Dinamik Dengeleme Çalışmaları

Doç. Dr. Gökhan Kiper

20-21 Kasım 2019

ODTÜ Makina Mühendisliği Bölümü, Ankara

Statik Dengeleme

Bir mekanizmada uzuvların ağırlığı ve esnekliği gibi etmenlerin dengelenerek mekanizmanın herhangi bir konumda statik dengede kalabilmesi için statik dengeleme yapılır.

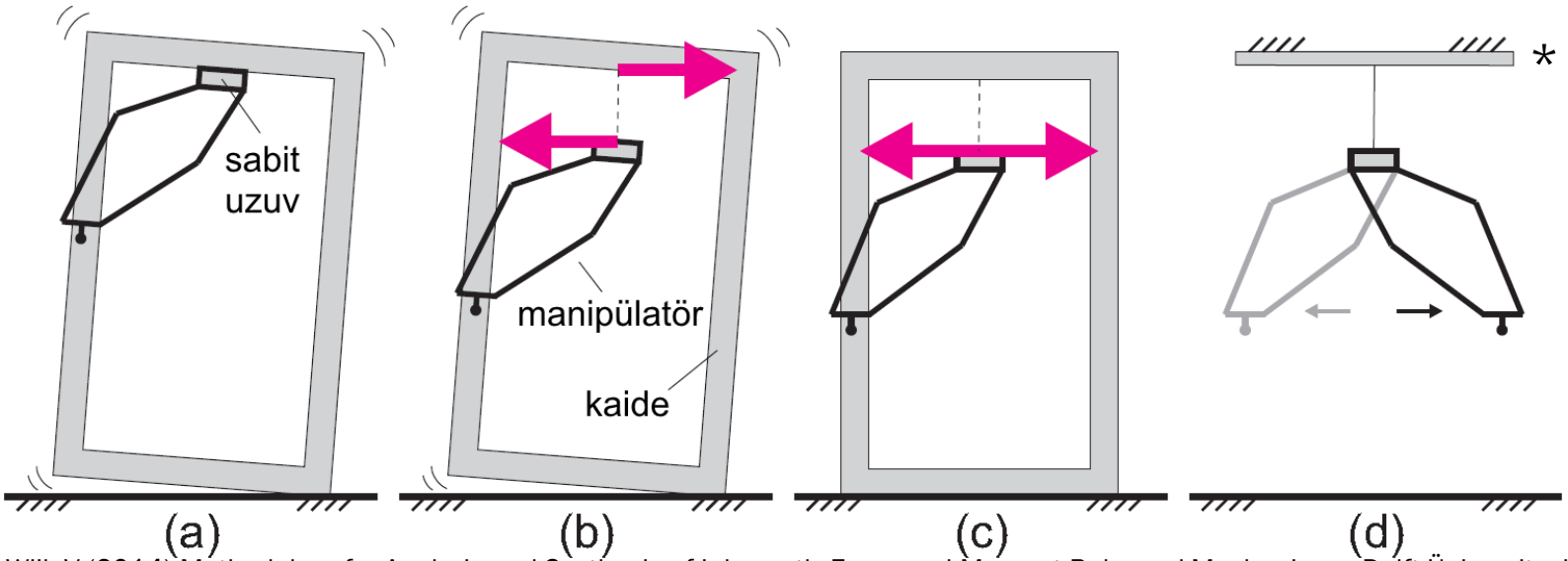
STATİK DENGELEME = SABİT SİSTEM POTANSİYEL ENERJİSİ

Statik dengelemede iki yaygın yöntem karşıt kütleler ile dengeleme ve yaylar ile dengelemedir.

Dinamik Dengeleme

Bir mekanizmada uzuvların atalet kuvvet/momentlerinden dolayı kaide oluşan sarsma kuvvet/momentlerini sıfırlamaya dinamik dengeleme denir.

DİNAMİK DENGELEME = SABİT SİSTEM MOMENTUMU



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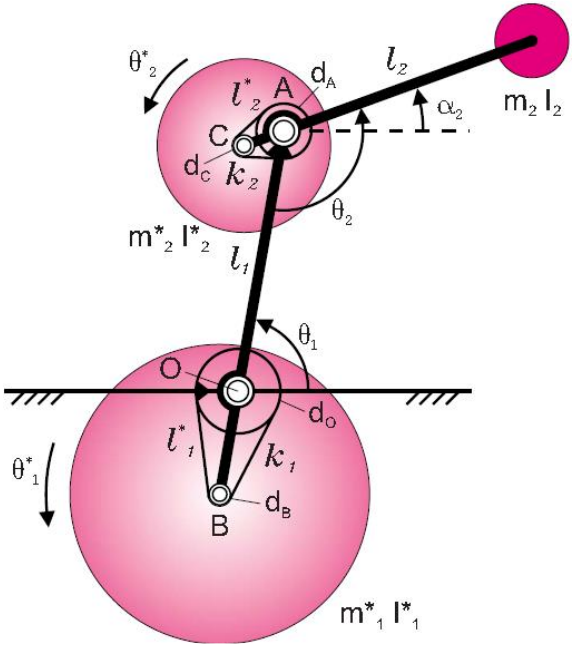
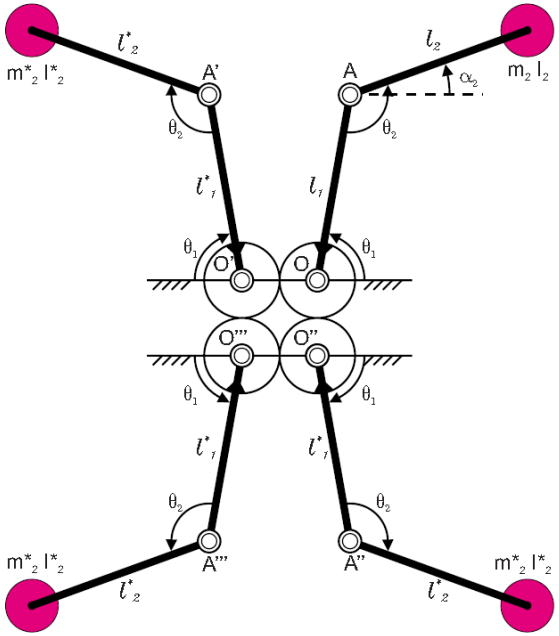
Dengelenmemiş manipülatör (a) kaidede sarsma kuvvet ve momentleri meydana getirir (b). Dinamik dengeleme ile sarsma etkileri sıfırlanabilirse manipülatör bir ipe bağlı olarak bile yüksek ivmelerde çok hassas çalışabilir.

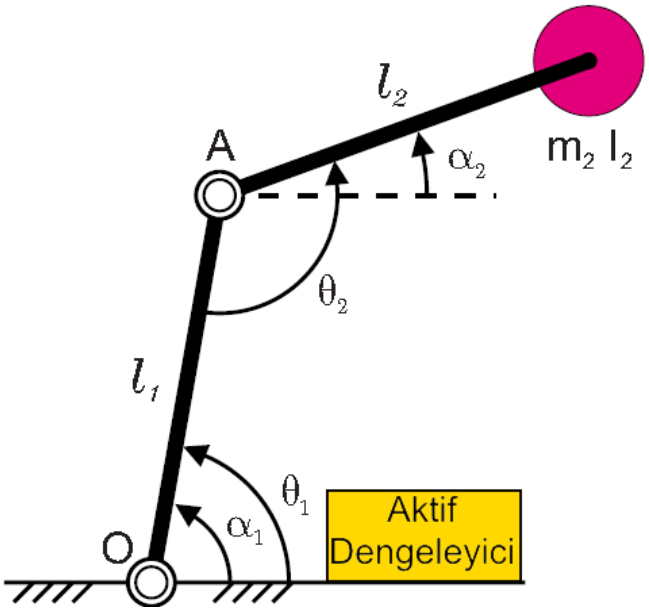
Dinamik Dengeleme Yöntemleri



Karşıt kütle/atalet momenti ile dengeleme



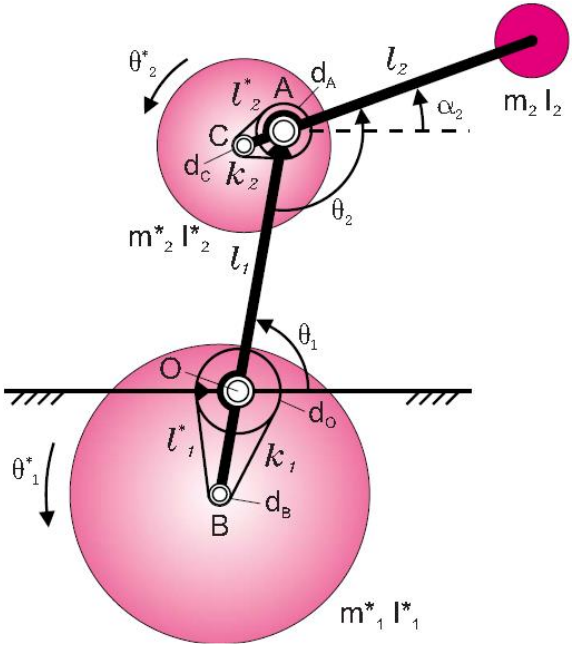
Mekanizma ayna görüntüsü ile dengeleme



Aktif dengeleme

Van der Wijk V, Herder J, Demeulenaere B (2009) Comparison of Various Dynamic Balancing Principles Regarding Additional Mass and Additional Inertia. J Mechanisms and Robotics, 1, 041006.

Dinamik Dengeleme Yöntemleri



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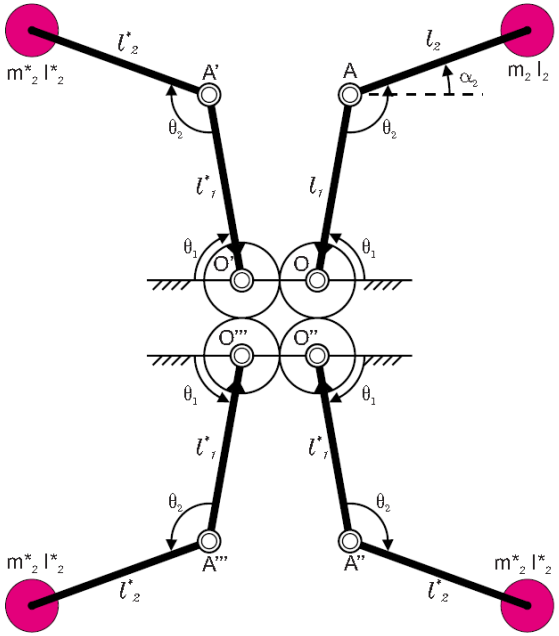

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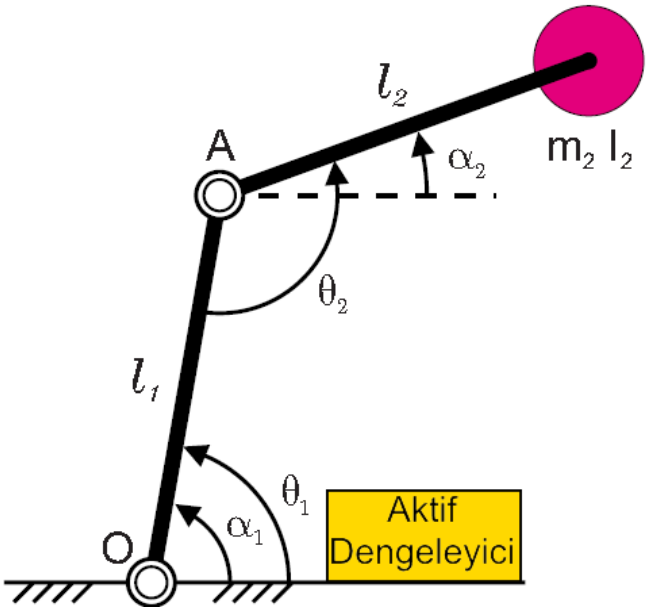

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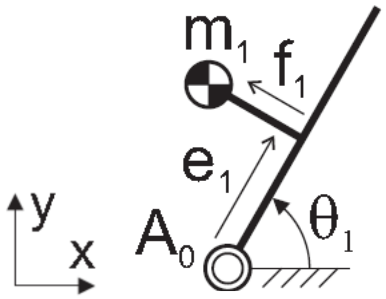
Seri Zincirlerin Dengelenmesi



$$\bar{r}_1 = \begin{bmatrix} r_{1x} \\ r_{1y} \end{bmatrix} = \bar{A}_0 + \begin{bmatrix} e_1 \cos\theta_1 - f_1 \sin\theta_1 \\ e_1 \sin\theta_1 + f_1 \cos\theta_1 \end{bmatrix}$$

