F-35 JSF F136/Gearbox Modeling and Simulation

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Agenda

- Background
- System of Interest
- Technical Issues
- Simplified Problem Set
- Q&A

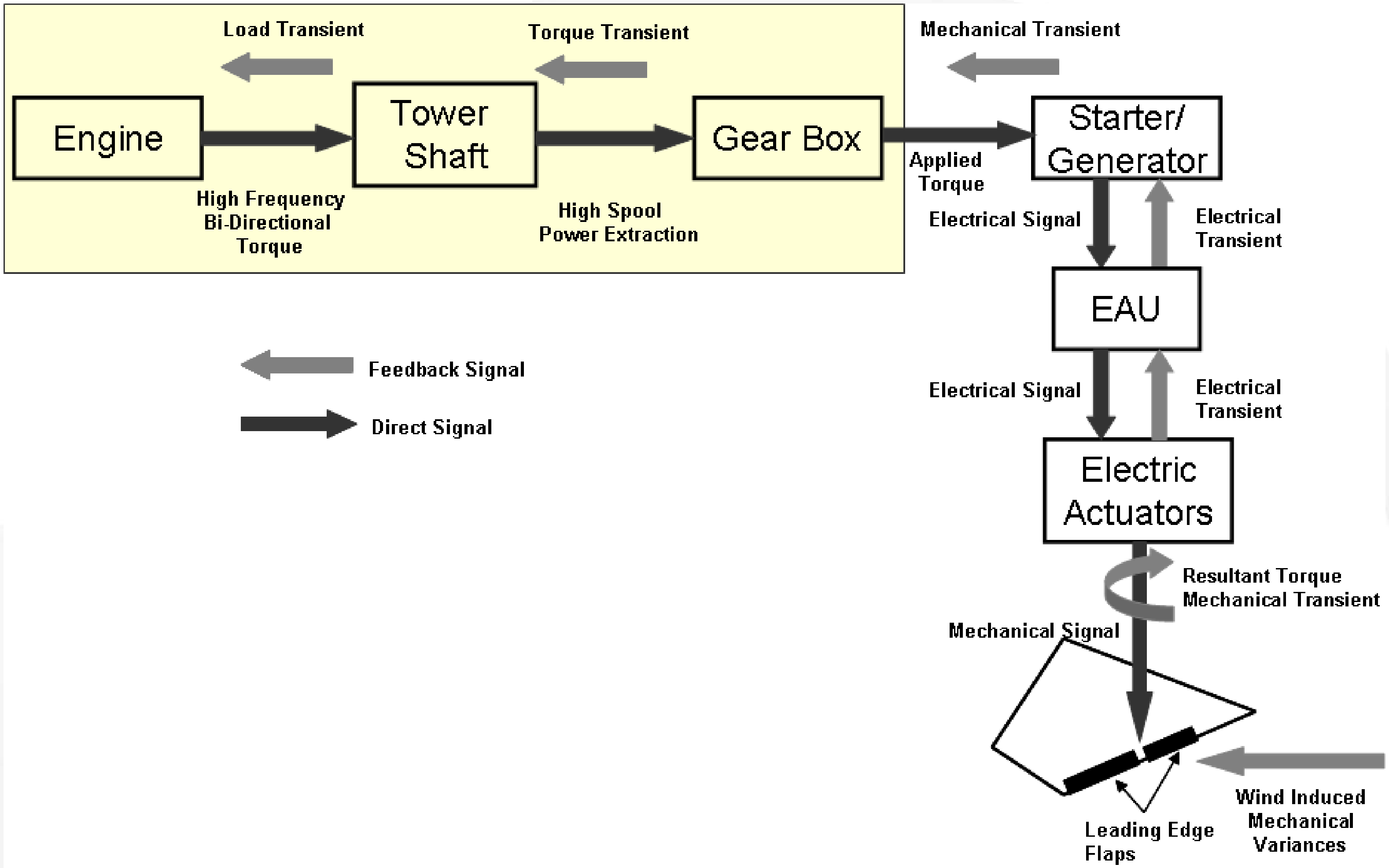
Background

- The AFRL's Integrated Vehicle Energy Technology Demonstration (INVENT) program seeks energy, power, and thermal advanced technology solutions for air vehicle systems and subsystems:
  - Adaptive Power & Thermal Management Systems
  - Robust Electrical Power Systems
  - High Performance Electric Actuation Systems
  - Integrated designs using high fidelity modeling and simulation techniques
  - Demonstrated benefits and performance oriented capabilities enhancements for chosen platform
  - Risk based planning that encompasses ground testing through engine integration and flight test
  - The selection of a single platform of interest to the INVENT program

