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MAGNETIC LEVITATION ON A BUDGET: A STUDENT DISCOUNT

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Abstract

The successful mechatronics development i. e. modelling, simulation, design, build and test of a magnetic levitation stage at the Diamond Light Source is presented. The concept was to use a low control bandwidth across the 6 degree of freedom MIMO system, to provide both an alignment stage and vibration isolation. The project simultaneously upskilled staff and developed a proof-of-concept system demonstrator at a low cost. The final motion stage was constructed for a component cost of less than £15,000.

INTRODUCTION

The Diamond Light Source (DLS) is the UK national synchrotron facility. Numerous beamlines focus X-ray beams to less than 100 nm and hence require relative sample & optics stability to be a fraction of this. The new flagship beamline I17 to be built as part of the Diamond II upgrade has extreme stability requirements yet to be achieved on existing beamlines. The sample position jitter specification is ± 0.5 nm Peak – Peak, 1-1000 Hz relative to the beam. To even come close to this performance significant mechatronics modelling, simulation, testing will be required. A component of this research and development has been performed by Year-in-Industry engineering students. The primary goal of their project was to deliver the knowledge & processes required to design a magnetically levitating motion stage (maglev), as this had never been done before at DLS. This paper details the significant achievements of two students to model, simulate, design, build and test a magnetic levitation stage suitable for synchrotron endstation vibration isolation.

The benefit of an active maglev solution as compared to a passive isolator is that the amplification at resonance can be eliminated, the system stiffness and damping adjusted in software and the isolation also provides a compact parallel kinematic 6 degree of freedom (DOF) system which may be stepped or rotated about any arbitrary co-ordinate system. The downside is the inherent mechanical system instability and complexity.

REQUIREMENTS

The top-level requirements defined for the project were:

- Load capacity > 10 kg
- Low profile ~ 0.5 × 0.5 × 0.2 m maximum envelope
- Vibration transmission < 10% from 10 – 500 Hz
- Provide 6 DOF motorised alignment
- Position Stability ± 500 nm, 1-1000 Hz Peak-Peak
- Angular Stability ± 500 nrad, 1-1000 Hz Peak-Peak
- Travel Range XYZ ± 1 mm, Pitch/Roll/Yaw ± 1 mrad

PROJECT PROCESS

A clear Mechatronics workflow was followed; requirements specification, hand calculations, literature review, concept simulation, design iteration, final system simulation including the motion control software and hardware, Dynamic Error Budget, build, commission, test, validate & update the original model to improve the process.

SYSTEM DESIGN

It was decided to use commercial voice coils (Motion Control Products AVA2-20-0.5) with sufficient clearance to meet the desired motion requirements rather than manufacturing custom coils to save resources. The flat rather than cylindrical design enabled the co-location of the position sensor. The design is deliberately symmetric with the centre of mass located at the geometric centre. The nominal required control bandwidth was calculated to be ~10 Hz via hand calculations [1]. The brackety was designed to have a 1st mode above 100 Hz i.e. 10 times the fundamental rather than the usual 3-5 time rule-of-thumb so a higher bandwidth could be tested.

GRAVITY COMPENSATOR

Most magnetically levitating motion stages employ a gravity compensator to minimise the power required to resist gravity [2–4].

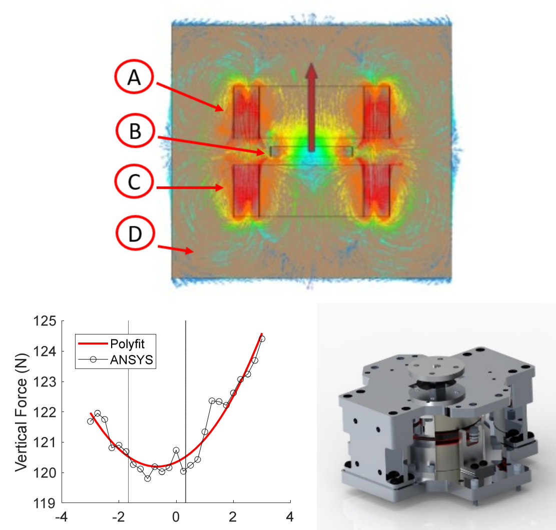

Figure 1: ANSYS Magnetostatic simulation of permanent magnet gravity compensator magnetic field vectors (Top) A) Upper fixed ring magnet, B) Floating magnet, C) Lower fixed magnet, D) Simulation space. Predicted vertical force variation with vertical translation (bottom left) and gravity compensator 3D design (bottom right).

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This is critical for vacuum applications to prevent overheating in the absence of convection. The ideal gravity compensator provides a constant force equal to the floating weight independent of position i.e. not a spring following Hook's Law. A negative stiffness spring could be used but as the main goal was to physically isolate vibration a non-contact permanent magnet compensator was designed. Although the magnetic attractive force is non-linear it is possible to optimise the geometry of fixed and moving magnets to provide an approximately constant force region with minimal off axis parasitic forces. Figure 1 gives a section view through a magnetostatic simulation from ANSYS. The large red ring magnets were fixed to the base and the smaller central ring magnet was connected to the levitating plate.

