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F-16/SPICE Separation Analysis-Summary of the Risk-Reduction Phase Program

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The full-scale development program of a new store includes determination of the aerodynamic configuration, mapping of the aerodynamic characteristics, and determination of the release envelope. In aircraft–store configurations involving expected tiny distances between the released store and other parts of the aircraft, the risk-reduction phase of the full-scale development program includes a preliminary store separation analysis. Usually, this preliminary analysis is based on captive trajectory system tests, which may yield inadequate data in cases with very close distances between store and aircraft. A new preliminary store separation analysis method is suggested that consists of a six-degrees-of-freedom simulation based on a few carriage wind-tunnel tests and freestream aerodynamics. This new method was successfully applied for the smart precise impact and cost-effective guidance kit development program, to determine its aerodynamic configuration, from a store separation point of view. The presented method is a quick, cost-effective and approximate version of the full simulative technique that includes grid tests. The method is described and a comparison is presented between the captive trajectory system tests and the six-degrees-of-freedom simulation results.

Nomenclature

C_l	=	rolling moment coefficient, positive clockwise
C_m	=	pitching moment coefficient, positive nose up
C_{m_α}	=	static stability derivative
C_{m_0}	=	zero angle-of-attack pitching moment
C_n	=	yawing moment coefficient, positive nose right
C_X	=	axial force coefficient, positive backward
C_Y	=	side force coefficient, positive right
C_Z	=	normal force coefficient, positive up
$d_{\min}$	=	minimal distance between the released store and the aircraft, in. (on 1:1 scale)
H	=	flight altitudes above sea level, kft
I_{xx}	=	store X-axis moment of inertia
I_{yy}	=	store Y-axis moment of inertia
I_{zz}	=	store Z-axis moment of inertia
M	=	Mach number
N	=	load factor, g
S_0, S_1, S_2	=	store wingspan identifiers
X	=	longitudinal axis, positive rearward
Y	=	lateral axis, positive rightward
Z	=	store vertical location relative to the carriage position, positive up, m
α_A	=	aircraft angle of attack, deg
α_S	=	store angle of attack, deg

Introduction

THE full-scale development (FSD) program of a new store includes determination of the aerodynamic configuration, mapping of the aerodynamic characteristics, and determination of the release envelope. In cases of a tight initial aircraft– (A/C–) store geometry, the risk-reduction phase (RR) of the FSD usually includes, additionally, a preliminary separation analysis. Usually, this preliminary analysis is based on captive trajectory system (CTS) tests.

For those cases where the tested store is very close to the A/C or adjacent stores, the CTS technique might be inadequate to determine the aerodynamic configuration. Another technique, a six-degrees-of-freedom (6DOF) simulation based on carriage wind-tunnel tests, grid tests, and freestream aerodynamics, is time consuming and costly and, therefore, unsuitable for this stage of the project.

An alternative store separation analysis is suggested, the Risk-Reduction 6 DOF Simulation (RR6DS) method. This method is a new preliminary store separation analysis approach suggested for the RR of the store separation analysis. It is a reduced 6DOF simulation based on a few carriage wind-tunnel tests and freestream aerodynamics. This is a quick, cost-effective approximate version of the full simulative technique.

The new method was applied to the smart precise impact and cost-effective guidance kit (SPICE) development program. SPICE is a kit that includes a tangent-ogive nose and a conical tail (shown in Fig. 1). The frontal part of the kit (the nose), incorporates an electrooptical guidance unit and has four cruciform aerodynamic surfaces (fixed canards). The rear appendage part of the kit, incorporating a servo unit, has a set of four cruciform fixed wings and four cruciform tail control fins. The nose and tail parts of the kit are mounted on standard general-purpose bombs (MK-84 or alike), thus creating a sophisticated precision guided munitions gliding bomb. SPICE is required to be compatible to a wide range of A/C on their air-to-ground stations.

When mounted on the F-16 A/C wing, the SPICE is very close to adjacent stores, imposing an RR for the store separation analysis. The RR had a primary goal to determine the SPICE wingspan.

The wind-tunnel tests were carried out at the 4×4 ft Israel Aircraft Industries, Ltd., trisonic wind-tunnel facility. This paper presents the CTS tests, the reduced 6DOF simulation results, and a comparison between the two techniques.

Method Description

There are two widely used approaches for store separation analysis. One is the CTS wind-tunnel test technique and the other is a 6DOF simulation. These methods are not always suitable to determine the aerodynamic configuration of a store. The suggested RR6DS is a method based on a reduced version of the 6DOF simulation technique.