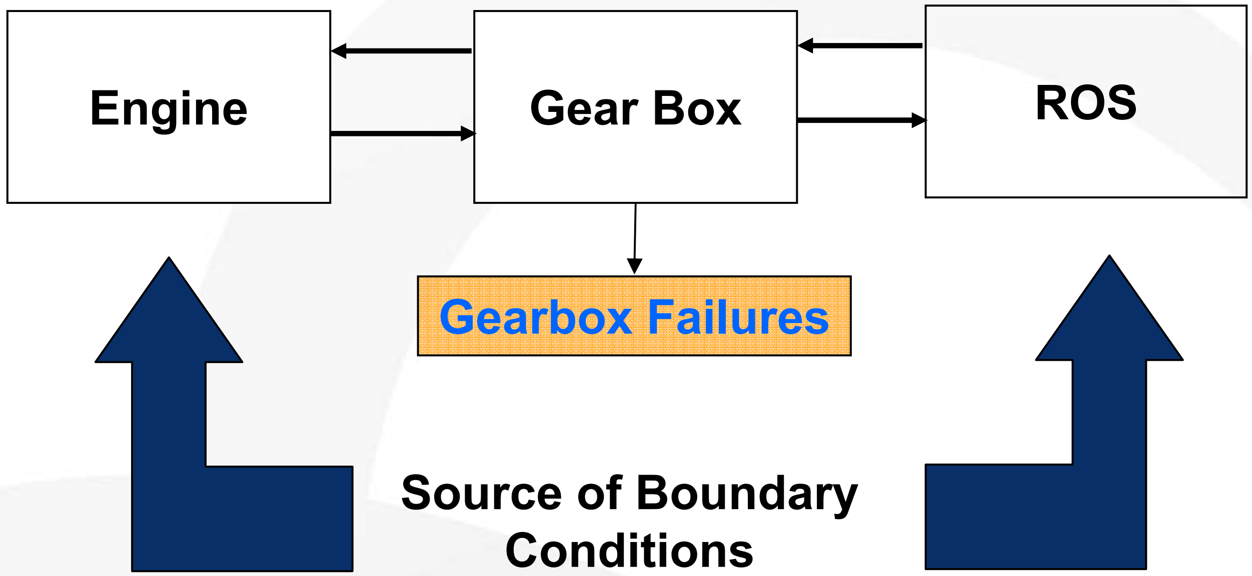
Background (continued)

- The F-35 Joint Strike Fighter (JSF) is one specific INVENT platform of interest
- Our INVENT effort has three tasks
  - Task 1: F136 engine-gearbox dynamic model
  - Task 2: Data acquisition and exchange between GE Rolls-Royce Fighter Engine Team (FET) and GE Aviation, GE Aviation Systems, and Liberty Works INVENT teams
  - Task 3: Development of a dynamic vehicle-level thermal model for the F-35 aircraft
- Awaiting contract award
  - I'm only going to discuss Task 1 here
  - Work described here is mostly background research

