F-35 Joint Strike Fighter: Store Separation Flight Test and Analysis

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F-35 Joint Strike Fighter

Advanced multi-role fighter consisting of three variants designed to meet the unique needs of US and partner military services while overcoming increasing trends in development, manufacturing, and support costs

- Pillars of the F-35 Program
  - Affordability
  - Lethality
  - Survivability
  - Supportability

- Cornerstone is Affordability
  - Leverage commonality of parts and systems
  - Streamlined assembly
  - International participation to share technology/cost
F-35 Lightning II Weapons Capability
Internal and External Carriage

5th GENERATION STEALTH AND LETHALITY
Early in the conflict, the F-35’s combination of stealth with enhanced lethality enables it to work with impunity in tomorrow’s high-threat combat environments. The Fifth Generation Fighter carries its weapons targeting systems and fuses internally – allowing it to easily destroy airborne and ground-based enemy integrated air defense systems.

INTERNAL WEAPONS CARRIAGE

Air-to-Air Missiles
- AIM-120 ASRAAM
- AIM-12C AMRAAM

Air-to-Ground Missiles
- Sidewinder
- Brimstone Anti-Armor
- Joint Common Missile
- AGM-75 JSOW

Internal Gun (CTOL Only)
- GAU-12/B

Guided Weapons
- GBU-38 Small Diameter Bomb
- GBU-38/DAM (500 lb MK-82 Warhead)
- GBU-39/DAM (BLU-117/117F Warhead)
- GBU-32/DAM (1000 lb MK-83 Warhead)
- GBU-31/32/39(W), JDAM, 2000 lb W80-1 WAPR Warhead
- GBU-32/31/39, JDAM, 2000 lb Mk-84 NTP Warhead
- GBU-32/31/39, JDAM, 2000 lb Mk-84 NTP Warhead
- GBU-12/20/24, 907 lbs Paveway IV 500 lb LD (MK-82 WAPR Warhead)
- 500 lb Paveway IV
- JDAM PGM KU-4
- JDAM PGM (KU-6)

Dispensers
- MK-23 Rockwell Cluster Munition Dispenser
- GBU-12/31/39, Cluster Munition
- GAU-12/SN

Gun Pod
- GAU-22/A Four-Barrel Gatling Gun

Utility/Training Pods
- GMU-18/B Baggage Pod
- GMU-64/B Baggage Pod

EXTERNAL WEAPONS CARRIAGE

Air-to-Air Missiles
- AIM-9 Sidewinder
- AIM-120 ASRAAM
- AIM-12C AMRAAM
- AIM-120 ASRAAM

Air-to-Ground Missiles
- AGM-84 Harpoon
- AGM-114 Hellfire
- AGM-154 JSOW
- AGM-84 Harpoon
- Joint Common Missile
- JDAM PGM

Dispensers
- JDAM PGM

Guided Weapons
- GBU-38/DAM, 2000 lb, Mk-84 17/17F Warhead
- GBU-32/DAM, 2000 lb, Mk-84 17/17F Warhead
- GBU-31/32/39(W)/JDAM, 2000 lb W80-1 WAPR Warhead
- GBU-32/31/39, JDAM, 2000 lb Mk-84 NTP Warhead
- GBU-31/32/39, JDAM, 2000 lb, Mk-84 NTP Warhead
- GBU-32/31/39, JDAM, 2000 lb, Mk-84 NTP Warhead
- GBU-32/31/39, JDAM, 2000 lb, Mk-84 NTP Warhead
- JDAM PGM (KU-4)
- JDAM PGM (KU-10)
- JDAM PGM (KU-110)
- JDAM PGM (KU-6)

Fuel Tank
- 450 Gallon External Fuel Tank

5th GENERATION MULTIROLE FORCE DOMINANCE
Once air dominance is established, the F-35 provides war fighting commanders a total arsenal of weapons options, with over 17,000 pounds of weapons – twice the payload of current fighters. Support for joint/coalition ground forces is unparalleled – thanks to low observability and an unsurpassed weapons arsenal.

