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Development of a Novel Pure Mechanical Decoupling Control Device for the Electro-hydraulic Dynamic Triaxial Instrument

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Abstract

This study is concerned with the development of a novel mechanical decoupling control device. The coupling is a widespread phenomenon in the hydrostatic transmission system. Many researchers have been doing a lot of work to find reasonable decoupling ways in the past. Unlike other decoupling control methods, a novel pure mechanical decoupling control device is developed for the electro-hydraulic dynamic triaxial instrument. This pure mechanical decoupling control device is used to decouple the strong coupling between the axial loading and the radial loading automatically. The structure of the electro-hydraulic dynamic triaxial instrument (including the mechanical decoupling control device) has been introduced. The strong coupling phenomenon between the axial loading subsystem and the radial loading subsystem has been analyzed. The working principle of the mechanical decoupling control device has been presented and the decoupling ability has been studied by simulation. In order to testify the decoupling ability of the mechanical decoupling control device, a series of experiments have been done in the laboratory. The experimental results show that this kind of pure mechanical decoupling control device works pretty well. This practical decoupling device could be adopted in other similar fields.

Keywords*: Mechanical decoupling control device, Coupling, dynamic triaxial instrument*

1. Introduction

The coupling is a widespread phenomenon in the hydrostatic transmission system. It is very important to analyze the coupling phenomenon and its effect correctly. The main elements of generating coupling include tube, fluid, temperature effects, machinery, vibration and so on, which may appear simultaneously and affect each other in the real system. The existence of the coupling makes positive and negative effects. On one hand, many useful machines or parts such as Hydraulic Coupling [1], Hydraulic Engine Mount [2], Hydraulic Transformer [3] and Continuously Variable Transmission [4] are invented based on fluid-force coupling, fluid–structure coupling, thermal- mechanical coupling and so on. On the other hand, the existence of coupling will increase the difficulty of control and sometime the system may be out of control. Typical coupling phenomenon can be easily found in the hydraulic 6-DOF parallel manipulator [5], Hydraulic Load Simulation Test Equipment for Engineering Machinery Vehicle [6], Flight Motion Simulator [7], Shield Tunneling Machine [8] and other test rig.

The coupling has interaction characteristics that make the controlled system extremely complex. Many scholars have been doing a lot of work to find reasonable decoupling ways. Cutting the coupling channel and connecting the compensation channel are the two intuitive methods. The decoupling control must be used to eliminate the coupling effects when there are pure mechanical couplings. The decoupling control methods include classical decoupling control method, feedback decoupling control method, adaptive

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decoupling control method and today's intelligent decoupling control method. The basic idea of the classical decoupling control method is to change the system transfer matrix of the input/output variables in MIMO control system into a diagonal matrix. The outstanding representatives include HOOD, Boksenbom A.S. [9], Bristol E.H. [10], *etc.* Advantage of the method is easy to understand, but sometimes the inverse matrix is difficult to calculate because of the high-order coupling matrix. The feedback decoupling control methods developed by Falb P. [11], EG Gilbert [12] and Silverman L. [13] include linear state feedback decoupling and linear output feedback decoupling. The feedback matrix in this method is used to make the system transfer function matrix become a diagonal rational polynomial matrix. The combination of adaptive control theory and decoupling technique forms the adaptive decoupling control method [14], whose purpose is to make the system closed-loop transfer become a diagonal matrix. In fact, the adaptive decoupling control method which has adopted optimal control and seeking optimizing parameter by establishing the objective function is the core issue. The adaptive decoupling method, which is the basement of the intelligent decoupling theory, is a breakthrough in the decoupling theory [15, 16]. If the precise mathematical model of the system can not be achieved, we have to resort to intelligent decoupling control [17, 18]. Intelligent decoupling control methods include neural network decoupling control [19, 20], fuzzy decoupling control [21] and their combination [22, 23]. Intelligent decoupling control with self-learning function is used in time-varying nonlinear unknown system. Fuzzy decoupling control is commonly used in the situation where there is no clear mapping between input and output signals.