System of Interest



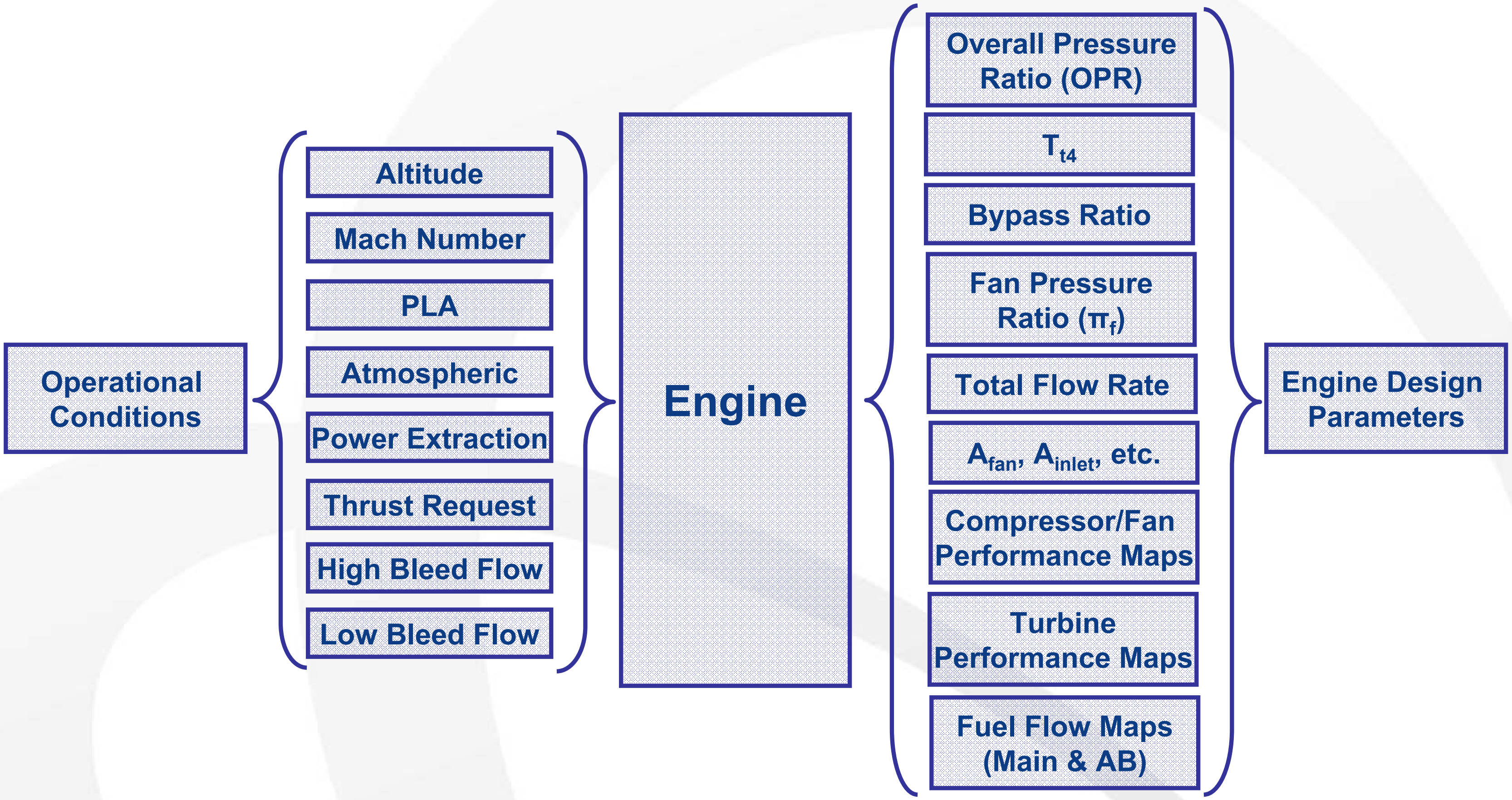
Simplified System End Goal



AF interested in real systems

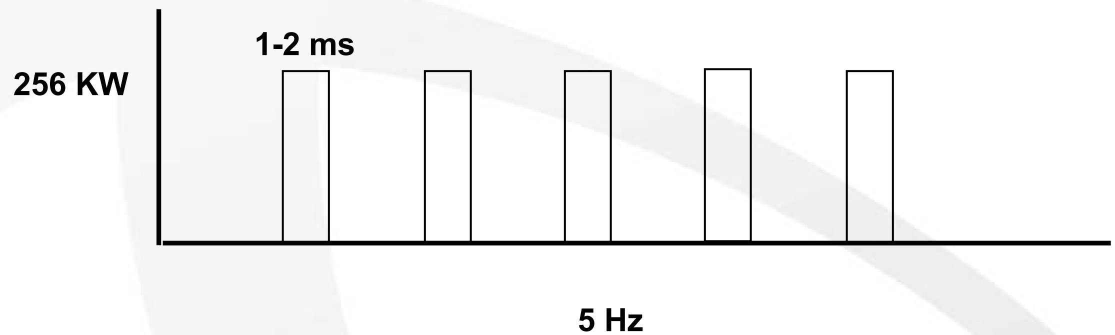
Teaming with GE Rolls-Royce Fighter Engine Team (FET)

