y' coordinates of the hook
$\Sigma X', \Sigma Y', \Sigma Z'$ = total forces in x', y', z' directions

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Index categories: Aircraft Landing Dynamics; Computer Technology and Computer Simulation Techniques.

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$\epsilon(S)$ = error signal
ϕ_R, ϕ_L = angle between the right- and left-hand cable and the y direction
θ_R, θ_L = angle between the right- and left-hand cable and the y' direction
Ψ = yawing angle of the aircraft

Superscripts

$(\dot{\ })$ = time derivative of ( )

Introduction

BY 1980, a STOL (Short-Take-Off-And-Landing) air transportation system will likely become one of the major means for intermediate range, intercity transportation. In order to take full advantage of the capability of STOL system in providing time savings and convenience for the passenger, it may be necessary to locate the STOL airport over a compatible building, pier or railroad yard near the city center. Undoubtedly, an elevated STOL port will require emergency containment devices to meet safety standards.

One of these emergency containment devices is the ARRESTED LANDING GEAR, which has many advantages both in emergency conditions and in routine landing operations.

This paper defines the working function of the arrested landing system to demonstrate the advantages of such a system, and describes a computer simulation study of arrested landings of STOL aircraft. The particular arrested landing gear under study is a standard water twister of the type recommended by the All American Engineering Company.[1] The derived equations of motion are second order, nonlinear differential equations based on Newton's second law. The following considerations have been made with regard to the forces and moments in their derivation. 1) The dynamics of the arresting gear and its matching hook, 2) The pilot's response to errors, 3) The aerodynamics of the aircraft during landing, 4) Wind effects, and 5) The forces and moments of the landing gears.

A computer program, written in FORTRAN IV, was developed for the CDC/6400 computing facilities at the University of Virginia. The fourth-order Runge-Kutta method was used to solve these equations numerically. A high degree of flexibility in defining the system has been maintained by providing different combinations of subroutines for each phase of the calculations. Thus, the program user can choose the subroutine for, say, the arresting gear, without changing the whole program.

Efforts have been concentrated on abnormal landing situations. A number of calculations of the motion of the aircraft under different landing conditions has been performed. Several particular situations of interest such as efficiency of deceleration, abnormal crosswind effects, pilot's input, hook position, and landing with damaged gear, etc., have also been studied. The analysis indicates that the arrested landing gear is a promising landing containment device.

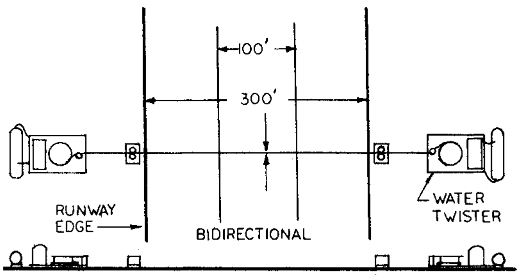

Fig. 1 Water twister type arresting gear.

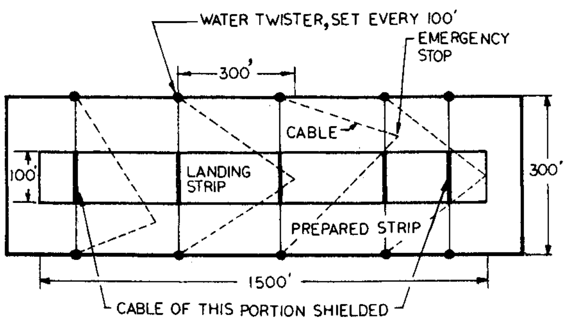

Fig. 2 Arrested landing in emergency case.

Part of this computer simulation has been complementary to an FAA field test program. The results of both computer simulation and field tests show good agreement.

Arrested Landing System Approach

Functions and Constraints

Functions

Arresting gear—As shown in Fig. 1, the arresting gear is a water twister of the type developed by the All American Engineering Company.[1] Located on both edges of the runway, the two water twisters serve as the energy absorbers. The cable will be extended from the twisters during arrested landing operations.

