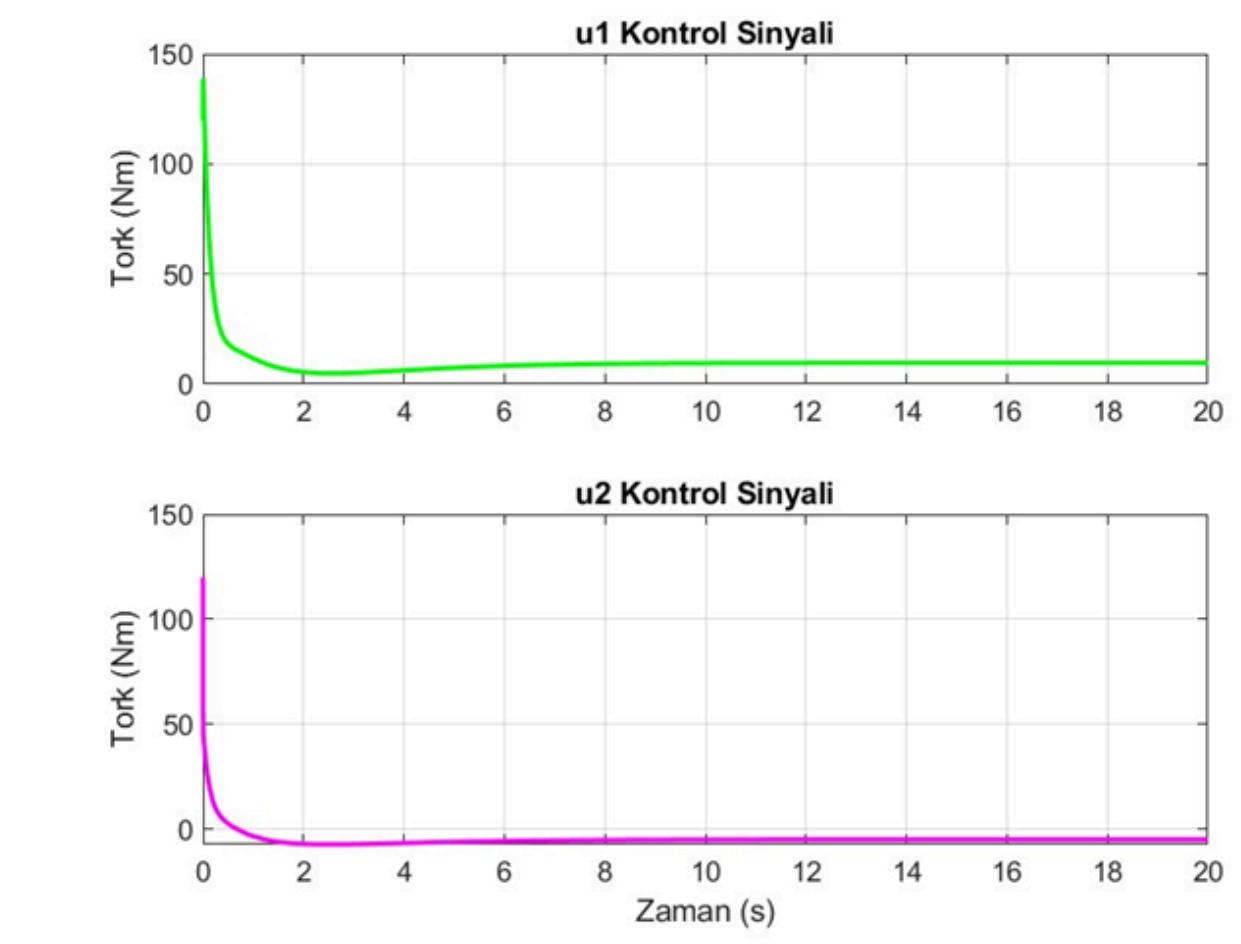
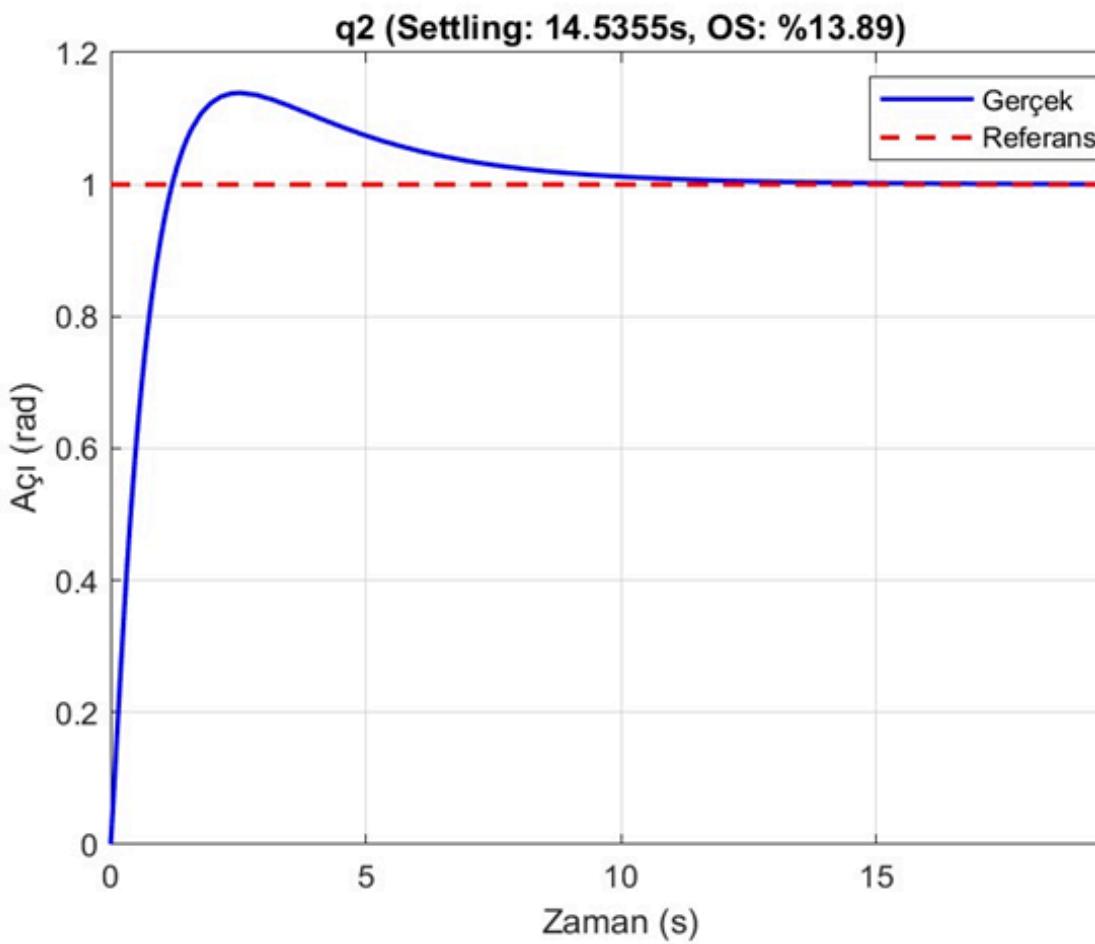
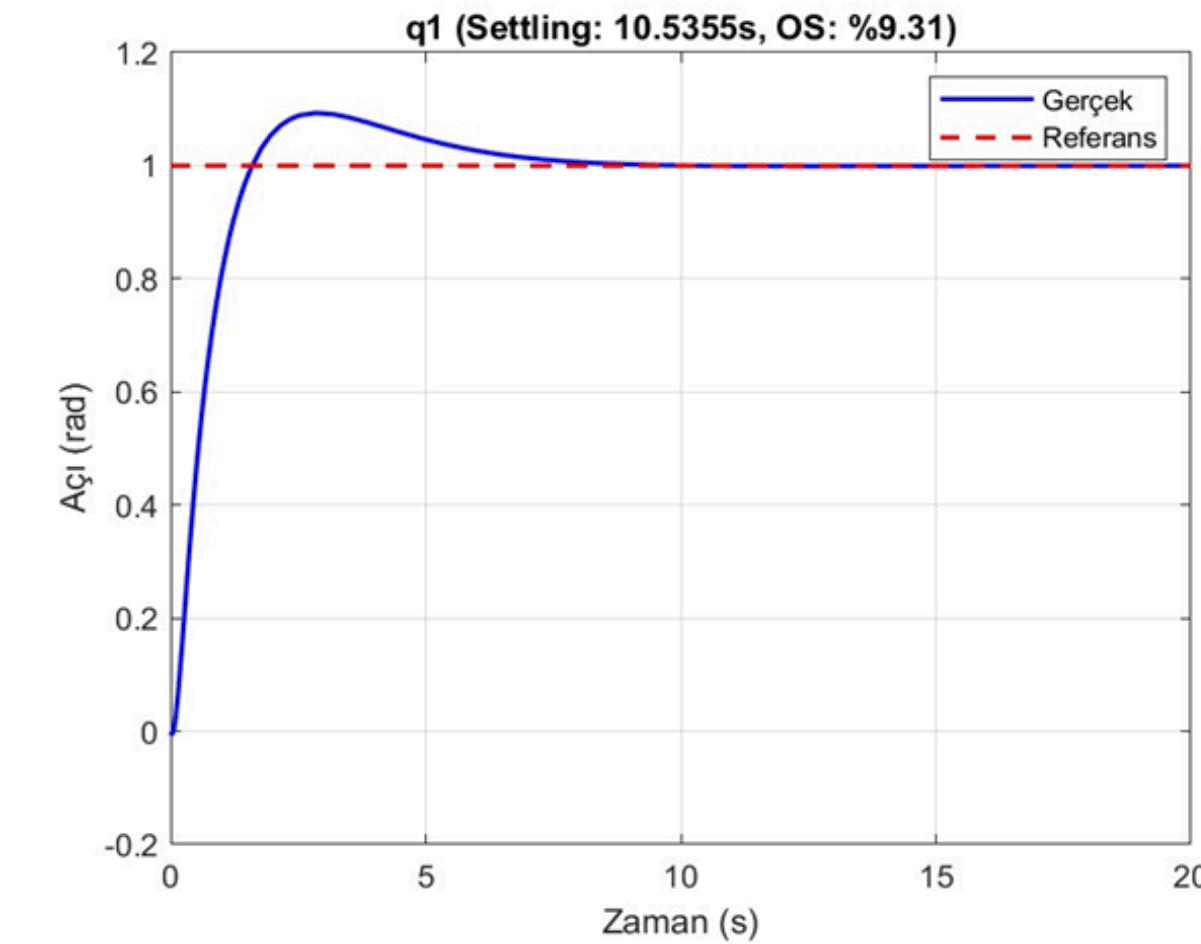


Classical Joint PID Control

$$\varepsilon = \dot{e}$$

$$\tau = K_d \dot{e} + K_p e + K_i \varepsilon$$



[q1 Sonuçları]

Settling Time (Kararlı): 10.5355 s

Overshoot (Aşım): %9.31

Ort. Mutlak Hata (Stable): 0.000512 rad

Ort. Normalize Hata (Stable): %0.0512

[q2 Sonuçları]

Settling Time (Kararlı): 14.5355 s

Overshoot (Aşım): %13.89

Ort. Mutlak Hata (Stable): 0.001194 rad

Ort. Normalize Hata (Stable): %0.1194

[Kontrol Sinyalleri Özeti]

u1 Max Tork: 138.7248 Nm

u1 Stable Ort. Tork: 9.6030 Nm

u2 Max Tork: 120.0000 Nm

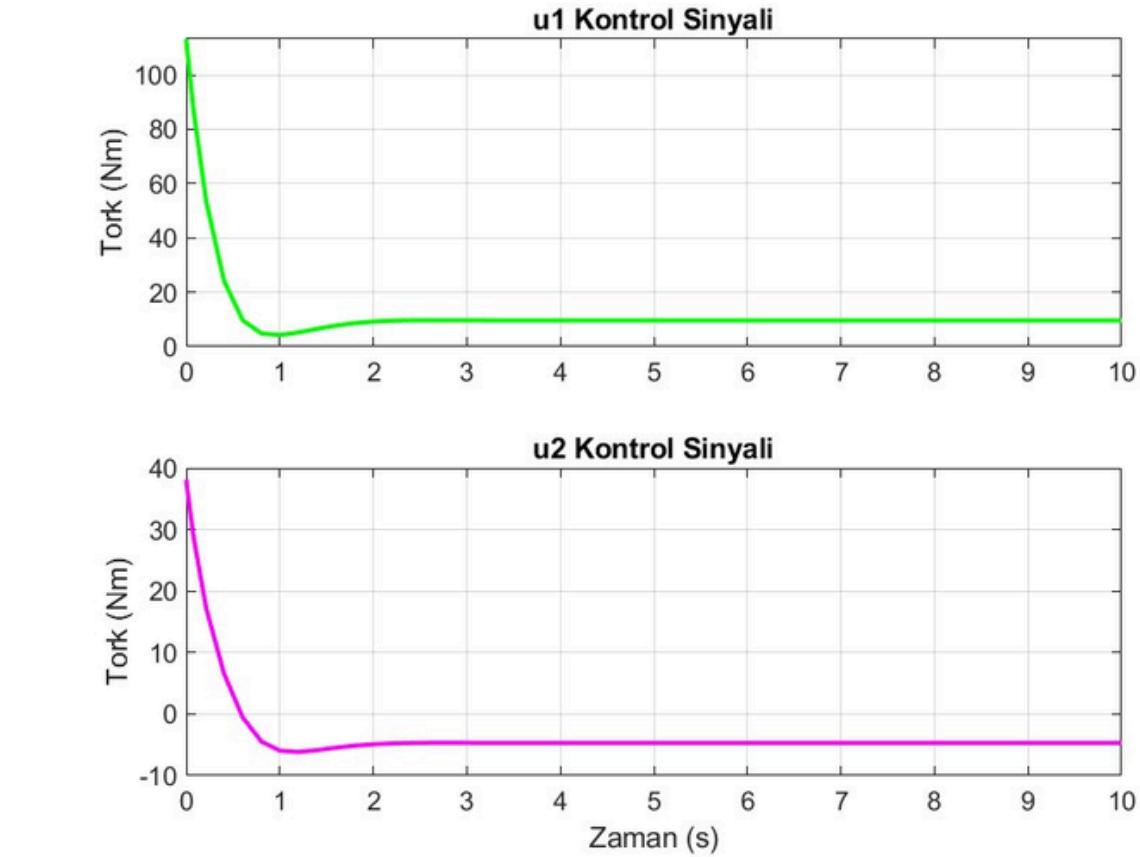
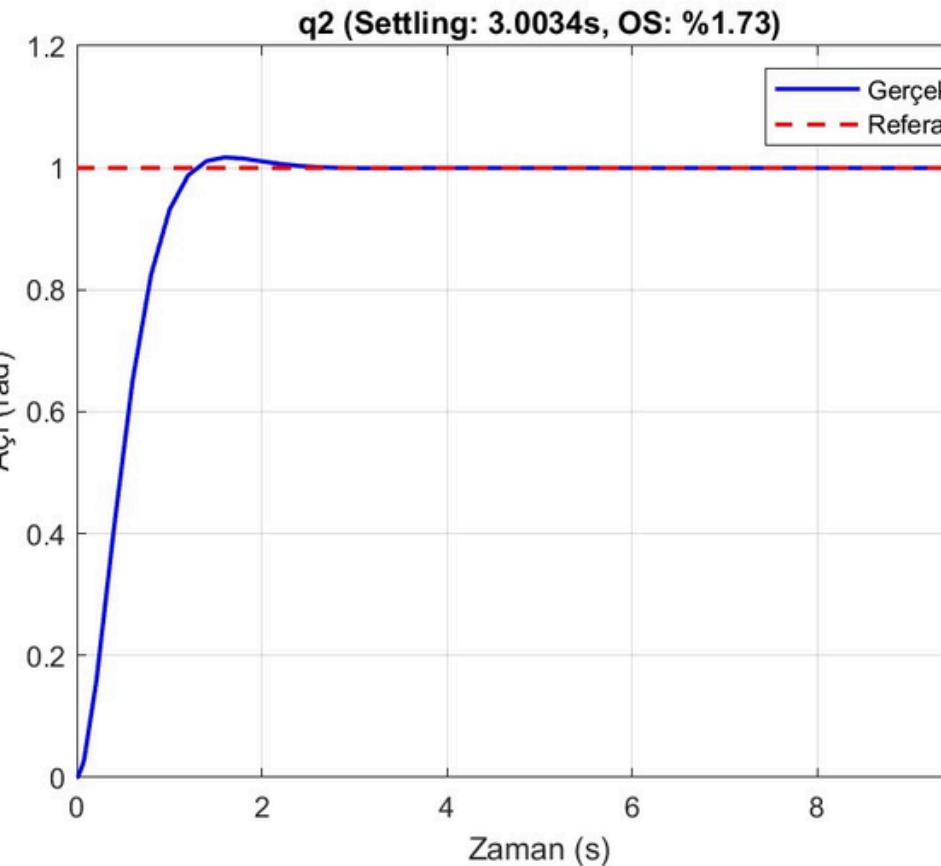
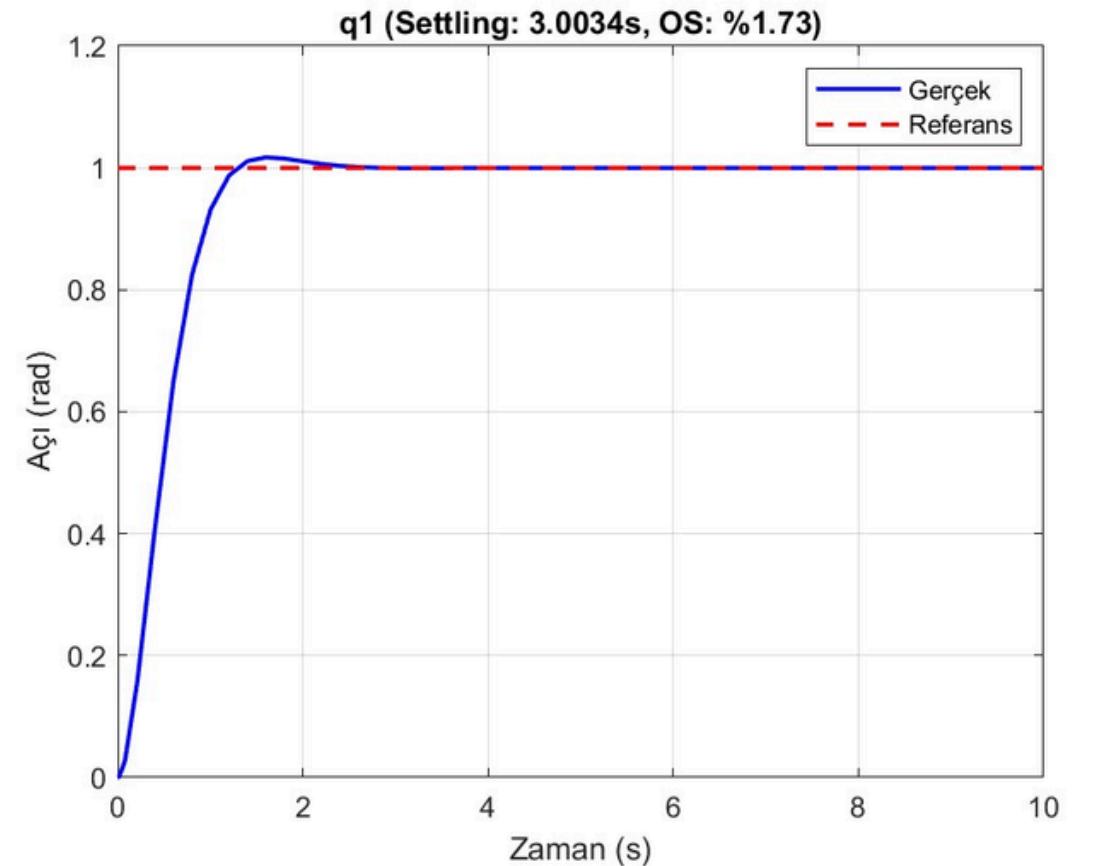
u2 Stable Ort. Tork: -4.7031 Nm

