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Vibration stabilization for the final focus magnet of a future linear collider

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Abstract - One of the accelerator projects currently being studied is the construction of a linear collider composed of two 16 km arms face to face. Nominal luminosity is of the order of $10^{34}cm^{-2}s^{-1}$. For such a performance, one must take into account the ground nanodisplacements induced by cultural noise. The machine optical elements must be stable and in particular the movements of the two final focus magnets must be smaller than a third of the beam size. This can only be achieved through active stabilization. The current mechatronics study focuses on three subjects. First, one needs adapted sensors and actuators to measure nanodisplacements and achieve the required stabilization. Secondly, mechanical models are being tested to help optimize the final design. In a third part, a feedback loop is being developed to obtain the vibration stabilization of the whole system.

I. INTRODUCTION

Searching for the infinitely small requires large instruments, in particular particle accelerators. One of the projects currently being studied is the construction of a linear collider composed of two 16 km arms face to face. In each arm, an electron and a positron beam circulate before colliding at the center of the machine. Nominal luminosity for this accelerator is of the order of $10^{34}cm^{-2}s^{-1}$. To obtain such a value, the beam size must be below a few nanometers in the vertical direction. The machine optical elements must be stable and in particular the movements of the two final focus magnets must be smaller than a third of the beam size. This can only be achieved through active stabilization. The scope of this study covers three aspects. First, to stabilize the beam to the nanometer level, one needs to compensate for the nanodisplacements induced by cultural noise. This supposes sensors and actuators that can measure and work at the nanometer level while placed in a harsh environment composed of particle beams, magnetic fields, vacuum pumps etc…. We started by assessing different sensors. The second part of the study focuses on mechanical simulations and measurements that will help with the design of the final focus magnets and their stabilization system. The third part of the study aims at developing a feedback loop that will stabilize the optical elements of the accelerator to the nanometer level.

Similar studies have already been carried out with first results showing the possibility of stabilizing down to the nanometer [Seryi et al, 2004], [Redaelli et al, 2004].

II. VIBRATION MEASUREMENTS

A. Set-up

In order to measure the nanodisplacements that have to be stabilized, one needs adapted sensors and actuators. Our first step was to study different types of sensors. We chose geophones for their ability to measure nanometers. The sensors are read out by either a dedicated commercial Data Acquisition (DAQ) system including software or a common National Instruments Data acquisition system with Labview. Quick data analysis can be done online with the Labview DAQ and completed offline with Matlab. Table 1 shows the sensors used for nanometer measurements.

TABLE I

SENSORS USED FOR NANOMETER MEASUREMENTS

Sensor	Characteristics		
	Calibration	Frequency range	Quantity
Geosig VE-13	±1mm/s	1-315Hz	2
Güralp CMG-40T	±12,5mm/s	0,033-50Hz	2
Geosig GSV-320	±0,5mm/s	1-315Hz	2
Eentec SP400U	±1mm/s	0,1-50Hz	2

The first three sensors are of a classical type, composed of a reference mass, a pick-up coil and a fixed magnet. The Eentec model is of a Molecular Electronic Transfer type which is amagnetic. This might prove useful if some of the accelerator components are placed in the experiment magnetic field.

B. Sensor assessment

Figs. 1 and 2 show measurements done with the VE-13 and the GSV-320 sensors. They were placed in identical environments in our laboratory in Annecy. To compare the sensor performance, we computed the integrated difference. The corresponding equation is given in (1). More details can be found in [Redaelli, 2003].

$$PSD_c(f) = (1 - C(f))\sqrt{PSD_1(f)PSD_2(f)} \quad (1)$$

Where the PSD_c is the Integrated Corrected Difference, the PSD_1 and PSD_2 respectively the Power Spectral Density (see (2)) of the first and second sensor used for the study, and C(*f*) the coherence (see (3)) between the two sensors:

$$PSD = \frac{1}{(2\pi f)^2}(FT(v(t)))^2 \quad (2)$$

$$C(f) = \frac{\left|\Re e\left(\left\langle \tilde{v}_1(f)\tilde{v}_2^*(f)\right\rangle\right)\right|}{\sqrt{\left|\left\langle \tilde{v}_1^*(f)\right\rangle\left\langle \tilde{v}_2^*(f)\right\rangle\right|}} \quad (3)$$