Lineer momentum: $\bar{L} = m_1 \dot{\bar{r}}_1 = \begin{bmatrix} -m_1 e_1 \sin\theta_1 - m_1 f_1 \cos\theta_1 \\ m_1 e_1 \cos\theta_1 - m_1 f_1 \sin\theta_1 \end{bmatrix} \dot{\theta}_1 = \begin{bmatrix} C_1 \\ C_2 \end{bmatrix}$

Dinamik kuvvet dengesi koşulu: $m_1 e_1 = 0 \quad m_1 f_1 = 0$

Ya uzuv baştan bu şekilde tasarlanır, ya da karşıt kütle ile dengeleme yapılır. Karşıt kütle dengelemesi sonrasında moment dengesi olumsuz etkilenir

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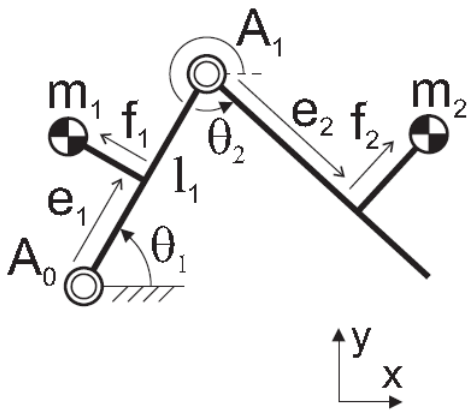
Seri Zincirlerin Dengelenmesi



$$\bar{r}_1 = \begin{bmatrix} r_{1x} \\ r_{1y} \end{bmatrix} = \bar{A}_0 + \begin{bmatrix} e_1 \cos\theta_1 - f_1 \sin\theta_1 \\ e_1 \sin\theta_1 + f_1 \cos\theta_1 \end{bmatrix}$$

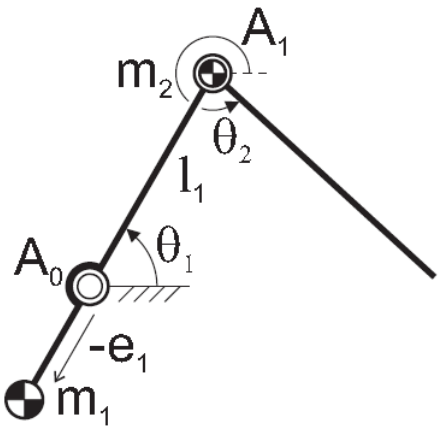
$$\bar{r}_2 = \begin{bmatrix} r_{2x} \\ r_{2y} \end{bmatrix} = \bar{A}_0 + \begin{bmatrix} l_1 \cos\theta_1 + e_2 \cos\theta_2 - f_2 \sin\theta_2 \\ l_1 \sin\theta_1 + e_2 \sin\theta_2 + f_2 \cos\theta_2 \end{bmatrix}$$

Lineer momentum:

$$\bar{L} = m_1 \dot{\bar{r}}_1 + m_2 \dot{\bar{r}}_2 = \begin{bmatrix} -(m_1 e_1 + m_2 l_1)\sin\theta_1 - m_1 f_1 \cos\theta_1 \\ (m_1 e_1 + m_2 l_1)\cos\theta_1 - m_1 f_1 \sin\theta_1 \end{bmatrix} \dot{\theta}_1 + \begin{bmatrix} -m_2 e_2 \sin\theta_2 - m_2 f_2 \cos\theta_2 \\ m_2 e_2 \cos\theta_2 - m_2 f_2 \sin\theta_2 \end{bmatrix} \dot{\theta}_2 = \begin{bmatrix} C_1 \\ C_2 \end{bmatrix}$$

Dinamik kuvvet dengesi koşulları:

$$m_1 e_1 + m_2 l_1 = 0 \quad m_1 f_1 = 0$$
$$m_2 e_2 = 0 \quad m_2 f_2 = 0$$



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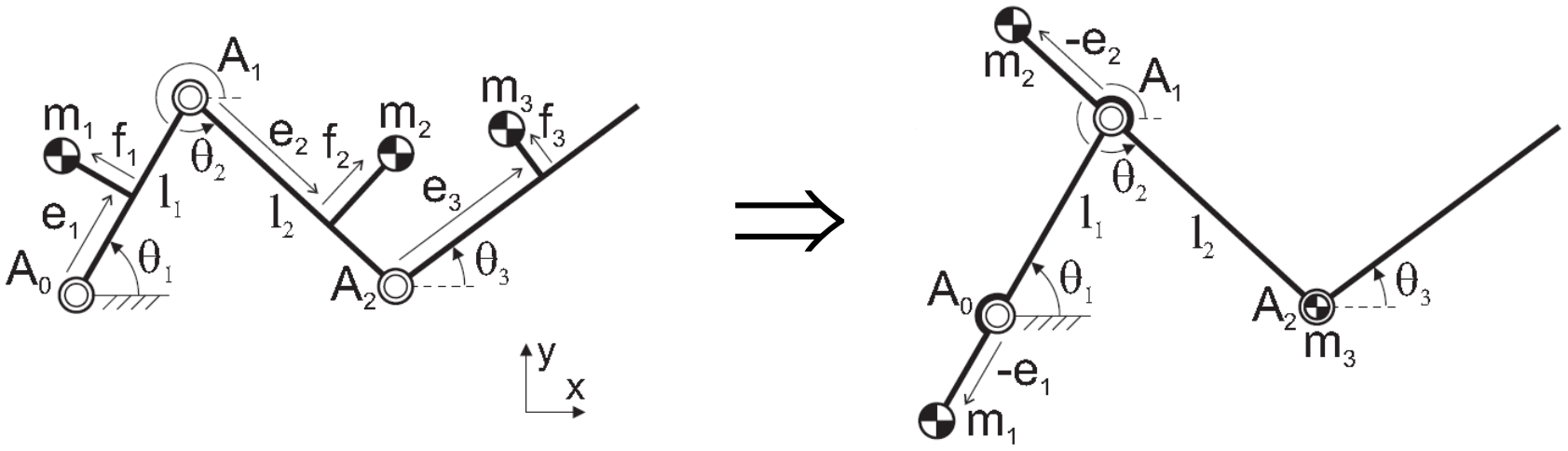

3 uzvunun kütle merkezi A_2 mafsalında (m_2), 2 ve 3 uzuvlarının toplam kütle merkezi A_1 mafsalında ($m_2 + m_3$), 1, 2 ve 3 uzuvlarının toplam kütle merkezi A_0 mafsalında ($m_1 + m_2 + m_3$) olmalı.

$$m_1 e_1 + m_2 l_1 + m_3 l_1 = 0 \quad m_1 f_1 = 0$$
$$m_2 e_2 + m_3 l_2 = 0 \quad m_2 f_2 = 0$$
$$m_3 e_3 = 0 \quad m_3 f_3 = 0$$

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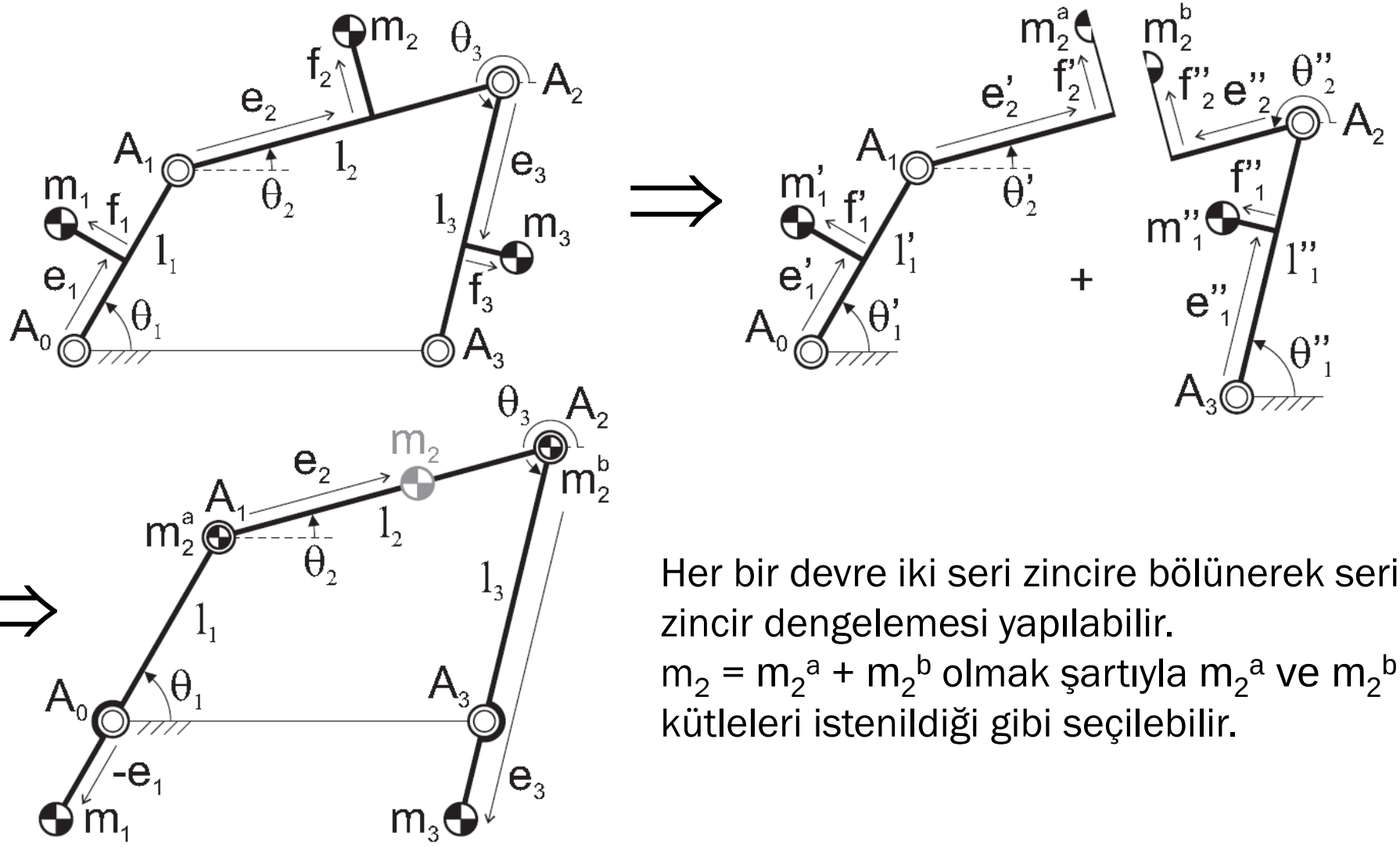
Kapalı Zincirlerin Dengelenmesi



Her bir devre iki seri zincire bölünerek seri zincir dengelemesi yapılabilir.

$m_2 = m_2^a + m_2^b$ olmak şartıyla m_2^a ve m_2^b kütleleri istenildiği gibi seçilebilir.

