Assignment - Dynamic Design for Improved Control

1 Introduction

In the design of Mechatronic Systems for Precision Positioning the design team must consider many different aspects. Multi-disciplinary trade-off is often required and each discipline can influence the system performance. In the conceptual stage of development the following four steps can be identified,

1. Assessment of the customer requirements to translate them to accuracy targets.
2. Identification of disturbances and quantitative estimation of their magnitude and frequency content.
3. Determination of the required feedback controller power to handle disturbances and achieve the required accuracy.
4. Design the system elements, using the multi-disciplinary knowledge, such that factors limiting the controller performance are avoided.

Limitations may be present in all disciplines. Here the attention will be put on designing the dynamics of the mechanical modules so as to allow for higher performance of the feedback system. This abstract first introduces the basic module that is discussed. The dynamics that influence the Controller design for the original system will be described. Next a number of steps that can be made to improve the system dynamics will be described.

2 System Description

As an example of a mechanical module a wafer stage for a semiconductor lithography machine will be used. An early example of such a module, (Philips/ASML, 1985), is shown in figure 1 side-by-side with a schematic drawing of the system. The wafer is supported on a mirror block that is used for interferometry measurement for the XY motion. For vertical motion an actuator assembly supports this mirror. For motion in the X-direction a linear motor is used and an air-bearing foot supports the whole system. The air-bearing floats over a granite base and allows for horizontal motion.

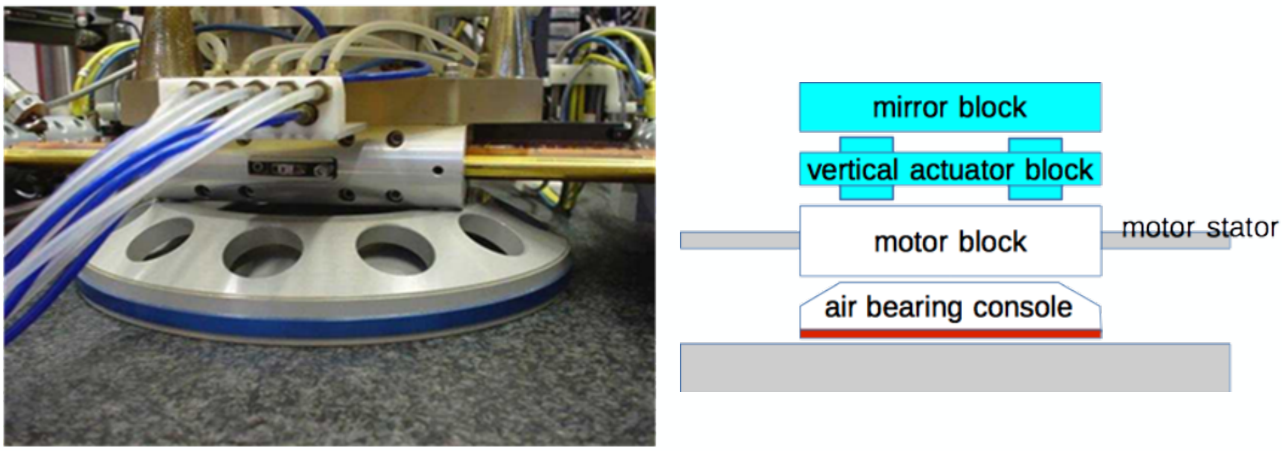


FIGURE 1. Photograph of a linear motor driven and air-bearing supported wafer stage, together with the schematic drawing showing the four modules in the system

This system must position the wafer over a stroke of about 250 mm with position stability better than 50 nm. Disturbances from floor vibrations and reaction forces in the frame call for a higher feedback control performance for next generation systems.

3 Single Body Model

When trying to improve the gains in the controller it proved that dynamic effects were leading to system instability. To describe the system dynamics a basic model can be made. In this initial study the system is modeled with one body movable in the XY plane. In this body all masses are rigidly connected to each other and the stiffness of the air-bearing is represented by two vertical springs.