A strong coupling between the axial loading and the radial loading in the electro-hydraulic dynamic triaxial system is studied in this paper. The coupling will greatly decrease the control accuracy of the radial loading. For the gaps and air bubbles' existence it is hard to establish a precise mathematical model of the specimen. So the traditional decoupling control methods can not be used. As a result, intelligent decoupling control methods have become preferred choices. As mentioned earlier, neural network decoupling control and fuzzy decoupling control are typical two kinds of intelligent decoupling control methods. Neural network decoupling control is not suite for online real-time control and its algorithms are complex. Fuzzy decoupling control does not need to establish a precise mathematical model except for fuzzy decoupling rules. It is an expert system obtained by the decoupling experiences and expert judgments. The current measurement data, facts and evidence will be stored in the database during decoupling control. Decoupling is achieved by fuzzy reasoning after selecting and implementing rules. The rules and algorithm of Fuzzy decoupling control need to be known. However, the fuzzy decoupling rules are only obtained through a large number of experiments. Different soil sample means different fuzzy decoupling rules, which will spend too much time on experiment and waste a lot of soil samples. Based on the above considerations, the research group presents a more suitable way to decouple automatically by the compensation in this paper.

A novel pure mechanical decoupling control device is applied in the electro-hydraulic dynamic tiaxial instrument and the coupling problem will be solved. The working principal of the mechanical decoupling control device is described in this paper and the decoupling ability is tested by simulation. In order to testify the decoupling ability of the mechanical decoupling control device, a series of experiments have been done in the laboratory, which will be showed at the end of the paper. This useful and practical decoupling method should be recommended.

2. Description of the Coupling Phenomenon in the Electro-hydraulic Dynamic Tiaxial Instrument

The stress-strain relationship of the soil is the precondition to evaluate the deformation and the stability of the geotechnical structures. A clear understanding of the soil's dynamical properties under different initial stress conditions and periodic loads is the basic need of studying geotechnical structures deformation, foundation failure and basis instability, which are caused by the earthquake, sea waves or other mechanical vibration loads. Studies on the stability and the deformation of the soil under the dynamic force become more and more important. These complex problems are usually carried out through the laboratory simulation experiments. The research on the intensity and the deformation of the soil under the periodic load is one of the most important topics in today's soil physical science. The device known as the electro-hydraulic dynamic triaxial instrument, which is a very important device for studying the instability, the stress/strain and the other mechanical properties of the soil, is used to simulate periodic excitations (sine wave, triangle wave, rectangular wave, *etc.*).

