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QFT Controller Synthesis For A Nonlinear Flexible Joint Robot

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Outline

- Introduction
- Nonlinear QFT
- QFT Controller design for FJR
- Composite QFT Design
- Simulation Results
- Conclusions

Introduction

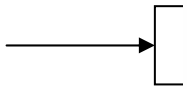
- FJR Applications
  - ✓ Space Robotics
  - ✓ Micro Robots
  - ✓ Dextereous Robotic Hand
  - ✓ Industrial Robots with Harmonic Drive
  - ✓ . . .

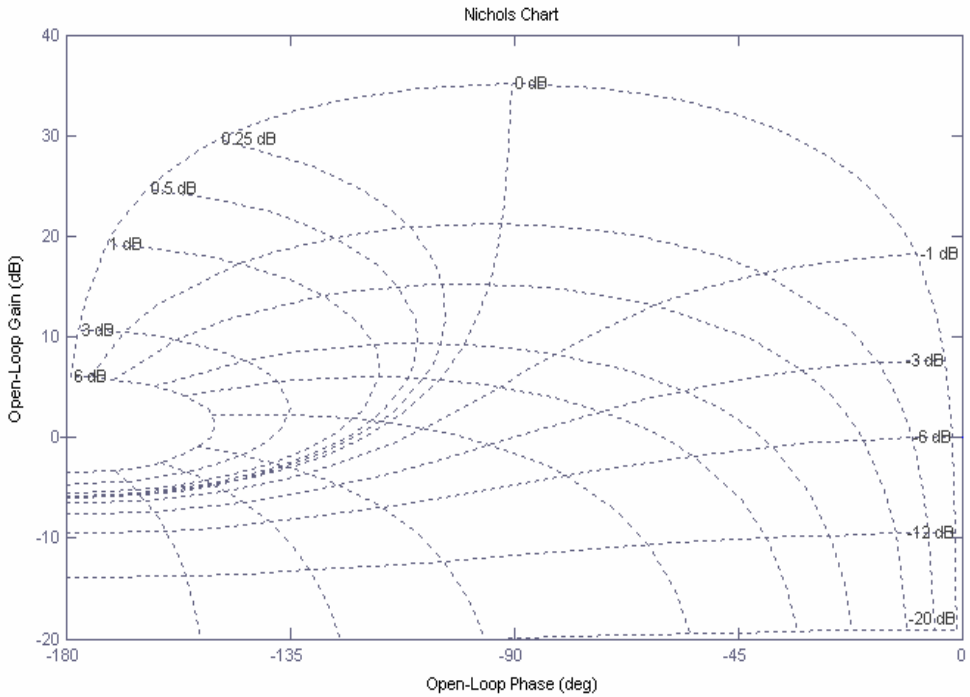
Background

- Marino, 1984
- Spong, 1986
- Kokotovic, 1987
- Ghorbel, 1991
- Khorasani, 1993
- Elmaraghi 1999
- Reshmin, 2000
- Schaffer, 2000
- Thummel, 2001
- Bakhshi, 2003
- Shaterian 2005
- Ozgoli 2005

QFT Overview

- Robust C
- Two Degr





- Frequency Domain (Nichols Chart)

QFT Overview

- Design Steps
  - ✓ Templates
  - ✓ Bounds
    - Stability
    - Tracking
    - Disturbance
  - ✓ FD Loop Shaping
  - ✓ Prefilter Design
  - ✓ FD Performance Check

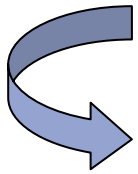
Nonlinear QFT

- Nonlinear Equivalent Disturbance Attenuation
- Equivalent LTI Family

$$A_R = \{A_r \,|\, r \in R\} \longrightarrow$$ ***set of acceptable output***

$$P = \{p_\theta : U \to Y, \theta \in \Theta\} \longrightarrow$$ *NLTV system*

$$U_{A,r} := \{u \in U \,|\, u = p_\theta^I(y), y \in A_r\} \longrightarrow$$ ***set of acceptable input***



Equivalent LTI Family

$$P_\theta(A_R) := \{p^y_{r,\theta} \,|\, y \in A_r, r \in R\}$$

$$P(A_R) := \{P_\theta(A_R) \,|\, \theta \in \Theta\} = \{P^y_{r,\theta} \,|\, y \in A_r, r \in R, \theta \in \Theta\}$$

QFT Controller Synthesis: Rigid Robot

Suppose rigid manipulator of:

$$\ddot{q} = -4.9 Sinq + \frac{1}{2}u$$

Find F(s) & G(s) such that:

*a) Stability margin: If L(s)=P(s) * G(s) then*

$$\left|\frac{L(j\omega)}{1+L(j\omega)}\right| \le M = 1.2 \qquad \forall \omega \in [0,\infty]$$

b) Tracking Condition:

$$|T_\ell(j\omega)| < \left|F(j\omega)\frac{L(j\omega)}{1+L(j\omega)}\right| \le |T_u(j\omega)| \qquad \forall \omega \in [0,\infty]$$

where

$$T_u(s) = \frac{c_1c_2c_3c_4(s+a)/a}{s(s+c_1)(s+c_2)(s+c_3)(s+c_4)} \qquad a = 5$$

$$T_\ell(s) = \frac{c_1c_2c_3c_4(s+a)/a}{s(s+c_1)(s+c_2)(s+c_3)(s+c_4)} \qquad a = 200$$

QFT Controller Synthesis: Rigid Robot

set of acceptable output:

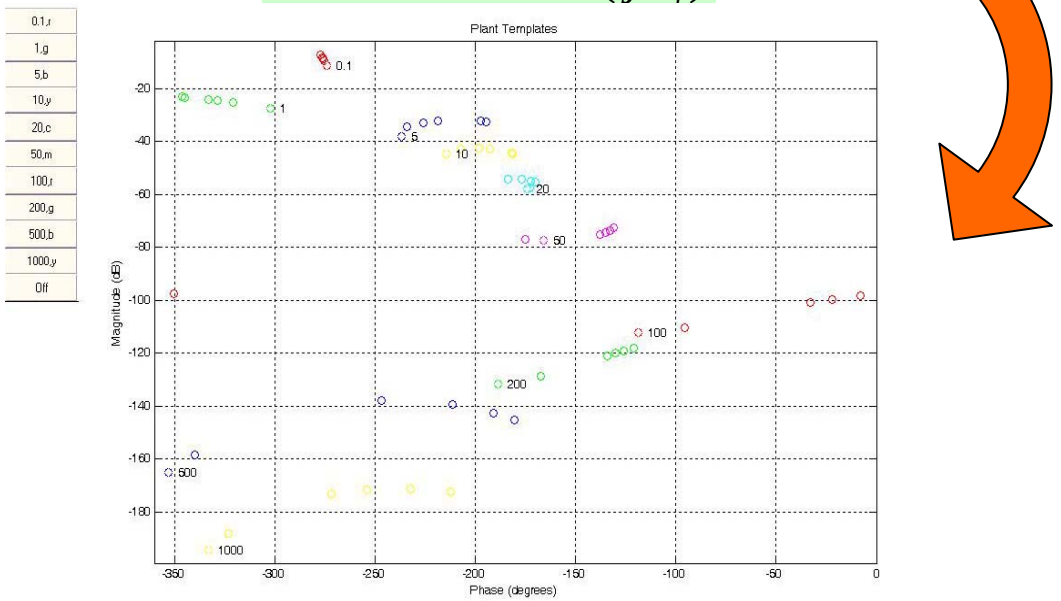
$$Y(s) = \frac{c_1 c_2 c_3 c_4 (s+a)/a}{s(s+c_1)(s+c_2)(s+c_3)(s+c_4)}$$

where c1=20 ، c2=21 ، c3=22,c4=25 and a=[5,10,15,20,100,200]