Computed Torque-PD Control

$$M(q)\ddot{q} + N(q, \dot{q}) + G(q) = \tau$$

$$u = -K_p e - K_d \dot{e}$$

$$\tau = M(q)(\ddot{q}_d + K_d \dot{e} + K_p e) + N(q, \dot{q}) + G(q)$$



[q1 Sonuçları]

Settling Time (Kararlı): 3.0034 s

Overshoot (Aşım): %1.73

Ort. Mutlak Hata (Stable): 0.000032 rad

Ort. Normalize Hata (Stable): %0.0032

[q2 Sonuçları]

Settling Time (Kararlı): 3.0034 s

Overshoot (Aşım): %1.73

Ort. Mutlak Hata (Stable): 0.000032 rad

Ort. Normalize Hata (Stable): %0.0032

[Kontrol Sinyalleri Özeti]

u1 Max Tork: 113.2685 Nm

u1 Stable Ort. Tork: 9.6194 Nm

u2 Max Tork: 38.1148 Nm

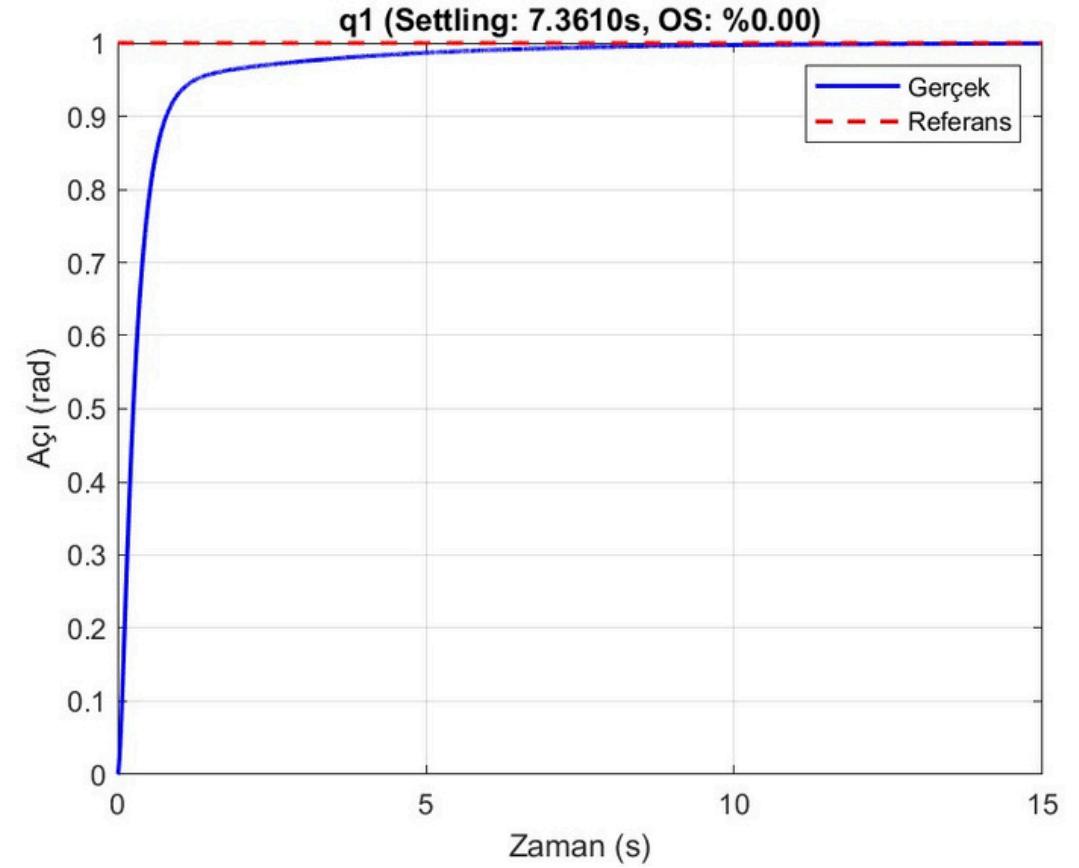
u2 Stable Ort. Tork: -4.6935 Nm

Computed Torque-PID Control

$$\tau = M(q)(\ddot{q}_d - u) + N(q, \dot{q}) + G(q)$$

$$u = -K_p e - K_d \dot{e} - K_i \int e$$

$$\tau = M(q) \left(\ddot{q}_d + K_d \dot{e} + K_p e + K_i * \int e \right) + N(q, \dot{q}) + G(q)$$



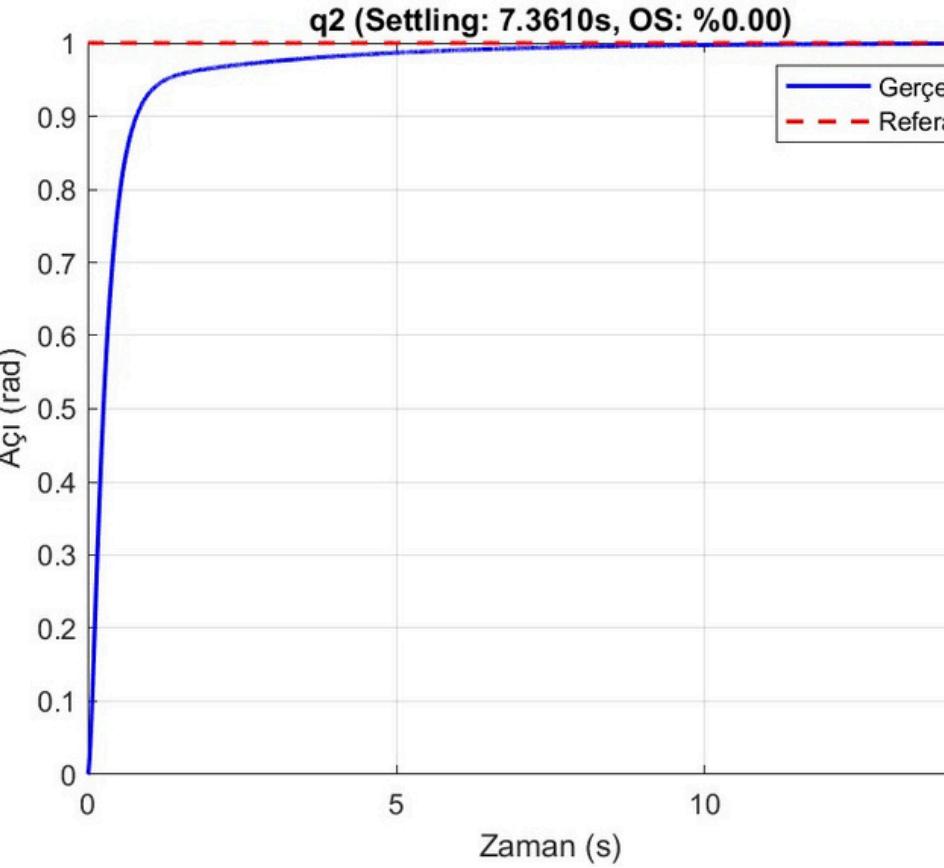
[q1 Sonuçları]

Settling Time (Kararlı): 7.3610 s

Overshoot (Aşım): %0.00

Ort. Mutlak Hata (Stable): 0.002424 rad

Ort. Normalize Hata (Stable): %0.2424



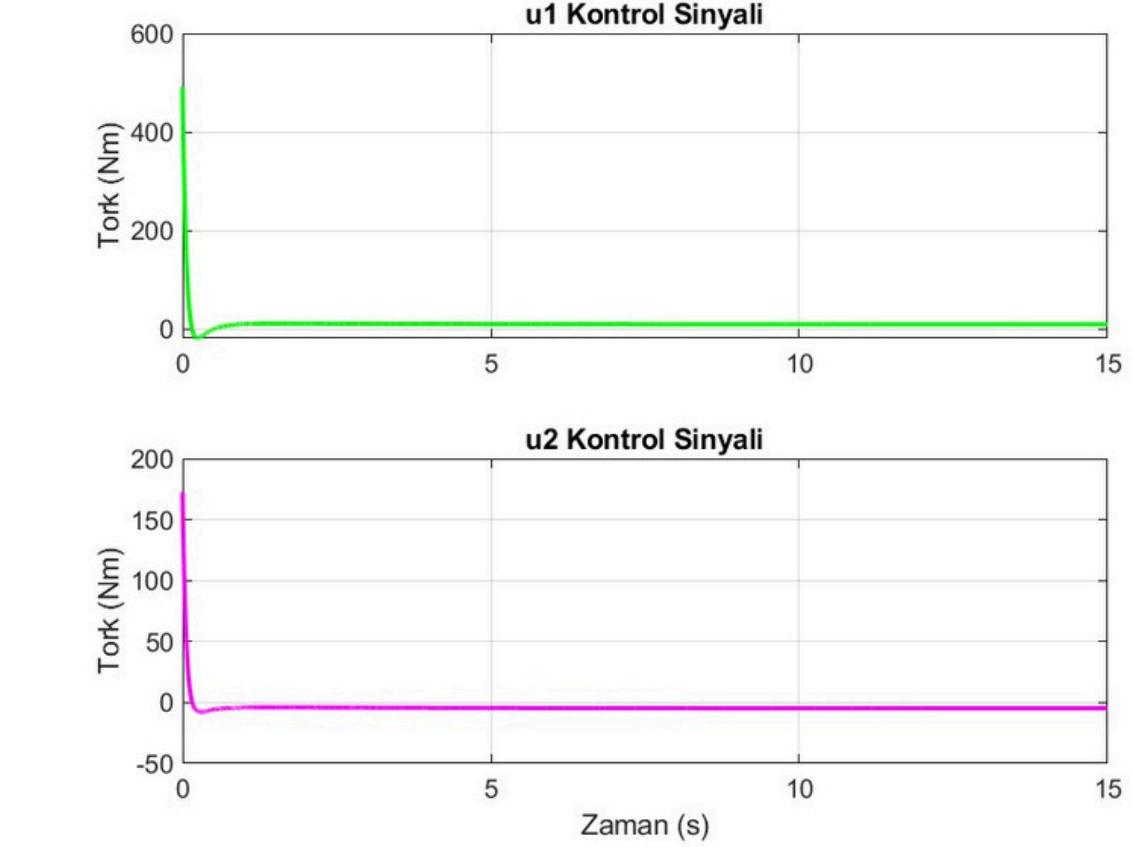
[q2 Sonuçları]

Settling Time (Kararlı): 7.3610 s

Overshoot (Aşım): %0.00

Ort. Mutlak Hata (Stable): 0.002424 rad

Ort. Normalize Hata (Stable): %0.2424



[Kontrol Sinyalleri Özeti]