The goal was to make measurements below 1 nm at 1 Hz. In figs. 1 and 2, the 1 nm goal is made visible with a horizontal line. One can see that the VE-13 sensors measure displacements below 1 nm only above 30Hz whereas the GSV-320 sensors obtain this resolution already around 0,5Hz. These measurements show that we are able to measure displacements in the nanometer range and that the GSV-320 sensors have a better resolution at low frequency. The other sensors were also able to measure in the nanometer range. These sensors can now be used for stabilization studies. The next step is to use these sensors in a realistic experimental environment.

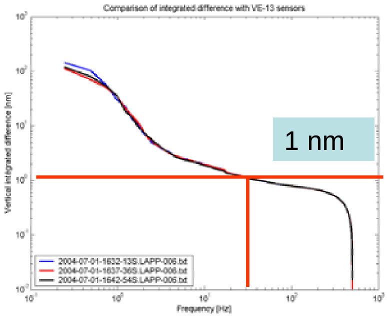

Fig. 1. Vertical integrated difference for different measurements done with the VE-13 sensors. The 1nm goal is highlighted by a horizontal line.

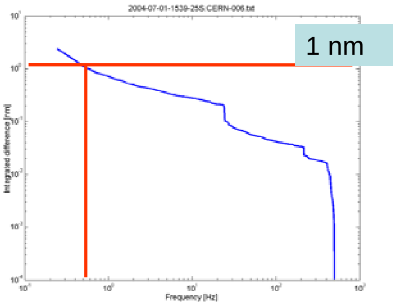

Fig. 2. Vertical integrated difference for different measurements done with the GSV-320 sensors. The 1nm goal is highlighted by a horizontal line.

C. Measurements with a stabilization table

The Güralp sensors were used for measuring the transfer function of a commercial table with an active stabilization system STACIS2000 from TMC. One sensor was placed on the floor, and the other sensor was placed on top of the table. Fig. 3 shows the results of the RMS calculation of the Güralp sensor placed on the ground, and the one placed on the stabilized table calculated as in (4).

$$RMS(f) = \sqrt{\sum_{f}^{f_{max}} PSD(f)df} \quad (4)$$

One can see that at 1Hz, the displacement on the ground is around 10nm, whereas on the stabilized table it is down to 1nm. These measurements reproduce the results shown in [Redaelli, 2003]. Active stabilization can reach the nanometer level. The next step will be to adapt an active stabilization system to be suitable for an accelerator environment.

III. MECHANICAL SIMULATIONS

A. Introduction

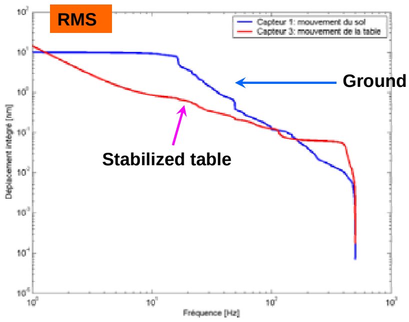

Fig. 3. RMS on the stabilized TMC table and of the ground measured with the Güralp sensors

The aim of these studies is to gain some know-how on the experimental aspect of modal analysis and consecutively on the use of software such as Pulse/ME'scope. The measurements are then compared to finite element analysis. This will enable us to build mechanical models of our accelerator components and ultimately help in the design of an almost resonance-free object by optimizing the component, but also by optimizing the actuator, support and sensor position.

B. Accelerometer setup

The first step for this study is to choose a simple case. We started with a rectangular aluminum beam 110cm long, 10cm wide and 2cm thick in different configurations : free-free, fixed-fixed and free-fixed. The latter configuration is the most probable case for the final focus magnet that will be close to, or even inside the experiment so that the support will be fixed outside the experiment and free on the detector side. The setup is shown in fig. 4.