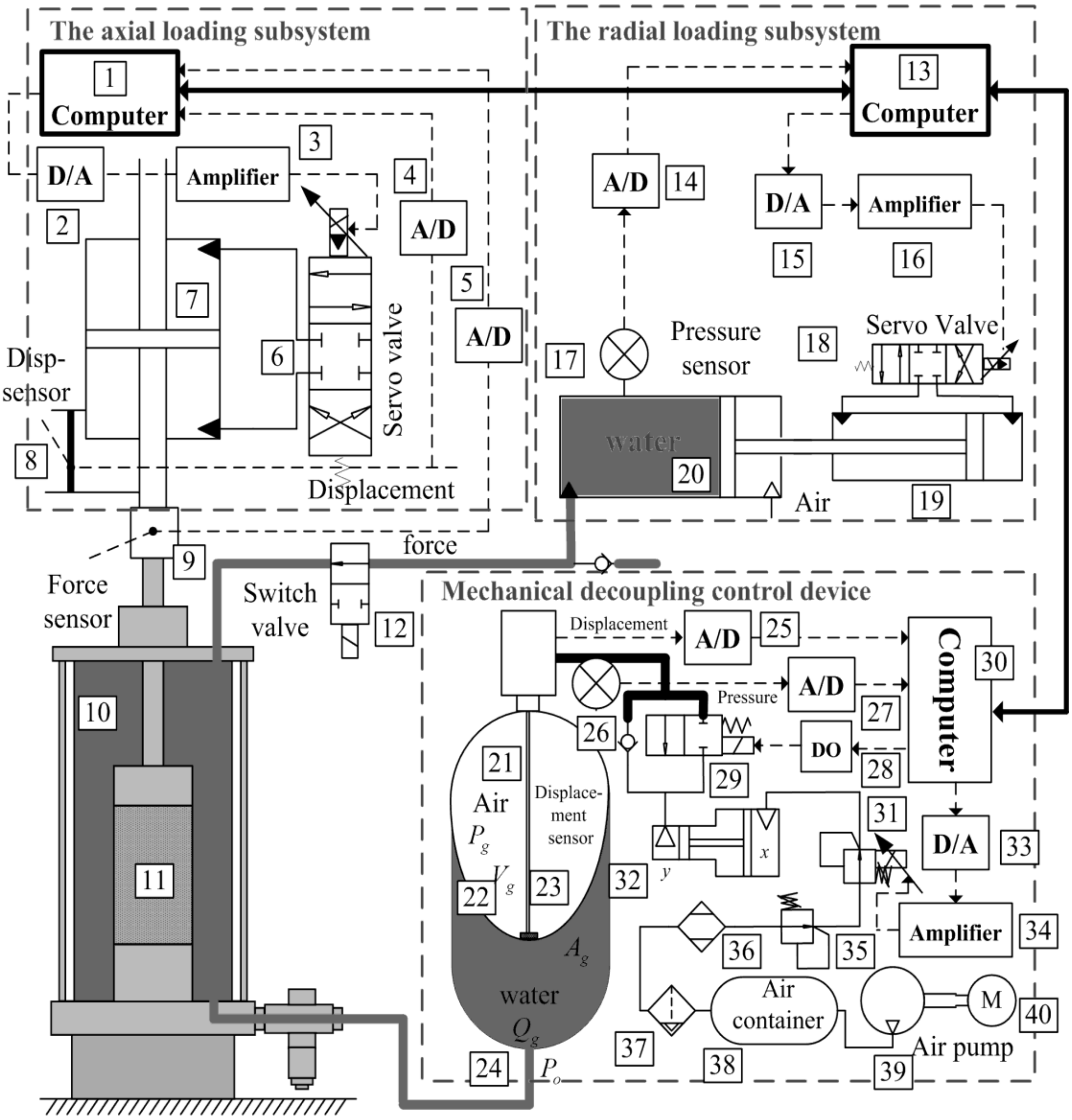
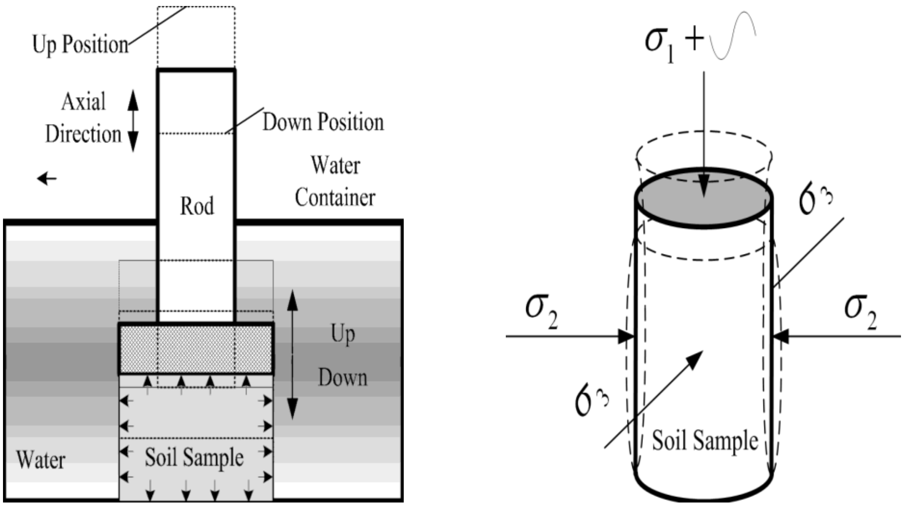


Figure 1. Schematic Diagram of the Electro-Hydraulic Dynamic Triaxial Instrument

1—Controlling Computer, 2—Digital/Analog Converter, 3—Amplifier, 4—Analog/Digital Converter, 5—4, 6—Hydraulic Servo Valve, 7—Double Acting Servo Cylinder, 8—Magneiostrictive Position Sensor, 9—Pressure Transducer, 10—Pressure Vessel, 11—Soil Sample, 12—Switch Valve, 13—1, 14—4, 15—2, 16—3, 17—9, 18—6, 19—Single Acting Servo Cylinder, 20—Water Cylinder, 21—Air Cell, 22—Rubber Airbag, 23—Displacement Sensor, 24—Air-water container, 25—4, 26—Pressure Transducer, 29—Switch Valve, 30—1, 31—SMC E/P Regulator, 32—Booster Valve, 33—2, 34—3, 35—Relief Valve, 36—Desiccator, 37—Filter, 37—Air Container, 39—Pump, 40—Electric Motor.