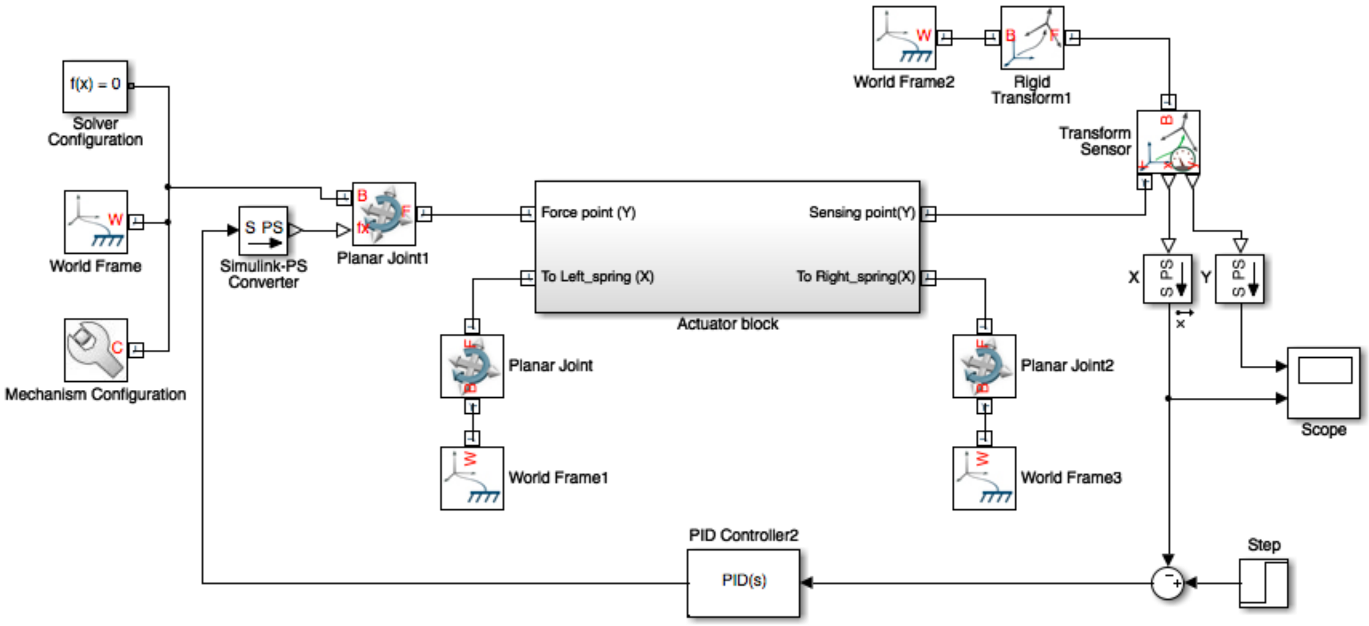


FIGURE 2. Basic Model of the stage in the XY plane.

The stage is modeled as a solid body with the specified mass and moments of inertia. The relative positions of the connection points of the air-bearing, the force actuator and the displacement sensor, with respect to the center of mass of the body are defined using rigid transform blocks.

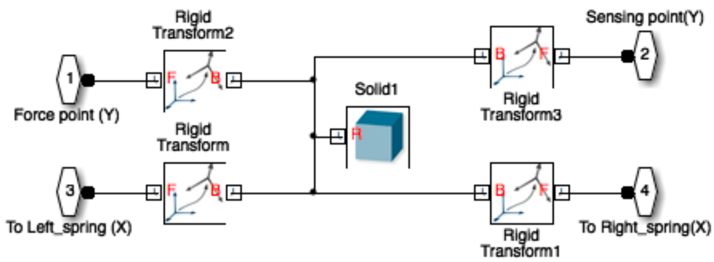
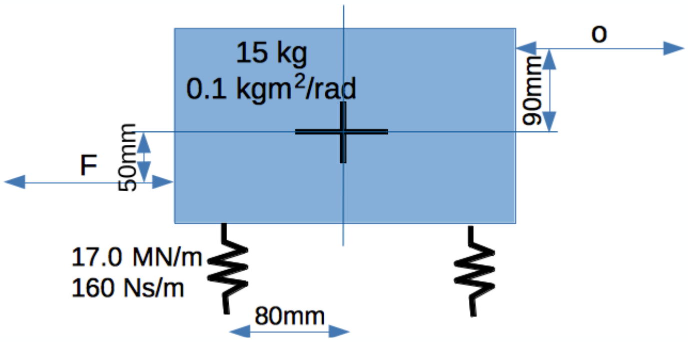