C. Measurements with PULSE/ME'scope

The PULSE/ME'scope software enables us to determine the eigen modes of our structure, and subsequently to visualize the three-dimensional deformation corresponding to the measurements. In this way, one can easily determine what type of mode corresponds to the measured resonances. Figure 5 shows the Pulse results showing the eigen modes of a fixed-free aluminum beam.

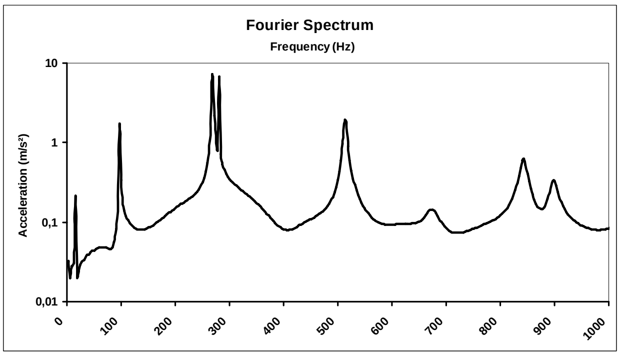

Fig. 5. Frequency spectrum of a fixed-free aluminum beam measured with the smart hammer test.

The figure shows the results up to 1000Hz, but the measurements were done up to higher frequencies. The numerical values of the first eigenmodes are shown in Table III described in the next section.

D. Comparison with Finite Element Analysis

Once the measurements were done, they were compared to mechanical simulations done with Samcef. The finite element analysis was performed considering a shell model. Table II shows the results for the comparison between the measured and the simulated eigenmodes on the aluminum bar for the vertical direction in a free-free configuration. One can see that the difference is in the range of one percent. The mechanical model reproduces well the measurements.

TABLE II

EIGEN MODES ON THE ALUMINUM BEAM FOR THE VERTICAL DIRECTION IN A FREE-FREE CONFIGURATION

Mode	Frequency (Hz)		
	Fundamental	First harmonic	Second harmonic
Measurement	88	242	471
Simulation	86,9	239	468
Error (%)	1,25	1,24	0,64

Table III shows the same comparison for a fixed-free configuration. First, one can see that the eigenfrequencies are lower than for the free-free configuration. This will have to be considered when studying the design of the final focus magnet. Secondly, one can see that the mechanical model reproduces well the measurements since the comparison shows a difference less than 10%.

This comforts us in continuing the study of mechanical models that will help us in the design of the final focus magnet. A preliminary study was done on a cylindrical model of a final focus magnet but the calculations are still ongoing. These results can be found in [Boulais et al, 2004].

TABLE III

EIGEN MODES ON THE ALUMINUM BEAM FOR THE VERTICAL DIRECTION IN A FIXED-FREE CONFIGURATION

Mode	Frequency (Hz)		
	Fundamental	First harmonic	Second harmonic
Measurement	15	95	264
Simulation	16,2	100,6	284,1
Error (%)	8,00	5,89	7,61

IV. VIBRATION REJECTION

A. Principle

This new control scheme is built in order to reject, or at least attenuate, the vibrations under the following assumptions:

- main effort is devoted to peaks that appear in the spectral decomposition of the measured signal. These peaks either correspond to resonant modes of the mechanical structure or to particular modes of the disturbances
- for these peaks, amplitudes of external disturbances are constant or at least slowly varying
- the peaks are independent with respect to each other
- the dynamical behavior of the system is not well known for these particular frequencies

The goal is to create an excitation signal with appropriate amplitude and phase such that the combination of excitation and disturbances is null at the sensor location.

In order to simplify the control scheme synthesis, instead of dealing with amplitude and phase, a decomposition on the (sine, cosine) basis is used. The main advantage is the linearity of the problem.

Since resonant peaks are independent, it is possible to treat each one separately, and to add the contributions to get the excitation signal.

