Diagonal control using the SVD and the Jacobian Matrix

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In this document, the use of the Jacobian matrix and the Singular Value Decomposition to render a physical plant diagonal dominant is studied. Then, a diagonal controller is used.

These two methods are tested on two plants:

- In Section 1 on a 3-DoF gravimeter
- In Section 7 on a 6-DoF Stewart platform
1 Gravimeter - Simscape Model

1.1 Introduction

In this part, diagonal control using both the SVD and the Jacobian matrices are applied on a gravimeter model:

- Section 1.2: the model is described and its parameters are defined.
- Section 1.3: the plant dynamics from the actuators to the sensors is computed from a Simscape model.
- Section 1.4: the plant is decoupled using the Jacobian matrices.
- Section 1.5: the Singular Value Decomposition is performed on a real approximation of the plant transfer matrix and further use to decouple the system.
- Section 1.6: the effectiveness of the decoupling is computed using the Gershgorin radii
- Section 1.7: the effectiveness of the decoupling is computed using the Relative Gain Array
- Section 1.8: the obtained decoupled plants are compared
- Section 1.9: the diagonal controller is developed
- Section 1.10: the obtained closed-loop performances for the two methods are compared
- Section 1.11: the robustness to a change of actuator position is evaluated
- Section 1.12: the choice of the reference frame for the evaluation of the Jacobian is discussed
- Section 1.13: the decoupling performances of SVD is evaluated for a low damped and an highly damped system

1.2 Gravimeter Model - Parameters

The model of the gravimeter is schematically shown in Figure 1.1.

The parameters used for the simulation are the following:
### 1.3 System Identification

```matlab
l = 1.0; % Length of the mass [m]
h = 1.7; % Height of the mass [m]
la = l/2; % Position of Act. [m]
ha = h/2; % Position of Act. [m]
m = 400; % Mass [kg]
l = 115; % Inertia [kg m^2]
k = 15e3; % Actuator Stiffness [N/m]
c = 2e1; % Actuator Damping [N/(m/s)]
deq = 0.2; % Length of the actuators [m]
g = 0; % Gravity [m/s^2]
```
The inputs and outputs of the plant are shown in Figure 1.3.

More precisely there are three inputs (the three actuator forces):

\[ \tau = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} \]  \hspace{1cm} (1.1)

And 4 outputs (the two 2-DoF accelerometers):

\[ a = \begin{bmatrix} a_{1x} \\ a_{1y} \\ a_{2x} \\ a_{2y} \end{bmatrix} \]  \hspace{1cm} (1.2)

We can check the poles of the plant:

-0.12243+13.551i
-0.12243-13.551i
-0.05+8.6601i
-0.05-8.6601i
-0.0088785+3.6493i
-0.0088785-3.6493i

As expected, the plant as 6 states (2 translations + 1 rotation)

<table>
<thead>
<tr>
<th>size(G)</th>
<th>Matlab</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Results</td>
</tr>
</tbody>
</table>

| State-space model with 4 outputs, 3 inputs, and 6 states. |  |

The bode plot of all elements of the plant are shown in Figure 1.4.
Figure 1.4: Open Loop Transfer Function from 3 Actuators to 4 Accelerometers
1.4 Decoupling using the Jacobian

Consider the control architecture shown in Figure 1.5.

The Jacobian matrix \( J \) is used to transform forces applied by the three actuators into forces/torques applied on the gravimeter at its center of mass:

\[
\begin{bmatrix}
\tau_1 \\
\tau_2 \\
\tau_3
\end{bmatrix} = J^{-T} \begin{bmatrix}
F_x \\
F_y \\
M_z
\end{bmatrix}
\]  

(1.3)

The Jacobian matrix \( J_a \) is used to compute the vertical acceleration, horizontal acceleration and rotational acceleration of the mass with respect to its center of mass:

\[
\begin{bmatrix}
a_x \\
a_y \\
a_R
\end{bmatrix} = J_a^{-1} \begin{bmatrix}
a_{x1} \\
a_{y1} \\
a_{x2}
\end{bmatrix}
\]  

(1.4)

We thus define a new plant as defined in Figure 1.5.

\[
G_x(s) = J_a^{-1} G(s) J^{-T}
\]

\( G_x(s) \) correspond to the 3\( \times \)3 transfer function matrix from forces and torques applied to the gravimeter at its center of mass to the absolute acceleration of the gravimeter’s center of mass (Figure 1.5).

\[F = \begin{bmatrix}
F_x \\
F_y \\
M_z
\end{bmatrix} \rightarrow G_x \rightarrow J^{-T} \rightarrow \tau \rightarrow G \rightarrow J^{-1} \rightarrow a \rightarrow A = \begin{bmatrix}
a_x \\
a_y \\
a_R
\end{bmatrix}\]

**Figure 1.5:** Decoupled plant \( G_x \) using the Jacobian matrix \( J \)

The Jacobian corresponding to the sensors and actuators are defined below:

```matlab
J_a = [1 0 -h/2; 0 1 l/2; 1 0 h/2; 0 1 0];
J_t = [1 0 -ha; 0 1 la; 0 1 -la];;
```

And the plant \( G_x \) is computed:

```matlab
Gx = pinv(Ja)*G*pinv(Jt);
Gx.InputName = {'Fx', 'Fy', 'Mz'};
Gx.OutputName = {'Dx', 'Dy', 'Rz'};
```
The diagonal and off-diagonal elements of $G_x$ are shown in Figure 1.6.

It is shown that the system is:

- decoupled at high frequency thanks to a diagonal mass matrix (the Jacobian being evaluated at the center of mass of the payload)
- coupled at low frequency due to the non-diagonal terms in the stiffness matrix, especially the term corresponding to a coupling between a force in the x direction to a rotation around z (due to the torque applied by the stiffness 1).

The choice of the frame in this the Jacobian is evaluated is discussed in Section 1.12.

1.5 Decoupling using the SVD

In order to decouple the plant using the SVD, first a real approximation of the plant transfer function matrix as the crossover frequency is required.

Let’s compute a real approximation of the complex matrix $H_1$ which corresponds to the transfer function $G(j\omega_c)$ from forces applied by the actuators to the measured acceleration of the top platform evaluated at the frequency $\omega_c$.

```
wc = 2*pi*10; % Decoupling frequency [rad/s]
H1 = evalfr(G, j*wc);
```
The real approximation is computed as follows:

\[
D = \text{pinv}(\text{real}(H_1/\text{Var}));
\]

\[
H_1 = \text{pinv}(D*\text{real}(H_1/\text{Var})*\text{diag}(\exp(j*\text{angle}(\text{diag}(H_1*D*H_1/\text{Var}))))/2));
\]

Table 1.1: Real approximate of \( G \) at the decoupling frequency \( \omega_c \)

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0092</td>
<td>-0.0039</td>
<td>0.0039</td>
</tr>
<tr>
<td>-0.0039</td>
<td>0.0048</td>
<td>0.00028</td>
</tr>
<tr>
<td>-0.004</td>
<td>0.0038</td>
<td>-0.0038</td>
</tr>
<tr>
<td>8.4e-09</td>
<td>0.0025</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

Now, the Singular Value Decomposition of \( H_1 \) is performed:

\[
H_1 = U \Sigma V^H
\]

\[
[U, S, V] = \text{svd}(H_1);
\]

Table 1.2: \( U \) matrix

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.78</td>
<td>0.61</td>
<td>-0.04</td>
<td>-0.68</td>
</tr>
<tr>
<td>0.48</td>
<td>0.61</td>
<td>-0.53</td>
<td>-0.2</td>
</tr>
<tr>
<td>0.48</td>
<td>-0.14</td>
<td>-0.85</td>
<td>0.2</td>
</tr>
<tr>
<td>0.03</td>
<td>0.73</td>
<td>0.06</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Table 1.3: \( V \) matrix

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.79</td>
<td>0.51</td>
<td>-0.6</td>
</tr>
<tr>
<td>0.51</td>
<td>0.67</td>
<td>-0.54</td>
</tr>
<tr>
<td>-0.35</td>
<td>0.73</td>
<td>0.59</td>
</tr>
</tbody>
</table>

The obtained matrices \( U \) and \( V \) are used to decouple the system as shown in Figure 1.7.

The decoupled plant is then:

\[
G_{\text{SVD}}(s) = U^{-1}G(s)V^{-H}
\]

\[
\text{Gsvd} = \text{inv}(U)*G*\text{inv}(V);
\]

Results

State-space model with 4 outputs, 3 inputs, and 6 states.

The 4th output (corresponding to the null singular value) is discarded, and we only keep the \( 3 \times 3 \) plant:
**Figure 1.7:** Decoupled plant $G_{SVD}$ using the Singular Value Decomposition

\[
G_{svd} = Gsvd(1:3, 1:3);
\]

The diagonal and off-diagonal elements of the “SVD” plant are shown in Figure 1.8.

**Figure 1.8:** Diagonal and off-diagonal elements of $G_{svd}$

### 1.6 Verification of the decoupling using the “Gershgorin Radii”

The “Gershgorin Radii” is computed for the coupled plant $G(s)$, for the “Jacobian plant” $G_x(s)$ and the “SVD Decoupled Plant” $G_{SVD}(s)$:

The “Gershgorin Radii” of a matrix $S$ is defined by:

\[
\zeta_i(j\omega) = \frac{\sum_{j \neq i} |S_{ij}(j\omega)|}{|S_{ii}(j\omega)|}
\]
1.7 Verification of the decoupling using the “Relative Gain Array”

The relative gain array (RGA) is defined as:

$$\Lambda(G(s)) = G(s) \times (G(s)^{-1})^T$$  \hspace{1cm} (1.5)

where $\times$ denotes an element by element multiplication and $G(s)$ is an $n \times n$ square transfer matrix.

The obtained RGA elements are shown in Figure 1.10.

The RGA-number is also a measure of diagonal dominance:

$$\text{RGA-number} = \|\Lambda(G) - I\|_{\text{sum}}$$  \hspace{1cm} (1.6)

1.8 Obtained Decoupled Plants

The bode plot of the diagonal and off-diagonal elements of $G_{SVD}$ are shown in Figure 1.12.

Similarly, the bode plots of the diagonal elements and off-diagonal elements of the decoupled plant $G_x(s)$ using the Jacobian are shown in Figure 1.13.

1.9 Diagonal Controller

The control diagram for the centralized control is shown in Figure 1.14.

The controller $K_c$ is “working” in an cartesian frame. The Jacobian is used to convert forces in the cartesian frame to forces applied by the actuators.
Figure 1.10: Obtained norm of RGA elements for the SVD decoupled plant and the Jacobian decoupled plant.

Figure 1.11: RGA-Number for the Gravimeter.
Figure 1.12: Decoupled Plant using SVD
Figure 1.13: Gravimeter Platform Plant from forces (resp. torques) applied by the legs to the acceleration (resp. angular acceleration) of the platform as well as all the coupling terms between the two (non-diagonal terms of the transfer function matrix)

Figure 1.14: Control Diagram for the Centralized control
The SVD control architecture is shown in Figure 1.15. The matrices $U$ and $V$ are used to decouple the plant $G$.

