Q1 (35 marks):

a) **Please find, read, and summarize the following patent. Write one page that clarifies your "main observations and findings."**

The given patent has been filed by Bruce Schena, Menlo Park, CA, on 19th June, 2007 and published on December 25th, 2008.

The patent describes a device that rotates an insertion axis about a remote center of motion two degrees of freedom. The insertion axis is supported by a driven link. The driven link is constrained by a parallelogram arrangement of rigid links so that it moves in parallel. The drive link is also coupled with an output shaft, whose rotation is controlled by an input shaft, set at a substantial angle. The output shaft is also supported by a housing. Motors located at the input shaft rotate it and cause the output shaft to rotate along with it. Another motor rotates the housing, which again rotates the output shaft about an axis that passes through the remote center of motion.

A useful application of this invention is in a Minimally invasive surgery (MIS) procedure. In MIS, the surgeon, after inserting his/her elongated surgical instruments through an incision, manipulates tissues in a body using end effectors. Because MIS requires minimizing the amount of equipment at the incision site, robotic manipulator include linkages to couple the motors for positioning the insertion axis at a distance from the center of motion. This distanced center of motion is referred to as a remote center of motion.

A robotic manipulator, in a form of a cantilevered structure, can position and support an insertion axis with a remote center of motion. The end effector needs to be controlled with great precision so it is desirable for the robotic manipulator to be stiff. This is achieved by providing a structure with a high resonant frequency and a low moment of inertia. This can be achieved by either minimizing the device mass or the distance of the mass from the supported end of the cantilevered structure. And in order to do this, the device provides a structure that places the motors in a compact configuration that minimizes the contribution of the motors to the moment of inertia of the manipulator.

Owing to these innovations, the device allows the surgical system to avoid damage to the point of tool insertion by maintaining the center of rotation at the point of entry regardless of the orientation and insertion.

b) Please also search on google scholar and discuss what the possible techniques or mechanisms that support such requirements are?

There are other ways to achieve the same goal. Trevor L et al. use an image guidance system to position their cochlear implant insertion tools in their paper, "An image guidance system for positioning robotic cochlear implant insertion tools." In this paper, the researchers describe an optical tracking system that localizes the insertion tool in physical space. At the same time, a graphical user interface incorporates the coordinates of the insertion tool with patient- specific anatomical data to provide error information to the surgeon in real-time. Guided by this interface, surgeons align the tool within the year and minimize the chances of damage to the point of insertion tool.

Yet another different approach was taken by Ben Mitchell et al. in their paper "Development and Application of a New Steady-Hand Manipulator for Retinal Surgery." The paper describes the development and testing of a steady-hand manipulator for retinal microsurgery. The robot described here senses forces exerted by the operator on the tool and utilizes it to deliver precise position control and force scaling, especially at the point of insertion of the tool in the retina.

c) Please also explain how this has been implemented in da Vinci Surgical System Xi in addition to the two following mechanisms.

The da Vinci system is composed of three subsystems: (1) the patient-side cart; (2) the surgeon console; and (3) the vision cart.

The robotic manipulators are part of the patient-side card. The cart itself is comprised of four patient-side manipulators or arms. These arms are docked to the trocars placed in the thoracic wall of the patient's body. On each of the manipulators, one can find either a stereo endoscopic camera or a surgical instrument, such as a grasper, a scissor, or a needle driver. On top of this, the manipulators are wrapped with a sterile drape, and sterile along with all of the trocars, camera, and instruments.

Among the manipulators, there exists a master manipulator with six DoFs. This master manipulator is constituted by a delta mechanism for 3-DoF translation and a serial gimbal mechanism with three intersecting rotational axes to control the orientation of the forceps tip. The patent was developed under Intuitive Surgical, which is the company behind the Da Vinci system.

Q2 (35 marks):

Research, learn, and write one page about CyberKife Robotic Technology.

What is CyberKnife Robotic Technology

CyberKnife Robotic System is a radiation therapy treatment for cancerous and non-cancerous tumors and is developed by the company Accuracy, based out of Sunnyvale, CA.