$$u = 2\ddot{q} + 9.8\,Sinq$$

$$Ltifam(j\omega_i) = \frac{Y(j\omega_i)}{U(j\omega_i)}$$

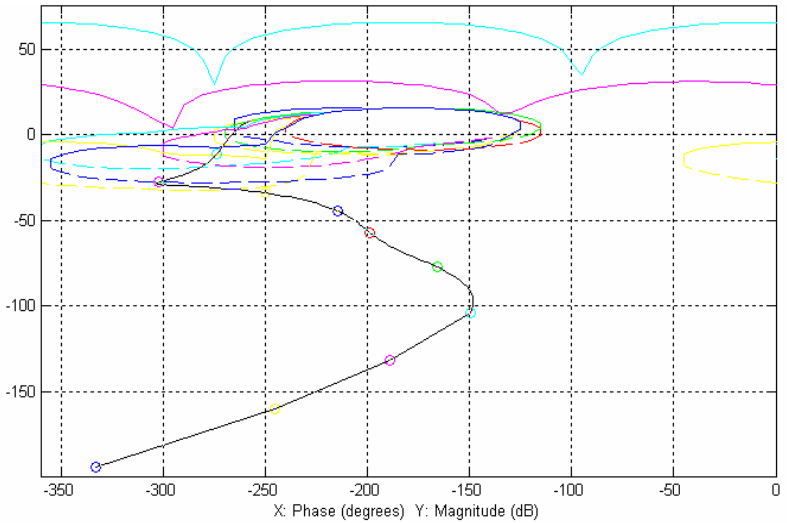
Inverse Equation



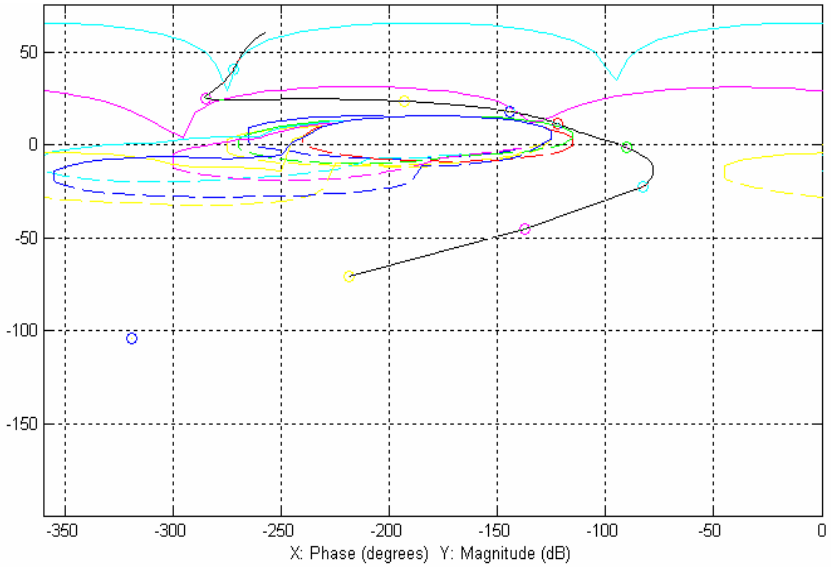
- Templates

QFT Controller Synthesis: Rigid Robot

- Loop Shaping



$$G(s) = \frac{3.296 \times 10^4 \, s + 1.033 \times 10^5}{s + 257.2}$$

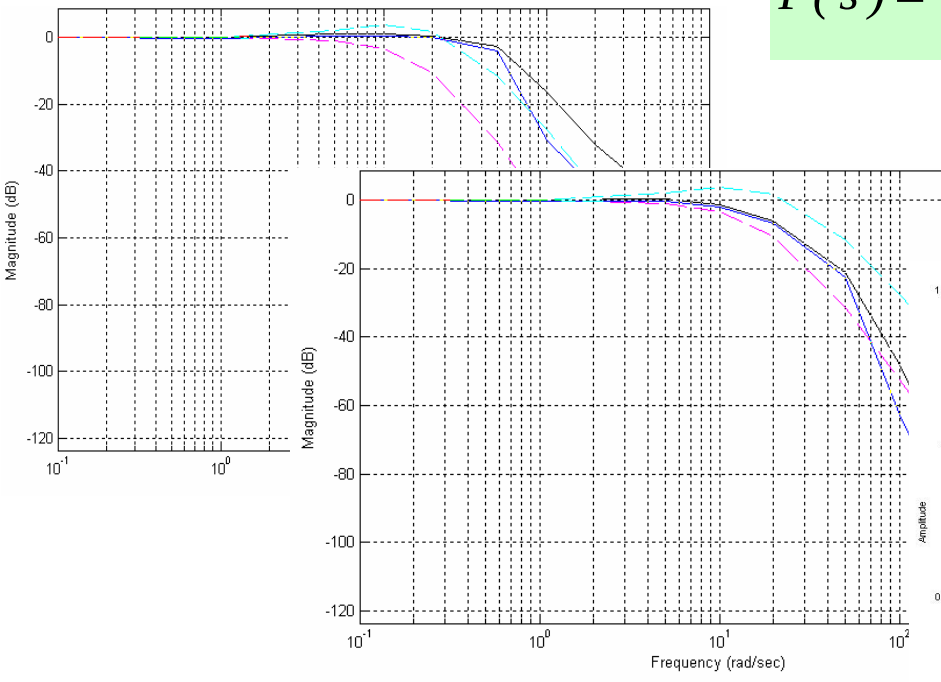


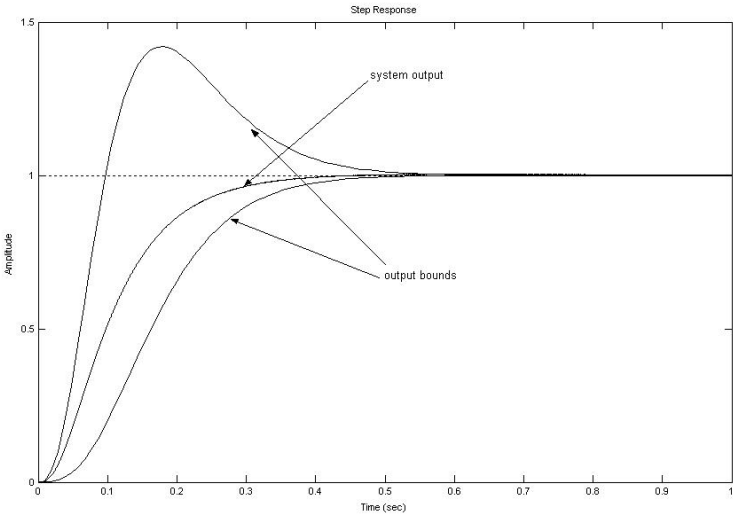
QFT Controller Synthesis: Rigid Robot

- Prefilter Design

$$F(s) = \frac{3.172 * 10^4}{s^3 + 112\,s^2 + 3720\,s + 3.146 * 10^4}$$

& G(s)

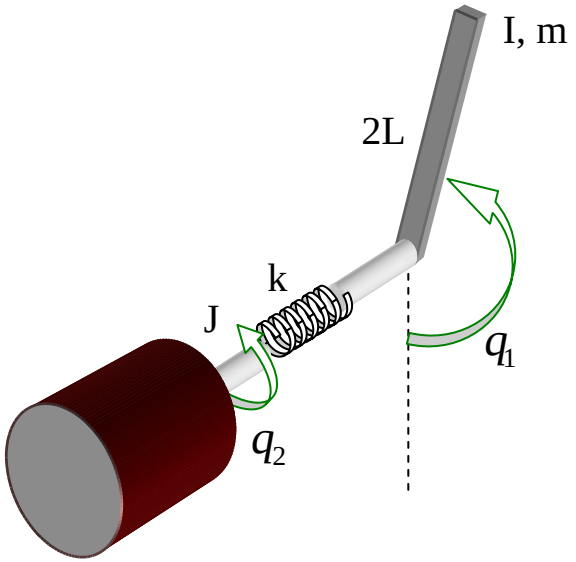




Step Response

QFT Controller Synthesis: Flexible Joint Robot (FJR)

- FJR Model



I=J=m=L=1 g=9.8, k=100

Dynamics

$$\begin{cases} I\ddot{q}_1 = k(q_2 - q_1) - mgL\sin q_1 \\ J\ddot{q}_2 = u - k(q_2 - q_1) \end{cases}$$

q=q1 ، z=k(q1-q2) ,ε=1/k

$$\begin{cases} \ddot{q} = \left(-1/I\right)z - \dfrac{mgL\ Sin\ q}{I} \\ \varepsilon\ddot{z} = \left(-1/I - 1/J\right)z - \dfrac{mgL\ Sin\ q}{I} - \left(1/J\right)u \end{cases}$$