General Purpose Weapons
- GAU-16 (30mm 1200RPM)
- GAU-16/17 (30mm 1200RPM)
- GAU-16/17 (25mm 1200RPM)
- GAU-16 (20mm 1200RPM)

Offensive/Defensive Training Systems
- M61A-1 or BDU-44 Practice Drones
- BDU-57/75/100 Lasso Guided Training Rounds

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.
Vi-Aircraft & Adams Usage

≈ 15 regular users (~11 Vi-Aircraft, ~4 Adams/View)

- **Landing & Arresting Gear**
  - Landing, taxi, turning, braking loads
  - Ride quality & braking/wet runway control
  - Arrestment, catapult, & short takeoff

- **Door Dynamic Loads**

- **Store Separation**
  - Safe & Acceptable Separation
  - Dynamic Loads/Response

- **Flexibility**
  - Rails, launchers, missiles, wings, pylons
  - Doors, landing gear components
  - Arresting gear cable & components

- **3-D Roads/Tires/Hook Contact**

- **Co-simulation & Integration with**
  - CFD, Controls, Aero, Tires, Gas/Damping

- **Geometry & Clearance Checking**

- **10,000’s of survey & MonteCarlo sims**
Store Separation… What is it?

- **Store** = Missile, Bomb, Baggage Pod, Fuel Tank, Training Round, etc.
- **Separation** = Get away from the airplane, **safely!**

### Safe

- Aircraft is flying at a “point in the sky”
  - Mach, Altitude, Nz (g’s), α, β, Dive Angle, Roll Rate, etc.

- Pilot “releases” a store … now what?
  - Store is forcefully pushed away from the aircraft:
    - Ejector rack: pushes store away
    - Rail Launcher: guides a thrusting missile
  - Store is subjected to aerodynamic forces
  - Store may be guided, via control system

### Not Safe

From: YouTube http://www.youtube.com/watch?v=cQeBgdsoTa4

From: Lessons Learned: Limitations of Modern Tools and Applications for Store Separation Prediction 2001 Aircraft-Store Compatibility Symposium Eddie Roberts March 5-8, 2001
ASEP is Used in **All** Phases of Store Separation Analysis

- **ASEP (Lockheed Martin)** ADAMS Store Separation
  - Customized **VI-Aircraft (VI-Grade)**
  - Customized **ADAMS (MSC Software)**

**ASEP**

**Automatic Dynamic Analysis of Mechanical Systems**

**Analysis** is the Basis for **Certification**

- *Modeling and simulation* (primary means of analysis)
  - Ejector rack models
  - Aerodynamic database development
  - Flight envelope trajectory predictions
  - Miss distance evaluation
  - Uncertainty analysis
- *Ground (pit) testing*
  - Verify installed ejector rack performance
- *Flight test*
  - Final verification and validation of pre-flight models
# F-35 Program Information – Non Export Controlled Information

## Path to Flight Clearance & Certification

### REQUIREMENTS
- Weapon Loadouts / Envelopes
- Pit Test
- Uncertainty Analysis
- Predictive Confidence
- Flight Test Verification and Validation of Modeling / Simulation

### Pathway

1. **Aerodynamic Properties**
2. **Store Mass Properties**
3. **Ejector Properties**
4. **Aero Database/Model**
5. **6DOF Model**
6. **Obtain Flight Clearance**

### Simulations
- Emergency Jettison
- Selective Jettison / Employment

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Store Mass Properties

Aerodynamic Properties

Store Mass Properties

Ejector Properties

Weapon Loadouts / Envelopes

Requirements

Aero Database/Model

6DOF Model

Simulations

Emergency Jettison

Obtain Flight Clearance

Simulations

Selective Jettison / Employment

Uncertainty Analysis

Predictive Confidence

Flight Test Verification and Validation of Modeling / Simulation

Mass

xCG, yCG, zCG

lxx, lyy, lzz
**F-35 Program Information – Non Export Controlled Information**

**Store Ejector**

**Aerodynamic Properties**
- Store Mass Properties
- Ejector Properties

**Requirements**
- Weapon Loadouts / Envelopes

**Aero Database/Model**
- Predictive Confidence
- Obtaining Flight Clearance

**Simulations**
- Flight Test Verification and Validation of Modeling / Simulation
- Emergency Jettison
- Selective Jettison / Employment
- Uncertainty Analysis

**Validate**
- Aero
- 6DOF

**Obtain Flight Clearance**

**Certification Recommendation**

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Ejector Rack Models

- Ejector rack: Push store away from aircraft
- ADAMS mechanical model obtained from rack supplier
- Gas piston force (compiled C/C++ “black box” obtained from rack supplier), integrated into Vi-Aircraft/ASEP
  - Pneumatic: gas expands into piston chambers
  - Gas piston force depends upon Store Mass, CG, Iyy, aerodynamics, etc.