In this paper the electro-hydraulic dynamic triaxial instrument consists of the axial loading subsystem, the radial loading subsystem and the novel mechanical decoupling control device as Figure 1 shows. The axial loading subsystem is used to apply the exciting force/stress on the soil sample in the axial direction and the radial loading subsystem is used to apply the constant stress on the soil sample in the circumferential direction. Each of the two subsystems employs the electro-hydraulic servo system for a good dynamic response. In addition, the advantage of the electro-hydraulic servo system could make the radial loading subsystem obtain a high-precision and high-pressure stress easily. The novel mechanical decoupling control device is designed in this paper, which is used to decrease the coupling relationship between the axial loading subsystem and the radial loading subsystem. In Figure 1 the high-precision A/D converter (National Instruments, U.S.) with 16-bit conversion accuracy is used to measure the field signals, meanwhile, a high-precision D/A converter (National Instruments, U.S.) with 16-bit conversion accuracy is used to control the hydraulic servo valves and the SMC E/P Regulator. The magneiostrictive position sensors with linearity of 0.01% and the load cell with non linearity of 0.02% are employed in the system. A high-precision pressure transducer with range from 0 Mpa to 2 Mpa is added to measure the pressure of water in the container. There are three controlling computers in the Figure 1 and the communications between them are based on field bus.



(1) The Rod Coupling (2) The Sample Coupling

Figure 2. Schematic Diagram of the Coupling in the System

There are strong couplings for the electro-hydraulic dynamic triaxial instrument as Figure 2 shows. One is the rod coupling ((1) in Figure 2) that caused by the movement of the rod and the other is the sample coupling ((2) in Figure 2) that caused by the distortion of the soil sample during the exciting force/stress test. The rod coupling can be explained as: the water container can be assured as a closed container and the soil sample is in balance under the axial and radial stresses. When the rod is moving down, the volume of the rod that is inserting into the water container will increase. Then, the pressure in the water container will increase too. Eventually, this change will lead to reducing of the accuracy of axial loading control. However, pure water has been adopted in the dynamic triaxial test and water is incompressible. For this reason the volume change of the rod will seriously affect the value of the radial constant force. Similarly, volume of the sample will change because there are pores and bubbles, which will lead to the sample coupling during the dynamic triaxial test. The change in the radial loading will seriously affect the control accuracy of the axial loading. The axial loading and the radial loading couple with each other and affect each other. This strong coupling will significantly decrease the control precision of the axial loading and the radial loading. To sum up, a suitable decoupling method should be studied urgently.

3. Working Principle of the Mechanical Decoupling Control Device

The mechanical decoupling control device is designed as Figure 1 shows. Unlike the decoupling control, it is a pure mechanical decoupling method. This mechanical decoupling control device can be considered as an automatic compensation device, which consists of air-water container, displacement sensor, rubber airbag, high-pressure transducer, switch valve, SMC E/P regulator, filter, desiccator, pump, air container, conventional pneumatic valves and other components. The working principle of the mechanical decoupling control device comes from the idea of the “pressured-air-water”, which uses the air compressibility to absorb the pressure fluctuation of the water. The core of the mechanical decoupling control device is the air-water container as Figure 1 (24) shows. Therefore, the coupling between the axial loading and the radial loading will be greatly decreased because the air has a greater compressibility.

The air-water container and the common hydraulic accumulator are essentially different. In order to ensure the same absorption capacity at different confining stresses (the radial loading), the volume of the rubber airbag (Figure 1 22) is required to keep constant. So the volume control of the rubber airbag is the key issue. A built-in rope displacement sensor is used to detect the volume changes. The initial phase of the test: The axial direction and the radial direction require slowly loading. At the same time, the volume of the rubber airbag is control by the SMC E/P regulator and the rooster valve and the volume remains unchanged during loading. Test phase: The mechanical decoupling control device makes automatically decoupling effect during loading. The end phase of the test: The axial direction and the radial direction require slowly unloading. The volume of the rubber airbag is controlled synchronously during unloading. The volume control of the rubber airbag relies on the high-precision SMC E/P regulator. The control precision requirement at the initial/end phase of the test is not high. So the conventional PID controller could meet the requirement. In addition, the mechanical decoupling control device plays an important role in stabilizing water pressure when a lack of water at filling water phase happens.