The CyberKnife System was designed to deliver Stereotactic radiosurgery (SRS) and Stereotactic body radiation therapy (SBRT) using image-guided linear accelerator (linac) technology [Linear Accelerator (LINAC) Commonly used device that delivers external beam radiation treatments for patients with cancer. It delivers high-energy x-rays or electrons to the region of a patient's tumor]. The system is known for the precision, delivered by its robotic arm, real-time adaptive delivery of the radiation beam to the tumor throughout treatment, and sub-millimetric accuracy, which helps reduce the risk of the radiation side effects to the patient.

The robot moves and bends around the patient, to deliver radiation doses from potentially thousands of unique beam angles, significantly expanding the possible positions to concentrate radiation to the tumor while minimizing dose to surrounding healthy tissue.

How the concept of Surgical CAD/CAM is implemented in this robotic system

Patient workflow starts with a CT scan to identify the primary image for treatment planning. Digitally reconstructed radiographs are then generated by the CyberKnife system. These are virtual projections at a 45° angle perpendicular to the patient couch transferred to the treatment delivery software.

The radiographs are later used as references for pre-treatment patient positioning and real-time motion tracking and correction. CyberKnife systems fully integrated image guidance system aligns the virtual projections to x-ray images taken prior to treatment delivery for patient positioning and continually during treatment delivery for automatic beam correction. The CyberKnife system uses specialized tracking algorithm to track the skull, the spine, fiducials or the tumor itself depending on the target location. For lung tumors, the Xsight Lung Tracking algorithm can distinguish tumor for surrounding lung tissue.

For tumors that move with respiration, the synchrony respiratory tracking system monitors the patient's breathing motion in real-time with an optical camera and led marker is placed on the patient's chest. Before initiating treatment delivery, the system automatically acquires a series of rapid x-ray images that represent the entire respiratory cycle combined with the breathing motion-captured with the optical camera. The system builds a personalized correlation model that predicts the tumor location and motion during treatment delivery. The system automatically acquires additional x-ray images continually validating and updating the correlation model. The images and the model are carefully monitored by the clinical team via the treatment delivery software intuitive display.

how CyberKnife Robotic has been used for the treatment of tumors in moving organs such as lung (how the motion of the lung is captured and used in control)

During treatment, patient may have erratic behavior such as head movement, coughing, muscle tension and relaxation. This is especially problematic for tumors in organs like the lungs where there is periodic movement. The CyberKnife System accommodates all forms of patient and tumor motion during treatment delivery. Using its motion adaptive delivery technology, the CyberKnife System minimizes the amount of healthy tissue exposed to high-dose radiation.

The CyberKnife System uses Surgical CAD/CAM to track tumors anywhere in the body, while mechanical structure keeps the radiation on the tumor when it moves. Before deploying the treatment, the CyberKnife System verifies the exact tumor position then adjusts the robot to precisely target the tumor. This helps to ensure radiation is delivered to the current location of the tumor is, and not the location it was in moments before. Additionally, the CyberKnife System features real-time adaptive delivery technology called Syncchrony. Synchrony adapts the delivery of the radiation treatment to tumors while they are in motion by synchronizing the treatment delivery beam position to the target location precisely and accurately during the delivery of a treatment fraction. The motion synchronization technology eliminates the need to use uncomfortable patient restraints.

Also, explain the benefit of such technology

A unique aspect of the CyberKnife System is that it is the only fully robotic radiation delivery system. The robotic design, coupled with real-time imaging, enables the CyberKnife System to eradicate the tumor from thousands of beam angles with sub-millimeter precision and accuracy.

Being a non-invasive surgery brings a host of benefits. Cyberknife system is preferred by patients because of its five or fewer treatments procedure, pain-free treatment, no anesthesia or incisions, little to no recovery time and few side effects. Hospitals appreciate that the Cyberknife system treats a variety of tumors and cancers, is operated by experienced physicians, lower risk of complications, and because patient does not need to stay in the hospital.

In addition, discuss what types of tumor treatment besides lung tumors it has been used for and why it could be preferable in comparison to conventional radiotherapy techniques

CyberKnife Robotic Technology is used to non-invasively treat tumors throughout the body, including the lung, spine, brain, kidney, head and liver, neck, pancreas, and prostate. The technology is especially useful for patients who have inoperable or surgically complex tumors. The system is preferable over conventional radiotherapy techniques which have to often invasively hold patient

Cyberknife Technology is also more accurate than conventional radiation therapy, which ensures that tumor surrounding tissue does not get damaged. The system can deliver radiation with a margin of one to five millimeters around a tumor, whereas, traditional radiotherapy delivers radiation at a margin of twenty to thirty millimeters.

