Comparison with Simulation Results

A digital computer simulation of the intake-engine configuration with bypass door control has been developed for the external compression mode. The validity of this simulation was established by comparing the actual and simulation responses to a throttle burst imposed during the closed-loop test phase. These data are compared in Fig. 17. The computer pressure recovery at the compressor face was not compared with actual data due to a lack of sufficient resolution on the strip chart record for $P_{T2_{AVG}}$. However, the good agreement shown for the other parameters attests to the overall integrity of the sumulation.

VI. Conclusions

Several conclusions can be drawn from the information obtained through the various steady-state and open- and closed-loop tests conducted on the $\frac{1}{4}$-scale intake model.

The experimentally determined steady-state operating boundaries indicated a constant control system setpoint could be used to maintain stable, high-performance intake operation during external compression. The steady-state control signal characteristics were used to establish the gain variation, range of effective bypass door operation, and level of the setpoint.

Although open-loop testing showed that control signal gain varied by as much as a factor of three over the range of throat Mach numbers considered, scheduling of gain with bypass door position was not required. Satisfactory closed-loop operation over the Mach number range from 0.9 to 1.5 was obtained using a constant electronic gain level in the outer loop.

The bypass door control response to engine weight flow transients was very satisfactory. Many of these transients were substantially faster than those expected in a full-scale intake, yet the pressure recovery at the compressor face was affected negligibly during each transient.

Data acquired from the many pulsator frequency sweep runs show good agreement with the mathematical model of the intake dynamics developed thus far. These data will aid in the further refinement of such analytic tools.

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DECEMBER 1971 J. AIRCRAFT VOL. 8, NO. 12

Wind-Tunnel Systems and Techniques for Aircraft/Stores Compatibility Studies

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A comprehensive presentation of advanced wind-tunnel techniques and facilities used in aircraft store carriage and delivery studies is presented. Extensive static stability, control, and metric store tests aid in predictions of aircraft performance and structural requirements. Investigations with scaled dynamic models are used to determine the flutter boundaries and aeroelastic effects caused by large store aerodynamic and inertia forces. Methods used to obtain mutual aerodynamic interference of wing-pylon-store combinations and external store aerodynamic interference on control surface effectiveness are described. State-of-the-art scaled dynamic separation and captive trajectory systems, their current and potential capabilities and limitations, are discussed. The quality of wind-tunnel simulation, in the general sense, is discussed and present limitations and potential improvements are pointed out.

Nomenclature

C_L = lift coefficient
E = modulus of elasticity
F = force
I = moment of inertia
L = lift, length
M = moment, Mach number, mass
P = load
PM = pitching moment
S = reference area, stress
V = velocity
W = weight
Z = linear displacement, vertical axis
$\dot{Z}$ = linear velocity
c = reference length, distance to neutral axis in bending
p = static pressure
q = dynamic pressure
x = longitudinal axis
y = lateral axis
z = vertical axis
λ = model scale, c_m/c_f
ρ = density
θ = pitch angle
$\dot{\theta}$ = angular velocity
β = yaw angle
ϕ = roll angle

Subscripts

b = bending, base
f = full scale
m = model
s = sting

Received February 16, 1971; revision received June 21, 1971.
Index category: Aircraft and Component Wind-Tunnel Testing.

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Introduction

STORE carriage and delivery studies have become a significant portion of wind-tunnel programs for many aircraft weapon systems. Extensive static stability, control and metric store tests are required to verify what can be carried, how much can be carried and where it can be carried. Separation characteristics of various aircraft/store combinations are explored by scaled dynamic tests and captive trajectory tests. Heavy payload aircraft, especially those with wing pylon mounted stores, require scaled dynamic models to determine the aeroelastic effects caused by large store aerodynamic and inertia forces.

This paper presents some advanced techniques in model design, instrumentation, test support equipment, and facilities used in wind-tunnel investigations of store carriage and delivery. The A-7 attack aircraft store program is used to exemplify the magnitude, complexity and thoroughness of wind-tunnel store studies. Particular emphasis is given to model instrumentation and captive trajectory facilities and techniques.

Methods used to obtain mutual aerodynamic interference of wing-pylon-store combinations are presented. Miniature strain gage instrumentation is used to obtain aerodynamic loads on scaled pylons, stores and store-pylon combinations. Control surface effectiveness and aerodynamic interference from external stores are evaluated.

Scaled dynamic store separations, normally confined to low-speed testing, are conducted for unpowered stores. The design of ejector racks simulating the time history of full-scale ejection forces has presented a problem in scaled dynamic testing. Current efforts in ejector design are presented. Test techniques and data recording methods are discussed. Unique model construction techniques and actuation mechanisms for retarded store tests are required. Some of the designs are described.

Captive trajectory systems for both a high-speed blowdown facility and a low-speed continuous facility are compared, highlighting the differences and commonalities. The systems discussed are computerized closed-loop, servo-controlled systems. The test concept of captive trajectory is presented and current and potential capabilities are discussed. The computer controlled captive trajectory systems are relatively new. A comparison to previous separation techniques shows the large advantages gained by the closed-loop computer controlled system. Many factors that influence the trajectory of the store, such as gravity vector, thrust time histories, dynamic derivatives, guidance, etc., can be readily incorporated into the computer program. This capability provides simulations that are extremely difficult, if not impossible, to otherwise obtain. Captive trajectory data forms and methods of presentation are included.

The quality of wind-tunnel simulation is discussed, in the general sense, pointing out some present limitations and potential improvements.