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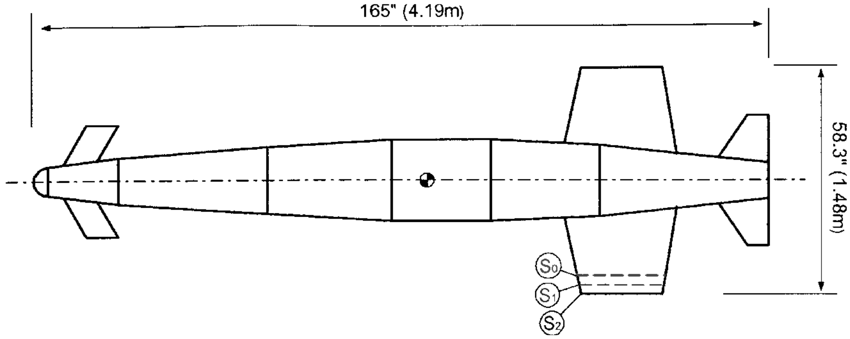

Fig. 1 SPICE configuration.

CTS Tests

The CTS test system has a sting on which the store is mounted. The sting is mounted on a support mechanism that enables 6DOF movement. The store motion is executed in small steps. Inertial data such as the store mass, reference data, precalculated damping aerodynamic coefficients, and precalculated ejection forces are supplied as input to the CTS system. At each step, the system translates the measured loads on the model to aerodynamic loads on the real store. These loads, combined with the ejection forces and other inertial data, are the input to a builtin 6DOF simulation. The simulation output is the incremental store movement. The trajectory determined by the simulation is used to evaluate the store minimal distances from the A/C and the adjacent stores.

The major advantage of the CTS technique is the short time required to produce results. Its major disadvantages include inaccurate load estimations,[1] mainly due to sting effect, and erroneous collision warning signals (see results section). Additionally, past experience for similar stores indicates major discrepancies between the CTS and flight tests, especially in the pitch motion.

Off-Line 6DOF Simulations

The 6DOF simulation (ASTOS6[2]) utilizes carriage, grid, and freestream wind-tunnel test results and inertial data.

Wind-Tunnel Tests

Accurate measurement of aerodynamic loads induced on the store by the flowfield around the parent A/C is essential to the method. The wind-tunnel tests cover all of the three phases of the store trajectory. The first phase is the captive one, which is covered by carriage tests, providing very accurate carriage-aerodynamic loads on the store. Aerodynamic loads are measured on the store model at different Mach numbers and A/C angles of attack. In this test method, the strain-gauge balance is fixed to the A/C model. The store model is mounted on the balance.

The second phase, the near-A/C phase, is covered by grid tests on the store model in the vicinity of the A/C model. In this test method, the store, mounted on a sting balance, scans the near-A/C flowfield. These tests provide the dependence of the aerodynamic loads acting on the store and on its position and orientation relative to the A/C.

The third is free flight. Wind-tunnel tests are carried out on the isolated store model to obtain free-flight aerodynamic loads at different Mach numbers. In this test method, the store, mounted on a sting balance, scans different angles of attack or Mach numbers. The second phase overlaps the first and third stages, so that cross checking of the experimental results may be carried out. Results from the first two types of wind-tunnel tests are usually available from the A/C–store separation analysis, whereas the free-flight tests results, are usually available from the store aerodynamics development phase.

Store Aerodynamic Model

The store aerodynamic model near the parent A/C is determined for each A/C–store configuration using the wind-tunnel test results. For illustration, the evaluation method is described for the pitching moment coefficient C_m.

1) A linear aerodynamic model is assumed:

$$C_m = C_{m_0} + C_{m_\alpha} \cdot \alpha_S$$

2) The C_{m_α}, the static stability derivative, is assumed to be similar to that of freestream.

3) The zero angle-of-attack pitching moment coefficient is calculated as

$$C_{m_0}(Z, M) = C_m^{\text{grid}}(Z, M) - C_{m_\alpha}(M) \cdot \alpha_S$$

4) $C_{m_0}(Z, M)$ is adapted to match the carriage wind-tunnel test value at $Z = 0$ and attain its freestream value at $Z = 5$ m.

The aerodynamic model is tuned using flight-test data.

Ejection Force Model

The ejection force modeling is based on a semi-empiric technique.

