```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Simple example for comparison and evaluation of BOP-DMD
%
% Here we fit data generated from 3
% spatial modes, each with time dynamics
% which are exponential in time.
%
% This example is used to compare between this reference code
% and the python version of this code.
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% ToDo:
% Loop of sigma
% Scatter plots of eigenvalues
% Alignment using match_vectors

clear all, close all, clc
```

generate synthetic data

```
% set up modes in space

x0 = 0;
x1 = 1;
nx = 200;

% space

xspace = linspace(x0,x1,nx);

% modes

f1 = sin(xspace);
f2 = cos(xspace);
f3 = tanh(xspace);

% set up time dynamics

t0 = 0;
t1 = 1;
nt = 100;

ts = linspace(t0,t1,nt);

% eigenvalues

e_1 = 1;
```

```
e_2 = -2;
e_3 = 1i;

true_eigenvalues = [e_1;e_2;e_3];

% create clean dynamics

xclean = f1'*exp(e_1*ts) + f2'*exp(e_2*ts) + f3'*exp(e_3*ts);

% %corrupt results
% sam= 60;
% Atest2 = zeros(nx,length(ts));
% Arand1 = rand(nx,length(ts));
% Arand2 = rand(nx,length(ts));
% r1k = randperm(length(ts)*n,sam);
%
% for j = 1:sam
%         Atest2(r1k(j))=1;
% end
% Anoise = Atest2.*(i*Arand1);
% Xnoise = xclean+Anoise;
```

Run the BOP-DMD for varying levels of noise (sigma)

```
% Turn off the rank deficient warning as this triggers constantly
% for the noisiest data.
warning('off', 'MATLAB:rankDeficientMatrix')

% Set an array of varying levels of noise.
sigma_array = [0.1, 0.01, 0.001];

% Determine the number of points along the time dimension.
n = length(ts);

% Set the number of samples to use for each ensemble member.
p = 50;

% Determine the number of realizations of the noisy data.
num_Noisecycles = 25;

% Determine the number of ensemble members for each BOP-DMD solution.
num_cycles =  100;

% Initialize the matrices of eigenvalue solutions...

% ... for optDMD
lambda_vec_optDMD = zeros(3, num_Noisecycles, length(sigma_array));

% ... for BOP-DMD
lambda_vec_ensembleDMD = zeros(3, num_Noisecycles * num_cycles, length(sigma_array));
```

```
% Initialize the random seed
rand(1);

for sigma_ind = 1:length(sigma_array)
    fprintf('Sigma=%f\n', sigma_array(sigma_ind))
    for k = 1: num_Noisecycles
        fprintf('%i \n', k)

        % Create data for this realization of noisy data.
        xdata = xclean + sigma_array(sigma_ind) * randn(size(xclean));

        % Run the optdmd.
        [w_opt,e_opt,b_opt] = optdmd(xdata,ts,3,1,varpro_opts('ifprint',0));

        % Compare to actual eigenvalues
        indices = match_vectors(e_opt, true_eigenvalues);
        lambda_vec_optDMD(:, k, sigma_ind) = e_opt;

        for j = 1:num_cycles
                % Generate the ensemble members.
                unsorted_ind = randperm(n,p);
                % Sort to be in ascending order. NOTE that we now have a
                % variable delta t between members.
                ind = sort(unsorted_ind);

                % Create dataset for this cycle using the ensemble indices.
                xdata_cycle = xdata(:,ind);
                % Provide the index times.
                ts_ind = ts(ind);

                % Run the BOP-DMD with the optDMD modes as the initial conditions.
                [w_cycle,e_cycle,b_cycle] = optdmd(xdata_cycle,ts_ind,3,1,varpro_opts(

                % Compare to actual eigenvalues.
                indices = match_vectors(e_cycle, true_eigenvalues);
                lambda_vec_ensembleDMD(:, j * k, sigma_ind) = e_cycle(indices);
        end
    end
end
```

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Sigma=0.100000
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2
3
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Warning: Rank deficient, rank = 2, tol =  2.770830e+00.
Warning: Rank deficient, rank = 2, tol =  2.760743e+00.