u1 Max Tork: 491.7530 Nm

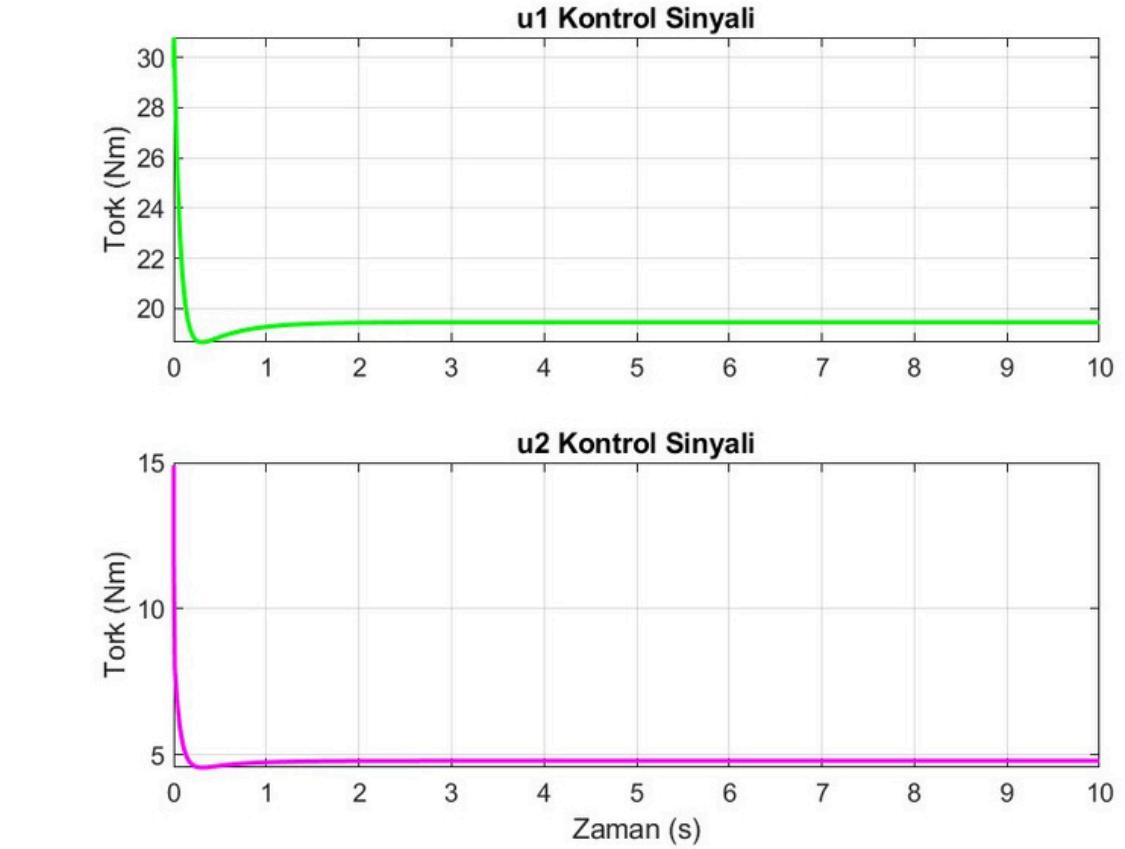
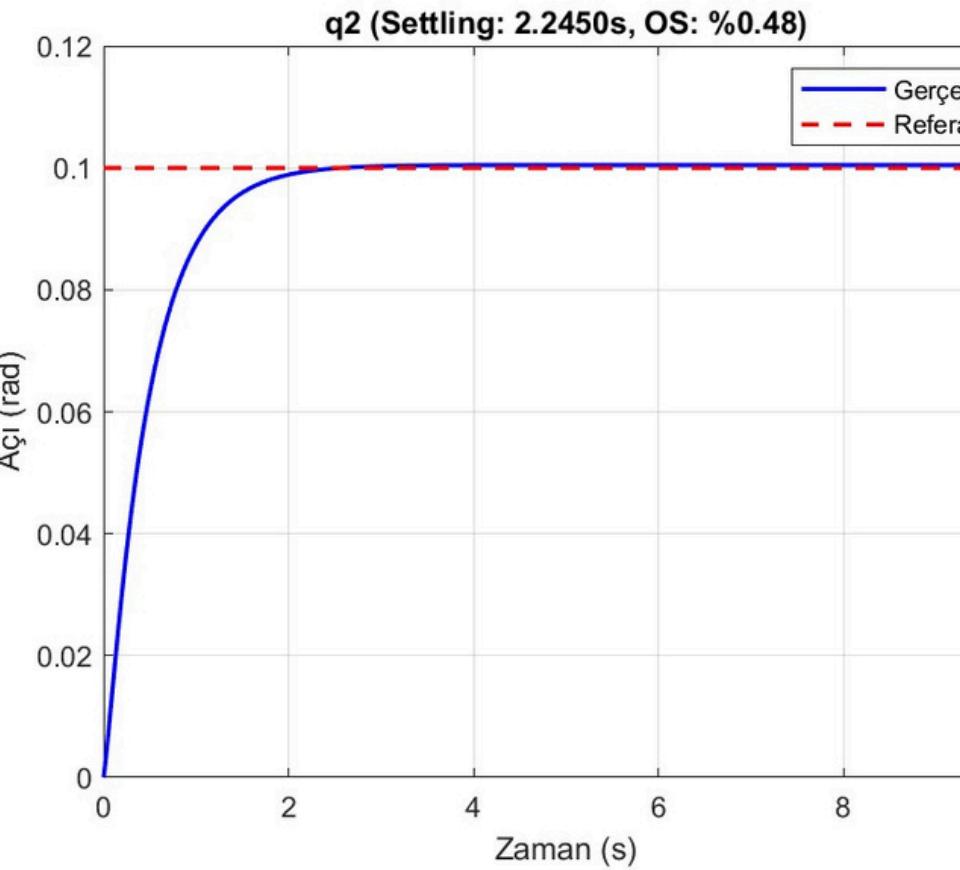
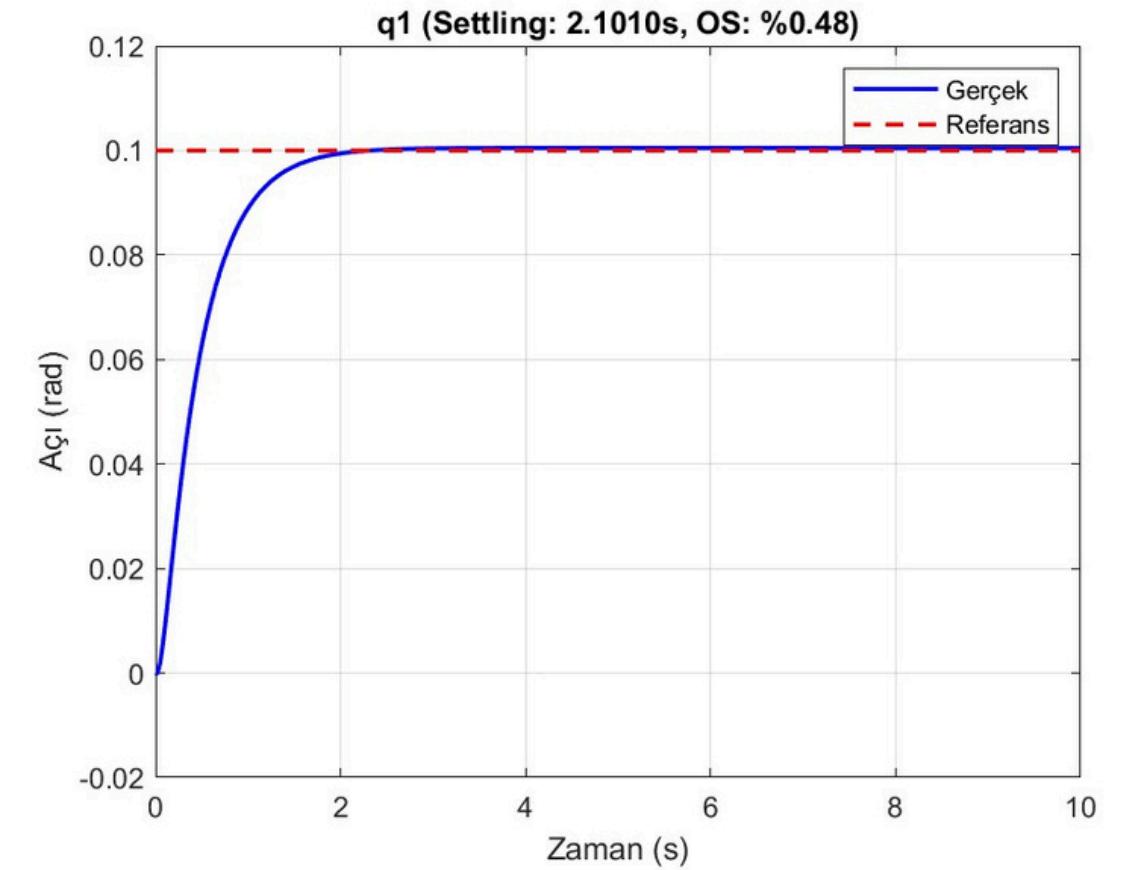
u1 Stable Ort. Tork: 9.7186 Nm

u2 Max Tork: 172.6314 Nm

u2 Stable Ort. Tork: -4.6455 Nm

PID Gravity Control

$$\tau = K_d \dot{e} + K_p e + K_i * \int e + G(q)$$



[q1 Sonuçları]

Settling Time (Kararlı): 2.1010 s
Overshoot (Aşım): %0.48
Ort. Mutlak Hata (Stable): 0.000443 rad
Ort. Normalize Hata (Stable): %0.4426

[q2 Sonuçları]

Settling Time (Kararlı): 2.2450 s
Overshoot (Aşım): %0.48
Ort. Mutlak Hata (Stable): 0.000435 rad
Ort. Normalize Hata (Stable): %0.4346

[Kontrol Sinyalleri Özeti]

u1 Max Tork: 30.8007 Nm
u1 Stable Ort. Tork: 19.4463 Nm
u2 Max Tork: 14.9050 Nm
u2 Stable Ort. Tork: 4.8061 Nm

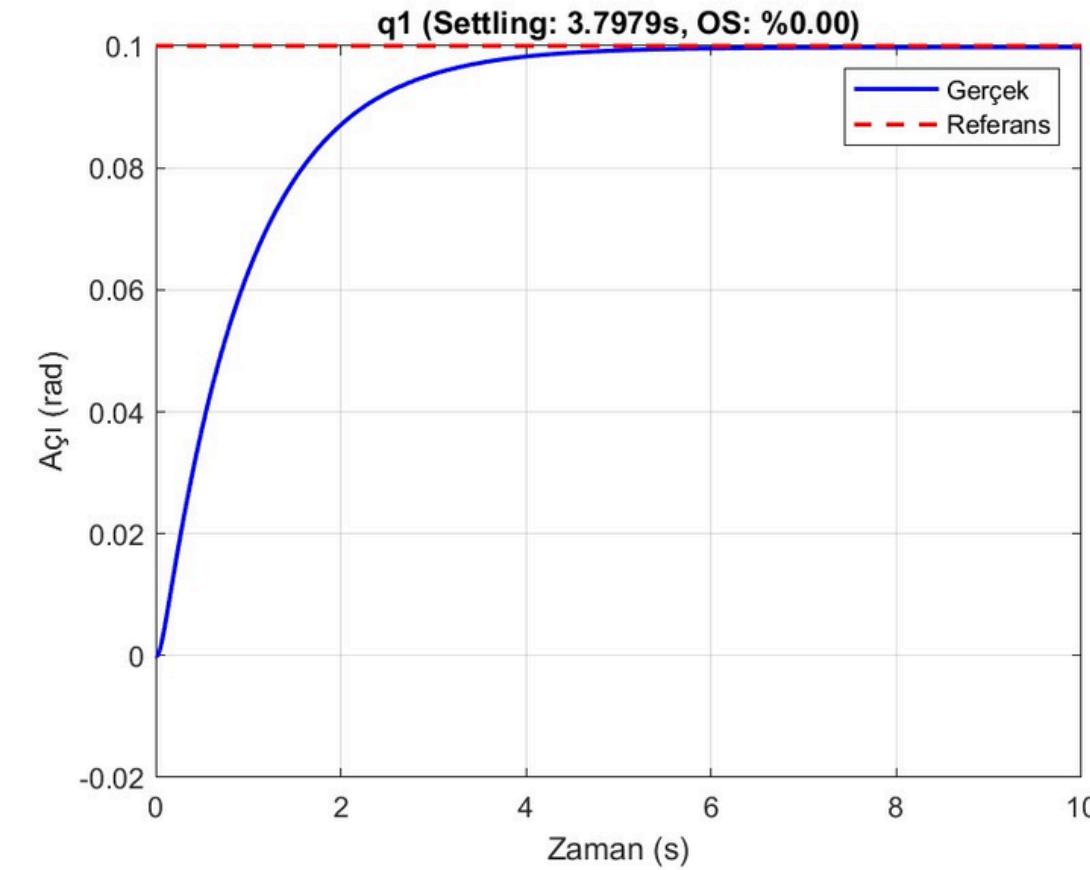
Robust Gravity Control

$$\tau = K_d r + G(q) - v$$

$$r = e + \lambda \dot{e}$$

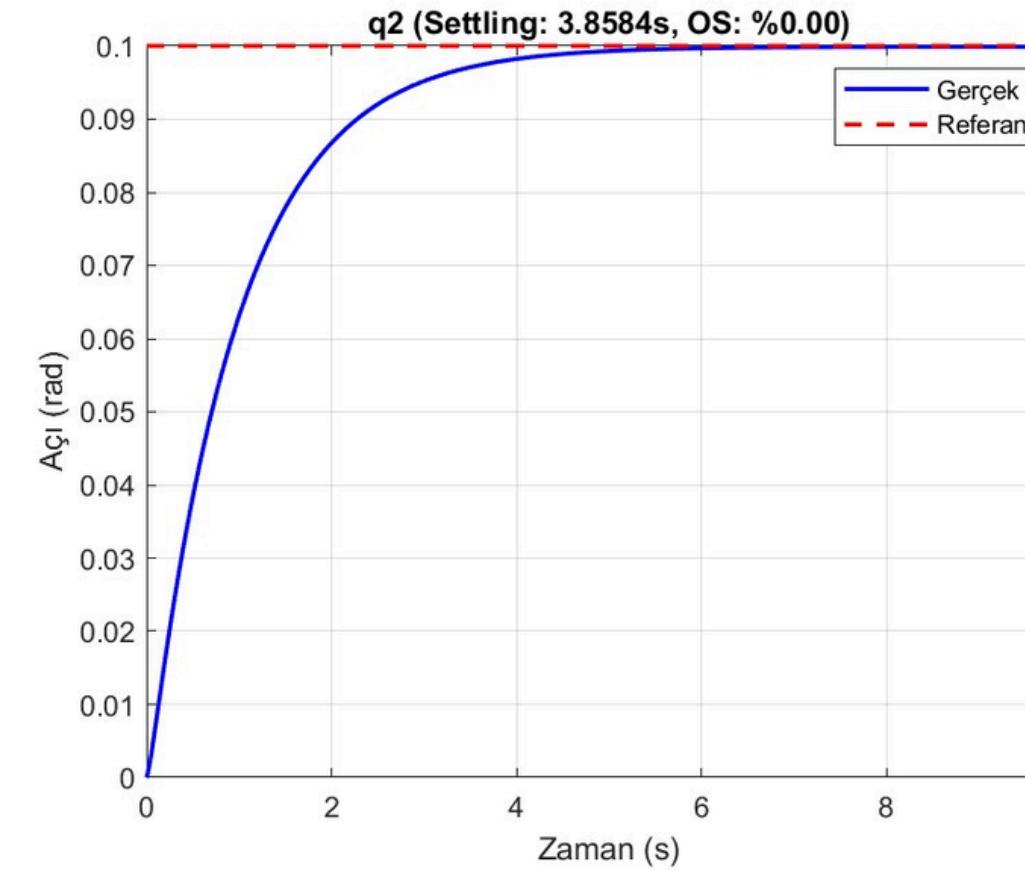
$$v = \begin{cases} \frac{-rF}{\|r\|}, & \|r\| \geq \varepsilon \\ \frac{-rF}{\varepsilon}, & \|r\| \leq \varepsilon \end{cases}$$

$$\|\tilde{F}\| \leq M_2 \cdot \|\ddot{q}_d + \lambda \dot{e}\| + v_B \cdot \|\dot{q}\| \cdot \|\dot{q}_d + \lambda e\| + f_B \cdot \|\dot{q}_d - \dot{e}\| + k_B$$



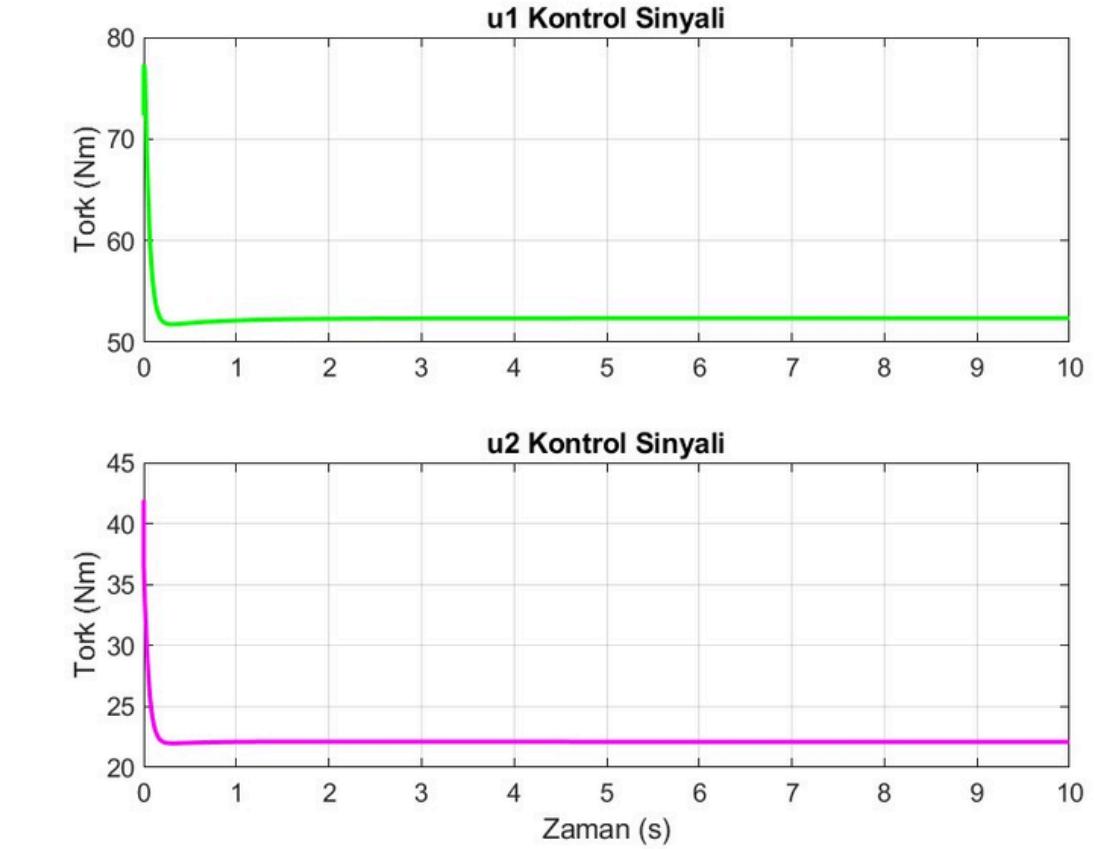
[q1 Sonuçları]

Settling Time (Kararlı): 3.7979 s
Overshoot (Aşım): %0.00
Ort. Mutlak Hata (Stable): 0.000494 rad
Ort. Normalize Hata (Stable): %0.4937



[q2 Sonuçları]

Settling Time (Kararlı): 3.8584 s
Overshoot (Aşım): %0.00
Ort. Mutlak Hata (Stable): 0.000397 rad
Ort. Normalize Hata (Stable): %0.3965



[Kontrol Sinyalleri Özeti]

u1 Max Tork: 77.3596 Nm
u1 Stable Ort. Tork: 52.3731 Nm
u2 Max Tork: 41.9496 Nm
u2 Stable Ort. Tork: 22.1150 Nm