In order to simplify the mechanical decoupling control device, the following assumptions are given to build the mathematical model of the mechanical decoupling control device in this paper: (1) The compressibility of the water would be omitted compared with the air; (2) The water flow in the pipeline can be considered as laminar flow; (3) The connecting pipeline would be considered as part of air-water container. (4) The influence of rubber airbag is neglected. (5) The total cavity volume is equal to the air volume. Under above conditions, the real model of the mechanical decoupling control device could be simplified as [24]:

$$P_o - P_g = \frac{1}{A_g^2}\left(m_g \frac{dQ_g}{dt} + B_g Q_g\right) \tag{1}$$

$$Q_g = -\frac{dV_g}{dt} \tag{2}$$

Where P_o is the inlet/outlet pressure of the mechanical decoupling control device; P_g is the air pressure in the mechanical decoupling control device, Pa ; A_g is the convertible cross-sectional area of the water cavity, m^2 ; m_g is the convertible quality of the water cavity (including pipelines, connecting valves), Kg ; Q_g is the inlet/outlet flow of the mechanical decoupling control device, $m^3/\min$; B_g is the convertible equivalent viscous damping, $N/(m/s)$; V_g is the air volume, m^3 .

The volume change of the air in the mechanical decoupling control device could be taken as a reversible multivariable process, which satisfies the law of the thermodynamics equation:

$$P_{g0}V_{g0}^n = P_g V_g^n \tag{3}$$

Where P_{g0} is the air pressure in balance, Pa ; V_{g0} is the air volume in balance, m^3 ; P_g and V_g have the same meanings as formula (1), which are changing over time; n is the coefficient.

According to the Taylor's theorem, the expansion equation of formula (3) around working balance point (P_{g0} , V_{g0}) could be expressed as:

$$P_g V_g^n = P_g V_{g0}^n + P_g n V_{g0}^{n-1}(V_g - V_{g0}) + \frac{P_g n(n-1)V_{g0}^{n-2}(V_g - V_{g0})^2}{2} + \cdots\cdots \tag{4}$$

Compared with the balance volume V_{g0} and the balance air pressure P_{g0}, the changes of the V_g and the P_g are relatively small. So the formula (4) could be simplified as:

$$P_g V_g^n \approx P_g V_{g0}^n + P_{g0} n V_{g0}^{n-1}(V_g - V_{g0}) \tag{5}$$

The formula (3) could be written as:

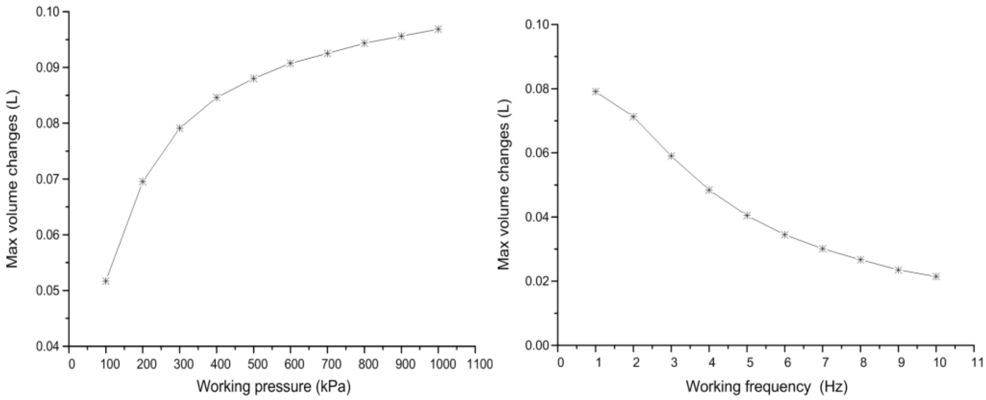
$$(P_{g0} - P_g)V_{g0}^n = P_{g0} n V_{g0}^{n-1}(V_g - V_{g0})$$

$$\Delta P V_{g0}^n = P_{g0} n V_{g0}^{n-1}(-\Delta V)$$

$$\frac{dP_g}{dt}V_{g0}^n = -P_{g0} n V_{g0}^{n-1}\frac{dV_g}{dt} \tag{6}$$

With the help of the Laplace transform, the following equation is obtained by merging formula (6), formula (2) and formula (1):

$$\frac{Q_g(s)}{P_o(s)} = \frac{\dfrac{V_{g0}}{nP_{g0}} \bullet s}{\dfrac{m_g V_{g0}}{nA_g^2 P_{g0}} \bullet s^2 + \dfrac{B_g V_{g0}}{nA_g^2 P_{g0}} \bullet s + 1} \tag{7}$$