![Figure 1.15: Control Diagram for the SVD control](image)

We choose the controller to be a low pass filter:

$$K_c(s) = \frac{G_0}{1 + \frac{s}{\omega_0}}$$

$G_0$ is tuned such that the crossover frequency corresponding to the diagonal terms of the loop gain is equal to $\omega_c$.

```
wc = 2*pi*10; % Crossover Frequency [rad/s]
w0 = 2*pi*0.1; % Controller Pole [rad/s]
```

```
K_cen = diag(1./diag(abs(evalfr(Gx, j*wc))))*(1/abs(evalfr(1/(1 + s/w0), j*wc)))/(1 + s/w0);
L_cen = K_cen*Gx;
```

```
K_svd = diag(1./diag(abs(evalfr(Gsvd, j*wc))))*(1/abs(evalfr(1/(1 + s/w0), j*wc)))/(1 + s/w0);
U_inv = inv(U);
```

The obtained diagonal elements of the loop gains are shown in Figure 1.16.

### 1.10 Closed-Loop system Performances

Now the system is identified again with additional inputs and outputs:

- $x$, $y$ and $R_z$ ground motion
- $x$, $y$ and $R_z$ acceleration of the payload.

```
mdl = 'gravimeter';
io io_i = 1;
io(io_i) = linio([mdl, '/Dx'], 1, 'openinput'); io_i = io_i + 1;
io(io_i) = linio([mdl, '/Dy'], 1, 'openinput'); io_i = io_i + 1;
io(io_i) = linio([mdl, '/Rz'], 1, 'openinput'); io_i = io_i + 1;
```
Figure 1.16: Comparison of the diagonal elements of the loop gains for the SVD control architecture and the Jacobian one
The loop is closed using the developed controllers.

Matlab

G_cen = lft(G, -pinv(Jt)*K_cen*pinv(Ja));
G_svd = lft(G, -inv(V)*K_svd*U_inv(1:3, :));

Let’s first verify the stability of the closed-loop systems:

Matlab

isstable(G_cen)

Results

ans =
    logical
    1

Matlab

isstable(G_svd)

Results

ans =
    logical
    1

The obtained transmissibility in Open-loop, for the centralized control as well as for the SVD control are shown in Figure 1.17.

1.11 Robustness to a change of actuator position

Let say we change the position of the actuators:

Matlab

la = l/2*0.7; % Position of Act. [m]
hb = h/2*0.7; % Position of Act. [m]
Figure 1.17: Obtained Transmissibility

Figure 1.18: Obtain coupling terms of the transmissibility matrix
The loop is closed using the developed controllers.

The new plant is computed, and the centralized and SVD control architectures are applied using the previously computed Jacobian matrices and \( U \) and \( V \) matrices.

The closed-loop system are still stable in both cases, and the obtained transmissibility are equivalent as shown in Figure 1.19.

**Figure 1.19:** Transmissibility for the initial CL system and when the position of actuators are changed
1.12 Choice of the reference frame for Jacobian decoupling

If we want to decouple the system at low frequency (determined by the stiffness matrix), we have to compute the Jacobian at a point where the stiffness matrix is diagonal. A displacement (resp. rotation) of the mass at this particular point should induce a pure force (resp. torque) on the same point due to stiffnesses in the system. This can be verified by geometrical computations.

If we want to decouple the system at high frequency (determined by the mass matrix), we have to compute the Jacobians at the Center of Mass of the suspended solid. Similarly to the stiffness analysis, when considering only the inertia effects (neglecting the stiffnesses), a force (resp. torque) applied at this point (the center of mass) should induce a pure acceleration (resp. angular acceleration).

Ideally, we would like to have a decoupled mass matrix and stiffness matrix at the same time. To do so, the actuators (springs) should be positioned such that the stiffness matrix is diagonal when evaluated at the CoM of the solid.

1.12.1 Decoupling of the mass matrix

![Diagram showing the choice of reference frame](image)

**Figure 1.20:** Choice of \{O\} such that the Mass Matrix is Diagonal

```matlab
la = l/2; % Position of Act. [m]
ha = h/2; % Position of Act. [m]
```

%% Name of the Simulink File
mdl = 'gravimeter';

%% Input/Output definition
clear io; io(1) = linio(mdl, '/F1', 1, 'openinput'); io(1) = io(1) + 1;
io(2) = linio(mdl, '/F2', 1, 'openinput'); io(2) = io(2) + 1;
io(3) = linio(mdl, '/F3', 1, 'openinput'); io(3) = io(3) + 1;
io(4) = linio(mdl, '/Acc_side', 1, 'openoutput'); io(4) = io(4) + 1;
io(5) = linio(mdl, '/Acc_side', 2, 'openoutput'); io(5) = io(5) + 1;
io(6) = linio(mdl, '/Acc_top', 1, 'openoutput'); io(6) = io(6) + 1;
io(7) = linio(mdl, '/Acc_top', 2, 'openoutput'); io(7) = io(7) + 1;

G = linearize(mdl, io);
G.InputName = ('F1', 'F2', 'F3');
G.OutputName = ('Ax1', 'Ay1', 'Ax2', 'Ay2');
Decoupling at the CoM (Mass decoupled)

\[
J_{Ma} = \begin{bmatrix} 1 & 0 & -h/2 \\ 0 & 1 & l/2 \\ 1 & 0 & h/2 \\ 0 & 1 & 0 \end{bmatrix};
\]

\[
J_{Mt} = \begin{bmatrix} 1 & 0 & -ha \\ 0 & 1 & la \\ 0 & 1 & -la \end{bmatrix};
\]

\[
GM = \text{pinv}(J_{Ma}) \times G \times \text{pinv}(J_{Mt});
\]

\[
GM.\text{InputName} = \{ 'Fx', 'Fy', 'Hz' \};
\]

\[
GM.\text{OutputName} = \{ 'Dx', 'Dy', 'Rz' \};
\]

Figure 1.21: Diagonal and off-diagonal elements of the decoupled plant

### 1.12.2 Decoupling of the stiffness matrix

Figure 1.22: Choice of {O} such that the Stiffness Matrix is Diagonal

Decoupling at the point where K is diagonal (x = 0, y = -h/2 from the schematic {O} frame):
And the plant $G_x$ is computed:

```matlab
GK = pinv(JKa)*G*pinv(JKt);
GK.InputName = {'Fx', 'Fy', 'Mz'};
GK.OutputName = {'Dx', 'Dy', 'Rz'};
```

**Figure 1.23**: Diagonal and off-diagonal elements of the decoupled plant

### 1.12.3 Combined decoupling of the mass and stiffness matrices

**Figure 1.24**: Ideal location of the actuators such that both the mass and stiffness matrices are diagonal

To do so, the actuator position should be modified
\( la = l/2; \) \% Position of Act. \([\text{m}]\)

\( ha = 0; \) \% Position of Act. \([\text{m}]\)

%% Name of the Simulink File
mdl = 'gravimeter';

%% Input/Output definition
clear io; io_i = 1;
io(io_i) = linio([mdl, 'F1'], 1, 'openinput'); io_i = io_i + 1;
io(io_i) = linio([mdl, 'F2'], 1, 'openinput'); io_i = io_i + 1;
io(io_i) = linio([mdl, 'F3'], 1, 'openinput'); io_i = io_i + 1;
io(io_i) = linio([mdl, 'Acc_side'], 1, 'openinput'); io_i = io_i + 1;
io(io_i) = linio([mdl, 'Acc_top'], 1, 'openoutput'); io_i = io_i + 1;
io(io_i) = linio([mdl, 'Acc_top'], 2, 'openoutput'); io_i = io_i + 1;

G = linearize(mdl, io);
G.InputName = {'F1', 'F2', 'F3'};
G.OutputName = {'Ax1', 'Ay1', 'Ax2', 'Ay2'};

JMa = [1 0 -h/2
 0 1 l/2
 1 0 h/2
 0 1 0];

JMt = [1 0 -ha
 0 1 la
 0 1 -la];

GKM = pinv(JMa)*G*pinv(JMt);
GKM.InputName = {'Fx', 'Fy', 'Mz'};
GKM.OutputName = {'Dx', 'Dy', 'Rz'};

Figure 1.25: Diagonal and off-diagonal elements of the decoupled plant
1.12.4 Conclusion

Ideally, the mechanical system should be designed in order to have a decoupled stiffness matrix at the CoM of the solid.

If not the case, the system can either be decoupled as low frequency if the Jacobian are evaluated at a point where the stiffness matrix is decoupled. Or it can be decoupled at high frequency if the Jacobians are evaluated at the CoM.

1.13 SVD decoupling performances

As the SVD is applied on a real approximation of the plant dynamics at a frequency $\omega_0$, it is foreseen that the effectiveness of the decoupling depends on the validity of the real approximation.

Let’s do the SVD decoupling on a plant that is mostly real (low damping) and one with a large imaginary part (larger damping).

Start with small damping, the obtained diagonal and off-diagonal terms are shown in Figure 1.26.

![Figure 1.26: Diagonal and off-diagonal term when decoupling with SVD on the gravimeter with small damping](image)

Now take a larger damping, the obtained diagonal and off-diagonal terms are shown in Figure 1.27.
Figure 1.27: Diagonal and off-diagonal term when decoupling with SVD on the gravimeter with high damping
2 Parallel Manipulator with Collocated actuator/sensor pairs

In this section, we will see how the Jacobian matrix can be used to decouple a specific set of mechanical systems (described in Section 2.1).

The basic decoupling architecture is shown in Figure 2.1 where the Jacobian matrix is used to both compute the actuator forces from forces/torques that are to be applied in a specific defined frame, and to compute the displacement/rotation of the same mass from several sensors.

This is rapidly explained in Section 2.2.

Depending on the chosen frame, the Stiffness matrix in that particular frame can be computed. This is explained in Section 2.3.

Then three decoupling in three specific frames is studied:

- Section 2.4: control in the frame of the legs
- Section 2.5: control in a frame whose origin is at the center of mass of the payload
- Section 2.6: control in a frame whose origin is located at the “center of stiffness” of the system

Conclusions are drawn in Section 2.7.

2.1 Model

Let’s consider a parallel manipulator with several collocated actuator/sensors pairs.

System in Figure 2.1 will serve as an example.

We will note:

- \( b_i \): location of the joints on the top platform
The parameters are defined as follows:

\[
\begin{align*}
I &= 1.0; \quad \text{Length of the mass [m]} \\
h &= 2*1.7; \quad \text{Height of the mass [m]} \\
l_a &= l/2; \quad \text{Position of Act. [m]} \\
h_a &= h/2; \quad \text{Position of Act. [m]} \\
m &= 400; \quad \text{Mass [kg]} \\
l &= 115; \quad \text{Inertia [kg m^2]} \\
c_1 &= 2e1; \quad \text{Actuator Damping [N/(m/s)]} \\
c_2 &= 2e1; \quad \text{Actuator Damping [N/(m/s)]} \\
c_3 &= 2e1; \quad \text{Actuator Damping [N/(m/s)]} \\
k_1 &= 15e3; \quad \text{Actuator Stiffness [N/m]} \\
k_2 &= 15e3; \quad \text{Actuator Stiffness [N/m]} \\
k_3 &= 15e3; \quad \text{Actuator Stiffness [N/m]}
\end{align*}
\]

Let’s express \(\mathbf{M}_b\) and \(\hat{s}_i\):

\[
\begin{align*}
\mathbf{M}_b_1 &= [-l/2, -h_a] \\
\mathbf{M}_b_2 &= [-l_a, -h/2] \\
\mathbf{M}_b_3 &= [l_a, -h/2]
\end{align*}
\]

\[
\begin{align*}
\hat{s}_1 &= [1, 0] \\
\hat{s}_2 &= [0, 1] \\
\hat{s}_3 &= [0, 1]
\end{align*}
\]
Frame \( \{K\} \) is chosen such that the stiffness matrix is diagonal (explained in Section 4).