Singularly Perturbed Model

$$\begin{cases} \ddot{q} = -9.8\ Sin\ q - z \\ (0.01)\ddot{z} = -2z - 9.8\ Sin\, q - u \end{cases}$$

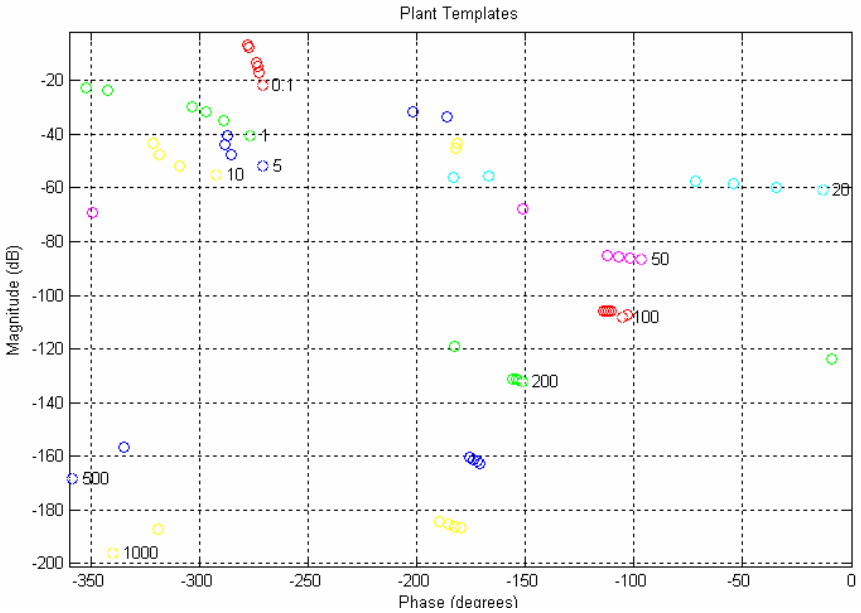
QFT Controller Synthesis: FJR

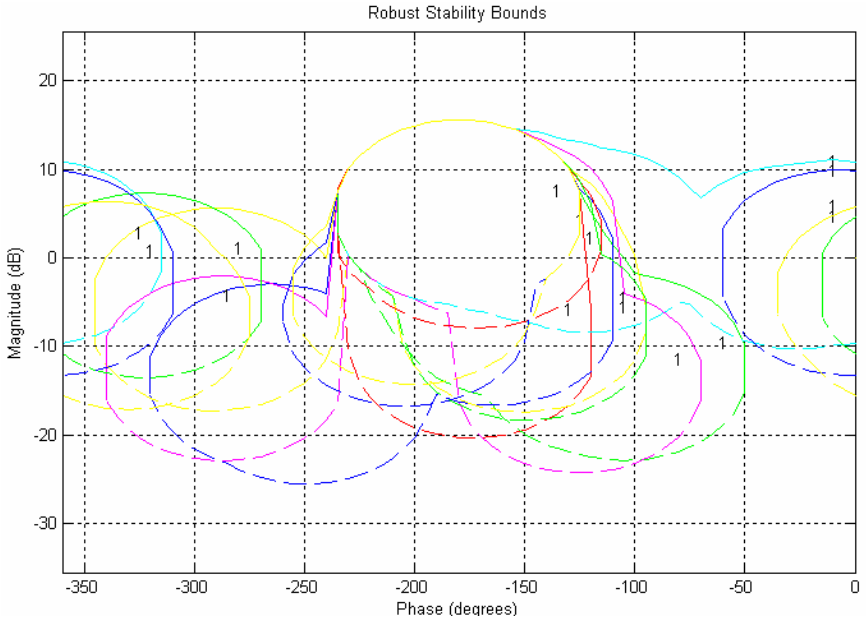
- Templates

Inverse model of FJR:

What causes large templates?

$$u = (q^{(4)} + (9.8\,Cos\ \ q + 2k)\ddot{q} - 9.8\,(Sin\ \ q)(\dot{q})^2 + 9.8k\ Sin\ \ q)\,/\,k$$