Functional Link Neural Network Controller

$$y = W^T \phi(x)$$

x : input vector

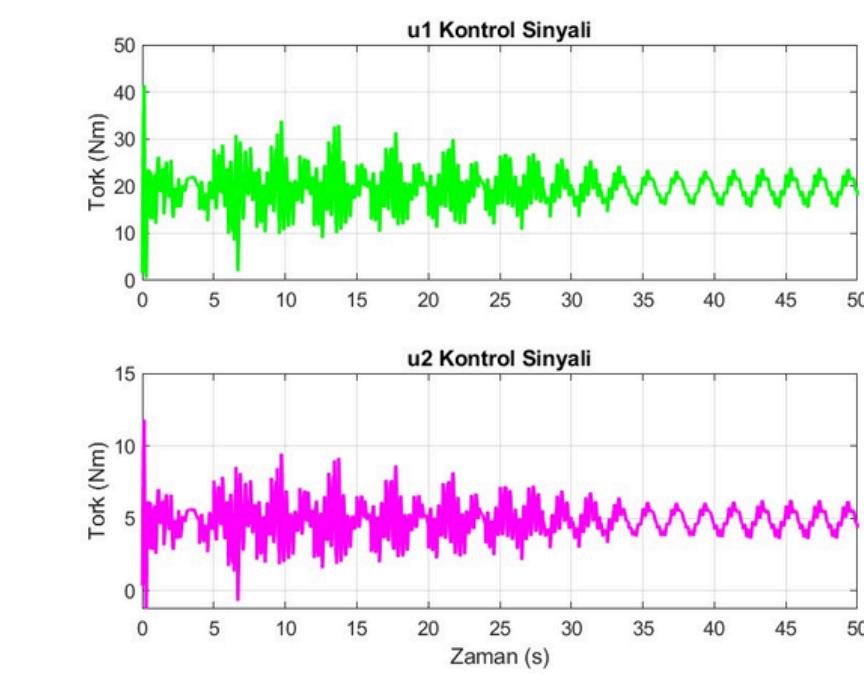
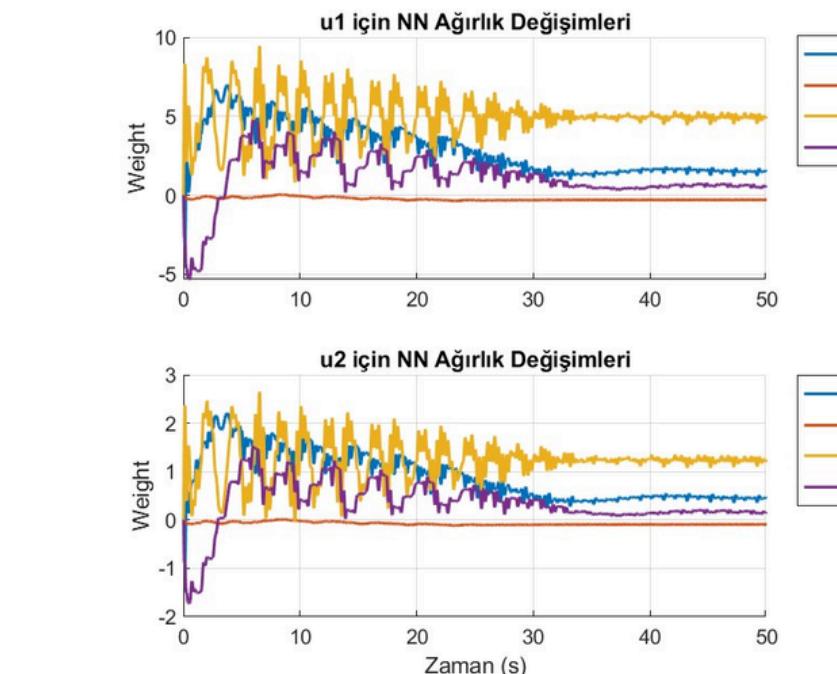
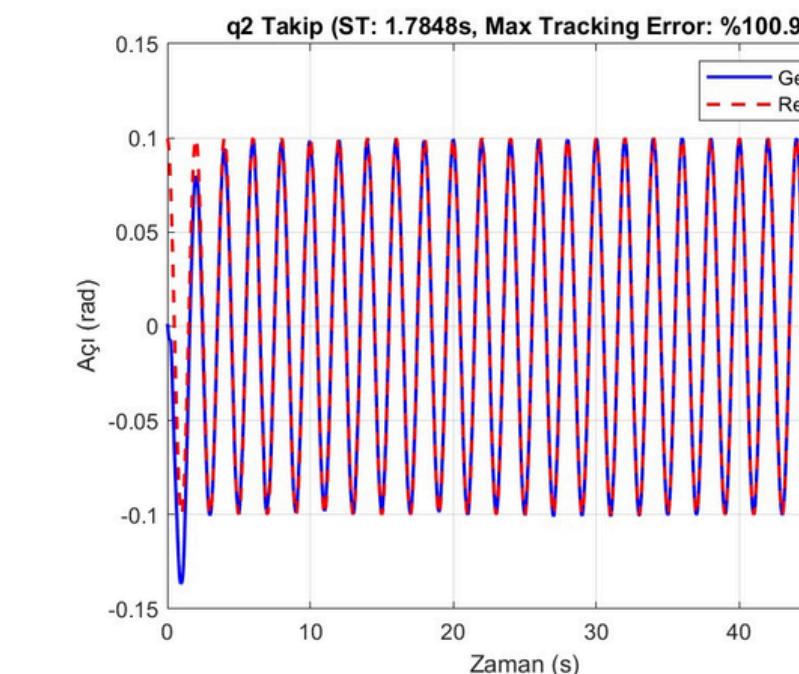
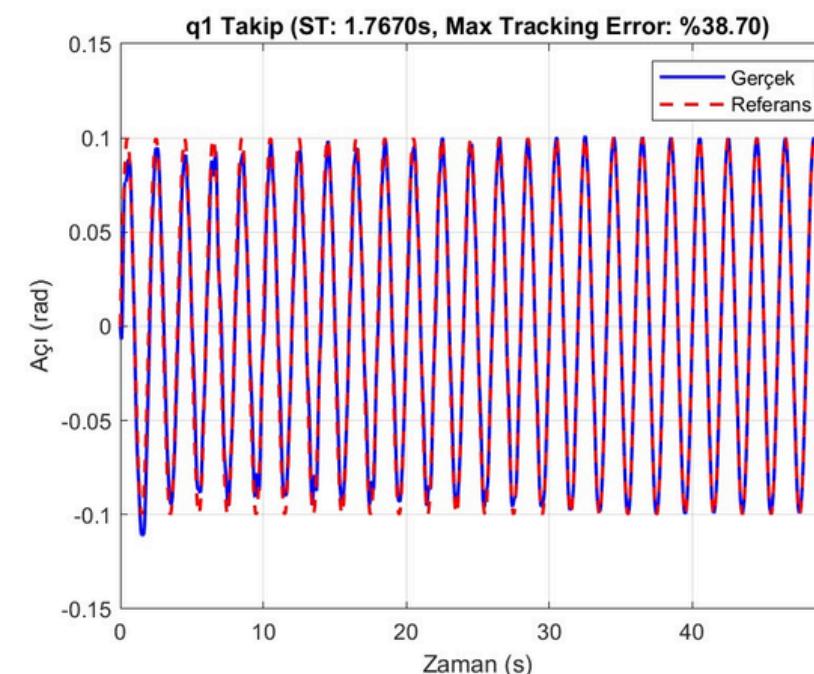
y : output vector

W : weight matrix

$\phi(x)$: main function

$$\text{control input : } \tau = \hat{W}^T \phi(x) + K_v r$$

$$\text{tuning algorithms : } \dot{\hat{W}} = F \phi r^T \quad F > 0$$



[q1 Sonuçları]

Settling Time (%5 Bandı): 1.7670 s

Ort. Mutlak Hata (Stable): 0.004148 rad

[q2 Sonuçları]

Settling Time (%5 Bandı): 1.7848 s

Ort. Mutlak Hata (Stable): 0.001548 rad

[Neural Network Final Weights]

u1 çıkışı için ağırlıklar:

w_{1,1}: 1.489521

w_{2,1}: -0.286696

w_{3,1}: 4.988083

w_{4,1}: 0.590930

u2 çıkışı için ağırlıklar:

w_{1,2}: 0.445860

w_{2,2}: -0.090647

w_{3,2}: 1.244937

w_{4,2}: 0.166163

Kontrol Sinyalleri Özeti]

u1 stable Ort. Tork: 19.5140 Nm

u2 stable Ort. Tork: 4.8653 Nm

Functional Link Nueral Network Controller

$$y = W^T \phi(x)$$

x : input vector

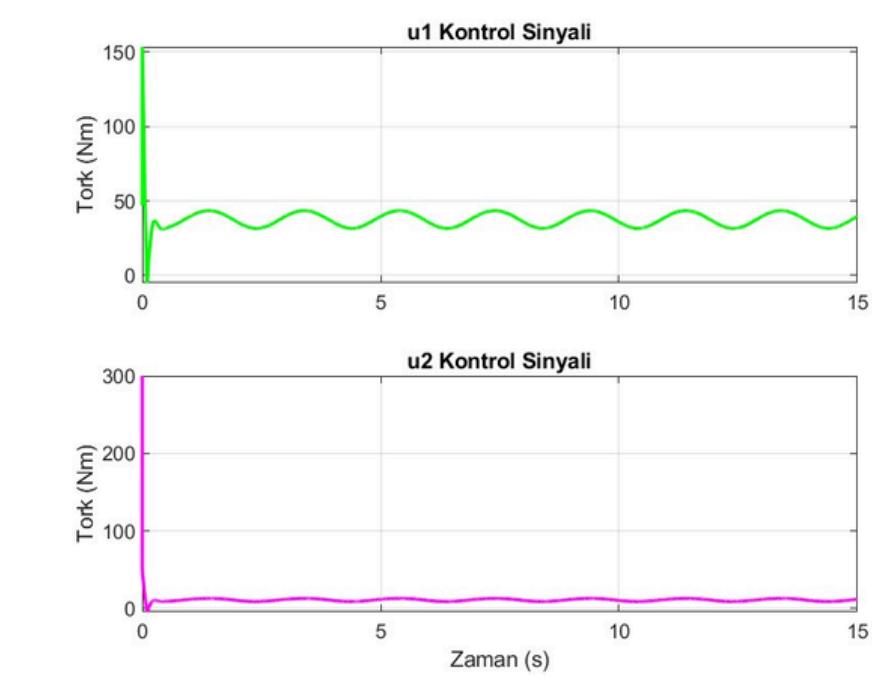
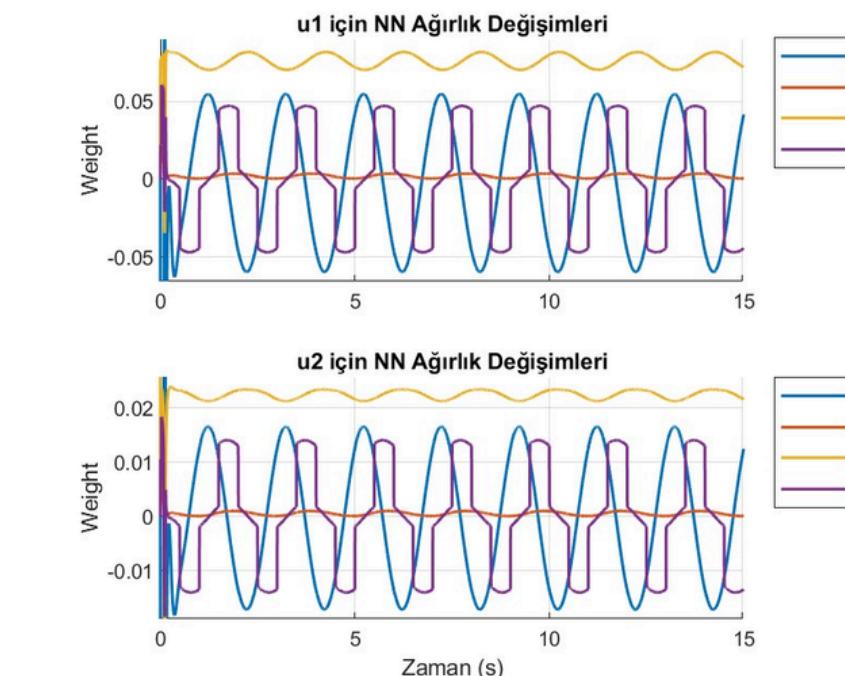
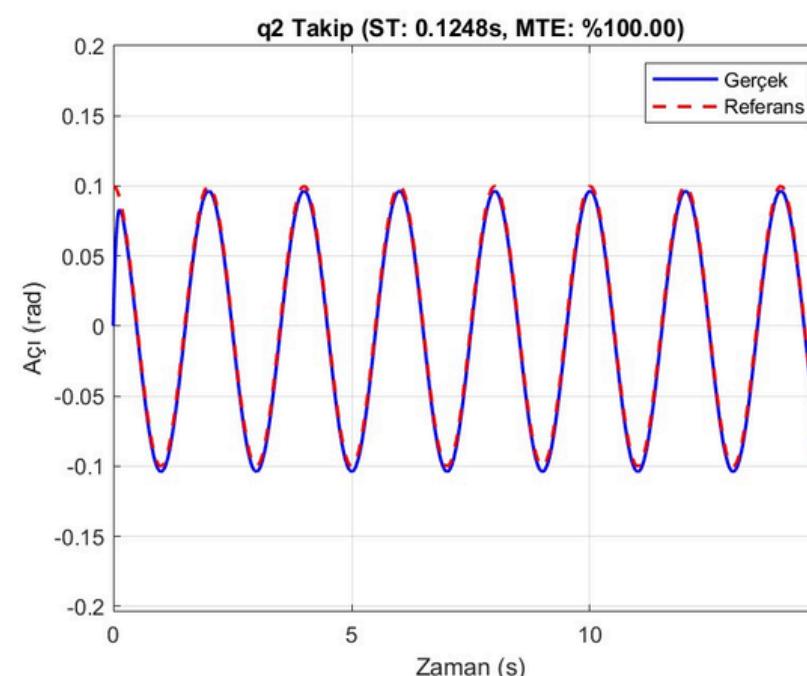
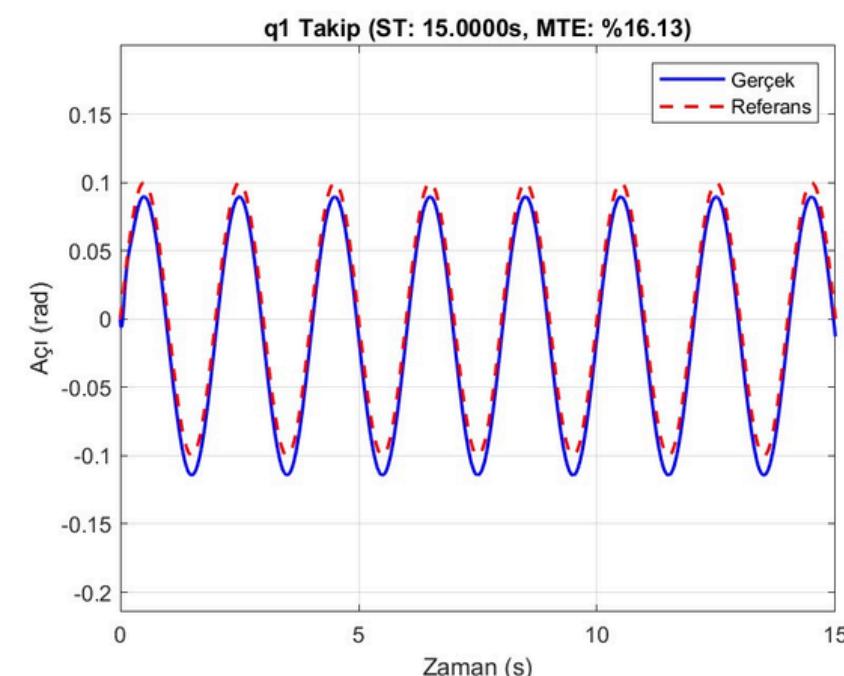
y : output vector

W : weight matrix

$\phi(x)$: main function

$$\text{control input} : \tau = \hat{W}^T \phi(x) + K_v r$$

$$\text{tuning algorithms} : \dot{\hat{W}} = F \phi r^T - W \| r \| F \kappa \quad F > 0$$



[q1 Sonuçları]

Settling Time (%5 Bandı): 15.0000 s

Ort. Mutlak Hata (Stable): 0.012763 rad

[q2 Sonuçları]

Settling Time (%5 Bandı): 0.1248 s

Ort. Mutlak Hata (Stable): 0.003689 rad

[Neural Network Final Weights]

u1 çıkışı için ağırlıklar:

w_{1,1}: 0.041425

w_{2,1}: 0.000353

w_{3,1}: 0.071845

w_{4,1}: -0.044486

u2 çıkışı için ağırlıklar:

w_{1,2}: 0.012503

w_{2,2}: 0.000107

w_{3,2}: 0.021685

w_{4,2}: -0.013427

[Kontrol Sinyalleri Özeti]

u1 stable Ort. Tork: 39.6306 Nm

u2 stable Ort. Tork: 11.1414 Nm

Adaptive Control

$$f(x) = M(q)(\ddot{q}_d + \Lambda \dot{e}) + V_m(q, \dot{q})(\dot{q}_d + \Lambda e) + F(\dot{q}) + G(q) = W(x)\phi$$

- $W(x)$ is matrix of known robot functions

- ϕ is vector of unknown parameter

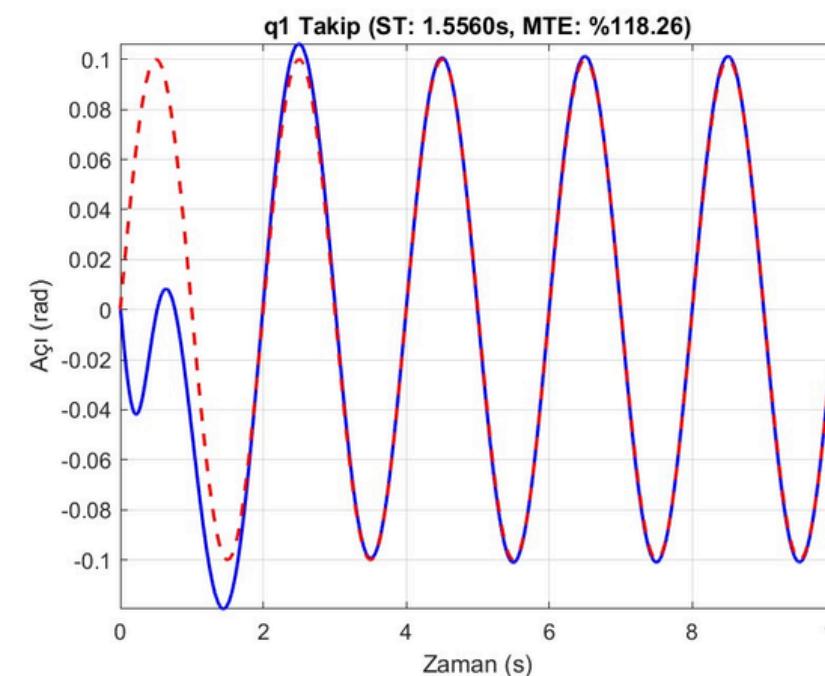
$$\tau = W(x)\phi + K_v r$$

$$\dot{\phi} = \Gamma W(x)^T r$$

$$r = \dot{e} + \lambda e$$

$$e = q_d - q \quad \dot{q}_r = \dot{q}_d + \lambda e \quad \ddot{q}_r = \ddot{q}_d + \lambda \dot{e}$$

