About optimal location of sensors and actuators for the control of flexible structures

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About optimal location of sensors and actuators

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Abstract ***– This work deals with the problem of efficient location of sensors and actuators encountered in the domain of active control of flexible structure. It appears that the optimal solution depends upon the type ofcontrol scheme that is used as well as the kinds of sensors and actuators that are implemented, and on the criterion that is considered. This paper recalls and discusses some approaches that are presented in the literature and presents some results that are obtained with a mock-up equipped with piezoelectric sensors and actuators.***

I. INTRODUCTION

This work about location of actuators and sensors for a flexible structure was motivated by the accuracy that is expected in future linear collider used in physics of particles. The process under consideration is similar to a 2.5 m long and 0.2m wide fixed-free pipe, and it is required that amplitude of vibration is less than a few nanometers [12]. Along with the design of an efficient control scheme, the problem of location of actuators and sensors is crucial, independently of technological constraints that will appear in the design of the pipe.

The literature provides with many references about active vibration control and collocation of sensors and actuators [3, 5, 11, 13, 15]. It appears that the advantages of this methodology depend upon the control scheme that is used, as well as the type of sensors and actuators, which are implemented in the process.

The first part of the paper presents the problem of active vibration reduction in the particular case of a long pipe.

The second part discusses the advantages and defects of collocation of sensors and actuators. In fact it is shown that it depends on the type of model that is used for designing the control scheme. Collocation presents some interesting features when dealing with transfer functions modelling, but this kind of model is not representative enough in the case of flexible structures.

The third part introduces the combined use of a Finite Element Method software and Structural Dynamics toolbox of Matlab, which provides with models that allow the analysis of the influence of location, especially when dealing with multiple modes. It requires a criterion, which allows a comparison between several configurations. This one is based on the grammian evaluation. This information refers to controllability and observability properties of the system according to the type of sensor as well as actuator that are used. It is then possible to get a convenient location for both devices with respect to the bandwidth of closed loop behavior.

The fourth part is devoted to an example, which consists in a steel beam. A piezoelectric actuator is used, and several types of sensors are analyzed, namely optical and piezoelectric sensors.

II. CONTEXT

The mechanical structure under consideration is rather simple since it consists in a clamped-free pipe, but the problem is to reduce at a minimal level the amplitude of vibration all along the pipe.

There are many sources of disturbances: ground motion as well as sounds or vibration induced by neighbouring equipments (coolers, vacuum pumps, …).

Since the final design of the pipe is not completely known at that time, we start with a small mock-up which allows many combinations of control schemes, actuator or sensor locations [9].

Since the objective is to reduce the amplitude of vibrations, the following assumptions are made:

- disturbances are periodic, which means that after a Fourier decomposition, it is possible to consider superposition of sinusoidal disturbances.
- the system is stationary, which means that characteristics of sinusoidal disturbances are constant or slowly varying

Furthermore we reduce the analysis in a plane, so we consider the motion of a blade with a fixed end at one side and a free end at the opposite side.

III. COLLOCATION OR NON-COLLOCATION

As mentioned before, there are two main parts in the design of the control scheme:

- the algorithm by itself
- the actuators and sensors location

There are many papers available in the literature on this subject [2, 10]. Two main classes appear with collocation on the one hand and non-collocation on the other hand.

Roughly speaking, the main advantages of collocation are:

- the reduction of the required space to install actuator and sensor (mechanical design)

- the possible use of simple control laws, such as positive position feedback [15]

Notice that this second argument can be reversed in that sense that the use of this simple control law requires the collocation of actuator and sensor. This is due to considerations about the phase evolution which must stay within a domain to guarantee the stability of the closed loop.

Typical Bode plots are given in figure 1 in the case of collocation of actuator and sensor used in the mock-up shown in figure 2.