FIGURE 3. Internal model of the mover (actuator block).



1. Build the model using the information in the Figures using SimMechanics.
2. Using this model the open loop frequency response for the mechanical system can be determined. This is based on the transfer function from a driving force applied to the motor to the measured displacement at the interferometer. Check this frequency response in your model.

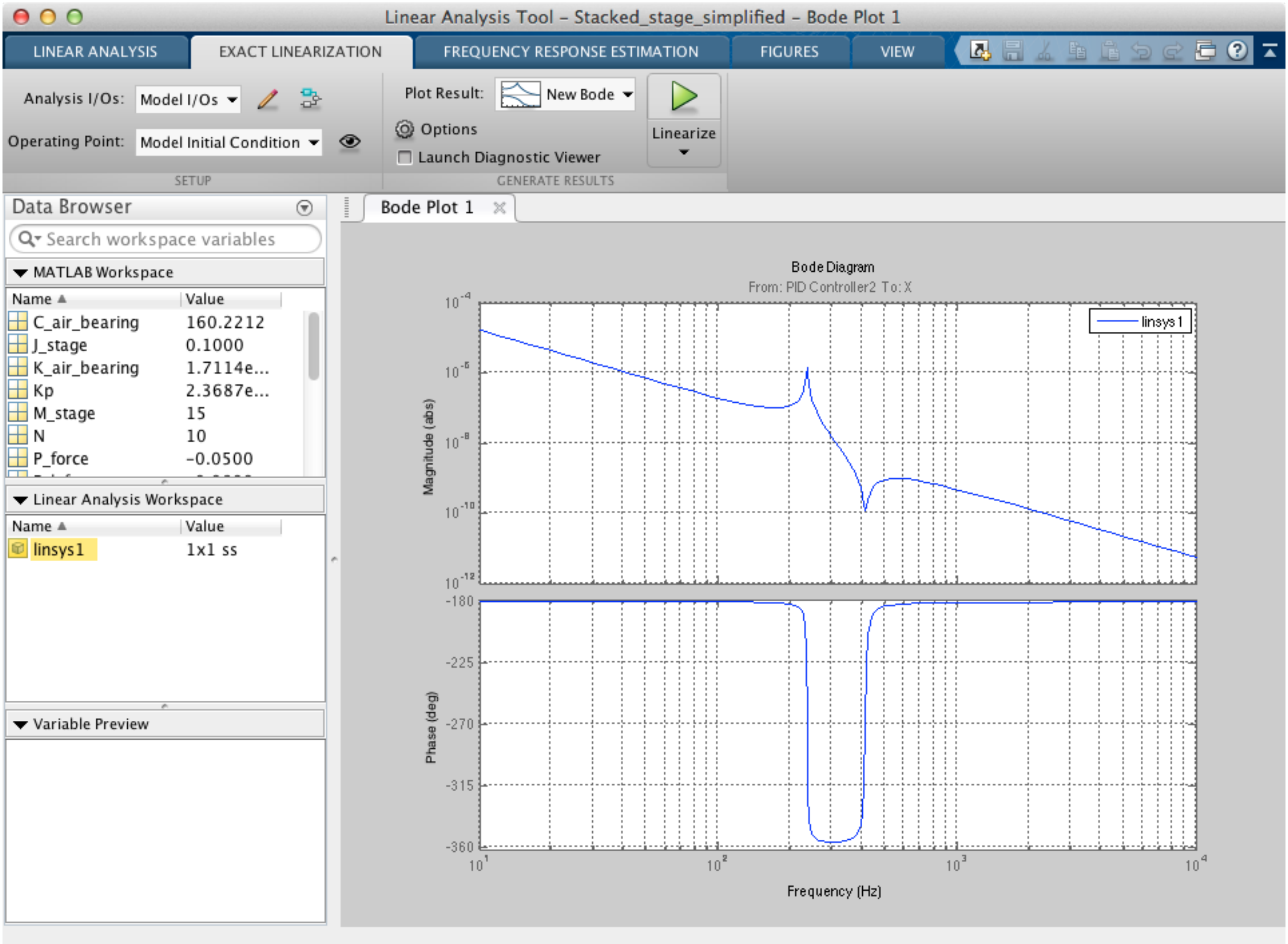


FIGURE 4. Frequency response from force input to interferometer output.

In the frequency response the presence of a resonance around 180 Hz is clearly visible. A serious negative phase shift of 180 degrees is due to this resonance. From the schematic drawing of the system (Figure 5) it is clear that the driving force is applied below the Centre of Gravity (CoG) and the measurement is located above the CoG.

3. Consider the stiffness of the air bearing and the properties of the body and the actuation and sensor location, and explain the overall shape of the frequency response.

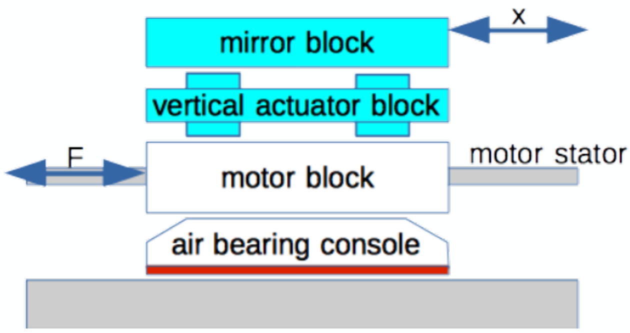


FIGURE 5. From this picture it is clear that the driving force is applied below the Center of Gravity. The Measurement is done above this CoG.

As this type of effect is common in many such systems a good guiding principle during design in a linear motor system is:

The driving Force should be applied through the Centre of Gravity and should be directed exactly in the desired direction of motion.

4 Improved Design

How can we redesign our example system to achieve this? A possible solution is to move the module with the linear motor up and the Actuator box down (Figure 6). This will make it possible for the driving force to act through the CoG.
This design leads to some complexity in the mechanical construction as the Actuator Box should be rigidly connected to the Mirror and the Motor must be fixed to the Air-bearing. Still the added mechanical complexity is offset by the potentially better performance.

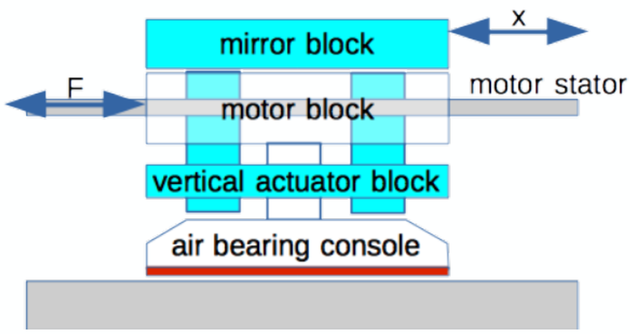


FIGURE 6. Redesign of the Stage to put Driving Force in CoG.

4. Adapt the model to assure that the Driving Force is applied in the X-direction in line with the CoG of the Stage and check the change in the frequency response.

From this frequency response it would appear that this modification should work beautifully. So, this adaptation was done in the real system and the result was observed. However, the real system was still showing similar resonances as in the initial design and thus the suggestion of driving in the CoG did not deliver the desired result.