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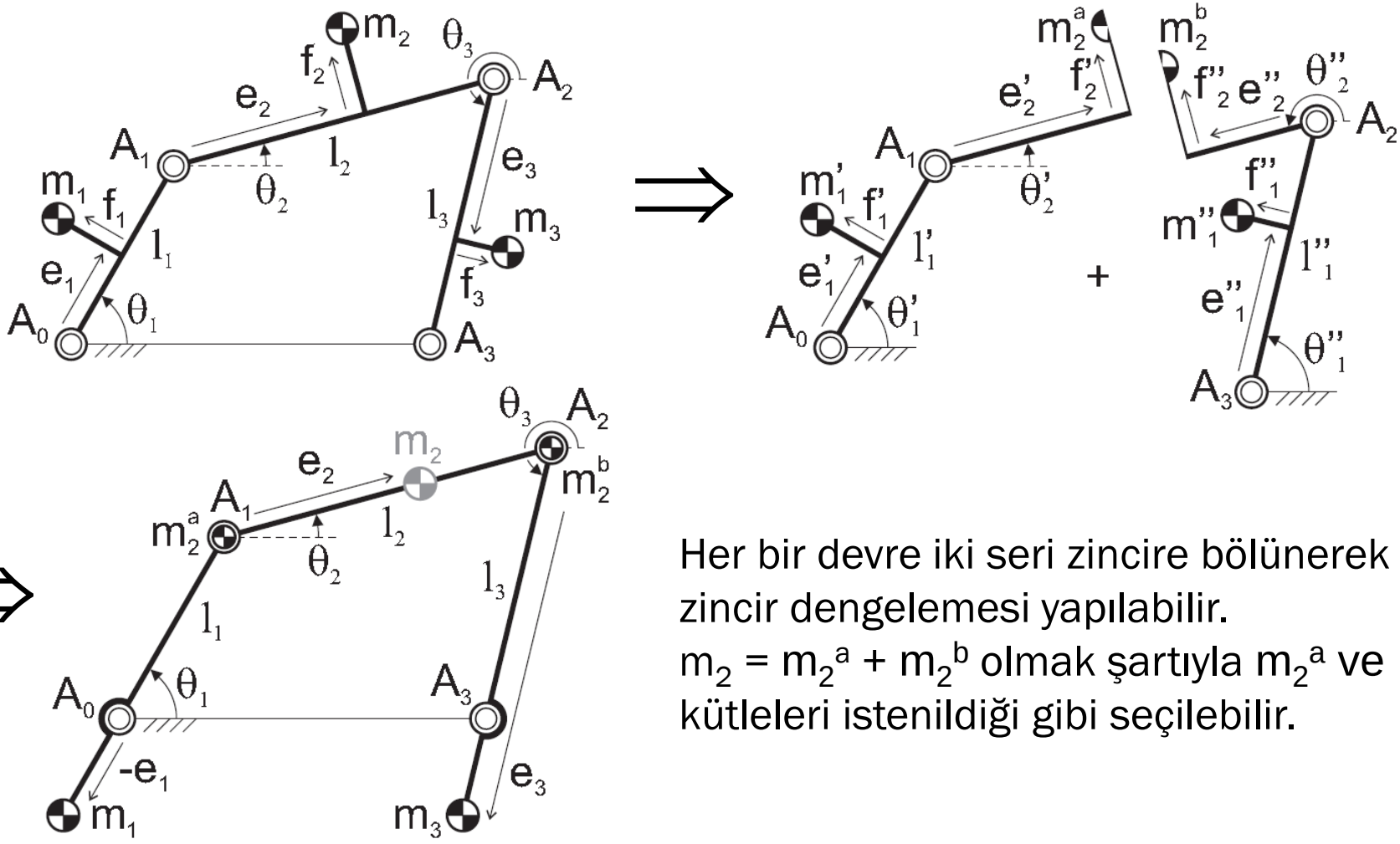
Kapalı Zincirlerin Dengelenmesi
Yöntem 1: seri zincirlere bölme



Her bir devre iki seri zincire bölünerek seri zincir dengelemesi yapılabilir.

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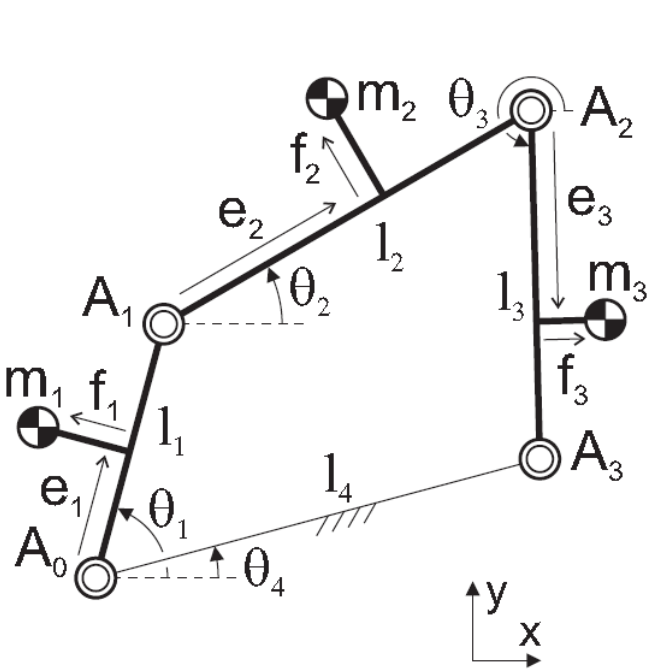
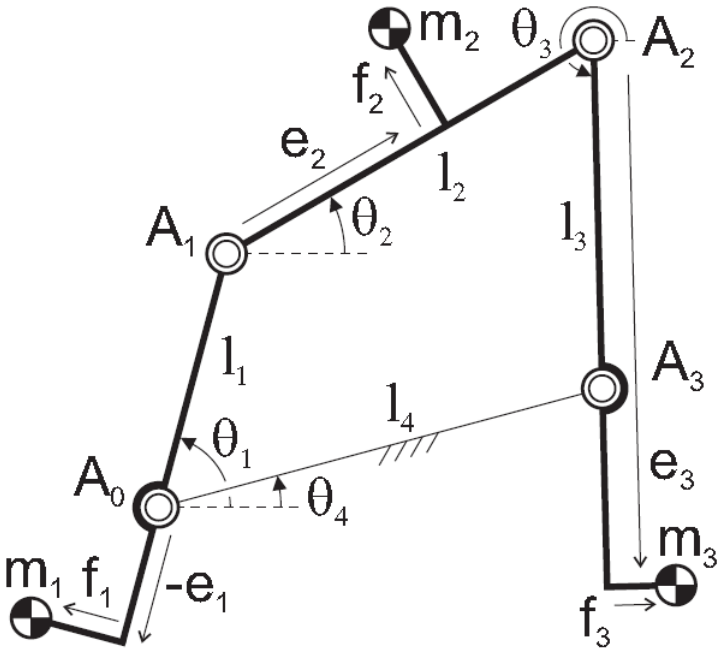
Kapalı Zincirlerin Dengelenmesi
Yöntem 2: devre kapalılık denklemi





$$\bar{L} = \begin{bmatrix} -(m_1 e_1 + m_2 l_1 + m_3 l_1)\sin\theta_1 - m_1 f_1 \cos\theta_1 \\ (m_1 e_1 + m_2 l_1 + m_3 l_1)\cos\theta_1 - m_1 f_1 \sin\theta_1 \end{bmatrix} \dot{\theta}_1 +$$
$$\begin{bmatrix} -(m_2 e_2 + m_3 l_2)\sin\theta_2 - m_2 f_2 \cos\theta_2 \\ (m_2 e_2 + m_3 l_2)\cos\theta_2 - m_2 f_2 \sin\theta_2 \end{bmatrix} \dot{\theta}_2 +$$
$$\begin{bmatrix} -m_3 e_3 \sin\theta_3 - m_3 f_3 \cos\theta_3 \\ m_3 e_3 \cos\theta_3 - m_3 f_3 \sin\theta_3 \end{bmatrix} \dot{\theta}_3$$

Devre kapalılık denklemi ve türevi:

$$l_1\cos\theta_1 + l_2\cos\theta_2 + l_3\cos\theta_3 - l_4\cos\theta_4 = 0$$
$$l_1\sin\theta_1 + l_2\sin\theta_2 + l_3\sin\theta_3 - l_4\sin\theta_4 = 0$$

$$\sin\theta_2\dot{\theta}_2 = -\frac{l_1}{l_2}\sin\theta_1\dot{\theta}_1 - \frac{l_3}{l_2}\sin\theta_3\dot{\theta}_3$$
$$\cos\theta_2\dot{\theta}_2 = -\frac{l_1}{l_2}\cos\theta_1\dot{\theta}_1 - \frac{l_3}{l_2}\cos\theta_3\dot{\theta}_3$$

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Kapalı Zincirlerin Dengelenmesi
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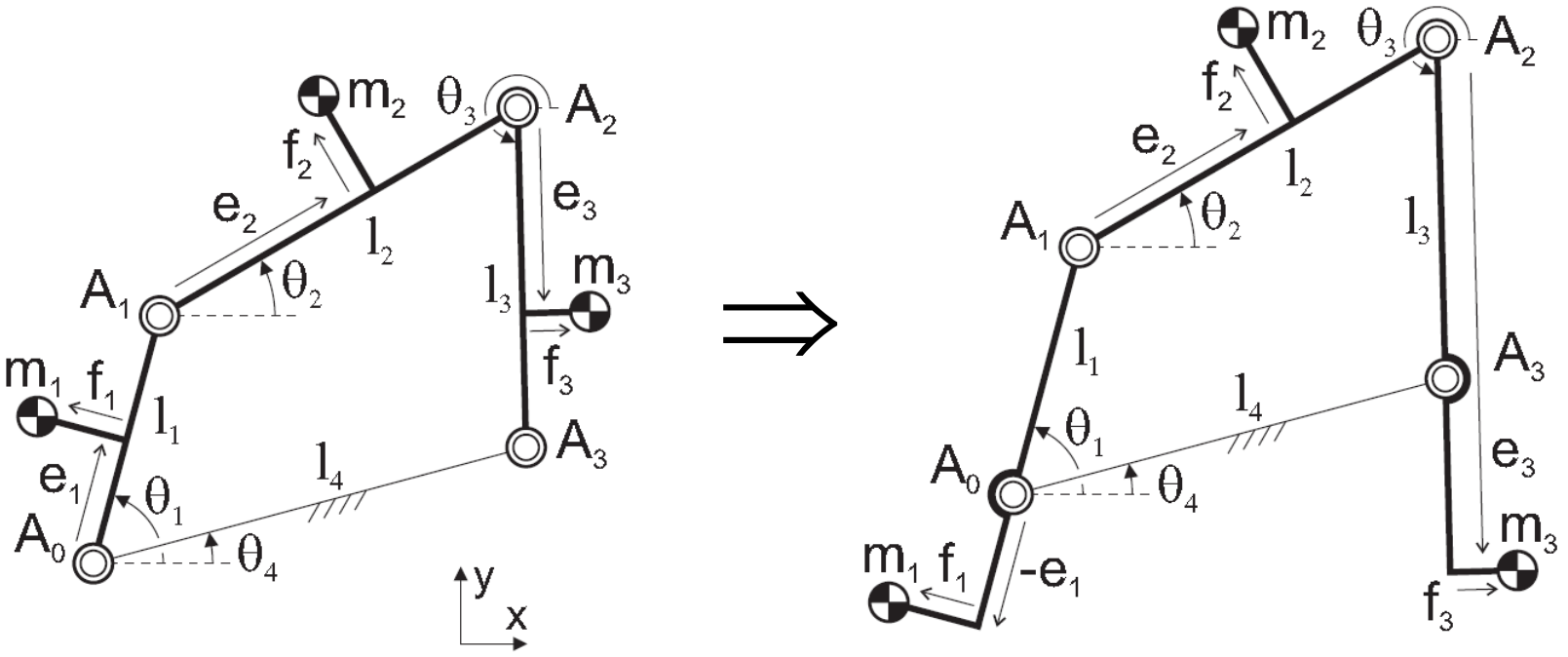

$$\overline{L} = \begin{bmatrix} -(m_1 e_1 + m_2(1-\frac{e_2}{l_2})l_1)\sin\theta_1 - (m_1 f_1 - m_2 \frac{f_2}{l_2} l_1)\cos\theta_1 \\ (m_1 e_1 + m_2(1-\frac{e_2}{l_2})l_1)\cos\theta_1 - (m_1 f_1 - m_2 \frac{f_2}{l_2} l_1)\sin\theta_1 \end{bmatrix} \dot{\theta}_1 + \begin{bmatrix} (m_3(l_3-e_3) + m_2 \frac{e_2}{l_2} l_3)\sin\theta_3 - (m_3 f_3 - m_2 \frac{f_2}{l_2} l_3)\cos\theta_3 \\ -(m_3(l_3-e_3) + m_2 \frac{e_2}{l_2} l_3)\cos\theta_3 - (m_3 f_3 - m_2 \frac{f_2}{l_2} l_3)\sin\theta_3 \end{bmatrix} \dot{\theta}_3$$

Dinamik kuvvet dengesi koşulları:

$$m_1 e_1 + m_2(1-\frac{e_2}{l_2})l_1 = 0 \qquad m_1 f_1 - m_2 \frac{f_2}{l_2} l_1 = 0$$
$$m_3(l_3-e_3) + m_2 \frac{e_2}{l_2} l_3 = 0 \qquad m_3 f_3 - m_2 \frac{f_2}{l_2} l_3 = 0$$