1) Ejection force data from a stiff wing at load factor 1 g is supplied by the ejection unit manufacturer.[3]

2) Simulation of A/C and store dynamics includes simplified representation of an elastic wing.

3) Ejection unit semi-empirical simulation (using steps 1 and 2) evaluates the real ejection force curve and its impulse, given the release condition.

After the determination of the aerodynamic and inertial models in the A/C near vicinity, extensive store release simulations are performed. The simulations include cases with perturbed aerodynamic coefficients and inertial input, for sensitivity analysis purposes. One of the main outcomes of the simulations is the minimal distance between the released store, the A/C, and the other loads.

The major advantage of this method is the ability to verify a large amount of sensitivity combinations and different flight conditions with no need of additional expensive wind-tunnel tests. Additionally, inaccurate measured aerodynamic loads can be modified, thus improving their accuracy. Its major disadvantage is the relatively long time needed to evaluate the aerodynamic model.

This technique has been used in the past to determine release envelopes and separation effects for different stores from different A/C.

RR6DS: Reduced 6DOF Simulation

In the time frame of the development program of a new store, the complete analysis is not realistic. Thus, to have a more reliable technique than the one based on the CTS test results, a reduced procedure is suggested.

The aerodynamic model is evaluated as described earlier based on a limited number of carriage wind-tunnel tests (without grid tests) and freestream aerodynamics. The variation of the aerodynamic coefficients, from the carriage flight value to its freestream value is assumed to be linearly dependent on the store vertical displacement. In some cases, to be more conservative, a step function was used instead. An extended sensitivity analysis is included, which compensates for these simplifications.

The analysis is performed in two stages. First, a sensitivity analysis of the aerodynamic coefficients is performed to define the problematic points in the release envelope. Next, the sensitivity to the other parameters (inertia, ejection force, etc.) is analyzed for these previously determined problematic points.