(1) Changing Working Pressure (2) Changing Working Frequency

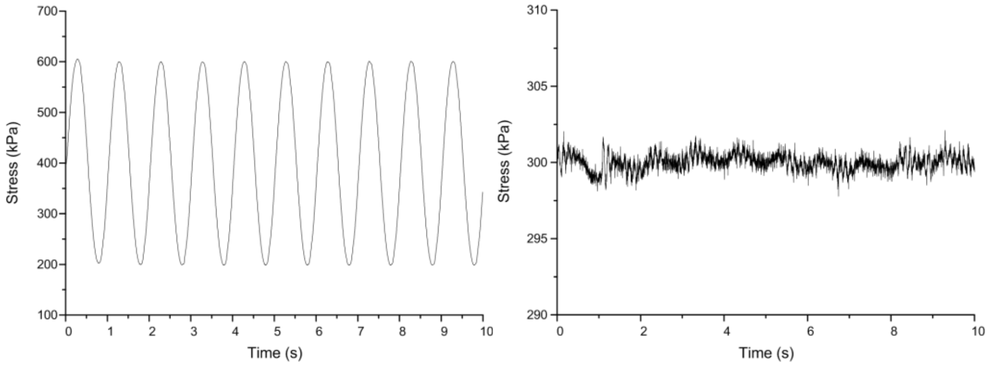
Figure 1. Decoupling Ability of the Mechanical Decoupling Control Device

Formula (7) has expressed the relationship between pressure and volume in the frequency domain. The following simulation work is used to test dynamic characteristic of the mechanical decoupling control device. The dynamic characteristic shows the decoupling ability in the system. A connecting pipe (length is 1 m and the diameter 15 mm) is adopted in the simulation. The air volume in balance is 3.15 L and the bulk modulus of water is 2200 MPa . The simulation results are shown in the Figure 3.

The decoupling ability test was conducted at different working pressures and different working frequencies. In Figure 3 (1), the working pressures (the horizontal axis) are 100 kPa , 200 kPa , 300 kPa , 400 kPa , 500 kPa , 600 kPa , 700 kPa , 800 kPa , 900 kPa and 1000 kPa and a 1 Hz sine wave pressure is added. The initial air volumes at different working pressures are the same, which are equal to 3.15 L . If the changes (1 Hz sine wave pressure) of the working pressure are about 5%, the max air volume changes (the vertical axis) could be obtained at the same time. The max air volume change represents the decoupling ability of the mechanical decoupling control device. The bigger the max air volume changes, the better the decoupling ability. From Figure 3 (1) it can be seen that the decoupling ability is increasing when the working pressure is increasing. Similarly, in Figure 3 (2), a 300 kPa pressure is applied and the working frequencies are 1 Hz , 2 Hz , 3 Hz , 4 Hz , 5 Hz , 6 Hz , 7 Hz , 8 Hz , 9 Hz and 10 Hz . The initial air volumes at different working frequencies are the same, which are also equal to 3.15 L . If the changes of the working pressure (300 kPa) are about 5%, the max air volume changes could also be obtained at the same time. From Figure 3 (2) we can see that the decoupling ability is decreasing when the working frequency is increasing. Compared with the sample coupling ((2) in Figure 2), the rod coupling ((1) in Figure 2) plays the main role during the dynamic triaxial test. The diameter of the rod is about 22 mm and the max movement of the rod is about 10 mm in the real experiment. The max volume change that caused by the movement of the rod is very small, which is about 0.0038 L . From Figure 3, we can infer that the change of the working pressure is much less than 5%. The strong couplings for the electro-hydraulic dynamic triaxial instrument will be decoupled by using the mechanical decoupling control device.