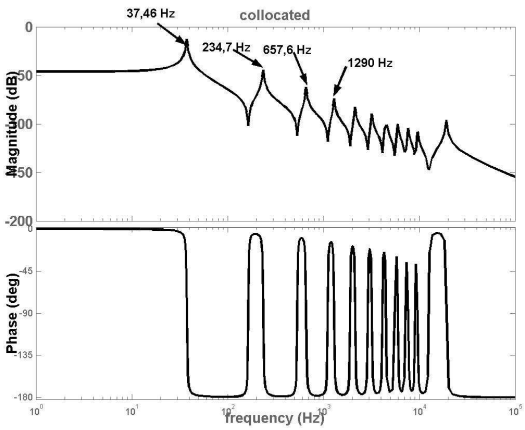

Fig. 1. Bode plots in the case of collocation

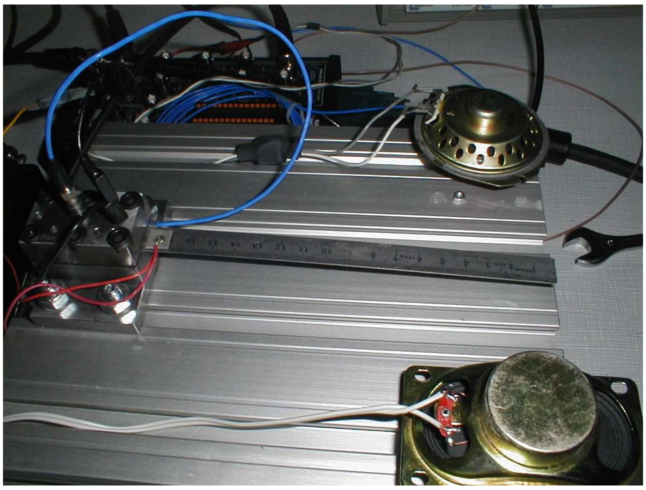

Fig. 2. Mock-up with collocated PZT actuator (above) and PZT sensor (under) close to fixed end of the beam

If it is not possible to do collocation for technological reasons, it becomes a problem since the design of the control scheme is more difficult.

Another main advantage of simple control scheme involved in case of collocation is that they not require accurate model of the system. But the corresponding drawback is the lack of confidence in the performances that are obtained. It is shown in other fields of control theory, typically flatness and non linear control, that better performances are attainable when there are no zeros in the transfer function, whereas in the collocation case, they are the most numerous.

However, there is another important point to consider. When dealing with a particular transfer function, attention is focused on the measurement at one point. In the case of vibration reduction, it is necessary to verify that attenuation at one point doesn't lead to amplification at another place. This imply a more global analysis of the system. The main consequence is the need of a more refined model, and then a more sophisticated control scheme.

Such a model should be viewed as a tool for a more global analysis of the behavior of the whole system, with the possibility to detect singular configurations, and to carry robustness studies.

Let us start with the problem of location of actuators and sensors.

IV. OPTIMAL LOCATION

Introducing the adjective "optimal" before the word location means that there is a criterion that allows the comparison between several situations in order to determine the best choice [1, 4, 7]. The problem is not easy for many reasons:

- several criteria should be considered simultaneously, one for the sensor, one for the actuator, namely controllability and observability which concern the control scheme, and another one for the quality of the rejection all along the beam
- models are complex, because of their large size, and it is not possible to get an analytical solution of the optimisation problem

In this paper, we focus on controllability and observability aspects of the control scheme [14]. Once again, several criteria are presented in the literature, and to illustrate the influence of actuator and sensor location, we consider a particular criterion called deg5, computed by this formula:

$$\deg 5 = \sum_{i=1}^{2N} \lambda_i . \frac{\sqrt[2N]{\prod_{i=1}^{2N} \lambda_i}}{\sigma(\lambda_i)}$$

where the λ_i are the eigenvalues of the controllability (or observability) grammian, and σ represents the standard deviation function. Meaning of this criteria may be found in [6].

Grammians are derived from a state space representation of the system and vary according to the location, as well as the nature, of the input or the output. Following results were obtained by considering a fixed-free steel beam, 16cm long, 1.5 cm wide and 0.1 cm thick. Input is a force and output is a position. Furthermore, the dynamic behavior changes according to location of the sensor and of the actuator since their mass are taken into account when building the model.

The state space representation is obtained using a Finite Element Model of the system. To do that, the ANSYS software is used to build a general FEM description of the system. Then the Structural Dynamics Toolbox with Matlab is used to derive a state space model, after activating appropriate nodes corresponding to the location of actuator and sensor.