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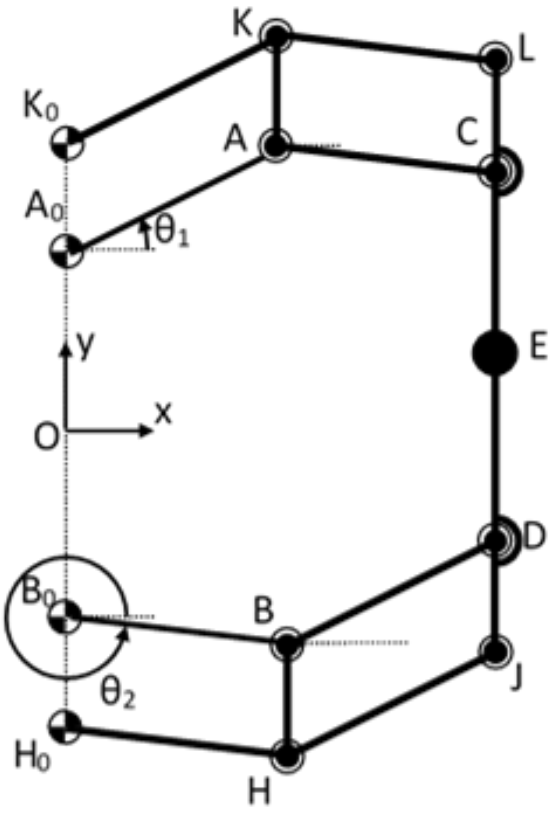
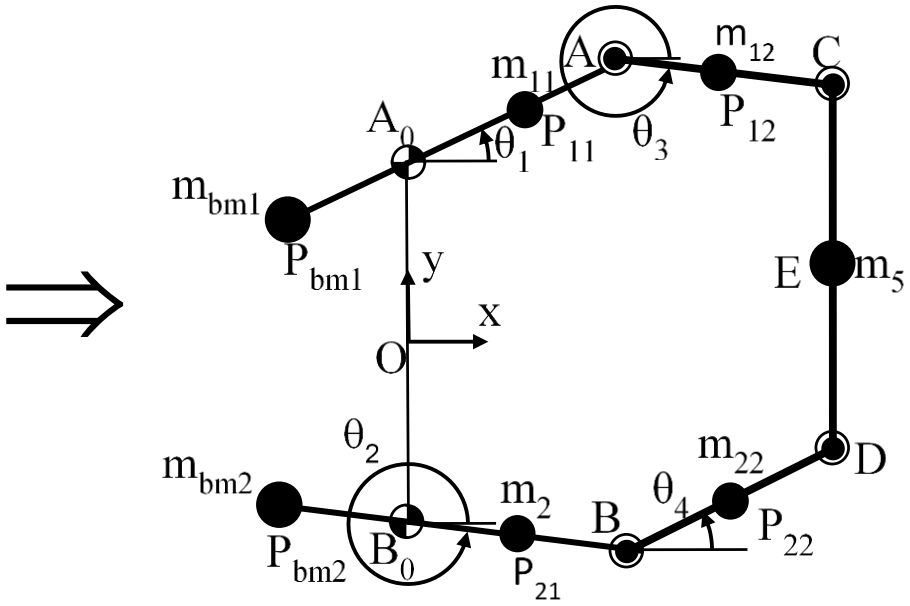
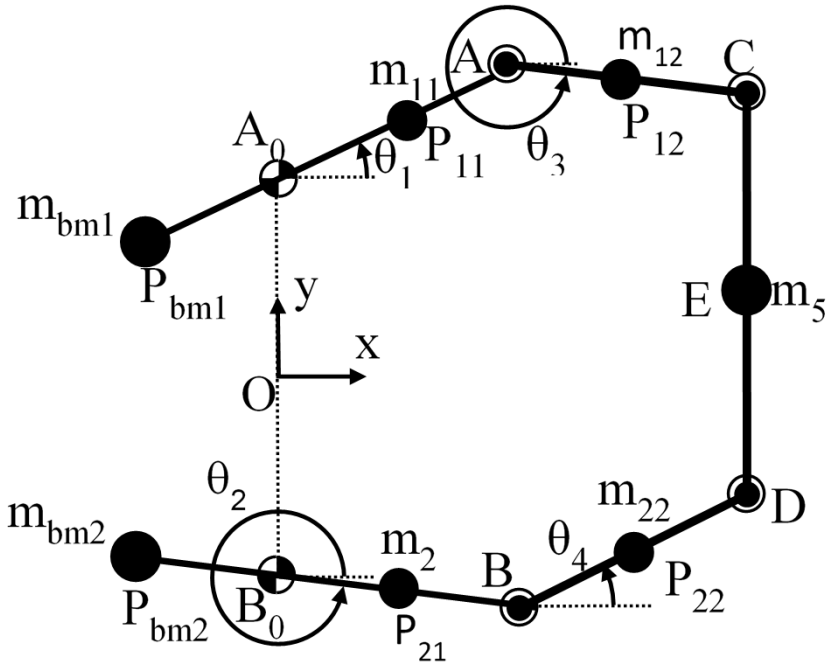
Paralelkenarlı 6-çubuk mekanizması





Paralel uzuvların momentum değişimleri kümülatif olacağından yan kollar (H_0H, HJ, K_0K, KL) iç kollara toplanmıştır. Ara kolların ise (AK ve BH) kütleleri yarım yarım olarak iç kollara toplanmıştır.

Paralelkenarlı 6-çubuk mekanizması



$|A_0P_{bm1}|=|B_0P_{bm2}|=p_{bm}$

$|A_0B_0|=|CD|=a$

$|A_0P_{11}|=|B_0P_{21}|=p_1$

$|AP_{12}|=|BP_{22}|=p_2$

$m_{11}=m_{21}=m_1$

$m_{12}=m_{22}=m_2$

$m_{bm1}=m_{bm2}=m_{bm}$

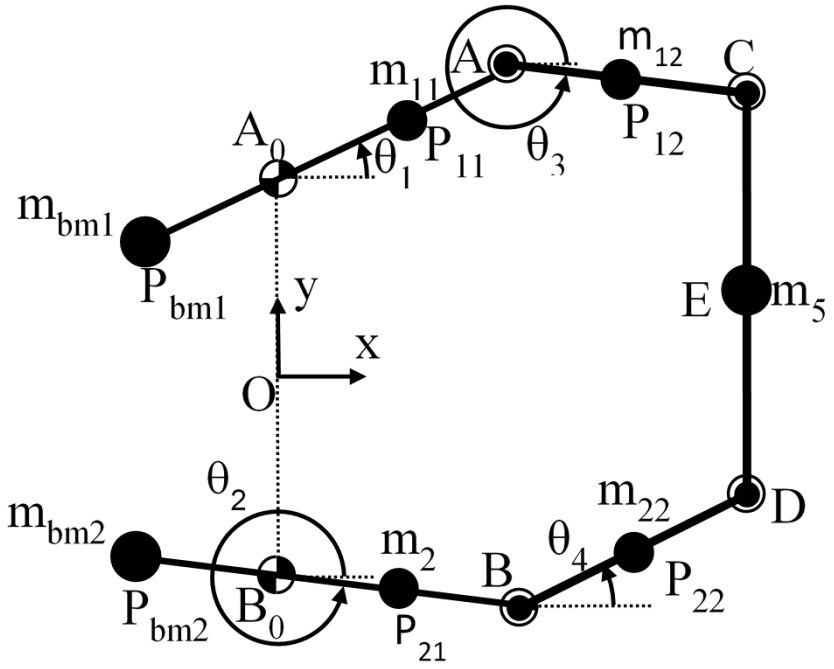
$\theta_4 = \theta_1,\ \theta_3 = \theta_2$

$$\overline{r_{P_{11}}} = p_1 e^{i\theta_1} = \begin{bmatrix} p_1 c\theta_1 \\ p_1 s\theta_1 \end{bmatrix} \Rightarrow \dot{\overline{r_{P_{11}}}} = \begin{bmatrix} -p_1 s\theta_1\dot{\theta}_1 \\ p_1 c\theta_1\dot{\theta}_1 \end{bmatrix} \;;\; \overline{r_{P_{12}}} = re^{i\theta_1} + p_2 e^{i\theta_2} = \begin{bmatrix} rc\theta_1 + p_2 c\theta_2 \\ rs\theta_1 + p_2 s\theta_2 \end{bmatrix} \Rightarrow \dot{\overline{r_{P_{12}}}} = \begin{bmatrix} -rs\theta_1\dot{\theta}_1 - p_2 s\theta_2\dot{\theta}_2 \\ rc\theta_1\dot{\theta}_1 + p_2 c\theta_2\dot{\theta}_2 \end{bmatrix}$$

$$\overline{r_{P_{21}}} = p_1 e^{i\theta_2} = \begin{bmatrix} p_1 c\theta_2 \\ p_1 s\theta_2 \end{bmatrix} = \dot{\overline{r_{P_{21}}}} = \begin{bmatrix} -p_1 s\theta_2\dot{\theta}_2 \\ p_1 c\theta_2\dot{\theta}_2 \end{bmatrix} \;;\; \overline{r_{P_{22}}} = re^{i\theta_2} + p_2 e^{i\theta_1} = \begin{bmatrix} rc\theta_2 + p_2 c\theta_1 \\ rs\theta_2 + p_2 s\theta_1 \end{bmatrix} \Rightarrow \dot{\overline{r_{P_{22}}}} = \begin{bmatrix} -rs\theta_2\dot{\theta}_2 - p_2 s\theta_1\dot{\theta}_1 \\ rc\theta_2\dot{\theta}_2 + p_2 c\theta_1\dot{\theta}_1 \end{bmatrix}$$

$$\overline{r_5} = re^{i\theta_1} + re^{i\theta_2} = \begin{bmatrix} rc\theta_1 + rc\theta_2 \\ rs\theta_1 + rs\theta_2 \end{bmatrix} \Rightarrow \dot{\overline{r_5}} = \begin{bmatrix} -rs\theta_1\dot{\theta}_1 - rs\theta_2\dot{\theta}_2 \\ rc\theta_1\dot{\theta}_1 + rc\theta_2\dot{\theta}_2 \end{bmatrix} \;;\; \overline{L} = m_1\dot{\overline{r_{P_{11}}}} + m_2\dot{\overline{r_{P_{12}}}} + m_5\dot{\overline{r_5}} + m_1\dot{\overline{r_{P_{21}}}} + m_2\dot{\overline{r_{P_{22}}}}$$

Paralelkenarlı 6-çubuk mekanizması



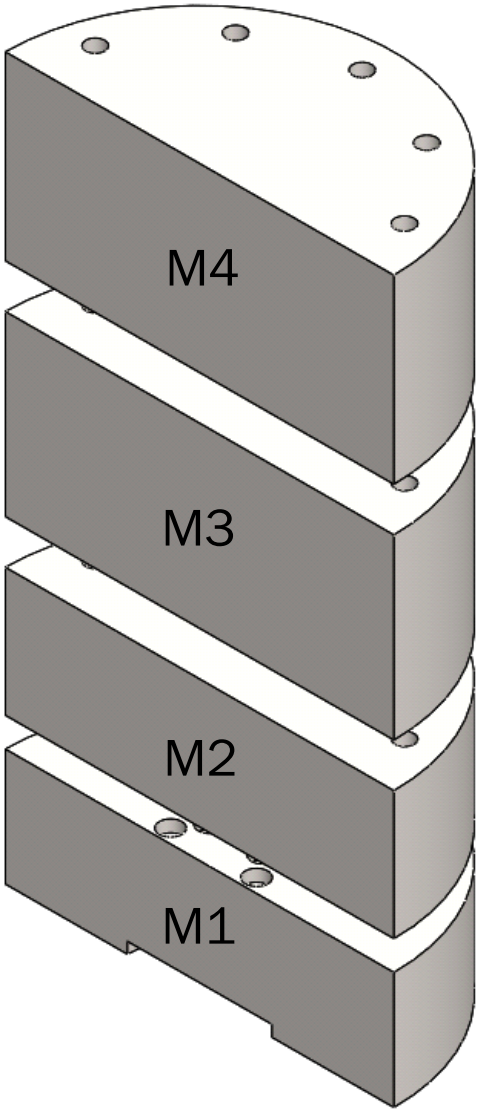
$|A_0P_{bm1}|=|B_0P_{bm2}|=p_{bm}$
$|A_0B_0|=|CD|=a$
$|A_0P_{11}|=|B_0P_{21}|=p_1$
$|AP_{12}|=|BP_{22}|=p_2$
$m_{11}=m_{21}=m_1$
$m_{12}=m_{22}=m_2$
$m_{bm1}=m_{bm2}=m_{bm}$

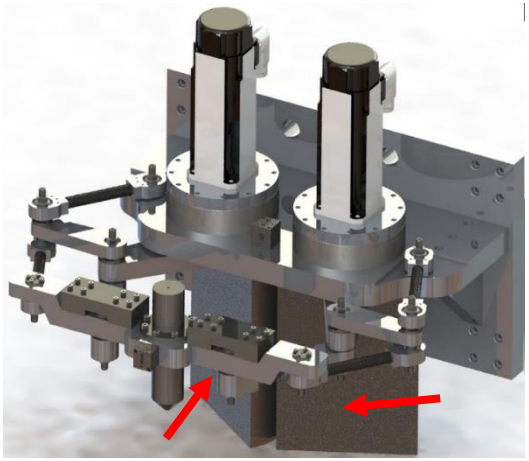
$$\bar{L}=m_1\dot{\bar{r}}_{P_{11}}+m_2\dot{\bar{r}}_{P_{12}}+m_5\dot{\bar{r}}_5+m_1\dot{\bar{r}}_{P_{21}}+m_2\dot{\bar{r}}_{P_{22}}$$