By engaging the cable after touchdown, the runout of the aircraft can be shortened and the chances of an overrun can be reduced.

Runway—The assumed runway (Ref. 2) of the elevated STOL airport is shown in Fig. 2, where the arresting gear is used only in emergency cases; and in Fig. 3, where the arresting gear is used in routine landing operations.

For the system to be used in emergency cases, the cable can be shielded across the primary landing strip so that it would only be engaged if the aircraft had swerved off this strip. The arresting gears may have to be placed at regular intervals along the runway, e.g., every 100 ft. Runout after arrestment would be about 300 ft.

For the system to be used in normal landings, the aircraft should engage the cable immediately after touchdown, so that without applying reverse thrust, the aircraft can be stopped safely and smoothly within a short distance, say 600 ft.

Two types of STOL aircraft with a pilot-operated tail hook have been studied, Breguet 941 and S-2A. The Breguet 941 has been assumed to represent the future commercial STOL aircraft, while S-2A is the one used by the FAA for field tests at Lakehurst, N.J.

Constraints

Passenger comfort—Deceleration after touchdown must be made acceptable to the passengers. Tentatively, the deceleration should be less than 0.5 g (comfortable limit)

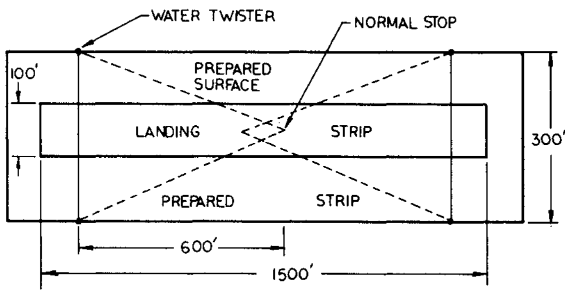

Fig. 3 Arrested landing in normal condition.

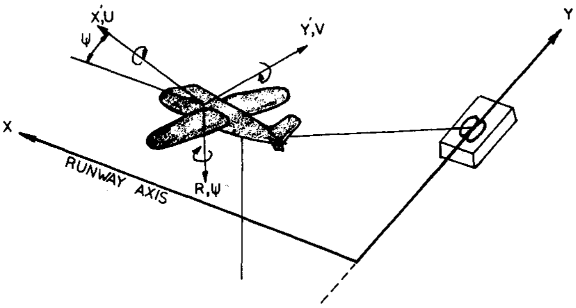

Fig. 4 Axes and motion of the aircraft.

for normal landing and 1.5 g (health limit) for emergency landing.[2]

Economy—The system should be within current technology; system cost and maintenance cost should be reasonable compared to the maintenance cost of the aircraft in high-power reverse thrust stopping landings.

Safety—The system should have the ability to handle the following abnormal situations: 1) abnormal landing (out of line or with large initial heading angle), 2) landing with damaged landing gears or without brakes, and 3) landing under high crosswinds.

Equations of Motion

Three degrees of freedom in the plane of the runway are considered with the runway being the fixed axis and the aircraft being the body axis. The state vector consists of the x, y coordinates of the c.g. on the runway; the velocity component u, v along the aircraft axes x', y', respectively; and the heading angle ψ and yaw rate R. They are all shown in Fig. 4.

The equations of motion,[3] according to Newton's Second Law, are

$$\Sigma X' = m(\dot{u} - Rv) \tag{1}$$
$$\Sigma Y' = m(\dot{v} + Ru) \tag{2}$$
$$\Sigma N' = I_{zz}\dot{R} \tag{3}$$

Expressed in state equations

$$\dot{u} = \Sigma X'/m + Rv \tag{4}$$
$$\dot{v} = \Sigma Y'/m - Ru \tag{5}$$
$$\dot{R} = \Sigma N'/I_{zz} \tag{6}$$
$$\dot{\psi} = R \tag{7}$$
$$\dot{x} = u\cos\psi - v\sin\psi \tag{8}$$
$$\dot{y} = u\sin\psi - v\cos\psi \tag{9}$$