Carriage Simulations

Extensive wind-tunnel tests are performed to determine the carried aerodynamic loadings on pylons and stores. These tests also produce static stability, control and performance data for the complete aircraft configuration.

Metric store and pylon tests obtain mutual aerodynamic interference of wing-store-pylon combinations. These tests incorporate specially designed strain gage balances installed within scaled stores and pylons. The store balances measure the aerodynamic loads on individual stores. The pylon balance measures pylon loads and/or loads on collective groups (MERs, TERs) of stores in the presence of the wing and adjacent stores (Fig. 1).

A 0.05 size A-7 high-speed wind-tunnel model was outfitted to measure 54 channels of information. A special metric

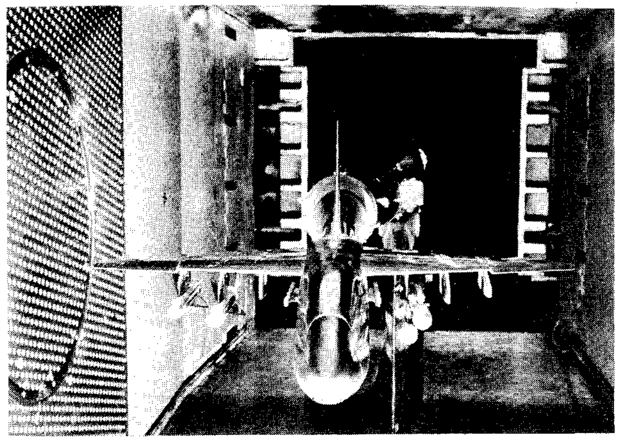

Fig. 1 Metric test installations.

wing was fabricated of high strength 17-4PH stainless steel. The wing was designed to accept three metric pylons on one side and three metric stores on the other. In this manner, one side of the wing will provide six-component load information on the store in the presence of its pylon, the wing, and other adjacent stores and pylons. The opposite side of the wing will provide pylon loads in the presence of the store, wing and adjacent stores, and pylons. Pylon loads are measured with strain gage balances that are located internally to the pylon.

In addition to extensive store and pylon instrumentation, ailerons, spoilers, and deflectors were gaged to obtain components of lift and hinge moment from which chordwise center-of-pressure can also be determined. These data provided information to define control effectiveness and changes of flow conditions.

The total airplane loads were measured by an internal six-component strain gage balance within the parent model. The design loads for model instrumentation are obtained from analytical, experimental, and empirical data. The objective of balance design is to structurally isolate each component so that a particular gaged section responds to only that component load for which it is designed to measure. If a gaged section is subjected to high strains other than that generated by the principal component, it responds to these strains and interaction can compromise the balance accuracies. Structural isolation becomes more difficult as gross strain increases. That is, the greater the loads and the smaller the structure or the more its geometry is restricted, the more difficult it is to design a given section to only one principal strain. These undesirable outputs, termed interactions, must be accounted for in data reduction.

Of all the problems a balance designer must avoid, mechanical hysteresis and dead band are foremost. Hysteresis and dead band, produced from mechanical friction of working joints or poor bonding of the strain gage to the balance material surface, cannot be accounted for in data reduction and can produce data errors that seriously compromise test results. The compound design conditions require structural strength to withstand safely the largest of the loading conditions while remaining sensitive enough to give satisfactory data for the least loading conditions.

Relations of Structural Properties and Model Scale

Force is proportional to the square of scale, $F \sim \lambda^2$

$$\text{Lift Force, } L = C_L q S \tag{1}$$

$$L_{\text{scale}} = \lambda^2 C_L q S \tag{2}$$

Moment is proportional to the cube of scale, $M \sim \lambda^3$

$$\text{Pitching Moment, } PM = C_L q S c \tag{3}$$

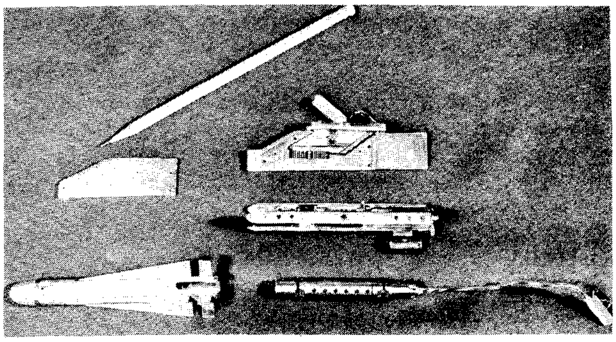

Fig. 2 Metric pylon, rack, store, and store balance.

$$PM_{\text{scale}} = \lambda^3 C_L q S c \quad (4)$$

Stress is independent of scale, $S \neq f(\lambda)$

$$\text{Bending Stress, } S_b = Mc/I \quad (5)$$

$$S_{b_{\text{scale}}} = \lambda^4/\lambda^4 Mc/I = Mc/I \quad (6)$$

Deflection (rigidity) is directly proportional to scale, $y \sim \lambda$

$$\text{Linear displacement, } y = PL^3/3EI \quad (7)$$

$$y_{\text{scale}} = (\lambda_5/\lambda^4)PL^3/3EI = \lambda PL^3/3EI \quad (8)$$

These relationships show that structural aspects remain the same for all scales. That is, stress magnitude and distribution is constant for constant dynamic pressure regardless of model size. Wind tunnels generally produce the same order of magnitude dynamic pressure as full-scale flight; therefore, model stresses are the same order as full scale.