The positions \( K_{b_i} \) are then:

\[
K_{b_1} = [-l/2, 0] \\
K_{b_2} = [-la, -h/2 + ha] \\
K_{b_3} = [la, -h/2 + ha]
\]  

2.2 The Jacobian Matrix

Let’s note:

- \( \mathcal{L} \) the vector of actuator displacement:

\[
\mathcal{L} = \begin{bmatrix} L_1 \\ L_2 \\ L_3 \end{bmatrix}
\]

(2.10)

- \( \tau \) the vector of actuator forces:

\[
\tau = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix}
\]

(2.11)

- \( \mathcal{F}_{\{O\}} \) the vector of forces/torques applied on the payload on expressed in frame \( \{O\} \):

\[
\mathcal{F}_{\{O\}} = \begin{bmatrix} F_{\{O\},x} \\ F_{\{O\},y} \\ M_{\{O\},z} \end{bmatrix}
\]

(2.12)

- \( \mathcal{X}_{\{O\}} \) the vector of displacement of the payload with respect to frame \( \{O\} \):

\[
\mathcal{X}_{\{O\}} = \begin{bmatrix} X_{\{O\},x} \\ X_{\{O\},y} \\ X_{\{O\},z} \end{bmatrix}
\]

(2.13)
The Jacobian matrix can be used to:

- Convert joints velocity $\dot{L}$ to payload velocity and angular velocity $\dot{X}$:
  \[
  \dot{X} = J_{(O)} \dot{L}
  \]

- Convert actuators forces $\tau$ to forces/torque applied on the payload $F_{(O)}$:
  \[
  F_{(O)} = J_{(O)}^T \tau
  \]

with $\{O\}$ any chosen frame.

If we consider small displacements, we have an approximate relation that links the displacements (instead of velocities):

\[
\dot{X}_{(M)} = J_{(M)} \mathcal{L}
\]

(2.14)

The Jacobian can be computed as follows:

\[
J_{(O)} = \begin{bmatrix}
O_{sT}^1 & O_{b1,x}^1 O_{s1,y}^1 - O_{b1,y}^1 O_{s1,x}^1 \\
O_{sT}^2 & O_{b2,x}^2 O_{s2,y}^2 - O_{b2,y}^2 O_{s2,x}^2 \\
\vdots & \vdots \\
O_{sT}^n & O_{bn,x}^n O_{sn,y}^n - O_{bn,y}^n O_{sn,x}^n
\end{bmatrix}
\]

(2.15)

Let’s compute the Jacobian matrix in frame $\{M\}$ and $\{K\}$:

\[
J_m = [s1', \text{Mb1(1)+s1(2)-Mb1(2)+s1(1)}]; \\
s2', \text{Mb2(1)+s2(2)-Mb2(2)+s2(1)}]; \\
s3', \text{Mb3(1)+s3(2)-Mb3(2)+s3(1)}];
\]

\[\text{Matlab}\]

\[
J_m = \begin{bmatrix}
1 & 0 & 1.7 \\
0 & 1 & -0.5 \\
0 & 1 & 0.5
\end{bmatrix}
\]

\[\text{Table 2.1: Jacobian Matrix } J_{(M)}\]

\[
J_k = [s1', \text{Kb1(1)+s1(2)-Kb1(2)+s1(1)}]; \\
s2', \text{Kb2(1)+s2(2)-Kb2(2)+s2(1)}]; \\
s3', \text{Kb3(1)+s3(2)-Kb3(2)+s3(1)}];
\]

\[\text{Matlab}\]

\[
J_k = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & -0.5 \\
0 & 1 & 0.5
\end{bmatrix}
\]

\[\text{Table 2.2: Jacobian Matrix } J_{(K)}\]

In the frame $\{M\}$, the Jacobian is:

\[
J_{(M)} = \begin{bmatrix}
1 & 0 & h_a \\
0 & 1 & -l_a \\
0 & 1 & l_a
\end{bmatrix}
\]

(2.16)
And in frame \{K\}, the Jacobian is:

\[
J_{\{K\}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & -l_a \\ 0 & 1 & l_a \end{bmatrix}
\]

(2.17)

### 2.3 The Stiffness Matrix

For a parallel manipulator, the stiffness matrix expressed in a frame \{O\} is:

\[
K_{\{O\}} = J_{\{O\}}^T K J_{\{O\}}
\]

(2.18)

where:

- \(J_{\{O\}}\) is the Jacobian matrix expressed in frame \{O\}
- \(K\) is a diagonal matrix with the strut stiffnesses on the diagonal

\[
K = \begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_2 & 0 \\ 0 & 0 & k_n \end{bmatrix}
\]

(2.19)

We have the same thing for the damping matrix.

Matlab

```matlab
KR = diag([k1,k2,k3]);
CR = diag([c1,c2,c3]);
```

### 2.4 Equations of motion - Frame of the legs

Applying the second Newton’s law on the system in Figure 2.1 at its center of mass \(O_M\), we obtain:

\[
(M_{\{M\}} s^2 + K_{\{M\}}) \mathbf{X}_{\{M\}} = \mathbf{F}_{\{M\}}
\]

(2.20)

with:

- \(M_{\{M\}}\) is the mass matrix expressed in \{M\}:

\[
M_{\{M\}} = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I \end{bmatrix}
\]

- \(K_{\{M\}}\) is the stiffness matrix expressed in \{M\}:

\[
K_{\{M\}} = J_{\{M\}}^T K J_{\{M\}}
\]

- \(\mathbf{X}_{\{M\}}\) are displacements/rotations of the mass \(x, y, R_z\) expressed in the frame \{M\}
\( \mathbf{\{M\}} \) are forces/torques \( F_x, F_y, M_z \) applied at the origin of \( \{M\} \)

Let’s use the Jacobian matrix to compute the equations in terms of actuator forces \( \mathbf{\tau} \) and strut displacement \( \mathbf{L} \):

\[
(M_{\{M\}} s^2 + K_{\{M\}}) J^{-1}_{\{M\}} \mathbf{L} = J^T_{\{M\}} \mathbf{\tau}
\]  

(2.21)

And we obtain:

\[
\left( J^{-T}_{\{M\}} M_{\{M\}} J^{-1}_{\{M\}} s^2 + K \right) \mathbf{L} = \mathbf{\tau}
\]  

(2.22)

The transfer function \( G(s) \) from \( \mathbf{\tau} \) to \( \mathbf{L} \) is:

\[
G(s) = \left( J^{-T}_{\{M\}} M_{\{M\}} J^{-1}_{\{M\}} s^2 + K \right)^{-1}
\]  

(2.23)

**Figure 2.2:** Block diagram of the transfer function from \( \mathbf{\tau} \) to \( \mathbf{L} \)

Let’s note the mass matrix in the frame of the legs:

\[
M_{\{L\}} = J^{-T}_{\{M\}} M_{\{M\}} J^{-1}_{\{M\}}
\]  

(2.24)

**Table 2.3:** \( M_{\{L\}} \)

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>680</td>
<td>-680</td>
</tr>
<tr>
<td>680</td>
<td>1371</td>
<td>-1171</td>
</tr>
<tr>
<td>-680</td>
<td>-1171</td>
<td>1371</td>
</tr>
</tbody>
</table>

As we can see, the Stiffness matrix in the frame of the legs is diagonal. This means the plant dynamics will be diagonal at low frequency.

The transfer function \( G(s) \) from \( \mathbf{\tau} \) to \( \mathbf{L} \) is defined below and its magnitude is shown in Figure 2.3.
\begin{table}[h]
\centering
\begin{tabular}{ccc}
\hline
\textbf{Table 2.4: $K_L = K$} \\
15000 & 0 & 0 \\
0 & 15000 & 0 \\
0 & 0 & 15000 \\
\hline
\end{tabular}
\end{table}

\texttt{G1 = im(M1\*s^2 + C1\*s + K1);}

We can indeed see that the system is well decoupled at low frequency.

![Dynamics from $\tau$ to $L$](image)

\textbf{Figure 2.3: Dynamics from $\tau$ to $L$}

\section{2.5 Equations of motion - “Center of mass” \{M\}}

The equations of motion expressed in frame \{M\} are:

\[(M_{(M)}s^2 + K_{(M)})X_{(M)} = F_{(M)}\]  \hfill (2.25)

And the plant from $F_{(M)}$ to $X_{(M)}$ is:

\[G_{(X)} = (M_{(M)}s^2 + K_{(M)})^{-1}\]  \hfill (2.26)

with:

- $M_{(M)}$ is the mass matrix expressed in \{M\}:

\[
M_{(M)} = \begin{bmatrix}
m & 0 & 0 \\
0 & m & 0 \\
0 & 0 & I
\end{bmatrix}
\]
• $K_{\{M\}}$ is the stiffness matrix expressed in $\{M\}$:

$$K_{\{M\}} = J_{\{M\}}^T K J_{\{M\}}$$

\[ \begin{align*}
& \mathbf{F}_{\{M\}} \quad J_{\{M\}}^{-T} \quad \mathbf{G} \quad \mathbf{L} \quad J_{\{M\}}^{-1} \quad \mathbf{X}_{\{M\}} \\
\end{align*} \]

\textbf{Figure 2.4:} Block diagram of the transfer function from $\mathbf{F}_{\{M\}}$ to $\mathbf{X}_{\{M\}}$

\begin{verbatim}
%% Mass Matrix in frame (M)
Mm = diag([m,m,I]);
\end{verbatim}

\textbf{Table 2.5:} Mass matrix expressed in $\{M\}$: $M_{\{M\}}$

\[
\begin{array}{ccc}
400 & 0 & 0 \\
0 & 400 & 0 \\
0 & 0 & 115 \\
\end{array}
\]

\begin{verbatim}
%% Stiffness Matrix in frame (M)
Km = Jm/var/kr*Jm;
\end{verbatim}

\textbf{Table 2.6:} Stiffness matrix expressed in $\{M\}$: $K_{\{M\}}$

\[
\begin{array}{ccc}
15000 & 0 & 25500 \\
0 & 30000 & 0 \\
25500 & 0 & 50850 \\
\end{array}
\]

\begin{verbatim}
%% Damping Matrix in frame (M)
Cm = Jm/var/cr*Jm;
\end{verbatim}

The plant from $F_{\{M\}}$ to $X_{\{M\}}$ is defined below and its magnitude is shown in Figure 2.5.

\begin{verbatim}
%% Plant in frame (M)
Gm = inv(Mm*s^2 + Cm*s + Km);
\end{verbatim}

\section*{2.6 Equations of motion - “Center of stiffness” $\{K\}$}

Let’s now express the transfer function from $\mathbf{F}_{\{K\}}$ to $\mathbf{X}_{\{K\}}$. We start from:

$$\left( M_{\{M\}} s^2 + K_{\{M\}} \right) J_{\{M\}}^{-1} \mathbf{L} = J_{\{M\}}^T \mathbf{\tau}$$

\ \ (2.27)
And we make use of the Jacobian $J_{(K)}$ to obtain:

$$
(M_{(M)} s^2 + K_{(M)}) J^{-1}_{(M)} J_{(K)} \mathbf{x}_{(K)} = J^T_{(M)} J^{-T}_{(K)} \mathbf{f}_{(K)}
$$

(2.28)

And finally:

$$
\left( J^T_{(K)} J^T_{(M)} M_{(M)} J^{-1}_{(M)} J_{(K)} s^2 + J^T_{(K)} K_{(K)} J_{(K)} \right) \mathbf{x}_{(K)} = \mathbf{f}_{(K)}
$$

(2.29)

The transfer function from $\mathbf{f}_{(K)}$ to $\mathbf{x}_{(K)}$ is then:

$$
G_{(K)} = \left( J^T_{(K)} J^T_{(M)} M_{(M)} J^{-1}_{(M)} J_{(K)} s^2 + J^T_{(K)} K_{(K)} J_{(K)} \right)^{-1}
$$

(2.30)

The frame $\{K\}$ has been chosen such that $J^T_{(K)} K_{(K)} J_{(K)}$ is diagonal.