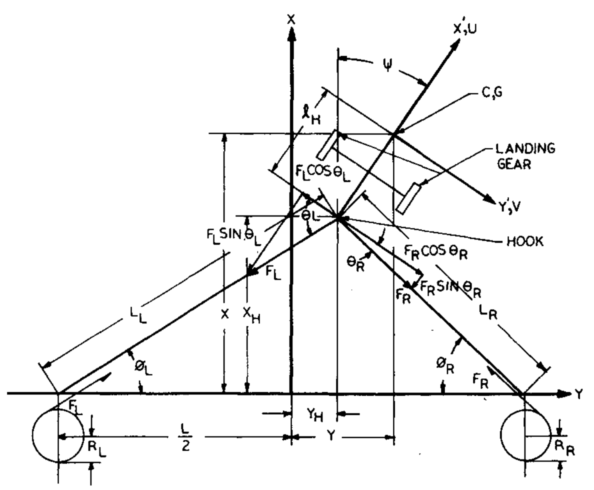

Fig. 5 Cable and hook dynamics.

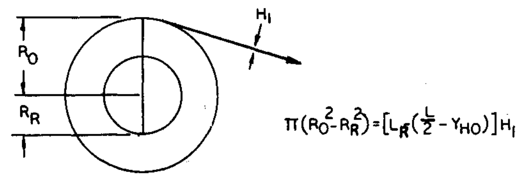

Fig. 6 Geometry of the water twister.

These six state equations are to be integrated to determine the motion of the airplane.

However, three static equations are also required to satisfy the equilibrium conditions in the other directions.

$$\Sigma Z' = 0 \tag{10}$$
$$\Sigma L' = 0 \tag{11}$$
$$\Sigma M' = 0 \tag{12}$$

The total forces ($\Sigma X'$, $\Sigma Y'$, $\Sigma Z'$) and total moments ($\Sigma L'$, $\Sigma M'$, $\Sigma N'$) result from the following contributions: 1) the dynamics of the arresting gear and its matching hook, 2) the pilot's response in attempting to maintain heading, 3) the aerodynamics of the aircraft during landing, 4) wind effect, and 5) the forces and moments of the landing gears. These are considered separately, then added together.

The deceleration, which is an important constraint of the system is defined as

$$\text{deceleration} = -\dot{V}_t/g \tag{13}$$

where $\dot{V}_t = (\dot{u}^2 + \dot{v}^2)^{1/2}$

Cable and Hook Dynamics

The dynamical behavior of the arresting cable of a water twister landing system is somewhat different from that of a typical arrested landing system on an aircraft carrier.

The damping torque is proportional to the drum rotation rate raised to some power, n ($1.0 \leq n \leq 2.0$). Therefore the left- and right-hand cable forces, which would arrest the engaged aircraft, can be written as

$$F_L = \frac{C}{R_L}\left(\frac{\dot{L}_L}{R_L}\right)^n \tag{14}$$

$$F_R = \frac{C}{R_R}\left(\frac{\dot{L}_R}{R_R}\right)^n \tag{15}$$

where C is the damping constant of the water twister.

As shown in Figs. 5 and 6, $\dot{L}_L$, $\dot{L}_R$, R_L, R_R can be determined from the motion of the aircraft and the geometry of the system.

Once F_L and F_R are determined, the forces and moments due to the arresting gear and its hook can be derived accordingly.

Pilot's Response

The entire arrested landing system can be considered as a kind of control system (Fig. 7). The pilot puts human

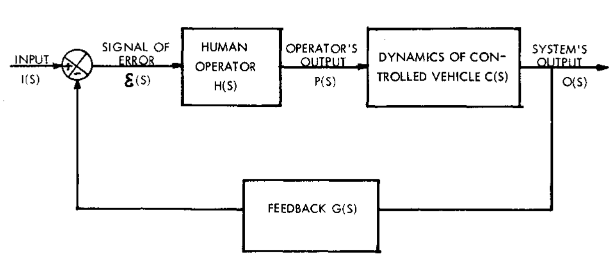

Fig. 7 Control system of the aircraft.