General Engine Parameters



Rest of System

- Still under study
- However, goal is not to model each component
- We do know that the regen power to the gearbox is:
  - 256 KW
  - 1 to 2 ms
  - 5 Hz
  - 5 second duration



Gear Box Parameters

Quantities for Analysis

- **Physical System**
  - Types of Gears Present
  - Input Torque
  - Gear Material
  - Heat/Surface Treatments
  - Operating Temperature Range
  - Mounting Distances
  - Bearing Properties and Locations
  - Hand of Spiral
  - Rotation Directions
- **Gear Characteristics**
  - N = Number of Teeth
  - P_d = Diametral Pitch
  - Φ = Pressure Angle
  - Ψ = Helix Angle
  - γ = Spiral Angle
  - F = Face Width
  - t = Circular Tooth Thickness
  - m = Contact Ratio
  - R = Pitch Radius
  - C = Center Mounting Distance
  - Shaft Angles
- **Lubrication System**
  - Application Method: Hand, Dip, Bath, Pressure
  - Lubricant Properties
  - Amount Applied and Rate
  - Application Location

Gearbox Failure Mechanisms

Fracture of Tooth and Surface Failure

Caused By:

Forces- Internal/External	Tooth Design
Initial Stresses	Lubrication Issues
Misalignment/Uneven Contact	Excessive Temperatures
Fatigue	Material Defects
Vibration	Manufacturing Error

Failure Mode:

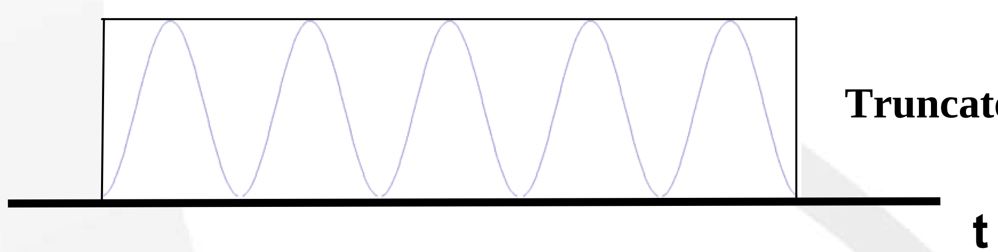
Pitting	Scoring	Ridging
Cracking	Abrasion	Gear Hammer
Flaking	Lapping	Surface Cracks
Scuffing	Wear	Metallurgical Defects

Evolution of Solutions (just for fun)

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = F(t) \qquad \omega_o = \sqrt{\frac{k}{m}}, \quad \gamma = \frac{b}{2m}, \quad \Omega^2 = (\gamma^2 - \omega_o^2)$$

$$F(t) = F - f(t)$$ **Constant Engine force minus regen force**

$$f(t) = A\sin^2 \omega(t - t_s)[u(t - t_s) - u(t - t_c)]$$



Truncated Sine Wave

Underdamped Solution

$$x(t) = x_0 e^{-\gamma t}\left[\cos\Omega t - \frac{\gamma}{\Omega}\sin\Omega t\right] + \frac{(v_o + 2\gamma x_o)}{\Omega} e^{-\gamma t}\sin\Omega t$$

$$+ \frac{F}{m\omega_0^2}\left[1 - e^{-\gamma t}(\cos\Omega t + \frac{\gamma}{\Omega}\sin\Omega t)\right]$$

$$- \frac{A}{2m\omega_0^2}\left\{1 - e^{-\gamma(t-t_s)}[\cos\Omega(t-t_s) + \frac{\gamma}{\Omega}\sin\Omega(t-t_s)]\right\} u(t-t_s)$$