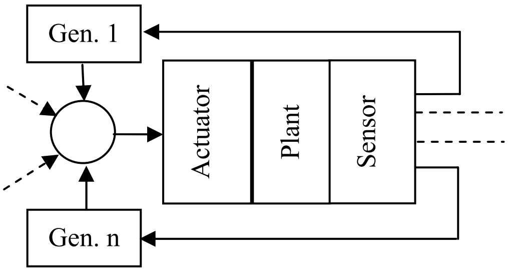

Fig. 6. Principle of vibration rejection

For each frequency under consideration, the problem consists in controlling a two-input two-output coupled system

Since for each frequency, the disturbance is supposed to have constant characteristics, the control scheme is based on Proportional-Integral loops. It means that control inputs, namely sine and cosine amplitudes of excitation signal, converge to constant value corresponding to the null values of sine and cosine amplitudes of output signal. Because of coupling effects between both inputs and outputs, a simple PI scheme is not suitable. Introducing state spaces approach, it is possible to get the expected results through static state feedback.

The main functions of the control scheme are organized as follows:

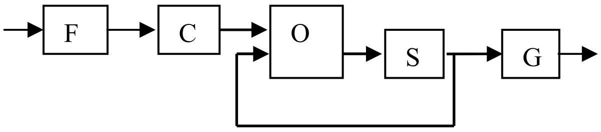

Fig. 7. Organization of the algorithm.

- Block F represents a narrow band digital filter whose frequency bandwidth is centered at the considered frequency its entry is the measured signal
- Block C computes the sine and cosine components of the signal at the considered frequency. Estimation is made by means of least squares criterion. Since this optimization problem is linear with respect to parameters, computations are fast.
- Block O is an observer whose role is to estimate the amplitudes (as sine and cosine components) of a virtual disturbance acting on the plant, and creating the same effect on the output as the actual but unknown disturbance.
- Block S is the state feedback. It computes the sine and cosine components of the control signal, on the basis of estimated virtual disturbance and matrix gain derived from transfers between virtual disturbance and output on the one hand and control input and output on the other hand.
- Block G represents the control signal generator. It creates the sinusoidal input at every sampling time on the basis of sine and cosine components computed by block S. This signal is applied to the plant.

All these blocks are duplicated as many times as there are peaks to attenuate. Each block parameters are tuned according the corresponding frequency. All the block G outputs are summed up in order to create the control signal which feeds the actuator.

B. Experimental setup

To test this rejection algorithm, a small mock-up is used (Fig. 8). It is composed of:

- a steel beam
- two disturbances sources created by means of small loudspeakers
- one PZT ceramic is used as an actuator, glued on one side of the beam (Fig. 9)
- another collocated PZT ceramic is used as a sensor, glued on the opposite side of the beam

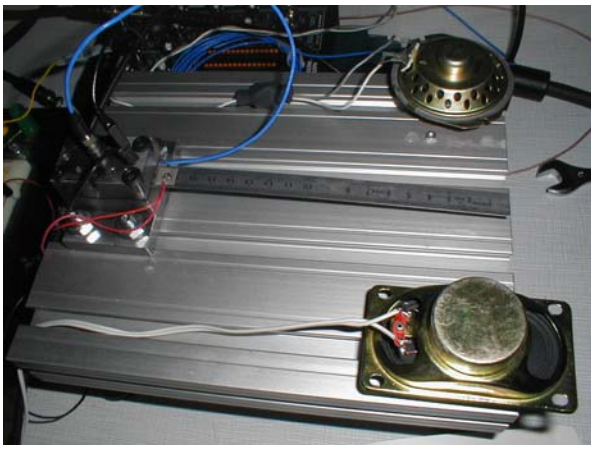

Fig. 8. Mock up.

Besides a PC with Matlab software is used to prepare the control algorithm, by means of Simulink and XPC target toolboxes. The final program is downloaded to another PC which is connected to the plant via a National Instruments data acquisition board.

The small size of this experimental set-up induces higher frequency range, and so higher sampling rate. It is why, XPC target is used instead of Real Time Windows Target. However the feasibility of the procedure with this mock-up guarantees efficiency when dealing with larger size of plants. The actual dimensions were chosen because of easy use of PZT ceramics in the corresponding frequency range.

