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VIBRATION STABILIZATION FOR A CANTILEVER MAGNET PROTOTYPE AT THE SUBNANOMETER SCALE

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In the future linear colliders, the size of the beams is in the nanometer range, which requires stabilization of the final magnets before the interaction point. In order to guarantee the desired luminosity, an absolute displacement lower than 1/3 of the beam size, above a few hertz, has to be obtained. This paper describes an adapted instrumentation, the developed feedback loops dedicated to the active compensation and an adapted modelling able to simulate the behaviour of the structure. The obtained results at the subnanometer scale at the free end of a cantilever magnet prototype with a combination of the developed active compensation method and a commercial active isolation system are described.

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Abstract

In the future linear colliders, the size of the beams is in the nanometer range, which requires stabilization of the final magnets before the interaction point. In order to guarantee the desired luminosity, an absolute displacement lower than 1/3 of the beam size, above a few hertz, has to be obtained. This paper describes an adapted instrumentation, the developed feedback loops dedicated to the active compensation and an adapted modelling able to simulate the behaviour of the structure. The obtained results at the subnanometer scale at the free end of a cantilever magnet prototype with a combination of the developed active compensation method and a commercial active isolation system are described.

INTRODUCTION

The luminosity of the CLIC collider will have to be of $10^{35}cm^{-2}s^{-1}$, which imposes a vertical beam size of 1 nm. In order to maximise the luminosity at the interaction point, the relative motion between the last two focusing magnets, the final doublets, should not exceed a third of the beam size above 4Hz [1].

Unfortunately, major vibration sources like ground motion [2] and acoustic noise can induce displacements of a few nanometres above 4Hz. Thus, an active stabilization of the final doublets must be carried out, particularly at their resonance frequencies.

We consequently need sensors and actuators which are able to measure and create displacements of mechanical structures at the sub-nanometre level while being placed in a harsh environment composed of high magnetic fields and radiation. We also need a feedback loop which controls actuators from sensor data. In addition, mechanical simulations and dynamic response calculations are included in this study for defining the active stabilisation feedback loops.

Concerning the mechanical structure, the design of the future linear collider will be very complex, so a few intermediary stages are needed. For this reason, the target of this study is to obtain a very low displacement at a specific point of an elementary mechanical structure which is similar to the future final doublet in the main aspects that concern our work.

SENSOR ASSESSMENT

In a first part, we started by assessing very sensitive, commercial vibration sensors, acquisition systems and instrumentation for displacement measurements at the sub-nanometre level.

When measuring nanodisplacements, resolution of the measurement chain is limited by internal noise of the chain itself, mainly composed of sensors and acquisition system noises. Consequently, these noises have been measured to evaluate sensors and acquisition systems performances.

Two types of vibration sensors which are liable to measure nanodisplacements have been studied: electromagnetic geophones using a servo loop to control the mass position and piezoelectric accelerometers coupled with sensitive charge amplifiers.

Because one measures velocity and the other one measures acceleration, performances of these two types of sensors were compared in order to know in which frequency range they are the most sensitive with respect to ground motion. With one model of geophones and two models of accelerometers, we are able to measure accurately ground motion in a quiet site from 0,1Hz up to 2000Hz, which is largely sufficient for our needs.

Because these two types of sensors are sensitive to high magnetic fields and to radiations, collaboration with PMD Scientific Company and SLAC laboratory has been created to develop electrochemical sensors resistant to such environment for the active stabilisation of the future linear collider final doublets. The performances of the SP500 have been measured thanks to a very low noise acquisition system compared to sensor noise: the noise of SP500 sensors was found to be of 0,06nm above 4Hz. In addition, an acquisition system compatible with the feedback loop developed at LAPP and adequate instrumentation allow us to measure displacements with SP500 sensors from 0,14nm to 500nm above 4Hz. This is sufficient for active compensation of structures at the sub-nanometre level.

Now that the sensor performances have been found to be compatible with sub-nanometre measurements, numerical calculations of the whole system have been performed.