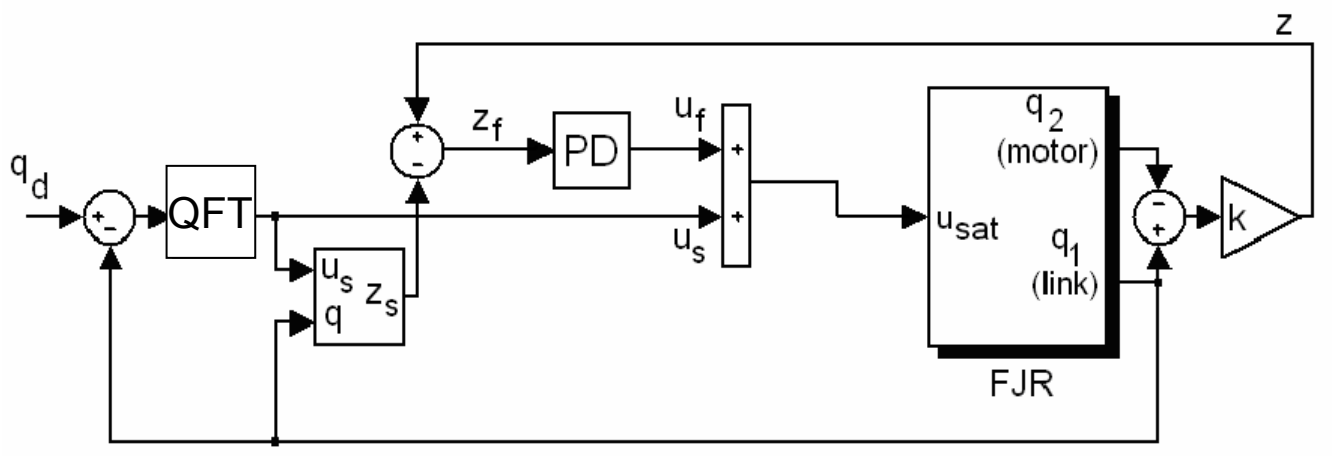


Composite QFT Design on FJR

- Composite Controller

$$u = u_s(q, \dot{q}, \varepsilon) + u_f(\eta, \dot{\eta})$$

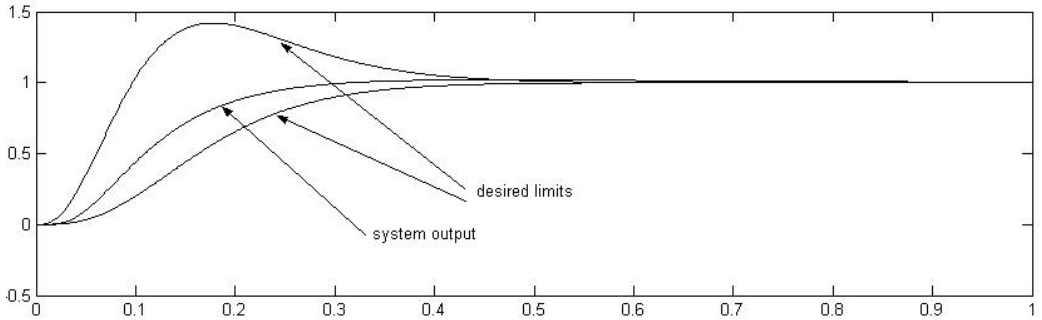
- Fast Controller: PD + Corrective term (IM)
- Slow Controller: QFT

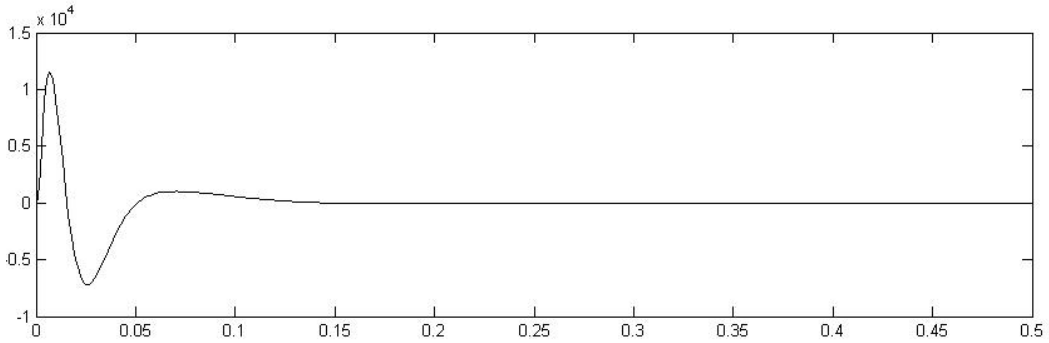


Composite QFT Design on FJR

- Rigid Controller

F(s) & G(s)