$$+ \frac{A}{2m\omega_0^2}\left\{1 - e^{-\gamma(t-t_c)}[\cos\Omega(t-t_c) + \frac{\gamma}{\Omega}\sin\Omega(t-t_c)]\right\} u(t-t_c)$$

$$+ \frac{A}{2m}\{2\,\mathrm{Re}(c_1)\cos 2\omega(t-t_s) + 2\,\mathrm{Im}(c_1)\sin 2\omega(t-t_s)$$

$$+ e^{-\gamma(t-t_s)}[2\,\mathrm{Re}(c_3)\cos\Omega(t-t_s) + 2\,\mathrm{Im}(c_3)\sin\Omega(t-t_s)]\}u(t-t_s)\}$$

$$- \frac{A}{2m}\{2\,\mathrm{Re}(c_1)\cos 2\omega(t-t_c) + 2\,\mathrm{Im}(c_1)\sin 2\omega(t-t_c)$$

$$+ e^{-\gamma(t-t_c)}[2\,\mathrm{Re}(c_3)\cos\Omega(t-t_c) + 2\,\mathrm{Im}(c_3)\sin\Omega(t-t_c)]\}u(t-t_c)\}$$

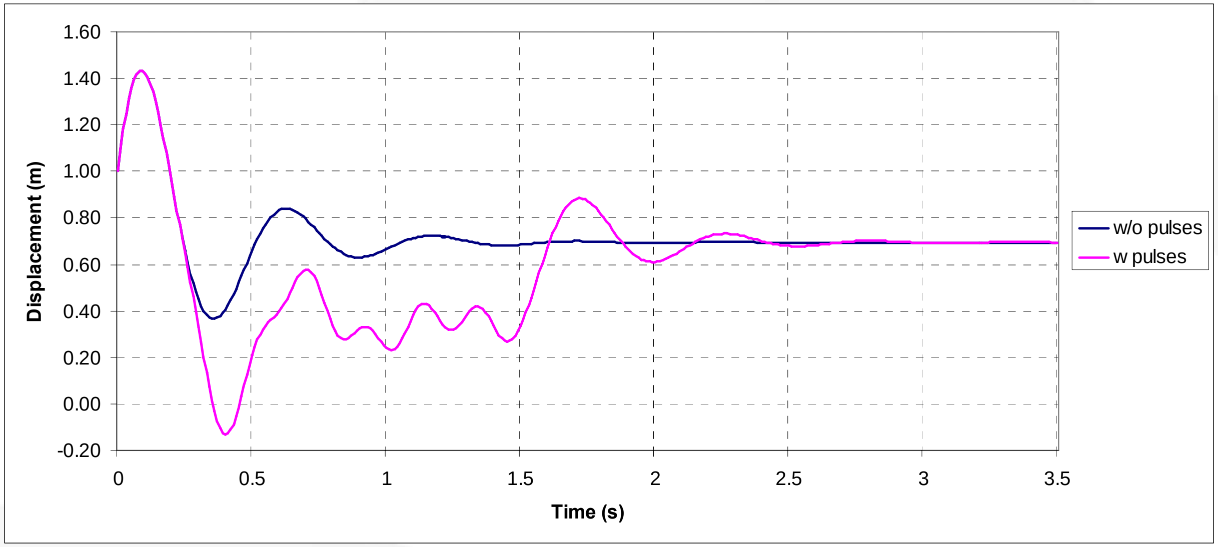
Coefficients

$$c_1 = \frac{(\omega_0^2 - 4\omega^2) + 4i\gamma\omega}{2[(\omega_0^2 - 4\omega^2)^2 + 16\gamma^2\omega^2]}; \quad c_2 = c_1^*$$

$$c_3 = \frac{-(\omega_0^2 - 4\omega^2) - i(\omega_0^2 + 4\omega^2)\gamma / \Omega}{2[(\omega_0^2 - 4\omega^2)^2 + 16\gamma^2\omega^2]}; \quad c_4 = c_3^*$$

