Mechatronics 49 (2018) 168–176

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Application of hybrid force/position control on parallel machine for mechanical test☆

Julien Le Flohic, Flavien Paccot, Nicolas Bouton, Hélène Chanal*

Université Clermont Auvergne, CNRS, SIGMA Clermont, Institut Pascal, Clermont–Ferrand, F-63000, France

ARTICLE INFO

Keywords:
Parallel machine
Hybrid control
Testing machine
Multi-axial test
Model

ABSTRACT

The quality of mechanical test is strongly linked to the control of boundary conditions and loaded tool path in applied forces or displacement of a tested specimen. In this article, a hybrid force/position control algorithm is adapted to parallel kinematic mechanical test machine with regards to the tested specimen behavior and realized mechanical test. This control algorithm is illustrated on a Nooru–Mohammed test performed on Gough Stewart platform and validated experimentally on a 5 bar parallel mechanism. The principle of the Nooru–Mohamed test consists in submitting a double notched concrete test part to a position slope, inducing a combination of shear and tension loading. The extra degrees of freedom of the parallel machine are used to control boundary conditions.

1. Introduction

Multi-axial tests are used to identify material behavior like concrete [1]. In most cases, damage is localized in areas submitted to multi-axial loading, leading to the failure of the global structure [2]. To explore the specificities of the multi-axial behavior of a material, a solution is to design the testing machine in order to induce multi- axial stress state from a uniaxial actuator. Multi-axial tests are therefore mainly realized with different synchronized structures. However, such machines are not versatile and are designed only for one specific load (tension/compression or tension/torsion for example).

Another solution is to apply directly a multi-axial loading on one specimen using 6 degrees of freedom (DOF) multi-axial testing machine. Thus, the stimulation of a specimen boundary can be achieved by a complete twist (3 translations + 3 rotations), wrench (3 momenta + 3 forces) or a combination of both [3]. This kind of machine can also be used to perform a pure tension test on a specimen with the requirement that non loaded specimen axis are still controlled with a null force.

In this context, the use of 6 DOF parallel kinematic machines can be relevant due to their benefit in term of ability and stiffness compared to serial structure machines [3]. Such parallel kinematic machines (PKMs) have largely been investigated for applications in robotics and machining [4,5]. However, the complexity of associated models and control laws, in addition to a reduced workspace, are their main drawbacks [6,7].

Today, only very few mechanical testing applications have been performed with parallel kinematic machines, and are mainly developed for biomechanical context with large displacements [8–11]. Indeed, extra degrees of freedom are often considerate as disruptive for the specimen load.

Previous works have demonstrated that hexapod architectures are suitable for multi-axial testing of materials through a specific case study, the Nooru–Mohamed (NM) test [2,3] (Fig. 1). Its principle is to load a double edge notched specimen to a combination of shear and tension (or compression) using numerous loading paths [1] and requiring position and/or force control. More clearly, it consists of applying a tool path in one specimen extremity along *X* and *Z* axis while no force in *Y* axis and no torque in *X, Y*, and *Z* axis loaded the specimen. According to Nooru–Mohamed, boundary conditions of the tests are difficult to control and since 1992, nobody has been able to perfectly reproduce it with conventional machine. This observation has motivated the development of a test machine based on Gough Stewart platform [2]. First experimentation, during NM test on this Gough Stewart platform, has demonstrated that the instrumentation set up allows a relevant measurement of the displacement field [2]. But this experiment shows an important rigid body motion of the specimen with unwanted force acting on its boundary [11].

Therefore, the aim of this paper is to design an advanced control law for parallel kinematic test machine which ensure to control specimen load and boundary conditions for NM test. In other words, the control algorithm has to control the position of the specimen boundaries on two

☆ This paper was recommended for publication by Associate Editor Lianqing Liu.

* Corresponding author.
E-mail address: helene.chanal@sigma-clermont.fr (H. Chanal).

https://doi.org/10.1016/j.mechatronics.2017.12.006
Received 3 May 2017; Received in revised form 14 November 2017; Accepted 20 December 2017