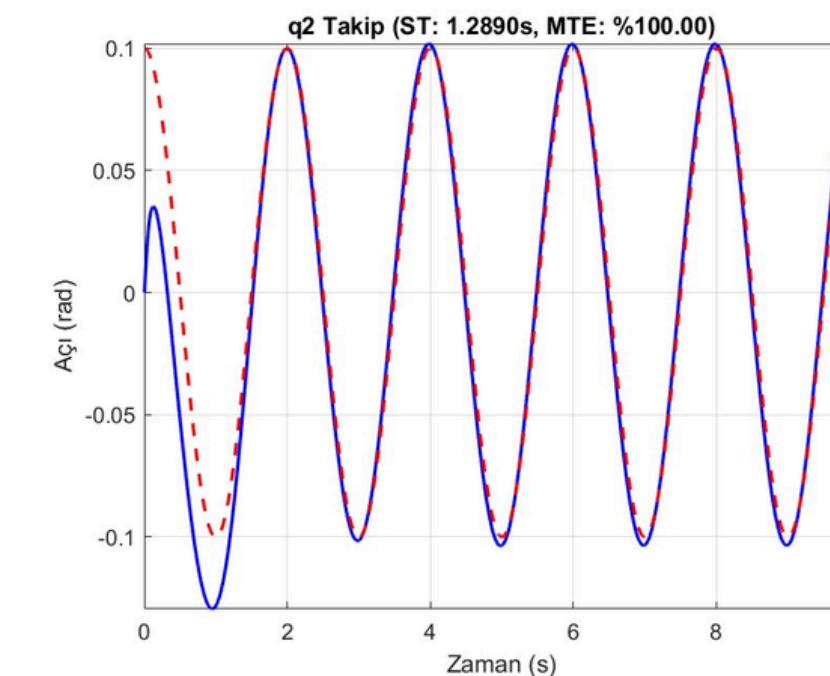
$$\phi = [m_1 \quad m_2]^T$$



[q1 Sonuçları]

Settling Time: 1.5560 s

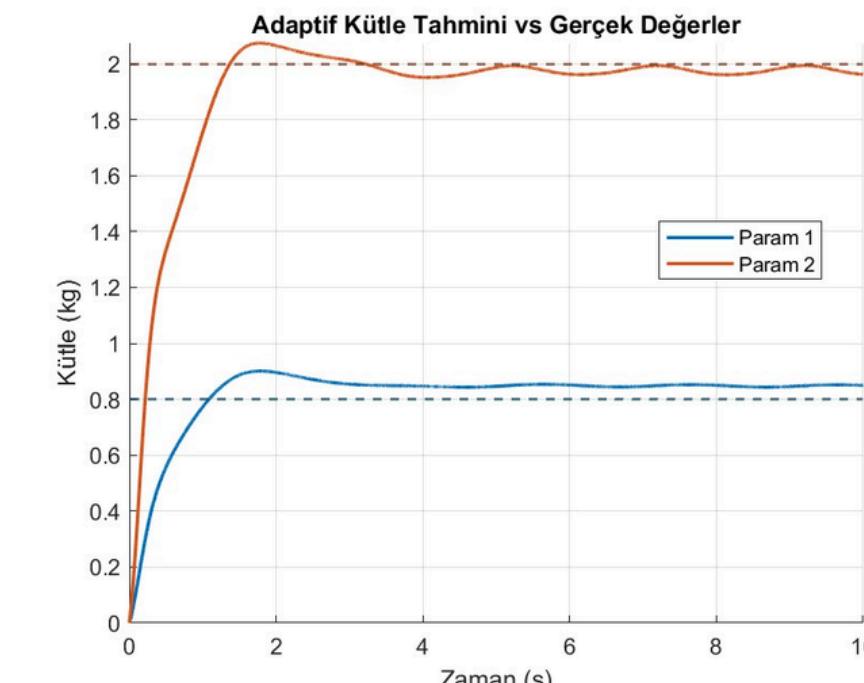
Ort. Mutlak Hata (Stable): 0.001649 rad



[q2 Sonuçları]

Settling Time: 1.2890 s

Ort. Mutlak Hata (Stable): 0.003954 rad



[Adaptif Kütle (Mass) Final Değerleri]

Mass1

Gerçek: 0.80 kg

Tahmin: 0.8494 kg

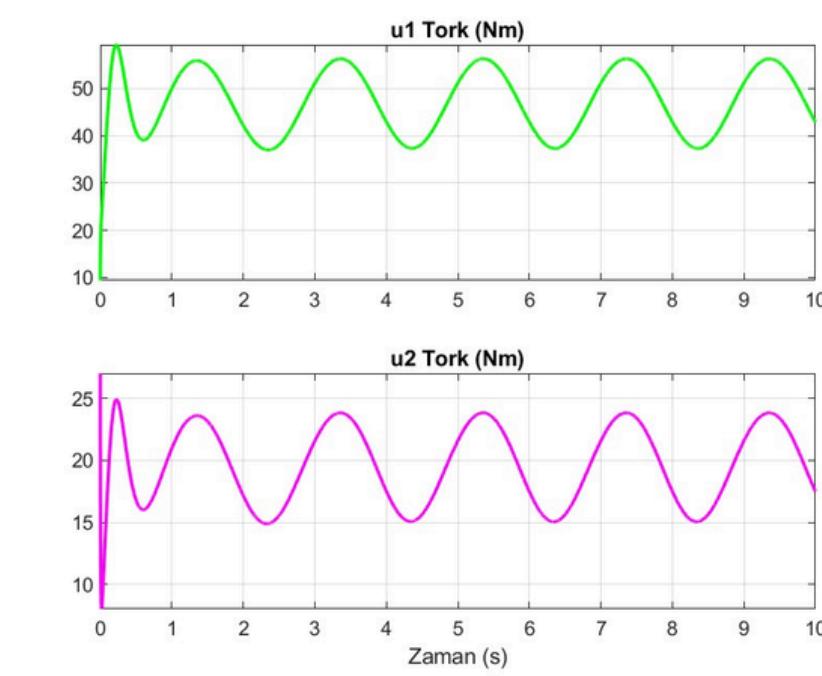
Hata: %6.18

Mass2

Gerçek: 2.00 kg

Tahmin: 1.9620 kg

Hata: %1.90



[Kontrol Sinyalleri Özeti]

u1 stable Ort. Tork: 46.9723 Nm

u2 stable Ort. Tork: 19.6591 Nm

Two Layer NN Controller

$$M(q)\ddot{q} + V_m(q, \dot{q})\dot{q} + F(\dot{q}) + G(q) + \tau_d = \tau$$

$$M\dot{r} = -V_m r + f(x) + \tau_d - \tau$$

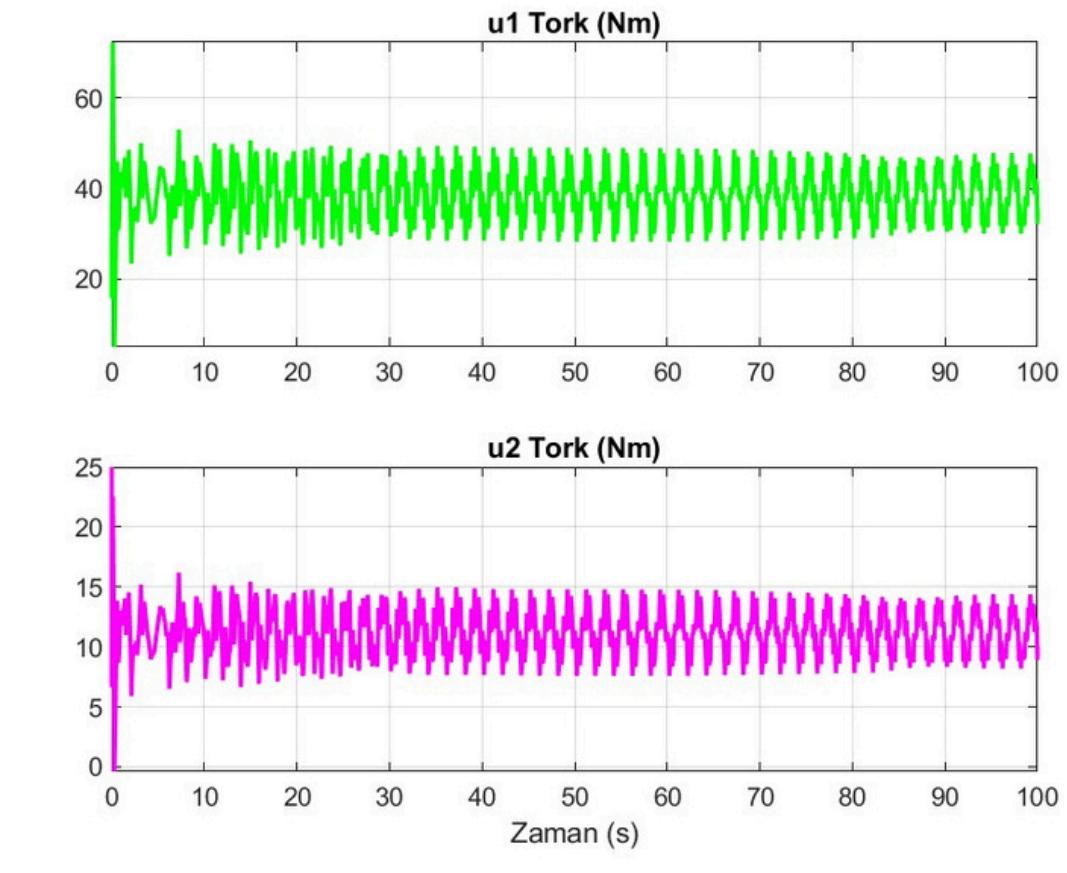
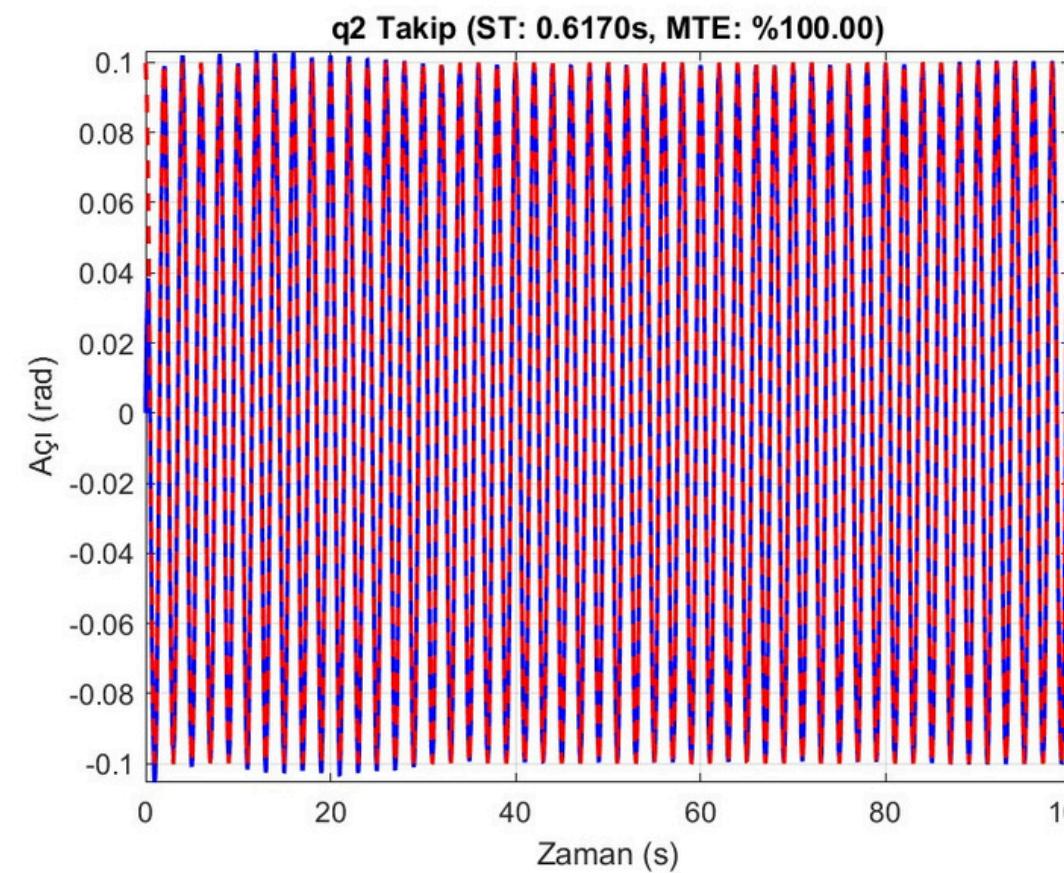
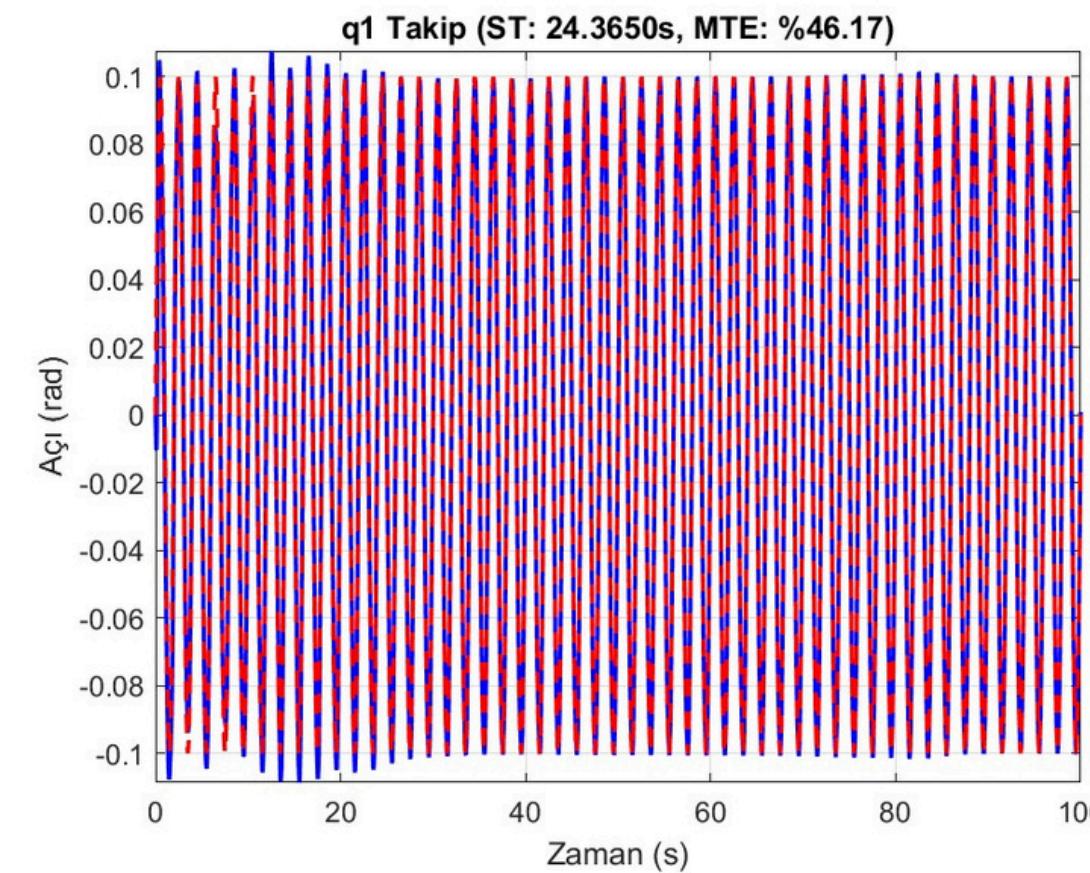
$$f(x) = M(q)(\ddot{q}_d + \lambda\dot{e}) + V_m(q, \dot{q})(\dot{q}_d + \lambda e) + F(\dot{q}) + G(q)$$

$$x = [e^T \quad \dot{e}^T \quad q_d^T \quad \dot{q}_d^T \quad \ddot{q}_d^T]^T$$

$$f(x) = W^T \sigma(V^T x) + \varepsilon$$

$$\tau = \hat{f}(x) + K_v r - \nu = \hat{W}^T \sigma(\hat{V}^T x) + K_v r - \nu$$

$$\dot{\hat{W}} = F \sigma r^T \quad \dot{\hat{V}} = Gx(\hat{\sigma} \hat{W}^T r)^T$$



[q1 Sonuçları]

Settling Time: 24.3650 s

Ort. Mutlak Hata (Stable): 0.001542 rad

[q2 Sonuçları]