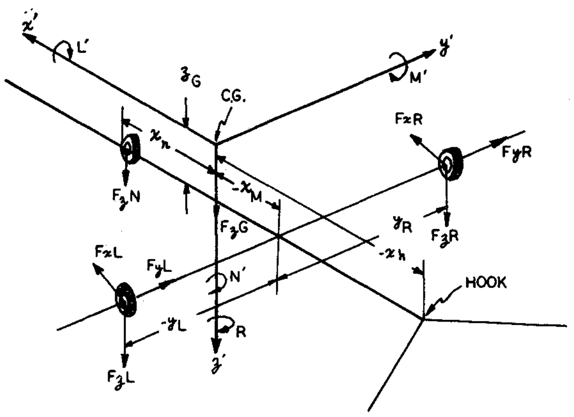

Fig. 8 Forces and moments of landing gears.

response into the system, by controlling the aircraft through either the rudder or the brake after touchdown. For these studies, the pilot was assumed to try to maintain a zero heading angle ψ.

An empirical form of the human operator transfer function *H(S)*, which has gained wide acceptance is used here (Ref. 5)

$$H(S) = \frac{K_p e^{-T_D S} (T_L S + 1)}{(T_I S + 1)(T_N S + 1)} \tag{16}$$

The coefficients of this transfer function represent the human operator's physical characteristics. They are defined as:

K_p = Operator's gain in the control loop.
T_D = Reaction time delay. This time delay is a psychological refractory period. (0.2 to 0.3 sec)[6]
T_L = Lead time constant, the operator's ability to make predictions (0 to 2.5 sec)
T_I = Lag time constant (0 to 2.0 sec)
T_N = Neuro-muscular time delay (0.1 to 0.16 sec)

Since the dynamics of the controlled vehicle are quite complicated, it is hard to define the transfer function of the controlled vehicle dynamics *C(S)*. However, by inverse Laplace transformation, the human transfer function *H(S)* can be transformed back to differential equation forms. Then, they can be solved numerically like all the other differential equations in the system. *P(t)*, the inverse Laplace transformation of *P(S)* is a new state variable and could be either the responding brake force or the responding rudder deflection. Calculated brake force will be used in landing gear dynamics, while rudder deflection will be used in computing the aerodynamic forces.

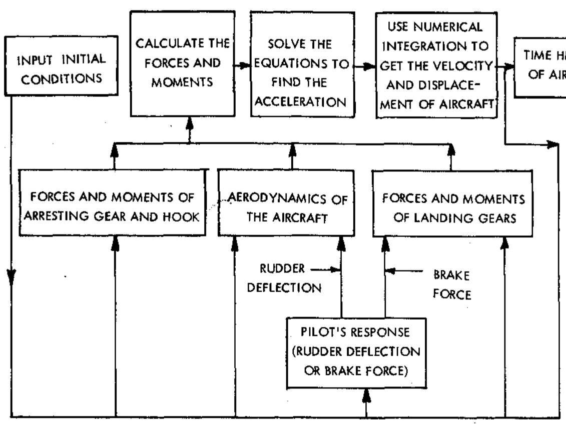

Fig. 9 Summary of arrested landing studies.

Table 1 Programs for arrested landing study

Program A:	This program includes the following considerations: 1) Arresting hook and cable forces and moments. 2) Lateral landing gear moments (Concept I).
Program B:	This program includes the following considerations: 1) Arresting hook and cable forces and moments. Hook slip, pickup and drop study. 2) Pilot applies the brake or the rudder or both in response to the error headings. 3) Aerodynamics and wind effects. 4) Landing gears forces and moments (Concept II).

Aerodynamics and Wind Effects

The crosswinds and headwinds have significant effects on the motion of the aircraft during landing. The total velocity used in calculating the dynamic pressure should be the air velocity including such wind effects. In calculating the aerodynamic forces and moments, the lift, drag, rudder deflection, together with such wind effects in side slip and yawing have been considered.