From: JSF Pneumatic S&RE and Beyond, Mr. Lynn D. Seal, Precision Strike Technology Symposium, 19 Oct 2005.
Store Aerodynamics

Aerodynamic Properties

Validated Aero

Pit Test
Validate Ejector

Simulations
Emergency Jettison
Selective Jettison/Employment

Obtain Flight Clearance

Flight Test Verification and Validation of Modeling/Simulation

Requires:

Weapon Loadouts/Envelopes

Aero Database/Model
6DOF Model

Ejector Properties

Uncertainty Analysis
Predictive Confidence

Stand Mass Properties

Obtain Flight Clearance

Certification Recommendation
Captive Trajectory Support (CTS)

- Computer controlled positioning of a store in close proximity to the aircraft
- 2 modes for Store Separation:
  Trajectory testing
    • “Hardware” in the loop
  Flow-field mapping
    • Aerodynamic grid database
6DOF & Simulations

Aerodynamic Properties

Store Mass Properties

Ejector Properties

Aero Database/Model

6DOF Model

Simulations
Emergency Jettison

Simulations
Selective Jettison / Employment

Obtain Flight Clearance

Validate Aero

Pit Test

Validate Ejector

Flight Test
Verification and Validation of Modeling / Simulation

Predictive Confidence

Uncertainty Analysis

Certification Recommendation

Weapon Loadouts / Envelopes

REQUIREMENTS

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.
F-35 Store Separation Analysis

Flight Envelope Trajectory Predictions

Normalized Miss

Mach
Altitude (feet)

0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6

10000
20000
30000
40000
50000
60000

Normalized Miss

1.0
0.6
0.2
0.0

150
200
250
300
350
400
450
500
550
600
650
700

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Uncertainty Analysis

REQUIREMENTS
- Weapon Loadouts / Envelopes
- Aerodynamic Properties
- Store Mass Properties
- Ejector Properties
- Aero Database / Model
- 6DOF Model

Simulations
- Emergency Jettison
- Selective Jettison / Employment

Pit Test
Validate Aero
Validate Ejector

Obtain Flight Clearance

Flight Test
Verification and Validation of Modeling / Simulation

Predictive Confidence

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Store Separation “Uncertainties”

**Store Mass Properties**
- Mass
- xCG, yCG, zCG
- Ixx, Iyy, Izz (Ixy, Izx, Iyz)

**Store Ejector Performance**
- Store Vz
- Store Pitch Rate
- Store Roll Rate

**Store Aerodynamics**
- Mx, My, Mz
- Fx, Fy, Fz
- Rotational aero damping

Wind tunnel Reynolds Number, bay/door model simplifications in geometry, real store differences from model, inlet flow/spillage, etc.

**Aircraft Maneuver**
- Mach, Alt, KCAS
- Angle of Attack, Angle of Sideslip
- Nx, Ny, Nz
- Roll, Pitch, Yaw Rates

**Monte Carlo Uncertainty Analyses**
- NOT used to assess probability of occurrence
- Used to understand/uncover ‘combined’ important drivers
  - Pay attention to those drivers, before & during flights
- Normal Distribution vs. Uniform Distribution:
  - Early in test program, Normal Distribution not safe/appropriate

**Safe Flight Testing → to Validate Simulation Models**
- Proceed through flight test SAFELY
- Control/remove uncertainties as much as possible
- Gain confidence in uncertainties (distribution type & 3σ) with more data
Pit Test

**Requirements**
- Weapon Loadouts / Envelopes
- Aerodynamic Properties
- Store Mass Properties
- Ejector Properties
- Store Mass Properties
- Aerodynamic Properties
- Ejector Properties

**Simulations**
- Emergency Jettison
- Selective Jettison / Employment

**Obtain Flight Clearance**

**Flight Test**
- Verification and Validation of Modeling / Simulation

**Uncertainty Analysis**

**Predictive Confidence**

**Validate**
- Aero
- 6DOF
- Ejector
Pit Test

- Verify installed/on-aircraft performance
- Adjust sim models, if necessary

From:

From:
YouTube: http://www.youtube.com/watch?v=YaJeA8P67cY&list=PLDF92451CB0870E9E&index=78
Flight Test