Model design problems result from instrumentation requirements. The load carrying structure, the balance, must be dimensionally smaller than the aerodynamically loaded member. A full-scale pylon, for instance, is an integral load bearing structure. A compromise in the optimum structural design is made in favor of approaching the optimum aerodynamic shape. To instrument a model pylon requires the balance to be encapsulated within the external surface. Clearances must be maintained between the load transferring aerodynamic structure and the load bearing internal balance. The reduction in allowable balance dimensions can cause complex design problems, especially with small-scale models where very close dimensional tolerances are required.

A pylon balance for a model such as the 5% A-7D high speed wind-tunnel model is difficult to design and fabricate due to high loads and restrictions in geometry. The pylon balances are one piece strain gage balances capable of measuring pylon or pylon plus store or rack and installed store loads (Fig. 2). Extensive electrical discharge machining (EDM) is used in balance fabrication in an effort to achieve proper isolation of each component and still retain suitable primary strains. The basic principle of design is conventional. The large design loads, the restrictions of balance configuration and stiffness requirements lead to design compromises.

Figure 3 shows a test installation used to evaluate interference drag for various pylon-store wing station locations. The store-pylons are not attached to the model but are independently supported to enable the evaluation of flowfield effects on the parent model. The parent loads are measured by an external balance with the store-pylons removed and again with the store-pylons in close proximity with the wing. The same type of information can be gained through metric store-pylon tests; but, metric installations severely restrict pylon location flexibility.

Pressure Tests

Pressure taps are strategically placed over the surfaces of the model to aid in the determination of flow conditions. Areas of flow interference due to carried stores can be evaluated for both local and over-all performance effects. Pressure surveys by total and static probes can aid in the description of the local flowfields in areas of mutual interference. Wake surveys, with total head rakes, supplement drag data obtained by force methods. The Scanivalve, an electromechanical switching device, allows many pressures to be rapidly sampled. The valve successively switches each pressure orifice to a single pressure transducer located within the unit. Scanivalves are small and can be located within a model or sting support minimizing pressure lead lengths. The short pressure lead lengths used with the Scanivalve considerably reduce pressure lag. If the model attitude is varied in a continuous manner, and not paused for data collection, allowance should be made for lag times. Multiple Scanivalve use has successfully sampled more than 400 pressure taps in as few as 5 sec.

Flow Visualization

In low-speed testing the use of smoke released into the air stream (or in the boundary layer of a surface) through spaced orifices follows the flow streamlines and allows a visual interpretation of flow conditions. Another useful visual aid in low-speed testing is the use of tuft studies to identify surface flow conditions. Tufts can effectively be used to observe mutual flow effects of pylon-store wing and fuselage and control surfaces.

Tuft studies are not generally used in high-speed, wind-tunnel testing because of the difficulty in keeping them in place during high flow rates and, in many instances, they cause unsuitable disturbances in the boundary layer. Much the same information produced by tuft studies in low-speed testing can be obtained by high speed oil flow tests. This method is extensively used at VAC and is quite successful. Airflow over the surface spreads the suspended pigmentation leaving a flow pattern clearly depicting areas of separation and inclined flow regions. Many facilities use fluorescent oils which give excellent definition to flow patterns.

Schlieren and shadowgraph photography define strong and weak shock formation and areas of shock interaction in transonic and supersonic flows. The shock wave refractory index differs from remaining stream flows and is easily discernible. Compressible flow energy losses attributed to installed store configurations and shock impingement on control surfaces are among the more informative data visually gained by these methods.

Flutter Tests

Tests are performed with models designed to aeroelastic scale to determine the flutter characteristics of lifting surfaces wihy pylons and stores. The stores are not normally elastically scaled but are c.g. and mass moment of inertia scaled. The principal objective, that of determining the parent sur-

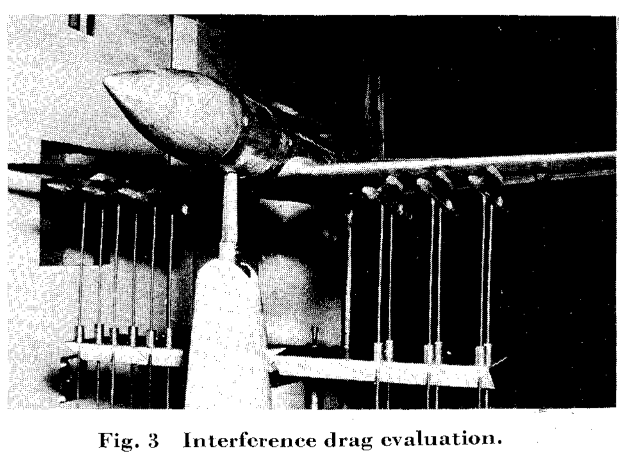

Fig. 3 Interference drag evaluation.

face flutter characteristics, is not substantially influenced by the store elastic properties. Flutter is influenced not only by the mass inertia and c.g. of the pylons and stores, but also by the flowfield changes as a result of their presence. Flutter tests are conducted in both low-speed and high-speed regimes. A 0.15 size A-7D low-speed flutter model with some of the many test stores is shown in Fig. 4.

Flutter or aeroelastic model design utilizes a basic load carrying substructure elastically scaled to support the aerodynamic loads. The surface structure is usually made of balsa thinly covered with silk or silkspan. The surfaces of the model are segmented to isolate the load path to the substructure.

The model frame is fabricated to computer predicted geometrical dimensions and then calibrated, making final dimensional corrections to material structure by hand to arrive at the scaled elastic properties desired. Strain gages are applied at various points on the load bearing members, calibrated and monitored during tests to define flutter modes, amplitudes and stabilities.