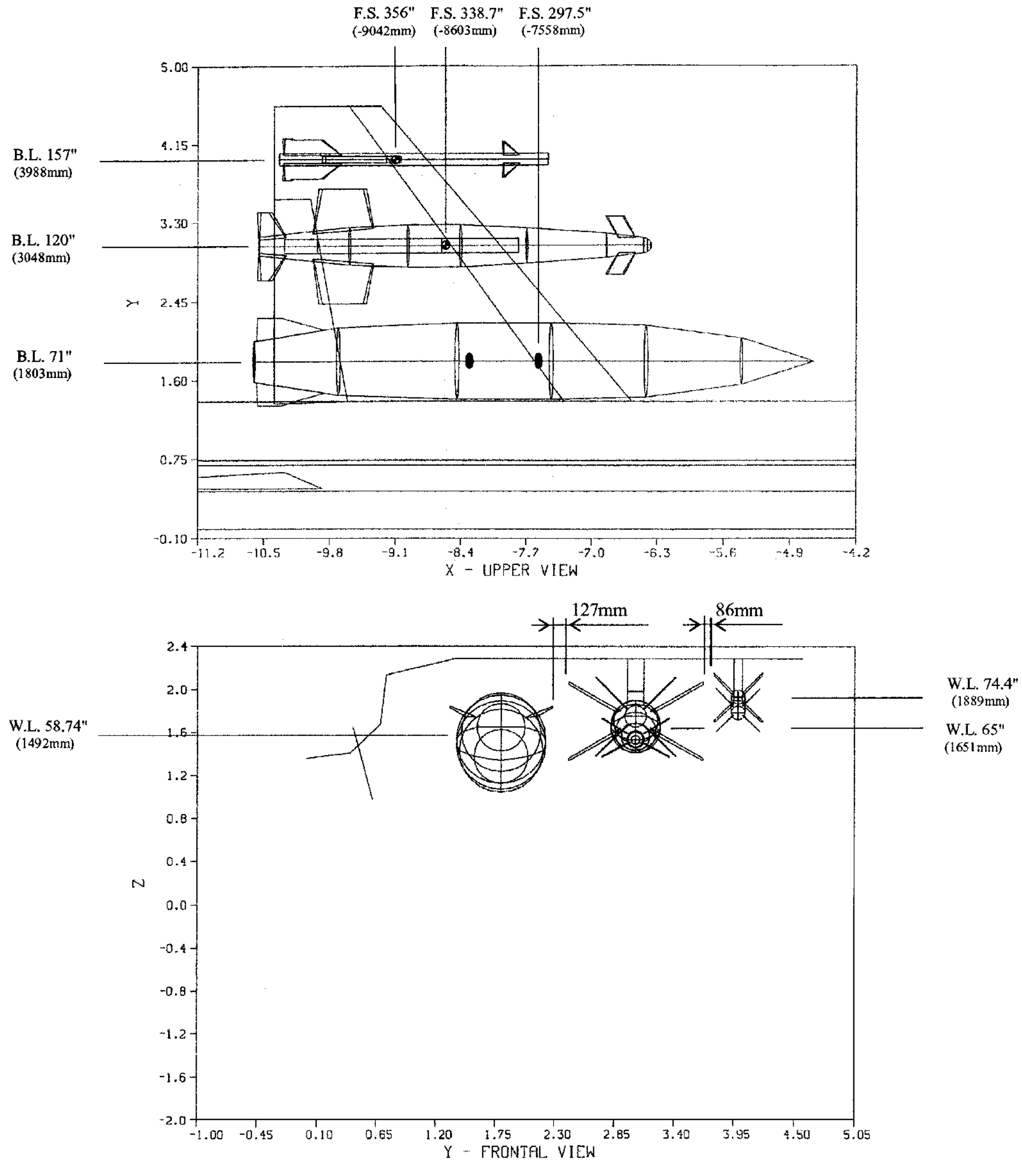

Fig. 2 A/C configuration.

The efficiency of this RR method has been successfully proved for the SPICE program. It proved to be a quick cost-effective method.

The next stage of this work will be the expansion of the reduced analysis to the complete 6DOF simulation method as described earlier with the selected store configuration only.

Store and A/C Configurations

As mentioned, the main goal of this RR was to determine SPICE wingspan. Three different wingspans were examined: S_0, S_1, and S_2 (Fig. 1).

The current work mainly focuses on MK-84 kit mounted on the F-16 wing station 3, with AIM-9L air-to-air (AA) missile on station 2 and with or without a 600-gall fuel tank on station 4 (Fig. 2). These configurations are considered to represent tight geometries and extreme aerodynamic characteristics.

Sensitivity Analysis

To reduce the sensitivity analysis combinations, proximity modes of the store were determined. Each of these modes is characterized by a severe movement of the store toward the A/C or one of its components, thus, resulting in small $d_{\min}$.

Aerodynamic Sensitivities

The sensitivity analysis is required due to tolerances in the wind-tunnel test results, uncertainties in the flowfield, and the usage of a partial aerodynamic model. Worst-case sensitivity combinations (A–E) are defined for five proximity modes (Table 1).

Table 1 Aerodynamic coefficient sensitivity combinations

Coefficient	$\lvert\Delta\rvert$	A	B	C	D	E
C_X	0.10	−	−	+	+	+
C_Y	0.25	−	−	+	+	+
C_Z	0.25	+	+	+	−	+
C_n	0.25	−	−	+	+	+
C_m	0.50	+	−	−	+	+
C_l	0.12	+	+	−	−	−

The tolerances in Table 1 are equivalent to a change of about 2 deg in the freestream angles of attack in pitch and yaw, while an equivalent change of 350 deg/s in rolling moment coefficient due to a higher uncertainty in measurement and prediction of the rolling moment.

Inertial Tolerances

The ejection force varies from a stiff wing (100%) to a flexible wing (70%). The nominal value was taken as 90% of the stiff wing, as given earlier. The piston stroke point, in inches, is

$$-2 < \Delta X < +2, \qquad -0.4 < \Delta Y < +0.4$$

The Load factor is $0.9 < N < 2\ g$. The moments of inertia are $\pm 5\%$. The A/C weight is ± 3000 lb.