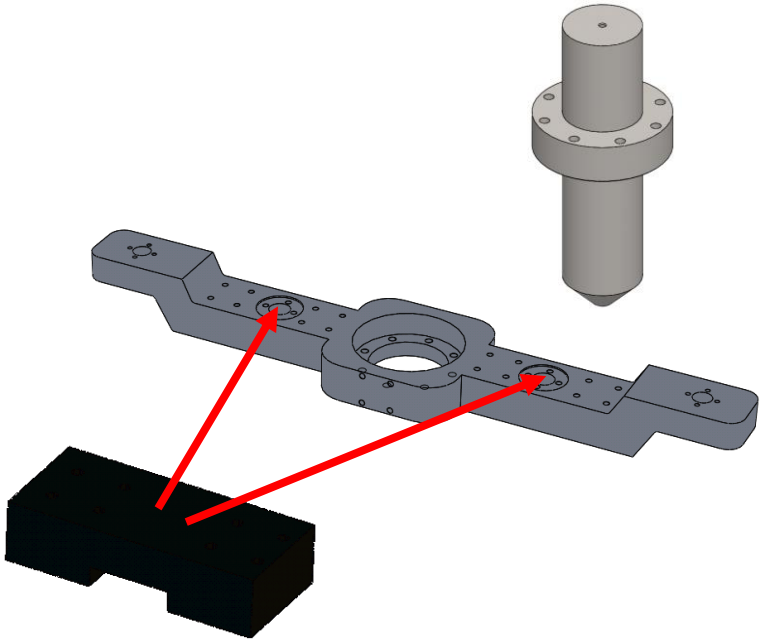
$$=\begin{bmatrix}(-m_1p_1-(m_2+m_5)r-m_2p_2)\sin\theta_1\\(m_1p_1+(m_2+m_5)r+m_2p_2)\cos\theta_1\end{bmatrix}\dot{\theta}_1+\begin{bmatrix}(-m_2p_2-(m_5+m_2)r-m_1p_1)\sin\theta_2\\(m_2p_2+(m_5+m_2)r+m_1p_1)\cos\theta_2\end{bmatrix}\dot{\theta}_2$$

$$\bar{L}=\sum_{i=1}^{2}m_{bm}\dot{\bar{r}}_{b_{mi}}=\begin{bmatrix}m_{bm}p_{bm}\sin\theta_1\\-m_{bm}p_{bm}\cos\theta_1\end{bmatrix}\dot{\theta}_1+\begin{bmatrix}m_{bm}p_{bm}\sin\theta_2\\-m_{bm}p_{bm}\cos\theta_2\end{bmatrix}\dot{\theta}_2\Rightarrow m_1p_1+(m_2+m_5)r+m_2p_2=-m_{bm}p_{bm}$$

Dengeleme Kütleleri Tasarımı







M1 + M2: Sadece platform dengeleme
M1 + M2 + M3: platform + uç işlemci dengeleme
M1 + M2 + M3 + M4: 5 kg dengeleme

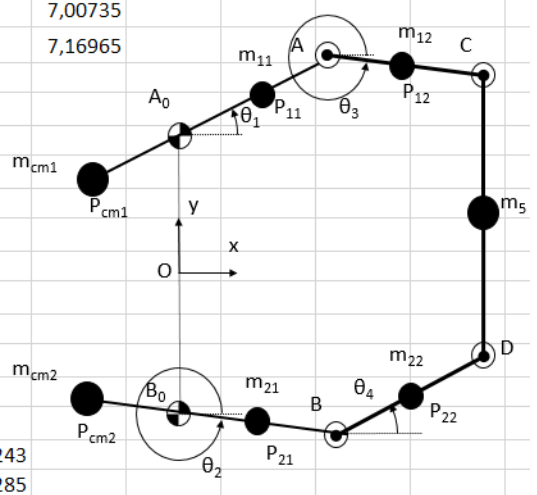
Yük	Dengeleme kütleleri
1.45 kg	$M_1 + M_2 = 10.1$ kg
3.41 kg	$M_1 + M_2 + M_3 = 17.1$ kg
5 kg	$M_1 + M_2 + M_3 + M_4 = 24.28$ kg

Dengeleme Hesabı

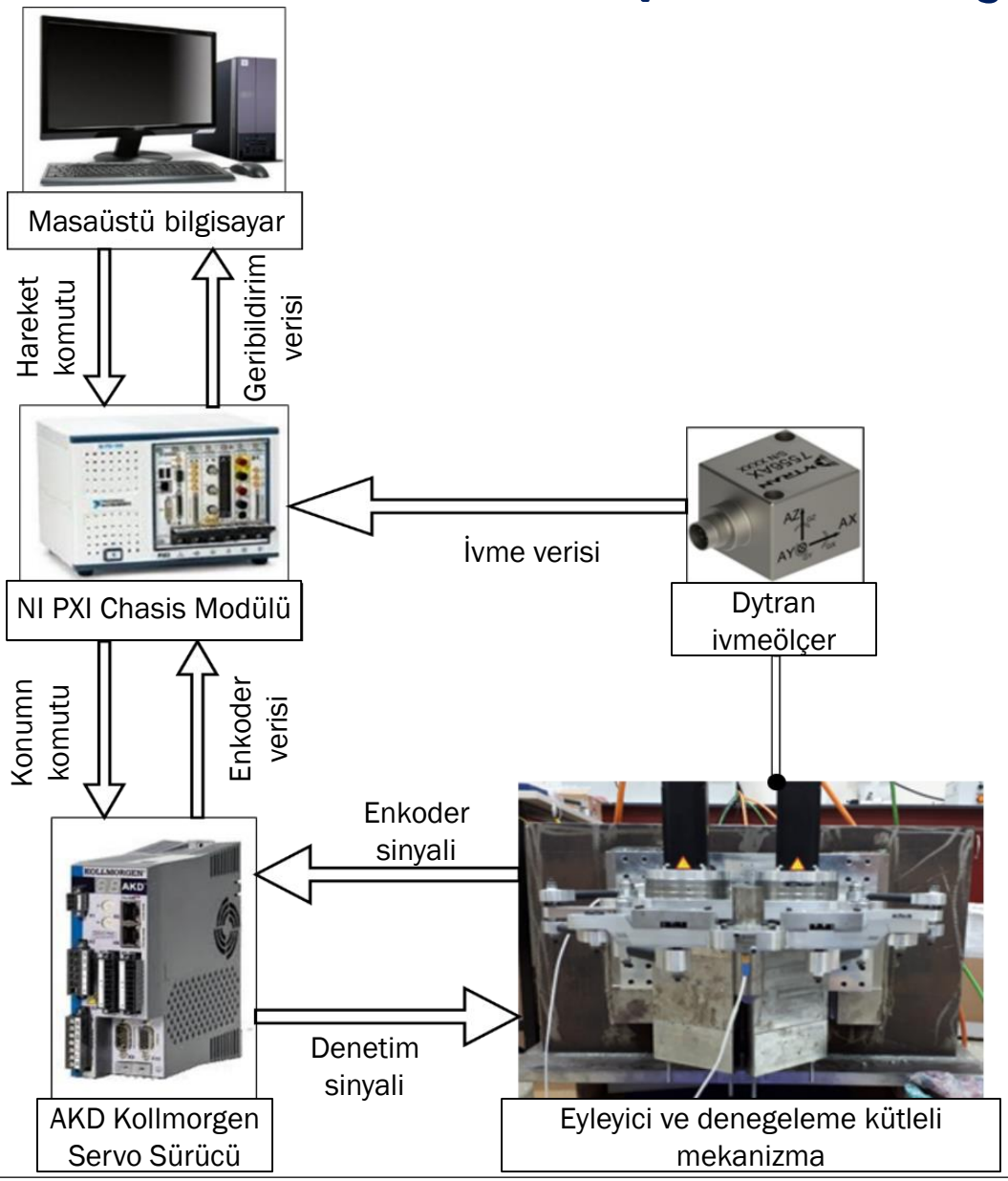
m11=m21	1,04642	kg		p11=p21	0,05943	m	r	0,15	m		m11	1,181		5lik	60,4	g	
m12=m22	0,58909	kg		p12=p22	0,0187	m					m22	0,34		saplama	462,65	g	
m3	5	kg								DK							
		m_{cm1}/m_{cm2}	p_{cm1}/p_{cm2}				miller+platform	1451	g	10,099	kg						
$m_{cm1}*p_{cm1}$	-0,9116	24,2761	-0,03755				uç işlemci ile	3411,6	g	17,1064	kg	7,00735					
$m_{cm2}*p_{cm2}$	-0,9116						5 kg	5000	g	24,276	kg	7,16965					
7075 Al Volume	13190	cm^3															
7075Al mass	37	g															
7075Al density	0,00281	g/cm^3															
Steel Volume	238692	cm^3		mass1	mass2	mass3	mass4	Toplam									
Steel Mass	1870	g		5027,46	5064,21	7018,82	7152,084471	24262,567	0,0135504								
Steel Density	0,00783	g/cm^3															
			1	5027,46													
5000Al Volume	2147116	cm^3	2	5064,21													
5000Al Mass	5684	g		10091,7													
5000Al Density	2,64727	kg/m^3	3	7018,82													
				17110,5								1,243					
			4	7152,08								26,285					
				24262,6													

Uzuvlar	Uzunluk (mm)
$IA_0AI=IB_0BI$	$l_1=l_2=150$
IAEI=IBEI	$l_3=l_4=150$
$IA_0P_{11}I=IB_0P_{21}I$	$r_1=r_2=33.6$
$IAP_{12}I=IBP_{22}I$	$r_3=r_4=75$
$IA_0P_{cm1}I=IB_0P_{cm2}I$	$r_{c1}=r_{c2}=79.7$

	Kütle (kg)		Atalet ($kg.mm^2$)		
$m_{11}=m_{21}$	1,168		18485,246		0,01849
$m_{12}=m_{22}$	0,267		3340,247		0,00334
m_5	5				0
$m_{cm1}=m_{cm2}$	10,658		83028,667		0,08303



Dengeleme Testleri (İvme-ölçer ile)

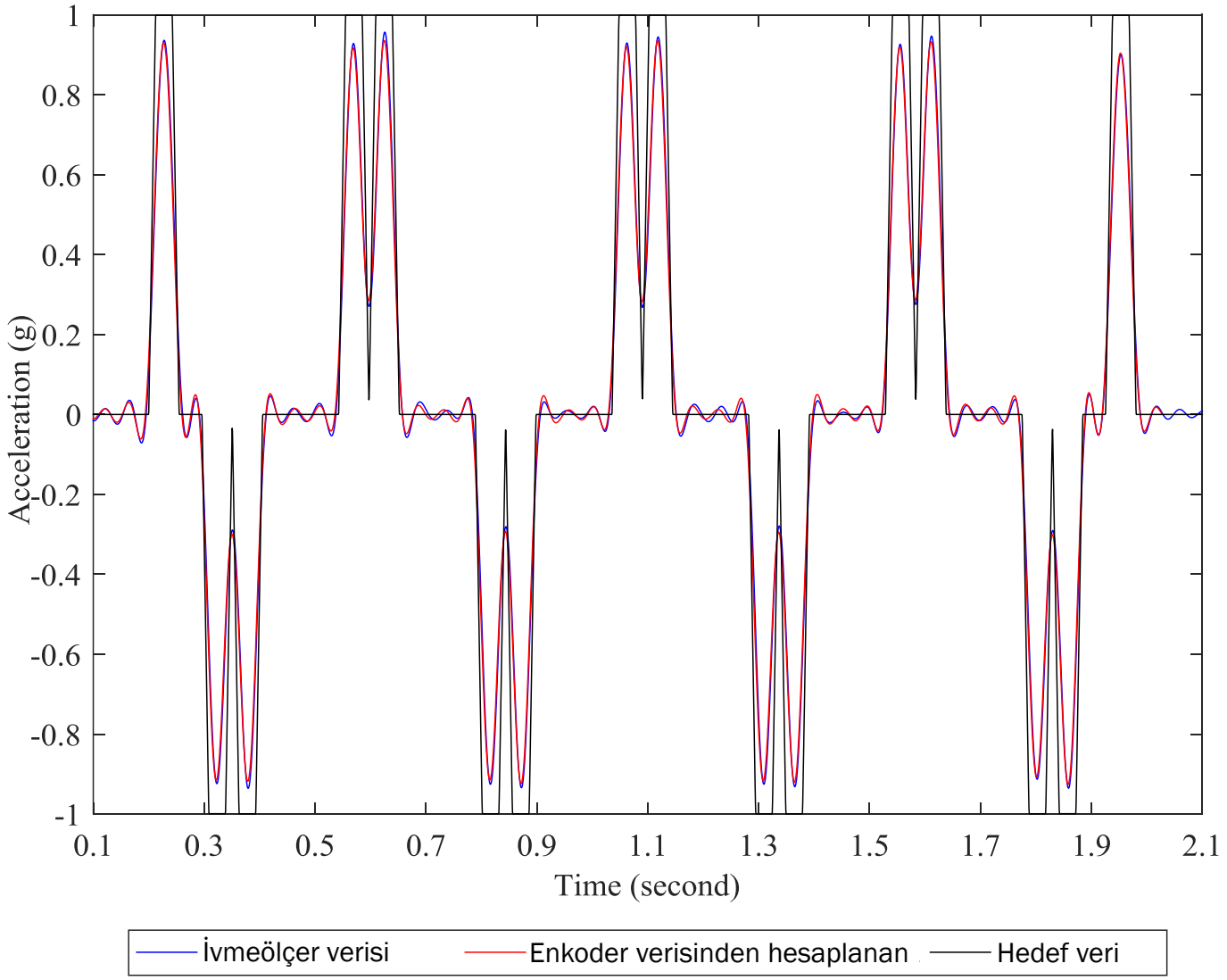


Dengeleme Testleri (İvme-ölçer ile)