Figure 2.6: Block diagram of the transfer function from $\mathbf{f}_{(K)}$ to $\mathbf{x}_{(K)}$

Table 2.7: Mass matrix expressed in $\{K\}$: $M_{(K)}$

\[
\begin{bmatrix}
400 & 0 & -680 \\
0 & 400 & 0 \\
-680 & 0 & 1271 \\
\end{bmatrix}
\]
\[ K_k = J_k^* K_r J_k; \]

**Table 2.8:** Stiffness matrix expressed in \( \{ K \} \): \( K_{(K)} \)

<table>
<thead>
<tr>
<th></th>
<th>15000</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30000</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>7500</td>
<td></td>
</tr>
</tbody>
</table>

The plant from \( F_{(K)} \) to \( X_{(K)} \) is defined below and its magnitude is shown in Figure 2.7.

\[ G_k = \text{inv}(M_k s^2 + C_k s + K_k); \]

![Figure 2.7: Dynamics from \( F_{(K)} \) to \( X_{(K)} \)](image)

**2.7 Conclusion**
3 SVD / Jacobian / Model decoupling comparison

The goal of this section is to compare the use of several methods for the decoupling of parallel manipulators.

It is structured as follow:

- Section 3.1: the model used to compare/test decoupling strategies is presented
- Section 3.2: decoupling using Jacobian matrices is presented
- Section 3.3: modal decoupling is presented
- Section 3.4: SVD decoupling is presented
- Section 3.5: the three decoupling methods are applied on the test model and compared
- Section 3.7: conclusions are drawn on the three decoupling methods

3.1 Test Model

Let’s consider a parallel manipulator with several collocated actuator/sensors pairs.

System in Figure 3.1 will serve as an example.

We will note:

- $b_i$: location of the joints on the top platform
- $\hat{s}_i$: unit vector corresponding to the struts direction
- $k_i$: stiffness of the struts
- $\tau_i$: actuator forces
- $O_M$: center of mass of the solid body
- $L_i$: relative displacement of the struts

The parameters are defined below.
Figure 3.1: Model use to compare decoupling techniques

%% System parameters
l = 1.0; % Length of the mass [m]
h = 2*1.7; % Height of the mass [m]
la = 1/2; % Position of Act. [m]
ha = h/2; % Position of Act. [m]
m = 400; % Mass [kg]
I = 115; % Inertia [kg m^2]

%% Actuator Damping [N/(m/s)]
c1 = 2e1;
c2 = 2e1;
c3 = 2e1;

%% Actuator Stiffness [N/m]
k1 = 15e3;
k2 = 15e3;
k3 = 15e3;

%% Unit vectors of the actuators
s1 = [1;0];
s2 = [0;1];
s3 = [0;1];

%% Location of the joints
Mb1 = [-l/2;-ha];
Mb2 = [-la; -h/2];
Mb3 = [ la; -h/2];

%% Jacobian matrix
J = [s1'*Var, Mb1(1)*s1(2)-Mb1(2)*s1(1);
s2'*Var, Mb2(1)*s2(2)-Mb2(2)*s2(1);
s3'*Var, Mb3(1)*s3(2)-Mb3(2)*s3(1)];

%% Stiffness and Damping matrices of the struts
Kr = diag([k1,k2,k3]);
Cr = diag([c1,c2,c3]);

%% Mass Matrix in frame {M}
M = diag([m,m,I]);

%% Stiffness Matrix in frame {M}
K = J'*Kr*J;

%% Damping Matrix in frame {M}
C = J'*Cr*J;

The plant from $\tau$ to $L$ is defined below
The magnitude of the coupled plant $G$ is shown in Figure 3.2.

![Figure 3.2: Magnitude of the coupled plant.](image)

### 3.2 Jacobian Decoupling

The Jacobian matrix can be used to:

- Convert joints velocity $\dot{\mathcal{L}}$ to payload velocity and angular velocity $\dot{\mathcal{X}}_{\{O\}}$:

$$\dot{\mathcal{X}}_{\{O\}} = J_{\{O\}} \dot{\mathcal{L}}$$

- Convert actuators forces $\tau$ to forces/torque applied on the payload $\mathcal{F}_{\{O\}}$:

$$\mathcal{F}_{\{O\}} = J_{\{O\}}^T \tau$$

with $\{O\}$ any chosen frame.
By wisely choosing frame \( \{O\} \), we can obtain nice decoupling for plant:

\[
G_{\{O\}} = J_{\{O\}}^{-1} \mathcal{J}_{\{O\}}^{-T}
\]  

(3.1)

The obtained plan corresponds to forces/torques applied on origin of frame \( \{O\} \) to the translation/rotation of the payload expressed in frame \( \{O\} \).

![Figure 3.3: Block diagram of the transfer function from \( \mathcal{F}_{\{O\}} \) to \( \mathcal{X}_{\{O\}} \)]

**Important**

The Jacobian matrix is only based on the geometry of the system and does not depend on the physical properties such as mass and stiffness.

The inputs and outputs of the decoupled plant \( G_{\{O\}} \) have physical meaning:

- \( \mathcal{F}_{\{O\}} \) are forces/torques applied on the payload at the origin of frame \( \{O\} \)
- \( \mathcal{X}_{\{O\}} \) are translations/rotation of the payload expressed in frame \( \{O\} \)

It is then easy to include a reference tracking input that specify the wanted motion of the payload in the frame \( \{O\} \).

### 3.3 Modal Decoupling

Let’s consider a system with the following equations of motion:

\[
M \ddot{x} + C \dot{x} + K x = \mathcal{F}
\]  

(3.2)

And the measurement output is a combination of the motion variable \( x \):

\[
y = C_{oo} x + C_{ox} \dot{x}
\]  

(3.3)

Let’s make a change of variables:

\[
x = \Phi x_m
\]  

(3.4)

with:

- \( x_m \) the modal amplitudes
- \( \Phi \) a matrix whose columns are the modes shapes of the system

And we map the actuator forces:

\[
\mathcal{F} = J^T \tau
\]  

(3.5)
The equations of motion become:

\[M \Phi \ddot{x}_m + C \Phi \dot{x}_m + K \Phi x_m = J^T \tau \]  

(3.6)

And the measured output is:

\[y = C_{ox} \Phi x_m + C_{ov} \Phi \dot{x}_m \]  

(3.7)

By pre-multiplying the EoM by \( \Phi^T \):

\[\Phi^T M \Phi \ddot{x}_m + \Phi^T C \Phi \dot{x}_m + \Phi^T K \Phi x_m = \Phi^T J^T \tau \]  

(3.8)

And we note:

- \( M_m = \Phi^T M \Phi = \text{diag}(\mu_i) \) the modal mass matrix
- \( C_m = \Phi^T C \Phi = \text{diag}(2\xi_i \mu_i \omega_i) \) (classical damping)
- \( K_m = \Phi^T K \Phi = \text{diag}(\mu_i \omega_i^2) \) the modal stiffness matrix

And we have:

\[\ddot{x}_m + 2\Xi \Omega \dot{x}_m + \Omega^2 x_m = \mu^{-1} \Phi^T J^T \tau \]  

(3.9)

with:

- \( \mu = \text{diag}(\mu_i) \)
- \( \Omega = \text{diag}(\omega_i) \)
- \( \Xi = \text{diag}(\xi_i) \)

And we call the **modal input matrix**:

\[B_m = \mu^{-1} \Phi^T J^T \]  

(3.10)

And the **modal output matrices**:

\[C_m = C_{ox} \Phi + C_{ov} \Phi \]  

(3.11)

Let’s note the “modal input”:

\[\tau_m = B_m \tau \]  

(3.12)

The transfer function from \( \tau_m \) to \( x_m \) is:

\[\frac{x_m}{\tau_m} = (I_n s^2 + 2\Xi \Omega s + \Omega^2)^{-1} \]  

(3.13)

which is a **diagonal** transfer function matrix. We therefore have decoupling of the dynamics from \( \tau_m \) to \( x_m \).

We now expressed the transfer function from input \( \tau \) to output \( y \) as a function of the “modal variables”:

\[\frac{y}{\tau} = (C_{ox} + s C_{ov}) \Phi \left( I_n s^2 + 2\Xi \Omega s + \Omega^2 \right)^{-1} \left( \mu^{-1} \Phi^T J^T \right) \]  

(3.14)
By inverting $B_m$ and $C_m$ and using them as shown in Figure 3.4, we can see that we control the system in the “modal space” in which it is decoupled.

By inverting $B_m$ and $C_m$ and using them as shown in Figure 3.4, we can see that we control the system in the “modal space” in which it is decoupled.

$$G_m \rightarrow B_m^{-1} \rightarrow G \rightarrow C_m^{-1} \rightarrow x_m$$

**Figure 3.4: Modal Decoupling Architecture**

The system $G_m(s)$ shown in Figure 3.4 is diagonal (3.13).

**Important**

Modal decoupling requires to have the equations of motion of the system. From the equations of motion (and more precisely the mass and stiffness matrices), the mode shapes $\Phi$ are computed. Then, the system can be decoupled in the modal space. The obtained system on the diagonal are second order resonant systems which can be easily controlled. Using this decoupling strategy, it is possible to control each mode individually.

### 3.4 SVD Decoupling

Procedure:

- Identify the dynamics of the system from inputs to outputs (can be obtained experimentally)

- Choose a frequency where we want to decouple the system (usually, the crossover frequency is a good choice)

```
% Decoupling frequency [rad/s]
wc = 2*pi*10;

% System's response at the decoupling frequency
H1 = evalfr(G, j*wc);
```

- Compute a real approximation of the system’s response at that frequency

```
% Real approximation of G(j.wc)
D = pinv(real(H1'*H1));
H1 = pinv(D*real(H1'*diag(exp(j*angle(diag(H1*D*H1.'))/2))));
```

- Perform a Singular Value Decomposition of the real approximation

```
[U,S,V] = svd(H1);
```

- Use the singular input and output matrices to decouple the system as shown in Figure 3.5

$$G_{svd}(s) = U^{-1}G(s)V^{-T}$$
In order to apply the Singular Value Decomposition, we need to have the Frequency Response Function of the system, at least near the frequency where we wish to decouple the system. The FRF can be experimentally obtained or based from a model. This method ensures good decoupling near the chosen frequency, but no guaranteed decoupling away from this frequency. Also, it depends on how good the real approximation of the FRF is, therefore it might be less good for plants with high damping.

This method is quite general and can be applied to any type of system. The inputs and outputs are ordered from higher gain to lower gain at the chosen frequency.

- Do we lose any physical meaning of the obtained inputs and outputs?
- Can we take advantage of the fact that $U$ and $V$ are unitary?

### 3.5 Comparison

#### 3.5.1 Jacobian Decoupling

Decoupling properties depend on the chosen frame $\{O\}$.