Separation Simulations

Scaled Dynamic Separation

Scaled separation studies are made by releasing or ejecting dynamically scaled store models from a parent model and following the free flight of the store(s) by photographic means. The recordings of separation characteristics are made by fast frame motion pictures or multiple exposure flash (strobe) pictures (Fig. 5).

The scaled dynamic separation technique can be used to investigate single, ripple, or salvo store separations. The store models are in free flight and are restricted to motion limits only by collision with the parent model, adjacent store models, or tunnel walls. A net downstream of the test section is the usual method of model retrieval in low-speed tests. Dynamic separations in high-speed tests are normally restricted to blowdown tunnels where the store models are destroyed.

It follows that static forces and moments generated by a flowfield will be scaled if the flowfield and model geometry are similar to that of full scale. Aerodynamic accelerations will be similar if the static forces and moments, mass, c.g. and mass moments of inertia are scaled.

The inability to scale gravity acceleration in the method of scaled dynamic separation studies can result in erroneous store separation characteristics. The method of light or Froude scaling, where velocity is scaled, produces correct dynamic response of the store model to aerodynamic loadings; but, since the stores gravitational acceleration is much too low (in comparison to aerodynamic accelerations) the store does not pass through the proper flowfield. Heavy scaling, where Mach number is held constant produces underdamped response of the store model to aerodynamic accelerations compared to gravitational acceleration. However, in heavy scaling the store c.g. will very nearly follow the correct separation path when the store pitch and yaw excursions are small. Comparisons of heavy and light scaling simulations with flight test data confirm the better agreements of heavy ($M_f = M_m$) scaling.[1]

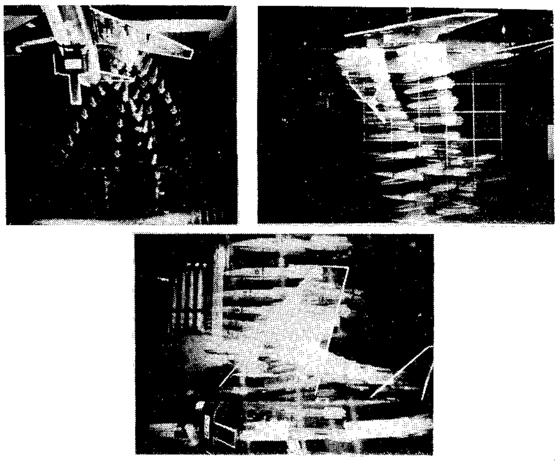

Fig. 5 Low-speed wind-tunnel store drop analysis photograph.

In light scaling dynamic separation tests, some compensation for the unscaled gravity vector may be obtained by an increase in store ejection force. Added velocity to the store can approximate the velocities that would be obtained if gravity were scaled, at least for the very near portion of the separation. Though the store is subjected to one g acceleration, where scaled acceleration should be an order of magnitude greater in many cases, the scaled gravitational velocities reached by the store while in close proximity to the parent are small when compared to most scaled ejection velocities.

The gravity scaling problem has led to investigations of magnetic fields as a means of scaling. A ferromagnetic sphere is placed at the store model c.g., and a field of constant flux distribution is imposed across the tunnel test section. Variations in field strength can simulate gravities to the order required for most light scaling studies (10 to 20 g). Preliminary work in this technique is presented in Ref. 3.

Dynamic separation simulations are in the main, limited to unpowered stores. Stores have been fired or launched using various propulsive means but this limited work has been very complicated and costly. It is extremely difficult to obtain proper thrust values and thrust time histories as well as to record the event with meaningful accuracy.

In the past, dynamic models for Froude scaling were fabricated as light as possible. The adjustments for scaled mass, c.g. and mass moments of inertia were then accomplished by ballast weights through trial and error. When a large number of the same store model was required, a mold was made and the models were constructed of dense styrofoam within a thin fiber glass and epoxy external shell.

A computer routine has recently been introduced which selects the most suitable material and determines the geometrical distribution necessary to meet the required mass, c.g. and mass moments of inertia. The program is slightly conservative and final dynamic balancing is precisely done with the addition of small quantities of mass. The amount and placement of the balancing mass is determined experimentally by a calibrated torsional pendulum.

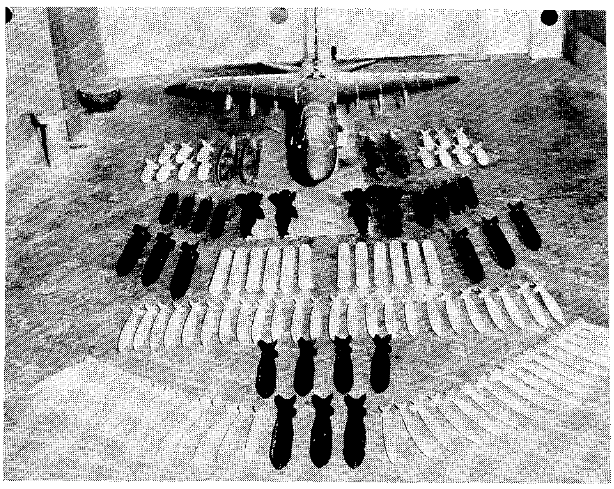

Fig. 4 A-7 0.15 size flutter model and stores.