Warning: Rank deficient, rank = 2, tol =  2.721727e+00.
Warning: Rank deficient, rank = 2, tol =  2.584320e+00.
Warning: Rank deficient, rank = 2, tol =  2.225997e+00.
Warning: Rank deficient, rank = 2, tol =  2.264083e+00.
Warning: Rank deficient, rank = 2, tol =  3.081639e+00.
Warning: Rank deficient, rank = 2, tol =  2.473401e+00.
Warning: Rank deficient, rank = 2, tol =  2.198233e+00.
Warning: Rank deficient, rank = 2, tol =  4.941389e+00.
Warning: Rank deficient, rank = 2, tol =  4.941389e+00.
Warning: Rank deficient, rank = 2, tol =  4.941389e+00.
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Warning: Rank deficient, rank = 2, tol =  4.941389e+00.
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Warning: Rank deficient, rank = 2, tol =  4.941385e+00.
Warning: Rank deficient, rank = 2, tol =  4.941373e+00.
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Warning: Rank deficient, rank = 2, tol =  4.941133e+00.
Warning: Rank deficient, rank = 2, tol =  4.940366e+00.
Warning: Rank deficient, rank = 2, tol =  4.937301e+00.
Warning: Rank deficient, rank = 2, tol =  4.925092e+00.
Warning: Rank deficient, rank = 2, tol =  4.877090e+00.
Warning: Rank deficient, rank = 2, tol =  4.697518e+00.
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Warning: Rank deficient, rank = 2, tol =  2.248863e+00.
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Warning: Rank deficient, rank = 2, tol =  2.231612e+00.
Warning: Rank deficient, rank = 2, tol =  2.178275e+00.
Warning: Rank deficient, rank = 2, tol =  1.990049e+00.
Warning: Rank deficient, rank = 2, tol =  5.706286e+00.
Warning: Rank deficient, rank = 2, tol =  3.296212e+00.
Warning: Rank deficient, rank = 2, tol =  2.020572e+00.
Warning: Rank deficient, rank = 2, tol =  3.096460e+00.
Warning: Rank deficient, rank = 2, tol =  2.134552e+00.
Warning: Rank deficient, rank = 2, tol =  2.819544e+00.
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Warning: Rank deficient, rank = 2, tol =  2.002827e+00.
Warning: Rank deficient, rank = 2, tol =  1.979157e+00.
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Warning: Rank deficient, rank = 2, tol =  7.016761e+00.
Warning: Rank deficient, rank = 2, tol =  7.016761e+00.
Warning: Rank deficient, rank = 2, tol =  7.016761e+00.
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Warning: Rank deficient, rank = 2, tol =  7.016761e+00.
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Warning: Rank deficient, rank = 2, tol =  7.016753e+00.
Warning: Rank deficient, rank = 2, tol =  7.016726e+00.
Warning: Rank deficient, rank = 2, tol =  7.016621e+00.
Warning: Rank deficient, rank = 2, tol =  7.016202e+00.
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Warning: Rank deficient, rank = 2, tol =  1.842336e+00.
Warning: Rank deficient, rank = 2, tol =  1.845587e+00.
Warning: Rank deficient, rank = 2, tol =  1.842453e+00.
Warning: Rank deficient, rank = 2, tol =  1.844281e+00.
Warning: Rank deficient, rank = 2, tol =  1.842518e+00.
Warning: Rank deficient, rank = 2, tol =  1.842077e+00.
Warning: Rank deficient, rank = 2, tol =  1.842334e+00.
Warning: Rank deficient, rank = 2, tol =  1.842087e+00.
Warning: Rank deficient, rank = 2, tol =  1.842045e+00.
Warning: Rank deficient, rank = 2, tol =  1.842035e+00.
Warning: Rank deficient, rank = 2, tol =  1.842032e+00.
Warning: Rank deficient, rank = 2, tol =  3.970911e+00.
Warning: Rank deficient, rank = 2, tol =  3.970911e+00.
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Warning: Rank deficient, rank = 2, tol =  3.970911e+00.
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Warning: Rank deficient, rank = 2, tol =  4.279661e+00.
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Warning: Rank deficient, rank = 2, tol =  4.279647e+00.
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Warning: Rank deficient, rank = 2, tol =  4.221256e+00.