Let’s take the CoM as the decoupling frame.

```matlab
Gx = pinv(J)*G*pinv(J);
Gx.InputName = {'Fx', 'Fy', 'Mz'};
Gx.OutputName = {'Dx', 'Dy', 'Rz'};
```
3.5.2 Modal Decoupling

For the system in Figure 3.1, we have:

\[ x = \begin{bmatrix} x \\ y \\ R_z \end{bmatrix} \]  
\[ y = L = Jx; \quad C_{ox} = J; \quad C_{ov} = 0 \]  
\[ M = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I \end{bmatrix}; \quad K = J^t \begin{bmatrix} k & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & k \end{bmatrix}J; \quad C = J^t \begin{bmatrix} c & 0 & 0 \\ 0 & c & 0 \\ 0 & 0 & c \end{bmatrix}J \]  

In order to apply the architecture shown in Figure 3.4, we need to compute \( C_{ox}, C_{ov}, \Phi, \mu \) and \( J \).

Matlab

```matlab
%% Modal Decomposition
[V,D] = eig(M/K);
%% Modal Mass Matrix
mu = V\'*M*V;
%% Modal output matrix
Cm = J*V;
%% Modal input matrix
Bm = inv(mu)*V\'*J';
```

<table>
<thead>
<tr>
<th>Table 3.1: ( B_m ) matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.0004</td>
</tr>
<tr>
<td>-0.0151</td>
</tr>
<tr>
<td>0.0</td>
</tr>
</tbody>
</table>

And the plant in the modal space is defined below and its magnitude is shown in Figure 3.7.
Table 3.2: $C_m$ matrix

<table>
<thead>
<tr>
<th></th>
<th>-0.1</th>
<th>-1.8</th>
<th>0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.2</td>
<td>0.5</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>-0.5</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

\[ G_m = \text{inv}(C_m) \times G \times \text{inv}(B_m); \]

Let’s now close one loop at a time and see how the transmissibility changes.

3.5.3 SVD Decoupling

Do we have something special when applying SVD to a collocated MIMO system?

- When applying SVD on a non-collated MIMO system, we obtained a decoupled plant looking like the one in Figure 1.8

\[
G_m(i,j) i \neq j
\]

\[
G_m(1,1)
\]

\[
G_m(2,2)
\]

\[
G_m(3,3)
\]

Figure 3.7: Modal plant $G_m(s)$
Table 3.3: Real approximate of $G$ at the decoupling frequency $\omega_c$

<table>
<thead>
<tr>
<th></th>
<th>-8e-06</th>
<th>2.1e-06</th>
<th>-2.1e-06</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8e-06</td>
<td>2.1e-06</td>
<td>-2.1e-06</td>
<td></td>
</tr>
<tr>
<td>2.1e-06</td>
<td>-1.3e-06</td>
<td>-2.5e-08</td>
<td></td>
</tr>
<tr>
<td>-2.1e-06</td>
<td>-2.5e-08</td>
<td>-1.3e-06</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.8: Svd plant $G_m(s)$

3.6 Robustness of the decoupling strategies?

What happens if we add an additional resonance in the system (Figure 3.9).

Having less actuator than DoF (under-actuated system):

- modal decoupling: can still control first $n$ modes?
- SVD decoupling: does not matter
- Jacobian decoupling: could give poor decoupling?

3.6.1 Plant

A multi body model of the system in Figure 3.9 has been made using Simscape.

Its parameters are defined below:

% Equilibrium length of struts [m]
leq = 20e-3;

% Mass [kg]
mr = 5;

% Stiffness [N/m]
kr = (2*pi*10)^2*mr;

% Damping [N/(m/s)]
cr = 1e1;

m = 400 - mr; % Mass [kg]
Figure 3.9: Plant with spurious resonance (additional DoF)

The plant is then identified and shown in Figure 3.10. The added resonance only slightly modifies the plant around 10Hz.

### 3.6.2 Jacobian Decoupling

The obtained plant is decoupled using the Jacobian matrix.

```
Gxr = pinv(J)*Gr*pinv(J);
Gxr.InputName = {'Fx', 'Fy', 'Mz'};
Gxr.OutputName = {'Dx', 'Dy', 'Rz'};
```

The obtained plant is shown in Figure 3.11 and is not much different than for the plant without the spurious resonance.

### 3.6.3 Modal Decoupling

The obtained plant is now decoupled using the modal matrices obtained with the plant not including the added resonance.

```
Gmr = inv(Cm)*Gr*inv(Bm);
```

The obtained decoupled plant is shown in Figure 3.12. Compare to the decoupled plant in Figure 3.7, the added resonance induces some coupling, especially around the frequency of the added spurious resonance.
Figure 3.10: Magnitude of the coupled plant without additional mode (solid) and with the additional mode (dashed).

Figure 3.11: Plant with spurious resonance decoupled using the Jacobian matrices $G_{x,r}(s)$
3.6.4 SVD Decoupling

The SVD decoupling is performed on the new obtained plant. The decoupling frequency is slightly shifted in order not to interfere too much with the spurious resonance.

```matlab
% Decoupling frequency [rad/s]
wc = 2*pi*7;

% System's response at the decoupling frequency
H1 = evalfr(Gr, j*wc);

% Real approximation of G(j.wc)
D = pinv(real(H1*H1'));
H1 = pinv(D*real(H1*diag(exp(j*angle(diag(H1*D*H1.'))/2))));

[U,S,V] = svd(H1);
Gsvdr = inv(U)*Gr*inv(V');
```

The obtained plant is shown in Figure 3.13.

3.7 Conclusion

The three proposed methods clearly have a lot in common as they all tend to make system more decoupled by pre and/or post multiplying by a constant matrix. However, the three methods also differ by a number of points which are summarized in Table 3.4.

Other decoupling strategies could be included in this study, such as:

- DC decoupling: pre-multiply the plant by $G(0)^{-1}$
- Full decoupling: pre-multiply the plant by $G(s)^{-1}$
<table>
<thead>
<tr>
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<tr>
<td>Decoupled Plant</td>
<td>$G_{\phi}(s) = J_{\phi}^{-1} G J_{\phi}^{-T}$</td>
<td>$G_m = C_m^{-1} G B_m^{-1}$</td>
<td>$G_{\text{svd}}(s) = U^{-1} G(s) V^{-T}$</td>
</tr>
<tr>
<td>Implemented Controller</td>
<td>$K_{\phi}(s) = J_{\phi}^{-1} K_{d}(s) J_{\phi}^{-T}$</td>
<td>$K_m = B_m^{-1} K_{d}(s) C_m^{-1}$</td>
<td>$K_{\text{svd}}(s) = V^{-T} K_{d}(s) U^{-1}$</td>
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<tr>
<td>Physical Interpretation</td>
<td>Forces/Torques to Displacement/Rotation in chosen frame</td>
<td>Inputs to excite individual modes</td>
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</tr>
<tr>
<td>Decoupling Properties</td>
<td>Decoupling at low or high frequency depending on the chosen frame</td>
<td>Good decoupling at all frequencies</td>
<td>Good decoupling near the chosen frequency</td>
</tr>
<tr>
<td>Pros</td>
<td>Physical inputs / outputs</td>
<td>Target specific modes</td>
<td>Good Decoupling near the crossover</td>
</tr>
<tr>
<td></td>
<td>Good decoupling at High frequency (diagonal mass matrix if Jacobian taken at the CoM)</td>
<td>2nd order diagonal plant</td>
<td>Very General</td>
</tr>
<tr>
<td></td>
<td>Good decoupling at Low frequency (if Jacobian taken at specific point)</td>
<td>Easy integration of meaningful reference inputs</td>
<td></td>
</tr>
<tr>
<td>Cons</td>
<td>Coupling between force/rotation may be high at low frequency (non diagonal terms in K)</td>
<td>Need analytical equations</td>
<td>Loose the physical meaning of inputs / outputs</td>
</tr>
<tr>
<td></td>
<td>Limited to parallel mechanisms (?)</td>
<td></td>
<td>Decoupling depends on the real approximation validity</td>
</tr>
<tr>
<td></td>
<td>If good decoupling at all frequencies $\Rightarrow$ requires specific mechanical architecture</td>
<td></td>
<td>Diagonal plants may not be easy to control</td>
</tr>
<tr>
<td>Applicability</td>
<td>Parallel Mechanisms</td>
<td>Systems whose dynamics that can be expressed with $M$ and $K$ matrices</td>
<td>Very general</td>
</tr>
<tr>
<td></td>
<td>Only small motion for the Jacobian matrix to stay constant</td>
<td>Need FRF data (either experimentally or analytically)</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.13: SVD decoupled plant including a spurious resonance $G_{svd,r}(s)$
4 Diagonal Stiffness Matrix for a planar manipulator

4.1 Model and Assumptions

Consider a parallel manipulator with:

- \( b_i \): location of the joints on the top platform are called \( b_i \)
- \( \hat{s}_i \): unit vector corresponding to the struts
- \( k_i \): stiffness of the struts
- \( \tau_i \): actuator forces
- \( O_M \): center of mass of the solid body

Consider two frames:

- \( \{M\} \) with origin \( O_M \)
- \( \{K\} \) with origin \( O_K \)

As an example, take the system shown in Figure 4.1.

![Figure 4.1: Example of 3DoF parallel platform](image)
4.2 Objective

The objective is to find conditions for the existence of a frame \( \{K\} \) in which the Stiffness matrix of the manipulator is diagonal. If the conditions are fulfilled, a second objective is to fine the location of the frame \( \{K\} \) analytically.

4.3 Conditions for Diagonal Stiffness

The stiffness matrix in the frame \( \{K\} \) can be expressed as:

\[
K_{\{K\}} = J_{\{K\}}^T K J_{\{K\}}
\]

(4.1)

where:

- \( J_{\{K\}} \) is the Jacobian transformation from the struts to the frame \( \{K\} \)
- \( K \) is a diagonal matrix with the strut stiffnesses on the diagonal

\[
K = \begin{bmatrix} k_1 & 0 & \cdots & 0 \\ k_2 & \ddots & \vdots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & k_n \end{bmatrix}
\]

(4.2)

The Jacobian for a planar manipulator, evaluated in a frame \( \{K\} \), can be expressed as follows:

\[
J_{\{K\}} = \begin{bmatrix}
K\hat{s}_1^T & K b_1, x K \hat{s}_1, y - K b_1, x K \hat{s}_1, y \\
K\hat{s}_2^T & K b_2, x K \hat{s}_2, y - K b_2, x K \hat{s}_2, y \\
\vdots & \vdots \\
K\hat{s}_n^T & K b_n, x K \hat{s}_n, y - K b_n, x K \hat{s}_n, y
\end{bmatrix}
\]

(4.3)

Let’s omit the mention of frame, it is assumed that vectors are expressed in frame \( \{K\} \). It is specified otherwise.

Injecting (4.3) into (4.1) yields:

\[
K_{\{K\}} = \begin{bmatrix}
k_i \hat{s}_i \hat{s}_i^T \\
k_i \hat{s}_i (b_i, x \hat{s}_i, y - b_i, y \hat{s}_i, x)
\end{bmatrix}
\]

(4.4)

In order to have a decoupled stiffness matrix, we have the following two conditions:

\[
k_i \hat{s}_i \hat{s}_i^T = \text{diag. matrix} \quad \text{(4.5)}
\]

\[
k_i \hat{s}_i (b_i, x \hat{s}_i, y - b_i, y \hat{s}_i, x) = 0 \quad \text{(4.6)}
\]

Note that we don’t have any condition on the term \( k_i (b_i, x \hat{s}_i, y - b_i, y \hat{s}_i, x)^2 \) as it is only a scalar.