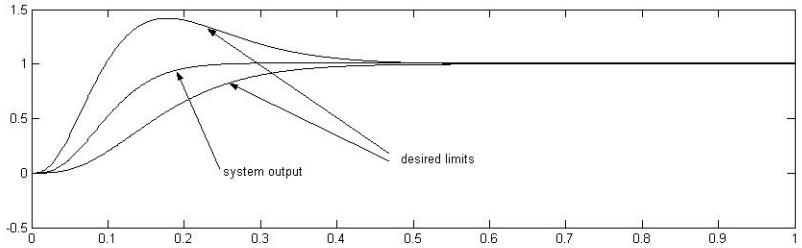


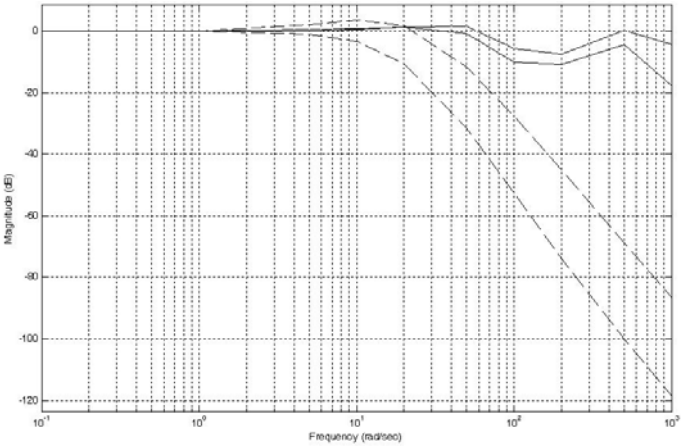


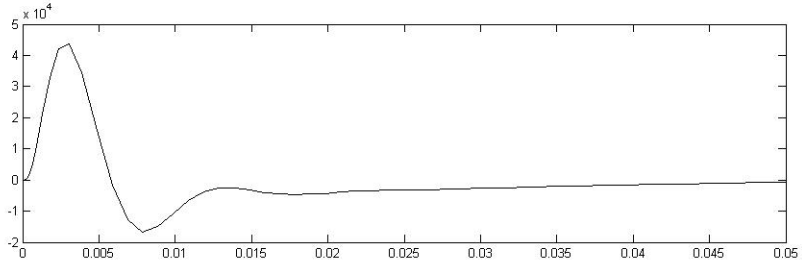
- Composite Controller

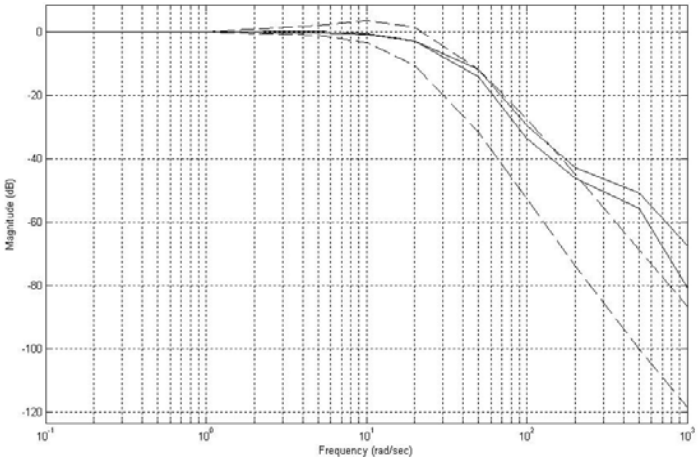
Composite QFT Design on FJR

$$G(s) = \frac{1644765.504(s+69.3)(s+36.83)}{(s+1861)(s+577.2)}$$





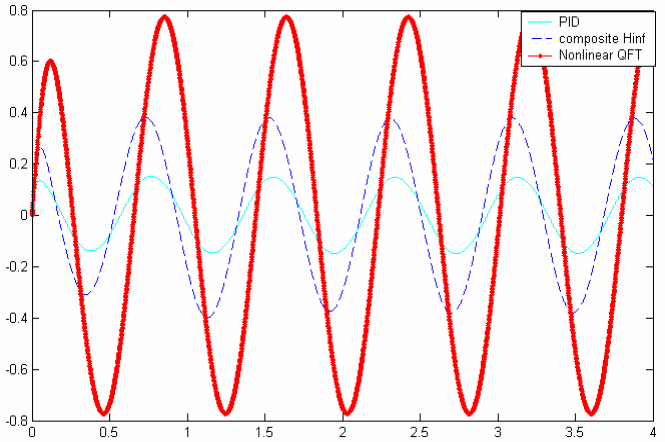




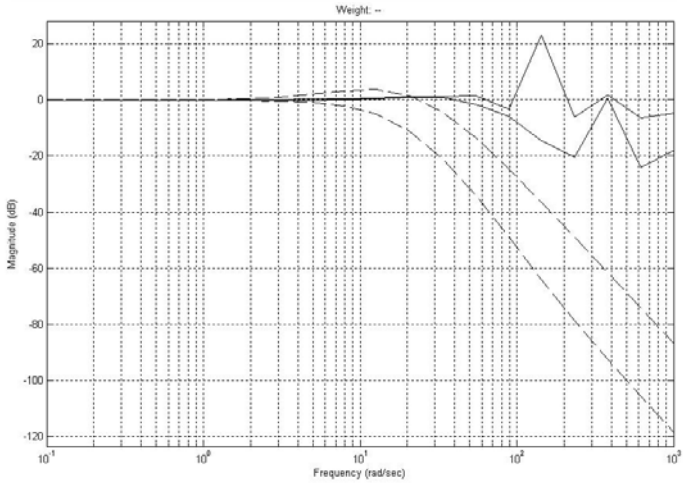
$$F_1(s) = \frac{24220.0786}{(s+34.59)(s+32.1)(s+21.72)}$$