SENSOR & ELECTRONICS

One of the challenges with a parallel kinematic closed-loop system is sensor selection. The ideal sensors only measure a single DOF with no cross coupling with the other 5. Conventional linear encoders would not operate over the motion range. Capacitance sensors, Eddy current sensors and interferometers were all too expensive, in fact almost any commercial sensor was too expensive, so the decision was made to build sensors in-house. A retro-reflective phototransistor (OSRAM SFH 9206) had been used previously for a very similar application[5]. The sensor exhibits 2 approximately linear regions. The shallower gradient and hence lower resolution negative slope was used due to the desired motion range. A significant benefit of this sensor was its compact size. The whole unit was approximately 4 × 3 × 2 mm. This enabled the sensor to be integrated within the voice coil to give truly co-located feedback. In theory this makes the single axis control inherently stable [1].

A mount within the voice coil, amplification and low pass filter printed circuit boards were designed using Cadence®. The sensor was fully characterised during the early stages of the project to measure the current vs. distance output relative to different target surfaces. The voltage to distance curve was approximated as a straight line for simplicity. The axis cross-coupling was measured to be nil in the translation axes and 0.001 mm/mrad in the 2 non-normal rotations. It was decided that this was decoupled enough to not affect the performance.

DYNAMIC ERROR BUDGET

One of the fundamental tenets of Mechatronics is the optimisation of the system via simulation prior to manufacture. This significantly reduces project risk, reduces design iteration time and system commissioning time along with potentially delivering a superior product. The process followed was; to create a 3D model using the CREO® design software, perform a modal analysis in ANSYS, extract a reduced order model (ROM) state space matrix and import the ROM into MathWorks® Simulink®. The Simulink® model was then used for time domain simulations using measured disturbances. A dynamic error budget [6] was performed by extracting the frequency dependent disturbance transfer functions from Simulink®. The square of the transfer functions were multiplied by the disturbance power spectral density (PSD). The dynamic error budget (DEB) given in Figure 2 not only shows the relative effects of disturbances on the system it also predicts the RMS stability via the square-root of the total Cumulative PSD.

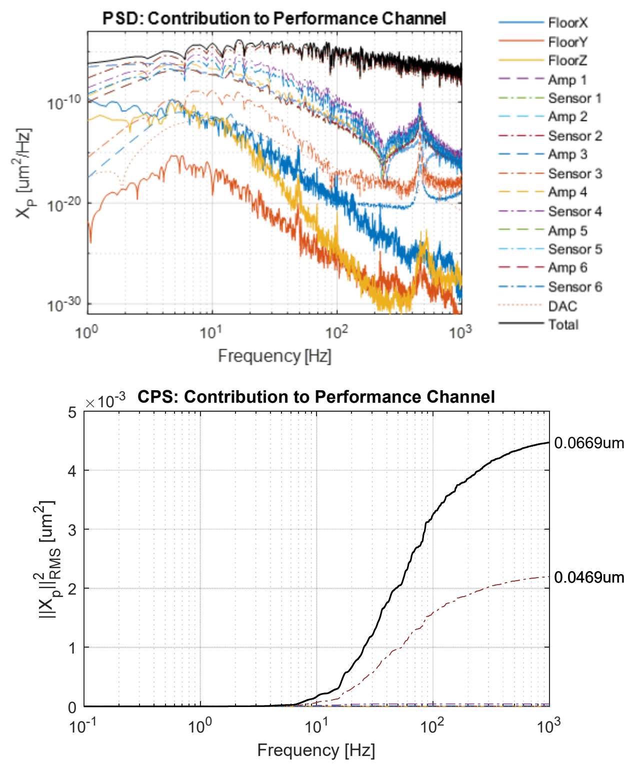

Figure 2: Maglev stage x direction PSD disturbance vs. frequency (top) and Cumulative PSD with RMS stability prediction (bottom).

It may be observed from the DEB that the sensor noise is by many orders of magnitude the dominant predicted disturbance limiting the position stability, which is not surprising when they cost about a Euro. The key data was that the predicted position jitter/error in the x direction was 70 nm RMS which is well within the required specification.

CO-ORDINATE TRANSFORMATIONS

A parallel kinematic system such as a 6 DOF maglev stage has intrinsically coupled actuators i.e. an open loop step applied to one actuator will be observed by the others. This means that classical single input single output (SISO) control can't be applied individually to each actuator. The method employed on this multiple input multiple output (MIMO) system was to create decoupling co-ordinate transformation matrices from the 6 actuator frames to the global reference frame located at the centre of mass. Once in the global reference frame, the 6 DOF decoupled axes used SISO PID control. The demand signals were then transformed back into the actuator frames to be fed to the power amplifiers.

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MOTION CONTROL & SYSTEM IDENTIFICATION

The dSPACE control platform was used to perform the motion control. This has the significant benefit that the simulated control functions could be directly compiled into C code and uploaded to the dSPACE. This coupled with accurate system modelling meant that no commissioning of the stage control parameters was required to make the system fly. The simulated plant was close enough to the real plant that the simulated control was functional and stable with the actual system. Once the system was operational system identification was performed in order to compare simulation with reality. The diagonal direct terms e.g. x demand to x position were quite similar however there was far more axis cross-coupling in reality than the perfect simulation. This is likely due to geometric position and alignment errors, sensor non-linearities, imperfect actuators and model imperfections. Figure 3 shows the final system with the motion control hardware and the test accelerometers mounted.