5 Two Body Model

This is due to the fact that the real system has limited stiffness between the different connecting modules. To investigate this the stage will be modeled in two elements. The Mirror Block and Actuator Box form one element and the Motor with the Airfoot form the other element. In the vertical direction the top module, Mirror and Actuator Box, will rest on the Airfoot with a limited stiffness.

In the horizontal direction the top and bottom module will also be connected with a connector allowing for relative horizontal motion. For this a flexure plate can be designed in the fixation between the two parts. In figure 7 is shown where this flexure plate is placed.

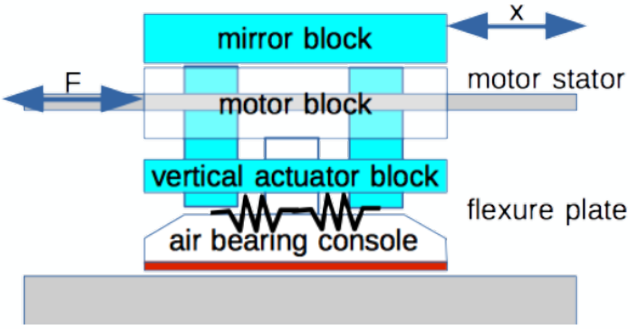
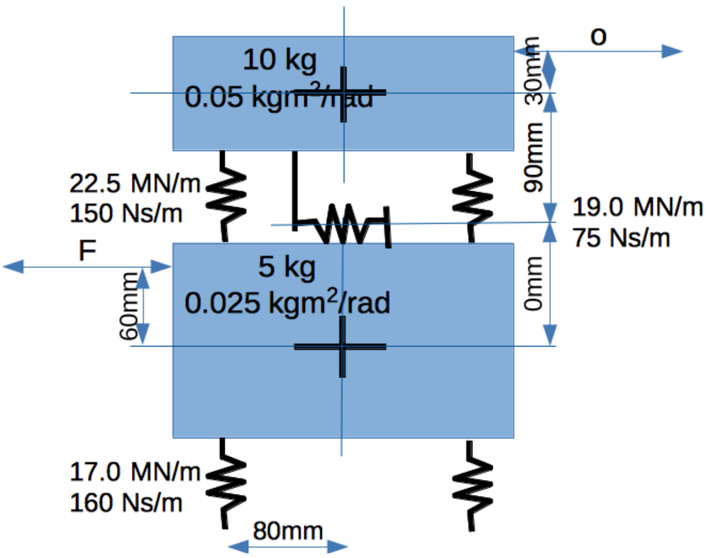


FIGURE 7. The Flexure Plate forms the horizontal connection between the two parts of the Stage.

In the improved model it is assumed that the stage consists of two bodies that can move in two directions, X and Y, and make small rotations Rz. In the upper right side the sensor measuring the motion of the upper mass at the desired point is located. On the left the actuator driving the lower mass is located. Vertical and horizontal springs and dampers are connecting the two bodies and are used to model the air-bearing.