$$\mathrm{Re}(c_3) = -\mathrm{Re}(c_1)$$

Sample Graph: Sine wave input



$$x_0 = 0 \qquad \omega = 15/\sec$$

$$v_0 = 0 \qquad t_s = 1/\gamma \approx 0.33\sec$$

$$\omega_0 = 12/\sec \qquad t_c = t_s + 6\pi/\omega$$

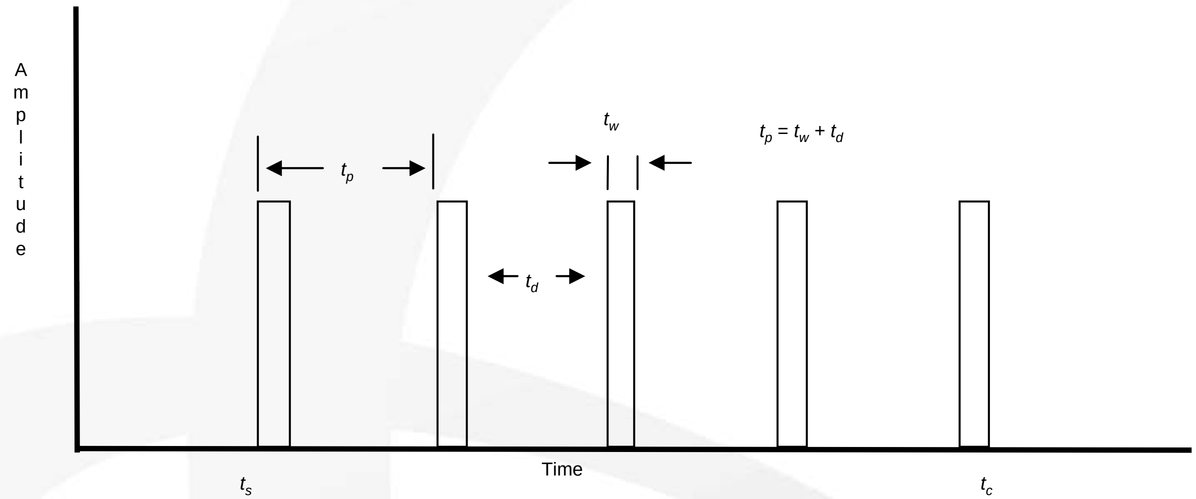
$$\gamma = 3/\sec$$

t_s=start time of pulses, t_c=cutoff time of pulses

Graph compares naturally decaying system without time dependent pulses (blue) with time dependent input (red)

Square Wave

$$P_1 = u(t - t_s) - u[t - (t_s + t_w)]$$



$$f(t) = A\sum_{n=1}^{N} \{u_n[t - (n-1)t_p - t_s] - u_n[t - (n-1)t_p - (t_w + t_s)]\}$$

Underdamped Solution

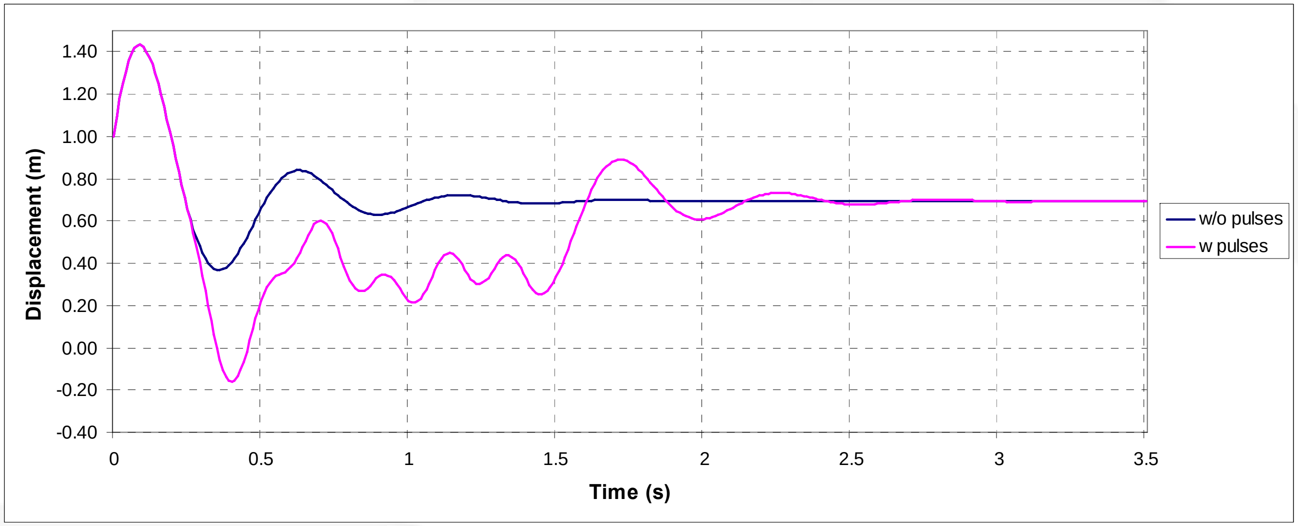
$$x(t) = x_0 e^{-\gamma t}\left[\cos\Omega t - \frac{\gamma}{\Omega}\sin\Omega t\right] + \frac{(v_o + 2\gamma x_o)}{\Omega} e^{-\gamma t}\sin\Omega t$$