Settling Time: 0.6170 s

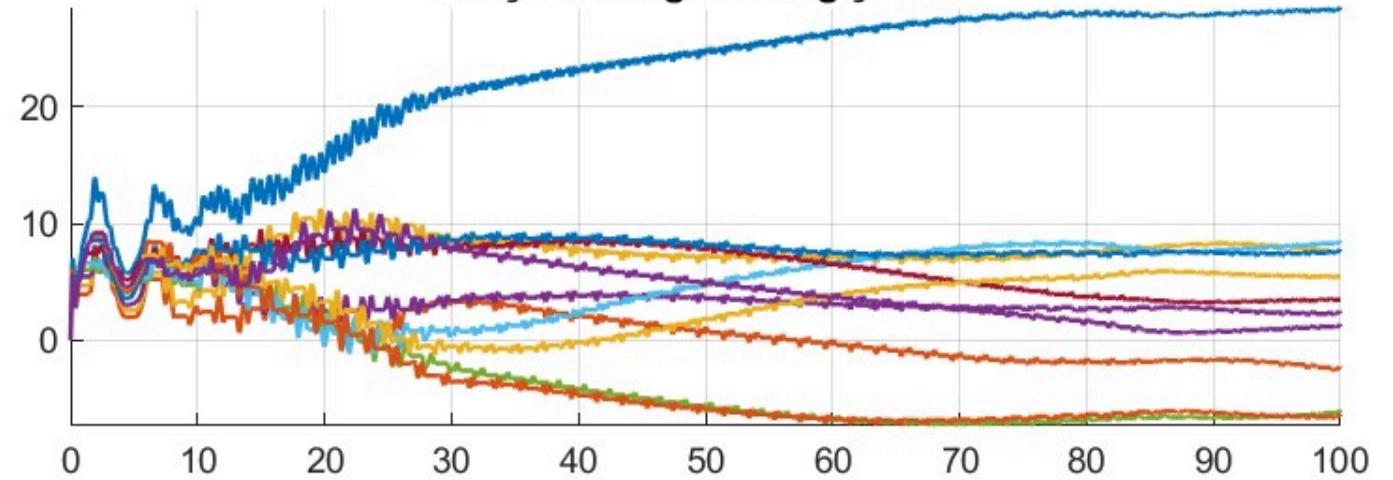
Ort. Mutlak Hata (Stable): 0.000848 rad

[Kontrol Sinyalleri Özeti]

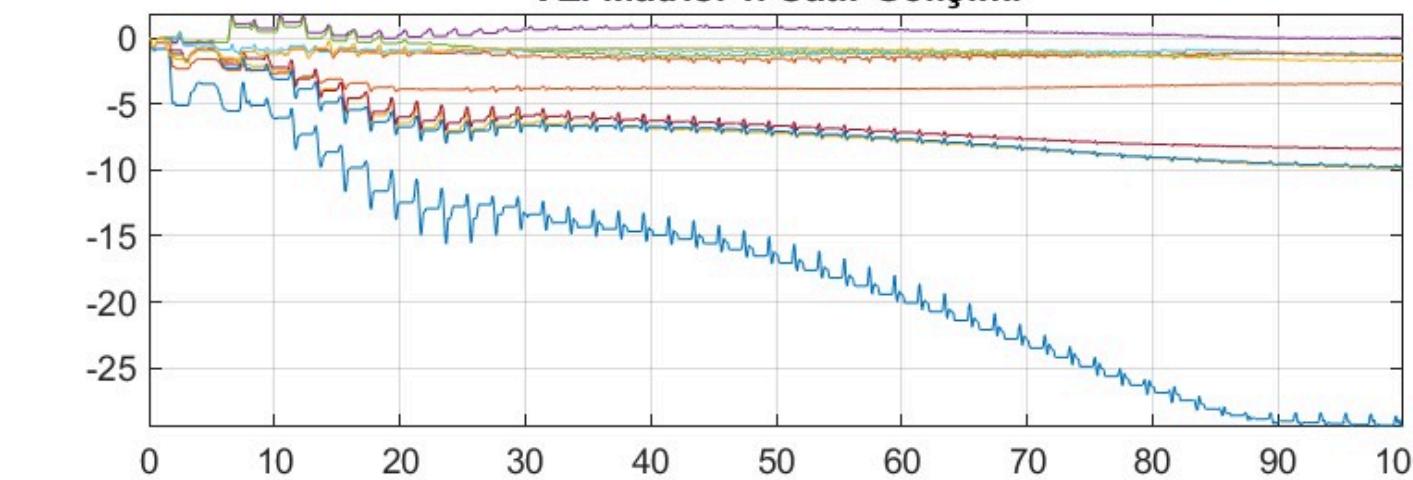
u1 stable Ort. Tork: 38.6427 Nm

u2 stable Ort. Tork: 11.2362 Nm

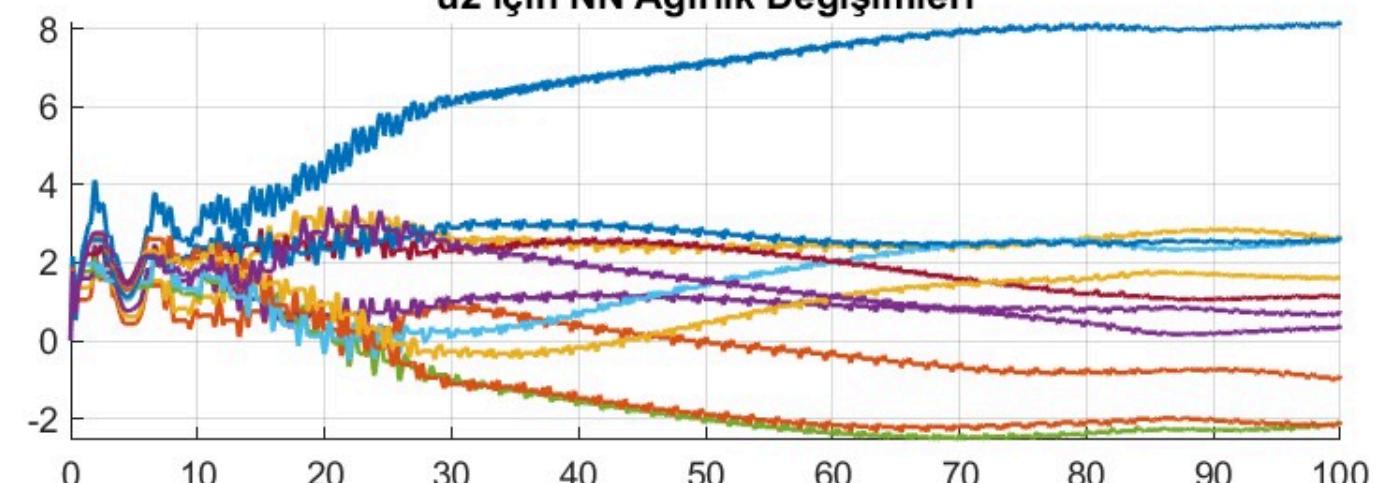
u1 için NN Ağırlık Değişimleri



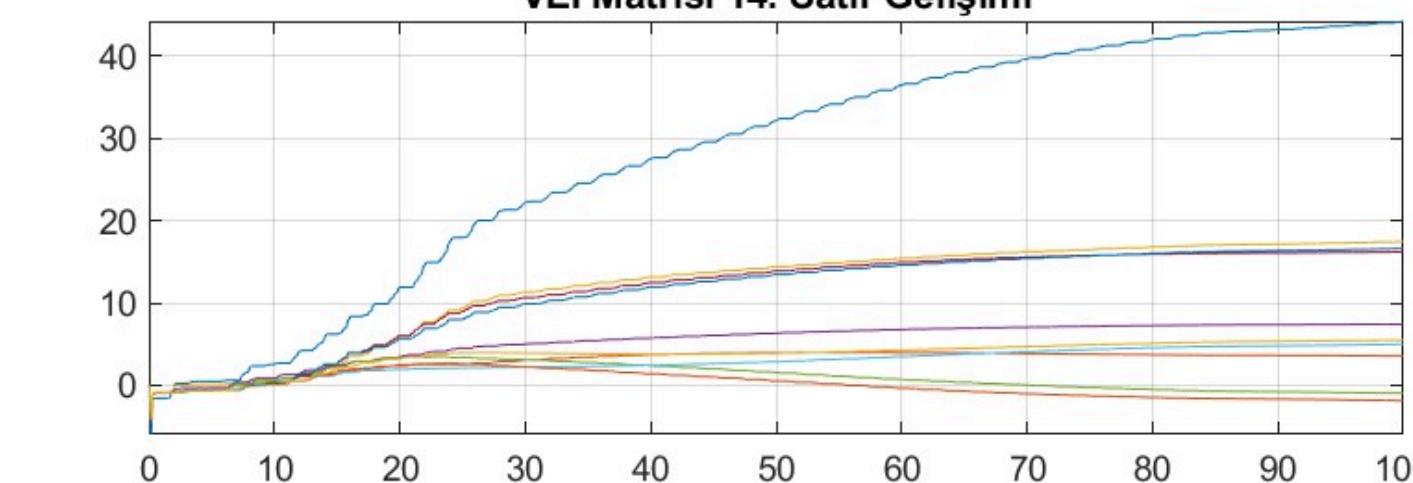
VEI Matrisi 1. Satır Gelişimi



u2 için NN Ağırlık Değişimleri



VEI Matrisi 14. Satır Gelişimi



[Neural Network Tüm Final Ağırlıkları]

u1_w1: 28.25581373 u2_w1: 8.09429699
u1_w2: -2.50222707 u2_w2: -0.99183862
u1_w3: 7.51892753 u2_w3: 2.60138121
u1_w4: 2.28826611 u2_w4: 0.67729910
u1_w5: -6.22342356 u2_w5: -2.15769539
u1_w6: 8.27956798 u2_w6: 2.53357666
u1_w7: 3.46582351 u2_w7: 1.13221743
u1_w8: 7.59069624 u2_w8: 2.59661520
u1_w9: -6.59198238 u2_w9: -2.16833386
u1_w10: 5.44772482 u2_w10: 1.61118210
u1_w11: 1.11480210 u2_w11: 0.30182930

[VEI Matrisi Tüm Final Değerleri (14 x 10)]

VEI(1,1): -29.34357585 VEI(1,2): -3.45432436
VEI(1,3): -9.91848757 VEI(1,4): -0.00629415
VEI(1,5): -1.19842636 VEI(1,6): -1.26614322
VEI(1,7): -8.41391909 VEI(1,8): -9.81161165
VEI(1,9): -1.29880122 VEI(1,10): -1.73458803

VEI(14,1): 44.26767087 VEI(14,2): 3.55939233
VEI(14,3): 17.47443798 VEI(14,4): 7.44524405
VEI(14,5): -0.97602414 VEI(14,6): 4.99150301
VEI(14,7): 16.22306149 VEI(14,8): 16.65391956
VEI(14,9): -1.87000107 VEI(14,10): 5.50678170

MLP Non-Ideal Case

$$M(q)\ddot{q} + V_m(q, \dot{q})\dot{q} + F(\dot{q}) + G(q) + \tau_d = \tau$$

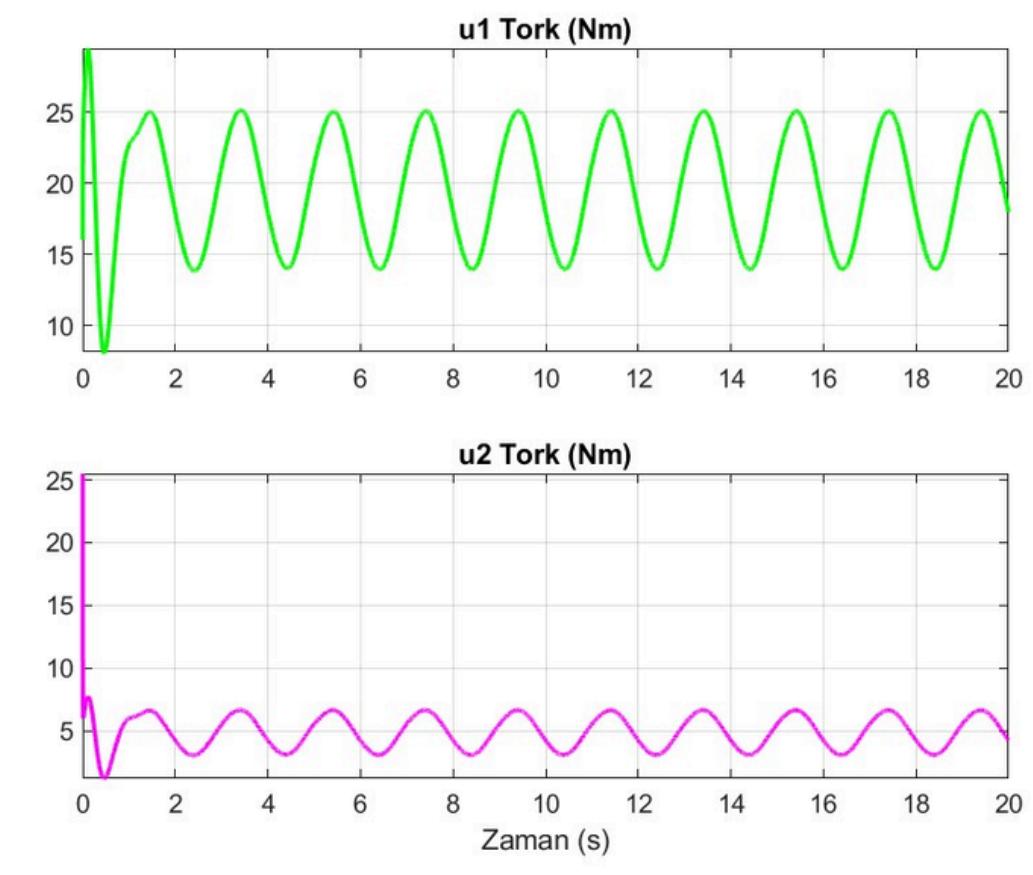
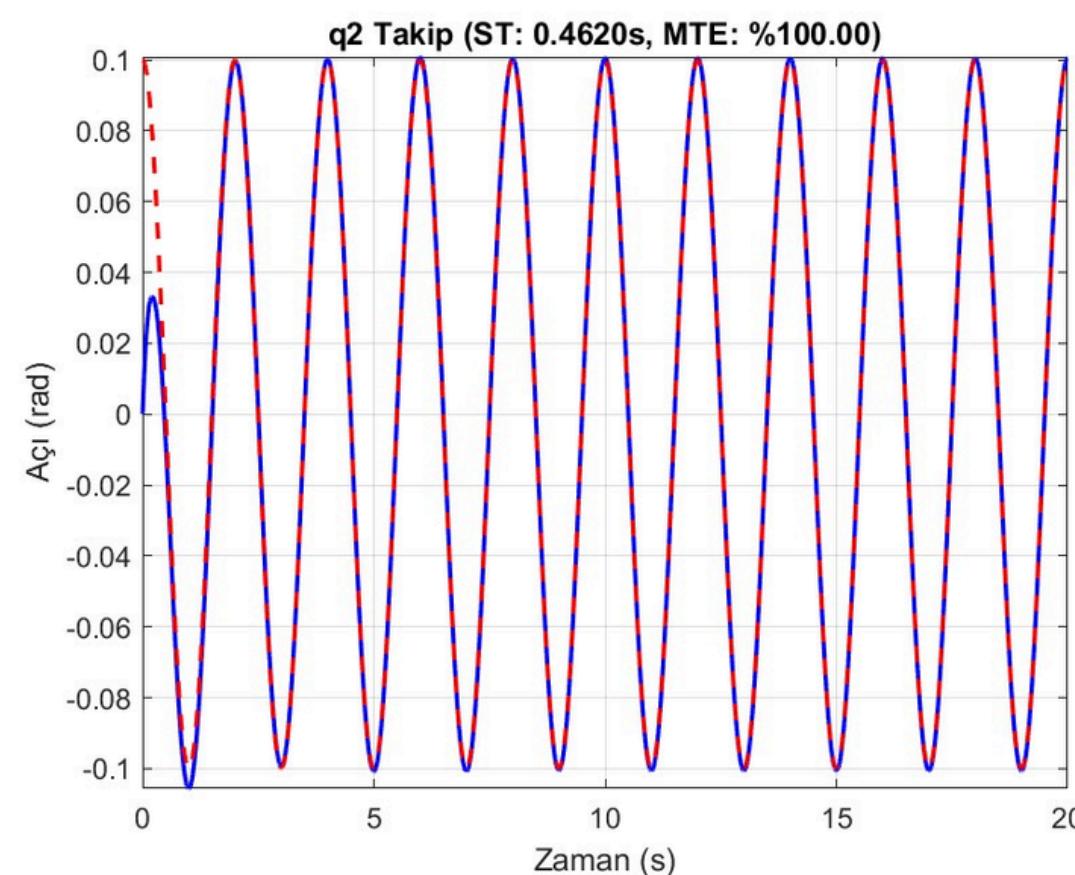
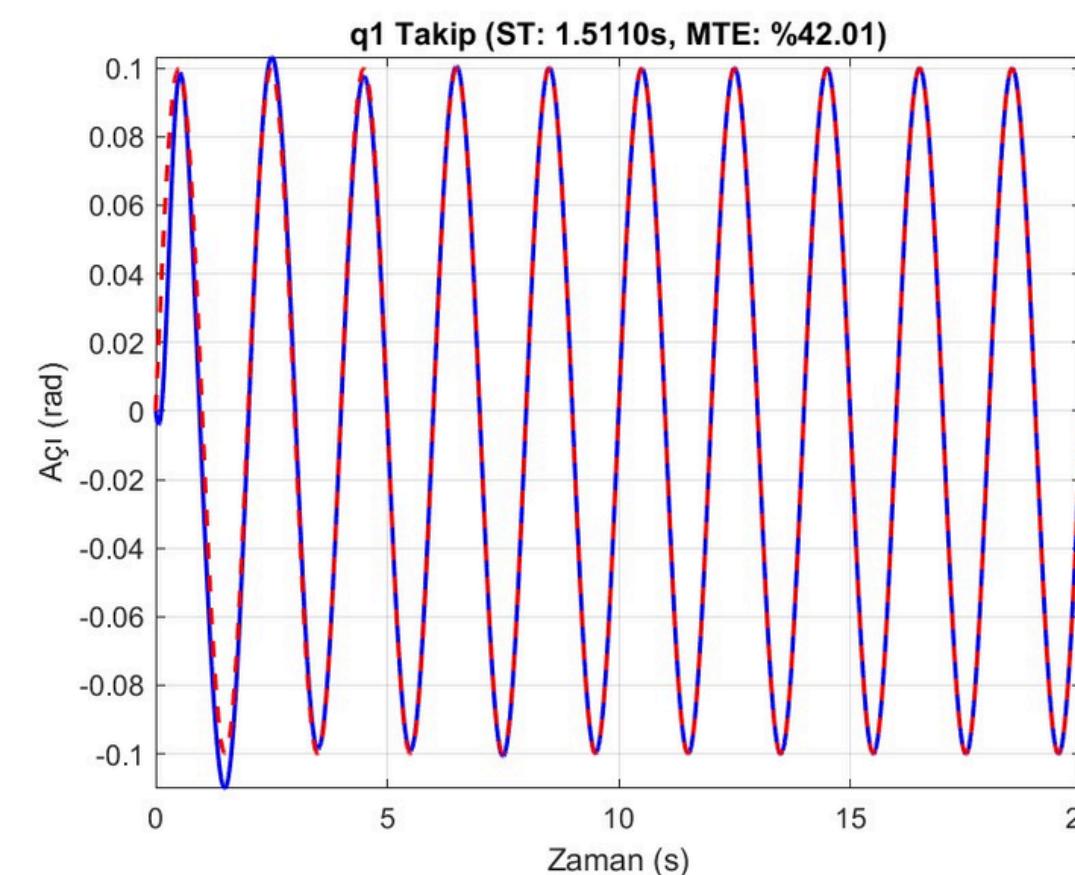
$$M\ddot{r} = -V_m r + f(x) + \tau_d - \tau$$

$$f(x) = M(q)(\ddot{q}_d + \lambda \dot{e}) + V_m(q, \dot{q})(\dot{q}_d + \lambda e) + F(\dot{q}) + G(q)$$

$$f(x) = W^T \sigma(V^T x) + \varepsilon \quad \text{NN functions}$$

$$\tau = \hat{W}^T \sigma(\hat{V}^T x) + K_v r - v \quad v = -K_z (\|\hat{Z}\| + \hat{Z}_B)$$

$$\dot{\hat{W}} = F \hat{\sigma} r^T - F \hat{\sigma}' \hat{V}^T x r^T - kF \|r\| \hat{W} \quad \dot{\hat{V}} = Gx(\hat{\sigma}'^T \hat{W} r)^T - kG \|r\| \hat{V}$$