Forces and Moments on the Landing Gears

Forces and moments on the main gears as well as the nose gear are considered. The vertical forces on the gears are balanced by gravity forces and other z' component forces. The y' component force of the gear, cornering force, is proportional to the cornering angle. Since the nose wheel is assumed to caster freely, the cornering force only acts through the main gears.

In calculating the x' component force and the yawing movement, friction force due to rolling, brake force due to pilot and damage force due to structural damage of landing gears are considered.

As shown in Fig. 8, there are seven components of forces to be solved. Seven equations including the three static equations (10), (11), (12) have been used to solve these unknowns. The forces and moments due to landing gears can be calculated accordingly. In summary, the arrested landing system approach can be shown in Fig. 9.

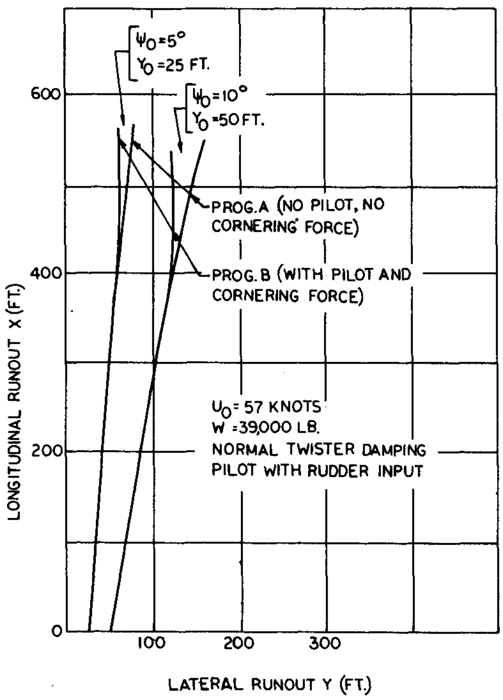

Fig. 10 Trajectories of arrested landing.

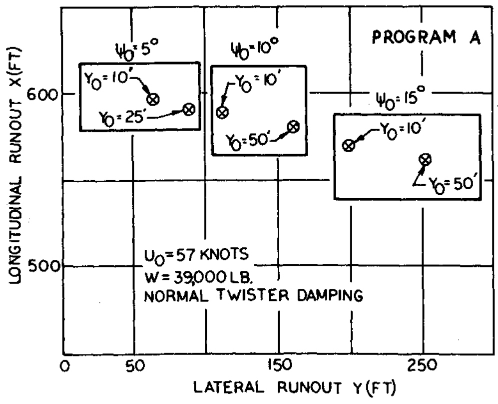

Fig. 11 Final stopping points of arrested landing (Program A).

Results and Analyses

Discussion of the Results

Several different programs have been developed for simulating the arrested landing. Table 1 shows the concepts for these programs.

Several calculations were made to determine the longitudinal and lateral runout (x, y), assuming various values for the initial offset (y_0) from the centerline, and initial heading angle (ψ_0). Both Program A and Program B were used. Results are shown in Figs. 10–12.

The results show that the length of the runway could be limited to a short distance by using the arrested landing system. This system is powerful in keeping the aircraft from going over the sides in abnormal landing (for example, 50 ft out-of-center and 15° out-of-line with pilot input). The results also indicate that the initial heading angle (ψ_0) would have more effect on lateral runout than the initial offset (y_0).

It is obvious that Program B represents the system more realistically. The discussions following this section will be based on the results of Program B. However, Program A shows that even without the effort of centering, the arresting gear is still dependable for a safe landing.

Efficiency of Deceleration

The deceleration distributions in arrested landings are shown in Fig. 13. It is clear that the higher the twister damping, the shorter the runout length, and the higher the deceleration. Also, by keeping the damping constant, the final readout increases and the maximum deceleration decreases as the weight of the aircraft is increased.

There are two options available to keep the deceleration acceptable for the passengers: 1) set appropriate twister damping, allow a variable runout to keep maximum deceleration acceptable, and 2) use an automatic system to sense deceleration and to adjust damping accordingly.