$$+\frac{F}{m\omega_0^2}\left[1 - e^{-\gamma t}\left(\cos\Omega t + \frac{\gamma}{\Omega}\sin\Omega t\right)\right]$$

$$-\frac{A}{m\omega_0^2}\sum_{n=1}^{N}\left\{1 - e^{-\gamma(t-c_n)}\left[\cos\Omega(t-c_n) + \frac{\gamma}{\Omega}\sin\Omega(t-c_n)\right]\right\}u(t-c_n)$$

$$+\frac{A}{m\omega_0^2}\sum_{n=1}^{N}\left\{1 - e^{-\gamma(t-d_n)}\left[\cos\Omega(t-d_n) + \frac{\gamma}{\Omega}\sin\Omega(t-d_n)\right]\right\}u(t-d_n)$$

Representative Square Wave Result



Inputs chosen to match earlier sine wave parameters explaining the similarities in results

Frequency Domain

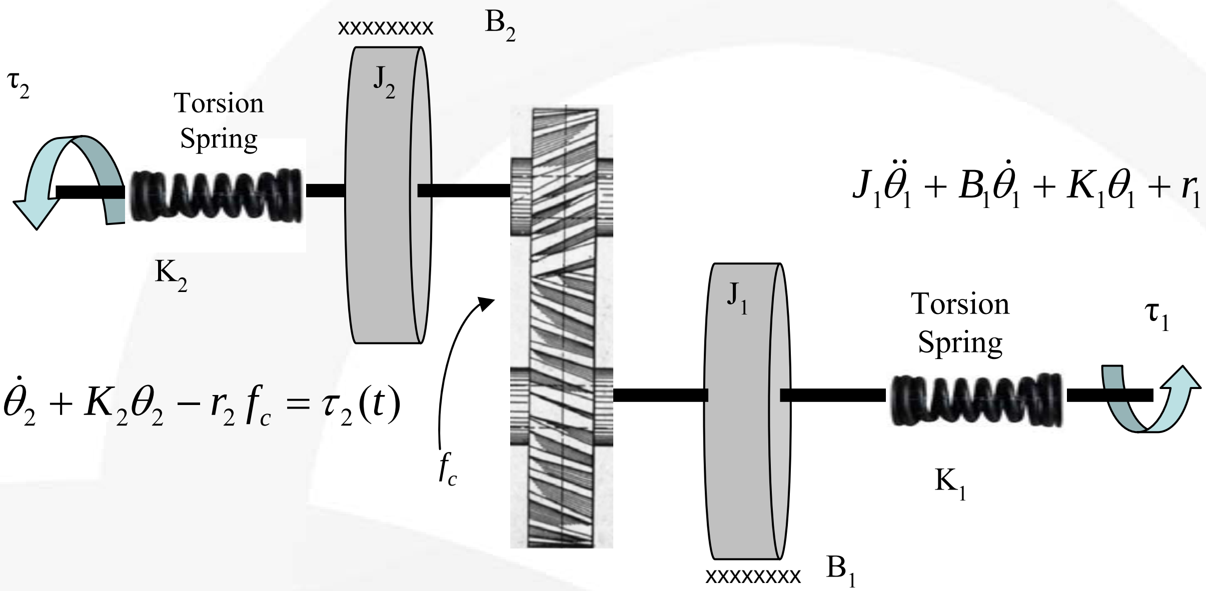
- **Square wave input**