**Aerodynamic Properties**
- Pit Test
- Validate Aero

**Store Mass Properties**
- Simulations
  - Emergency Jettison
  - Selective Jettison / Employment
- Simulations
  - Predictive Confidence
- Validate Ejector

**Ejector Properties**
- Obtain Flight Clearance
- Validate 6DOF
- Uncertainty Analysis

**Aero Database/Model**
- 6DOF Model
- REQUIREMENTS
  - Weapon Loadouts / Envelopes

**Certification Recommendation**
- Flight Test
  - Verification and Validation of Modeling / Simulation

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Flight Test – 1st F-35 Store Separation

From: http://www.jsf.mil/gallery/gal_video.htm#f35test
Key Sep Flight Test Instrumentation

• Airborne Separation Video System (ASVS) Imagery
  – Digitize/Compute **Store Positions** \((D_x, D_y, D_z, \psi, \theta, \Phi)\), in Aircraft Axes
  – Photogrammetry

From: Airborne Separation Video System  
2001 Aircraft-Store Compatibility Symposium  
Rob Crandall, March 5-8, 2001

• 6DOF Telemetry Kit
  – Measure Store **Translational Accels** \((n_x, n_y, n_z)\), in Store Axes  
  – Measure Store **Rotation Rates** \((\omega_x, \omega_y, \omega_z)\), in Store Axes

From: Telemetry Solutions for Weapon Separation Testing  
2003 Aircraft-Store Compatibility Symposium  
Edward Getson, February 18-20, 2003
Photogrammetry Input to ASEP

- **Airborne Separation Video System (ASVS) Imagery**
  - *Take Digitized/Computed Store Positions*
    - \((D_x, D_y, D_z, \psi, \theta, \Phi)\), in Aircraft Axes:
    - Create time-history position of store, relative to aircraft
  - *ADAMS MOTIONs drive yellow “Motion-only store” … PhotoG Solution*
  - *ADAMS REQUESTs for velocities (noisy)*
  - *ADAMS REQUESTs for accelerations (more noisy)*
    - To get smoother velocities/accelerations, smooth the input position time-histories

- *ADAMS REQUEST to Compute “Actual Aero”*

\[
\Sigma F_x = m a_x \\
\Sigma F_y = m a_y \\
\Sigma F_z = m a_z \\
\Sigma M_x = I_x \omega \text{dot}_x - (I_y - I_z) \omega_y \omega_z \\
\Sigma M_y = I_y \omega \text{dot}_y - (I_z - I_x) \omega_z \omega_x \\
\Sigma M_z = I_z \omega \text{dot}_z - (I_x - I_y) \omega_x \omega_y
\]

- **Measured Store Mass Properties**
- **REQUESTS on Yellow Motion Store**
- *Compare to looked-up “Database Aero”*
6DOF TM Kit Input to ASEP

• 6DOF Telemetry Kit
  – Measure Store Translational Accels \((a_x, a_y, a_z)\), in Store Axes
  – Measure Store Rotation Rates \((\omega_x, \omega_y, \omega_z)\), in Store Axes
    • Differentiate to obtain \(\omega_{\dot{x}}, \omega_{\dot{y}}, \omega_{\dot{z}}\)
    • Create time-history input file for TM Kit Rates/Accels, in Store Axes
  – Separate ADAMS Part “TM Kit” to handle 6DOF measurements
    • TM Kit PartCM Located at installed TM Kit location
    • Attach duplicate Magenta store geometry to TM Kit Part
    • \(m=1\text{lb}_m, I_{xx}=I_{yy}=I_{zz}=1\text{lb}_m\text{-in}^2\) (negligible mass, compared to store)

• ADAMS GFORCE to “Push” the TM Kit Part
  \[\Sigma F_x = 1*a_x\]
  \[\Sigma F_y = 1*a_y\]
  \[\Sigma F_z = 1*a_z\]
  \[\Sigma M_x = 1*\omega_{\dot{x}}\]
  \[\Sigma M_y = 1*\omega_{\dot{y}}\]
  \[\Sigma M_z = 1*\omega_{\dot{z}}\]