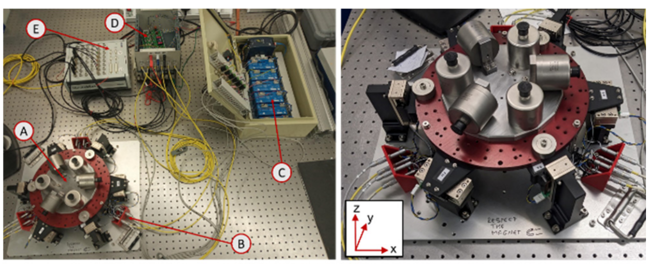

Figure 3: Operational maglev system, A) Maglev stage, B) Cable Interface, C) Trust Automation Amplifiers, D) Sensor Signal Conditioning, E) dSPACE Controller.

TEST RESULTS

The predicted x direction position jitter was 70 nm RMS Figure 4 shows the measured jitter was 40 nm RMS.

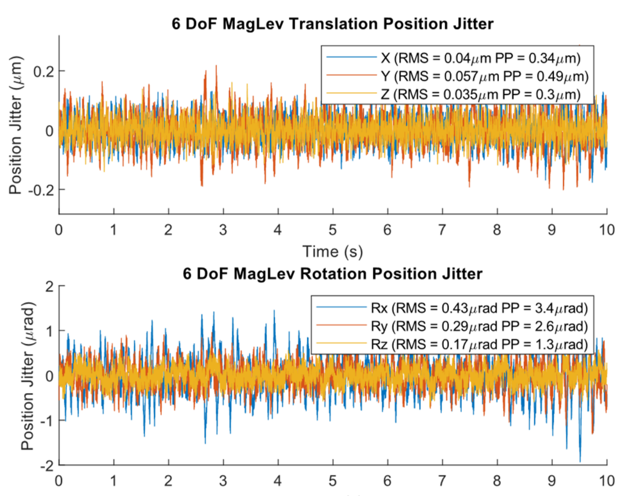

Figure 4: Position jitter measured by the internal stage sensors in translation (top) and in rotations (bottom).

Both the linear and angular measured stability data are close to the simulated values however only the translation data meet the project requirements. The best angular stability was Rz at 170 nrad RMS.

The system was tested on an optical table with a strong fundamental resonance at 12 Hz which is clear in the measured accelerometer data given in Figure 5 . The closed loop stage is effectively tracking the table motion but decouples above 15 Hz to provide vibration isolation above this. The upper plot is for the maglev stage floating on the table with the background disturbances. In this case the sensor noise can be seen to set a lower signal limit. The lower plot is for the same configuration as the first but with the table impacted to increase the vibration signal to make it the dominant disturbance. The vibration is isolated by 4 orders of magnitude at 250 Hz. This clearly demonstrates the potential performance if the sensors were upgraded.

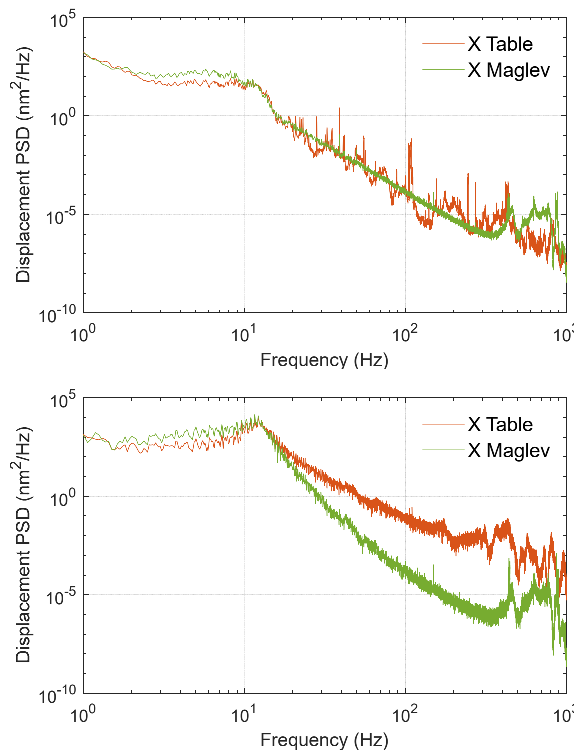

Figure 5: Integrated accelerometer signal to give horizontal stage and table displacement PSD, with background vibration (top), with table impact to improve signal to noise ratio (bottom).

CONCLUSION

A magnetically levitating stage was successfully designed, simulated, built and tested. The motion control parameters may be adjusted to balance position stability, tracking error and vibration isolation. The performance limiting factor was the in-house built position sensors which gave a position jitter around ± 60 nm RMS with a control bandwidth of 10 Hz. It would be easy to upgrade the sensors to interferometers to give even better performance suitable for new beamline applications.

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