NUMERICAL SIMULATIONS

Numerical simulations can be a great help to test the efficiency and the robustness of the active control algorithm in realistic conditions. The main objective is to obtain a state-space model of the structure to control, in order to use it in Matlab/Simulink to get dynamic response of this structure under predefined loads. To do this the first step can be the finite element modelling of the structure.

Finite element modelling is of prime importance, insofar as the finite element model is required for the future results to be representative. Indeed, the state-space model will use the formulations of the finite element model (FE model). In order to get the most realistic results (in terms of dynamic and control), the FE model must be as accurate as possible.

Consequently, updating the FE model is a step of the utmost importance. Thus, experimental vibration measurements are required to get, on the one hand the different eigenfrequencies and their corresponding mode shapes, and on the other hand their level of damping. Then a model updating can be performed. Note that most of the time, the use of Super-Elements can be realized to reduce the size of the system to solve, which is a non-negligible aspect for the future dynamic computations.

The State-Space model results exclusively from the FE model, namely the mass, damping and stiffness matrices without forgetting the external applied loads. The latter act as the input of the model, the output being the motion of some predefined locations (in terms of acceleration, velocity and displacement). In the general method, it is assumed that only external forces are applied to the structure. Nevertheless, an extended method has been proposed [3], in which external disturbances can be not only pinpoint forces, but also prescribed acceleration for instance.

Finally, by correctly initializing the different matrices of the State-Space model in Simulink, it is possible to get the dynamic response of the structure under prescribed acceleration. The active control can be coupled to this computation by adding for instance pinpoint forces (if pinpoint actuators are required) in the input vector of the state-space model.

CANTILEVER MAGNET PROTOTYPE

The prototype used for this experiment is a 2,5m long steel beam in cantilever mode, respecting the elementary parameters planned for the final doublet. Furthermore, the eigenfrequencies of this linear structure are included in the desired range. The measurement of the motion is performed with the velocity sensor SP500 presented in the sensor assessment part. Concerning the actuators, assemblies of piezoelectric patches are used. They allow creating very low displacements at a nanometre scale all along the beam. The built prototype is presented in fig.01.

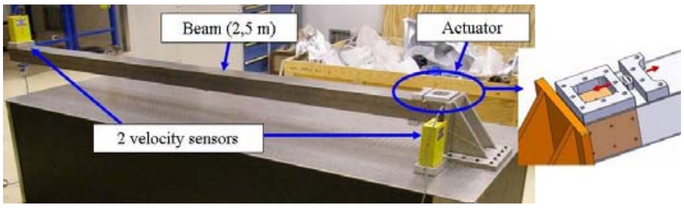

Figure 01: the cantilever magnet prototype.

ACTIVE STABILIZATION

In order to attenuate the motion of this prototype, the influence of the perturbations has to be analysed. In fact, there are two types of motions that can be identified:

- The vertical motions of the clamping created by the ground motion. Their effects excite indirectly the mechanical structure, mainly its resonant modes.
- The acoustic perturbations which excite directly the mechanical structure in all directions.

To treat both problems, two methods are used. First of all, the target is to obtain a very low displacement of the clamping by the use of passive and active isolation, in order to isolate the whole system from the ground motion. For this part, an industrial active table (TMC table with 4 STACIS active isolators) is tested [4]. Regarding the very strict allowed tolerances (1/3 nm), even if this solution is efficient, it is not sufficient; because the acoustic perturbations are not treated and even the slightest motion of the clamping will be amplified by the structure, mainly for its resonant modes. For this reason, active compensation is developed. This method consists in applying a force that creates a motion in opposition with the motion created by the perturbations. This will maintain the mechanical structure in a straight horizontal position along its axis.

Several algorithms were developed. The originality of the first approach is to consider only the measurable behaviour of the system instead of considering a fine model representative of the system. This algorithm is based on a state space representation and is dedicated to lumped perturbation [5].