Using its robot-mounted multi-leaf collimator (MLF) technology, the Cyberknife system can be used to deliver a much stronger dose of radiation and can shape the beam to target large tumors with fewer beams. This is an improvement over traditional radiotherapy where relatively low doses of radiation are administered because doctors can only use static images of the tumor rather than real-time updated images like those in the Cyberknife system.

Discuss what aspects of CyberKnife technology can be improved.

While the CyberKnife system has matured as a product, there is still a lot of scope for the technology to improve. The system, although the best in the industry in terms of precision and accuracy, still causes some side effects due to damaged tumor surrounding tissue. The accuracy and precision can further be improved to eliminate the chance of these side effects altogether.

The system is relatively larger in size than other radiation therapy treatment equipment which makes it costly for hospitals and doctors to afford. This leads to lower accessibility because only large hospitals will be able to afford such systems.

Q3)

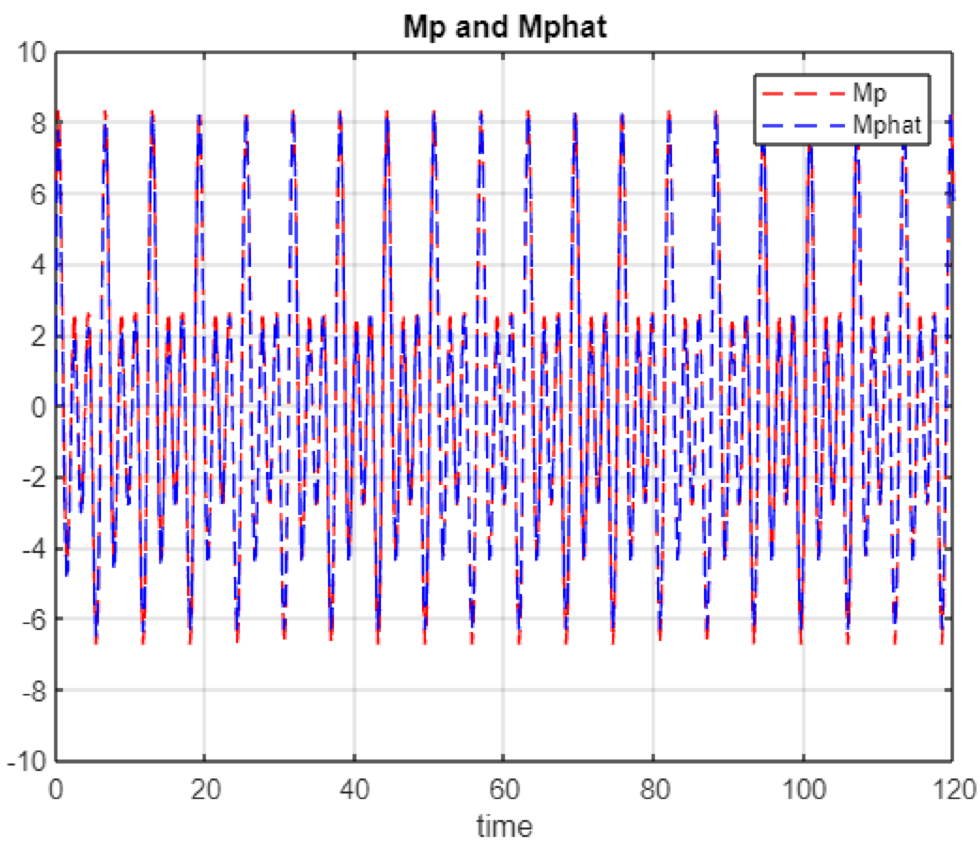


Figure 1: Mp and Mphat (Main signal and estimated signal)

a) As seen in Figure 1, yes, the estimated signal does match the main signal. We see that from t=0s to t=20s, the main signal and estimated signal do not match since the weights are still readjusting and the error is becoming smaller. We see a progression in the difference between the trajectories as the main signal and estimated signal come closer. From t=20s to t=120s we see that estimated signal perfectly estimates the main signal and we see a very close overlap between both signals such that the main signal is completely being overlapped by the estimated signal by t=120s. As time passes, the error between the main signal and estimated signal is minimized so both signals overlap.

