Model-Based Engineering and Cyber-Physical Systems

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MODELING & SIMULATION
Physics-based science and engineering
Newton’s Second Law

\[ F = ma \]

1D EQUATION
2D Physical Model
2D Physical Model

Applied Load, P

Deflection, $\delta$
2D Physical Model

Applied Load, $P$

Length, $L$
2D Physical Model

Applied Load, \( P \)

Length, \( L \)
2D Physical Model

Vertical Force, \( P' = mg \)
Rotational Force, \( M = mgL \)

2D PHYSICAL MODEL
3D Geometry Model

Structural Rigidity

\[ I = \frac{\pi d^4}{64} \]

\[ I = \frac{bh^3}{12} \]

\[ I = \frac{bh^3}{36} \]
3D Analysis Model

Material Stiffness

- Aluminum
- Steel
- Titanium
- Composite
- Wood

Length, L
3D Analysis Model – Deflection

Deflection, \( \delta = \frac{PL^3}{3El} \)

- \( P \) is the Applied Force
- \( L \) is the Length
- \( E \) is the Material stiffness
- \( I \) is the Structural rigidity

Geometry

Material Stiffness

Structural Rigidity

\[ I = \frac{\pi d^4}{64} \]
\[ I = \frac{bh^3}{12} \]
\[ I = \frac{bh^3}{36} \]
Geometry

Structural Shape

Structural Rigidity

\[ I = \frac{\pi d^4}{64} \]
\[ I = \frac{bh^3}{12} \]
\[ I = \frac{bh^3}{36} \]

**Stress, \( \sigma_a \)**

\[ \sigma_a = \frac{\text{bending moment}}{\text{section modulus}} = \frac{PL}{I/z} \]

3D ANALYSIS MODEL
3D Simulation

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Margin of Safety = \frac{Material Strength}{Stress \times Safety Factor}

Material Strength

Safety Factor

1.25 Unmanned
1.4 Spacecraft
1.5 Aircraft
3D Structural Simulations

Margin of Safety

Structural Life

Inspection Interval

Static (σ-ε)

Fatigue (S-N)

Fatigue Crack Growth (da/dN)
Functional Model

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- Atmosphere
  - Weather
  - Noise

2D Geometry

3D

Material Type

Loading Condition

Load Cycling

As-Built State

Variations
- Flaws
- Damage

- Operating Environ.

Yes

No

- Safe
- Strong
- Durable
- Light
- Affordable

2D

3D

Geometry

Material Type

Ok?
Multifunctional Model
Aerodynamic Model

Airfoil geometry and orientation

Wing loading
Wing Cantilever Beam Model

Net Loading, q

Fuselage Weight, W
Fuselage Weight

Wing Geometry

Airfoil Geometry

\[ \delta = 0.018 \frac{W}{\varepsilon \tau (\tau^2 + \varepsilon^2)} (1 + \lambda)^3 (1 + 2\lambda) \frac{b}{c^4} \]
Breguet Range Equation

Range = \( V \cdot \frac{L}{D} \cdot I_{sp} \cdot \ln\left(\frac{W_i}{W_f}\right) \)
Trade-Offs

MISSION SIMULATION
Models and Simulations

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1D Equation

2D Physical Model

3D Geometry Model

3D Analysis Model

Functional Model (physics-based)

Multi-Functional Model

Performance Model

Mission Simulation
DIGITAL TWIN OF PRODUCT

As-Built Simulation with Cyber-Physical Linkage
Control Theory

Dynamic System

Feedback

Inputs → Decision Engine → Output
Cyber-Physical System

Simulation (Decision Engine)

Physical System
DIGITAL TWIN

As-Built Condition → Vehicle Simulation → Flight Operations → As-Operated Condition

Inputs
Control, Feedback & Learning
Flight Output
Extend the Product Lifecycle
FACTORY
MANUFACTURING

FACTORY

Extend the Product Lifecycle
ENGINEERING

MODEL-BASED ENGINEERING
DIGITAL THREAD

ENGINEERING

MANUFACTURING

As-Sold Condition

Program Dev Sim

Engineering

Engineering Operations

As-Designed Condition

Process Simulation

Fabrication/Assy

As-Designed Condition

Supply Chain Sim

Supply Chain

As-Sold Condition

Supply Chain

Engineering Operations