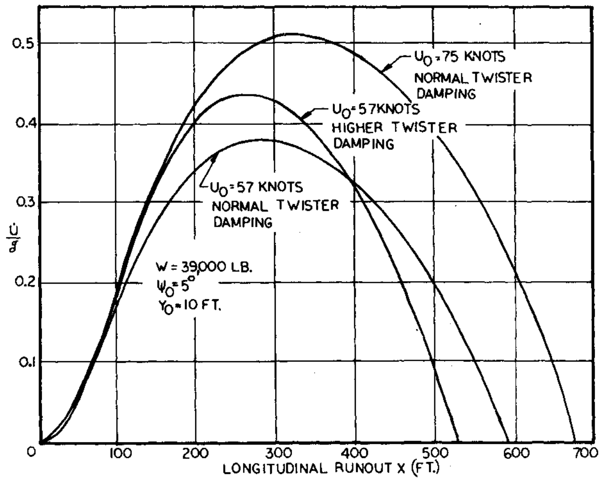

Fig. 13 Efficiency of decelerations.

Pilot's Function

Responding to the out-of-line heading of the aircraft, the pilot applies either the brake or the rudder deflection to make corrections. The left brake and the positive rudder are applied for the positive heading. The error and response relation is shown in Fig. 14. The effect of variations of the pilot's gain is shown in Fig. 15. The following ranges of value of the gain were found to maintain the stability and to give reasonable agreement with FAA tests.

K_B (Brake gain) 0 to 300 lbf/deg heading
K_r (Rubber gain) 0 to 3° rudder deflection/deg heading

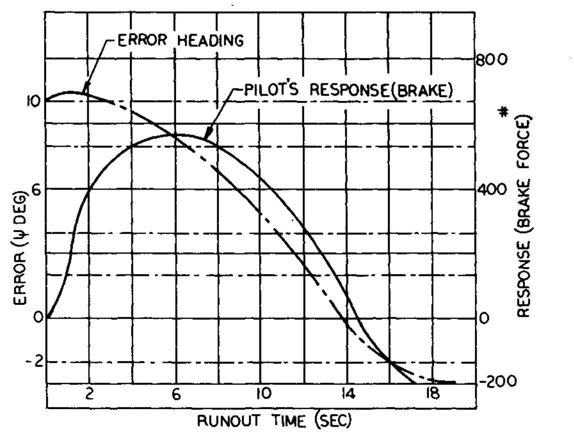

Fig. 14 Error and response relation.

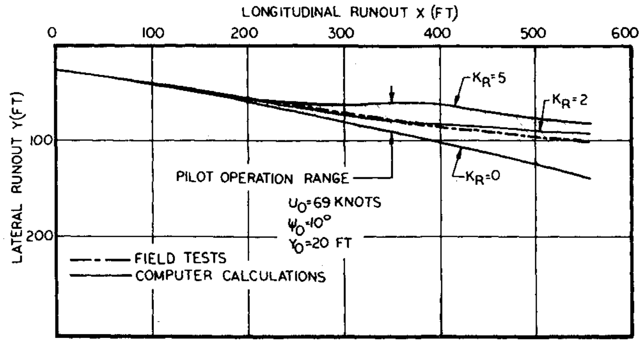

Fig. 15 Effects of pilot's gain.

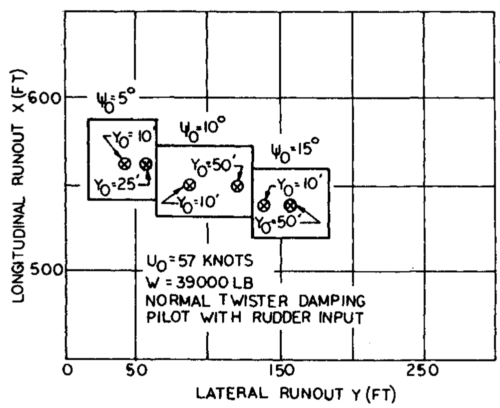

Fig. 12 Final stopping points of arrested landing (Program B).