[q1 Sonuçları]

Settling Time: 1.5110 s

Ort. Mutlak Hata (Stable): 0.000783 rad

[q2 Sonuçları]

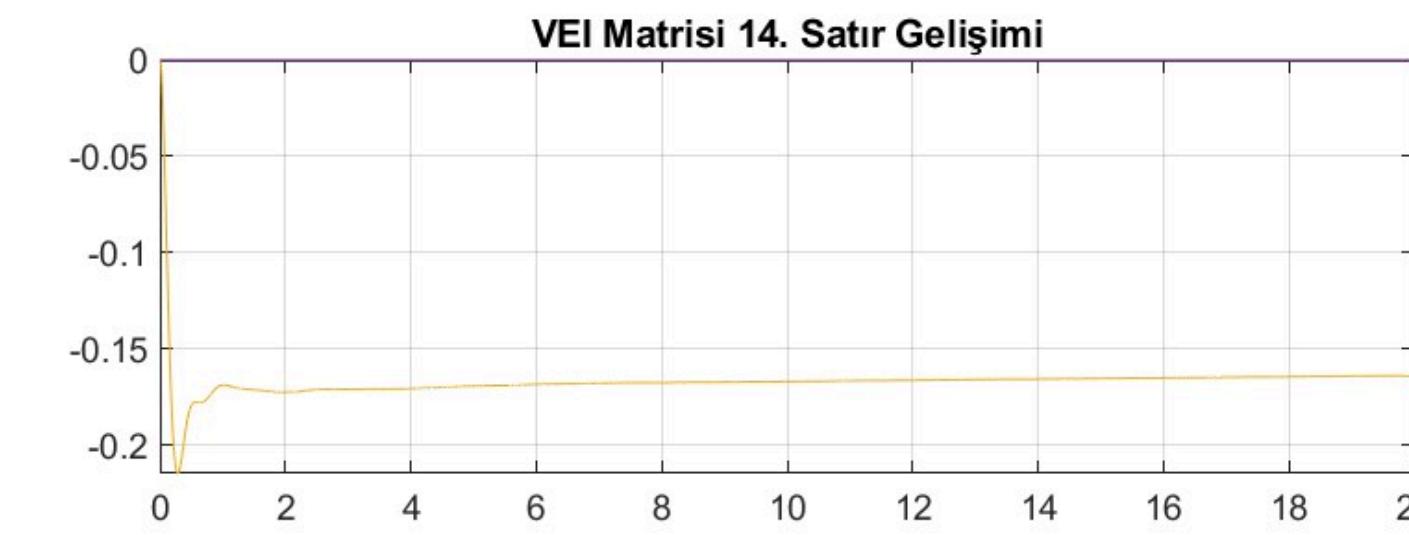
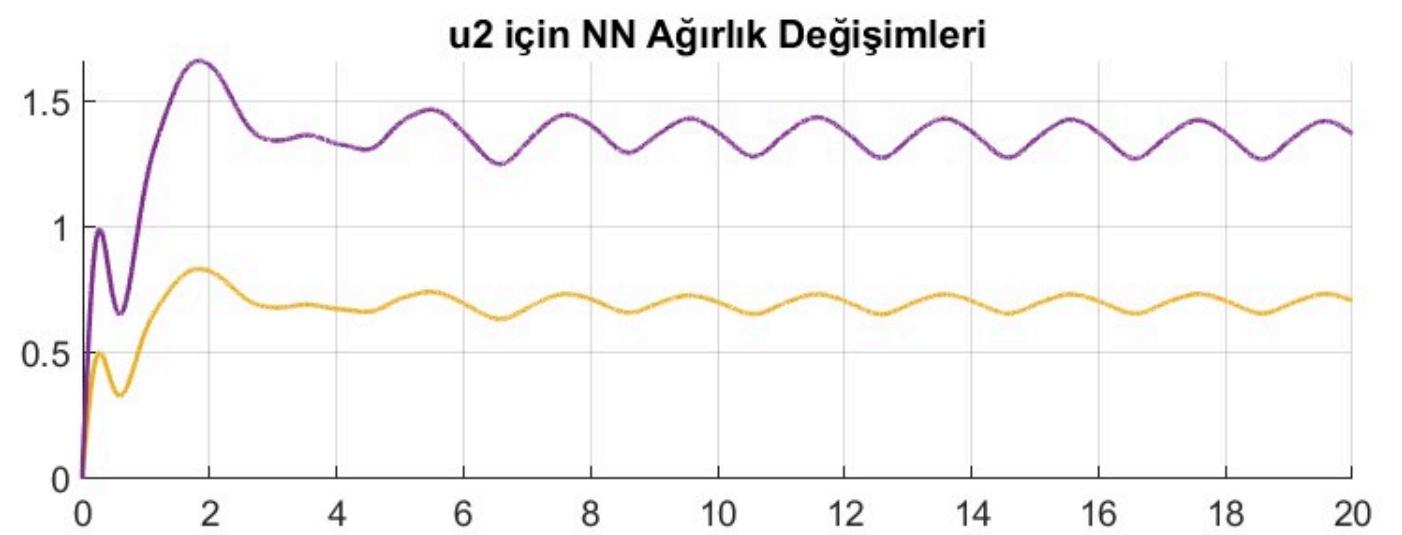
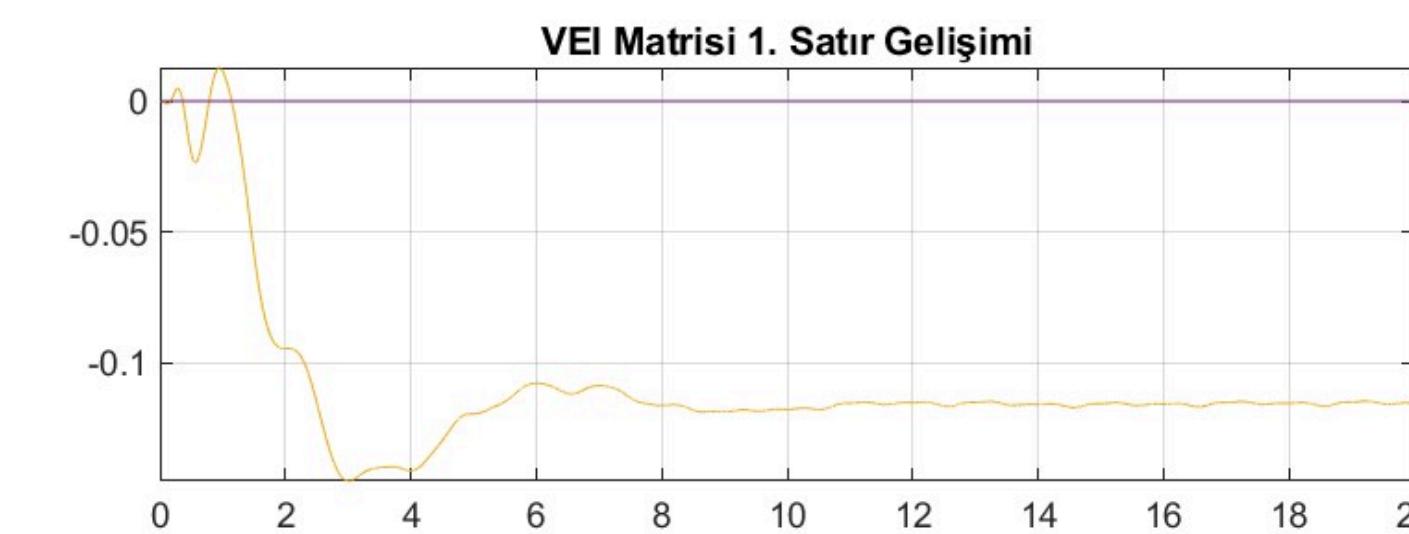
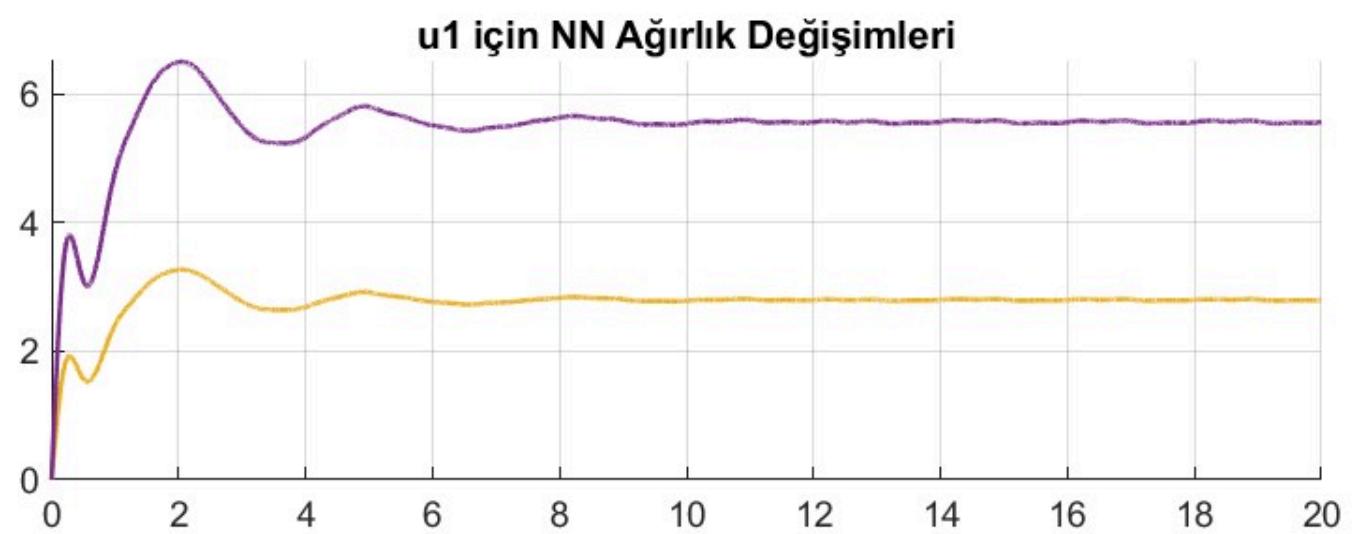
Settling Time: 0.4620 s

Ort. Mutlak Hata (Stable): 0.000773 rad

[Kontrol Sinyalleri Özeti]

u1 stable Ort. Tork: 19.6144 Nm

u2 stable Ort. Tork: 4.9034 Nm



[Neural Network Tüm Final Ağırlıkları]

u1_w1: 2.79698607	u2_w1: 0.70900783
u1_w2: 2.79698607	u2_w2: 0.70900783
u1_w3: 2.79698607	u2_w3: 0.70900783
u1_w4: 2.79698607	u2_w4: 0.70900783
u1_w5: 2.79698607	u2_w5: 0.70900783
u1_w6: 2.79698607	u2_w6: 0.70900783
u1_w7: 2.79698607	u2_w7: 0.70900783
u1_w8: 2.79698607	u2_w8: 0.70900783
u1_w9: 2.79698607	u2_w9: 0.70900783
u1_w10: 2.79698607	u2_w10: 0.70900783
u1_w11: 5.56260431	u2_w11: 1.37071095

[VEI Matrisi Tüm Final Değerleri (14 x 10)]

VEI(1,1): -0.11523086	VEI(1,2): -0.11523086
VEI(1,3): -0.11523086	VEI(1,4): -0.11523086
VEI(1,5): -0.11523086	VEI(1,6): -0.11523086
VEI(1,7): -0.11523086	VEI(1,8): -0.11523086
VEI(1,9): -0.11523086	VEI(1,10): -0.11523086
VEI(14,1): -0.16363944	VEI(14,2): -0.16363944
VEI(14,3): -0.16363944	VEI(14,4): -0.16363944
VEI(14,5): -0.16363944	VEI(14,6): -0.16363944
VEI(14,7): -0.16363944	VEI(14,8): -0.16363944
VEI(14,9): -0.16363944	VEI(14,10): -0.16363944