Condition (4.5):
• represents the coupling between translations and forces

• does only depend on the orientation of the struts and the stiffnesses and not on the choice of frame

• it is therefore a intrinsic property of the chosen geometry

Condition (4.6):

• represents the coupling between forces/rotations and torques/translation

• it does depend on the positions of the joints \( b_i \) in the frame \( \{ \mathcal{K} \} \)

Let’s make a change of frame from the initial frame \( \{ \mathcal{M} \} \) to the frame \( \{ \mathcal{K} \} \):

\[
K b_i = M b_i - M O K
\]

\[
K \dot{s}_i = M \ddot{s}_i
\] (4.7) (4.8)

And the goal is to find \( M O K \) such that (4.6) is fulfilled:

\[
k_i (M b_{i,x} \hat{s}_{i,y} - M b_{i,y} \hat{s}_{i,x}) \hat{s}_i = M O K_{,x} k_i \ddot{s}_i - M O K_{,y} k_i \ddot{s}_i
\]

\[
k_i (M b_{i,x} \hat{s}_{i,x} - M b_{i,y} \hat{s}_{i,y}) \hat{s}_i = M O K_{,x} k_i \ddot{s}_i - M O K_{,y} k_i \ddot{s}_i
\] (4.9) (4.10)

And we have two sets of linear equations of two unknowns.

This can be easily solved by writing the equations in a matrix form:

\[
k_i (M b_{i,x} \hat{s}_{i,y} - M b_{i,y} \hat{s}_{i,x}) \hat{s}_i = \begin{bmatrix} k_i \hat{s}_{i,x} \hat{s}_{i,y} - k_i \hat{s}_{i,y} \hat{s}_{i,x} \\ k_i \hat{s}_{i,x} \hat{s}_{i,y} - k_i \hat{s}_{i,y} \hat{s}_{i,x} \end{bmatrix} \begin{bmatrix} M O K_{,x} \\ M O K_{,y} \end{bmatrix}
\] (4.11)

And finally, if the matrix is invertible:

\[
M O K = \begin{bmatrix} k_i \hat{s}_{i,x} \hat{s}_{i,y} - k_i \hat{s}_{i,y} \hat{s}_{i,x} \\ k_i \hat{s}_{i,x} \hat{s}_{i,y} - k_i \hat{s}_{i,y} \hat{s}_{i,x} \end{bmatrix}^{-1} k_i (M b_{i,x} \hat{s}_{i,y} - M b_{i,y} \hat{s}_{i,x}) \hat{s}_i
\] (4.12)

Note that a rotation of the frame \( \{ \mathcal{K} \} \) with respect to frame \( \{ \mathcal{M} \} \) would make not change on the “diagonality” of \( K_{\{K\}} \).

### 4.4 Example 1 - Planar manipulator with 3 actuators

Consider system of Figure 4.2.

The stiffnesses \( k_i \), the joint positions \( M b_i \) and joint unit vectors \( M \hat{s}_i \) are defined below:
Let’s first verify that condition (4.5) is true:

\[
\begin{bmatrix} 5 & 0 \\ 0 & 2 \end{bmatrix}
\]

Now, compute \(MOK\):

\[
\text{Matlab}
\begin{align*}
\text{Ok} &= \text{inv}(\text{sum}(ki.*si(2,:).*si, 2), -\text{sum}(ki.*si(1,:).*si, 2))\text{sum}(ki.*(bi(1,:).*si(2,:) - bi(2,:).*si(1,:)).*si, 2);}
\end{align*}
\]

\[
\begin{bmatrix} -1 \\ 0.5 \end{bmatrix}
\]

Let’s compute the new coordinates \(Kbi\) after the change of frame:

\[
\text{Matlab}
\begin{align*}
\text{Kbi} &= bi - Ok;
\end{align*}
\]

In order to verify that the new frame \(\{K\}\) indeed yields a diagonal stiffness matrix, we first compute the Jacobian \(J_{\{K\}}\):

\[
\text{Matlab}
\begin{align*}
\text{Jk} &= [si', (\text{Kbi}(1,:).*si(2,:) - \text{Kbi}(2,:).*si(1,:))'];
\end{align*}
\]

\[
\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & 1 & 1 \end{bmatrix}
\]
And the stiffness matrix:

\[
K = Jk' \cdot \text{diag}(k) \cdot Jk
\]

\[
\begin{pmatrix}
5 & 0 & 0 \\
0 & 2 & 0 \\
0 & 0 & 2
\end{pmatrix}
\]

4.5 Example 2 - Planar manipulator with 4 actuators

Now consider the planar manipulator of Figure 4.3.

![Planar Manipulator](image)

**Figure 4.3:** Planar Manipulator

The stiffnesses \(k_i\), the joint positions \(M b_i\) and joint unit vectors \(M \hat{s}_i\) are defined below:

\[
\begin{align*}
k_i &= [1,2,1,1]; \\
\hat{s}_i &= \left[ \begin{array}{c} 1;0 \\ 0;1 \end{array} \right], \left[ -1;0 \right], \left[ 0;1 \right]; \\
\hat{s}_i &= \hat{s}_i / \text{vecnorm}(\hat{s}_i); \\
h &= 0.2;
\end{align*}
\]
\[ L = 2; \]
\[ b_i = \{[-L/2; h], [-L/2; -h], [L/2; h], [L/2; -h]\}; \]

Let’s first verify that condition (4.5) is true:

\[
\text{Matlab} \\
\text{ki.*si*si'} \\
\begin{bmatrix} 2 & 0 \\ 0 & 3 \end{bmatrix}
\]

Now, compute \( \mathbf{M} O \mathbf{K} \):

\[
\text{Matlab} \\
\text{Ok} = \text{inv}([\text{sum(ki.*si(2,:).*si, 2)}, -\text{sum(ki.*si(1,:).*si, 2)]*\text{sum(ki.*(bi(1,:).*si(2,:) - bi(2,:).*si(1,:)).*si, 2)}];
\]

\[
\begin{bmatrix} -0.3333 & 0.2 \end{bmatrix}
\]

Let’s compute the new coordinates \( \mathbf{K} b_i \) after the change of frame:

\[
\text{Matlab} \\
\text{Kbi = bi - Ok;}
\]

In order to verify that the new frame \( \{ \mathbf{K} \} \) indeed yields a diagonal stiffness matrix, we first compute the Jacobian \( J(\mathbf{K}) \):

\[
\text{Matlab} \\
\text{Jk} = [\text{si', (Kbi(1,:).*si(2,:) - Kbi(2,:).*si(1,:)).*si(1,:)'}];
\]

\[
\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & -0.6667 \\ -1 & 0 & 0 \\ 0 & 1 & 1.3333 \end{bmatrix}
\]

And the stiffness matrix:

\[
\text{Matlab} \\
\text{K = Jk'*diag(ki)*Jk}
\]

\[
\begin{bmatrix} 2 & 0 & 0 \\ 0 & 3 & -2.2204e-16 \\ 0 & -2.2204e-16 & 2.6667 \end{bmatrix}
\]

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5 Diagonal Stiffness Matrix for a general parallel manipulator

5.1 Model and Assumptions

Let’s consider a 6dof parallel manipulator with:

- \( b_i \): location of the joints on the top platform are called \( b_i \)
- \( \hat{s}_i \): unit vector corresponding to the struts
- \( k_i \): stiffness of the struts
- \( \tau_i \): actuator forces
- \( O_M \): center of mass of the solid body

Consider two frames:

- \( \{M\} \) with origin \( O_M \)
- \( \{K\} \) with origin \( O_K \)

An example is shown in Figure 5.1.

![Figure 5.1: Parallel manipulator Example](image-url)
5.2 Objective

The objective is to find conditions for the existence of a frame \( \{ K \} \) in which the Stiffness matrix of the manipulator is diagonal. If the conditions are fulfilled, a second objective is to find the location of the frame \( \{ K \} \) analytically.

5.3 Analytical formula of the stiffness matrix

For a fully parallel manipulator, the stiffness matrix \( K_{\{ K \}} \) expressed in a frame \( \{ K \} \) is:

\[
K_{\{ K \}} = J_{\{ K \}}^T K J_{\{ K \}}
\]  
(5.1)

where:

- \( J_{\{ K \}} \) is the Jacobian transformation from the struts to the frame \( \{ K \} \)
- \( K \) is a diagonal matrix with the strut stiffnesses on the diagonal:

\[
K = \begin{bmatrix}
    k_1 & 0 \\
    k_2 & \ldots \\
    0 & k_n
\end{bmatrix}
\]  
(5.2)

The analytical expression of \( J_{\{ K \}} \) is:

\[
J_{\{ K \}} = \begin{bmatrix}
    K \hat{s}_1^T (K b_1 \times K \hat{s}_1)^T \\
    K \hat{s}_2^T (K b_2 \times K \hat{s}_2)^T \\
    \vdots \\
    K \hat{s}_n^T (K b_n \times K \hat{s}_n)^T
\end{bmatrix}
\]  
(5.3)

To simplify, we ignore the superscript \( K \) and we assume that all vectors / positions are expressed in this frame \( \{ K \} \). Otherwise, it is explicitly written.

Let’s now write the analytical expressing of the stiffness matrix \( K_{\{ K \}} \):

\[
K_{\{ K \}} = \begin{bmatrix}
    \hat{s}_1 & \ldots & \hat{s}_n \\
    (b_1 \times \hat{s}_1) & \ldots & (b_n \times \hat{s}_n)
\end{bmatrix}
\begin{bmatrix}
    k_1 & \ldots & k_n
\end{bmatrix}
\begin{bmatrix}
    \hat{s}_1^T (b_1 \times \hat{s}_1)^T \\
    \hat{s}_2^T (b_2 \times \hat{s}_2)^T \\
    \vdots \\
    \hat{s}_n^T (b_n \times \hat{s}_n)^T
\end{bmatrix}
\]  
(5.4)

And we finally obtain:

\[
K_{\{ K \}} = \begin{bmatrix}
    k_i \hat{s}_i \hat{s}_i^T & k_i \hat{s}_i (b_i \times \hat{s}_i)^T \\
    k_i (b_i \times \hat{s}_i) \hat{s}_i^T & k_i (b_i \times \hat{s}_i)(b_i \times \hat{s}_i)^T
\end{bmatrix}
\]  
(5.5)
We want the stiffness matrix to be diagonal, therefore, we have the following conditions:

\[ k_i \hat{s}_i \hat{s}_i^T = \text{diag. matrix} \]  
(5.6)

\[ k_i (b_i \times \hat{s}_i)(b_i \times \hat{s}_i)^T = \text{diag. matrix} \]  
(5.7)

\[ k_i \hat{s}_i (b_i \times \hat{s}_i)^T = 0 \]  
(5.8)

Note that:

- condition (5.6) corresponds to coupling between forces applied on \( O_K \) to translations of the payload. It does not depend on the choice of \{K\}, it only depends on the orientation of the struts and the stiffnesses. It is therefore an intrinsic property of the manipulator.

- condition (5.7) corresponds to the coupling between forces applied on \( O_K \) and rotation of the payload. Similarly, it does also correspond to the coupling between torques applied on \( O_K \) to translations of the payload.

- condition (5.8) corresponds to the coupling between torques applied on \( O_K \) to rotation of the payload.

- conditions (5.7) and (5.8) do depend on the positions \( K b_i \) and therefore depend on the choice of \{K\}.

Note that if we find a frame \{K\} in which the stiffness matrix \( K_{\{K\}} \) is diagonal, it will still be diagonal for any rotation of the frame \{K\}. Therefore, we here suppose that the frame \{K\} is aligned with the initial frame \{M\}.