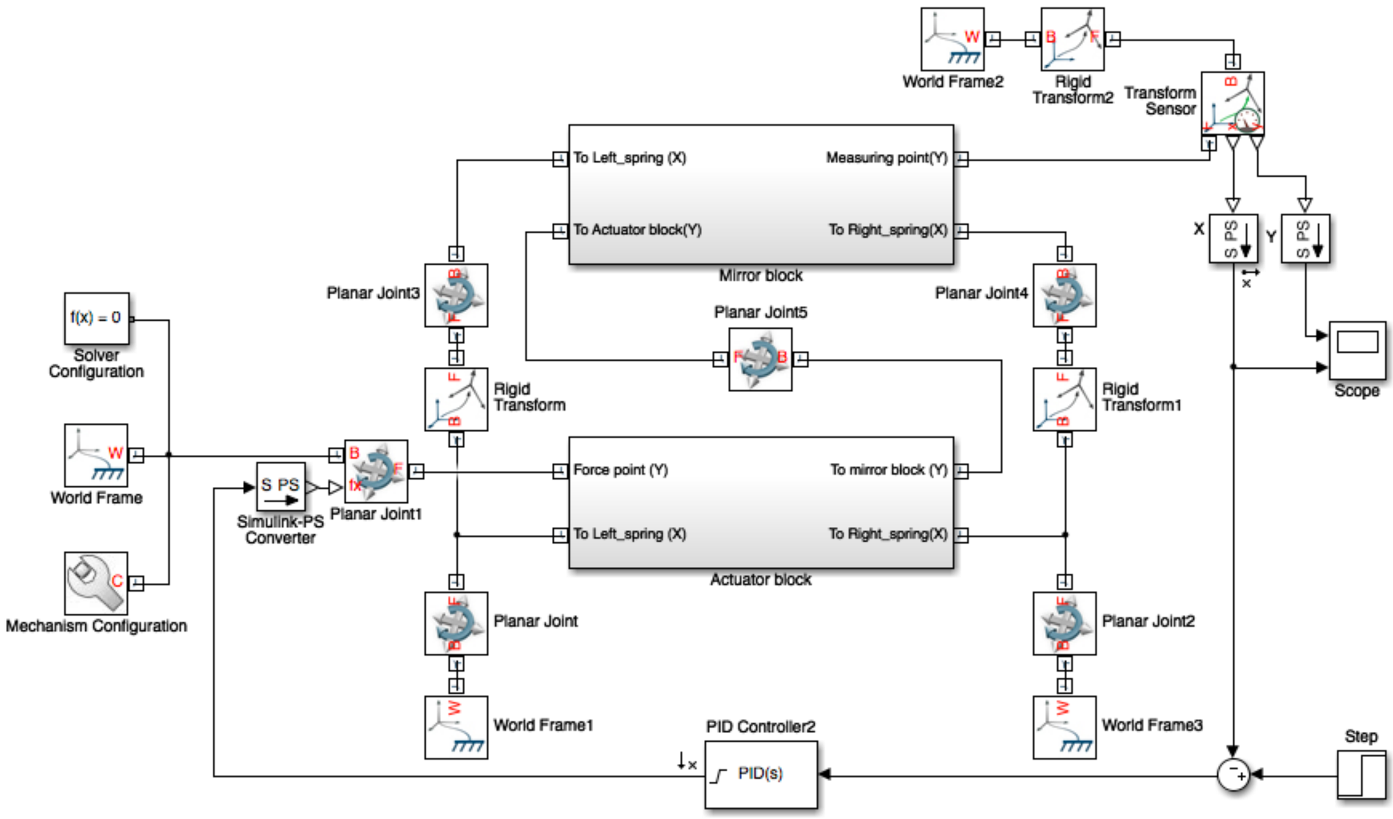


FIGURE 8. Iconic Diagram for the two body model of the stage driven in the overall CoM

5. Build the model using the information in the Figures using SimMechanics.
6. Check the frequency response from force to displacement sensor.