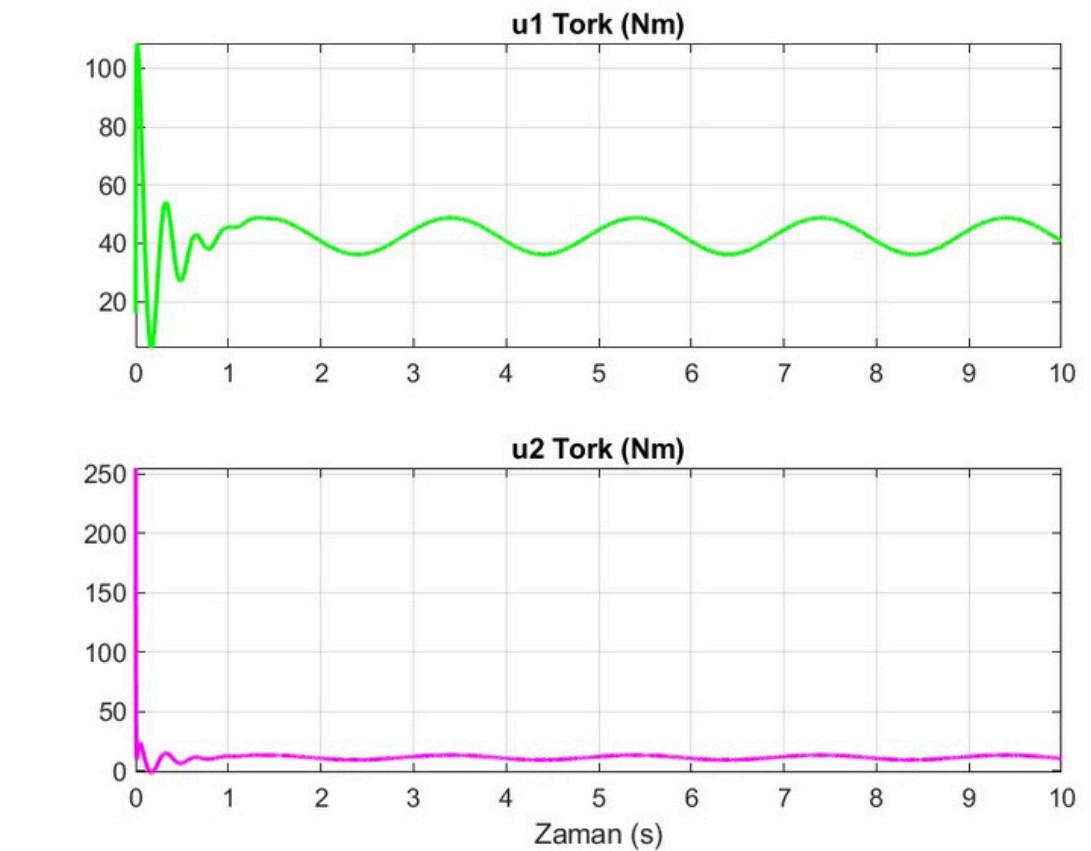
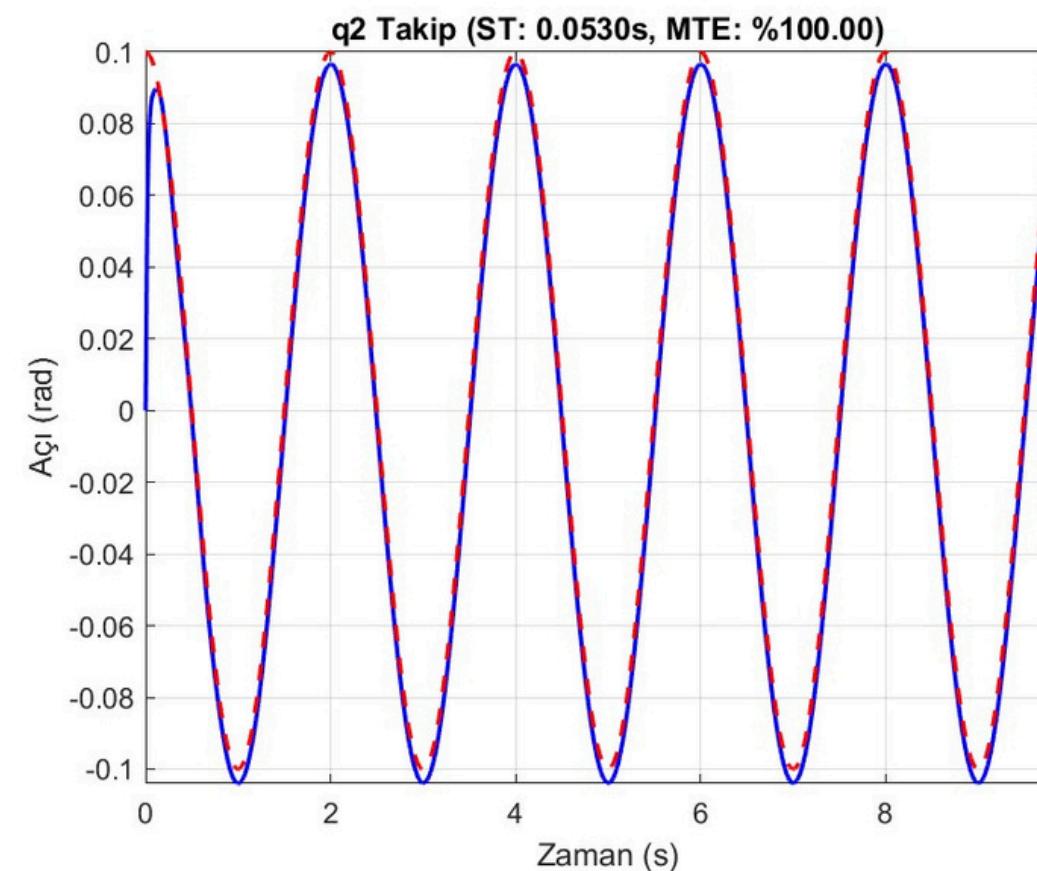
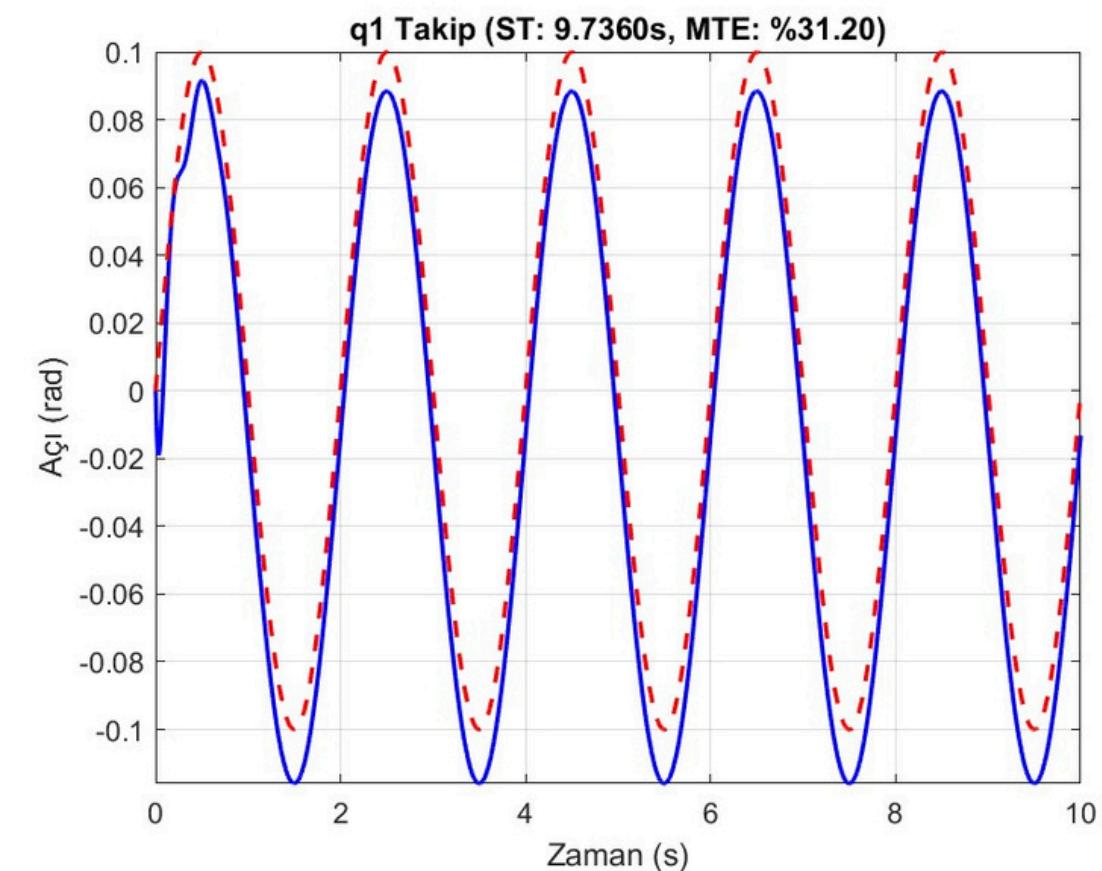
Non ideal Hebbian NN Control

$$\tau = \hat{W}^T \sigma(\hat{V}^T x) + K_v r - v$$

$$v = -K_z (\|\hat{Z}\|_F + Z_B) r$$

$$\dot{\hat{W}} = F \hat{\sigma} r^T - k F \|r\| \hat{W}$$

$$\dot{\hat{V}} = G \|r\| x \hat{\sigma}^T - k G \|r\| \hat{V}$$



[q1 Sonuçları]

Settling Time: 9.7360 s

Ort. Mutlak Hata (Stable): 0.014127 rad

[q2 Sonuçları]

Settling Time: 0.0530 s

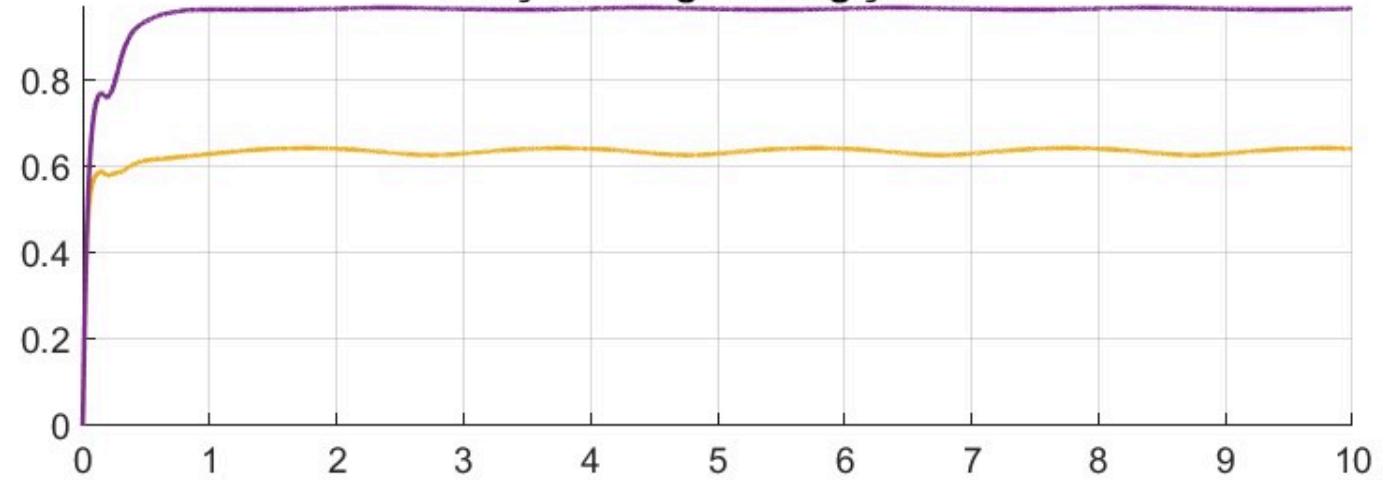
Ort. Mutlak Hata (Stable): 0.003653 rad

[Kontrol Sinyalleri Özeti]

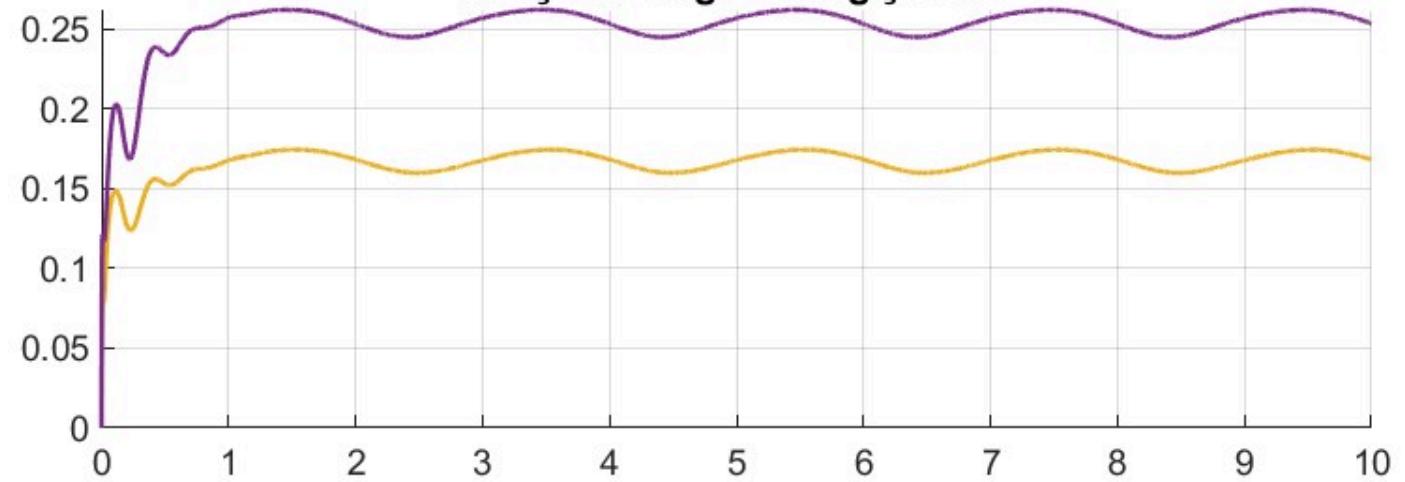
u1 stable Ort. Tork: 43.2427 Nm

u2 stable Ort. Tork: 11.1859 Nm

u1 için NN Ağırlık Değişimleri



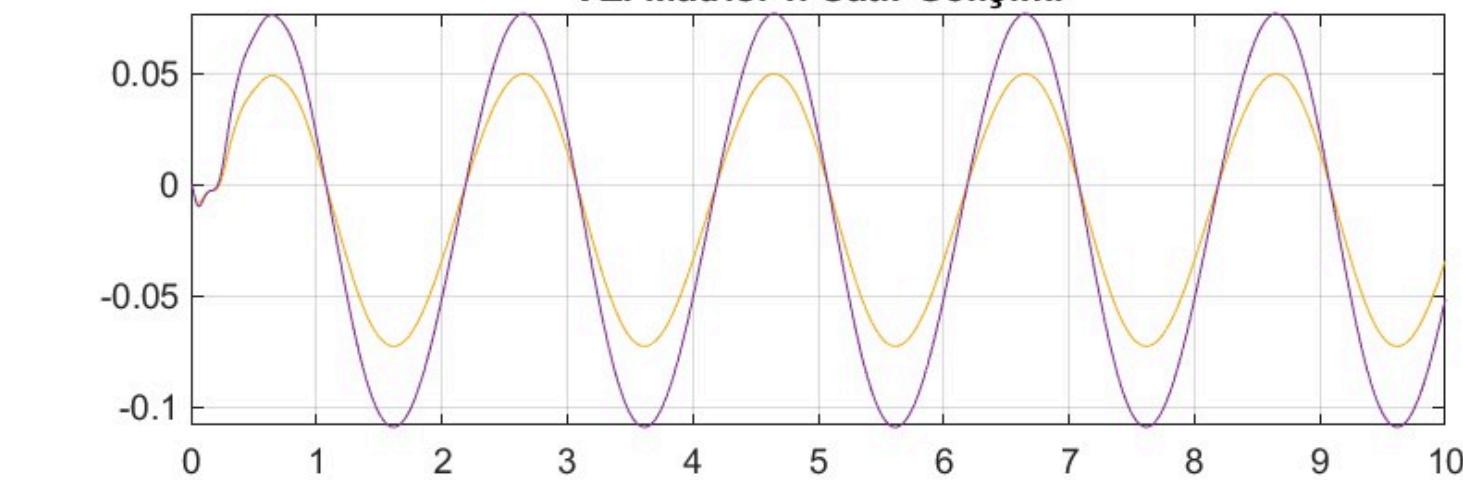
u2 için NN Ağırlık Değişimleri



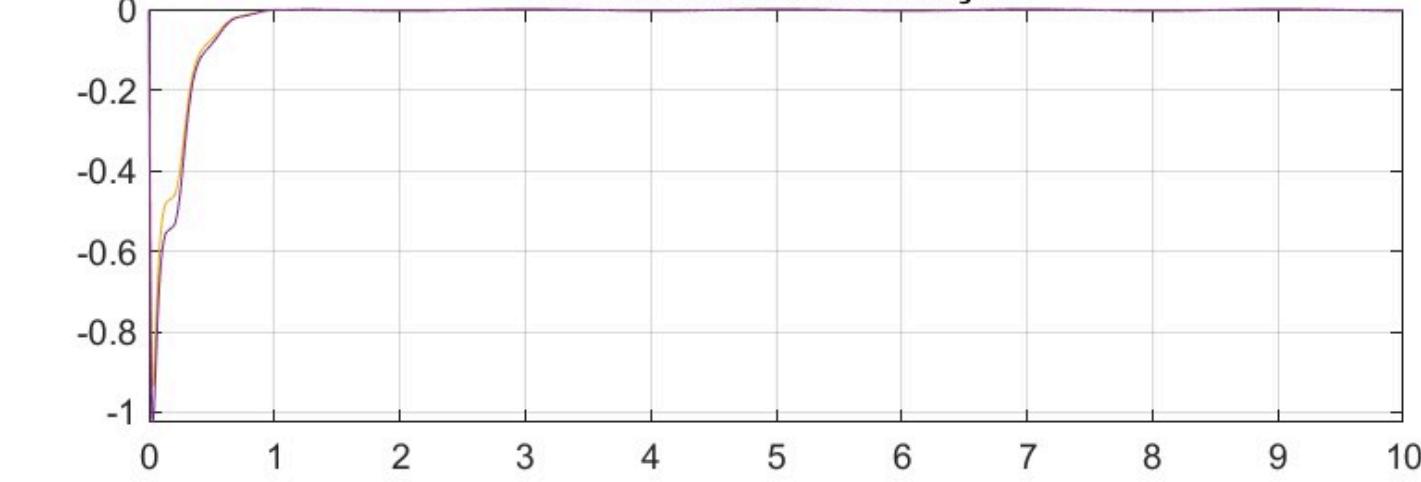
[Neural Network Tüm Final Ağırlıkları]

u1_w1: 0.64248851	u2_w1: 0.16827825
u1_w2: 0.64248851	u2_w2: 0.16827825
u1_w3: 0.64248851	u2_w3: 0.16827825
u1_w4: 0.64248851	u2_w4: 0.16827825
u1_w5: 0.64248851	u2_w5: 0.16827825
u1_w6: 0.64248851	u2_w6: 0.16827825
u1_w7: 0.64248851	u2_w7: 0.16827825
u1_w8: 0.64248851	u2_w8: 0.16827825
u1_w9: 0.64248851	u2_w9: 0.16827825
u1_w10: 0.64248851	u2_w10: 0.16827825
u1_w11: 0.96736528	u2_w11: 0.25335978

VEI Matrisi 1. Satır Gelişimi



VEI Matrisi 14. Satır Gelişimi



[VEI Matrisi Tüm Final Değerleri (14 x 10)]

VEI(1,1): -0.03419445	VEI(1,2): -0.03419445
VEI(1,3): -0.03419445	VEI(1,4): -0.03419445
VEI(1,5): -0.03419445	VEI(1,6): -0.03419445
VEI(1,7): -0.03419445	VEI(1,8): -0.03419445
VEI(1,9): -0.03419445	VEI(1,10): -0.03419445
VEI(14,1): -0.00143818	VEI(14,2): -0.00143818
VEI(14,3): -0.00143818	VEI(14,4): -0.00143818
VEI(14,5): -0.00143818	VEI(14,6): -0.00143818
VEI(14,7): -0.00143818	VEI(14,8): -0.00143818
VEI(14,9): -0.00143818	VEI(14,10): -0.00143818

1D KALMAN FILTER

$$K_t = \frac{E_{est_t}}{E_{est_t} + E_{mea}}$$

$$\hat{x}_{t+1} = \hat{x}_t + K_t(z_t - \hat{x}_t)$$

$$E_{est_{t+1}} = (1 - K_t)E_{est_t}$$