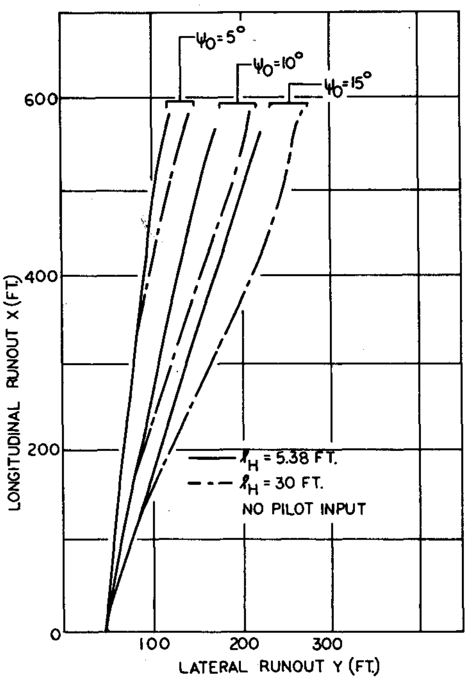

Fig. 16 Effects of hook position.

Effects of Hook Position

The yawing moment due to the arresting gear and its matching hook would decenter the aircraft in arrested landings. This yawing moment could be limited by moving the hook position as close to the c.g. as possible. The effect of hook position on the lateral runout of the trajectories is shown in Fig. 16.

Landing with Damaged Gear

Should one or all of the landing gears be damaged, the emergency arrested landing system is needed. In this case the twister damping should be set higher than the normal to stop the airplane within a shorter distance.

Due to the abnormal friction force from the damaged gear, the aircraft would tend to turn after touchdown. The frictional force is proportional to the degree of the damage of the structure. The effects of arrested landing are two-fold. 1) To counterbalance the turning tendency due to the damaged gear. 2) To stop the aircraft within a shorter distance (before it overruns the runway).

Aircraft trajectories and final stopping points with one of the main gear damaged are shown in Fig. 17.

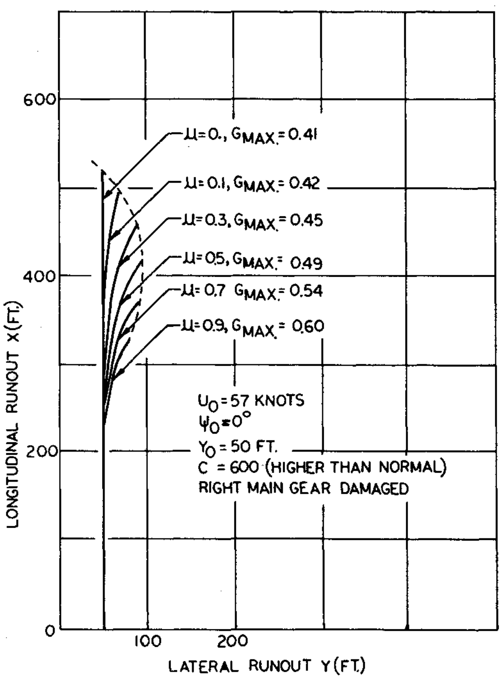

Fig. 17 Landing with damaged gear.

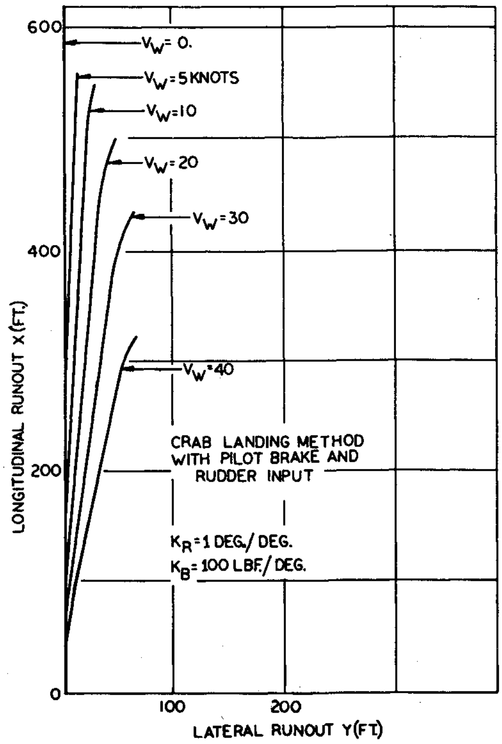

Fig. 18 Landing under abnormal crosswinds.