After the simulation stage described in the previous section, this algorithm was evaluated on the large prototype at a nanometer scale. Fig.02 represents the result of the stabilization, more precisely the amplitude spectral density (ASD) of the displacement at the end of the beam in a natural environment, without adding any external disturbances. The first two modes of flexion of the beam can be recognized (large peaks) and a lot of unknown other disturbances can be noticed (narrow peaks). For the presented illustration, one of the narrow peaks has been arbitrarily selected (the surrounded peak). Notice that it is possible to parallelize the algorithms that reject each of these narrow peaks.

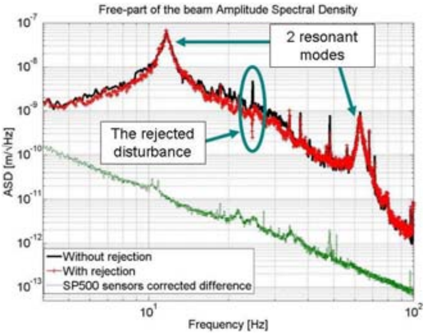

Figure 02: ASD of the displacement at the end of the beam with and without rejection

One can state that this algorithm is able to reject narrow peaks at a nanometre scale. However, for the eigenfrequencies, this method is quite limited, because working at a given frequency does not allow treating a bandwidth.

Considering these remarks, a second algorithm was developed. It is based on a command with internal model [6]. In order to meet the needs of our specific problem of stabilization, this method was adapted. In fact, the proposed algorithm uses only an elementary model which is representative of the structure behaviour and of a given bandwidth corresponding to a resonant mode. For the purpose of controlling all the desired ranges, there are as many algorithms as there are frequencies or bandwidths to process.

Two bandwidths were processed, each of them corresponding to a resonant mode of the mechanical structure (12 and 68 Hz). Fig.03 represents the transfer function between the measured displacement at the end of the beam and the measured displacement at the clamping (left plot) and the integrated displacement root mean square at the clamping and at the end of the beam (right plot).

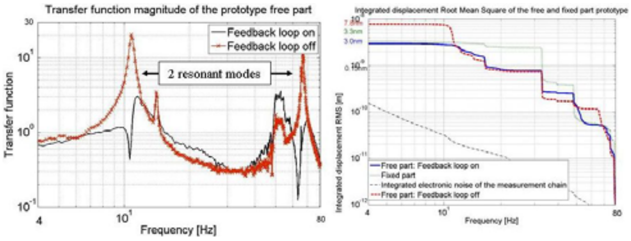

Figure 03: Transfer function between the motion at the end of the beam and at the clamping (left) and the integrated displacement RMS (right), with and without compensation.

These results reveal that for the two treated bandwidths the algorithm is efficient, since the amplification is considerably reduced.

Considering these results, the combination of active compensation with active isolation (TMC table) was tested in order to investigate if the approach can be applied at a sub-nanometre scale (Fig. 04).

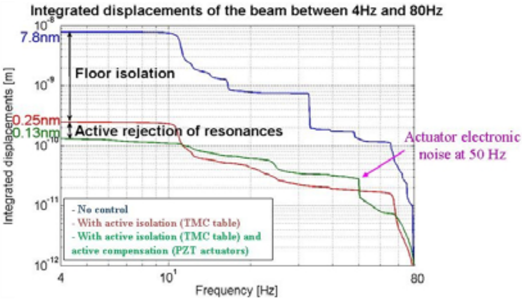

Figure 04: Integrated displacement RMS obtained with the combination of active compensation and active isolation with the cantilever magnet prototype

This test proves that the instrumentation is not a limitation and that it is possible to stabilize an elementary structure at the tenth of nanometre scale.

The next stage is to obtain these results not only on a selected point of the beam, but along the whole length. In this prospect, we are working on a multi-sensor – multi-actuator algorithm with a complete model of the structure. Promising results were obtained in simulation, so the approach will be tested in real time on the prototype.

CONCLUSION

Thanks to some electrochemical vibration sensors and piezoelectric actuators associated with an appropriate instrumentation, a control algorithm has been developed. The feasibility of actively rejecting structure vibrations down to 0.1 nm has been proven by using in parallel a commercial system performing passive and active stabilization of the clamping.

ACKNOWLEDGMENT

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