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Warning: Rank deficient, rank = 2, tol =  3.743970e+00.
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Warning: Rank deficient, rank = 2, tol =  2.147175e+00.
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Warning: Rank deficient, rank = 2, tol =  2.147112e+00.
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Warning: Rank deficient, rank = 2, tol =  2.147109e+00.
Warning: Rank deficient, rank = 2, tol =  5.498620e+00.
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Warning: Rank deficient, rank = 2, tol =  5.498554e+00.
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Warning: Rank deficient, rank = 1, tol =  2.110418e+02.
Warning: Rank deficient, rank = 1, tol =  2.110366e+02.
Warning: Rank deficient, rank = 1, tol =  2.110160e+02.
Warning: Rank deficient, rank = 1, tol =  2.109336e+02.
Warning: Rank deficient, rank = 1, tol =  2.106043e+02.
Warning: Rank deficient, rank = 1, tol =  2.092944e+02.
Warning: Rank deficient, rank = 1, tol =  2.041647e+02.
Warning: Rank deficient, rank = 1, tol =  1.852858e+02.
Warning: Rank deficient, rank = 1, tol =  1.298457e+02.
Warning: Rank deficient, rank = 1, tol =  4.562049e+01.
Warning: Rank deficient, rank = 2, tol =  7.644233e+00.
Warning: Rank deficient, rank = 2, tol =  4.156114e+00.
Warning: Rank deficient, rank = 2, tol =  2.408317e+00.
Warning: Rank deficient, rank = 2, tol =  3.422740e+00.
Warning: Rank deficient, rank = 2, tol =  2.453648e+00.
Warning: Rank deficient, rank = 2, tol =  2.242085e+00.
Warning: Rank deficient, rank = 2, tol =  2.208044e+00.
Warning: Rank deficient, rank = 2, tol =  2.238004e+00.
Warning: Rank deficient, rank = 2, tol =  2.209125e+00.
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Warning: Rank deficient, rank = 2, tol =  2.201943e+00.
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Warning: Rank deficient, rank = 2, tol =  2.201084e+00.
Warning: Rank deficient, rank = 2, tol =  2.200831e+00.
Warning: Rank deficient, rank = 2, tol =  2.200978e+00.
Warning: Rank deficient, rank = 2, tol =  2.200837e+00.
Warning: Rank deficient, rank = 2, tol =  2.200813e+00.
Warning: Rank deficient, rank = 2, tol =  2.200804e+00.
Warning: Rank deficient, rank = 2, tol =  2.200809e+00.
Warning: Rank deficient, rank = 2, tol =  2.200804e+00.
Warning: Rank deficient, rank = 2, tol =  2.200803e+00.
Warning: Rank deficient, rank = 2, tol =  2.200804e+00.
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Warning: Rank deficient, rank = 1, tol =  2.005832e+01.
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Warning: Rank deficient, rank = 2, tol =  2.175209e+00.
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Warning: Rank deficient, rank = 2, tol =  2.171857e+00.
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Warning: Rank deficient, rank = 2, tol =  2.171850e+00.
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Warning: Rank deficient, rank = 1, tol =  9.592291e+01.
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Warning: Rank deficient, rank = 1, tol =  6.553461e+01.
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Warning: Rank deficient, rank = 2, tol =  1.904282e+00.
Warning: Rank deficient, rank = 2, tol =  2.859462e+00.
Warning: Rank deficient, rank = 2, tol =  2.336602e+00.
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Warning: Rank deficient, rank = 2, tol =  3.176645e+00.
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Warning: Rank deficient, rank = 1, tol =  5.165531e+02.
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Warning: Rank deficient, rank = 1, tol =  5.164542e+02.
Warning: Rank deficient, rank = 1, tol =  5.161576e+02.
Warning: Rank deficient, rank = 1, tol =  5.149736e+02.
Warning: Rank deficient, rank = 1, tol =  5.102739e+02.
Warning: Rank deficient, rank = 1, tol =  4.920410e+02.
Warning: Rank deficient, rank = 1, tol =  4.272874e+02.
Warning: Rank deficient, rank = 1, tol =  2.587198e+02.
Warning: Rank deficient, rank = 1, tol =  6.714543e+01.
Warning: Rank deficient, rank = 1, tol =  9.625705e+00.