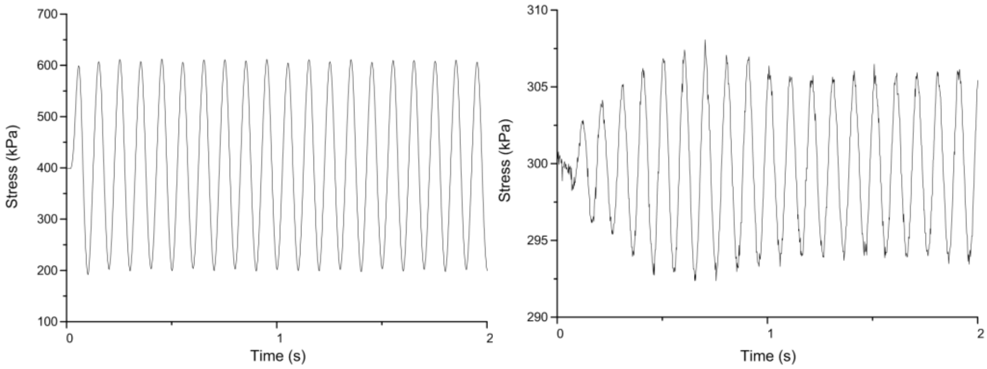
4. Experiments

In order to testify the decoupling ability of the mechanical decoupling control device, a series of experiments have been done in the laboratory. The diameter of the soil sample is about 101 mm and the height of the soil sample is about 200 mm . First, the axial loading subsystem applies the constant stress (400 kPa) on the soil sample in the axial direction and the radial loading subsystem applies the constant stress (300 kPa) on the soil sample in the circumferential direction. Then, the axial loading subsystem adds another sine wave stress (the frequency is 1 Hz /10 Hz and the amplitude is 200 kPa). The diameter of the rod is 22 mm and the max movement of the rod is less than 10 mm in the test. The experiments are conducted with or without the mechanical decoupling control device. 500 testing data will be recorded per second during the test. The testing results are shown in the Figure 4, Figure 5, Figure 6 and Figure 7.



(1) The Axial Exciting with 1Hz Sine Wave Load (2) Coupling Result

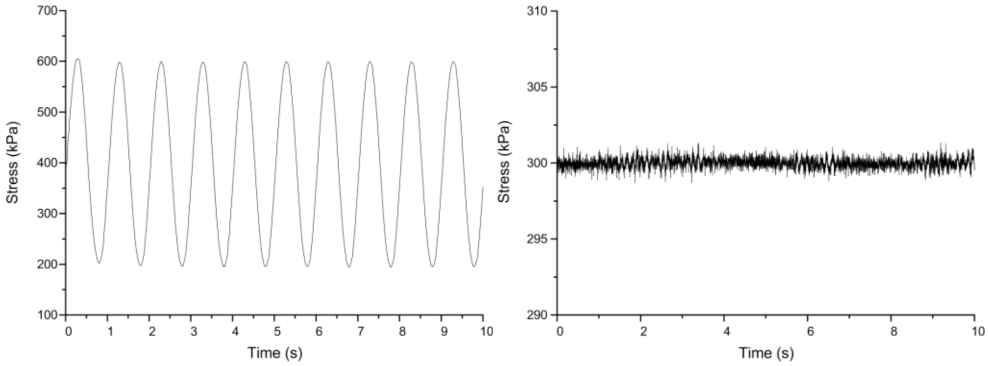
Figure 2. 1Hz Exciting Load without the Mechanical Decoupling Control Device