• ADAMS REQUEST to Compute “Actual Aero”

\[\Sigma F_x = ma_x\]
\[\Sigma F_y = ma_y\]
\[\Sigma F_z = ma_z\]
\[\Sigma M_x = I_x\omega_{\dot{x}} - (I_y - I_z)\omega_y\omega_z + \ldots\]
\[\Sigma M_y = I_y\omega_{\dot{y}} - (I_z - I_x)\omega_z\omega_x + \ldots\]
\[\Sigma M_z = I_z\omega_{\dot{z}} - (I_x - I_y)\omega_x\omega_y + \ldots\]

• Compare to looked-up “Database Aero”

Measured Store Mass Properties
REQUESTS on Magenta TM Kit Store Part @CG

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6DOF TM Kit Concept Demo

Concept Demo:

“Simulation/Test” Store Part
- Geometry/Trajectory & DATABASE Aero Curve
  - Perform Sim with Database Aero
  - Request/Output Rates/Accels at “somewhere other than CG”

“TM Kit” Part
- Geometry/Trajectory & Computed Aero Curve
  - CM at “somewhere other than CG”
  - Use Output Rates/Accels From “Simulation/Test” store, above, Create Input File
  - Push TM Kit Part, from Input File Accels (F=ma)

Must Match
PhotoG & 6DOF TM Kit in ASEP

- **Yellow PhotoG/Motion Store**
  - *Driven by Measured Positions (photogrammetry)*
    - Accuracy depends upon ASVS & photoG point digitization
  - *Velocity/Acceleration … Usually more noisy, unless smoothing*

- **Magenta 6DOF TM Store**
  - *Driven by Measured 6DOF TM Kit Accels*
    - high-quality; so, good “Computed/Real Aero”
  - *Position/Trajectory … quality/accuracy depends on Initial Conditions*
    - At Carriage, Attach/FIX Magenta 6DOF TM Store to Yellow Motion Store
    - Release/deactivate Fixed Joint at:
      - Carriage
      - End-of-ejector
      - Later in the Yellow Motion Store’s trajectory

- Store Position/Trajectory/Clearance
- Store Velocity/Rates
- Store Accelerations
- Store Computed Flight Test Aero

Available from 2 sources
- Complementary
- Each has pros/cons
Flight Test – 6DOF TM Kit Pitch Example

Use this portion for Magenta 6DOF TM Kit Store

• Differentiate for Pitch Acceleration, Create Input Time-History File
• Drive Magenta Store in ASEP ‘sim’
• Post-Process Extract/Request Aero Pitch Moment, CLM from
  \[ \Sigma M_y = I_y \dot{\omega}_y - (I_z - I_x) \omega_z \omega_x + \ldots \]
Flight Test – Aero Extract/Adjust

Near Carriage
In Aircraft Flowfield
In Freestream, Away from Aircraft

Aero Pitch Moment Coefficient

Distance Below Aircraft

Actual Store aero pitch more nose-up in flowfield (vs. Database)

Actual Store aero pitch more nose-down near carriage (vs. Database)

Δ Flight Test Increment/Adjustment
Modify AeroDatabase for future sims

CLM_{TMKitComputed} (Unfiltered)  CLM_{TMKitComputed} (FilterB) (FilterC)  CLM_{AeroDatabase}

Actual Store aero pitch similar, away from aircraft (vs. Database)
Postdiction

Prediction

- Nominal Store Mass Properties
- Nominal Ejector
- Baseline Store Aero Database
- Steady Aircraft Maneuver

“Post”diction

- EXACT/Measured Store Mass Properties
- Ejector Performance from 6DOF TM Kit
- Adjusted (FT Increment) Store Aero Database
- Aircraft Time-History from EXACT FT Maneuver
Summary

• VI-Aircraft & Adams: used in all phases of Store Sep analyses
  – Aero database/grid validation
  – Component/subsystem performance verification
    • Verify components, then include in assemblies
  – Pit test simulation & post-processing
  – Pre-flight simulation
    • Including clearance checking, MonteCarlo/uncertainty analysis, etc.
  – Post-event data analysis, aero database adjustment, investigation, & simulation

• Easily customized to handle Sep FT
  – Use same pre-flight simulation models/tools
  – Multiple FT data sources; compare/contrast each
  – Let Adams handle the equations, signs, integration, etc.

• Simulation: basis for Store Separation certification recommendation to our customers
  – Use FlightTest-validated models
  – After Flight Testing … understand & apply uncertainties, with greater certainty
Store Sep Flight Testing

From: YouTube: http://www.youtube.com/watch?v=YaJeA8P67cY&list=PLDF92451CB0870E9E&index=78