Warning: Rank deficient, rank = 2, tol =  2.774490e+00.
Warning: Rank deficient, rank = 2, tol =  7.208179e+00.
Warning: Rank deficient, rank = 2, tol =  3.029730e+00.
Warning: Rank deficient, rank = 2, tol =  2.315251e+00.
Warning: Rank deficient, rank = 2, tol =  2.727892e+00.
Warning: Rank deficient, rank = 2, tol =  2.331710e+00.
Warning: Rank deficient, rank = 2, tol =  2.238982e+00.
Warning: Rank deficient, rank = 2, tol =  2.216189e+00.
Warning: Rank deficient, rank = 2, tol =  2.229478e+00.
Warning: Rank deficient, rank = 2, tol =  2.216665e+00.
Warning: Rank deficient, rank = 2, tol =  2.059794e+00.
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Warning: Rank deficient, rank = 2, tol =  2.059793e+00.
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Warning: Rank deficient, rank = 2, tol =  2.059780e+00.
Warning: Rank deficient, rank = 2, tol =  2.059738e+00.
Warning: Rank deficient, rank = 2, tol =  2.059572e+00.
Warning: Rank deficient, rank = 2, tol =  2.058907e+00.
Warning: Rank deficient, rank = 2, tol =  2.056253e+00.
Warning: Rank deficient, rank = 2, tol =  2.045736e+00.
Warning: Rank deficient, rank = 2, tol =  5.292511e+00.
Warning: Rank deficient, rank = 2, tol =  4.934523e+00.
Warning: Rank deficient, rank = 2, tol =  4.033160e+00.
Warning: Rank deficient, rank = 2, tol =  2.898876e+00.
Warning: Rank deficient, rank = 2, tol =  2.277912e+00.
Warning: Rank deficient, rank = 2, tol =  2.077136e+00.
Warning: Rank deficient, rank = 2, tol =  2.023415e+00.
Warning: Rank deficient, rank = 2, tol =  2.014347e+00.
Warning: Rank deficient, rank = 2, tol =  2.012060e+00.
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Warning: Rank deficient, rank = 2, tol =  3.129965e+00.
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Warning: Rank deficient, rank = 2, tol =  3.129963e+00.
Warning: Rank deficient, rank = 2, tol =  3.129960e+00.
Warning: Rank deficient, rank = 2, tol =  3.129946e+00.
Warning: Rank deficient, rank = 2, tol =  3.129892e+00.
Warning: Rank deficient, rank = 2, tol =  3.129676e+00.
Warning: Rank deficient, rank = 2, tol =  3.128809e+00.
Warning: Rank deficient, rank = 2, tol =  3.125354e+00.
Warning: Rank deficient, rank = 2, tol =  3.111680e+00.
Warning: Rank deficient, rank = 2, tol =  3.059230e+00.
Warning: Rank deficient, rank = 2, tol =  2.879991e+00.
Warning: Rank deficient, rank = 2, tol =  2.449711e+00.
Warning: Rank deficient, rank = 2, tol =  2.405600e+00.
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Warning: Rank deficient, rank = 2, tol =  2.233343e+00.
Warning: Rank deficient, rank = 2, tol =  2.482093e+00.
Warning: Rank deficient, rank = 2, tol =  2.253185e+00.
Warning: Rank deficient, rank = 2, tol =  2.186611e+00.
Warning: Rank deficient, rank = 2, tol =  2.169289e+00.
Warning: Rank deficient, rank = 2, tol =  2.166378e+00.
Warning: Rank deficient, rank = 2, tol =  2.165281e+00.
Warning: Rank deficient, rank = 2, tol =  2.165098e+00.
Warning: Rank deficient, rank = 1, tol =  1.101216e+01.
Warning: Rank deficient, rank = 1, tol =  1.101216e+01.
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Warning: Rank deficient, rank = 1, tol =  1.101214e+01.
Warning: Rank deficient, rank = 1, tol =  1.101211e+01.
Warning: Rank deficient, rank = 1, tol =  1.101195e+01.
Warning: Rank deficient, rank = 1, tol =  1.101133e+01.
Warning: Rank deficient, rank = 1, tol =  1.100886e+01.
Warning: Rank deficient, rank = 1, tol =  1.099899e+01.