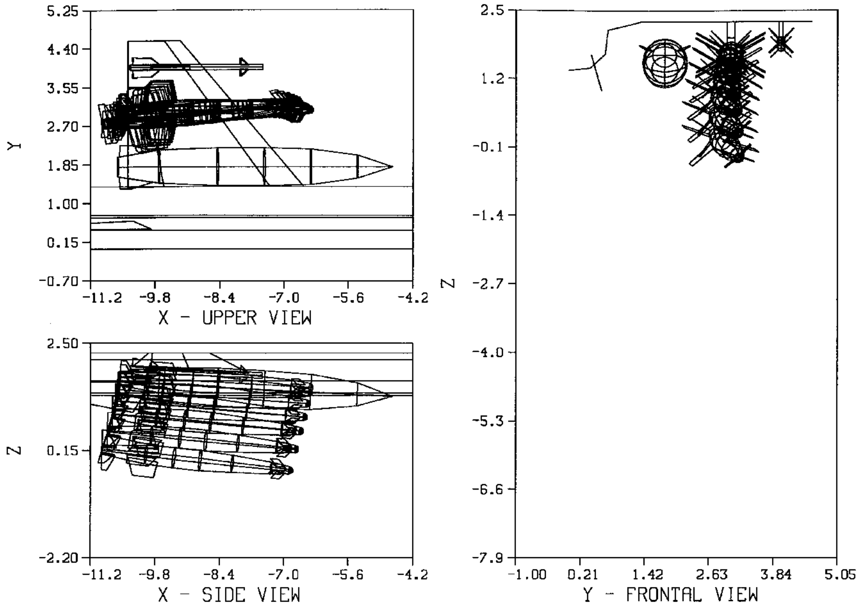

Fig. 3 Store separation dynamics for A/C configuration with 600-gal tank.

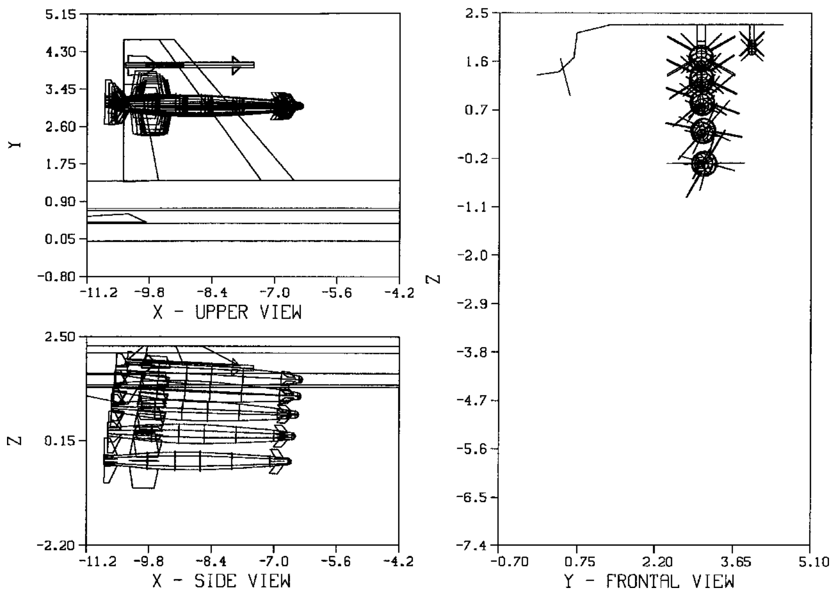

Fig. 4 Store separation dynamics for A/C configuration without 600-gal tank.

Success Criteria

The success criteria defined for this program are as follows. For the nominal aerodynamic coefficients and CTS tests, a minimal distance of 3 in. (4.5 cm) in the entire release envelope is allowed (at a 1:1 scale). For the sensitivity analysis results, a minimal distance of 1 in. (2.5 cm) in the entire release envelope is allowed. The weighted contributions of the inertial parameter tolerances were superimposed on those of the aerodynamic tolerances.

CTS Test Results

The CTS tests series main findings are as follows.

1) As anticipated, very small minimal distances resulted from the tight geometry. The resulting minimal distance ranged between 5 in. (13 cm) to collisions with the adjacent stores.

2) For the A/C configuration with the 600-gal tank, the worst case is at low altitude and high Mach number ($M = 0.95$). The most dangerous proximity mode is a nose-out yawing motion that moves the store's wing toward the fuel tank. This motion is shown in Fig. 3.

3) For the A/C configuration without a 600-gal tank (wing station 4 is clear), the worst case is at high altitude and $M = 0.9$. The dangerous mode is a nose-in yawing motion that moves the store wing toward the AA missile stabilizer. This motion is shown in Fig. 4. Other references[4] quoted a similar anomaly in Mach influence.

To decrease the yawing motion, the canard configuration was changed during the CTS wind-tunnel tests from four X type to two horizontal canards. This change resulted in only a small improvement in $d_{\min}$ (about 0.5-in. (1.2 cm) increase).

A close examination of the results indicated that most collisions warning signals of the CTS system were erroneous. In one case a collision was indicated when the store was at a minimal distance of about 3.5 in. (8.4 cm) from the tank according to the CTS simulation.