Let’s make a change of frame from the initial frame \{M\} to the frame \{K\}:

\[ K b_i = M b_i - M O_K \]  
(5.9)

\[ K \hat{s}_i = M \hat{s}_i \]  
(5.10)

The goal is to find \( M O_K \) such that conditions (5.7) and (5.8) are fulfilled.

Let’s first solve equation (5.8) that corresponds to the coupling between forces and rotations:

\[ k_i \hat{s}_i ((M b_i - M O_K) \times \hat{s}_i)^T = 0 \]  
(5.11)

Taking the transpose and re-arranging:

\[ k_i (M b_i \times \hat{s}_i)\hat{s}_i^T = k_i (M O_K \times \hat{s}_i)\hat{s}_i^T \]  
(5.12)

As the vector cross product also can be expressed as the product of a skew-symmetric matrix and a vector, we obtain:

\[ k_i (M b_i \times \hat{s}_i)\hat{s}_i^T = M O_K (k_i \hat{s}_i \hat{s}_i^T) \]  
(5.13)

with:

\[ M O_K = \begin{bmatrix} 0 & -M O_{K,z} & M O_{K,y} \\ M O_{K,z} & 0 & -M O_{K,x} \\ -M O_{K,y} & M O_{K,x} & 0 \end{bmatrix} \]  
(5.14)
We suppose $k_i \hat{s}_i \hat{s}_i^T$ invertible as it is diagonal from (5.6).

And finally, we find:

$$M_O K = (k_i (M_b \times \hat{s}_i) \hat{s}_i^T) \cdot (k_i \hat{s}_i \hat{s}_i^T)^{-1}$$

(5.15)

If the obtained $M_O K$ is a skew-symmetric matrix, we can easily determine the corresponding vector $M_O K$ from (5.14).

In such case, condition (5.7) is fulfilled and there is no coupling between translations and rotations in the frame \{\textit{K}\}.

Then, we can only verify if condition (5.8) is verified or not.

**Note**

If there is no frame \{\textit{K}\} such that conditions (5.7) and (5.8) are valid, it would be interesting to be able to determine the frame \{\textit{K}\} in which is coupling is minimal.

### 5.4 Example 1 - 6DoF manipulator (3D)

Let’s define the geometry of the manipulator ($M_b$, $M_s$ and $k_i$):

\[
\begin{align*}
  &k_i = [2,2,1,3,3,1,1,1,2,2]; \\
  &s_i = [[-1;0;0],[-1;0;0],[-1;0;0],[-1;0;0],[0;0;1],[0;0;1],[0;0;1],[0;0;1],[0;-1;0],[0;-1;0],[0;-1;0],[0;-1;0]]; \\
  &b_i = \text{Matlab} \quad \text{Cond 1:} \\
  &\text{Matlab}
\end{align*}
\]

\[
\begin{align*}
  &ki.*si*si' \\
  &6 0 0 \\
  &0 6 0 \\
  &0 0 8
\end{align*}
\]

Find Ok

\[
\begin{align*}
  &\text{Matlab} \\
  &\text{OkX} = (ki.*cross(bi, si)*si')/(ki.*si*si'); \\
  &\text{if all(diag(OkX) == 0) && all(all((OkX + OkX') == 0))} \\
  &\text{disp('OkX is skew symmetric')} \\
  &\text{Ok = [OkX(1,2);OkX(1,3);OkX(2,1)];} \\
  &\text{else} \\
  &\text{error('OkX is not skew symmetric')} \\
  &\text{end}
\end{align*}
\]

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% Verification of second condition
si = cross(bi - Ok, si)'

0 0 0
0 0 0
0 0 0

Verification of third condition

ki.*cross(bi - Ok, si)*cross(bi - Ok, si)'

14 4 -2
4 14 2
-2 2 12

Let’s compute the Jacobian:

Jk = [si', cross(bi - Ok, si)'];

And the stiffness matrix:

Jk*diag(ki)*Jk

6 0 0 0 0 0
0 6 0 0 0 0
0 0 8 0 0 0
0 0 0 14 4 -2
0 0 0 4 14 2
0 0 0 -2 2 12

figure;
hold on;
set(gca, 'ColorOrderIndex',1)
plot(b1(1), b1(2), 'o');
set(gca, 'ColorOrderIndex',2)
plot(b2(1), b2(2), 'o');
set(gca, 'ColorOrderIndex',3)
plot(b3(1), b3(2), 'o');
set(gca, 'ColorOrderIndex',4)
quiver(b1(1),b1(2),0.1*s1(1),0.1*s1(2))
quiver(b2(1),b2(2),0.1*s2(1),0.1*s2(2))
quiver(b3(1),b3(2),0.1*s3(1),0.1*s3(2))
set(gca, 'ColorOrderIndex',3)
5.5 Example 2 - Stewart Platform
6 Stiffness and Mass Matrices in the Leg’s frame

6.1 Equations

Equations in the $\{M\}$ frame:
\[
\left( M_{\{M\}} s^2 + K_{\{M\}} \right) x_{\{M\}} = f_{\{M\}} \tag{6.1}
\]

Thank to the Jacobian, we can transform the equation of motion expressed in the $\{M\}$ frame to the frame of the legs:
\[
J_{\{M\}}^{-T} \left( M_{\{M\}} s^2 + K_{\{M\}} \right) J_{\{M\}}^{-1} \dot{L} = \tau \tag{6.2}
\]

And we have new stiffness and mass matrices:
\[
(M_{\{L\}} s^2 + K_{\{L\}}) \dot{L} = \tau \tag{6.3}
\]

with:

- The local mass matrix:
  \[
  M_{\{L\}} = J_{\{M\}}^{-T} M_{\{M\}} J_{\{M\}}^{-1}
  \]

- The local stiffness matrix:
  \[
  K_{\{L\}} = J_{\{M\}}^{-T} K_{\{M\}} J_{\{M\}}^{-1}
  \]

6.2 Stiffness matrix

We have that:
\[
K_{\{M\}} = J_{\{M\}}^{-T} K J_{\{M\}}
\]

Therefore, we find that $K_{\{L\}}$ is a diagonal matrix:
\[
K_{\{L\}} = K = \begin{bmatrix}
k_1 & & 0 \\
& \ddots & \\
0 & & k_n
\end{bmatrix} \tag{6.4}
\]

The dynamics from $\tau$ to $\mathcal{L}$ is therefore decoupled at low frequency.
6.3 Mass matrix

The mass matrix in the frames of the legs is:

\[ M_{\{L\}} = J_{\{M\}}^{-T} M_{\{M\}} J_{\{M\}}^{-1} \]

with \( M_{\{M\}} \) a diagonal matrix:

\[
M_{\{M\}} = \begin{bmatrix}
m & m & 0 \\
m & I_x & \\
0 & I_y & I_z
\end{bmatrix}
\]

(6.5)

Let’s suppose \( M_{\{L\}} = M \) diagonal and try to find what does this imply:

\[ M_{\{M\}} = J_{\{M\}}^T M J_{\{M\}} \]

with:

\[
M = \begin{bmatrix}
m_1 & 0 \\
\vdots & \ddots \\
0 & m_n
\end{bmatrix}
\]

(6.6)

We obtain:

\[
M_{\{M\}} = \begin{bmatrix}
m_i \hat{s}_i \hat{s}_i^T & m_i \hat{s}_i (b_i \times \hat{s}_i)^T \\
k_i \hat{s}_i (b_i \times \hat{s}_i)^T & m_i (b_i \times \hat{s}_i)^T (b_i \times \hat{s}_i)^T
\end{bmatrix}
\]

(6.7)

Therefore, we have the following conditions:

\[
m_i \hat{s}_i \hat{s}_i^T = m I_3
\]

(6.8)

\[
m_i \hat{s}_i (b_i \times \hat{s}_i)^T = O_3
\]

(6.9)

\[
m_i (b_i \times \hat{s}_i)^T (b_i \times \hat{s}_i)^T = \text{diag}(I_x, I_y, I_z)
\]

(6.10)

6.4 Planar Example

The stiffnesses \( k_i \), the joint positions \( M b_i \) and joint unit vectors \( M \hat{s}_i \) are defined below:

Matlab

\[
\text{Matlab}:
\begin{align*}
\text{ki} = [1,1,1]; & \quad \text{Stiffnesses [N/m]} \\
\text{si} = [[1;0],[0;1],[0;1]]; & \quad \text{si} = \text{s}$/\text{vecnorm(s)}; \quad \text{Unit Vectors} \\
\text{bi} = [[-1; 0],[-10;-1],[0;-1]]; & \quad \text{Joint positions in frame \{M\}}
\end{align*}
\]

Jacobian in frame \{M\}:
And the stiffness matrix in frame \{K\}:

\[
K_m = J_m \, \text{diag}(k_i) \, J_m;
\]

\[
\begin{bmatrix}
2 & 0 & 1 \\
0 & 1 & -1 \\
1 & -1 & 2
\end{bmatrix}
\]

Mass matrix in the frame \{M\}:

\[
m = 10; \quad \text{[kg]}
\]
\[
I = 1; \quad \text{[kg}\cdot\text{m}^2]
\]

\[
M_m = \text{diag}([m, m, I]);
\]

Now compute \(K\) and \(M\) in the frame of the legs:

\[
M_L = \text{inv}(J_m) \, \text{diag}(m) \, \text{inv}(J_m)
\]

\[
K_L = \text{inv}(J_m) \, \text{diag}(k_i) \, \text{inv}(J_m)
\]

\[
G_m = 1/(M_L \, s^2 + K_L);
\]

\[
\text{freqs} = \text{logspace}(-2, 1, 1000);
\]
\[
\text{figure;}
\]
\[
\text{hold on;}
\]
\[
\text{for } i = 1:\text{length}(k_i)
\]
\[
\text{plot(}\text{freqs}, \text{abs(squeeze(freqresp(G_m(i,i), freqs, 'Hz')))}, 'k-')
\]
\[
\end
\]
\[
\text{for } i = 1:\text{length}(k_i)
\]
\[
\text{for } j = i+1:\text{length}(k_i)
\]
\[
\text{plot(}\text{freqs}, \text{abs(squeeze(freqresp(G_m(i,j), freqs, 'Hz')))}, 'r-')
\]
\[
\end
\]
\[
\text{hold off;}
\]
\[
\text{xlabel('Frequency [Hz]');}
\]
\[
\text{ylabel('Magnitude');}
\]
\[
\text{set(gca, 'yscale', 'log');}
\]
\[
\text{set(gca, 'yaxis', 'log');}
\]
7 Stewart Platform - Simscape Model

In this analysis, we wish to applied SVD control to the Stewart Platform shown in Figure 7.1.

Some notes about the system:

- 6 voice coils actuators are used to control the motion of the top platform.
- the motion of the top platform is measured with a 6-axis inertial unit (3 acceleration + 3 angular accelerations)
- the control objective is to isolate the top platform from vibrations coming from the bottom platform

![Figure 7.1: Stewart Platform CAD View](image)

The analysis of the SVD/Jacobian control applied to the Stewart platform is performed in the following sections:

- Section 7.1: The parameters of the Simscape model of the Stewart platform are defined
- Section 7.2: The plant is identified from the Simscape model and the system coupling is shown
- Section 7.3: The plant is first decoupled using the Jacobian
- Section 7.4: The decoupling is performed thanks to the SVD. To do so a real approximation of
the plant is computed.