Warning: Rank deficient, rank = 1, tol =  1.095967e+01.
Warning: Rank deficient, rank = 1, tol =  1.080489e+01.
Warning: Rank deficient, rank = 1, tol =  1.022341e+01.
Warning: Rank deficient, rank = 2, tol =  8.380551e+00.
Warning: Rank deficient, rank = 2, tol =  4.830334e+00.
Warning: Rank deficient, rank = 2, tol =  5.133980e+00.
Warning: Rank deficient, rank = 2, tol =  2.823321e+00.
Warning: Rank deficient, rank = 2, tol =  2.267297e+00.
Warning: Rank deficient, rank = 2, tol =  2.605305e+00.
Warning: Rank deficient, rank = 2, tol =  2.283107e+00.
Warning: Rank deficient, rank = 2, tol =  2.475137e+00.
Warning: Rank deficient, rank = 2, tol =  2.291170e+00.
Warning: Rank deficient, rank = 2, tol =  2.245705e+00.
Warning: Rank deficient, rank = 2, tol =  2.272299e+00.
Warning: Rank deficient, rank = 2, tol =  2.246678e+00.
Warning: Rank deficient, rank = 2, tol =  2.240284e+00.
Warning: Rank deficient, rank = 2, tol =  2.238687e+00.
Warning: Rank deficient, rank = 2, tol =  2.239619e+00.
Warning: Rank deficient, rank = 2, tol =  2.238720e+00.
Warning: Rank deficient, rank = 2, tol =  2.239244e+00.
Warning: Rank deficient, rank = 2, tol =  2.238739e+00.
Warning: Rank deficient, rank = 1, tol =  9.817871e+00.
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Warning: Rank deficient, rank = 2, tol =  8.482345e+00.
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Warning: Rank deficient, rank = 2, tol =  2.202488e+00.
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Warning: Rank deficient, rank = 2, tol =  2.152775e+00.
Warning: Rank deficient, rank = 2, tol =  2.150242e+00.
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Warning: Rank deficient, rank = 2, tol =  2.149965e+00.
Warning: Rank deficient, rank = 2, tol =  4.666988e+00.
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Warning: Rank deficient, rank = 2, tol =  4.666986e+00.
Warning: Rank deficient, rank = 2, tol =  4.666982e+00.
Warning: Rank deficient, rank = 2, tol =  4.666965e+00.
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Warning: Rank deficient, rank = 2, tol =  4.666623e+00.
Warning: Rank deficient, rank = 2, tol =  4.665531e+00.
Warning: Rank deficient, rank = 2, tol =  4.661165e+00.
Warning: Rank deficient, rank = 2, tol =  4.643769e+00.
Warning: Rank deficient, rank = 2, tol =  4.575258e+00.
Warning: Rank deficient, rank = 2, tol =  4.317431e+00.
Warning: Rank deficient, rank = 2, tol =  3.496105e+00.
Warning: Rank deficient, rank = 1, tol =  2.177627e+01.
Warning: Rank deficient, rank = 2, tol =  6.881326e+00.
Warning: Rank deficient, rank = 2, tol =  2.970512e+00.
Warning: Rank deficient, rank = 2, tol =  2.154073e+00.
Warning: Rank deficient, rank = 2, tol =  2.647826e+00.
Warning: Rank deficient, rank = 2, tol =  2.177636e+00.
Warning: Rank deficient, rank = 2, tol =  5.533100e+00.
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Warning: Rank deficient, rank = 2, tol =  5.533093e+00.
Warning: Rank deficient, rank = 2, tol =  5.533075e+00.
Warning: Rank deficient, rank = 2, tol =  5.533000e+00.
Warning: Rank deficient, rank = 2, tol =  5.532700e+00.
Warning: Rank deficient, rank = 2, tol =  5.531503e+00.
Warning: Rank deficient, rank = 2, tol =  5.526719e+00.
Warning: Rank deficient, rank = 2, tol =  5.507667e+00.
Warning: Rank deficient, rank = 2, tol =  5.432766e+00.
Warning: Rank deficient, rank = 2, tol =  5.152777e+00.
Warning: Rank deficient, rank = 2, tol =  4.279326e+00.
Warning: Rank deficient, rank = 2, tol =  2.643851e+00.