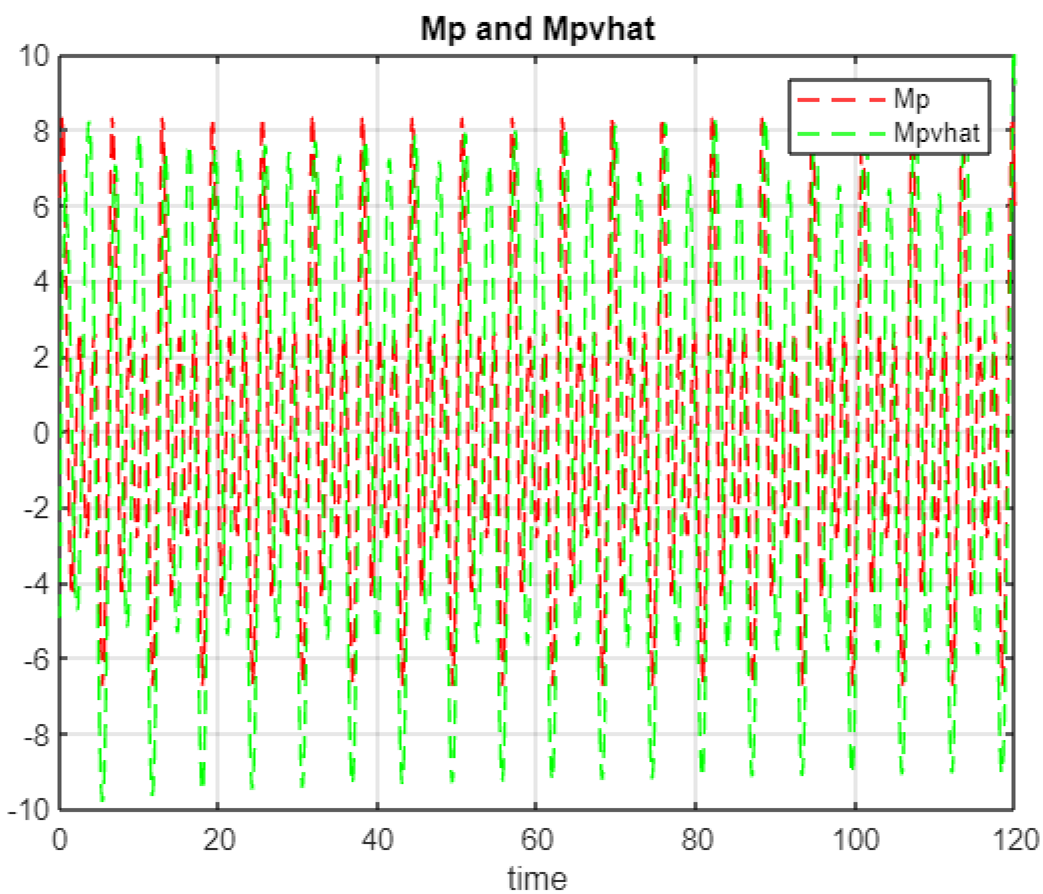


Figure 2: Mp (main signal) and Mpvhat (voluntary estimated main signal)

b) Mp here, is the main signal, whereas, Mpvhat is the voluntary estimated signal and includes the low frequency components of the main signal. The frequency cutoff taken here is 2 Hz (converted to radians/sec). Any component that has frequency below 2 Hz is considered here. Due to the low frequencies which make up Mpvhat, we see that this signal has a larger time period compared to Mp. This leads Mpvhat to be a poor estimate of Mp since it only has some components of the estimated frequencies. But as time progresses, we see that Mpvhat improves and is better able to estimate Mp even though it does a relatively poor job when compared to Mphat.

c) Yes, the BMFLC did follow the behavior explained in the lecture. Tweaking beta to lower values made a poor estimated signal prediction but ran the model faster whereas high beta values made the signal run slower but gave better predictions. Tweaking nu to different values was also interesting to observe how much weightage was given to the error after calculating it. Lower adaptive gain did not change the estimated signal at all whereas high adaptive gain changed it too much between subsequent instances and led to poor prediction.

d) The signal given in the question is periodic. This means that once the model has been trained on its period, it will be able to estimate future periods in an effective manner. This is why I believe that forgetting factor is not required in this case. The estimated signal will not be as accurate in predicting the main signal if a forgetting factor was added. It would be better to add the forgetting factor to a signal that does not behave periodically and instead has some interruptions. Then the adding a forgetting factor ensures that estimated signal does not overfit a periodic motion estimation.