It is known that at distances of less than 1 in., collisions can occur due to vibrations or during a movement from one calculated point to another. A collision in the case of $d_{\min} = 3.5$ in. (8.4 cm) is not acceptable. A possible explanation is a loose bearing in the CTS arm mechanism that can cause a strong uncontrollable movement when the side force changes direction.

As a consequence of these CTS tests, S_2 wingspan was rejected. The S_1 wingspan was chosen for SPICE resulting in $d_{\min} \approx 2.5$ in.

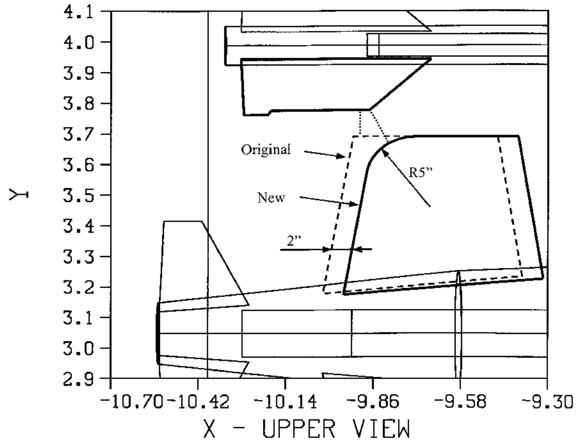

Fig. 5 Geometric changes in wing configuration.

(6.2 cm) (between the AA missile stabilizer and the store wing at high altitude and $M = 0.9$). To increase this minimal distance, some changes have been made to the SPICE configuration: The wings were moved forward, and the wings rear tip were trimmed off (Fig. 5). These changes increased the minimal distance to about 3.3 in. [(8.2 cm), in agreement with the already mentioned criterion].

At that point it was decided that to improve confidence in choosing the proper wingspan, an alternative technique will be used: the reduced 6DOF simulation.

RR6DS Simulation Results

Comparison with CTS Results

The nominal simulation results, using the aerodynamic model based on carriage wind-tunnel experiments, differ from the CTS results due to the differences in the aerodynamic coefficients, mainly in C_l, C_Z, and C_n. These differences are shown in Fig. 6. The aerodynamic coefficients based on the CTS measurements at $Z = 0$ differ

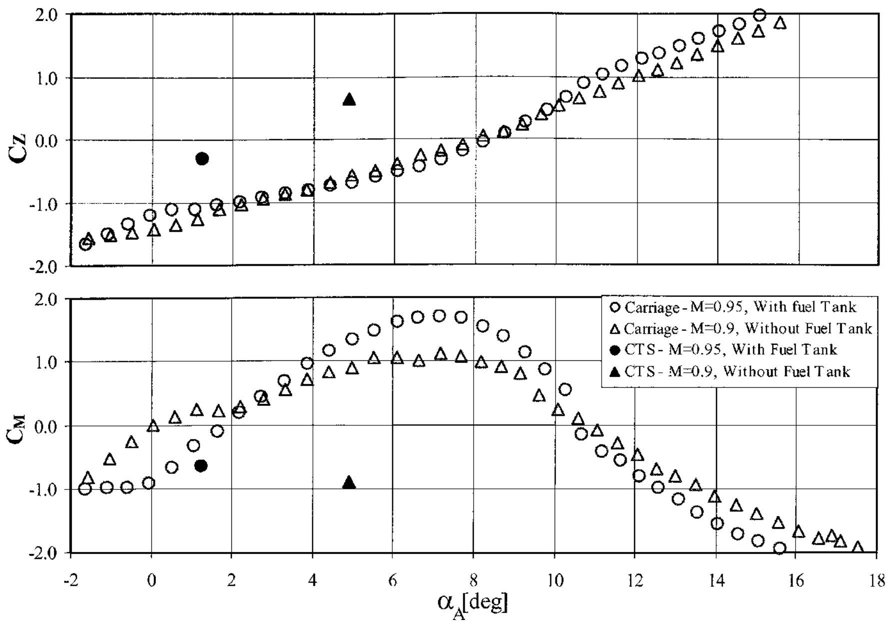

Fig. 6a Aerodynamic coefficients vs α_A at Z = 0 for wingspan S_1: C_Z and C_m.