Warning: Rank deficient, rank = 2, tol =  2.476566e+00.
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Sigma=0.010000
1
2
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Sigma=0.001000
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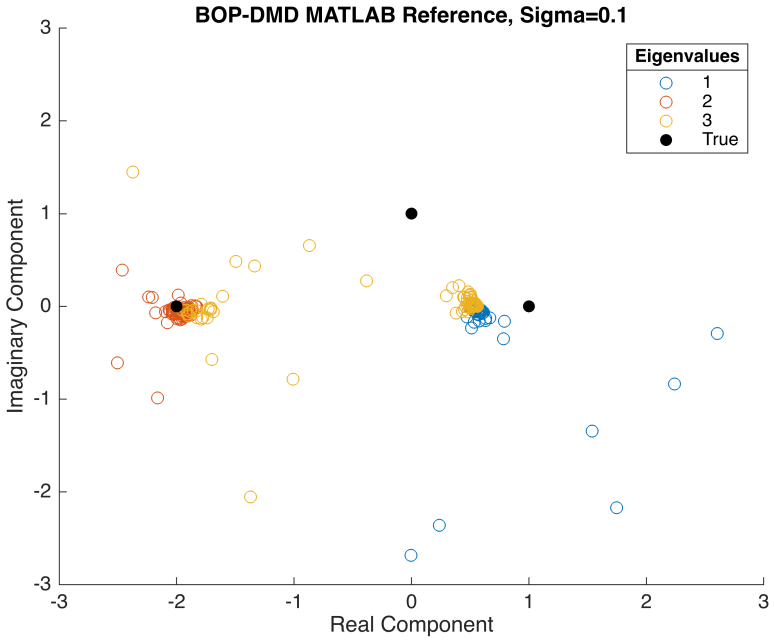
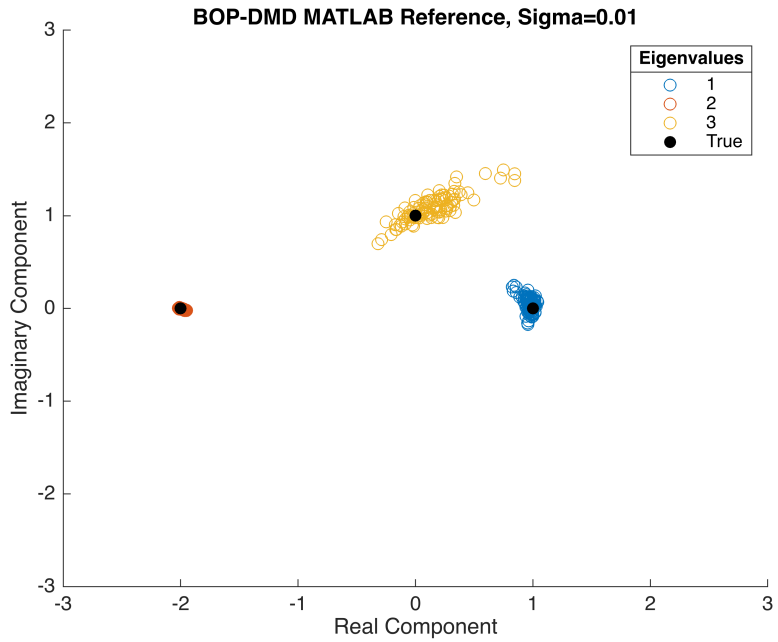
```
for sigma_ind = 1:length(sigma_array)
    sigma = sigma_array(sigma_ind);
    figure()
    hold on
    for j = [1, 2, 3]
        scatter( ...
            real(lambda_vec_ensembleDMD(j, :, sigma_ind)), ...
            imag(lambda_vec_ensembleDMD(j, :, sigma_ind)) ...