(1) The Axial Exciting with 10Hz Sine Wave Load (2) Coupling Result

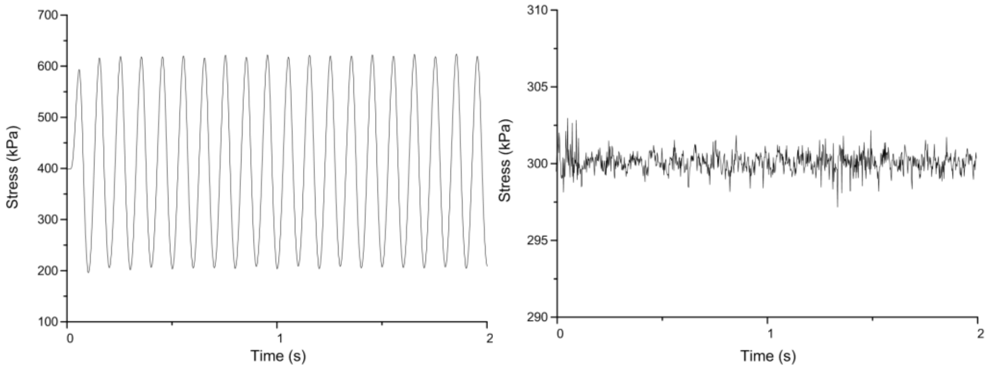
Figure 3. 10Hz Exciting Load without the Mechanical Decoupling Control Device

Figure 4 and Figure 5 are conducted at different exciting frequencies without the mechanical decoupling control device. Figure 4 (1) and Figure 5 (1) are results of axial loading subsystem adding two sine wave loads with 1 Hz and 10 Hz respectively in the axial direction, which causes the movement of the rod and the distortion of the soil sample. The volume change of the rod and the distortion of the soil sample affect the constant stress in the circumferential (radial) direction. Figure 4 (2) and Figure 5 (2) show the coupling result (Because only 500 testing data are recorded in 1 s, the coupling result in Figure 4 (2) looks more dense compared with the coupling result in Figure 5 (2)). Comparing Figure 4 (2) with Figure 5 (2), it could be found that the coupling in the axial exciting with 10 Hz is more serious. Here is the explanation. The radial loading subsystem has a good response and the frequency of the axial exiting is only 1 Hz. In this condition, the radial loading subsystem can automatically compensate the change of the stress/pressure. So the coupling influence is not apparent. However, the radial loading subsystem could not automatically compensate the change of the stress/pressure when the frequency of the axial exiting is increased up to 10 Hz . That's why the coupling influence in Figure 5 (2) looks more serious.



(1) The Axial Exciting with 1Hz Sine Wave Load (2) Decoupling Result

Figure 4. 1Hz Exciting Load with the Mechanical Decoupling Control Device



(1) The Axial Exciting with 10Hz Sine Wave Load (2) Decoupling Result

Figure 5. 10Hz Exciting Load with the Mechanical Decoupling Control Device

Figure 6 and Figure 7 are conducted at different exciting frequencies with the mechanical decoupling control device. Figure 6 (1) and Figure 7 (1) are results of additional two sine wave loads with 1 Hz and 10 Hz that are applied in the axial direction. Comparing the sine wave loads in Figure 4 (1)/Figure 6 (1) and Figure 5 (1)/ Figure 7 (1), it could be found that the additional axial exciting loads are almost same. The same soil sample is used in the experiment. So the movement of the rod and the distortion of the soil sample are same. Comparing Figure 6 (2) with Figure 7 (2), it could be found that the couplings under the axial exciting stresses with 1 Hz and 10 Hz are very tiny. The volume change of the rod and the distortion of the sample do not affect the constant stress/pressure in the circumferential (radial) direction. The mechanical decoupling control device can automatically compensate the change of the stress/pressure. It works pretty well.

5. Conclusion

The coupling has interaction characteristics that make the system hard to be controlled. This is the reason why many scholars have been doing a lot of work to find reasonable decoupling ways. The decoupling control methods, including classical decoupling control method, feedback decoupling control method, adaptive decoupling method and today's intelligent decoupling control method, has been studied in the past. Unlike those decoupling control methods, a novel pure mechanical decoupling control device has been developed in this paper, which is used for the electro-hydraulic dynamic triaxial instrument to decouple the strong coupling between the axial loading subsystem and the radial loading subsystem automatically. The working principle of the mechanical decoupling control device has been presented and the decoupling ability has been studied by simulation. A series of experiments have been done to testify the decoupling ability of the mechanical decoupling control device. The experimental results show that this kind of mechanical decoupling control device works pretty well for the electro-hydraulic dynamic triaxial instrument. The mechanical decoupling control device has some advantages like low cost, simple structure and convenient control, which could be easily used in other similar occasions.

Acknowledgments

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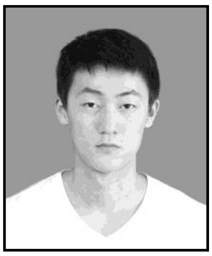

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