Composite QFT Design on FJR

- Performance:
  - ✓Error is too large



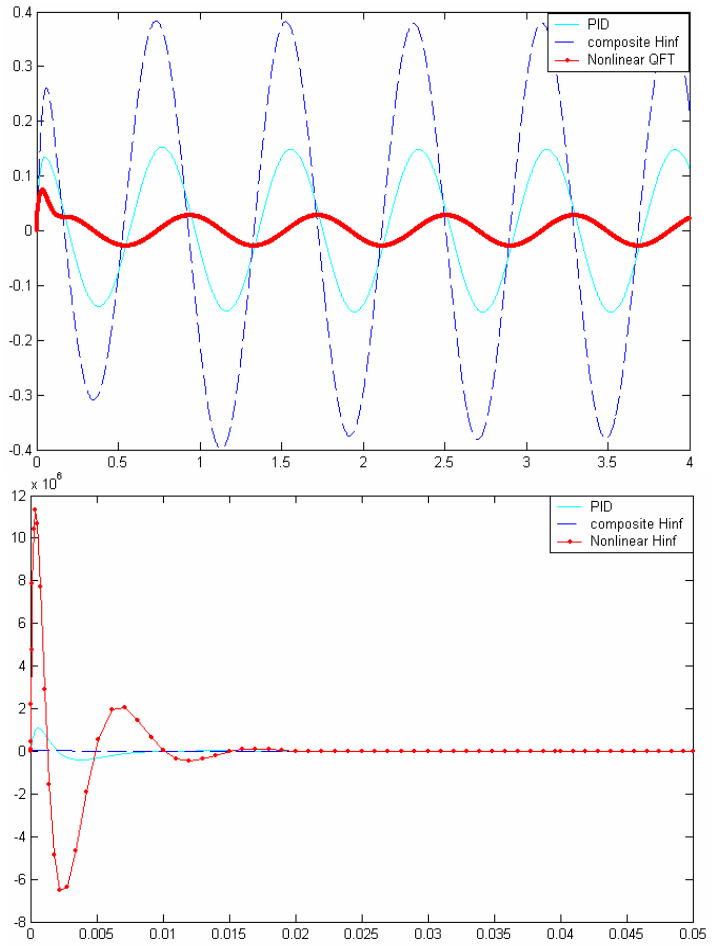
- Modify F(s)
  - ✓ $F_2(s)=0.9716$



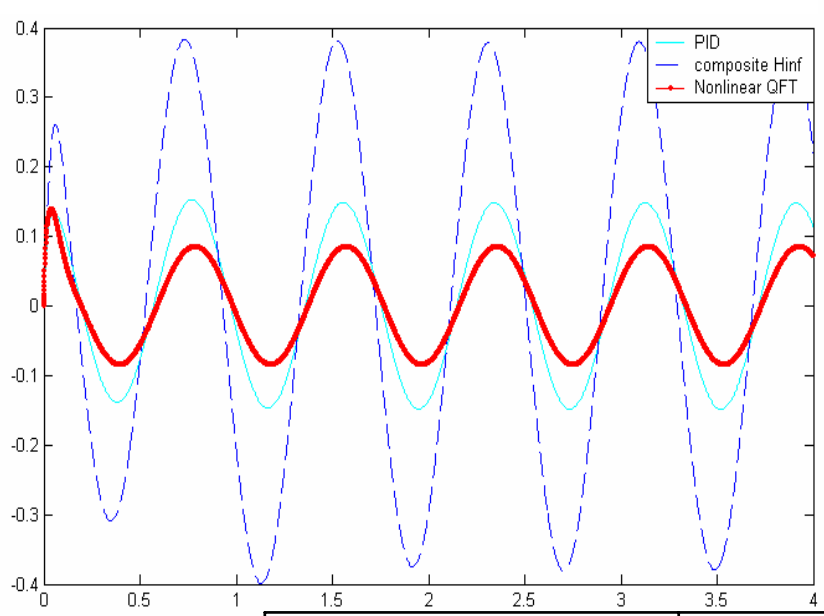
Composite QFT Design on FJR

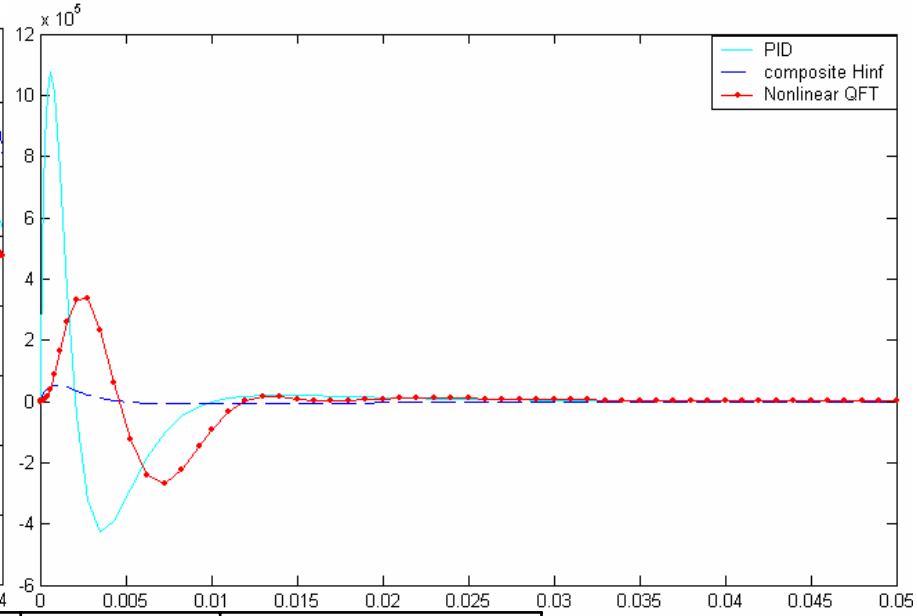
- Performance:
  - ✓Good Tracking
  - ✓Control Effort too large
- Modify F(s) : A Tradeoff