$$f(t) = A\sum_{n=1}^{N}\{u_n[t-(n-1)t_p - t_s] - u_n[t-(n-1)t_p - (t_w + t_s)]\}$$

- **Fourier Series**

$$f(t) = a_0 + \sum_{n=1}^{\infty}\left[a_n \cos(2\pi nt/t_p) + b_n \sin(2\pi nt/t_p)\right]$$

Simple two gear system



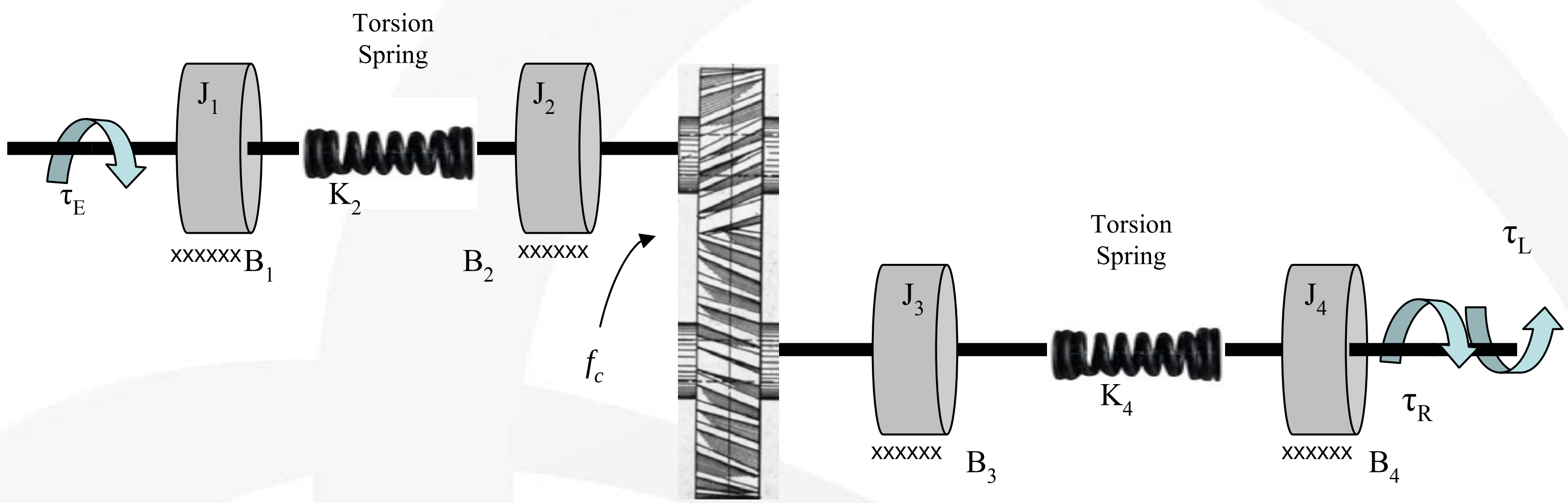
$$J_1\ddot{\theta}_1 + B_1\dot{\theta}_1 + K_1\theta_1 + r_1 f_c = \tau_1(t)$$

$$J_2\ddot{\theta}_2 + B_2\dot{\theta}_2 + K_2\theta_2 - r_2 f_c = \tau_2(t)$$

$$N = \frac{\theta_1}{\theta_2} = \frac{\omega_1}{\omega_2} = \frac{r_2}{r_1}$$

$$J_{2_{eq}}\ddot{\theta}_2 + B_{2_{eq}}\dot{\theta}_2 + K_{2_{eq}}\theta_2 = N\tau_1(t) + \tau_2(t)$$

A more complex system



Questions