Yük	Dengeleme Kütlesi	İvme (g: 9.81 m/s^2)
Sadeceplatform (1.45 kg)	10.1 kg	1g, 2g, 3g, 4g
platform + uç işlemci (3.41 kg)	17.1 kg	0.5g, 1g, 2g, 3g, 3.5g
platform + uç işlemci + ekstra kütleler (5 kg)	24.28 kg	0.5g, 1g, 2g, 3g, 3.5g

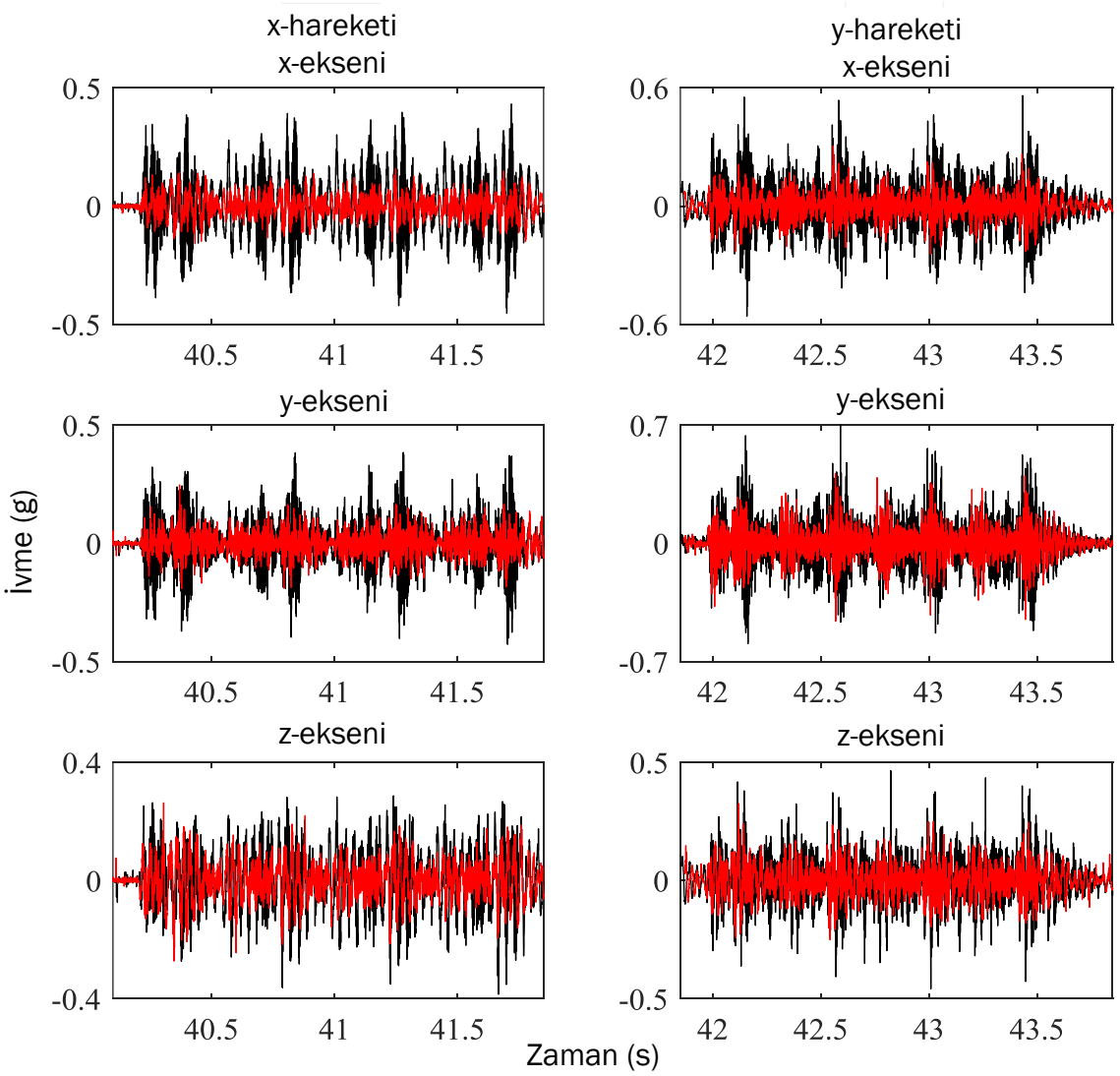
Platform hareketi: önce ± 40 mm dikey hareket, sonra ± 40 mm yatay hareket

Dengeleme Testleri (İvme-ölçer ile)



İvme komutu başarımı – Azami 1g ivme ile platform hareketi

Dengeleme Testleri (İvme-ölçer ile)



Dengelemeli-dengelemesiz karşılaştırma / 5 kg platform / Azami 3g ivme

Dengeleme Testleri (İvme-ölçer ile)

	İvme	x-ekseni	y-ekseni	z-ekseni
x-hareketi	1 g	52.31 %	43.77 %	35.57 %
	2 g	44.45 %	39 %	33.61 %
	3 g	40.77 %	34.37 %	37.57 %
	4 g	50.94 %	34.66 %	29.40 %
y-hareketi	1 g	49.85 %	54.58 %	46.1 %
	2 g	44.32 %	54.41 %	42.52 %
	3 g	43.07 %	52.45 %	41.15 %
	4 g	41.59 %	29.02 %	34.99 %

Dengeleme sonrası ivme genliklerindeki düşüşler – Sadece platform ile

Dengeleme Testleri (İvme-ölçer ile)

	İvme	x-ekseni	y-ekseni	z-ekseni
x-hareketi	0.5 g	73.06 %	58.54 %	37.42 %
	1 g	70.93 %	51.83 %	43.2 %
	2 g	70.48 %	53.29 %	41.29 %
	3 g	72.37 %	49.14 %	45.06 %
	3.5 g	68.72 %	40.22 %	28.61 %
y-hareketi	0.5 g	62.70 %	50.73 %	47.72 %
	1 g	71.4 %	54.71 %	51.87 %
	2 g	70.65 %	57.95 %	52.22 %
	3 g	66.56 %	50.97 %	44.92 %
	3.5 g	55.04 %	35.16 %	33.29 %

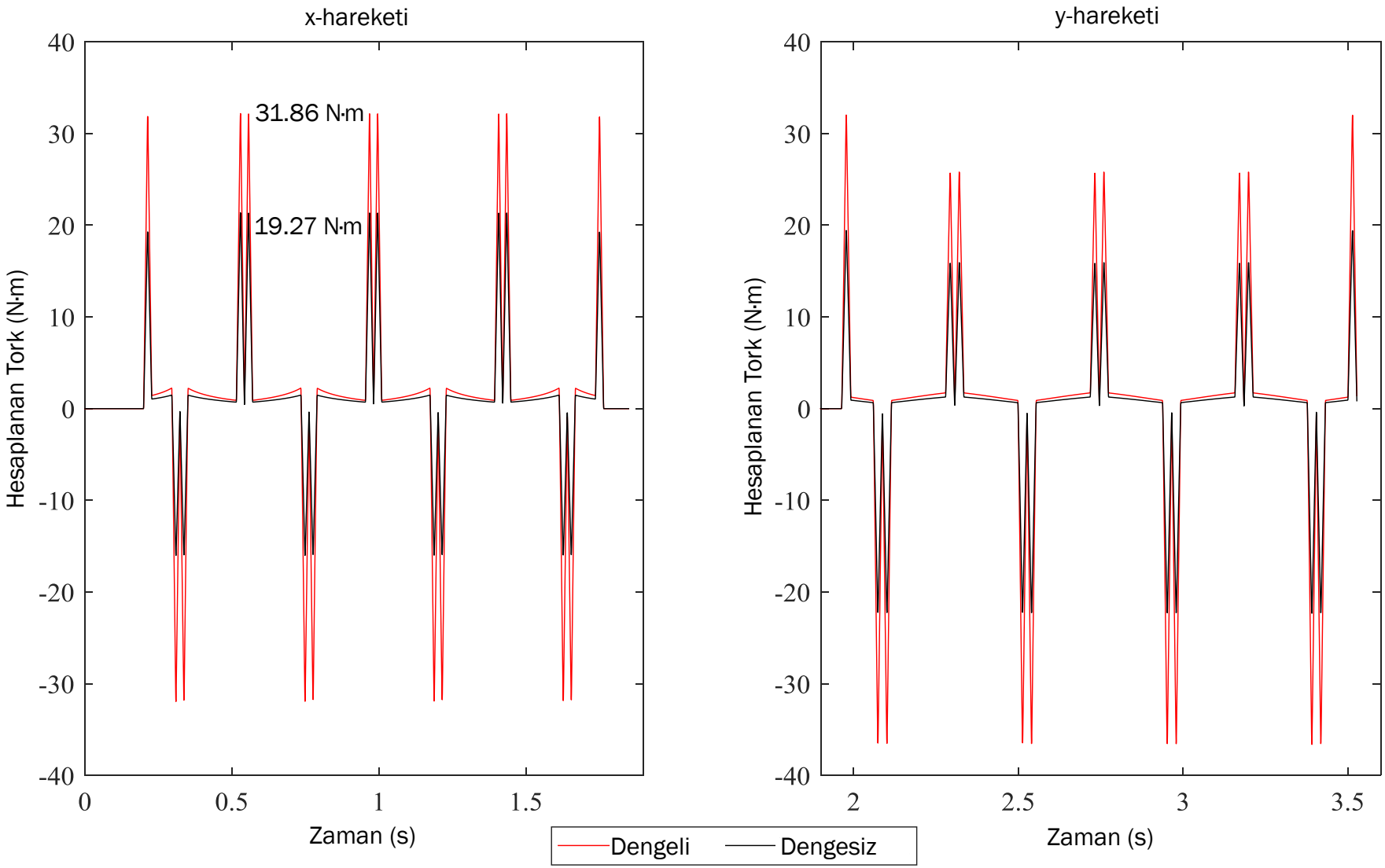
Dengeleme sonrası ivme genliklerindeki düşüşler – Platform + uç işlemci ile

Dengeleme Testleri (İvme-ölçer ile)

	İvme	x-ekseni	y-ekseni	z-ekseni
x-hareketi	0.5 g	66.38 %	59.2 %	40.24 %
	1 g	64.73 %	56.33 %	28.01 %
	2 g	53.11 %	54.95 %	30.19 %
	3 g	62.76 %	51.42 %	35.24 %
y-hareketi	0.5 g	60.84 %	51.64 %	37.16 %
	1 g	69.35 %	56.39 %	36.27 %
	2 g	68.31 %	65.90 %	42.78 %
	3 g	53.19 %	35.72 %	34.04 %