Gaurang Ruparelia BMFLC

Part 1: Create signal

```
t = 0:0.001:120;     % time vector
N = length(t);       % signal length
nu = 0.0001;          % adaptive gain


% Mp voluntary (high frequency) row vector
Mpv = sin(t) + 2*sin(2*t) + 3*sin(3*t) + cos(t) + 2*cos(2*t) + 3*cos(3*t);
% Mp involuntary (low frequency) row vector
Mpi = 0.1*sin(30*t) + 0.1*sin(35*t) + 0.1*cos(30*t) + 0.1*cos(35*t);
% combine the voluntary frequencies and involuntary frequencies row vector
Mp = Mpi + Mpv
Mp = 1×120001
    6.2000    6.2204    6.2405    6.2604    6.2799    6.2993    6.3183    6.3370    6.3555
6.3736    6.3915    6.4090    6.4263    6.4432    6.4598    6.4761    6.4920    6.5077
6.5230    6.5379    6.5526    6.5669    6.5808    6.5945    6.6077    6.6207    6.6333
6.6456    6.6575    6.6691    6.6804    6.6913    6.7019    6.7122    6.7221    6.7317
6.7410    6.7500    6.7587    6.7671    6.7752    6.7829    6.7904    6.7976    6.8045
6.8112    6.8175    6.8236    6.8295    6.8351
```

Part 2: Create frequency range

```
w_a = 1;    % minimum freq
w_b = 35;    % maximum freq
beta = 2000;   % # freq between w_a and w_b (try different values)
freq_vec = linspace(w_a,w_b,beta);
```

Part 3: Create placeholder vectors

```
Mp_hat = zeros(1,N);
theta = zeros(1,2*beta); % [1, beta] is for "a" and [beta+1, beta+beta] is for
"b"
phi = zeros(1,2*beta);
```

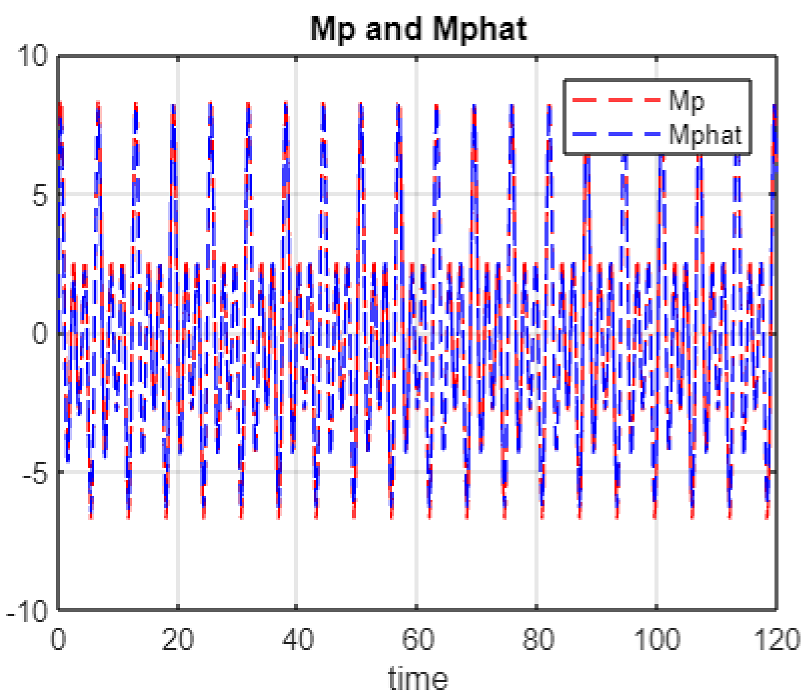
Part 4: Estimate Mp_hat

```
for i = 1:N
    for j = 1:beta
        phi(j) = sin((w_a+freq_vec(j))*t(i));           % sine component
        phi(j+beta) = cos((w_a+freq_vec(j))*t(i));     % cosine component
    end
    Mp_hat(i) = phi*theta';
    Err = Mp(i) - Mp_hat(i);
    theta = theta + 2*nu*phi*Err;                  % update theta using error
end
```