It is usually a simple matter to meet the mass, c.g. and mass moment of inertia requirements for light scaling; but is becomes more difficult for mechanically functioning models such

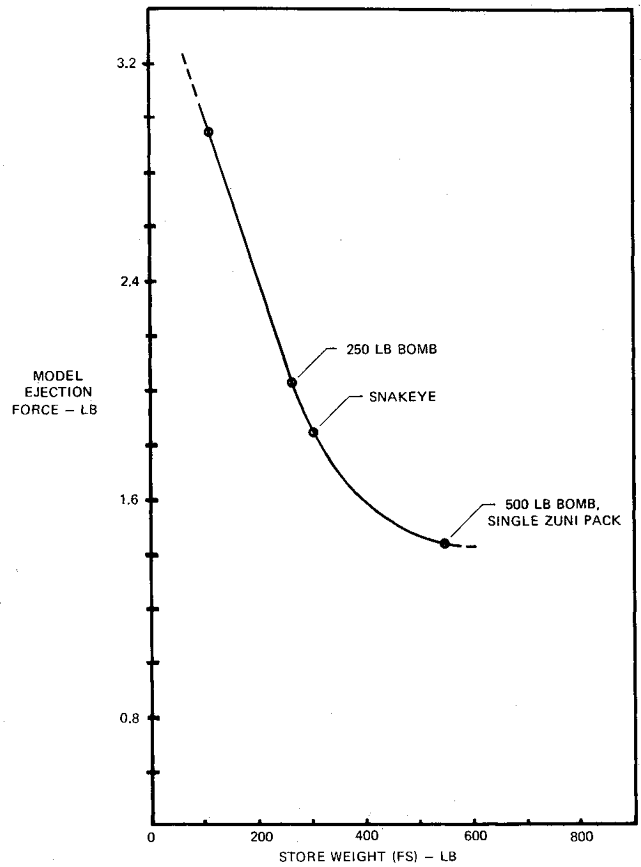

Fig. 6 Model ejection forces.

as the retarded *Mk* 81. In these cases where the geometry of the store changes, to be absolutely correct, the mass and mass moments of inertia of the portion of the model that changes geometry must be independently scaled.

The following relationship are used in dynamic scaling:

Incompressible (Froude) scaling	Compressible (Mach) heavy-model scaling†	
$V_m = \lambda^{1/2} V_f$	$M_m = M_f$	(9, 10)
$(W/\rho)_m = \lambda^3 (W/\rho)_f$	$(W/p)_m = \lambda^2 (W/p)_f$	(11, 12)
$(I/\rho)_m = \lambda^5 (I/\rho)_f$	$(I/p)_m = \lambda^4 (I/p)_f$	(13, 14)

Typical model ejection force requirements (0.15 scale) are presented in Fig. 6. These forces must be applied to the model in such a manner that the momentum of the store is to scale at separation. A common means of obtaining the required impulse is the spring loaded ejector.

The linear momentum (which is equal in magnitude to linear impulse) is related for heavy-model scaling by

$$M_m \dot{Z}_m = M_f \dot{Z}_f \lambda^{5/2} q_m / q_f \tag{15}$$

If the stroke distance is scaled, the force (constant) applied to the model is

$$F_m = F_f \lambda^2 q_m / q_f \tag{16}$$

If scaling of stroke distance is not desired, the force required to simulate impulse is related by

$$F_m / F_f = \lambda (\Delta Z_f / \Delta Z_m) M_m / M_f \tag{17}$$

† Usual boundary assumptions: $\dot{\theta}_m = \dot{\theta}_f \lambda^{-1/2}$, $\dot{Z}_m = \dot{Z}_f \lambda^{1/2}$, $\Delta \dot{Z}_m = \lambda \Delta \dot{Z}_f$.

A spring-loaded ejector will produce a linear force vs displacement. The average force over the displacement would be used in the above relationships. The spring force vs displacement is calibrated prior to test series. Variations in impulse require changes in spring rate or degree of compression.

Another method of supplying the ejection impulse is via a pressure actuated piston. There are some advantages of this method to that of the spring actuator. One such ejector uses two separate pressure chambers and pistons permitting independent ejection forces to be applied at each of two store lugs. The chambers are precharged to desired levels prior to a run. A nichrome burn wire, when separated, allows a spring-loaded retension slide to release the store. The magnitude of the force is easily varied by adjustments in pressure level(s). The force is constant over the stroke. The force level can be very accurately determined. The pressure plenum volume must be large compared to the piston displacement and pressure lag from plenum to piston chamber must be kept small. In most instances these conditions are easily met.

Captive Separation

Store separation is the most difficult of wind-tunnel simulations. Captive separation using a computerized, closed-loop servo controlled sting support can accmplish nearly all separation simultaion objectives in the wind tunnel. The aforementioned areas of difficulty, i.e., gravity vector scaling, thrust time histories, ejection forces, rail launch constraints, etc. can readily be accomplished by captive trajectory tests. A digital (or analog) computer is utilized to control the system positioning as a function of store aerodynamic loads, i.e., the store model is moved in response to the loads acting on it. An internal strain gage balance senses the loading on the store. The balance signals are amplified, passed through an analog to digital converter (ADC) and introduced in digital form to the computer. The computer performs a double integration process, weighed by other fixed programed information to obtain six degree-of-freedom position outputs. The computer position outputs are converted to analog voltages by D/A conversion and actuate the servo valves and electric motor proportional to their respective sense and magnitude. The system is thus actuated to track the computer determined

