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Non-linear modelling and optimal control of a hydraulically actuated seismic isolator test rig

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ABSTRACT

This paper investigates the modelling, parameter identification and control of an unidirectional hydraulically actuated seismic isolator test rig. The plant is characterized by non-linearities such as the valve dead zone and frictions. A non-linear model is derived and then employed for parameter identification. The results concerning the model validation are illustrated and they fully confirm the effectiveness of the proposed model.

The testing procedure of the isolation systems is based on the definition of a target displacement time history of the sliding table and, consequently, the precision of the table positioning is of primary importance. In order to minimize the test rig tracking error, a suitable control system has to be adopted. The system non-linearities highly limit the performances of the classical linear control and a non-linear one is therefore adopted. The test rig mathematical model is employed for a non-linear control design that minimizes the error between the target table position and the current one. The controller synthesis is made by taking no specimen into account. The proposed approach consists of a non-linear optimal control based on the state-dependent Riccati equation (SDRE). Numerical simulations have been performed in order to evaluate the soundness of the designed control with and without the specimen under test. The results confirm that the performances of the proposed non-linear controller are not invalidated because of the presence of the specimen.

1. Introduction

Structural responses under strong external excitations, such as earthquakes and wind storms, can be mitigated by means of base isolation strategies [1,2]. The base isolation is typically realized using passive, semi-active or active systems [3,4] whose characteristics can be determined with specific tests. As regards the isolation performances of passive and semi-active isolators, the restoring force and the energy loss are considered of primary importance. For these reasons, such devices are tested in order to obtain the force-displacement cycle that allows an analytical description of their dynamic characteristics to be deduced [5,6]. The test rigs typically use hydraulic cylinders to impose periodic deformations on the isolator and a control system to guarantee the desired displacement law is tracked. The hydraulic actuation system is characterized by a high power/mass ratio and a fast response [7]. At the same time, it exhibits significant non-linear behaviour due to the pressure-flow rate relationship, the dead zone of the control valve [8] and frictions [9]; these

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non-linearities make the mathematical model more complex and, at the same time, highly limit the performance achieved by the classical linear controller [10].

The traditional and widely used approach to the control of hydraulic systems is based on a linear model or on the local linearization of the non-linear dynamics about the nominal operating point [7,11,12]. A Kalman based controller is developed in [13]. The controller utilized an optimal reference trajectory obtained by minimizing acceleration tracking error. The non-linear system model was linearized about the reference trajectory and the resulting non-autonomous system was used to develop time-varying feedback gains. Suitable adaptive approaches are also employed when there is no knowledge of the parameter values [14] and when initial adaptation stages are acceptable.

In the following, an activity carried out on a seismic isolator test rig, realized at the Department of Mechanics and Energetics of the University of Naples "ederico II" (Italy), is described. The test rig mainly consists of a sliding table, driven by a hydraulic cylinder, on which the isolator under test is connected; the other end of the isolator is connected to a reaction structure. The peculiarity of the machine is that it may also have other purposes; it can be employed to deduce friction between sliding surfaces or, by disassembling the reaction structure, it can be adopted as a mono-axial shaking table.

In this paper, with reference to the isolator test rig configuration, a model based hydraulic actuator control system, able to follow the desired displacement law, is presented and its robustness properties are checked. Indeed, it is important in these applications to design control systems that are insensitive to the unknown forces caused by devices under test [12,15]. The main step to achieve this target is to design the controller based on a mathematical model that is able to reproduce satisfactorily the dynamic behaviour of the system to be controlled.

To this end, a non-linear mathematical model has been derived and its parameters identified. A validation procedure has been executed by means of experimental tests. The theoretical-experimental comparisons confirm the soundness of the proposed model. The validated model has been employed for a feedback control design able to enhance the performances in terms of the error between the target position and the current one in presence of the external disturbance due to the specimen under test. The proposed approach, novel for seismic machines, consists of a non-linear optimal control based on the state-dependent Riccati equation (SDRE). Differently from other techniques, the SDRE algorithm fully captures the hard and soft non-linearities and, at the same time, guarantees the optimal performance of the closed loop system together with real-time implementability, inherent robustness with respect to parametric uncertainties and unmodelled dynamics, as well as disturbance rejection. The controller design procedure has been carried out with no isolator employed as specimen under test. On the contrary, simulations have been executed in presence of an isolator model in order to evaluate controller sensitiveness. The numerical results highlight controller effectiveness both in terms of tracking error and robustness.

The paper is organized as follows: a detailed description of the test rig is given in Section 2 and its mathematical model is derived in Section 3. Identification procedure and model validation are described in Sections 4 and 5, respectively. The validated model is employed for control development, whose details are illustrated in Section 6. Finally, simulation results are shown in Section 7.

2. Test rig description

The test rig (Figs. 1 and 2) consists of movable and fixed parts made in structural steel. Particularly, it is constituted by:

- fixed base;
- reaction structures;
- sliding table (1.8 m × 1.6 m);

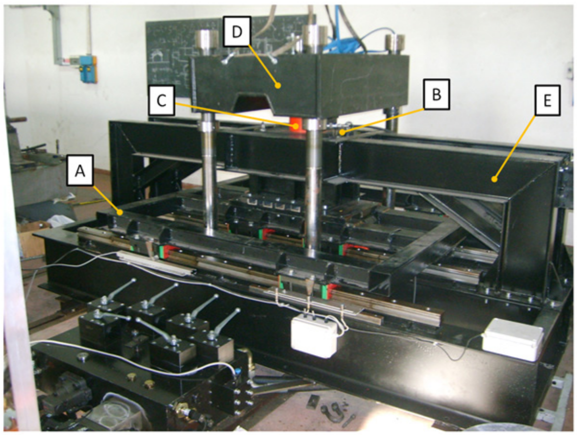

Fig. 1. Test rig.