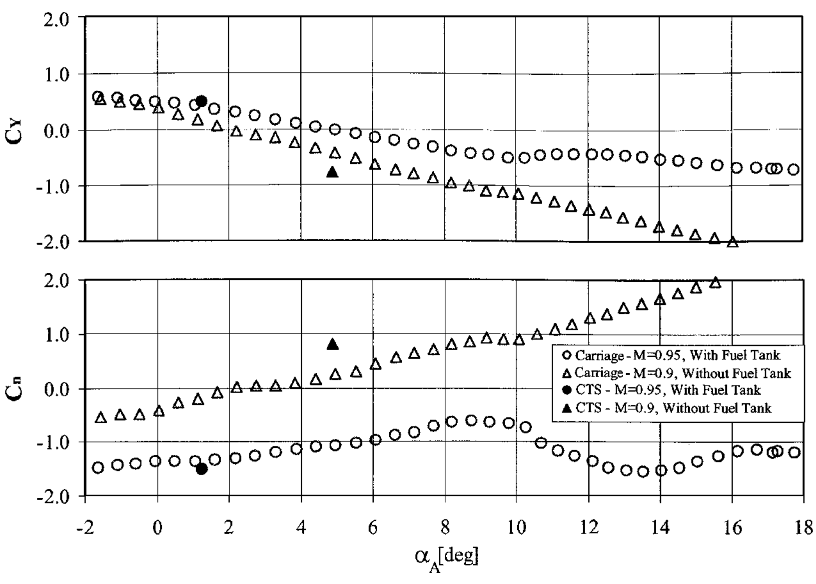

Fig. 6b Aerodynamic coefficients vs α_A at Z = 0 for wingspan S_1: C_Y and C_n

from the carriage wind-tunnel experiments and are equivalent to a change of up to 3 deg in the freestream angles of attack.

For comparison between the CTS and the simulation-based technique, the 6DOF simulation was run with the aerodynamic model based on the CTS coefficients. The store separation dynamics and minimal distances were in very good agreement (Fig. 7), and both the erroneous and correct collision warning signs were confirmed (Figs. 8 and 9).

Nominal Simulation Results

As in the CTS tests, for the A/C configuration with the 600-gal tank, the worst case is at low altitude and at $M = 0.95$. For the A/C configuration without a 600-gal tank, the worst case is at $M = 0.9$.

The minimal distances, for nominal simulations, were 5.0 and 4.7 in. (12 cm) for the S_0 and S_1 wingspans, respectively, both acceptable according to the success criterion.

Sensitivity Analysis Simulation Results

For the A/C configuration with the 600-gal tank, the worst aerodynamic sensitivity combination is A (Table 1). For the A/C configuration without the 600-gal tank, the worst sensitivity combination is E. The results indicate that the aerodynamic coefficients, the ejection force, and N had the most significant effect on the minimal distances. For illustration, the sensitivity analysis for the A/C configuration with the fuel tank is shown in Table 2. (The nominal $d_{\min}$ for this case is 5.85 in.)

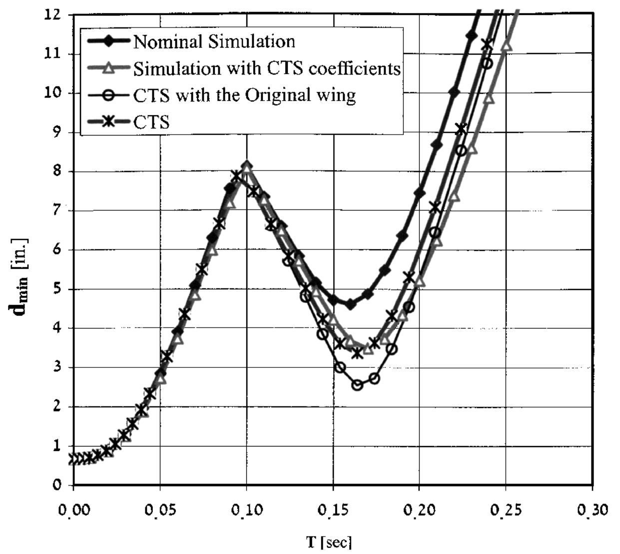

Fig. 7 Separation dynamics established using the different techniques for wingspan S_1, $M = 0.9$, $H = 40{,}000$ ft, and A/C configuration without fuel tank.