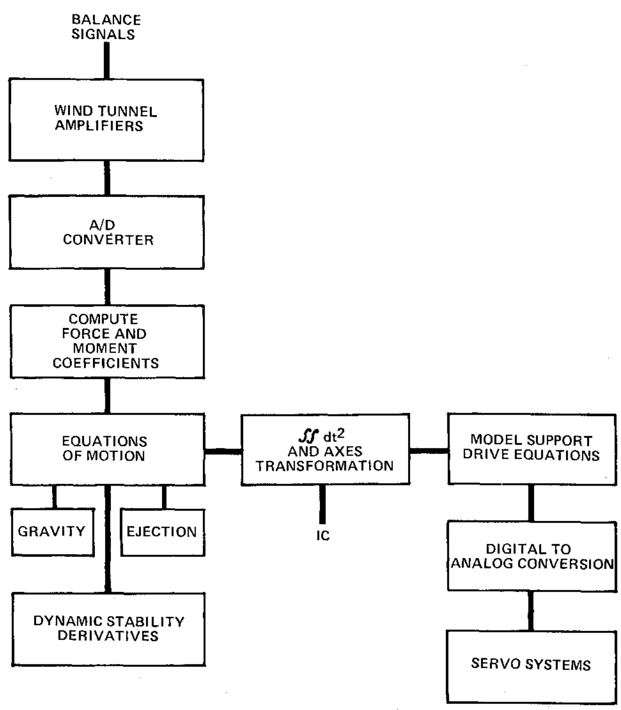

Fig. 7 Captive separation system block diagram.

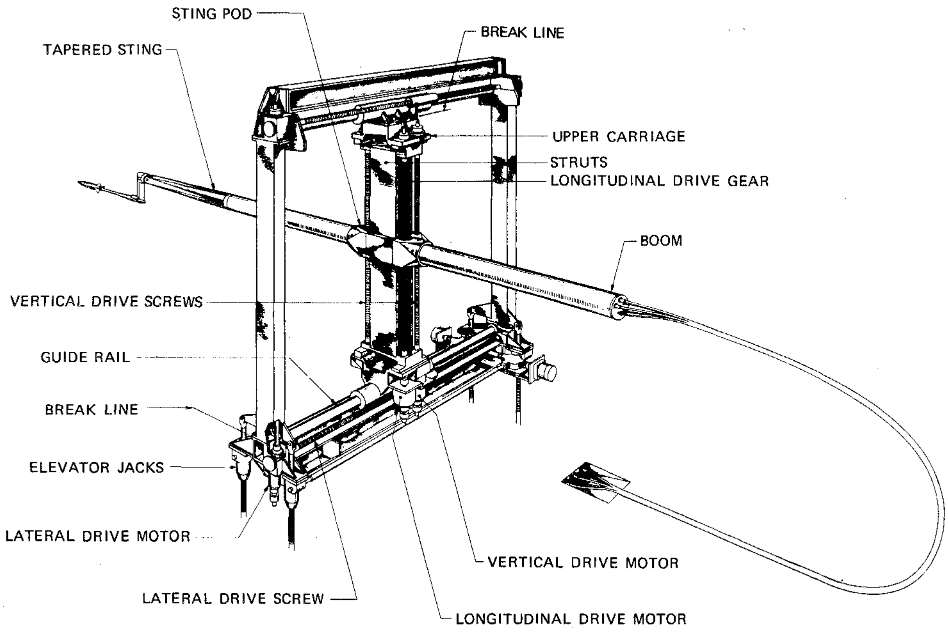

Fig. 8 VAC low-speed wind-tunnel servo controlled captive separation system.

path. A block diagram typical of current systems is presented in Fig. 7. Several of these systems are operational.[4,5] Two such systems will be discussed, the VAC high-speed wind-tunnel system and the VAC low-speed wind-tunnel system, highlighting basic design considerations, performance, commonalities and differences.

Background

Early captive trajectory tests investigating store separation characteristics were limited in their objectives. These limitations were imposed primarily due to lack of instrumentation capabilities and experience in techniques. The Korean conflict initiated many studies of aircraft store separation characteristics and continuous growth in these studies has progressed with weapon evolution.

The mid-50's saw captive tests by Cornell Aeronautical Laboratory, David Taylor Model Basin (NSRDC), Vought Aeronautics, et al. The test hardware was crude. In Vought tests an auxiliary sting, mounted from the aft fuselage of the model, was manually adjusted to place the store at various trajectory positions. A four-component balance, measuring lift, side force, pitching moment and yawing moment obtained airloads at each position.

In the late fifties similar trajectory tests were made at Vought with modest improvements. These tests were automated by a servo controlled drive but were limited to motion along a single axis. Cornell and David Taylor Model Basin built remote manually operated systems with several degrees-of-freedom in the early sixties. Automation of the auxiliary sting supporting the store has progressed to six degree-of-freedom servo controlled systems. The VAC low-speed wind-tunnel system and the VAC high-speed wind-tunnel system are shown in Figs. 8 and 9.

A six degree-of-freedom support system, whether manual or servo controlled, can be employed for grid survey studies. The grid survey method of separation simulation positions the store model successively at discrete points throughout the expected separation envelope. The survey envelope grows larger as the distance from initial separation point increases. Air load data are taken throughout the envelope via a store balance. The data are reduced by computer, using various programs, to determine separation characteristics for a variety of conditions. The grid survey technique, though very time consuming, is an effective means of separation prediction.

The Flight Path Simulation System (FPSS) is a captive separation system comprised of a six degree-of-freedom, servo-driven, closed-loop computer controlled sting support, The system is a part of the VAC Low Speed Wind Tunnel facility and is installed in a 7 ft × 10 ft test section.[6] The tunnel is a horizontal single-return closed circuit facility. The 7 ft × 10 ft test section (in tandum with a 15 ft × 20 ft test section) has a velocity capability from 40 to 350 fps and operates at atmospheric pressure. The section has a maximum Reynolds number per foot of 2.1×10^6.