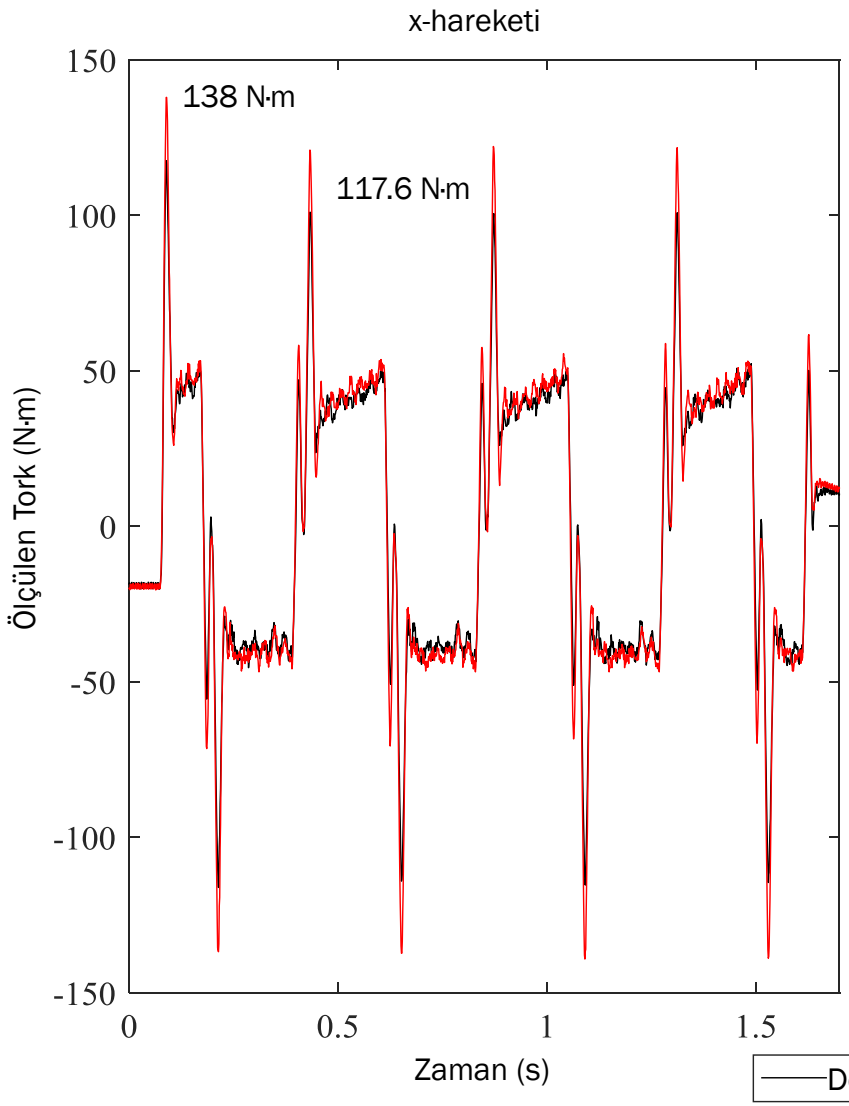
Dengeleme sonrası ivme genliklerindeki düşüşler – 5 kg ile

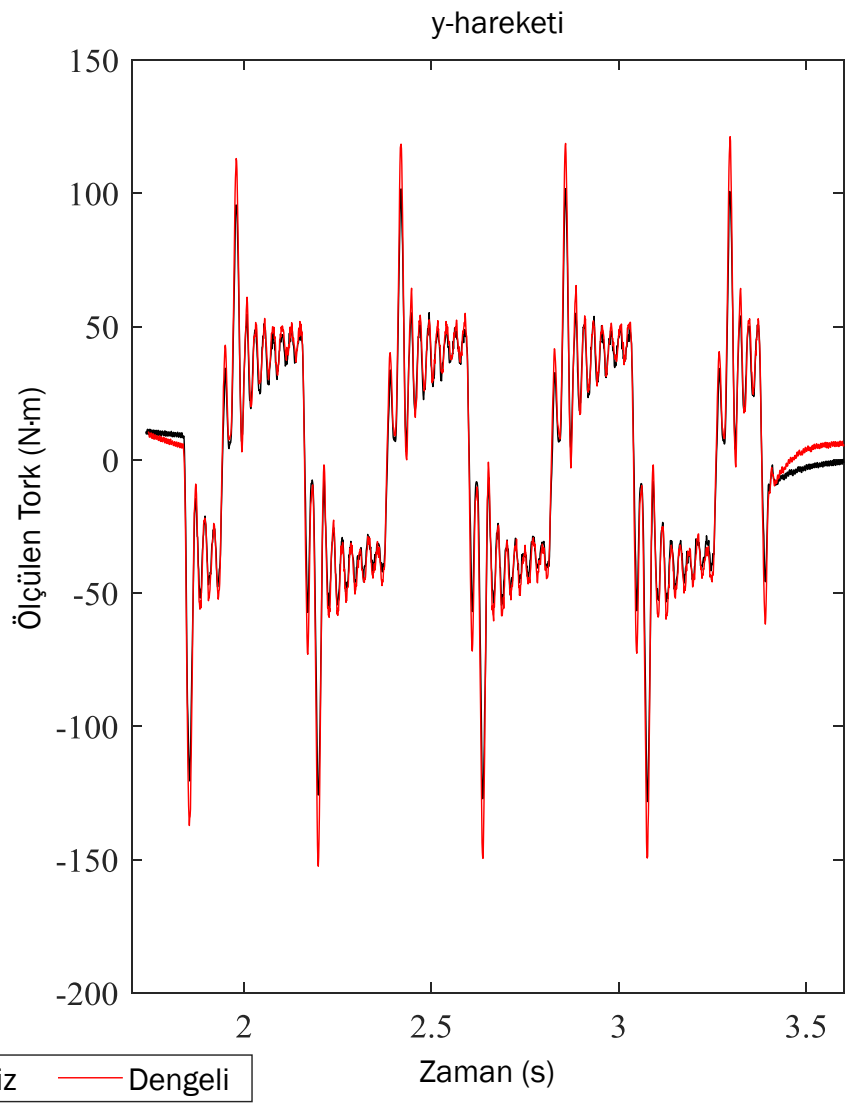
Dengeleme Testleri – Tork Değerleri



Dengelemeli-dengelemesiz karşılaştırma / 5 kg platform / Azami 3g ivme

Dengeleme Testleri – Tork Değerleri

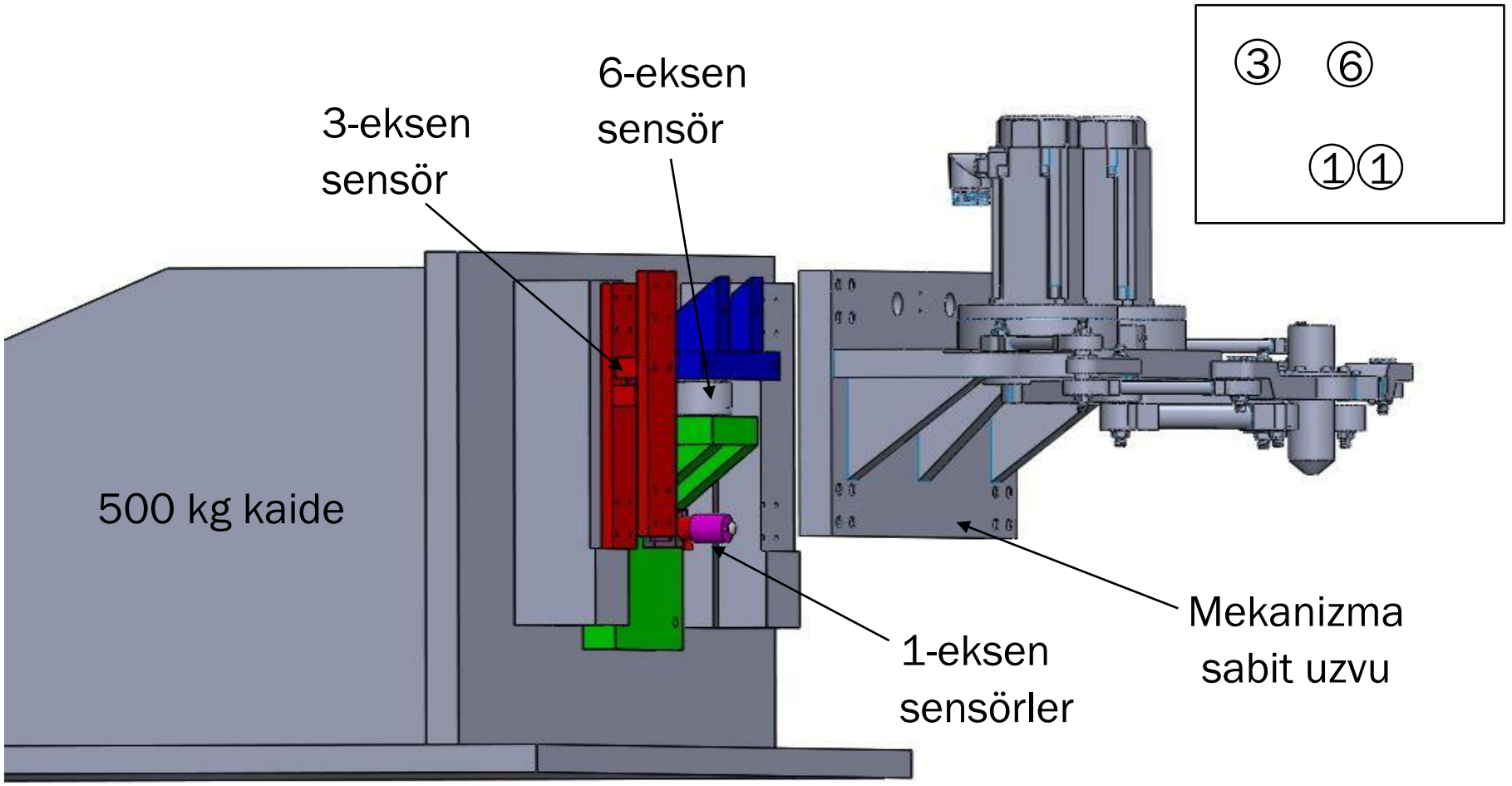




Dengesiz Dengeli

Dengelemeli-dengelemesiz karşılaştırma / 5 kg platform / Azami 3g ivme

Dengeleme Testleri (Kuvvet-ölçer ile)



Mekanizma grubu ile kaide arasında 4 kuvvet-ölçer var

Dengeleme Testleri (Kuvvet-ölçer ile)

Kuvvet-ölçerler:

6-eksen kuvvet-ölçer: ME-K6D40; kapasite:

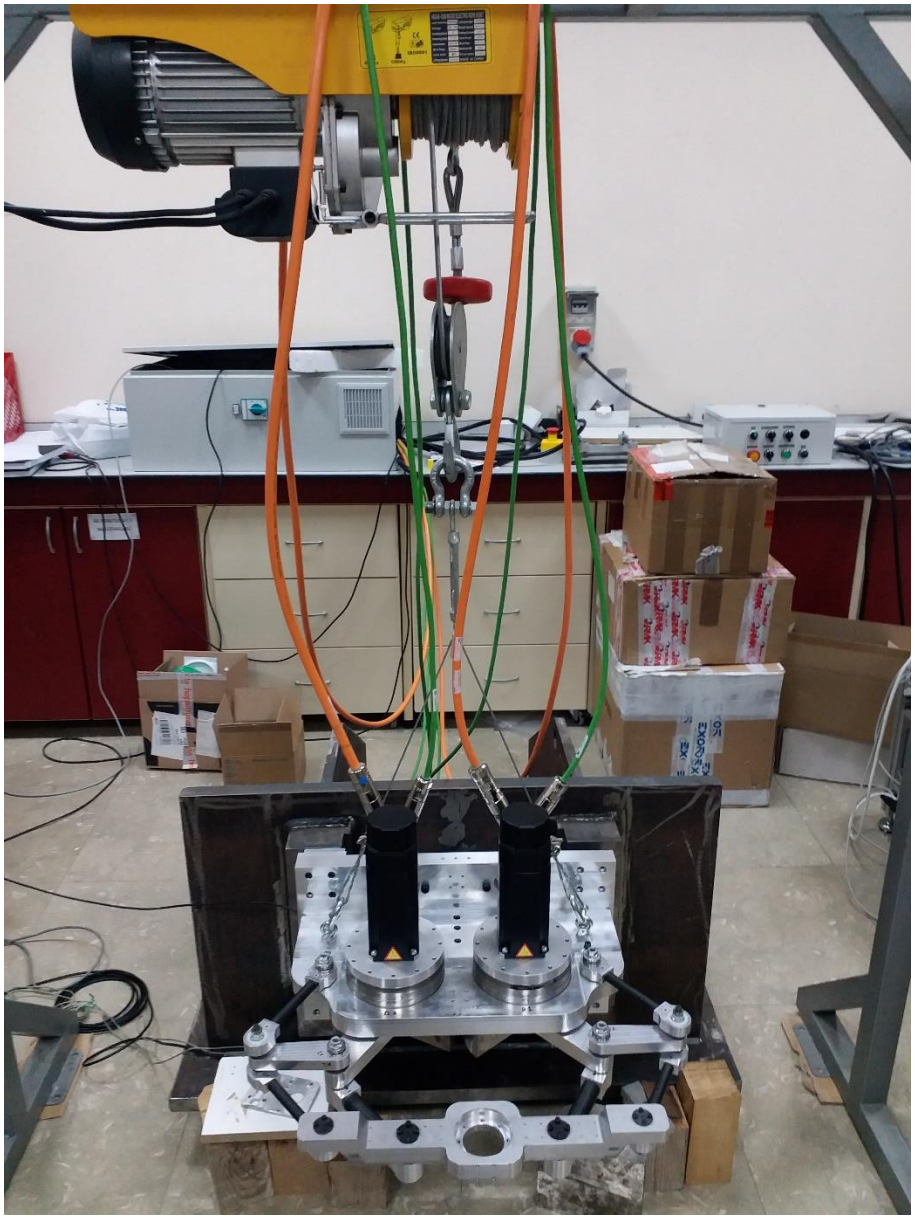
x- ve y- ekseninde ±500 N, z-ekseninde ±2000 N
3 eksende 20 N·m moment