Figures 3 and 4 show respectively the values of the controllability and observability criteria.

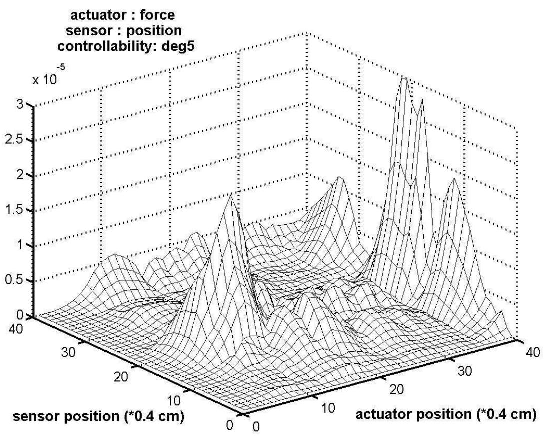

Fig. 3. Controllability criterion

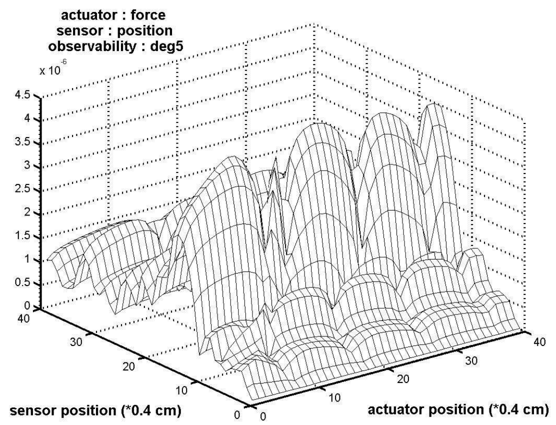

Fig. 4. Observability criterion

First of all, it is mainly a qualitative information, and both criteria must be considered simultaneously. It appears that collocation is not good at all, but the choice of force and position as input and output is not appropriate for PPF control.

The case of PZT actuator and PZT sensor is not yet available, since it requires the computation of ANSYS FEM model for each location of actuator and sensor.

V. EXPERIMENTAL RESULTS

In parallel with this simulation analysis, experiments were carried out to get information about the quality of rejection with respect to actuator and sensor location.

To do that, a second mock-up was built, with three PZT patches, acting as sensor or actuator, plus an optical sensor added to the system, as shown in figure 5.

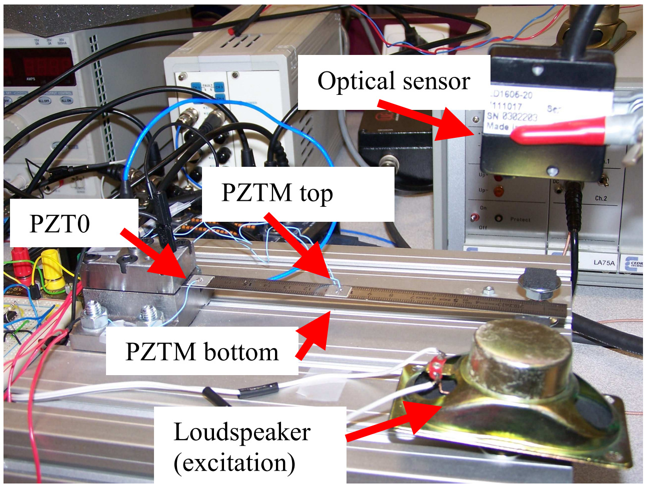

Fig. 5. Second platform

The figure 6 below describes the system.

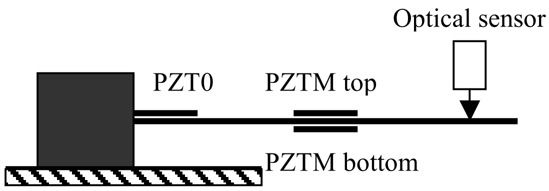

Fig. 6. Second mock-up description

Tests are carried out using specific control scheme described in [8]. This algorithm consists in a compensation of sinusoidal disturbances by computing appropriate sinusoidal actions corresponding to most relevant frequencies in the output spectrum. Real Time Control is performed using XPC target, after having described the control algorithm by means of Matlab and Simulink software.