Figure 8 shows a general assembly of the FPSS support system as mounted in the low-speed wind tunnel. The parent model is inverted and mounted to the tunnel's external balance. A frame surrounding the tunnel and a through-strut mechanism provide three linear motions; longitudinal, lateral, and vertical. Actuators in the sting head provide three angular motions; roll, pitch, and yaw. The sting con-

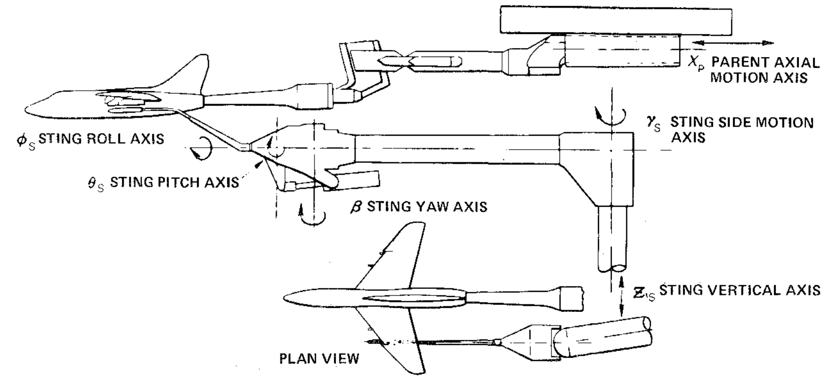

Fig. 9 VAC high-speed wind-tunnel captive separation system motions.

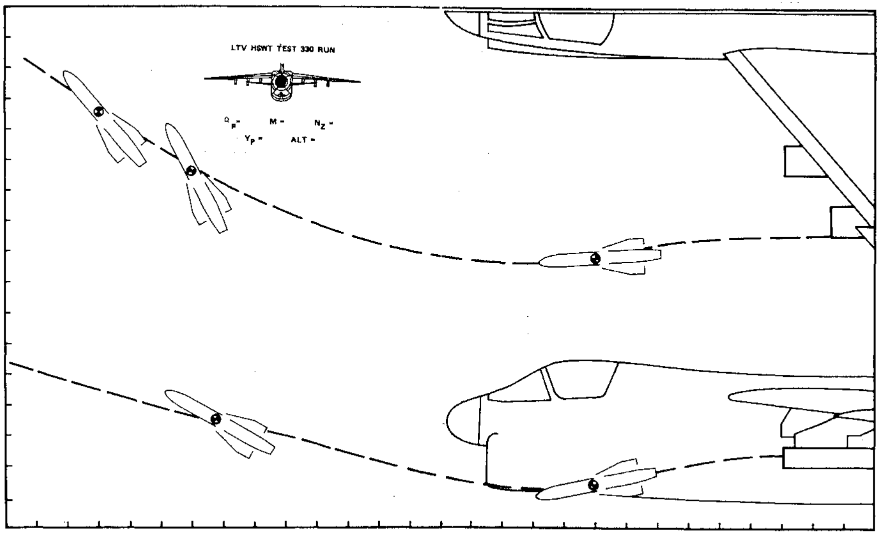

Fig. 10 Typical captive trajectory data presentation.

figuration is versatile, providing for straight tip, offset tip or 45° bent tip. A manual control console computes, amplifies, indicates, and actuates the servo control systems.

A unique capability, and one of significant value, is available with the FPSS. Store launches during parent maneuver can be simulated. The parent model rates of change in attitude can be synchronized, via the computer, with the store release and trajectory. The parent motion must be time scaled to store separation in order to provide proper rates of change of the parent-store flowfield.

The sting design loads are presented in Table 1. The sting head and tips are designed to a minimum factor of safety of 2.5 based on material tensile yield strength. The boom and frame are designed principally for small deflections and the factors of safety are large. The mechanical operating ranges and rates are tabulated for each of the six motions in Table 2.

Hydraulic powered pitch and yaw actuators are controlled by servo valves. The flow rate to these actuators is proportioned by the servo valves from a supply source at 3000 psi. The three translational motions of the system are powered by hydraulic motors controlled by the servo valves at a supply pressure of 2200 psi. The only electrically driven motion, roll, is controlled by the power input to an electric motor.

The system can be manually controlled via a manual control console. Each actuator is independent and is adjusted by a potentiometer setting. The system drives to a null point comprised of the input settings and the position feedback potentiometers. It should be noted that to obtain pure motions of pitch or yaw, the translation occuring as a result of the displaced rotational axes must be compensated for by corresponding translocational displacement in the pure translatory modes of the system.

The VAC High-Speed Wind Tunnel captive separation system, like the VAC Low-Speed Wind Tunnel system, is a six degree-of-freedom servo-driven closed-loop computer controlled system. The VAC High-Speed Wind Tunnel is an intermittent blowdown facility exhausting to atmospheric pressure.[7] The facility has a Mach number range of 0.5 to 5.0 at Reynolds numbers per foot to 37×10^6. Two interchangeable test sections, 4 × 4 ft in cross section, provide polysonic operation. The subsonic-transonic section has a wall porosity of 22%. The wall plenum uses an ejector pump for Mach control. The supersonic section run time varies from 15–120 sec at dynamic pressures from 200 to 5000 psf.