Abnormal Crosswind Effects

STOL operations, particularly if only a single runway is available, will generally encounter high frequencies of crosswind exposure, and with low approach airspeed, the

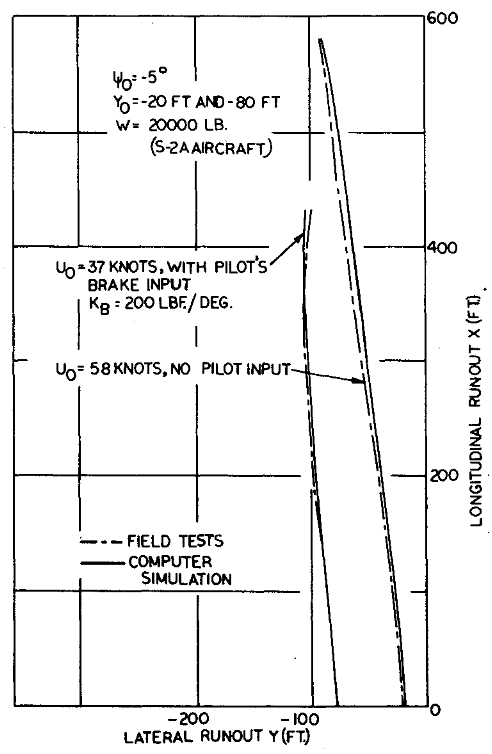

Fig. 19 Comparisons of computer simulation and field tests.

effects of crosswind are more significant. It is difficult to design STOL aircraft to operate safely in crosswinds that are over 40% of the approach speed.[7] In other words, for the approach speed to be 60 knots, the maximum crosswind for safe landing is 25 knots. But as long as the aircraft can survive until landing, the arrested landing system can handle the crosswind even up to 40 knots.

It is recommended here that two methods for landing under high crosswinds be utilized with the help of arrested gear.

Crab landing—The approach heading ψ of the aircraft is keeping constant until engagement. (Without the help of arresting gear, it is necessary to decrab the airplane just prior to touchdown, but with the help of arresting gear it is not necessary to decrab).

Initial rudder deflection landing—The aircraft is decrabbed and the pilot applies rudder deflection upon landing so as to counterbalance the effect of side slip angle due to crosswind (Ref. 9). Aircraft trajectories and final stopping points under different strengths of crosswinds are shown in Fig. 18.

Applications of the Computer Stimulation Study to FAA Field Tests

A field test program of arrested landing has been performed at Lakehurst, N.J., by NATF (Navy Air Test Facilities) under the supervision of FAA (Federal Aviation administration).[8] The current computer simulation study is complementary to that field test.

The over-all program consisted of the following tasks: 1) preliminary computer runs to predict the aircraft trajectories and to assist in designing the tests, 2) field tests to confirm the predicted behavior of the aircraft when arrested, and 3) collection of the test results and input data (relating to the airplane, arresting gear and test parameters) for the adaptation and verification of the computer program.

The results confirm the expected behavior of the arrested landing system. Figure 19 shows typical trajectories of arrested landings for both computer simulation and field tests. The computer results show excellent agreement with the field test after certain sensitive parameters in the system, such as damping constant C, pilot's gain K_p, etc., are properly adjusted.

Conclusions

The arresting gear, with the backup of several other containment devices such as side barriers or curbs, is a very promising containment device in emergency cases. It would handle the following situations: 1) Abnormal landing (out of the landing strip or landing with large initial heading), 2) Landing with damaged gear, and 3) Landing under abnormal crosswinds.

The analyses also show that, in satisfying the constraints of the system, the arresting gear is advantageous in normal landing too. Although, psychologically it may not be appreciated by the passengers.

This computer simulation program would be helpful in evaluating the feasibility of such an arrested landing system, and eventually, in designing commercial STOLports.

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