Main results are summarized in table I:

- first and second columns indicate respectively which devices are used as actuator and sensor for the control scheme
- the following columns give information about the quality of the rejection, as seen by the sensor (for these experiments, the optical sensor remains at the extremity of the beam).

It can be seen that very good rejection is always obtained at the location of the sensor which is used to give information to the control algorithm. However looking at other places along the beam, it appears that the performance is really bad when using the central PZT, and anyone of the sensor at the extremities of the beam.

Table I. Rejection quality
(vg: very good, g: good, n: neutral, vb: very bad)

actuator	*sensor*	PZT0	PZTM	Optical
PZT0	*PZTM*		vg	g
PZT0	*Optical*		g	vg
PZTM	*PZT0*	vg	vb	n
PZTM	*PZTM*	n	vg	g
PZTM	*Optical*	g	vb	vg

Is it an argument for collocation ? The answer is not so easy. In fact these results exhibit another problem. It concerns the information that is used in the control scheme, as well as the kind of action that is applied to the system. Indeed, for a good rejection, it is necessary to control position *and* rotation at each point of the beam. However, PZT patches can only produce torque and can measure rotation. At the same time, optical sensor can only measure position. This means that both translation and rotation should be jointly considered to get good performance at any location. Work is carried out in that sense.

VI. CONCLUSION

The main conclusion of this study is the necessity to manage several sensors and actuators in order to guarantee global quality of vibration rejection along the beam. More precisely, according to the variety of measurements and actions, it will be more or less easy to build the corresponding control scheme.

Another aspect of this study concerns the level of the attainable vibration reduction. Indeed, if disturbances come from the basis, it is not possible to eliminate its influence at the clamped end of the beam. In this case, the use of several actuators may lead to an acceptable compensation of their effect along a large section of the beam.

Let us recall that the requirement is a vibration amplitude of a few nanometers. This involves very accurate sensors, already available in the seismic domain, as well as very sensitive actuators. The figure 7 and 8 give an overview of the last mock-up and the corresponding actuator respectively.

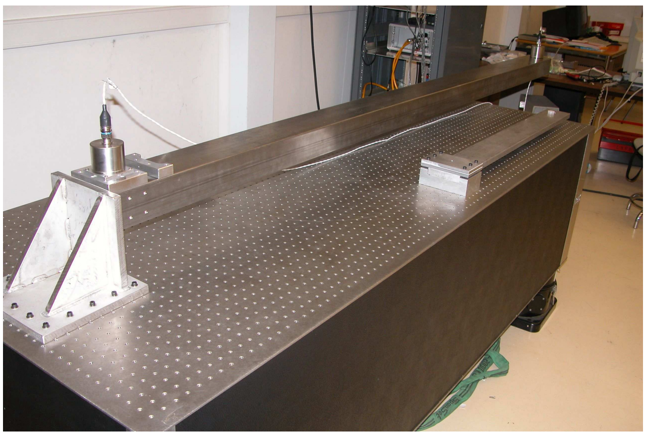

Fig. 7. Real size mock-up

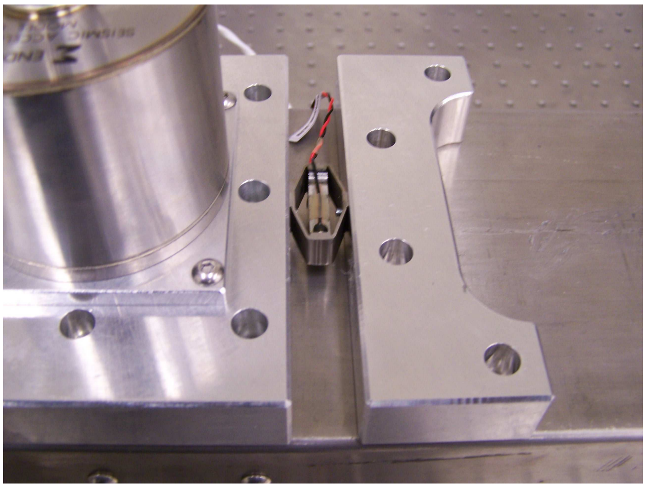

Fig. 8. New actuator

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