- Section 7.5: The effectiveness of the decoupling with the Jacobian and SVD are compared using the Gershgorin Radii

- Section 7.6:

- Section 7.7: The dynamics of the decoupled plants are shown

- Section 7.8: A diagonal controller is defined to control the decoupled plant

- Section 7.9: Finally, the closed loop system properties are studied

### 7.1 Simscape Model - Parameters

```matlab
open('drone_platform.slx');
```

Definition of spring parameters:

```matlab
kx = 0.5e3/3; % [N/m]
y = 0.5e3/3;
z = 1e3/3;
```

```matlab
cx = 0.025; % [Nm/rad]
cy = 0.025;
```

```matlab
cz = 0.025;
```

We suppose the sensor is perfectly positioned.

```matlab
sens_pos_error = zeros(3,1);
```

Gravity:

```matlab
g = 0;
```

We load the Jacobian (previously computed from the geometry):

```matlab
load('jacobian.mat', 'Aa', 'Ab', 'As', 'I', 'J');
```

We initialize other parameters:
7.2 Identification of the plant

The plant shown in Figure 7.4 is identified from the Simscape model.

The inputs are:

- $D_w$ translation and rotation of the bottom platform (with respect to the center of mass of the top platform)
- $\tau$ the 6 forces applied by the voice coils

The outputs are the 6 accelerations measured by the inertial unit.
Figure 7.3: Simscape model of the Stewart platform

Figure 7.4: Considered plant $G = \begin{bmatrix} G_d \\ G_u \end{bmatrix}$. $D_w$ is the translation/rotation of the support, $\tau$ the actuator forces, $a$ the acceleration/angular acceleration of the top platform
The elements of the transfer matrix $G$ corresponding to the transfer function from actuator forces $\tau$ to the measured acceleration $a$ are shown in Figure 7.5.

One can easily see that the system is strongly coupled.

![Figure 7.5: Magnitude of all 36 elements of the transfer function matrix $G_u$](image)

### 7.3 Decoupling using the Jacobian

Consider the control architecture shown in Figure 7.6. The Jacobian matrix is used to transform forces/torques applied on the top platform to the equivalent forces applied by each actuator.

The Jacobian matrix is computed from the geometry of the platform (position and orientation of the actuators).
### Table 7.1: Computed Jacobian Matrix

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.811</td>
<td>0.0</td>
<td>0.584</td>
<td>-0.018</td>
<td>-0.008</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>-0.406</td>
<td>-0.703</td>
<td>0.584</td>
<td>-0.016</td>
<td>-0.012</td>
<td>-0.025</td>
<td></td>
</tr>
<tr>
<td>-0.406</td>
<td>0.703</td>
<td>0.584</td>
<td>0.016</td>
<td>-0.012</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>0.811</td>
<td>0.0</td>
<td>0.584</td>
<td>0.018</td>
<td>-0.008</td>
<td>-0.025</td>
<td></td>
</tr>
<tr>
<td>-0.406</td>
<td>-0.703</td>
<td>0.584</td>
<td>0.002</td>
<td>0.019</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>-0.406</td>
<td>0.703</td>
<td>0.584</td>
<td>-0.002</td>
<td>0.019</td>
<td>-0.025</td>
<td></td>
</tr>
</tbody>
</table>

#### Figure 7.6: Decoupled plant \( G_x \) using the Jacobian matrix \( J \)

We define a new plant:

\[
G_x(s) = G(s)J^{-T}
\]

\( G_x(s) \) correspond to the transfer function from forces and torques applied to the top platform to the absolute acceleration of the top platform.

Matlab

\[
G_x = G \times \text{inv}(J');
Gx.InputName = {'Fx', 'Fy', 'Fz', 'Mx', 'My', 'Mz'};
\]

### 7.4 Decoupling using the SVD

In order to decouple the plant using the SVD, first a real approximation of the plant transfer function matrix as the crossover frequency is required.

Let’s compute a real approximation of the complex matrix \( H_1 \) which corresponds to the transfer function \( G_u(j\omega_c) \) from forces applied by the actuators to the measured acceleration of the top platform evaluated at the frequency \( \omega_c \).

Matlab

\[
w_c = 2\pi*30; \quad % Decoupling frequency [rad/s]
H1 = evalfr(Gu, j*w_c);
\]

The real approximation is computed as follows:

Matlab

\[
D = \text{pinv}(\text{real}(H1' \times H1));
H1 = \text{inv}(D' \times \text{real}(H1') \times \text{diag}(\text{exp}(\text{angle}(\text{diag}(H1' \times D \times H1'))/2))) ;
\]

Note that the plant \( G_u \) at \( \omega_c \) is already an almost real matrix. This can be seen on the Bode plots where the phase is close to 1. This can be verified below where only the real value of \( G_u(\omega_c) \) is shown

72
Table 7.2: Real approximate of $G$ at the decoupling frequency $\omega_c$

\[
\begin{array}{ccccccc}
4.4 & -2.1 & -2.1 & 4.4 & -2.4 & -2.4 \\
-0.2 & -3.9 & 3.9 & 0.2 & -3.8 & 3.8 \\
3.4 & 3.4 & 3.4 & 3.4 & 3.4 & 3.4 \\
-367.1 & -323.8 & 323.8 & 367.1 & 43.3 & -43.3 \\
-162.0 & -237.0 & -237.0 & -162.0 & 398.9 & 398.9 \\
220.6 & -220.6 & 220.6 & -220.6 & 220.6 & -220.6 \\
\end{array}
\]

Table 7.3: Real part of $G$ at the decoupling frequency $\omega_c$

\[
\begin{array}{ccccccc}
4.4 & -2.1 & -2.1 & 4.4 & -2.4 & -2.4 \\
-0.2 & -3.9 & 3.9 & 0.2 & -3.8 & 3.8 \\
3.4 & 3.4 & 3.4 & 3.4 & 3.4 & 3.4 \\
-367.1 & -323.8 & 323.8 & 367.1 & 43.3 & -43.3 \\
-162.0 & -237.0 & -237.0 & -162.0 & 398.9 & 398.9 \\
220.6 & -220.6 & 220.6 & -220.6 & 220.6 & -220.6 \\
\end{array}
\]

Now, the Singular Value Decomposition of $H_1$ is performed:

\[
H_1 = USV^H
\]

\[
[u,~,v] = svd(H1);
\]

Table 7.4: Obtained matrix $U$

\[
\begin{array}{ccccccc}
-0.005 & 7e-06 & 6e-11 & -3e-06 & -1 & 0.1 \\
-7e-06 & -0.005 & -9e-09 & -5e-09 & -0.1 & -1 \\
4e-08 & -2e-10 & -6e-11 & -1 & 3e-06 & -3e-07 \\
-0.002 & -1 & -5e-06 & 2e-10 & 0.0006 & 0.005 \\
1 & -0.002 & -1e-08 & 2e-08 & -0.005 & 0.0006 \\
-4e-09 & 5e-06 & -1 & 6e-11 & -2e-09 & -1e-08 \\
\end{array}
\]

The obtained matrices $U$ and $V$ are used to decouple the system as shown in Figure 7.7.

The decoupled plant is then:

\[
G_{SVD}(s) = U^{-1}G_u(s)V^{-H}
\]

\[
Gsvd = inv(U)*Guv*inv(V);\]

7.5 Verification of the decoupling using the “Gershgorin Radii”

The “Gershgorin Radii” is computed for the coupled plant $G(s)$, for the “Jacobian plant” $G_x(s)$ and the “SVD Decoupled Plant” $G_{SVD}(s)$:

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Table 7.5: Obtained matrix $V$

\[
\begin{bmatrix}
-0.2 & 0.5 & -0.4 & -0.4 & -0.6 & -0.2 \\
-0.3 & 0.5 & 0.4 & -0.4 & 0.5 & 0.3 \\
-0.3 & -0.5 & -0.4 & -0.4 & 0.4 & -0.4 \\
-0.2 & -0.5 & 0.4 & -0.4 & -0.5 & 0.3 \\
0.6 & -0.06 & -0.4 & -0.4 & 0.1 & 0.6 \\
0.6 & 0.06 & 0.4 & -0.4 & -0.006 & -0.6
\end{bmatrix}
\]

Figure 7.7: Decoupled plant $G_{SVD}$ using the Singular Value Decomposition

The “Gershgorin Radii” of a matrix $S$ is defined by:

\[
\zeta_i(j\omega) = \frac{\sum_{j \neq i} |S_{ij}(j\omega)|}{|S_{ii}(j\omega)|}
\]

This is computed over the following frequencies.

Figure 7.8: Gershgorin Radii of the Coupled and Decoupled plants

7.6 Verification of the decoupling using the “Relative Gain Array”

The relative gain array (RGA) is defined as:

\[
\Lambda(G(s)) = G(s) \times (G(s)^{-1})^T
\]  

(7.1)
where \( \times \) denotes an element by element multiplication and \( G(s) \) is an \( n \times n \) square transfer matrix.

The obtained RGA elements are shown in Figure 7.9.

![Figure 7.9: Obtained norm of RGA elements for the SVD decoupled plant and the Jacobian decoupled plant](image)

**7.7 Obtained Decoupled Plants**

The bode plot of the diagonal and off-diagonal elements of \( G_{SVD} \) are shown in Figure 7.10.

Similarly, the bode plots of the diagonal elements and off-diagonal elements of the decoupled plant \( G_x(s) \) using the Jacobian are shown in Figure 7.11.

**7.8 Diagonal Controller**

The control diagram for the centralized control is shown in Figure 7.12.

The controller \( K_c \) is “working” in an cartesian frame. The Jacobian is used to convert forces in the cartesian frame to forces applied by the actuators.
The SVD control architecture is shown in Figure 7.13. The matrices $U$ and $V$ are used to decouple the plant $G$.

We choose the controller to be a low pass filter:

$$K_c(s) = \frac{G_0}{1 + \frac{s}{\omega_0}}$$

$G_0$ is tuned such that the crossover frequency corresponding to the diagonal terms of the loop gain is equal to $\omega_c$.

Matlab

```matlab
wc = 2*pi*80; % Crossover Frequency [rad/s]
w0 = 2*pi*0.1; % Controller Pole [rad/s]

K_cen = diag(1./diag(abs(evalfr(Gx, j*wc))))*(1/abs(evalfr(1/(1 + s/w0), j*wc)))/(1 + s/w0); % Centre Controller
L_cen = K_cen*Gx;
G_cen = feedback(G, pinv(V' )*K_cen, [7:12], [1:6]);

K_svd = diag(1./diag(abs(evalfr(Gsvd, j*wc))))*(1/abs(evalfr(1/(1 + s/w0), j*wc)))/(1 + s/w0); % SVD Controller
L_svd = K_svd*Gsvd;
G_svd = feedback(G, inv(V')*K_svd*inv(U), [7:12], [1:6]);
```

**Figure 7.10**: Decoupled Plant using SVD
Figure 7.11: Stewart Platform Plant from forces (resp. torques) applied by the legs to the acceleration (resp. angular acceleration) of the platform as well as all the coupling terms between the two (non-diagonal terms of the transfer function matrix)

Figure 7.12: Control Diagram for the Centralized control

Figure 7.13: Control Diagram for the SVD control
The obtained diagonal elements of the loop gains are shown in Figure 7.14.

![Figure 7.14: Comparison of the diagonal elements of the loop gains for the SVD control architecture and the Jacobian one](image)

7.9 Closed-Loop system Performances

Let’s first verify the stability of the closed-loop systems:

```matlab
issstable(G_cen)  # Matlab

ans =
    logical
   1

issstable(G_svd)  # Matlab
```

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The obtained transmissibility in Open-loop, for the centralized control as well as for the SVD control are shown in Figure 7.15.

![Figure 7.15: Obtained Transmissibility](image_url)