            )
    end
```

```
    scatter(real(true_eigenvalues),imag(true_eigenvalues),'ko', 'filled')
    xlim([-3, 3])
    ylim([-3, 3])
    title(['BOP-DMD MATLAB Reference, Sigma=', num2str(sigma)])
    xlabel('Real Component')
    ylabel('Imaginary Component')
    lgd = legend('1', '2', '3', 'True');
    title(lgd, 'Eigenvalues')
    fname = ['../py_optDMD/examples/matlab_reference.BOP-DMD.sigma=', num2str(sigma),
    saveas(gcf, fname);
end
```

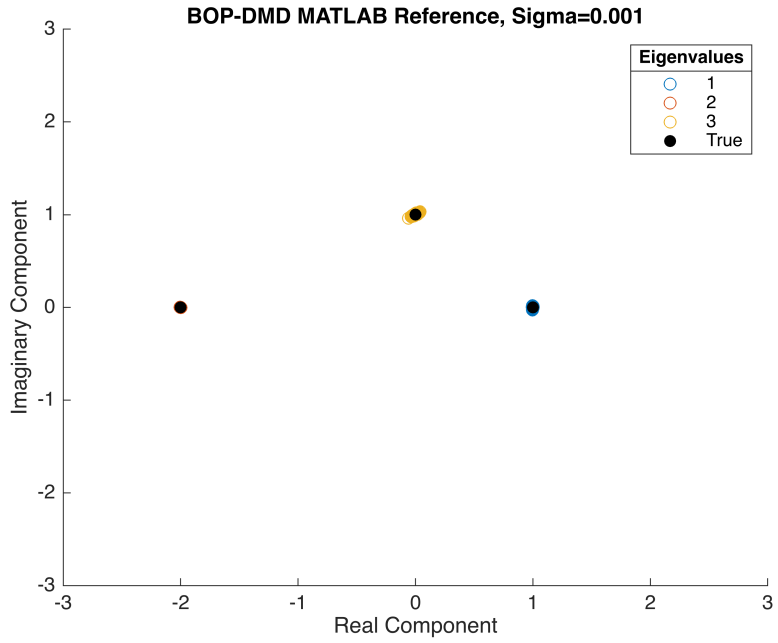
```
sigma = 0.1000
fname =
'../py_optDMD/examples/matlab_reference.BOP-DMD.sigma=0.1.png'
```




```
sigma = 0.0100
fname =
'../py_optDMD/examples/matlab_reference.BOP-DMD.sigma=0.01.png'
```




```
sigma = 1.0000e-03
fname =
'../py_optDMD/examples/matlab_reference.BOP-DMD.sigma=0.001.png'
```



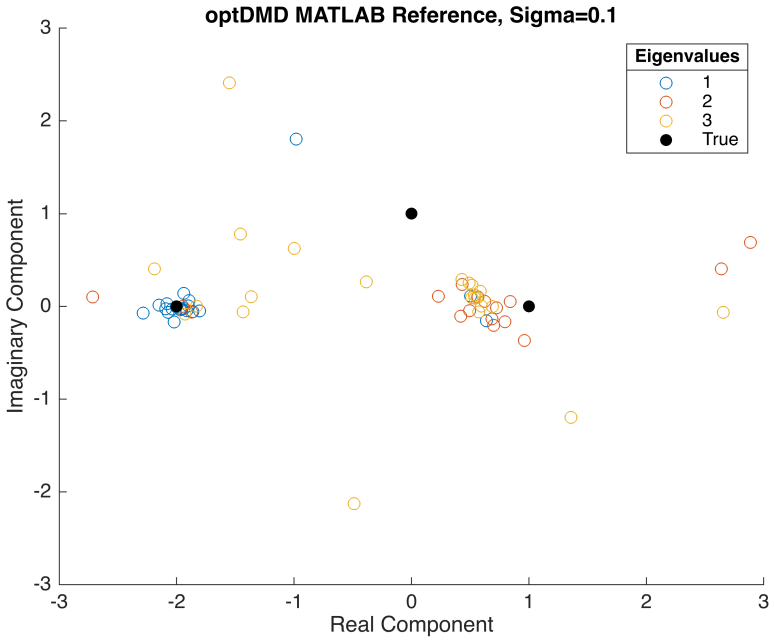

```
ans =
'../py_optDMD/examples/matlab_reference.optDMD.sigma= .png'
```

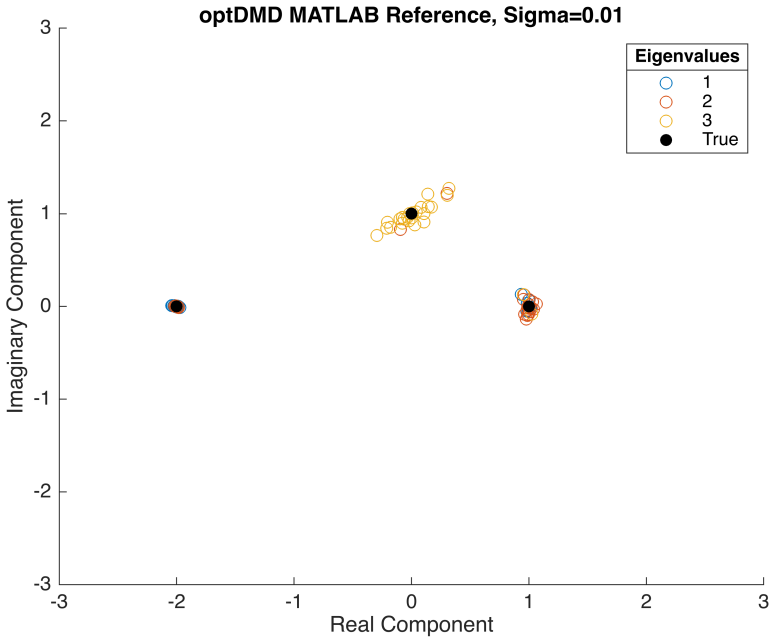
```