Part 5: Plot Mp_hat and Mp on the same figure

```


plot(t, Mp,"r--", t, Mp_hat,'b--')
title("Mp and Mphat")
axis([0 120 -10 10]) % set time on x-axis betweeen 0 to 120 and y-axis between 10
and -10
xlabel("time")
legend('Mp', "Mphat")
grid on
```



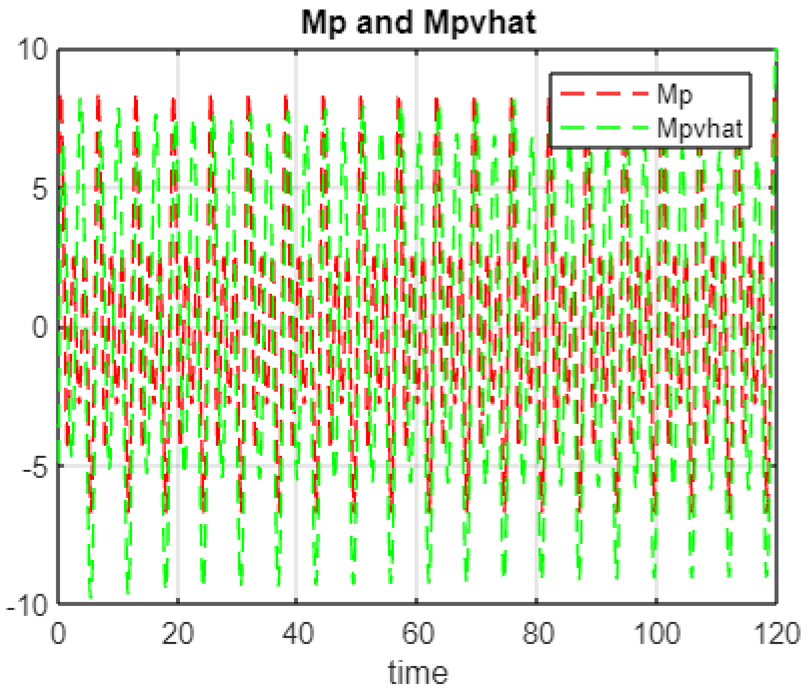
Part 6: Extract the voluntary and involuntary component

Hint: the final theta contains the weights for the fourier series. The first half contains the weights ('λ') for the sine components, and the second half contains the weight for the cosing components ('ϑ'). These are ordered from lowest frequency to the highest frequency.

```
Mp_v_hat = zeros(1,N);
w_cutoff = 2*6.8; % 2 Hz in rad/sec
idx = length(find(freq_vec <= w_cutoff));
lambda = theta(1:idx);
vartheta = theta(beta+1:beta+idx);
theta_v = [lambda vartheta];
phi=zeros(1,2*idx);
for i = 1:N
    for j = 1:idx
        phi(j) = sin(freq_vec(j)*t(i));         % sine component
        phi(j+idx) = cos(freq_vec(j)*t(i));    % cosine component
    end
    Mp_v_hat(i) = phi*theta_v';
end
```

Part 7: Plot the estimated voluntary Mp_v_hat with the actual Mp_v

```
% To Do:
Mp_v_hat
Mp_v_hat = 1×120001
   -4.9247   -4.8747   -4.8246   -4.7745   -4.7243   -4.6741   -4.6238   -4.5734   -4.5230   -
4.4725   -4.4220   -4.3715   -4.3209   -4.2703   -4.2197   -4.1690   -4.1183   -4.0676   -
4.0168   -3.9661   -3.9153   -3.8645   -3.8137   -3.7629   -3.7121   -3.6613   -3.6105   -
3.5597   -3.5089   -3.4582   -3.4074   -3.3567   -3.3059   -3.2552   -3.2046   -3.1539   -
3.1033   -3.0528   -3.0022   -2.9517   -2.9013   -2.8509   -2.8005   -2.7502   -2.7000   -
2.6498   -2.5997   -2.5496   -2.4996   -2.4497
plot(t, Mp,"r--", t, Mp_v_hat,'g--')
title("Mp and Mpvhat")
axis([0 120 -10 10]) % set time on x-axis betweeen 0 to 120 and y-axis between 10
and -10
xlabel("time")
legend('Mp', "Mpvhat")
grid on
```


Mp and Mpvhat
Mp
Mpvhat
10
5
0
-5
-10
0
20
40
60
80
100
120
time