Table 1 VAC low-speed wind-tunnel captive separation system sting design loads

Load	Tapered sting load	Major support sting load
Normal force	85 lb	200 lb
Side force	85 lb	200 lb
Axial force	25 lb	40 lb
Pitching moment	1350 in. lb	2500 in. lb
Yawing moment	1350 in. lb	250 in. lb
Rolling moment	32.5 in. lb	70 in. lb

Table 2 VAC low-speed wind-tunnel captive separation system mechanical operating ranges and rates

Controlled variable	Mechanical range	Maximum rate
X_b (Longitudinal)	−54.0 in., +75.5 in.	1.7 fps
Y_b (Lateral)	±48.0 in.	1.0 fps
Z_b (Vertical)	±33.0 in.	1.7 fps
θ_s (Pitch)	±90°	40°/sec
B_s (Yaw)	±72°	40°/sec
ϕ_s (Roll)	±360°	50°/sec

The VAC High-Speed Wind Tunnel captive separation system became operational in 1963.[8] Five degrees-of-freedom are provided by the store support; the sixth, that of longitudinal motion, is produced by relative motion of the parent model (Fig. 9). The kinematics of the store support are interdependent such that to obtain either pure translation or pure rotation requires a coupling of two or more rotary actions. The physical motion envelope because of tunnel size is, naturally, smaller than that of the low-speed system (normal model scales are one-third that of low speed). The motion capabilities are presented in Table 3 for comparison to those of the low-speed support (Table 2).

An example of data produced from the high-speed wind-tunnel separation system, and typical of captive systems in general, is presented in Fig. 10. Collision of the store model with the wind tunnel wall and with the parent model must be prevented. Wall collision of the VAC low-speed captive separation system is prevented by two independent systems: limit switches arranged in a series-parallel circuit; and a programed geometrical limit within the computer. The proximity of the store relative to the tunnel walls is a function of fixed geometrical relationships. The pitch position is coupled to the vertical translation and the yaw position is coupled to

Table 3 VAC high-speed wind-tunnel captive separation system mechanical operating ranges and rates

Controlled variable	Mechanical range	Maximum rate
X_p	0–36 in.	10 in./sec
Y_s	±21 in.	8.8 in./sec
Z_s	±22 in.	5.7 in./sec
θ_s	±22.5°	19°/sec
γ_s	±22.5°	19°/sec
ϕ_s	±170°	20°/sec

the lateral translation to provide a shutdown condition if the series-parallel circuit is broken. If circumstances require absolute maximum travel, an override can be manually activated. The second wall collision avoidance system, that of the computer limit, uses a coupling of the six-position indicators in a logic comprising the fixed geometrical relationships of the system to arrive at the precise shutdown positions. The computer will deactivate the entire system just prior to wall collision.

Collision avoidance with the parent model presents a more complex problem. Whereas the tunnel walls are geometrically simple and fixed with respect to the system, the model geometry is mathematically very complicated and varies with the particular configuration. A simplified geometric description of the parent model configuration can be programed into the computer boundary limits for the tunnel walls. This method alone is less than ideal from the lack of a "fail-safe" feature and precision of position limits. The simplified geometric representation of the parent model can compromise the desired close proximity testing of near miss separation. Another method can be used to aid in preventing store-parent collisions. Conductor "whiskers" are placed on the store and charged electrically. Contact of the whiskers with a conducting surface of the parent will activate shutdown. This method is satisfactory at relatively low system velocities. Some aerodynamic disturbance is caused by the whiskers and alters the mutual flowfield between parent and store. This disturbance if large, may significantly influence the separa tion. Conductor whiskers are often used to initially position the store relative to the parent.

Simulation Results, Limitations and Potential Improvements

Aircraft-store carriage and separation systems and techniques in wind-tunnel simulation have been presented. The value of these techniques is real only when the simulations can be related to true carriage and separation conditions. Metric tests can produce very accurate information for carried stores and these data, carefully obtained, correlate well with flight test data. More hardware developments, especially on troublesome pylon instrumentation, can complete carried load predictions. Store pylon interference drag evaluation techniques are adequate only for gross interference measurements. Test methods which enable more precision need to be developed.

The scaled dynamic separation technique yields much useful information, though it is incapable of maneuvering separation and powered launch simulations. The technique is most useful for evaluation of multiple separations or separations with large, rapid motion excursions. Investigations to extend the present scaled dynamic separation limitations should be pursued. Some study is needed to extend model recovery techniques to transonic/supersonic simulations. Correlation with flight test has been good for separations within applicable delivery conditions.

In conjunction with scaled dynamic separation techniques, progress should continue on ejector mechanism development. It may be desirable to instrument the ejector in order to measure force time histories rather than the present practice of pretest calibration and repeatability measurements.

In the manual or computer controlled captive separation technique, support interference (aerodynamic) is present and if of significant magnitude must be accurately accounted for in data interpretations. Flowfield grid survey techniques, although consuming much time, can yield data enabling optimization of a particular separation. Most data currently obtained with this method establish a separation path for predetermined conditions. The flowfield survey technique can make more significant contributions with expanded computer data reduction programing.

The captive trajectory tests using the computer in a closed-loop system is a most efficient separation simulation technique. Captive system hardware developments have progressed to the stage where only refinements are necessary, particularly in support geometries. Much can be accomplished in software programing if a particular system employs a computer of adequate storage capacity and speed.

Excellent correlation has been made between wind-tunnel carriage and separation techniques in many instances. However, as in the case of most simulations, disagreements are not at all uncommon. Improvements in correlation techniques are needed. More direction can be given to wind-tunnel duplication of actual flight test parameters rather than attempting difficult flight test duplications of wind-tunnel test parameters. Future advances in flight test instrumentation may help solve some apparent differences in wind-tunnel and flight test results.

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