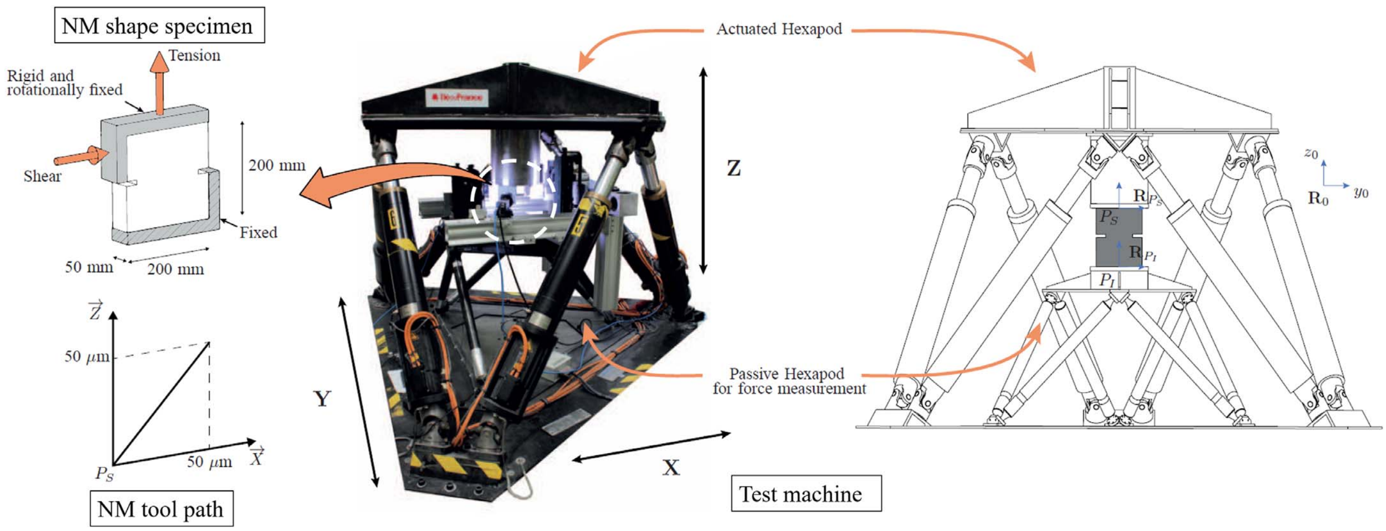

Fig. 1. Principle of Nooru–Mohamed test [1] and test machine.

directions in order to generate the shear and tension load and null forces and torques on the other directions.

To achieve this objective, different methods could be considered and can be classified in two categories: impedance control and hybrid control [12].

Impedance control consists in regulating the mechanical impedance, which is defined as the ratio of force to motion [13]. Therefore, the effort applied by the end-effector on the environment is not directly regulated [14]. It is mainly used for assembling [15], manipulation [16], polishing [17], or more generally for any tasks requiring a position control of a robot which may come into contact with the environment.

The hybrid force control is chosen in particular when the environment is highly deformable, as in a medical context, using flexible environment and tool [18], or when the task requires accurate tracking coupled with high loads, as in a machining context [19,20]. This method is based on the decomposition of the task space into purely motion controlled directions and purely force controlled directions [21,22]. For a 6 DOF parallel manipulator, the n force controlled directions and the 6-n position controlled directions in the Cartesian coordinate system are independently regulated. However, in case of parallel kinematic machine, the movement and force applied by each actuated joint has an influence on the position and the force applied by the mobile platform to the specimen in all Cartesian coordinate system axis.

Then, considering the necessity to control specimen boundaries conditions for a parallel kinematic machine despite the test machine structure deflections for a quasi-static test with complex load trajectory, hybrid force/position control is chosen [11]. Moreover, for NM test, boundaries conditions (null force or torque) and position tool path are defined in the Cartesian space with regard to the specimen.

However, the main limitation of this kind of force control is due to the sensitivity to errors in the implemented dynamic model [10,11]. For NM test, this limitation is overcome assuming that:

– NM test is a quasi-static test. Thus, the test machine static model can be used instead of dynamic model as inertial forces can be neglected. Indeed, the movement of the test machine is very small during the NM test thus just the force and torque applied to the specimen should be controlled.
– NM test generated small movement of actuated joint. Thus, test machine Jacobian matrix can be considered as constant during the test.

The validation of these hypotheses is realized in this article.

In this paper, a hybrid force control law for parallel mechanical test machine is implemented for NM test. This paper presents a method to define a hybrid force control law and its tuning method from the mechanical behavior modeling of the tested specimen and the machine with regard to the test requirement. The experimental validation of the proposed control law is realized on a 5 bar parallel robot as the implementation on the final hexapod requires other important developments.

The proposed control law was firstly introduced in references [23] and [24]. This paper particular contribution is the discussion of this control law and experimental validation on 5 bar parallel mechanism. Thus, this last study ensures to validate the real application of the control scheme and the possible generalization of the proposed method.

The paper is organized as follows. Section 2 presents the hexapod test machine and the model associated. Based on this formalism, Section 3 describes the control scheme implemented. Section 4 presents a first result discussion based on simulations realized on a Simulink®/Adams™ environment. Finally, the defined control law is applied and validated on a 5 bar parallel mechanism.

2. Presentation of test machine

A first experimentation of NM test with a hexapod mechanical test machine has been performed in reference [8]. It revealed that an advanced control law is needed to use extra DOF to have an accurate control of boundary conditions. This test shown that displacement at failure is negligible in comparison to the specimen dimension (0.01%).

During this test, position of the upper limit of the specimen and the load on the specimen are measured with a position sensors and force/torque sensors (Fig. 1).

In a first time, the hexapod test machine and its instrumentation is introduced before the definition of associated model.

2.1. Hexapod test machine

The hexapod test machine is composed of an actuated machine (6 DOF Bosch–Rexroth hexapod with ballscrew electrically actuated cylinder) and a passive hexapod for force measurement. The specimen is placed between this two hexapodes (Figs. 1 and 2). The force and torque measurement is realized with an uncertainty of 80 N and 20 N.m [25]. This instrumentation enables a resolution of 0.2 μm with a 20 Hz frame rate.

The displacement between the two specimen extremities is achieved