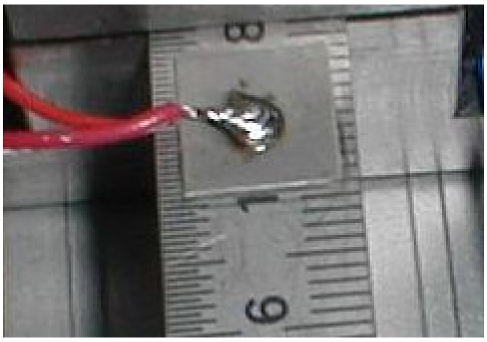

Fig. 9. PZT used as sensor.
Another PZT on the opposite side is used as actuator.

C. Results

A rough harmonic analysis of the system reveals two resonant modes in the frequency range under consideration: at 13.5 and 82.5 Hz. When excited by the loudspeakers at these frequencies, the spectral analysis exhibits another peak at 67 Hz, as shown in figure 10.

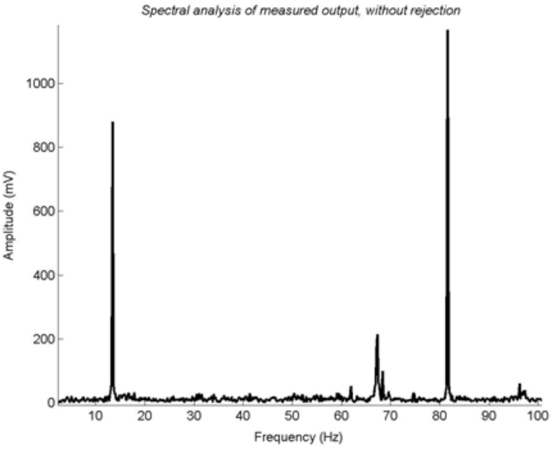

Fig. 10. Frequency spectrum before rejection

Then three parallel algorithms are activated to elaborate the three contributions of the input signal. When feeding the system with this control excitation, the new spectral decomposition shown in figure 11 is obtained.

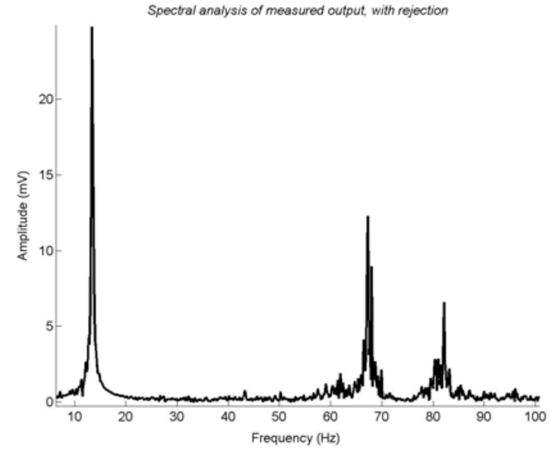

Fig. 11. Frequency spectrum after rejection

Though not perfect, the result is fairly good:

- peaks are reduced

- no other peak is created

Since the amplitudes are not null, it is necessary to investigate and find some explanations. One of these could be a mismatch between frequencies used in sinusoidal signal generators and actual disturbance frequencies. This is due to quantification of the spectrum, which is related to the sampling rate.

V. CONCLUSION

Up to now the three main parts of the project have been studied separately. It is the first step towards the feasibility analysis. Indeed there exist sensors able to measure the displacements with the required accuracy. These can be found in the field of seismometry. It is also possible to adapt actuators found in stabilization devices of tables used in optic measurements.

However, these systems must be redesigned in order to increase efficiency in the context of final focus stabilization. It is why the second part is very useful. The mechanical modeling gives information about optimal location of sensors and actuators, as well as expected values of eigenmodes that must be considered first by the rejection system. Since the definitive project is not known, this tool provides the designer with means that update the information according to external considerations that affect the behavior of the final focus.

As for the third part, it is only the first sketch of a stabilization scheme which must be sufficiently robust with respect to parameter uncertainties. It is necessary to test this new algorithm in more realistic conditions, namely vibration amplitudes. Another aspect that merits consideration is the extension of the method to continuous spectrum instead of particular frequency peaks. Work is already done in that direction.

Yet these three parts make a whole. The harmonious sizing of each element can only be found in a global mastery of the project. This requires sharing of various skills. It is just the matter of mechatronics.

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