3-eksen kuvvet-ölçer: Kistler 9016-b; kapasite: 3 ekseninde ±2000 N

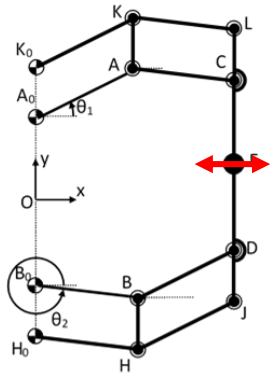
1-eksen kuvvet-ölçerler: Futek FSH03886; kapasite: ±1112 N

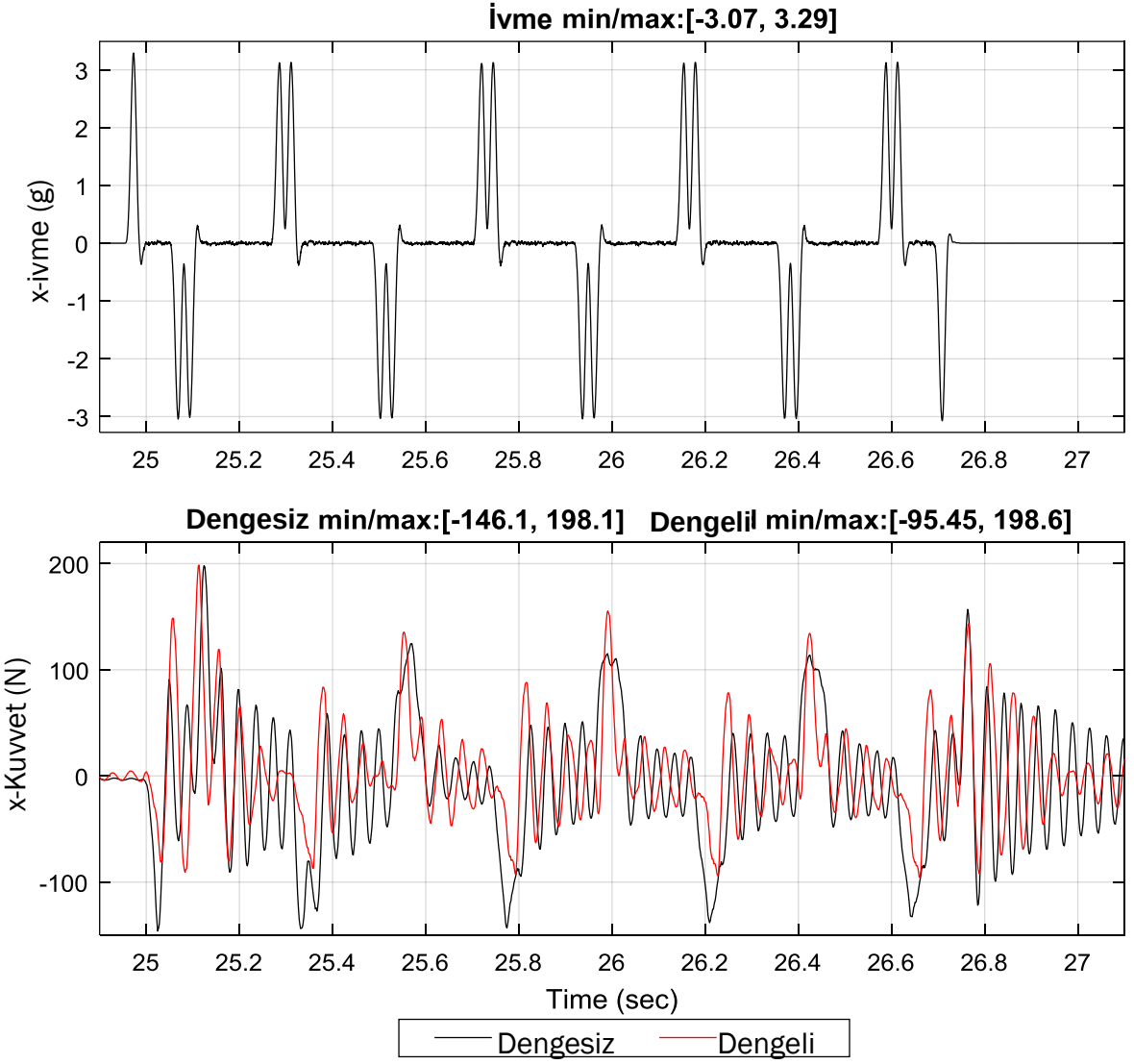
Platform hareketi: 1) ± 40 mm dikey hareket,
2) ± 40 mm yatay hareket, 3) boyu 40 mm, eni 50 mm olan üçgen

Dengeleme Testleri (Kuvvet-ölçer ile)



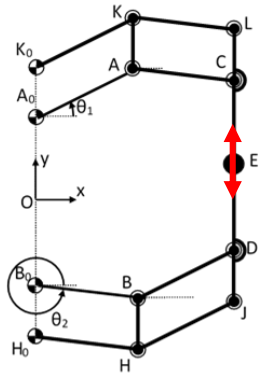
Dengeleme Testleri (Kuvvet-ölçer ile)

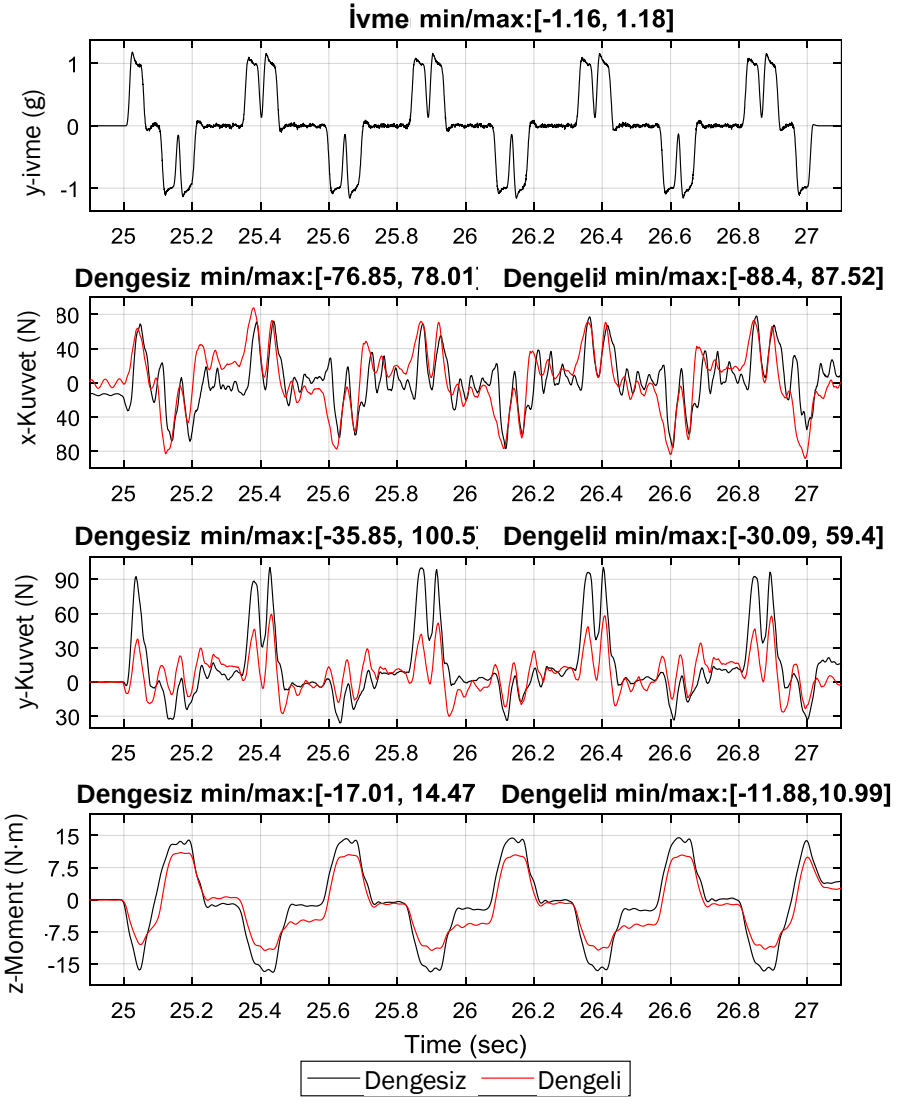




x-ekseni hareketi / 5 kg platform / Azami 3g ivme

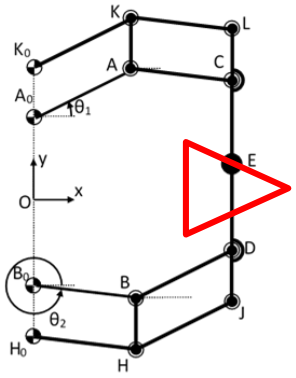
Dengeleme Testleri (Kuvvet-ölçer ile)

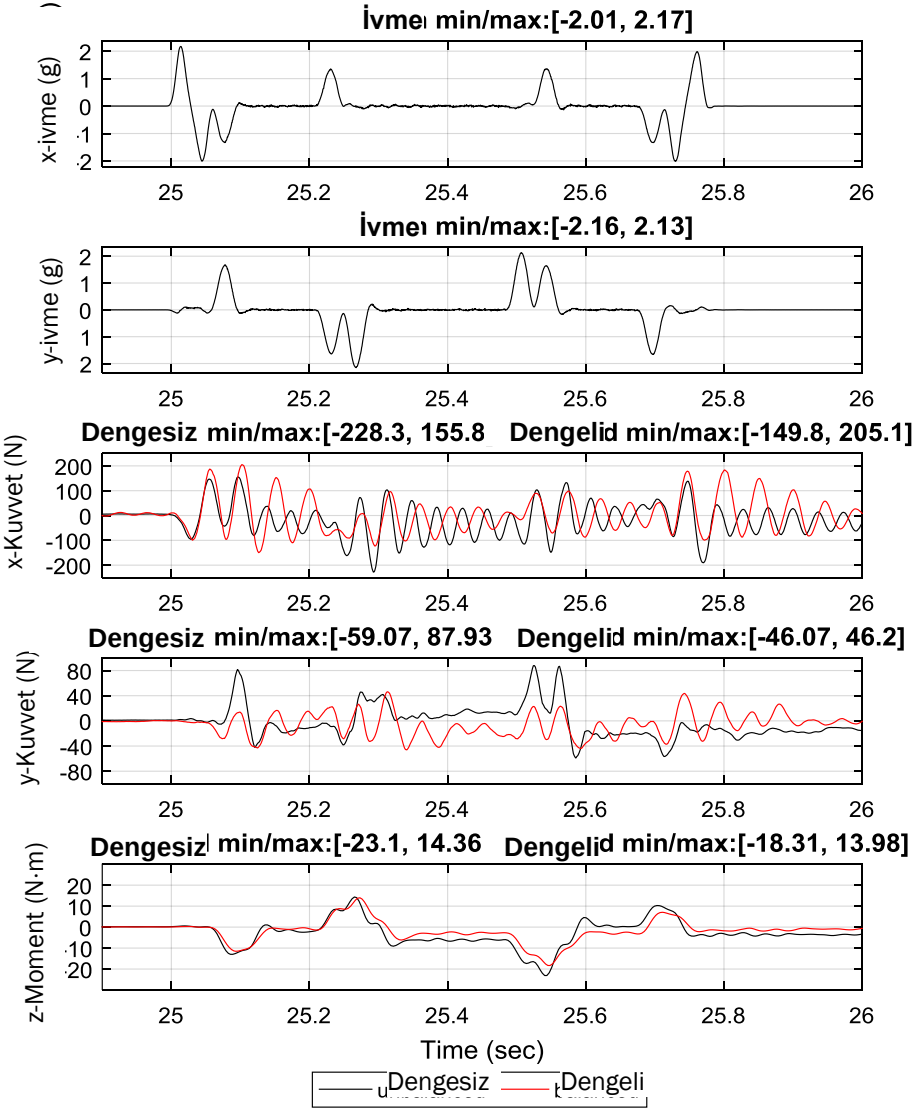




y-ekseni hareketi / 5 kg platform / Azami 1g ivme

Dengeleme Testleri (Kuvvet-ölçer ile)





Üçgen hareketi / 5 kg platform / Azami 1g ivme