for sigma_ind = 1:length(sigma_array)
    figure()
    hold on
    for j = [1, 2, 3]
        scatter( ...
            real(lambda_vec_optDMD(j, :, sigma_ind)), ...
            imag(lambda_vec_optDMD(j, :, sigma_ind)) ...
```

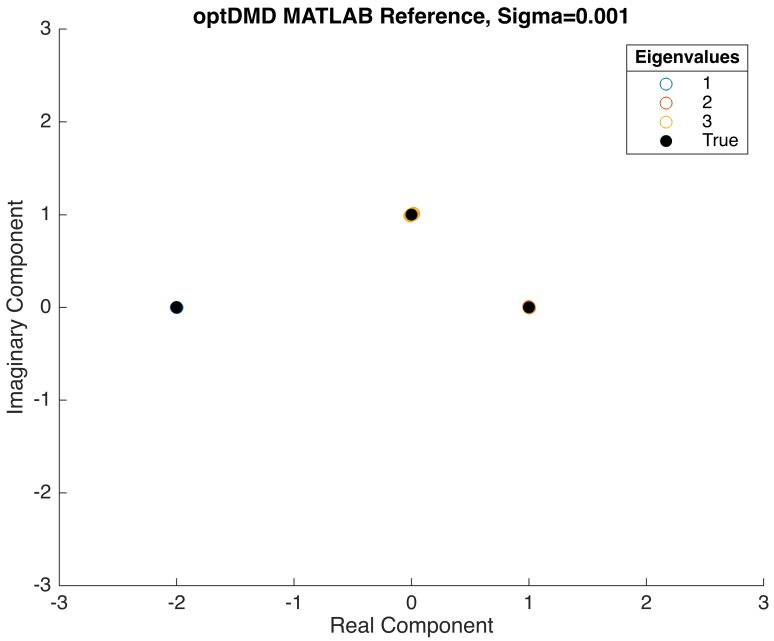
```
            )
    end
    scatter(real(true_eigenvalues),imag(true_eigenvalues),'ko', 'filled')
    xlim([-3, 3])
    ylim([-3, 3])
    title(['optDMD MATLAB Reference, Sigma=', num2str(sigma_array(sigma_ind))])
    xlabel('Real Component')
    ylabel('Imaginary Component')
    lgd = legend('1', '2', '3', 'True');
    title(lgd, 'Eigenvalues')

    fname = ['../py_optDMD/examples/matlab_reference.optDMD.sigma=', num2str(sigma), '
    saveas(gcf, fname);

end
```




optDMD MATLAB Reference, Sigma=0.01
Eigenvalues
1
2
3
True
Imaginary Component
Real Component
3
2
1
0
-1
-2
-3


optDMD MATLAB Reference, Sigma=0.001
Eigenvalues
1
2
3
True
Imaginary Component
Real Component
3
2
1
0
-1
-2
-3