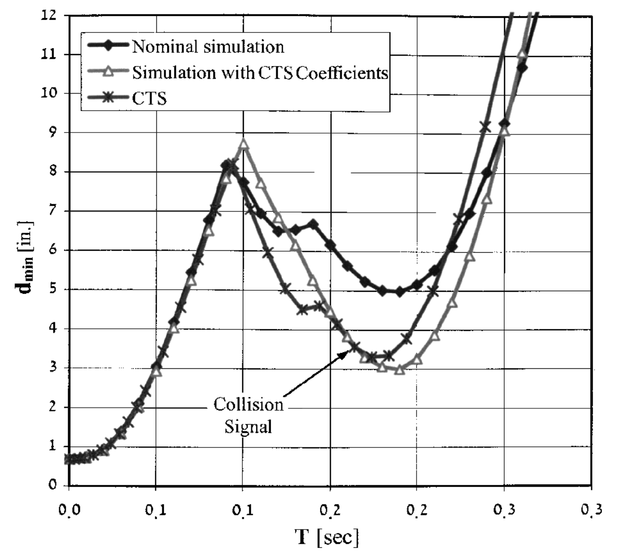

Fig. 8 Separation dynamics in a case of erroneous CTS collision warning, wingspan S_1, $M = 0.95$, $H = 8000$ ft, and A/C configuration with fuel tank.

Table 2 Sensitivity analysis for the A/C configuration with the fuel tank, S_0 wingspan, $M = 0.95$, and $H = 8000$ ft

Parameter	Tested value	$d_{\min}$, in.	$\Delta d_{\min}$, in.
Aerodynamics	ΔA	2.25 (Base line)	——
Ejection force	Stiff wing	2.65	+0.40
	Elastic wing	1.25	−1.00
N, g	0.9	2.00	−0.25
	2	4.05	+1.80
Piston action point, cm	$X - 5$	2.30	+0.05
	$X + 5$	2.10	−0.15
	$Y - 1$	2.15	−0.10
	$Y + 1$	2.50	+0.25
Moments of inertia, 5%	I_{xx}	2.25	0
	I_{yy}	2.20	−0.05
	I_{zz}	2.10	−0.15
α_A (due to A/C weight variation), deg	1.2	2.20	−0.05
	1.4	2.25	0

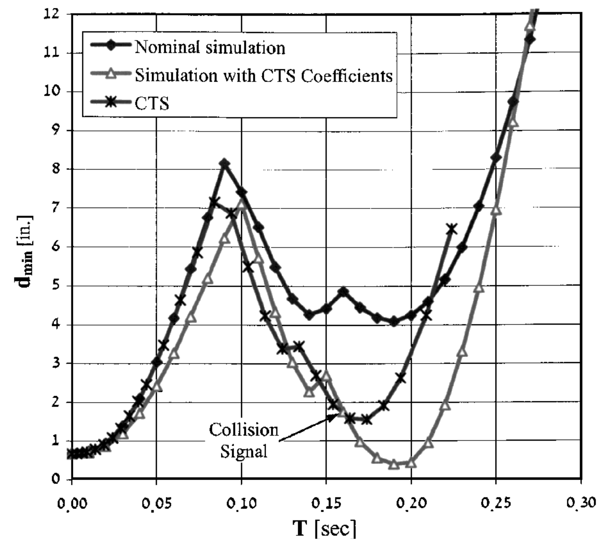

Fig. 9 Separation dynamics in a case of correct CTS collision warning, wingspan S_2, $M = 0.95$, $H = 8000$ ft, and A/C configuration with fuel tank.

The minimal distances, for the sensitivity analysis simulations, were 1.2 (3 cm) and 0.2 in. (0.5 cm) for S_0 and S_1 wingspans, respectively, with the 600-gal tank configuration (at low altitude and at $M = 0.95$). The result for S_0 is acceptable according to the success criterion. In accord with the results, the S_0 wingspan was chosen.

Conclusions

A new preliminary store separation analysis method is presented. The method was successfully applied to determine the aerodynamic configuration of the SPICE as part of the FSD RR phase.

The main advantages of the method are as follows.

1) It yields more reliable results than the CTS for tight A/C–stores configurations.

2) It requires a relatively short time to select the adequate aerodynamic configuration.

3) The separation analysis evaluated using this method is based on a few accurate aerodynamic loads measured in carriage and freestream wind-tunnel tests.

4) It enables detailed sensitivity studies of a variety of tolerance combinations, both aerodynamic and inertial, indicating the hazardous release envelope points. This is in contrast to CTS and higher-order (computational fluid dynamics-) based methods.

The RR6DS method is highly recommended for those cases where the tested store is very close to the A/C or adjacent stores.

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