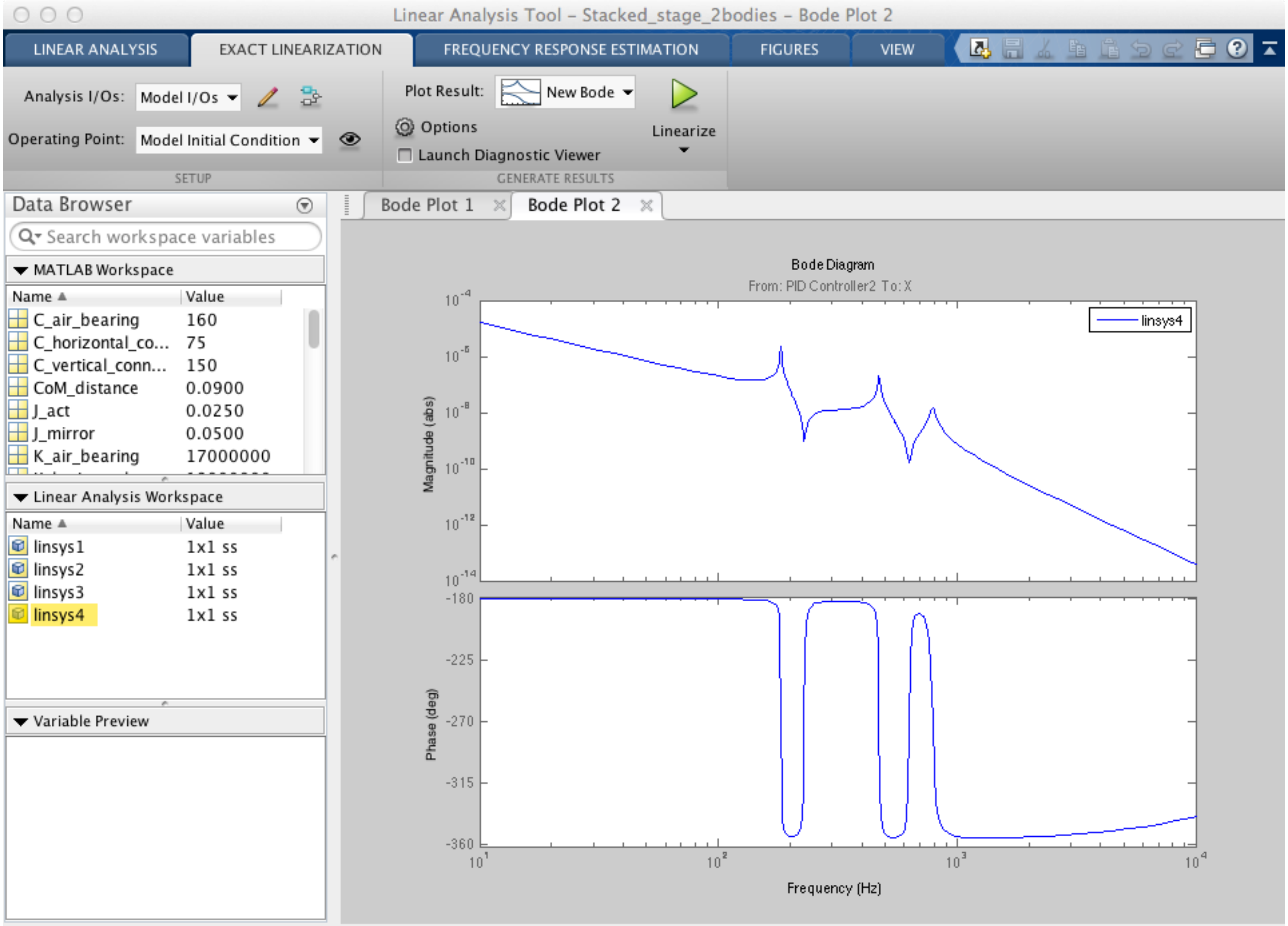


FIGURE 8. The frequency response for the improved system still contains a significant resonance at 200 Hz.

From this graph it is clear that the "improved" system still shows a significant resonance around 200 Hz. Although the module is driven in the overall Centre of Gravity resonances due to the limited stiffness of the air-bearing will still be limiting the system control performance.

7. For the resonance around 200 Hz the amplitudes of the 6 body motions can be determined to sketch the associated Mode Shape. Make such a schematic representation. HINT: Use additional displacement sensors connected to the two CoGs, or derive the equations of motion and use similar Matlab-based techniques as were used in assignment 2.
   For this last approach see the m-files on BlackBoard. The main file is 'stage_assignment.m'.
8. Based upon this develop a solution for a further improvement of the mechanical design. Implement the improvement and calculate the improved frequency response. HINT: Think of ways to change the mode shape: Change the vertical position of the plate spring, or the vertical positions of the actuator and sensor. The spring stiffnesses cannot be increased, the vertical spring positions cannot be changed, and the masses cannot be decreased.
9. Estimate the potential increase in Bandwidth of a PID controller for the improved Stage design.