$$F_3(s) = \frac{35251}{s^2 + 305s + 3.23\times10^4}$$



Simulation Results

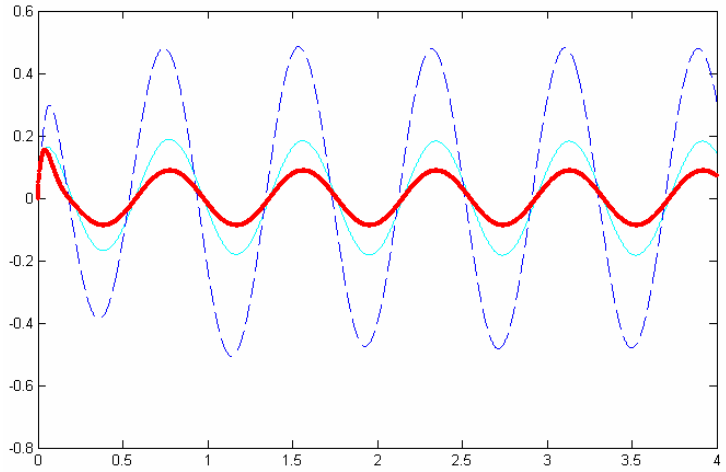


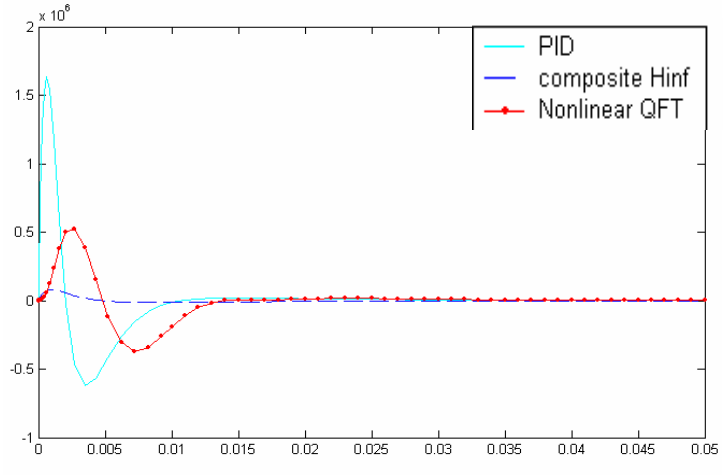


Control method	$\|e\|_2$	$\|e\|_\infty$	$\|\Delta u\|_\infty$
PID	0.21	0.15	1.07×10^{6}
Composite H_∞	0.52	0.40	0.54×10^{5}
Nonlinear QFT	0.12	0.14	0.04×10^{5}

Simulations:

25% Parameter Perturbation

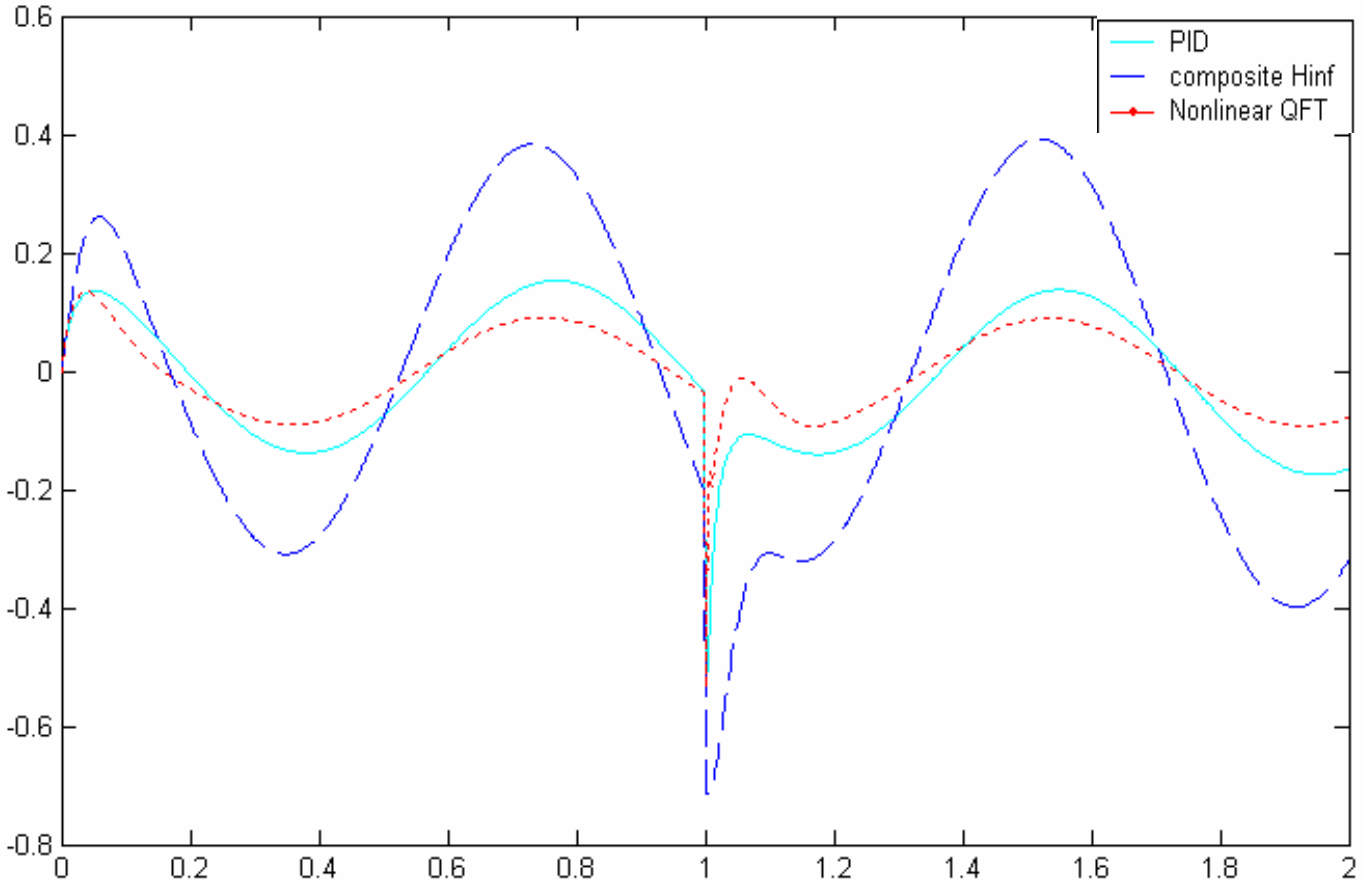




Control method	$\|e\|_2$	$\|e\|_\infty$	$\|\Delta u\|_\infty$
PID	0.26	0.19	1.63×10^{6}
Composite H_∞	0.67	0.50	8.16×10^{4}
Nonlinear QFT	0.13	0.15	5.19×10^{5}

Simulations:

Disturbance Rejection



Conclusions

- Implementation of Nonlinear QFT for FJR
  - ✓ Equivalent LTI Family
  - ✓ Composite Controller Structure
- Simulation Analysis
  - ✓ Performance Tradeoffs
  - ✓ Performance Comparison
  - ✓ Robustness
  - ✓ Disturbance Rejection
- Drawbacks
  - ✓ Skill of Designer
  - ✓ Sensitive to Noise

Q & A

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